

Relationships between typhoon types and debris flow disasters in Taiwan

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Abstract Frequent debris flow disasters caused by heavy precipitation during the annual typhoon season are some of the most serious disasters in Taiwan. This study is on the debris flow disasters associated with the typhoons that hit Taiwan between 1986 and 2004. Typhoon data and records of debris flow disasters available for Nantou and Hualien counties in Taiwan were analyzed. The paths and rainfall characteristics of typhoons were found to have a great effect on the debris flows at these locations. Accordingly, the typhoons were grouped into four major types based on their paths and related disasters. The relationships between rainfall intensity and accumulation and debris flow are discussed for the four major typhoon types. The information may form the basis for providing useful indicators for disaster management.

Keywords Debris flow · Hazard · Disaster · Rainfall characteristics · Typhoon

1 Introduction

The impact of disasters in Taiwan has grown tremendously in the past few decades as a result of land development in the mountainous areas. The moist air currents coming from China and the Pacific Ocean induce frequent heavy rains in Taiwan, and it is severely

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affected by typhoons. The 2,500 mm annual average rainfall is very concentrated in a specific, short period within the typhoon season, from May to October. In recent years, debris flows have become one of the major types of disasters in Taiwan, causing casualties, injuries, and major property loss. After typhoons and heavy downpours, piles of gravel and boulders transported by water were deposited on the roadways and sometimes posed serious threats. Many of these sites were repeatedly affected by debris flows.

According to the statistics of the Soil and Water Conservation Bureau (SWCB), the agency responsible for all issues related to debris flow in Taiwan, there has been a total of 1,503 streams vulnerable to debris flow, according to the classification system of SWCB. Records of past debris flow disasters showed that Nantou and Hualien (Fig. 1) are the two counties that are most vulnerable to debris flows. There are a total of 199 and 160 debris flow prone streams in Nantou and Hualien, respectively. These areas show the most serious accumulated losses according to the National Fire Agency (NFA 2004), the agency responsible for disaster management and rescue operations. Thus, these two neighboring counties are selected as the study areas.

The relationships between weather and disaster features are undoubtedly location-specific. There are many publications that discussed typhoon and rainfall accumulation in Taiwan (e.g., Chang 1982; Chang et al. 1993; Chen and Yan 2003; Wu et al. 2002). However, many studies focused on specific typhoon events and explored the features of debris flow occurrences or their resulted failures (such as Chen and Petley 2005; Cheng et al. 2005; Yu et al. 2006; Wang 2006; Wang et al. 2008). There were also some papers discussing the relationship between typhoons and debris flow occurrences with an emphasis on the rainfall features. For example, Lin and Jeng (2000) pointed out the characteristics of landslides and debris flows induced by heavy rainfall in Taiwan. Some other studies were centered on the rainfall accumulation and rainfall intensity, and debris flow occurrence and rainfall accumulation (Lin and Jeng 2000; Chen 2005). There were also many researches on the rainfall threshold criteria for debris flow occurrence, such as Shieh et al. (1995) and Fan et al. (1999). The above-mentioned papers were focused on the rainfall features and debris flow occurrence.

Besides, there were also some other researches, such as Liu (2000) and Chang (1994), that discussed the indicators leading to debris flow disasters in certain areas, and Wang et al. (2008) who documented different types of geological and structural failures caused by recent debris flows. Some studies considered the features of typhoon, such as Chen et al. (2003, 2004). However, there is still a lack of research that is focused on the relationships between debris flow disasters and the types of typhoons. Typhoon rainfall data, such as the relationships between rainfall characteristics and the distance between rain gauge stations and typhoons, have never been related to debris flow occurrences. Therefore, in this study, the meteorological data were reviewed and reorganized to illuminate the relationship between rainfall intensity and occurrence of debris flows, the relationship between the data from the rain gauge stations and their location/distance with debris flows, and the relationship between rainfall accumulation and debris flow disasters. The main purpose of this study is to clarify the features of typhoon paths that resulted in debris flow disasters in Taiwan. The insights gained from this study can be used by emergency management agency to prepare for disasters and estimate needed response efforts.

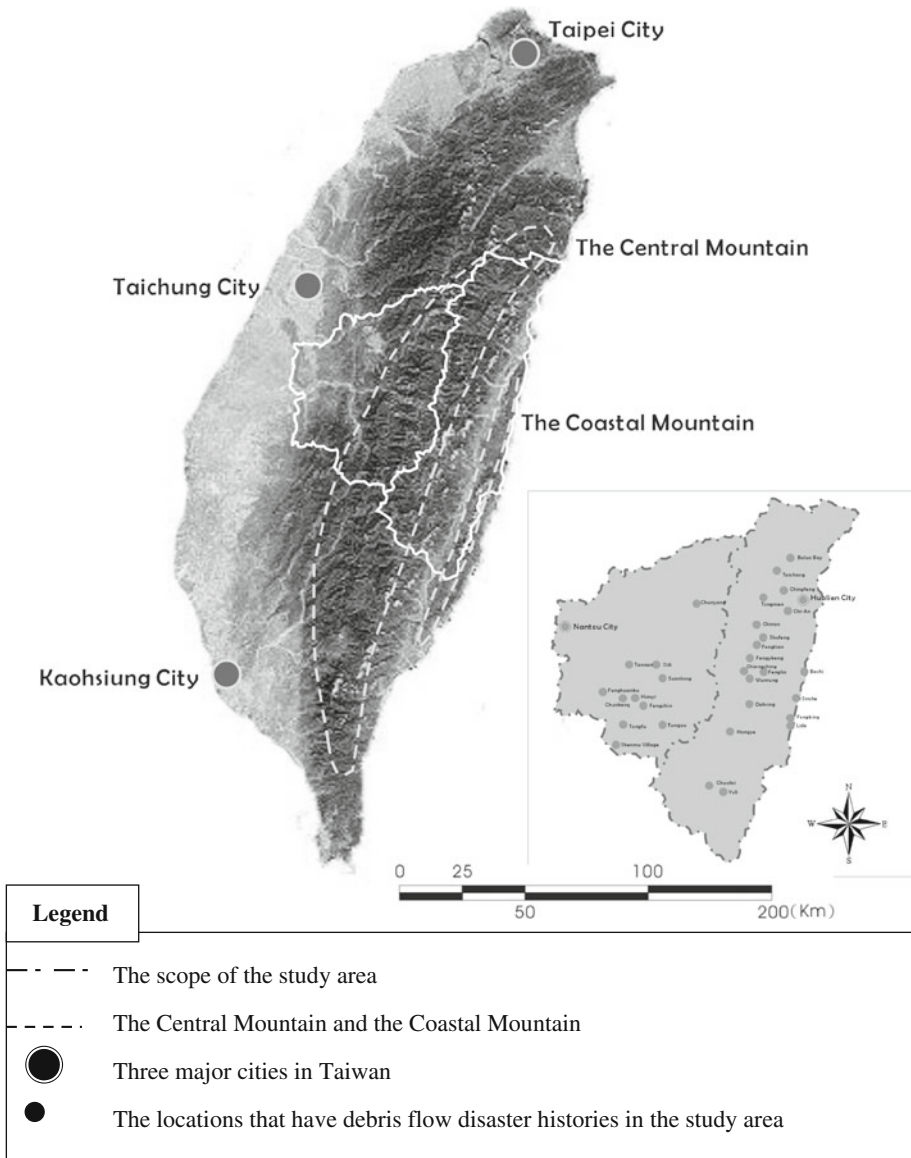


Fig. 1 The study area comparative location to Taiwan and the comparative locations of disaster affected area mentioned in Table 1

2 Typhoon types associated with debris flow disasters

Typhoons can be classified according to their paths, accumulated rainfall, and rainfall characteristics. Meteorological data from rain gauge stations were sorted according to the rainfall reports from the Central Weather Bureau (CWB).

In this study, a total of 15 typhoons that occurred between 1986 and 2004 were analyzed. These storms caused 354 debris flow disasters in the study area. The nationwide

losses of life and property resulting from these 15 typhoons are shown in Table 1. Table 2 and Fig. 1 summarize the history of disasters caused by these typhoons in the study area. Based on the classification by the CWB, the magnitude of typhoons can be classified as *tropical depression*, *tropical storm*, *typhoon*, and *super typhoon*. These 15 typhoons are all at “typhoon” and “super typhoon” level. The numbers of the minimum central pressure are between 920 and 928 hPa, and a maximum wind velocity of around 38–55 m/s except Typhoon Sarah.

The following factors were considered in the classification: the difference between rainfall intensities measured by rain gauges in different locations, the relationship between rainfall intensity and duration, and the relationship between typhoon type and rainfall intensity.

Meteorological data contained single and accumulated rainfall records that could be related to typhoon paths. The time of occurrence of all previous debris flows was also taken into account. Since 1962, the CWB has defined a typhoon affecting Taiwan as “a tropical cyclone whose center lands in Taiwan; or that passes by offshore Taiwan instead of having landed in it, but results in disaster conditions being reported en route (Chi 1962).” Affiliated with the CWB and the Water Resource Agency (WRA), there are 90 rain gauge stations throughout the study area (Fig. 2) from which rainfall data was obtained.

2.1 Classifications

CWB classifies typhoon paths into 9 types and 1 other type according to past statistics (CWB Website). There were some factors, such as the occurrence history of debris flow disasters, their severity, the typhoon path, and rainfall characteristics, concerned to explore the impacts of 15 typhoons on the study areas. In order to better understand the relationships between rainfall features and debris flow disasters and also for the purpose of further analysis and organization, this research regrouped the paths defined by the CWB into four types (Fig. 3). Based on the analyzed disaster history and the affected conditions, Types 3 and 4 were regrouped as Type A; Types 1 and 2 as Type B; and Type 9 as Type C. Types 6 and 8 have very similar influences to the study area, so they were regrouped as Type D in this study. Note that not all types of typhoon paths resulted in debris flow disasters in the study area, thus Types 5 and 7 were not included in this study. The comparison between the four types established in this paper and the 9 types presented by the CWB is shown in Table 3. The four types of typhoons in this study are elaborated as follows:

Type A (CR): passing through the mainland of Taiwan from east to west and then moving to the west or northwest. For example, Typhoon Toraji belongs to Type A, and its 4-day duration resulted in 42 debris flow disasters.

Type B (NE): moving along the upper eastern coast and then moving toward the west or northwest. These typhoons were less likely to be affected by the mountains, so the high rainfall intensity resulted in significant damages. For example, Typhoon Herb, which affected Taiwan from July 29 to August 1, 1996. The circulating air currents brought about heavy rainfall and resulted in many debris flow disasters and floods throughout the western region of Taiwan.

Type C (SW): Most typhoons arrived from the east and landed first on the eastern portion of Taiwan. In contrast, typhoons of Type C either arrived from the west or directly targeted the western margin of Taiwan and had direct impact on the central western area.

Type D (SE): slipping to the northeast coast or the Pacific Ocean from the southeast side of Taiwan. These types of typhoon generally caused fewer disasters. For example,

Table 1 Nationwide property and life losses resulting from typhoons from 1986 to 2004

Year	Warming period	Typhoons	Minimum central pressure (hpa)	Maximum wind velocity (m/s)	Reported magnitude	Property Economic losses (US\$ Millions) ^a	Life Death/missing (persons)	Buildings		
								Injuries (persons)	Collapsed (households)	
								Semi-collapsed (households)		
1986	08/20–08/23	WAYNE	951.0	46.0	Typhoon	376.59	87	422	6,624	31,532
	08/24–08/25									
	08/28–09/03									
1989	09/08–09/13	SARAH	952.0	28.0	Super typhoon	186.79	52	47	430	760
1990	06/21–06/24	OFELIA	968.0	38.0	Typhoon	53.68	38	10	88	139
1990	09/06–09/08	DOT	960.0	38.0	Typhoon	40.94	10	4	47	71
1991	09/22–09/24	NAT	945.0	51.0	Super typhoon	10.87	7	11	29	52
1994	07/09–07/11	TIM	945.0	53.0	Super typhoon	193.60	23	70	181	180
1996	07/29–08/01	HERB	920.0	53.0	Super typhoon	1,476.34	73	463	503	880
1998	10/13–10/17	ZEB	920.0	55.0	Super typhoon	324.72	38	27	4	26
2000	08/21–08/23	BILIS	930.0	53.0	Super typhoon	252.76	21	112	434	1,725
2000	10/30–11/01	XANGSANE	960.0	38.0	Typhoon	177.78	89	65	N/A	N/A
2001	07/28–07/31	TORAJI	962.0	38.0	Typhoon	503.95	214	188	645	1,972
2001	09/08–09/10	NARI	960.0	40.0	Typhoon	176.41	104	265	N/A	N/A
	09/13–09/19									
2004	06/28–07/03	MINDULLE	942.0	45.0	Typhoon	240.69	4	4	270	0
2004	08/23–08/26	AERE	960.0	48.0	Typhoon	54.92	29	395	72	44
2004	12/03–12/04	NANMADOL	940.0	45.0	Typhoon	27.82	4	1	N/A	N/A

Based on the classification by the Central Weather Bureau, Taiwan, the magnitude of typhoons can be classified as tropical depression, tropical storm, typhoon, and super typhoon in Taiwan

^a Includes losses of crop, livestock, fishery, forestry, and related losses of cultivated land, fishery facility, forestry facility, and soil and water conservation, railway system, highway system and harbors, not includes the losses of physical infrastructures, such as roads and bridges

Source: Central Weather Bureau and National Fire Agency, Taiwan

Table 2 Disaster history of the study area

Year	Name	The locations and conditions of debris flows
1986.08	WAYNE	Singyi, Nantou
1989.10	SARAH	Ruisui, Yuli and Fenglin River in Hualien
1990.06	OFELIA	Tongmen, Chingfeng and Yuli, Hualien (The typhoon brought in 430 mm rainfall (106 mm/h max))
1990.09	DOT	Hongye; Fahuashan Temple, Taichang, Hualien. four deaths
1991.09	NAT	Sinfeng, Bachi and Lide, Hualien
1994.08	TIM	Fahua Mountain, Chi-an, Sinshe, Gaoliao, Hedong, and Yuli
1996.08–09	HERB	Singyi (Fengchui, Chunkeng, Shenmu Village and Tongfu) alongside Chenyoulan River in Nantou
1998.10	ZEB	Fengyikeng, Fenglin, Chianching, Dongxing, Wanrong, Sinshe, Fengbing and Shoufengchi in Hualien
2000.08	BILIS	Yuli and Fengli, Hualien
2000.01	XANGSANE	268 debris flow sites reported. The losses in agricultural, forestry, fishery, and pasturing fields reached approximately US\$ 108 million
2001.07	TORAJI	Luku, Shuili, Hsinyi of Nantou. Chianching, Fenglin, Dahsing, Hualien
2001.09	NARI	Wudu, Huoshaoliao
2004.07	MINDULLE	51 debris flow sites in Nantou. The losses in agricultural, forestry, fishery, and pasturing fields were over US\$ 30 million
2004.08	AERE	The losses in agricultural, forestry, fishery, and pasturing fields reached approximately US\$ 60 million
2004.12	NANMADOL	Buluo Bay, Hualien. 4 deaths/missing. The losses in agricultural, forestry, fishery, and pasturing fields reached approximately US\$ 2 million

Source: Collected from Typhoon Reports of the Central Weather Bureau and Disaster Reports of the National Fire Agency and records of the Soil and Water Conservation Bureau

Typhoons Zeb of 1998 and Xangsane of 2000 arrived in Taiwan and both occurred in October. The surrounding circulation currents with abundant rainfall carried by the northeastern wind season resulted in debris flow disasters in Hualien, though the losses were less severe than those caused by typhoons of Types A and B.

According to the proposed classification scheme, Type C directly influenced Nantou, while Type A had a direct impact on Hualien. Generally, because of the barrier of the Central Mountain ranges, the typhoons from the east had a limited influence on the Nantou area. However, debris flow disasters frequently occurred as a result of abundant rainfall brought about by the surrounding circulating currents following the typhoons. Particularly, the surrounding circulating air current in the autumn plus the availability of rainfall introduced by the northeastern seasonal winds increased the risk of debris flow disasters.

The rainfall data obtained from CWB and WRA were analyzed and classified according to the types defined above. The relationships between rainfall characteristics and types are discussed next.

2.2 Definition of points and phases in the typhoon event

In this study, in order to better analyze the features of each typhoon type, five points along each typhoon path were considered. Points 1 and 5 were set based on the announcement of the CWB. Point 3 was chosen by observation. Points 2 and 4 were

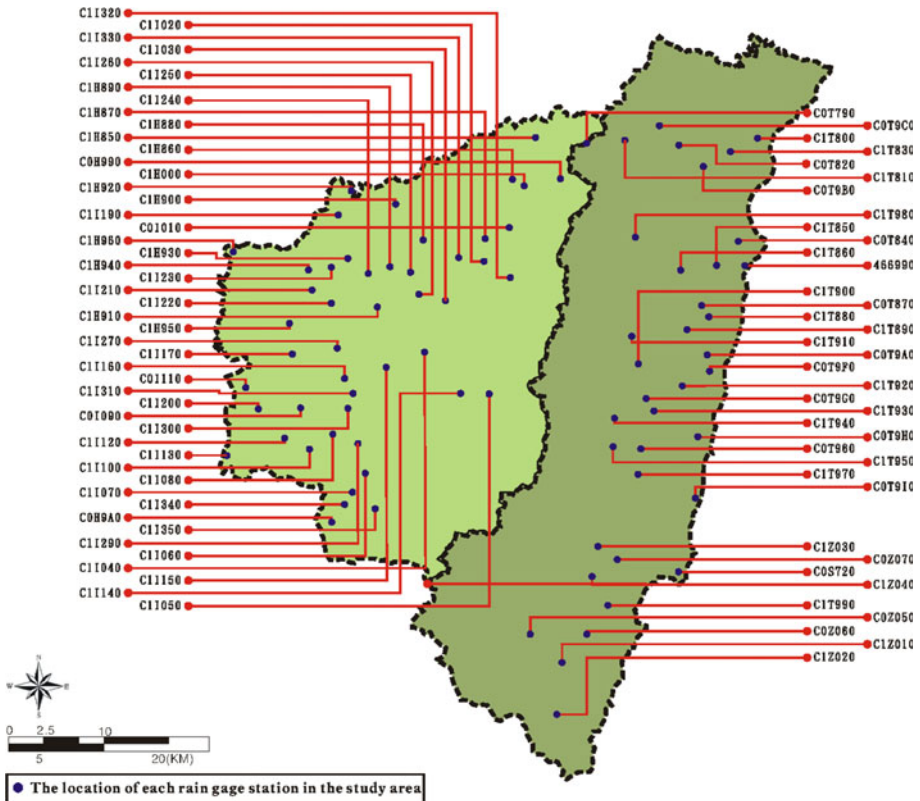
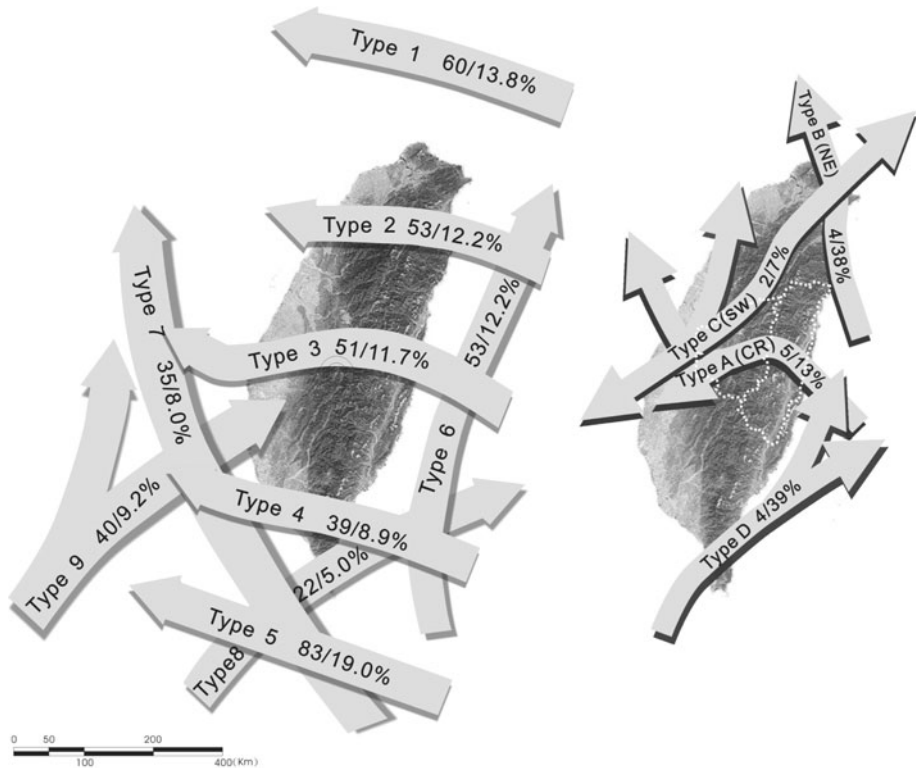


Fig. 2 Black dots denote the locations of rain gauge stations located within the study area

chosen in this study for the needs of future analysis. Each typhoon event can thus be divided into four phases (Fig. 4). The definition of, and detailed information about, these five points are as follows:

- Point 1 (Starting point): beginning of the rainfall record. This point is considered to be the point where any of the rainfall stations recorded the first rainfall associated with the event.
- Point 2 (Interim point I): the location in the middle of the starting point and the nearest point (Point 3). It is based on the geographical point of the moving path.
- Point 3 (Nearest point): the nearest point of the typhoon’s path to the study area. If the typhoon passed through the study area, this point was chosen in the middle of the study area.
- Point 4 (Interim point II): the location in the middle of the nearest point and the relief point (Point 5).
- Point 5 (Point of Relief): either the typhoon warning was dismissed by CWB or the rainfall was no longer recorded at any rain gauge stations. Usually, after the dismissal of typhoon warnings, the rainfall intensity would also decrease. However, under certain specific conditions, rainfall continued, in which case the point meeting both conditions was set as Point 5.



9-path classification of the CWB (left); 4-path classification of this research (right)
Source: Modified from Central Weather Bureau website.

Fig. 3 9-path classification of the CWB (*left*); 4-path classification of this research (*right*)

The four phases are defined as follows:

- Phase 1 (Initial Stage): this is the developing stage of the typhoon—the duration between the starting point and the interim Point 1.
- Phase 2 (Approaching Stage): the interval between the interim Point 1 and the point in the typhoon's path nearest to the study area.
- Phase 3 (Leaving Stage): the time between the nearest point and the interim Point 2. This is the stage where the typhoon departed from the study area.
- Phase 4 (Distant Stage): the duration between the interim Point 2 and the point of relief. This is the period in which the typhoon event ended.

The rainfall trends are classified according to the number of peaks. If a particular period experienced rainfall intensity much higher than any other period of the same storm, it is considered to have a single peak. If rainfall intensity is observed to reach a peak, then diminish, and then increase again to another peak, the trend is classified as a double peak.

Different models can be used to calculate the distances between points on the earth surface. "Ellipsoidal [Earth] models define an ellipsoid with an equatorial radius and a polar radius. The best of these models represents the shape of the Earth (Dana 1995)." In this study, the WGS-84 geoid height model, which was adapted by the US National Imagery and Mapping Agency (formerly the Defense Mapping Agency) (National Imagery

Table 3 The comparison between the four types established in this study and the nine types presented by the CWB

Typhoon paths classified by this study				Typhoon paths classified by the CWB			
Type	Total numbers	Ratio of selected typhoons (%)	Typhoons' name	Type	Total numbers	Ratio of typhoons (%)	Ratio of all typhoons (%)
A	5	33.3	Toraji (2001), Tim (1994), Sarah (1989)	3	51	11.7	20.6
			Bilis (2002), Dot (1990)	4	39	8.9	
B	4	26.7	Aere (2004)	1	60	13.8	26.0
			Mindulle (2004), Herb (1996), Ofelia (1990)	2	53	12.2	
C	2	13.3	Nari (2001), Wayne (1986)	9	40	9.2	9.2
D	4	26.7	Xangsane (2000), Zeb (1998)	6	53	12.2	17.2
			Nanmadol (2004), Nat (1991)	8	22	5	
–				5	83	19	19
				7	35	8	8

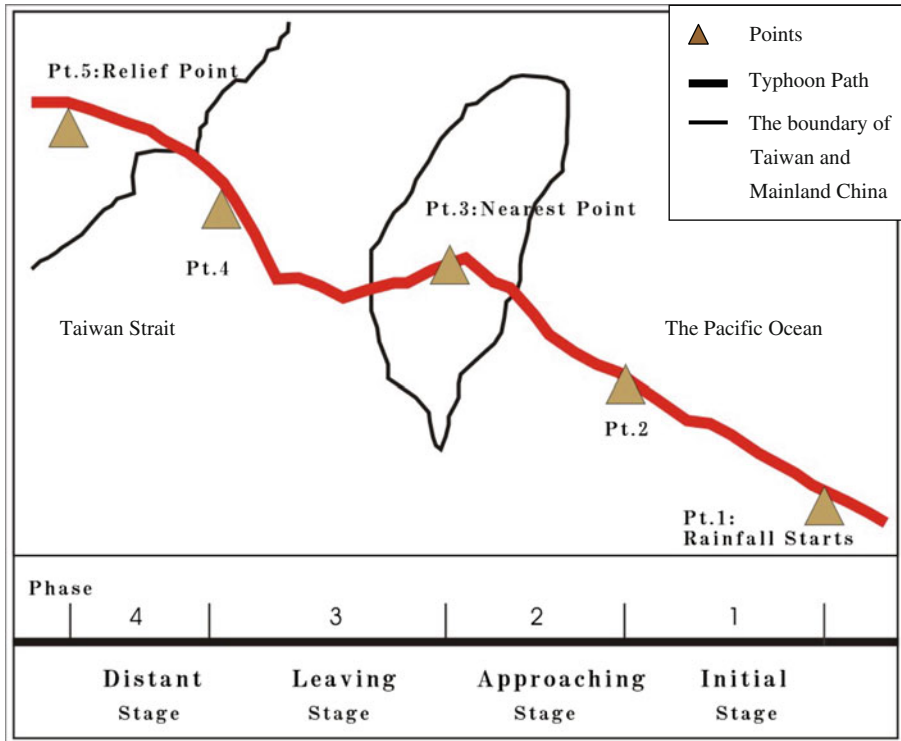


Fig. 4 Illustration of points and phases

and Mapping Agency 1997), was used to calculate the distance at any point in the typhoon path to each rain gauge station. Some major definitions and values of this ellipsoid are as follows:

- Semi minor axis = polar radius = b (WGS-84 value = 6,356,752.3142 m)
- Semi major axis = polar radius = a (WGS-84 value = 6,378,137.0 m)
- Flattening = $f = (a - b)/a$ (WGS-84 value = 1/298.257223563)
- First eccentricity squared = $e^2 = 2f - f^2$ (WGS-84 value = 6.6944×10^{-3})

A sample calculation of points and rain gauge stations is shown in Table 6.

3 Rainfall, debris flow features, and disaster responses associated with different typhoon types

This section discusses rainfall intensity, distance, and rainfall accumulation according to typhoon paths. It then deals with typhoon rainfall data measured by rain gauge stations in each area. The relationships between rainfall accumulation and rainfall intensity for each type of typhoons are established. The rainfall trend in each phase is classified as having either a single peak or a double peak. Finally, the areas with “Debris Flow Disasters” (DFD) and those with “No Debris Flow Disasters” (NDFD) were distinguished, and these areas were analyzed based on their characteristics and differences.

Data on debris flow occurrence were gathered from the SWCB, statistical reports on disasters from the Ministry of Internal Affairs, reports on disaster situations and records on search and rescue from the NFA, as well as relevant studies from the National Science and Technology Center for Disaster Reduction and the office of National Science and Technology Program for Hazards Mitigation. The time and location of debris flow disasters could be determined from 354 data sets on the conditions of the rescue efforts. Relevant debris flow locations were then associated with the closest rain gauge station. Accumulated rainfall data and positions of debris flow areas were obtained. The frequency and history of debris flows in the vicinity of each rain gauge station were summarized. The proportions of debris flows caused by different types of typhoons (Types A–D) during different Phases (1–4) were determined. The timings were used to analyze the characteristics of each disaster event, and these were made available for reference by disaster management organizations. According to current accumulated data, the numbers of debris flow disasters caused by the four different types of typhoons are 94, 148, 44, and 68, respectively. That is, the disaster cases for Types A, B, C, and D typhoons, respectively, account for 26.55, 41.48, 12.43, and 19.21% of total debris flow disasters.

Furthermore, the validity of the four types of classifications was confirmed by comparing the common situations and results of each typhoon. In addition, based on the statistics from all rain gauge stations, the probability of debris flow occurrence following a given rainfall in each area could be determined. This study tried linear, logarithmic, and trinomial analyses to test the relationship between rainfall intensity and distance. Trinomial analysis resulted in the best fit to the data and revealed obvious differences among the four typhoon types. The regression model was used to reveal the relationship between rainfall intensity, distance, and typhoon phases. The CWB also provides a classification standard in evaluating the severity of rainfall events, which also helped to assess the rainfall conditions causing debris flow disasters. The results obtained for the four typhoon types are discussed below.

3.1 Type A

From the statistical data, it was found that typhoons of Type A, which directly crossed Taiwan, resulted in relatively serious damages and casualties due to debris flows. When the areas were subjected to direct typhoons, a vicious circle was formed. The burden of recovery efforts left the communities, both the environment and the residents, more vulnerable to the disasters, worsening the disaster conditions.

It was found during observations of these types of typhoons that the rainfall in the first phase tended to be the lowest among the four phases of typhoons classified in this study. However, as typhoons approached or swept over Taiwan, the accumulated rainfall increased substantially. Over 40% of debris flow disasters occurred in the second phase (Fig. 5). Of all the debris flow disasters (DFD) caused by all typhoon types (Table 5), more than 10% occurred in the second phase of Type A typhoons.

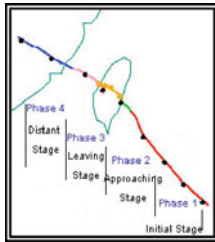
It was discovered that 20% of debris flows for typhoons of Type A occurred when rainfall accumulation reached 120 mm. This amount can be viewed as an important threshold for debris flow hazard occurrence. Nearly three quarters of all debris flow disasters occurred when rainfall accumulated between 120 and 180 mm. This period is classified as “high risk” (Table 4) and has a debris flow disaster occurrence ratio higher than 8% in each interval. However, some extreme cases resulted in continuous debris flow disasters, such as Typhoon Toraji in 2001, when the rainfall accumulation in Nantou ranged from 90 to 220 mm/h.

In Type A typhoons, it was found from the trinomial analysis (Fig. 6) that rainfall intensity had a positive correlation with the path, while the peak of rainfall occurred in Phase 2 about 150 km away from the study area. The hourly average rainfall intensity (provided by the CWB) was approximately 30 mm/hr in the debris flow disaster areas reported by the SWCB and NFA. In the area not affected, it was relatively low, at about 10 mm/h. On average, rainfall was generated when the typhoons were at a distance of 600 km away from the study area and stopped when the storm was 1,300 km away. However, for such typhoons, the rainfall intensity varied to a great extent. The CWB standard classifies heavy rain as 50 mm/day with cloudbursts being 130 mm/day. Precipitation in many rain gauge stations was recorded up to 120 mm/h.

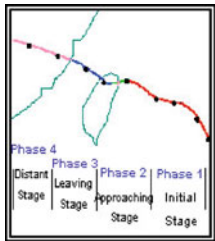
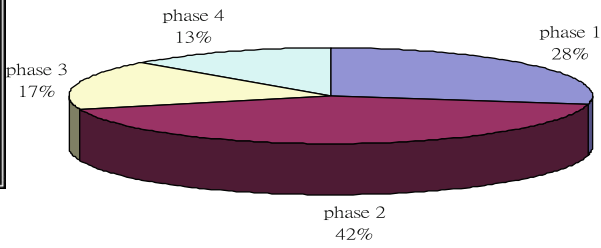
3.2 Type B

The relevant statistical data showed that when Type B typhoons swept over the north-eastern part of Taiwan, there was very severe damage and many casualties resulting from debris flows, and the total amount of debris flow disasters in Type B typhoons accounted for roughly half of all documented debris flow disasters. This typhoon path requires special attention. Among the four phases of typhoons classified in this study, the main disasters occurred in the period when the typhoon started to leave Taiwan (Table 5). Continuous rainfall gradually increased the water content of soils to a saturation level as the typhoons approached Taiwan. This type of typhoon introduced a large amount of southwest airflow as they moved away from Taiwan, which resulted in a rapid increase in rainfall. This rainfall makes slopes unstable. Debris flows carried debris to other unstable slopes, which then collapsed and resulted in more landslides and debris flows.

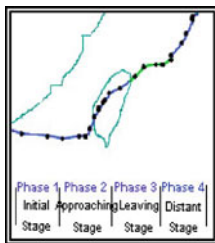
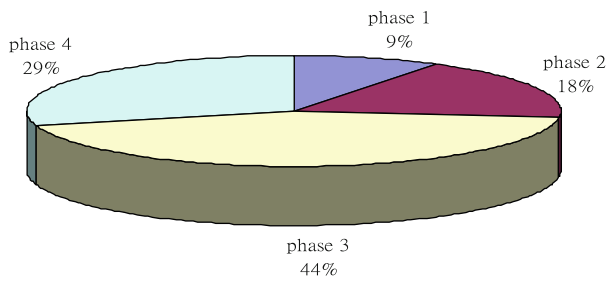
This chain effect makes response work very difficult, thereby resulting in large-scale casualties and losses. From the statistical data, it was found that 40% of debris flow disasters occurred in the third phase of Type B (Fig. 5), accounting for nearly 20% of all debris flow disasters analyzed.



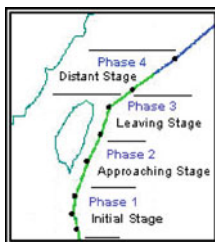
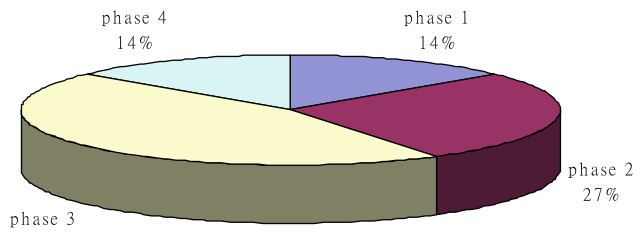
Type A(CR): DFD Occurrence



Type B(NE): DFD Occurrence



Type C(SW): DFD Occurrence



Type D(SE): DFD Occurrence

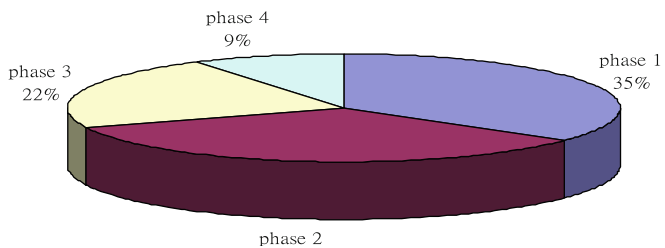


Fig. 5 Distribution of debris flow disasters (DFD) in phases of four types

Table 4 Debris flow occurrence and rainfall accumulation of four types

RA	Type A			Type B			Type C			Type D		
	DFD No.	% of type	% of total	DFD No.	% of type	% of total	DFD No.	% of type	% of total	DFD No.	% of type	% of total
70	0	0.0	0.00	0	0.0	0.00	0	0.0	0.00	1	1.5	0.28
80	0	0.0	0.00	0	0.0	0.00	0	0.0	0.00	1	1.5	0.28
90	1	1.1	0.28	1	0.7	0.28	0	0.0	0.00	2	2.9	0.56
100	1	1.1	0.28	1	0.7	0.28	0	0.0	0.00	3	4.4	0.85
110	0	0.0	0.00	0	0.0	0.00	0	0.0	0.00	2	2.9	0.56
120	20	21.3	5.65	1	0.7	0.28	1	2.3	0.28	6	8.8	1.69
130	13	13.8	3.67	11	7.4	3.11	1	2.3	0.28	9	13.2	2.54
140	15	16.0	4.24	14	9.5	3.95	5	11.4	1.41	9	13.2	3.11
150	12	12.8	3.39	31	20.9	8.76	7	15.9	1.98	10	14.7	2.82
160	10	10.6	2.82	24	16.2	6.78	6	13.6	1.69	8	11.8	2.26
170	8	8.5	2.26	24	16.2	6.78	5	11.4	1.41	7	10.3	1.98
180	8	8.5	2.26	20	13.5	5.65	9	20.5	2.54	3	4.4	0.85
190	4	4.3	1.13	16	10.8	4.52	5	11.4	1.41	2	2.9	0.56
200	1	1.1	0.28	1	0.7	0.28	3	6.8	0.85	2	2.9	0.56
210	1	1.1	0.28	2	1.4	0.56	1	2.3	0.28	1	1.5	0.28
220	0	0.0	0.00	1	0.7	0.28	1	2.3	0.28	1	1.5	0.28
230	0	0.0	0.00	1	0.7	0.28	0	0.0	0.00	1	1.5	0.28
Total no.	94		26.6%	148		41.8%	44		12.4%	68		19.2%
	354 (100%)											

RA rainfall accumulation, DFD debris flow disaster

The **bold italic** indicate the major period of debris flow occurrence and rainfall accumulation of four types

The final total accumulated rainfall from this type of typhoon was astonishing, with an average value exceeding 300 mm. Observations of the data showed that the number of debris flow disasters started to increase significantly when rainfall reached 130 mm and reached a peak when the accumulated rainfall was 150 mm, but continued to occur up to 190 mm. Debris flow disasters that coincided with rainfall between 130 and 190 mm were about 80% of the total debris flow disasters (Table 4).

There were also some extreme cases; for instance, Typhoon Herb of 1996 brought about tremendous disasters in Nantou with a maximum rainfall intensity of about 74 mm/h and with a precipitation reaching 645 mm per day. Rainfall accumulation was low when this type of typhoon approached Taiwan, so most of the rainfall accumulated after the typhoon left Taiwan. For these typhoons, an accumulated rainfall of 130 mm can be viewed as the threshold for debris flow disaster. Accumulated rainfall from 130 to 190 mm results in a high risk for debris flow disasters; this interval deserves a high level of alert from the disaster response system. Debris flow disaster conditions tend to abate once rainfall accumulation exceeds 190 mm.

For Type B typhoons, trinomial analysis (Fig. 6) shows that the peak of rainfall occurred when the typhoon left the study area and was at a distance of about 200 km. The southwest airflow after such typhoons was the main cause for debris flow disasters. The average rainfall intensity in the debris flow disaster areas was ~ 13 mm/h, while that in the areas not affected was only 8 mm/h. The typhoons of this type had two important features.

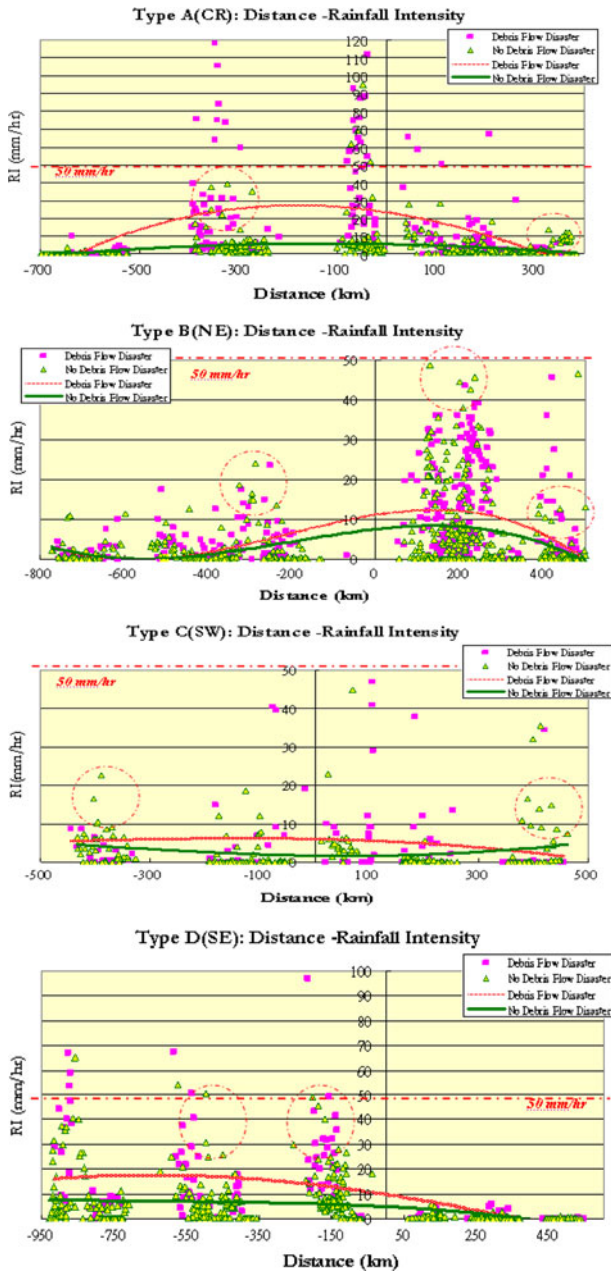


Fig. 6 Trinomial analysis of rainfall intensity and distance of four types

First, the rainfall quantity was not large, but the rainfall duration was long. Secondly, the rainfall characteristics, such as intensity and duration, recorded at all of the rain gauges were very similar, indicating that this type of typhoon resulted in an overall uniform rainfall as well as a very widespread spatial distribution of debris flow disaster conditions,

Table 5 The phases of debris flow occurrence in four types

Phase	Type A			Type B			Type C			Type D		
	DFD	% of type	% of total	DFD	% of type	% of total	DFD	% of type	% of total	DFD	% of type	% of total
I	26	27.7	7.35	13	8.8	3.67	6	13.6	1.70	24	35.3	6.78
II	40	42.5	11.30	27	18.2	7.63	12	27.3	3.39	23	33.8	6.50
III	16	17.0	4.52	65	43.9	18.36	20	45.5	5.65	15	22.1	4.24
IV	12	12.8	3.39	43	29.1	12.15	6	13.6	1.70	6	8.8	1.70
Total	94		26.6%	148		41.8%	44		12.4%	68		19.2%

DFD debris flow disasters

The words in **bold italic type** show the risky phases in each type

posing challenges to emergency response. Rainfall was initiated a large distance away from the study area. Intermittent rainfall was recorded at 800 km and more at 500 km. The long duration of rainfall means that a long stand-by response is needed for emergency response systems.

3.3 Type C

Typhoons typically hit Taiwan from the east to the west. In contrast, Type C typhoons arrive from the west. This type has greater impacts in Nantou than in Hualien, with 74% of associated debris flow disasters occurring in Nantou.

However, compared with the other types of typhoons, Type C typhoons resulted in relatively fewer debris flow disasters. This is due to the fact that this type of typhoon has a short lifecycle, with a low water vapor absorption capacity and a slow rate of rainfall accumulation. This type of typhoon was responsible for 12% of the total debris flow disasters (Table 4). The third phase was the period of maximum risk and caused about 45% of debris flows induced by Type C typhoons. Even so, this was only 5.65% of all debris flows caused by the third phase of all typhoons.

The period of highest risk for debris flow disasters associated with Type C typhoon occurs when rainfall accumulation was between 140 and 190 mm (Table 4), with a peak at 180 mm. In this type of typhoons, peak periods of rainfall generally came in pairs, and mainly during the second and third phases (Table 5). Disasters were more common during the second rainfall peak period. However, this type of typhoon brought about relatively low impacts in terms of disaster management efforts. In Type C typhoons, the rainfall was relatively sporadic and there was no apparent trend (Fig. 6).

3.4 Type D

This type mainly stayed off the coast of Taiwan and traveled in the eastsouth direction. Among the four phases classified in this study, debris flow disasters occurred mostly in the first two phases (Table 5). From the analysis of a total of 68 debris flow disasters, the first three phases, respectively, account for 35.3, 33.8, and 22.1% of the total disasters (Fig. 5). Debris flow disasters associated with Type D typhoons accounted for only about 20% of the total disasters. The average total rainfall for these events was approximately 200 mm.

As these typhoons approached Taiwan, debris flow disasters began to occur. When the rainfall accumulated to approximately 90 mm, there were reports of initiation of debris flows. For example, in 1998, Typhoon Zeb brought in a maximum rainfall intensity of 91 mm/h on Hualien, which led to debris flow disasters. At 140 mm of rain accumulation, the greatest number of debris flow disasters occurred. Thereafter, the number of such disasters gradually decreased.

In every phase, when the rainfall ranged between 90 and 230 mm, debris flow disasters occurred. Although the disasters were relatively minor, the periods of consecutive occurrences were prolonged. The uncertainties associated with this type could be a concern to emergency teams. For these typhoons, an accumulated rainfall of 120–170 mm could be viewed as an apparent threshold for debris flow disasters (Table 4). Moreover, the rainfall mainly accumulated in the first phase. On the whole, disasters probably occurred while the storms were approaching Taiwan, with the first phase having the maximum likelihood of incidence.

In Type D, trinomial analysis (Fig. 6) showed that there was a very apparent tendency for rainfall in the first phase, which would begin to affect the area when the storm was about 900 km away. As the precipitation continued to increase, the peak period was determined to be at a distance of about 350–700 km. After the typhoons approached the study area, precipitation decreased rapidly.

It is difficult to provide useful guidelines for disaster management based on these precipitation trends. Fortunately, this type of typhoon occurred less frequently, and the proportion of disasters associated with them was low. For such typhoons, emergency responses must be immediately carried out after a warning has been issued. This type of early response would be challenging compared with the ordinary mitigation measures.

4 Rainfall comparison and discussions

The results discussed in the previous section showed that rainfall characteristics, such as rainfall accumulation and rainfall intensity, affected debris flow. Comparisons of the total rainfall caused by all types of typhoons, as well as the relationship between intensity distribution and path of maximum rainfall are shown in Tables 4 and 5 and discussed next.

Typhoon rainfall forecasting is an extremely complex meteorological challenge. By observing the maximum hourly rainfall intensity in this study (Fig. 7), it was found that Type A had the most intense precipitation, frequently accompanied by intense rainfall bursts. Typhoons of both Types A and B caused several debris flow disasters but those associated with Type A generally occurred when the typhoon approached the study area (Phase 2), while for Type B they occurred when the typhoon left the area (Phase 3). As for the relationship between rainfall accumulation and typhoon paths (Fig. 8), the largest total precipitation was caused by Type B, with debris flows resulting from the cyclones' effects accounting for 41.81% of the total. After Type B, Type A produced the second greatest amount of precipitation, with its proportion of debris flow disasters accounting for 26.55% of all debris flow disasters. In contrast, Type C produced the least precipitation and the lowest incidence of debris flows, accounting for only 12.43% of total debris flow disasters, mainly in Nantou.

The southwest airflow introduced after typhoons usually resulted in severe debris flow disasters in the study areas. However, after typhoons left the area, disasters were sometimes more serious because of a lack of preparedness and disaster mitigation efforts.

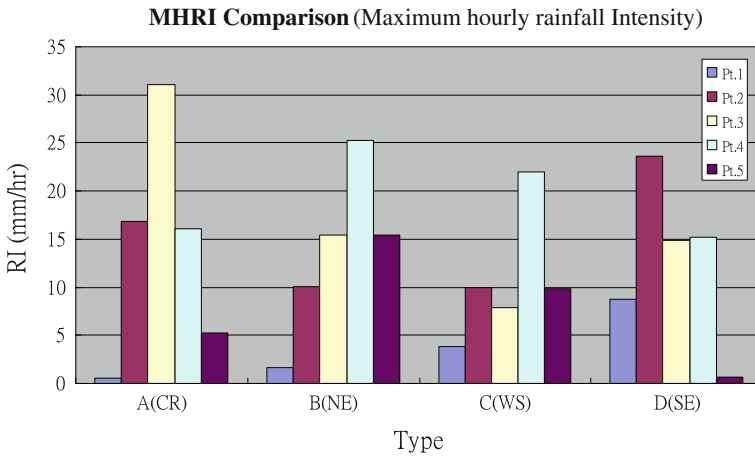


Fig. 7 The maximum rainfall intensity comparison among four types

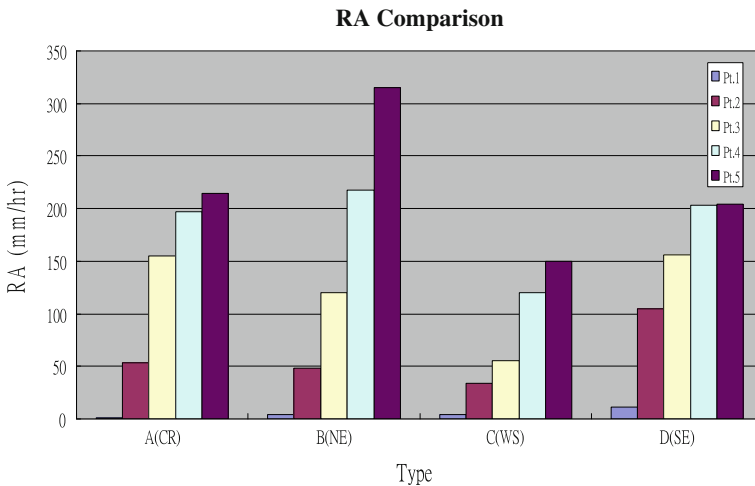


Fig. 8 The rainfall accumulation comparison among four types

The relationship between maximum rainfall intensity distribution and typhoon path shows that the precipitation center for Type B typhoons was in the mountainous area of Nantou, conforming to the area where debris flows occurred. The precipitation center of Type A was on the whole the same as its total precipitation center, also approximating the area of debris flow occurrence. As for Types C and D, their paths and total precipitation amounts were generally similar. Observing the total precipitation and maximum rainfall intensity distribution, when a typhoon approached and at the nearest point, the maximum rainfall intensity of Type A was higher than that of Type B (Fig. 9), while having a much lower risk of debris flow disaster.

According to the data from Nantou, the rainfall peaked during Phase 3. Every type but Type D caused significant effects, especially Type B, because the whole midland became the windward side as the typhoon passed through. In addition, because of the obstruction of

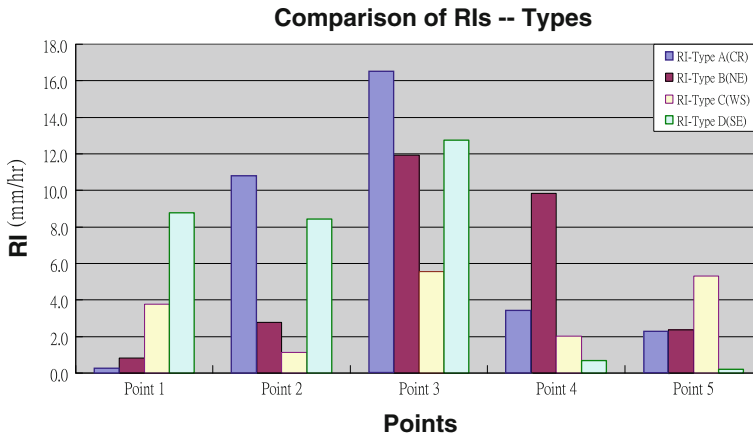


Fig. 9 Comparison of rainfall intensity at points among types

the Central Mountains, the typhoons created mass rainfall and as a result, the rainfall accumulation from Type B was much greater than others. Type A typhoons had powerful rainfall that had great impact on Nantou and Hualien, but the obstruction of the Central Mountains decreased their damage. Type C did not occur often, but it had the potential to cause great disasters because of its direct attack. The research found that the rainfall in Nantou decreases from the mountains toward the plains. Additionally, typhoons created heavy rainfall in areas near the Central Mountains, which have a great potential for debris flow disasters. In Hualien, the rainfall peaked during Phase 3, and in the last phase, the maximum rainfall occurred during the middle and later periods. Except for Type C, all typhoons followed a straight path and the region received direct impact from the typhoons. Streams prone to debris flow were, therefore, always susceptible to these hazards. So far, Type A, which had a direct impact, had the most serious influence on Hualien. Hualien has varied topography with mountains, basins, and plains. In the west, there are the Central Mountains with a height of more than 2,000 m, in the middle (East Hualien), there is a longitudinal valley, and in the littoral regions, there are mountains and basins along the seacoast. On the whole, rainfall increased with altitude; however, it tended to level off above a certain altitude. Type C typhoons had a very small impact on Hualien, while the rainfall from Types A and B was strong. However, many potentially catastrophic areas in Hualien have not been developed, so the debris flow hazards have not produced disasters that affect populated areas.

Type A mainly affected Hualien, while Types B and C mainly affected Nantou. However, if typhoons of Type B occurred during the seasonal change between fall and winter, they brought in sufficient moisture and led to heavy rainfall. In these cases, the affected area was expanded to include the whole study area.

On the whole, there were many debris flow cases for Type B with the most frequent disaster occurrences (Fig. 10), exceeding 40% of all disasters. The disasters caused by Type B typhoons occurred more often in Phases 3 and 4, as the typhoons were leaving the area. Phases 3 and 4 accounted for nearly 20% of the total disaster events. Type B storms deserve attention even as they are leaving.

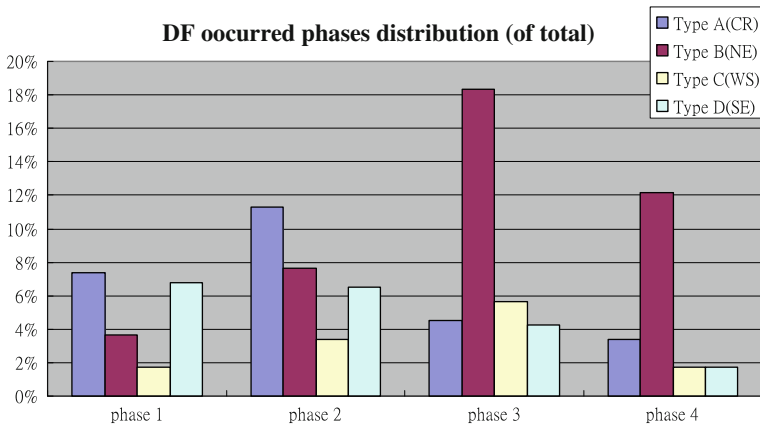


Fig. 10 Comparison of distribution phases of debris flow occurrence among four types

Type A had a greater impact on Hualien than on Nantou, but there is a relatively low population in Hualien and therefore less infrastructure and buildings that might be affected. The debris flow disasters in other phases each contributed less than 10% of total disasters, with the exception of Phase 2 of Type A, which had the third highest incidence of debris flow disasters overall, accounting for 11.30% of total disasters. In Fig. 6, there are scattered points indicating that some rain gauge stations often had high rainfall intensity. The present analysis indicated that those points are often located on the windward hills of Hualien, either in the Central Mountains or the Seacoast Mountains. However, because the geological conditions are stable, the frequency of debris flow disasters is comparatively low (Table 6).

The qualitative and quantitative features of rainfall and debris flows caused by the different types of typhoons are summarized in Tables 7 and 8, respectively.

Table 6 Sample of calculation of points and rain gauge stations

Points				1	2	3	4	5	
Coordinates				118.2/ 17.5	117.5/ 20.5	120.5/ 22.5	121.8/ 23	124.2/ 23.5	
County	Stations	Number	Longi.	Lati.	Distance (km)				
Hualien	Hualien	466990	121.27	24.12	<i>799.50</i>	<i>558.13</i>	<i>195.94</i>	<i>135.33</i>	<i>331.24</i>
Nantou	Ho-Huan Mt.	COF950	120.83	23.54	<i>722.72</i>	<i>481.13</i>	<i>120.04</i>	<i>115.88</i>	<i>344.20</i>
Nantou	Kun-Yuan	COH990	121.20	24.11	<i>795.60</i>	<i>552.35</i>	<i>192.15</i>	<i>137.35</i>	<i>313.09</i>
Nantou	Sheng-Mu Vil.	COH9A0	121.22	24.19	<i>804.54</i>	<i>560.13</i>	<i>201.13</i>	<i>144.48</i>	<i>313.06</i>
Nantou	Tsui-Feng	C1H000	121.18	24.13	<i>796.82</i>	<i>552.52</i>	<i>193.46</i>	<i>140.25</i>	<i>315.54</i>
Nantou	Tsui-Luan	C1H850	121.12	24.02	<i>783.21</i>	<i>539.53</i>	<i>179.90</i>	<i>132.61</i>	<i>319.22</i>
Nantou	Zui-Yan	C1H860	121.01	24.02	<i>778.85</i>	<i>531.76</i>	<i>176.24</i>	<i>138.82</i>	<i>330.25</i>
Nantou	Zen-Ai	C1H870	120.94	23.97	<i>771.01</i>	<i>522.84</i>	<i>168.91</i>	<i>138.78</i>	<i>336.44</i>
Nantou	Ling-Shiao	C1H880	120.95	24.08	<i>782.68</i>	<i>532.45</i>	<i>180.94</i>	<i>147.79</i>	<i>337.40</i>

The italic values are the sample distances calculated in this study

Table 7 Qualitative features of rainfall and debris flows for the four typhoon types

Type	Accordance	Rainfall features	Features of debris flow disasters
A (CR)	This type crossed the center of the study area from east to west and then moved to the west or northwest	The rainfall in the first phase of the typhoon tended to be the lowest among the four phases When the typhoon approached or swept over Taiwan, the accumulated rainfall increased significantly. There were sudden increases in rainfall intensity exceeding 50 mm/h The accumulated rainfall suddenly increased between the second and the third points	Type A typhoons resulted in relatively serious damage and casualties due to debris flows Debris flow disasters often occurred when the typhoons were approaching Taiwan
B (NE)	This type moved along the upper eastern coast and then toward the west or northwest	The hourly rainfall intensity was continuously increasing, especially as the typhoons left the study area The accumulated rainfall from this type is astonishing, with an average total accumulated rainfall of all such typhoon events exceeding 300 mm	The structures of these typhoons were not disrupted by mountain ranges, so they resulted in heavy impacts Debris flow disasters from this type account for roughly half of all documented debris flow disasters Debris flow disasters often occurred during the later phases as the typhoon left Taiwan This type has the maximum possibility of debris flow and is worthy of special attention in disaster management
C (SW)	This type either came from the west side or directly targeted western Taiwan	The rainfall accumulation is relatively lower There are often two or more rainfall peaks in a phase	The debris flow disasters often occurred during later peak of rainfall This type has direct impacts upon the central western area
D (SE)	This type flipped to the northeast coast or the Pacific Ocean from the southeast side of Taiwan	The rainfall accumulation is less than for other types There was a very apparent tendency for rainfall in the first phase	Debris flow disasters mostly occurred during the initial two phases The disasters often occurred when the rainfall was heavy; however, the water was not sufficient to result in large-scale debris flows

Table 8 Quantitative features of rainfall and debris flow occurrence of Types

Type	Threshold ^a (mm)	Peak period ^b (mm)	Risky phase ^c
A	120	120–180	2
B	130	130–190	3
C	180	140–190	3
D	90	120–170	1 and 2

^a Rainfall accumulation calculated from Point 1, when rainfall started

^b The relationship of peak period of debris flow occurrence and rainfall accumulation

^c The phase had the most documented debris flow disasters

5 Conclusions

This study reviewed recent typhoons and regrouped them into four major types (A, B, C, and D) according to their paths, each having four Phases (1–4) ranging from the start to the end of event. The relationships between the rainfall characteristics caused by the four types of typhoons and the occurrence of debris flows were identified.

Some of the major conclusions obtained from this study are as follows:

1. Each typhoon type has a potential to trigger debris flow at different phase of their paths. That is, Phases 2, 3, 3, and 1 for Typhoon Types A, B, C, and D, respectively.
2. When the rainfall accumulated up to 120, 130, 180, and 90 mm in typhoon Types A, B, C, and D, respectively, the study areas are vulnerable to debris flow disasters.
3. Type A typhoons resulted in relatively serious damages and casualties due to debris flows, while Type B typhoons had maximum likelihood of debris flow.
4. Rainfall accumulation was a dominant factor for debris flow disasters. More emphasis should be placed on flash rainfalls in Type A, high occurrence of debris flow disasters in Type B, and limited response time for Type D.

The systematic classification of typhoon types as proposed in this study has revealed characteristic rainfall patterns that can be used in predicting debris flow hazards and disaster management.

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