Rainfall Thresholds for Homeland Security in Mountainous Townships of Taiwan during Typhoon Morakot

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Abstract—**Global warming is causing rapid changes in weather patterns. Such changes have brought extreme rainfall in Taiwan and caused numerous hazards in recent years. Typhoon Morakot made landfall in Taiwan on 8 August 2009 and caused 677 deaths, with 22 missing. Its extreme rainfall was concentrated in the mountainous areas of southern Taiwan in Chiayi, Tainan, Kaohsiung, and Pingtung counties. The rainfall caused the most severe natural hazards in the southern mountainous areas of Taiwan in recent years. This study performs a statistical analysis of hazards and rainfall distribution in the mountainous areas of Chiayi County during Typhoon Morakot. The results of the analysis show that the number of hazards in the mountainous areas increased with the rainfall. As rainfall increased over a threshold value, the number of hazards also increased abruptly. The cumulative number of hazards and the time of rainfall duration showed a power-law distribution over a threshold rainfall. A novel rainfall threshold index, the DI_t or Disaster Intensity in a time interval for torrential rainfall-induced hazards caused by typhoons is proposed herein to indicate the intensity of increasing hazards during Typhoon Morakot. The proposed index could be extended to future typhoons to aid in hazard warnings for homeland security. The threshold rainfall can be used as an index for hazard prevention and emergency response in the studied mountainous townships and other areas.**

Index Terms—**Typhoon morakot, rainfall threshold, hazard warning, GIS.**

I. INTRODUCTION

Climate change induced extreme rainfall has caused numerous global disasters in recent years [1]-[3]. Typhoon Morakot made landfall in Taiwan on 8 August 2009, bringing heavy rainfall. The typhoon caused 677 deaths with a further 22 missing. It cut water supplies to 769,159 households, electric power to 1,595,419 households, and communications to 22,221 households [4]. Water resources facilities and levees were damaged in 824 places, roads were blocked in 250 locations, 196 bridges were damaged, and the total flooded area reached 765 km^2 [4]. The economic losses of agricultural and fisheries industries were estimated at NT$ 192 billion [5]. The typhoon, combined with south-western winds, brought heavy rainfall concentrated in southern Taiwan (Fig. 1). The typhoon caused the most serious flood hazards in the recorded history of Taiwan.
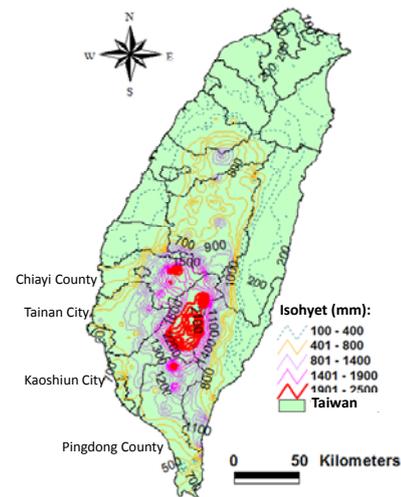
Fig. 1. Rainfall distribution during 7-10 august 2009 typhoon Morakot landed on Taiwan (source [6]).

The disaster areas induced by Typhoon Morakot were located in central and southern Taiwan. The main hazards included floods, debris flows, landslides, broken bridges, damaged levees, communications cutoffs, natural dams, and agricultural losses [7]. Typhoon Morakot brought 5 days of rainfall (6-10 August) to southern Taiwan. Rainfall intensity of 20-30 mm/hr was prolonged for 48 hours, with intensities over 50 mm/hr that lasted up to 24 hours. The maximum rainfall intensity reached 90-100 mm/hr in many rain gauge stations. The long rainfall duration caused a cumulative rainfall reaching 2,000 mm in the plains areas and 3,000 mm in the mountainous areas of southern Taiwan [4]. The intense, prolonged rainfall occurred because Morakot was a slow moving typhoon [8].

The highest rainfall recorded was 3,060 mm at the Alishan station in Chiayi County in southern Taiwan [6]. In the study area of Chiayi County, this abnormally heavy rainfall led to 10 deaths with a further two missing, electricity outages for 11,300 buildings, hydraulic structures damaged in 30 places, roads damaged in 25 places, and 206 villages inundated by floods, landslides, and debris flows in over 700 locations, 22 bridges collapsed and 4 damaged, and estimated agricultural losses reaching NT$ 26 billion [9]. A rainfall threshold that combines the intensity, duration, and cumulative rainfall is commonly used for landslide and debris flow warnings [10]-[15]. At present this rainfall threshold warning model only addresses a single type of hazard (landslides, debris flows, or flood) and is less concerned about the hazards for relief workers and for potential disaster preparedness.

The characteristics of many natural hazards show a

power-law distribution [16]-[18]. For example, the relationship between the size and frequency of landslides follows a power law distribution [19]-[23].

This study investigates the cumulative number of reported hazards and rainfall during Typhoon Morakot using a power-law distribution analysis. The purpose of the study is promotion of an early warning system for disasters by monitoring of real time rainfall.

II. STUDY AREA AND METHODOLOGY

The study area, Chiayi County, is located in south-central Taiwan (Fig. 2). The elevation of the mountainous areas reaches 3,800 m. The geology consists largely of sandstone and shale layers, with portions of traversing layers of sandstone, mudstone, and shale, and layers of shale, sandy shale, and mudstone in the mountainous area (Central Geology Survey in Taiwan, http://www.moeacgs.gov.tw). The annual rainfall in Taiwan is 2,151 mm in the center, 2,523 mm in the south, and 2,926 mm in the north, with 2,500 mm being the average for Taiwan between 1949 and 2010 [24]. This study focuses on six mountain villages, including Jhongpu, Dapu, Chuchi, Fanlu, Meishan, and Alishan villages.
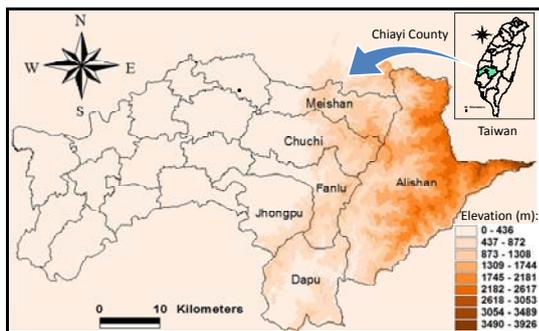
Fig. 2. Site location and elevation of Chiayi County in south-central Taiwan.

This study analyzes the relationships between cumulative hazards and rainfall for the period of 6-28 August, 2009, during and after Typhoon Morakot, in the mountainous areas of Chiayi County. The database includes site location, time of initiation, and the types of hazards. The relationships between hazards and the corresponding rainfall were analyzed using GIS for spatial data analysis.

III. STATISTICS ANALYSIS OF HAZARDS INDUCED BY TYPHOON MORAKOT

The reported hazards to the EOC (Emergency Operation Center, EOC) in Chiayi County during Typhoon Morakot totaled 1,695 events during the period 6-28 August. There were 1,182 reported events during the emergency response stage of 6-14 August, and 513 during the recovery stage of 15-28 August, 2009. The number of hazards increased dramatically on 8 to 9 August (Fig. 3). The highest number of hazards, 342 events, occurred on 9 August, with 190 on 10 August during the emergency response stage. The hazards during the recovery stage mainly occurred from 15-17 August, during which 303 hazards occurred in the coastal villages and 182 in the plains. Most of the hazards occurred

in the mountainous areas, with 303 cases (66%). An additional 92 cases lacked identified locations.
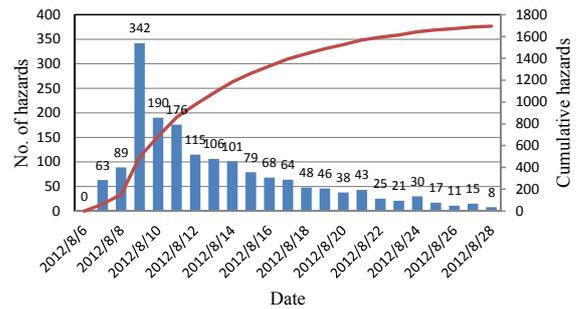
Fig. 3. Daily hazard distribution during and after Typhoon Morakot, 6-28 August 2009 (source: Chiayi County EOC, http://www.cyhg.gov.tw).
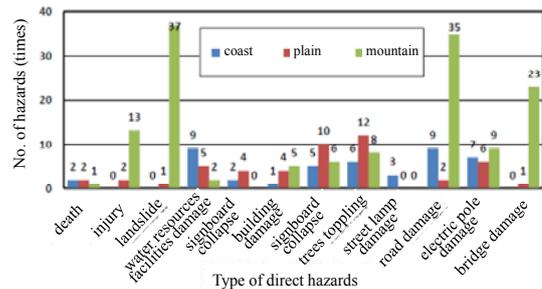
Fig. 4. Number of direct hazards, 6-28 August, 2009, during and after Typhoon Morakot in Chiayi County.

Fig. 5. One of the large landslides in Meishan Township, Chiayi County.

Two categories of hazard, direct and indirect hazards, were identified for the analysis. The direct hazards consist of hazards directly attributable to the typhoon-induced rainfall, including death, injury, road and bridge damage, and landslides and debris flows. Indirect hazards are those not identified as well as secondary hazards such as individuals missing or trapped, building inundation, ponding areas, and power and water outages.

This study identified 241 direct hazards and 1,459 indirect hazards totaling 1,695 events. There were more cases of road damage (46 cases), landslides (38 cases), and bridge damage (24 cases) in direct hazards (Fig. 4). Fig. 5 shows one of the large landslides in the study area. Most of the indirect hazards consisted of people being trapped (313 cases) and ponding (125 cases) in addition to other un-categorized hazards (888 cases) (Fig. 6). Direct hazards such as water resources facilities damage (9 cases) and road damage (9 cases), along with indirect hazards such as ponding (83 cases) were common in the coastal areas. Direct hazards such as signboard collapse (10 cases) and trees along highways toppling (12 cases), along with the indirect hazard of ponding (31 cases) were highest in plain areas. In mountainous areas, landslides (37 cases) and road damage (35 cases) accounted for most of the direct hazards, while residents isolated by

road cutoff (275 cases) were the common indirect hazard.
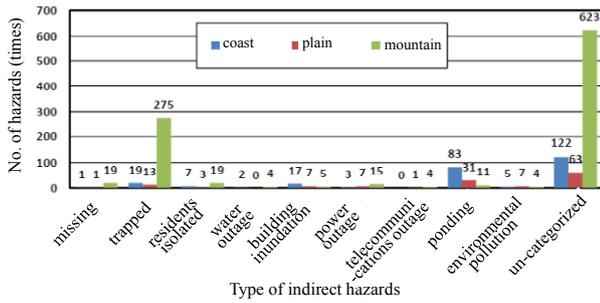
Fig. 6. Number of indirect hazards, 6-28 August, 2009, during and after Typhoon Morakot in Chiayi County.
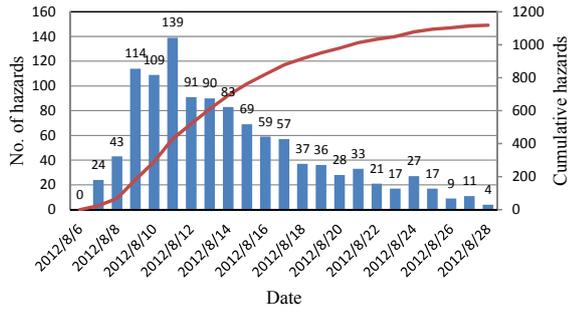
Fig. 7. Number of daily hazards, 6-28 August, 2009, in the mountainous areas of Chiayi County during and after Morakot.
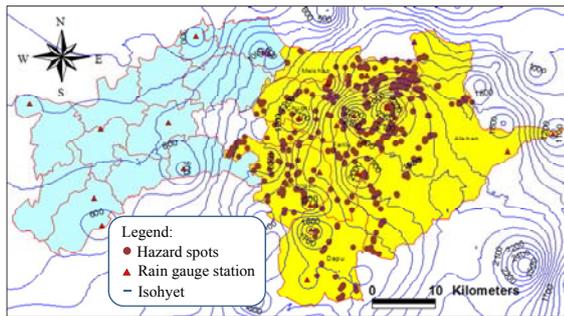
Fig. 8. Isohyet of cumulative rainfall 7-10 August, (source: [6]) and locations of hazards (source: Chiayi county Fire Bureau, 2009) in the mountainous areas of Chiayi County during Typhoon Morakot.

The daily hazard distribution in the mountainous areas of Chiayi County is shown in Fig. 7. The hazards began on the 7th and increased on the 8th through 11th of August during Morakot. The greatest number of daily hazards, 139 cases, occurred on the 11th, followed by the 9th (114 cases), and the 10th (109 cases). Hazards increased abruptly from the 8th to 9th. Follow on or secondary hazards occurred after the 10th in the post hazard recovery stage.

IV. RAINFALL DISTRIBUTIONS AND HAZARDS

Fig. 8 shows the locations of hazards during Typhoon Morakot in the mountainous areas of Chiayi County. Debris flows, landslides, road blockages, and broken bridges isolated residents in the mountains. The rainfall data were retrieved from the nearest rain gauge stations (14 stations) in the mountain areas. The rainfall was concentrated from the 6th to the 10th and affected mountain areas from 17:00 on the 7th to 5:00 on the 10th.

Fig. 9 shows the time history of rainfall distribution for the number of hazards and cumulative rainfall at the Alishan rain gauge station during 7-10 August 2009. The time of day

hazards occurred was 6-7 (9 cases), 9-10 (9 cases), and 10-11 (12 cases) in 9 August. In general, the number of hazards increased with the cumulative rainfall during the period the typhoon affected the study area (17:00 on the 7 until 5:00 on the 10 of August).
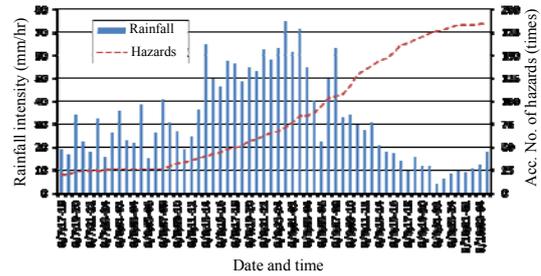
Fig. 9. Rainfall intensity at the Alishan rain gauge station and cumulative hazards, 7-10 August, 2009.
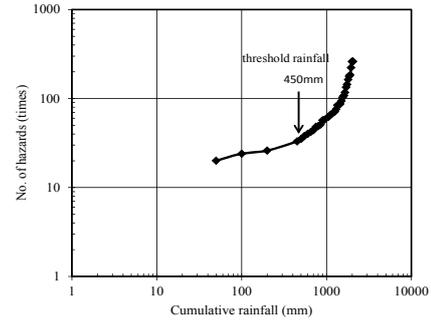
Fig. 10. Cumulative hazards and rainfall (Alishan rain gauge station) in the mountainous areas of Chiayi County, 7-10 August 2009.
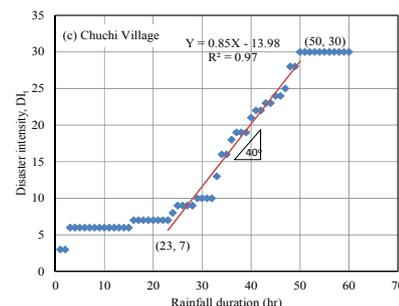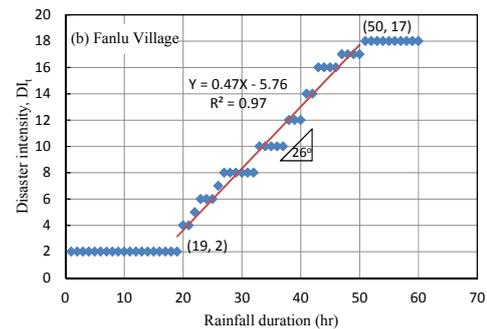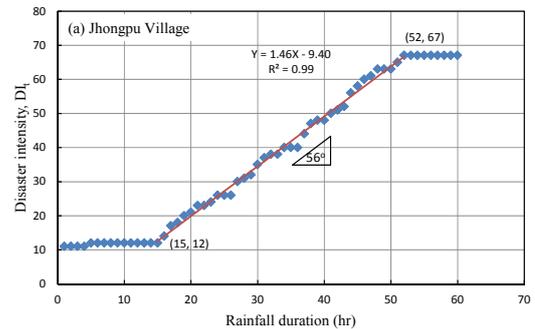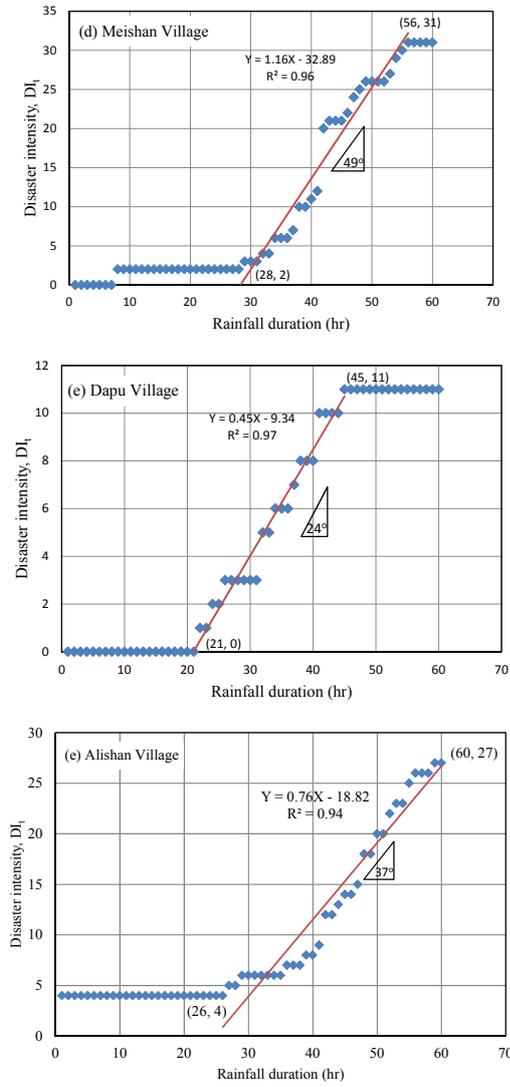
Fig. 11. Disaster intensity (DI$_t$) and rainfall duration at the nearest rain gauge station during Typhoon Morakot in Chiayi County in (a) Jhongpu (b) Fanlu (c) Chuchi (d) Meishan (e) Dapu and (f) Alishan villages.

V. RESULTS AND DISCUSSION

This study plots the distribution of the cumulative rainfall and the number of hazards (Fig. 10). The number of hazards rose with every 50 mm of increased rainfall. Most of the villages have a high threshold rainfall corresponding to an abrupt increase in hazards in the plot. The threshold rainfall, at which level there is an abrupt increase in hazards, is estimated 450 mm over the study area as a whole. As the gradient of rainfall increases, the number of hazards also increases.

To address this issue of unclear cumulative rainfall thresholds and the number of hazards for early warning of hazards, a novel index is proposed herein. The number of hazards was calculated for every one hour of rainfall duration (dT). This time interval, one hour, was chosen for the accessibility of rainfall data. For instance, rainfall data per ten minutes is available in Taiwan. The Disaster Intensity (DI$_t$) is defined as the cumulative number of hazards (N$_c$) with increasing rainfall duration in a specified interval (one hour).

$$DI_t = f(T) = dN_c/dT \qquad (1)$$

The relationships between the hazard intensity and rainfall duration show a power-law distribution in the main rainfall period during Typhoon Morakot in the study area (Fig. 11). The data show a parallel distribution if no new hazards occurred within the time interval (dT). The relationship between DI$_t$ and rainfall duration (T) in the mountains area and the Alishan rain gauge station is presented in Fig. 12 and its regression equation listed below.

$$DI_t = 4.24T^{-52.8} \ (r^2 = 0.98) \qquad (2)$$
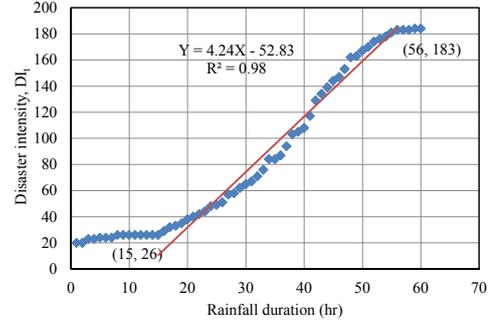
Fig. 12. Disaster Intensity (DI$_t$) and rainfall duration at the Alishan rain gauge station in the mountainous areas of Chiayi County.

The sharp increases in hazards began after 15 hours of rainfall duration and a corresponding cumulative rainfall of 372 mm. The model show its validation from a small area of township to the whole studied wide mountainous area with a scale invariant feature. The gradient of the regression line shows the increasing of hazards with the rainfall duration. The steeper of the gradient, the higher vulnerability of the area to hazards. Jongpu Village shows its high vulnerability to hazards and Dapu Village shows less feasible to hazards among the study villages.

TABLE I: COMPARISONS OF RAINFALL THRESHOLD FOR HAZARDS BY THIS STUDY AND BY THE SWCB FOR DEBRIS FLOW WARNING

Village	Threshold rainfall (mm)	Threshold duration (hr)	Threshold rainfall* (mm)
Jhongpu	200	15	400
Fanlu	500	19	450
Chuchi	750	23	350
Meishan	600	28	300
Dapu	750	21	400
Alishan	900	26	250
Mountainous areas	450	15	-

*Published by SWCB (http://www.swcb.gov.tw)

A Rainfall Triggering Index (RTI) was proposed by real time rainfall monitoring for debris flow early warning in Taiwan [25]. The threshold rainfall considered the effective accumulated rainfall and antecedent rainfall published by the SWCB for villages with debris flow potential areas. This study compared the proposed threshold rainfall and the published threshold for debris flows (Table I). It is found that the published rainfall threshold for debris flows was lower than this study's proposed threshold rainfall in most of the villages. The minimum rainfall duration for hazards increasing abruptly is 15 hrs. In addition to Jhongpu village, the published threshold rainfall is higher than herein, which

could lead to failure to provide early warning of potential hazard occurrences for residents.

VI. CONCLUSION

The study explores the relationships between hazards, rainfall amount, and duration of rainfall during Typhoon Morakot in 2009 in Chiayi County, Taiwan. The hazards mainly occurred in mountainous areas on 9-10 August, 2009. Most of the hazards were located in areas of high cumulative rainfall, between 1,500 and 2,000 mm. The number of hazards increased with increases in cumulative rainfall. The cumulative number of hazards and rainfall duration displays a power-law distribution over a threshold rainfall (450 mm in mountainous areas). The threshold rainfall can be used for hazard early warning and evacuation. This study thus provides a novel approach to rainfall-induced hazard warning for homeland security.

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C. Y. Chen, F. C. Yu, S. C. Lin, and K. W. Cheung, "Discussion of landslide self-organized criticality and the initiation of debris flow," *Earth Surface Processes and Landform*, vol. 32, i2, pp. 197-209, 2007, ect.