MORAKOT TYPHOON: CAPACITY OF RAINFALL TO LANDSLIDE IN TAIWAN

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ABSTRACT

Typhoon Morakot brought heavy rainfall caused landslides and flash floods in southern Taiwan from August 6 – 10, 2009. Rainfall is one of the primary factors causing landslides on the hillslopes during this event. In this study, we performed a statistical analysis with slope, elevation and maximum 72-hour precipitation from historical rainfall records to investigate the effect of cumulative rainfall on the occurrence of landslide events during this typhoon event. The result represents that the landslide distribution after typhoon Morakot has highly correlated with the distribution of gradient and rainfall. 80% of landslides occurred in areas with slopes from 20° to 50°. Furthermore 95% landslides occurred in areas with more than 300 mm of the cumulative rainfall amount and over 40% of the maximum 72-hour precipitation of historical rainfall record.

Keywords: Typhoon Morakot, landslide, heavy rainfall, slope failure

INTRODUCTION

Rainfall is one of the primary factors causing landslides on hillslopes (Fujii, 1969; Varnes, 1978; Fukuoka, 1980; Corominas, 1999; Guzzetti et al., 2004). Oberste-Lehn (1976) found that the hillslope will become unsteady when the cumulative rainfall is more than 250 mm. Bhandari et al. (1991) used a three-day cumulative rainfall amount of more than 200 mm as an indicator to estimate the probability of landslide occurrence in Sri Lanka. Corominas and Moya (1999) analyzed the landslide events in Pyrenees Mountains in Spain and found that landslide events occur when the amount of cumulative rainfall in a period of 24 to 48 hours is more than 300 mm. Rainfall intensity and amount are important indices for issuing early warnings and estimating the landslide susceptibility of geologically sensitive areas currently (Caine, 1980; Keefer et al., 1987; Crosta, 1998; Crozier, 1999; Glade et al., 2000). On the basis of results of these studies, the threshold of rainfall to induce landslide is about 200 mm. However, the application of this threshold to early-warnings for landslide in Taiwan is an important question for mitigating slopeland disasters. Presently, the early-warning about slopeland disasters are emphasized on debris flow disasters (Jan, 2005; Chen et al., 2005). The thresholds of rainfall for debris flow early warning in Taiwan were determined to be cumulative rainfall amounts in the range of 200 to 600 mm for a 24-hour period after typhoon Morakot. These values are the standard for issuing evacuation command. However, it is difficult to determine the amount of cumulative rainfall that may induce landslides, which is a critical parameter of issuing early warning.

With this background, the first step in this study is to collect the digital database, which includes rainfall records and digital elevation models (DEM) for the analysis. Then we examined the distribution of landslides induced during typhoon Morakot. Finally, the process is to determine the effects of land slope, land elevation, cumulative rainfall and historical rainfall distribution on landslide events by GIS spatial analysis because we considered that these investigations would

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provide important information for issuing early warnings about rainfall-induced disasters on the slopeland in the future.

PHYSIOGRAPHIC ANALYSIS OF LANDSLIDES

The principle landslide data utilized in this study was made from Formosat-2 satellite images before and after typhoon Morakot by the Central Geological Survey of the Ministry of Economic Affairs. We calculated the landslide area variation between typhoon Sinlaku in September 2008 and typhoon Morakot in August 2009. Fig. 1 shows the distribution of landslides after each typhoon, which suggests that the landslide area after typhoon Sinlaku was 194 km^2 and that after typhoon Morakot was 563 km^2, indicating that the landslide area increased by 369 km^2 between the two typhoon events. Considering that parts of the area were identified as landslide spots due to the natural change on slopeland, the landslide area resulting from typhoon Morakot was still estimated as 435 km^2 according to the data from the central geological survey. This landslide magnitude is larger than that after the events following the 1999 Chi-chi earthquake.

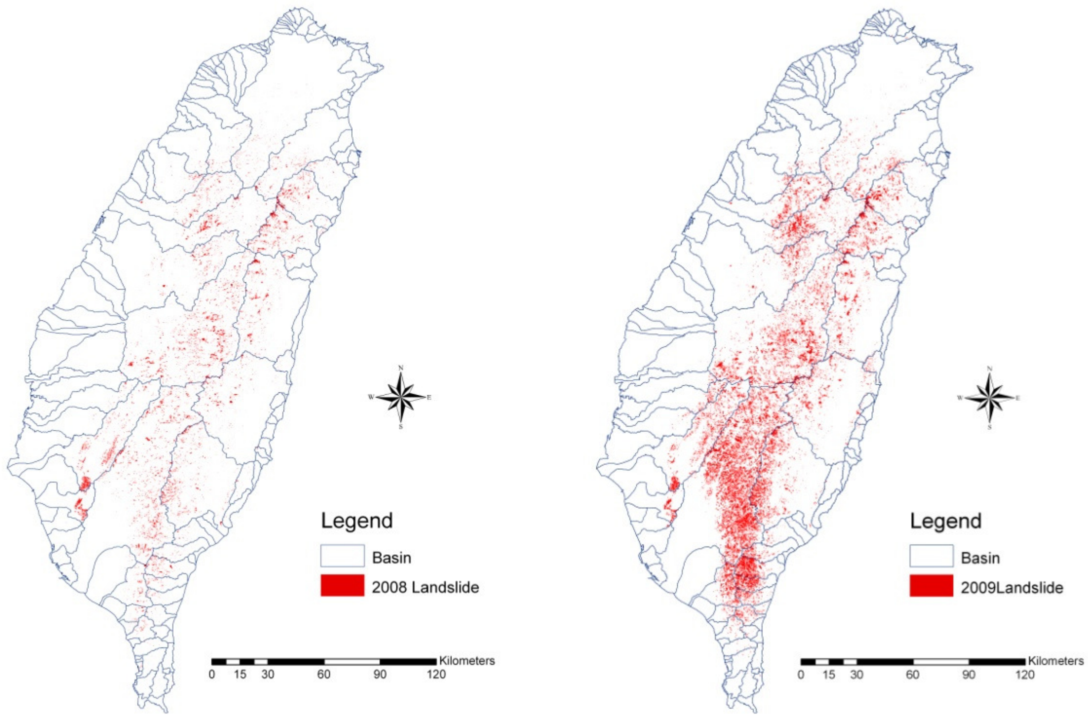

Fig. 1 The landslide distribution after typhoon Sinlaku in 2008 (left) and Morakot in 2009 (right)

In order to gain a deeper understanding of the physiographic characteristics of a landslide, this study focuses on the original elevation and slope distribution of a landslide area. At first an analysis was carried out by overlaying data from the of original digital elevation model (DEM) in 5 m grid-cell resolution with landslide data collected after typhoon Morakot. The output of this overlaying was an elevation map. According to the result we found out that 75% of the landslide area was distributed at an elevation of 200 to 2000 m. Out of this area approximately 50% of the landslide area was distributed at an elevation between 600 and 1600 m (Fig. 2). The area between this elevation range (600 - 1600 m) is also where villages and developmental land use are located. As a result this area suffered severe damages and losses after typhoon Morakot. However, the area between the elevation range from 3200 to 4000 m is the main landslide area because the landslide ratio, which is defined as the range of landslide area and the total area in a certain elevation range is more than 10% in this entire area. In particular in this area the landslide ratio at the elevation range from 3800 to 4000 m is large with a value greater than 40%.

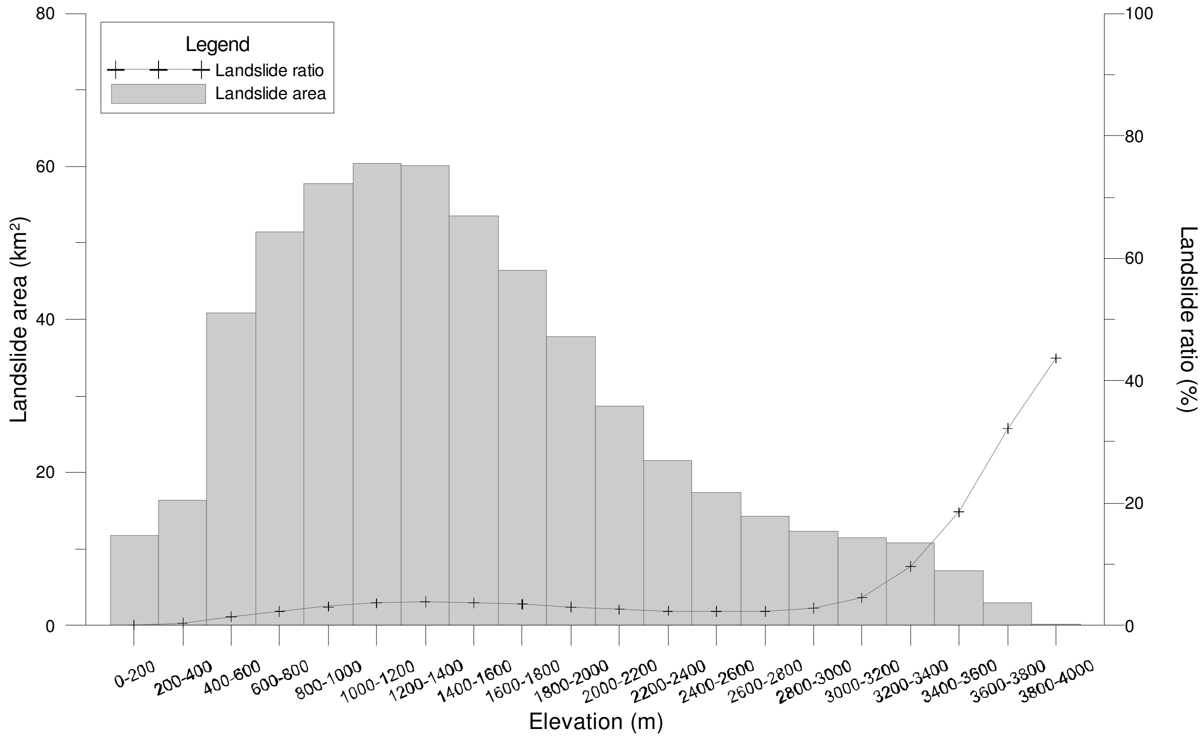

Fig. 2 The distribution of elevation vs. landslide area and vs. landslide ratio

At next we analyzed the landslide slopes by overlaying the elevation map constructed in the first part with the gradient map made from DEM data. The analysis results (Fig. 3) reveal that most of the landslide areas were located at slopes of less than 50°, out of which 80% of the landslide areas were located at slopes of 30° to 50°. Again, within this slope range 35% of the landslide areas were located at slopes of 30° to 40°. Furthermore 16% of the landslide areas were located at slopes of 20° to 30°, which is generally the area of development limits in the related regulations of land use identification and classification and of the conservation treatment classification. We also consider different areas in a classification of each slope of hillslope for understanding the relation between landslide ratio and slope. A landslide ratio for slope classification is obtained by dividing the landslide area in a classification of a certain slope by the total landslide area. The relation between landslide ratio and slope classification has a positive correlation.

The results of physiographic analysis, described in this section, show that the elevation between 600 and 1600m and the slope between 20° to 50° were highly sensitive to the landslide event that occurred during typhoon Morakot. Therefore we conclude that unrestricted development in this high-sensitivity slopeland should be avoided in order to prevent landslide hazards.

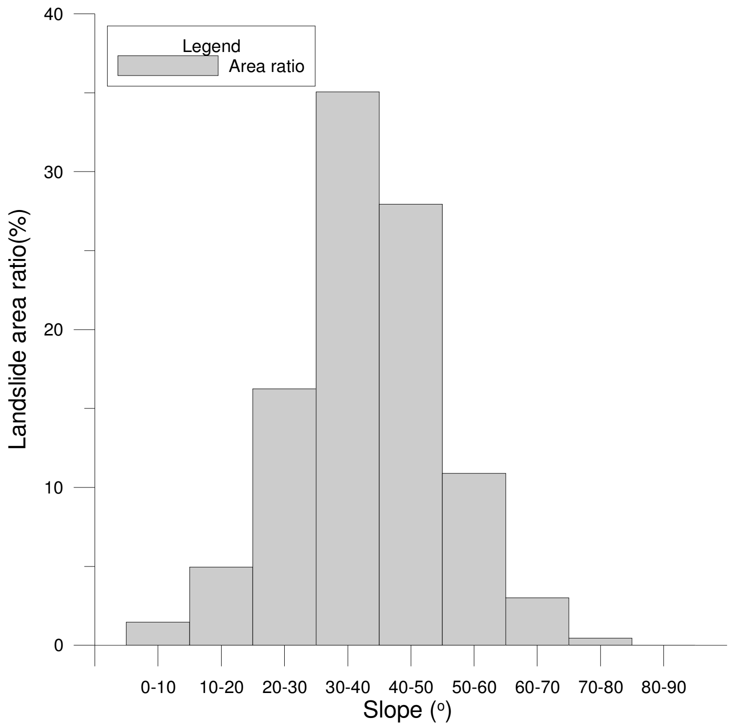

Fig. 3 Landslide area ratios versus slope angles

RAINFALL AND LANDSLIDE DISTRIBUTION AFTER TYPHOON MORAKOT

In order to elucidate the relation between landslide occurrence and cumulative rainfall amount, the study analyzed the cumulative rainfall data recorded during typhoon Morakot (from August 5 to August 10, 2009) by the Central Weather Bureau (Fig. 4). First, the entire island of rainfall map was divided into different areas according to multiples of 100 mm of measured cumulative rainfall amount; that is, areas receiving rainfall from 0 to 100 mm were classified in one group, and so on. Then these rainfall depth maps were overlaid with the landslide map. At next the landslide area for each 100-mm group was divided by the total landslide area, resulting in the landslide area ratio. We used statistical regression analysis to calculate the correlation between landslide area ratio and the cumulative landslide area. Fig. 5 shows a plot of the landslide area ratio versus cumulative rainfall amount. The landslide area ratio is greater than 4% in the area with cumulative rainfall between 1000 and 2200 mm but the landslide area ratio is close to 19.5% in the area where the cumulative rainfall ranges from 900 to 1200 mm. Furthermore the landslide area ratio shows an increasing trend for cumulative rainfall amounts greater than 400 mm and 900 mm; the landslide area ratio is close to 3.6% in the cumulative rainfall range of 1100 to 1200 mm, and the maximum value of landslide area ratio (6.6%) is observed in the cumulative rainfall range of 2100 to 2200 mm. Therefore this study conclude that 400 mm and 900 mm are the two critical cumulative rainfall depths that are likely to trigger more than 4% landslide area occurred in a mountainous area.

The analysis results show that 80% of the landslides were triggered in areas where the cumulative rainfall depth was above 700 mm, whereas 50% of the landslides were triggered in areas where the cumulative rainfall depth was more than 1300 mm; 4.5% of all landslides occurred in the cumulative rainfall depth range of 400 to 500 mm. The landslide area in the range of 0 to 500 mm was around 50 km2; further, the landslide areas were approximately 124 km2, 238 km2, 342 km2, and 428 km2 when the cumulative rainfall amounts were 1000 mm, 1500 mm, 2000 mm, and 2500 mm, respectively (Tab. 1).

Further, an investigation (Fig. 6) of the landslide spots at the area per 500 mm of the cumulative rainfall amount and landslide magnitude revealed that all the precipitation ranges are related with the occurrence of the big scale landslide (over 10 ha). The result indicates that rainfall-induced landslide magnitude is strongly related to physical geographic factors, regardless with the cumulative rainfall amount.

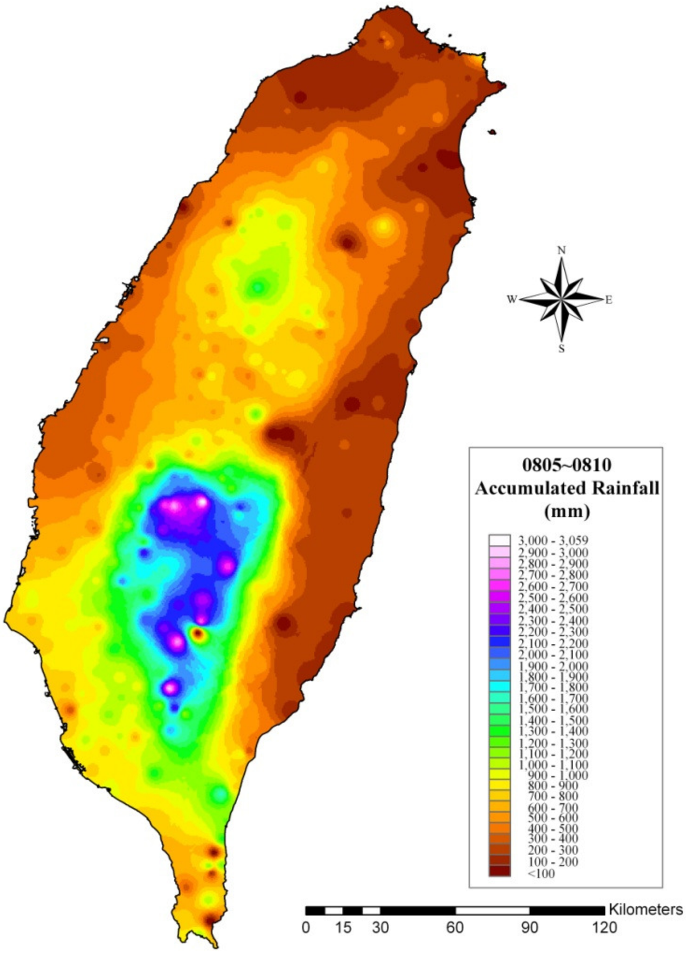

Fig. 4 The cumulative rainfall map after typhoon Morakot

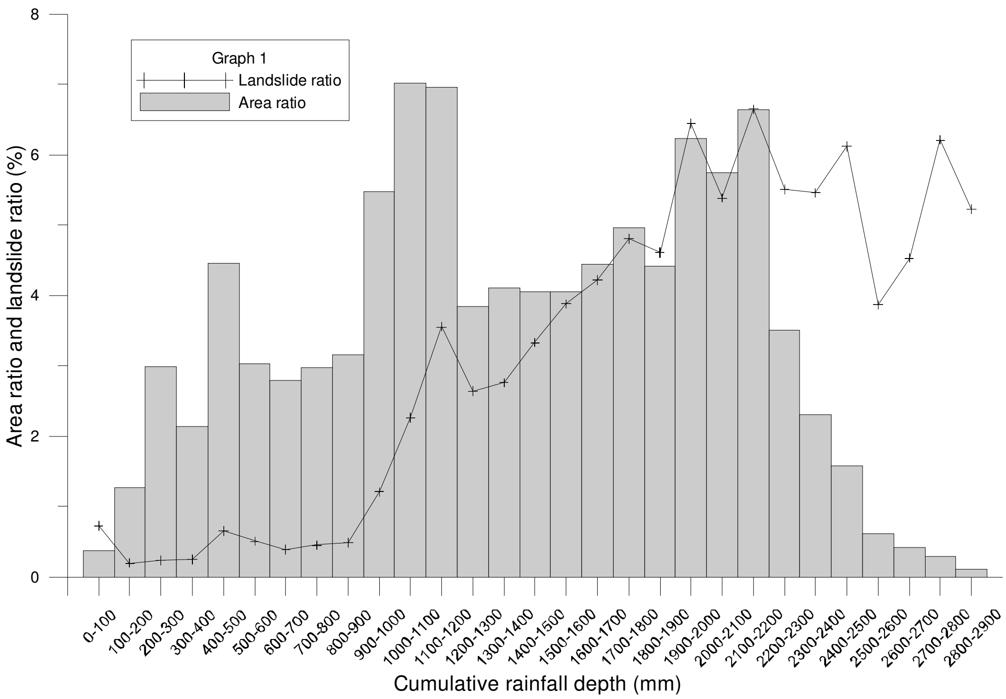

Fig. 5 The distribution of landslide with cumulative rainfall during typhoon Morakot

Tab. 1 The relation of landslide area and cumulative rainfall depth

Cumulative rainfall depth (mm)	Landslide area (km^2)	Landslide ratio (%)
0-500	50	2.08
500-1000	124	3.06
1000-1500	238	14.57
1500-2000	342	23.99
2000-2500	428	29.15
2500-3000	7	25.98

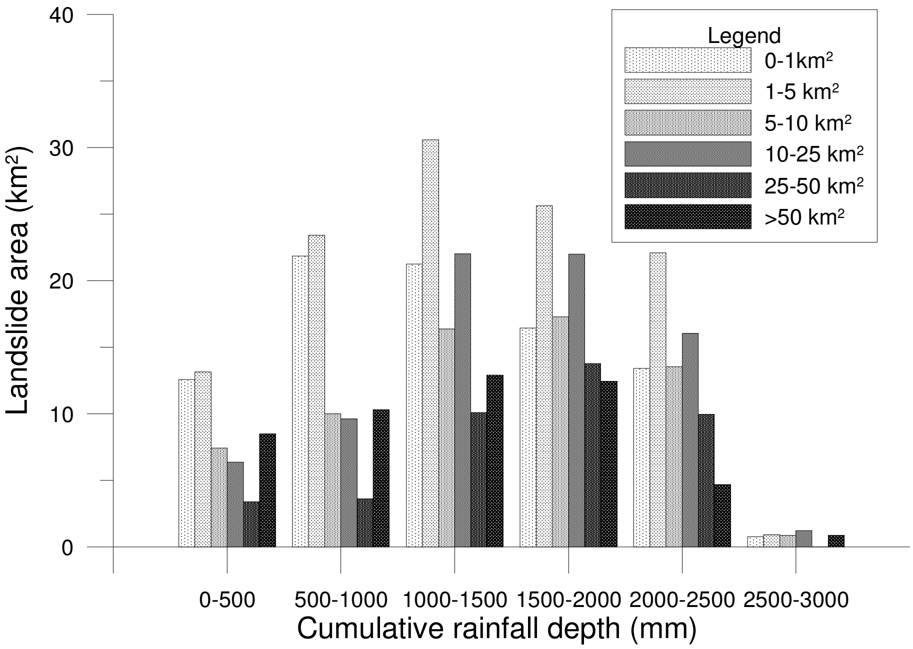

Fig. 6 The landslide magnitude and the distribution of cumulative rainfall amount

Next, the physiographic analysis results described in Fig. 2 were combined with the cumulative rainfall amount recorded after typhoon Morakot (Fig. 7). The landslide induced by the rainfall was divided into two categories according to the rainfall amount. In one category the cumulative rainfall amount was between 300 and 500 mm and the landslide was triggered in the mountainous area above 2600 m. The landslide particularly occurred in the area at an elevation above 3000 m because in this area the landslide ratio was greater than 40%. In the other category, the cumulative rainfall amount was greater than 900 mm and the landslide occurred in the mountainous area above 600 m. In this category the landslide ratio shows a clear increasing trend with increasing amount of cumulative rainfall. However, the landslide ratio is greater than 10% in the following two cases: if the elevation reaches 1400 m with a cumulative rainfall amount of 1200 mm or the elevation reaches 800 m with a cumulative rainfall depth of 2800 mm. These results indicate that the potential influence of these two cases on triggering of landslides should not be ignored.

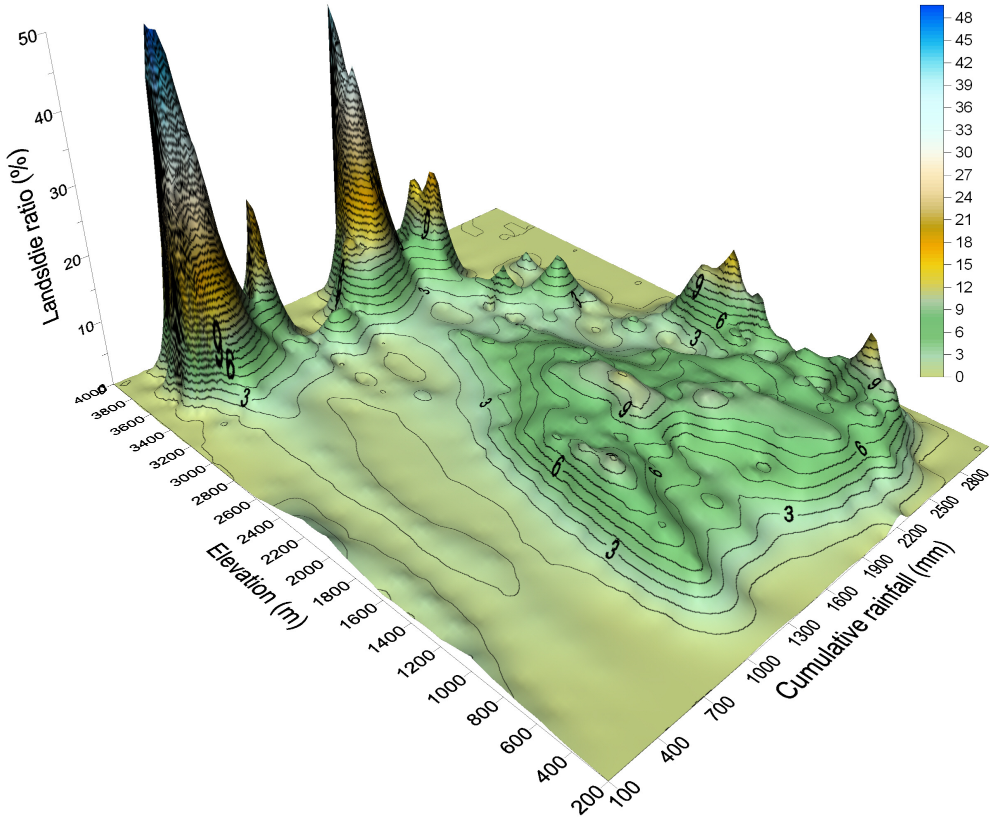

Fig. 7 The distribution between rainfall amount during typhoon Morakot, slopeland elevation, and landslide ratio

THREAT OF SEDIMENT DISASTER INDUCED BY TYPHOON PRECIPITATION

More than 80% of the annual precipitation usually occurs in the typhoon season (from May to August) because a typhoon is accompanied by heavy rainfall. We considered heavy rainfall ratio from the precipitation amount in typhoon Morakot and from the historical records (1947 – 2009). The heavy rainfall ratio is defined as dividing the total precipitation amount in typhoon Morakot by the maximum 72-hour rainfall amount in the historical records. The relation has shown that approximately 70% of landslide events occurred when the heavy rainfall ratio is more than 80% (Fig. 8). In other words, more than 900 mm of the accumulated rainfall during typhoon Morakot induced 70% of the landslides. We also looked at the 400 mm and 800 mm of the cumulative rainfall during typhoon Morakot, the percentages of landslide area are 90% and 75%, respectively. The results can be an important reference for determining the landslide occurrence in this event and for estimating the future slopeland disasters.

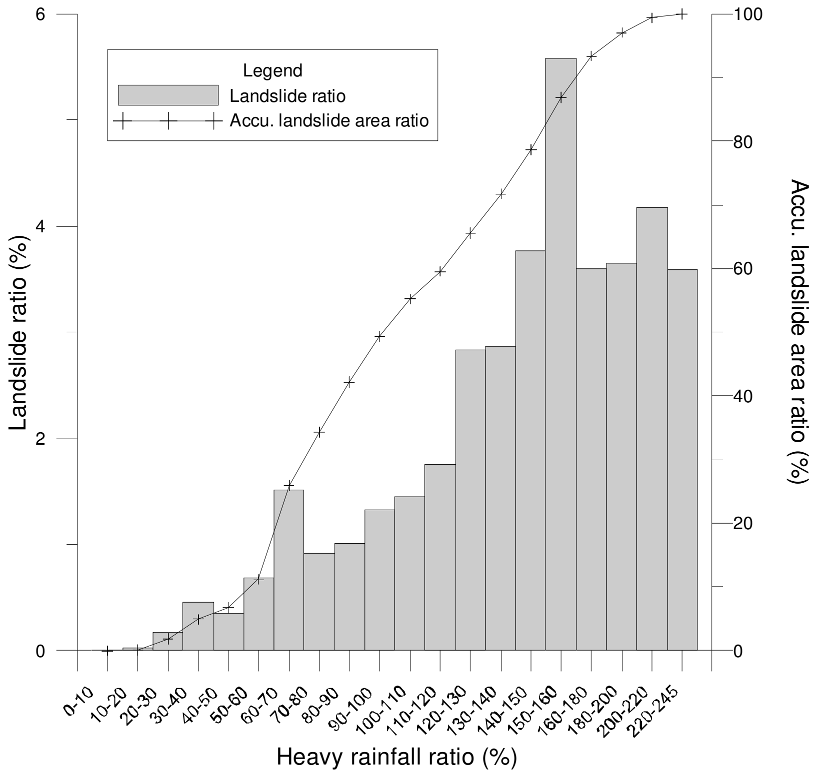

Fig. 8 The distribution of landslide ratio and the heavy rainfall ratio, heavy rainfall ratio is of the total amount during Morakot typhoon to the maximum value in 72-hour period of historical records (1947 -2009)

The relation among the number of typhoon events, annual rainfall, and the number of slopeland disaster cases has been investigated by the National Science and Technology Center for Disaster Reduction (NCDR) (Fig. 9). Their results show that the cumulative rainfall brought by typhoon Morakot was the highest in the local rainfall stations located in the central, southern, and eastern parts of mountainous areas. This highest proportion accounted for more than 70% of the annual precipitation, and caused slopeland disasters in large magnitude and scale. As a result, more than 500 severe slopeland disasters were probably induced when the long-term accumulated precipitation caused by a typhoon event was more than 30% of the annual precipitation and when rainfall was concentrated in the mountainous area.

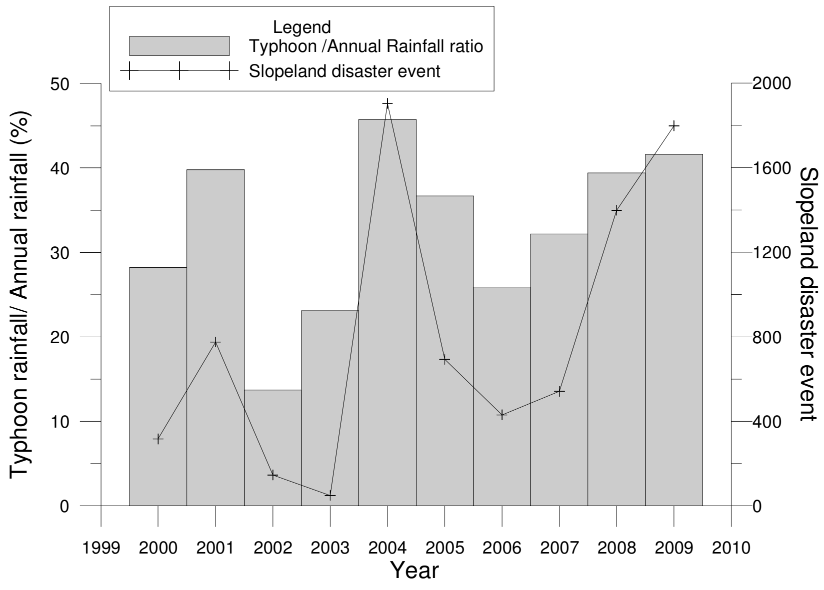

Fig. 9 Relations between rainfall ratio and slopeland disaster events, rainfall ratio is shown by the amount ratio of typhoon rainfall and annual precipitation

This study also analyzed records of rainfall brought by the typhoon events from 2000 to 2009 and calculated the rainfall ratio, which is defined as the rainfall amount during a typhoon event divided by annual rainfall amount. The average rainfall ratio was 30.1% for the first five years (2000 – 2004) and 35.1% for the last five years (2005 – 2009). That is, the rainfall ratio increased by 5% in the last five years, which indicates that the potential threat of slopeland disasters is also increasing with environmental changes. However, the changes in this trend of heavy rainfall are still unknown, and therefore, it is necessary to conduct a more detailed study and discussion about this issue in the near future. Restriction and management policies for land use in Taiwan should be improved to account for changes in climate and environment; further, improved protection strategies should be developed by implementing both engineering and non-engineering measures for area susceptible to slopeland disasters. Such strategies would greatly reduce the threat to local residents and properties in susceptible areas.

CONCLUSION

In this study, we discussed the physiographic factors and cumulative rainfall amount to clarify the landslides distribution induced by typhoon Morakot in 2009. We summarized the key results as follows: Approximately 75% of the landslide area is distributed over the elevation range of 200 to 2000 m; out of this, 50% of the landslide area is located at elevation ranging from 600 to 1600 m. In terms of slope, the landslide ratio shows a positive increase trend with a slope gradient up to 40°, and 80% of the landslide area is located on slopes ranging from 20° to 50°. These are the areas that contain developmental area and village settlements. Therefore it is necessary to formulate effective strategies for reducing disaster threats in these areas.

The area with landslides induced by rainfall could be classified into two main categories: in one area, the cumulative rainfall amount is between 300 and 500 mm and the landslides appear in a mountainous area with elevation above 2600 m, especially the area above 3000 m; in the second area, the cumulative rainfall amount is over 900 mm and the landslide event occurs in an area at an elevation above 600 m, especially the area between 600 m and 1400 m. The landslide area ratio shows positive increase trend with cumulative rainfall amount.

95% of the landslide occurred in areas where the cumulative rainfall depth exceeded 300 mm and over 40% of the maximum 72-hour precipitation from historical rainfall record. Furthermore the landslide magnitude was found to have no remarkable relation with the cumulative rainfall amount.

Results of a statistical analysis reveal that the serious and large scale slopeland disasters would be triggered when the long-term cumulative precipitation is more than 30% of the annual precipitation and if it is concentrated in the mountainous area.

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