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DEBRIS FLOWS AND LANDSLIDES CAUSED BY TYPHOON MORAKOT IN TAIWAN

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ABSTRACT

Typhoon Morakot was "born" on August 4, 2009 at approximately 22.4° N and 133.8° E in the North Pacific Ocean, about 1,000 km far from northeastern Philippines, moving west at a speed of 10-30 km/hr towards Taiwan, landing on Hualien, eastern Taiwan on August 7, and then moving across over northwestern Taiwan on August 8 with a wind speed up to 40 m/s. Unexpectedly, Typhoon Morakot brought severe rainfalls and caused catastrophic disasters, such as a large number of debris flows, shallow landslides, deep-seated landslides, debris dams and inundations in the mountainous areas of central and southern Taiwan. The catastrophic disasters killed more than 700 people. The rainfall brought by Typhoon Morakot was record-breaking, not only on rainfall amount and rainfall duration but also on total area covered with high rainfall. For example, the maximum 1-hour, 12-hour, 24-hour and 48-hour rainfalls at Alishan rainfall station were 123 mm, 934 mm, 1623 mm and 2,361 mm, respectively. This paper will report the rainfall conditions when the debris flows and landslides occurred and the characteristics of debris flows in Gaoping river watershed basing on the data of field investigations and satellite image analyses.

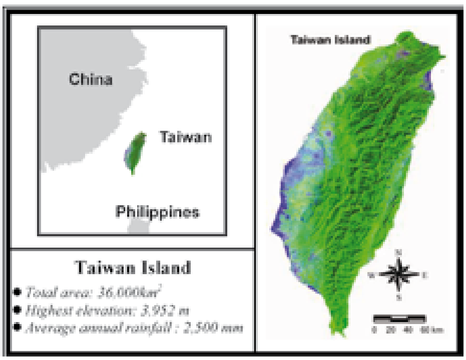

Fig.1 - Geographical location of Taiwan Island in SPOT image

Key words: *Typhoon Morakot, Debris Flow, Landslide, Gaoping river watershed, Taiwan*

INTRODUCTION

Taiwan is an island of 36,000 km^2 in size, oval in shape with a length of 394 km and a maximum width of 144 km. The island was formed by the collision of an island arc with the Asian continental margin. Orogenesis resulted in two-thirds of the island being covered by rugged mountains and hills, and about 31% of the total island area has an elevation exceeding 1,000 m (Gio, 2003). Most mountains are quite steep with slope gradients exceeding 25° (as shown in Figure 1). The ongoing orogenesis also causes frequent and strong earthquakes. In addition, significant denudation results in landslides, debris flows, and soil erosion in such mountainous terrain. Landslides generate a large amount of loose, weathered materials, which are delivered to creeks, thus forming the dominant sediment to supply mechanism for sediment-related hazards (Huang, 2002).

Furthermore, Taiwan possesses plentiful rainfall. It receives an annual rainfall of 2,500 mm, and the maxima rainfall exceeds 5,000 mm in some high mountainous regions. About 80% of the annual rain falls from May to October, especially during typhoons. As the result of heavy rain brought by typhoons, steep topography, young and weak geological formations, strong earthquakes, loose soils, and land development in mountainous terrain, many areas in Taiwan are susceptible to landslides and debris flows (TGRU, 2001). Among these contributors, typhoons are especially the major agent of landslides, debris flows and sediment-related hazards in Taiwan. On average, three typhoons hit Taiwan annually. Rainfall intensity during some destructive typhoons may exceed 100 mm/hr and 1,000 mm/24 hr.

On August 8, 2009, Typhoon Morakot landed on Taiwan, It covered almost the entire southern region of Taiwan and parts of eastern and central Taiwan and brought heavy rainfall. A large number of debris flows, shallow landslides, deep-seated landslides, debris dams and inundations in the mountainous areas are caused by its record-breaking rainfall. According to the estimation of CEOC (Central Emergency Operation Center), Typhoon Morakot resulted in 665 people deaths, 34 people missing, and about NT$141 billion economic losses.

Typhoon Morakot brought catastrophic damage in southern Taiwan, especially in Gaoping river watershed. Over 60% debris flow events and 50% landslide areas in Taiwan occurred in that watershed. The present paper focuses on and studies this area. The rainfall characteristics, debris flow events, landslide areas, and the relationship between the rainfall characteristics and debris flows as well as landslide areas will be discussed by means of rainfall data, field investigations and satellite image analyses.

Fig. 2 - Location map of the Gaoping river watershed, locations of landslides and 20 debris flow events caused by Typhoon Morakot.

STUDY AREA

Gaoping River is the largest river in southern Taiwan with a 3257 km2 drainage area and a 171 km long main stream in southwest Taiwan (as shown in Figure 2). The river originates in the south of the Jade Mountain with high altitude of 3952 m and has four main tributary drainages, Cishan river watershed, Laonong river watershed, Ailiao river watershed and Gaoping downriver watershed, whose drainage areas are 833 km2, 1375 km2, 623 km2, and 414 km2, respectively

Gaoping river watershed receives an annual rainfall of 3,000 mm, about 90% of annual rain falls from May to October, especially during typhoons. Gaoping river possess a high average slope gradient of 1/150 and high rainfall which result in the highest erosion rates in the world (10,934 ton/ km2 year) (Chung et al., 2009). Weak geological conditions, steep slopes, high potential rainfall and frequent earthquakes make severe debris-flow hazards and landslides disasters occur frequently in the watershed with years (see Tab. 1). The sediment-related hazards, debris flows, shallow landslides, deep-seated landslides caused about 572 deaths, 29 injured, and about 650 houses damaged in Gaoping river watershed during Typhoon Morakot. In this paper, severe debris flow events and landslides disasters brought by Typhoon Morakot within Gaoping river watershed were analyzed by the examination of Formosa Satellite II Image and field investigations.

Year	Typhoons	Debris Flows	Landslide Areas (ha)	Landslide Rate (%)
2004	9	0	2330.6	0.70
2005	7	3	3444.5	1.04
2006	7	2	4655.2	1.40
2007	6	4	3924.0	1.18
2008	6	6	4190.4	1.26
2009	4	20	18314.1	5.52

Tab. 1 - Number of severe debris flow events and landslide areas from 2004 to 2009 in the Gaoping river watershe

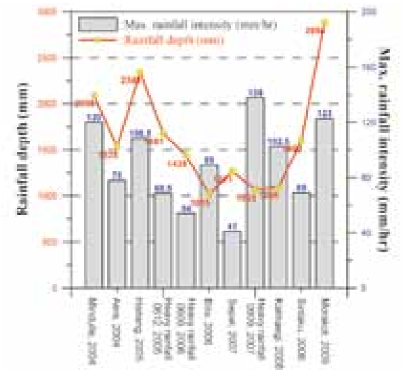

Fig. 3 - Rainfall depth and maximum rainfall intensity brought by Typhoons in Taiwan from 2004 to 2009

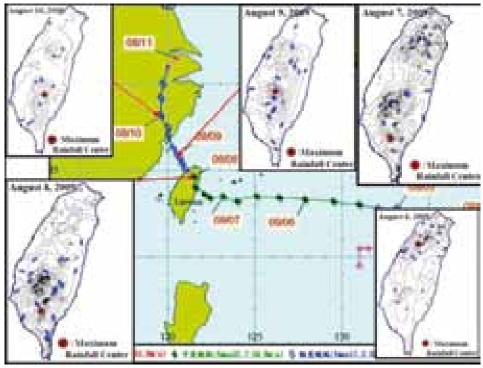

Fig. 4 - Path of Typhoon Morakot (from August 6 to August 10, 2009)

Year	Typhoons	Numbers	Debris Flows
2004	Conson, Mindulle, Kompasu, Rananim, Aere, Haima, Meari, Nock-Ten, Nanmadol	9	10
2005	Haitang, Matsa, Sanvu, Talim, Khanun, Damrey, Long-Wang,	7	18
2006	Chanchu, Ewiniar, Bilis, Kaemi, Saomai, Bopha, Shanshan	7	3
2007	Pabuk, Wutip, Sepat, Wipha, Krosa, Mitag	6	6
2008	Kalmaegi, Fung-Wong, Nuri, Sinlaku, Hagupit, Jangmi	6	16
2009	Linfa, Molave, Morakot, Parma	4	45

Tab. 2 - Number of severe debris flow hazards in Taiwan from 2004 to 2009

RAINFALL BROUGHT BY TYPHOON MORAKOT

Typhoons and heavy rainfalls are major agents of sedimentrelated hazards in Taiwan. The rainfall data of typhoon events was collected and analyzed from 2004 to 2009, as shown in Figure 3. The results show that the rainfall characteristics, rainfall depth and rainfall intensity have an increasing trend in recent years. The rainfall depth of Typhoon Morakot reached 2884 mm, which is the largest rainfall depth within a single typhoon event from 1960 to 2009. According to the estimation from SWCB (Soil and Water Conservation Bureau), the number of severe debris flow events and landslide disasters in Taiwan has increased, as shown in Table 2.

Typhoon Morakot was born on August 4, 2009 in the North Pacific Ocean, about 1,000 km far from north-eastern Philippines, moving west at a speed of 10-30 km/hr towards Taiwan, landing on Hualien, Eastern Taiwan on August 7, and then moving across over north-western Taiwan on August 8 with a wind speed up to 40 m/s. The moving path is shown in Figure 4. Considering wind speed and effect radius of a typhoon, Typhoon Morakot was not the strongest typhoon that had stricken Taiwan in the past four decades, Therefore, Typhoon Morakot had not been considered a serious threat before it struck Taiwan. However, in contrary to the prediction, after landing on Taiwan, it caused much more damage than any other typhoons because of record-breaking severe rainfall conditions, especially in the mountainous areas of central and southern Taiwan. Figure 5 shows the spatial distribution of rainfall depth from August 6 to August 11, 2009. The duration of the rainfall is about 108 hours in Taiwan.

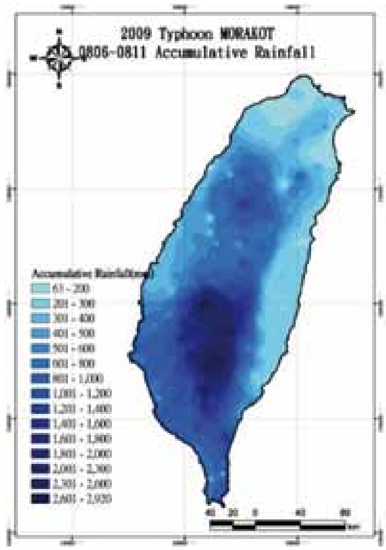

Fig. 5 - Isohyetal map of the 108-hour rainfall during Typhoon Morakot from

Among all rainfall stations in Taiwan, the maximum 1-hour, 6- hour, 12-hour, 24-hour, 48-hour and 72-hour rainfalls were recorded at Alishan Station, located above Gaoping river watershed, the rainfall depth

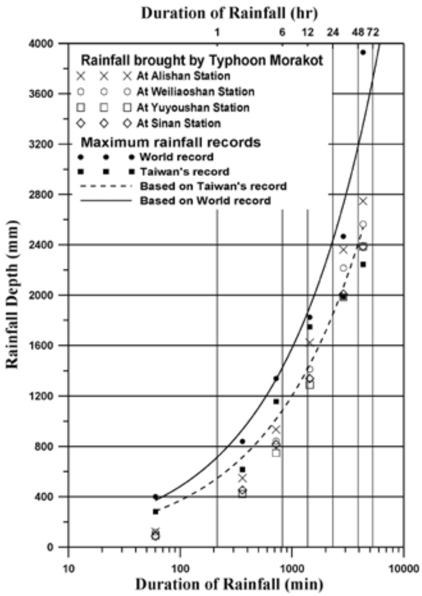

Fig. 6 - Magnitude-duration graph of rainfall at Alishan, Sinan, Welliaoshan and Yuyoushan rainfall stations during Typhoon Morakot

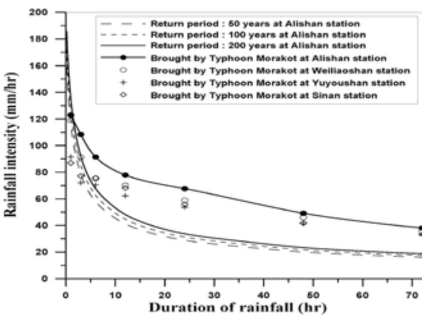

Fig. 7 - Intensity-duration graph of rainfall at Alishan Sinan, Welliaoshan and Yuyoushan rainfall stations during Typhoon Morakot

were 123 mm, 548.5 mm, 934.5 mm, 1,623.5 mm, 2,361 mm and 2,748 mm, respectively (see Figure 6). The previous rainfall records in Taiwan, 48-hour rainfall (1,986 mm) and 72-hour rainfall (2,243 mm) were broken. The 24-hour and 48-hour recorded rainfall approach the world records (2,467 mm and 1,825 mm, respectively). For comparison, Sinan, Welliaoshan, and Yuyoushan rainfall stations within Gaoping river watershed were plotted in Figure 6 as well.

Figure 7 shows the rainfall intensity-duration graph for the estimated return periods for 1-hour to 72-hour rainfall at Alishan Station well exceeded 200 years. In total, 2,884 mm rain fell at Alishan Station

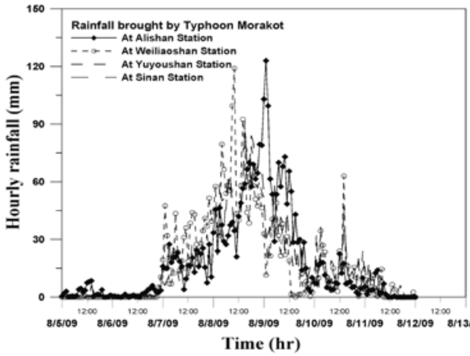

Fig. 8 - Hourly rainfall measured at Alishan Sinan, Welliaoshan, and Yuyoushan rainfall stations during Typhoon Morakot

over a period of 108 hours during Typhoon Morakot. This total amount equals about 70% of the regional annual rainfall at Alishan Station. The hourly rainfall exceeding 78 mm persisted for 12 hours, from 16: 00 on August 8 to 03:00 on August 9, 2009, at Alishan Station (see Fig. 8). The maximum hourly rainfall exceeded 120 mm at Alishan and Weiliaoshan rainfall stations.

LANDSLIDES CAUSED BY TYPHOON MORAKOT

The strong rainfall during Typhoon Morakot caused 370 km^2 landslide areas in central and southern Taiwan. Over 50% landslide areas occurred in Gaoping river watershed, for example, Xiaolin, Xinfa, and Nanshalu Villages having a lot of severe catastrophic disasters are also involved in this watershed. The positions and distributions of landslide areas after Typhoon Morakot were showed in Figure 2.

The landslide areas were confirmed and documented after each strong typhoon event from 2004 to 2009 by Formosa Satellite II Image analyses and field investigations. The results showed that the landslide areas in Gaoping river watershed were at an average value below 5000 ha/year before 2009. The areas immediately increase up to 18314 ha from 4190 ha, New landslide areas about 14124 ha were made after Typhoon Morakot, see Table 2. According to the estimation from SWCB (Soil and Water Conservation Bureau, 2009), landslide disasters in Gaoping river watershed were collected and documented, as shown in Table 3. The locations of landslide disasters, rainfall records and damage,adopted from rainfall stations are described.

In Figure 9, the Isohyetal map was plotted in dif-

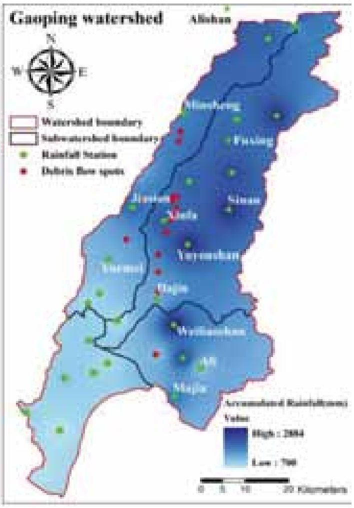

Fig. 9 - *Isohyetal map of the 108-hour rainfall during Typhoon Morakot from August 6 to August 11, 2009*

Fig. 10 - *The catastrophic landslides and debris flow hazards in Xiaolin Village and Xinfa Village in Gaoping river watershed*

Sub-watershed	Village/Rainfall station	Rainfall depth/Max. intensity	Landslide areas	Damage
Cishan	Xian/Jiasian	1,916 (mm) / 94 (mm/hr)	------	11 houses damaged 800 m roadways damaged
			11.3 (ha)	6 houses damaged 250 m roadways damaged
	Dongan/Jiasian	1,916 (mm) / 94 (mm/hr)	------	4 houses damaged 500 m roadways damaged 1 bridges damaged
	Xiaolin/Jiasian	1,916 (mm) / 94 (mm/hr)	190.0 (ha)	200 houses damaged 3,000 m roadways damaged 4 bridges damaged 490 people killed
			1.4 (ha)	4 houses damaged 250 m roadways damaged
	Nanshalu/ Minsheng	1,698 (mm) / 96 (mm/hr)	18.0 (ha)	15 m roadways damaged
Laonong	Xinfa/Xinfa	2,080 (mm) / 103 (mm/hr)	20.5 (ha)	6 houses damaged 180 m roadways damaged 5 people killed 12 people wounded
	Baolai/Xinfa	2,080 (mm) / 103 (mm/hr)	34.0 (ha)	12 houses damaged 800 m roadways damaged 5 people killed
	Xinglong/Xinfa	2,080 (mm) / 103 (mm/hr)	15.0 (ha)	8 houses damaged 800 m roadways damaged
			0.6 (ha)	4 houses damaged 80 m roadways damaged
			------	5 houses damaged 200 m roadways damaged 2 bridges damaged 8 people wounded
	Liugui/Xinfa	2,080 (mm) / 103 (mm/hr)	0.66 (ha)	2 houses damaged 500 m roadways damaged Landslide area of 0.66 ha
	Meishan/Fuxing	1,943 (mm) / 116 (mm/hr)	1.98 (ha)	5 houses damaged 500 m roadways damaged
Ailiao	Wanshan/Dajin	1,318 (mm) / 53 (mm/hr)	3.7 (ha)	1houses damaged 120 m roadways damaged
	Jiwu/Ali	1,102 (mm) / 53 (mm/hr)	95.0 (ha)	45 houses damaged 1,100 m roadways damaged
	Haocha/Majia	1,813 (mm) / 76 (mm/hr)	180.0 (ha)	125 houses damaged 2,000 m roadways damaged
	Dashe/ Weiliaoshan	2,702 (mm) / 117 (mm/hr)	------	5 houses damaged 20 m roadways damaged
	Dewen/Majia	1,813 (mm) / 76 (mm/hr)	12.0 (ha)	7 houses damaged 200 roadways damaged
Note : ------ No data				

Tab.3 - *Landslde disasters bought by Typhoon Morakot in Gaoping river watershed*

ferent gradation of blue colors to show the rainfall depth from 27 rainfall stations records in Gaoping river watershed during Typhoon Morakot from August 6 to August 11, 2009. According to the estimation from CWB (Central Weather Bureau, 2009), there are 8 rainfall stations with rainfall depth of over 2,000 mm. The maximum rainfall depth reached to 2,701 mm at Weiliaoshan Station. Its return periods for 1-hour to 72-hour rainfall exceeded 200 year. Considerable rainfall depth, high intensity and long duration caused a lot of landslides and disasters in Gaoping river watershed. The most miserable hazard of all landslides is in Xiaolin Village in Cishan river watershed see Figure 10 and 11. It caused the deep-seated landslides with 190 ha landslides and 160 ha sediment deposited which destroyed 200 houses, 3 bridges, 3 km road, 490 deaths, and about 3.5 km^2 inundation areas. Typhoon Morakot also brought significant landslide hazards in other villages as well, see Tab.3.

The relationship between the rainfall depth and landslide areas is analyzed as well as topographic conditions to understand the impact of Typhoon Morakot. By mans of the Isohyetal map (in Fig. 9), the representative rainfall depth can be calculated from isohyetal map and landslides map in overlap program with GIS (Geographic Information System) system.

The rainfall depth and landslide areas in the Gaoping river watershed have been analyzed in Table 4. The results show the landslide areas have an

rainfall depth (mm)	(a) Landslide areas (ha)	(b) Isohyet areas (ha)	(c) Landslide rate (%)
< 1000	6.16	57218.56	0.01
1000～1300	241.38	31809.66	0.76
1300～1600	2696.60	50057.52	5.39
1600～1900	5439.60	72121.72	7.54
1900～2200	7280.39	93014.61	7.83
2200～2500	2497.75	26510.39	9.42
> 2500	152.22	1308.92	11.60
Landslide rate (c)= Landslide areas (a)/ Isohyet areas (b)			

Tab. 4 - The relationship between Isohyet areas and landslides areas

Fig. 11 - The catastrophic deep-seated landslides in Xiaolin Village in Gaoping river watershed after Typhoon Morakot

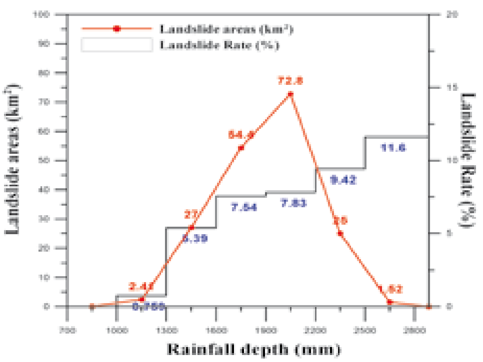

Fig. 12 - The relationship between accumulated rainfall and landslides in Gaoping river watershed

Sub-watershed	Village/Rainfall ststion	Rainfall depth/Max. intensity	Debris flow volumes	Damage
Cishan	Dongan /Jiasian	1,916 (mm) / 94 (mm/hr)	500 (10^3m^3)	5 houses damaged 2,300 m roadways damaged Landslide area of 10.0 ha
			50 (10^3m^3)	1 people killed 5 houses damaged 100 m roadways damaged Landslide area of 1.4 ha
	Jilai /Yuemei	1,247 (mm) / 80 (mm/hr)	840 (10^3m^3)	13 houses damaged 500 m roadways damaged Landslide area of 10.0 ha
	Guanshan / Guanshan	1,254 (mm) / 49 (mm/hr)	0.8 (10^3m^3)	13 houses damaged 50 m roadways damaged Landslide area of 0.1 ha
	Nanshalu/ Minsheng	1,698 (mm) / 96 (mm/hr)	75 (10^3m^3)	80 houses damaged 1,000 m roadways damaged 41 people killed Landslide area of 1.0 ha
	Maya/Minsheng	1,698 (mm) / 96(mm/hr)	40 (10^3m^3)	20 houses damaged 500 m roadways damaged Landslide area of 1.8 ha
			50 (10^3m^3)	3 houses damaged 400 m roadways damaged Landslide area of 0.9 ha
Laonong	Jianshan/Fuxing	1,943 (mm) / 116 (mm/hr)	1,300 (10^3m^3)	1,200 m roadways damaged Landslide area of 8.0 ha 1 bridges damaged
	Meilan/Fuxing	1,943 (mm) / 116 (mm/hr)	46.7 (10^3m^3)	2 houses damaged 300 m roadways damaged Landslide area of 1.2 ha
	Xinfa/Xinfa	2,080 (mm) / 103 (mm/hr)	45 (10^3m^3)	7 houses damaged 90 m roadways damaged 2 people killed 9 people wounded Landslide area of 0.8 ha
			800 (10^3m^3)	6 houses damaged 700 m roadways damaged
			1,000 (10^3m^3)	38 houses damaged 700 m roadways damaged 28 people killed Landslide area of 20.0 ha
			28 (10^3m^3)	5 houses damaged Landslide area of 2.3 ha
	Baolai/Xinfa	2,080 (mm) / 103 (mm/hr)	30 (10^3m^3)	3 houses damaged 300 m roadways damaged Landslide area of 4.5 ha
			50 (10^3m^3)	3 houses damaged 800 m roadways damaged Landslide area of 20.0 ha 1 bridges damaged
			3 (10^3m^3)	3 houses damaged 300 m roadways damaged Landslide area of 4.5 ha
	ZhongXing/ Xinfa	2,080 (mm) / 103 (mm/hr)	100 (10^3m^3)	6 houses damaged 700 m roadways damaged
			500 (10^3m^3)	12 houses damaged 400 m roadways damaged Landslide area of 10.0 ha
	Dajin/Dajin	1,318 (mm) / 53 (mm/hr)	50 (10^3m^3)	4 houses damaged 40 m roadways damaged Landslide area of 0.5 ha
Ailiao	Koushe/ Weiliaoshan	2,702 (mm) / 117 (mm/hr)	50 (10^3m^3)	1 houses damaged 300 m roadways damaged Landslide area of 0.3 ha

Tab. 5 - Consequences of Typhoon Morakot in Kaoping river watershed

increasing trend with rainfall depth. In Figure 12, the maximum landslide areas is 72.8 km^2 with rainfall depth of 1900~2200mm. The maximum landslide rate is 11.6% with rainfall depth over 2500 mm. The high landslide rate indicates that landslide areas within high Isohyetal areas are more than low Isohyetal.

The slope and landslide areas are selected to study as well. From Figure 13, the results show that the landslide areas increase as the slope rises. While the slope is between 24.8° and 45.0°, both landslide area and landslide rate are at maximum values, which are 109 km^2 and 8.83%, respectively. The relationship between elevation and landslide areas was shown in Figure 14, in which the major landslides took place at the elevation from 400 m to 2000 m, and the maximum landslide rate is within 800~1000 m, 12%.

DEBRIS FLOWS CAUSED BY TYPHOON MORAKOT

Typhoon Morakot brought heavy rainfall which triggered 45 debris flows in central and southern Taiwan. About 45% debris flows took place in Gaoping river watershed. These severe debris flow events caused serious disasters to some villages in this wa-

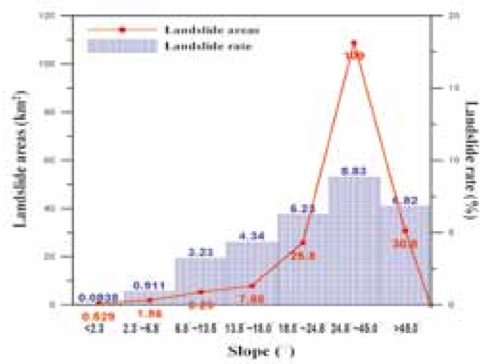

Fig. 13 - The relationship between slop and landslides in Gaoping river watershed

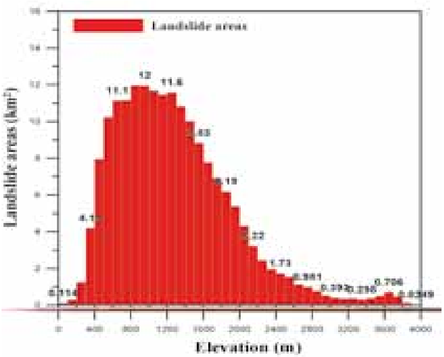

Fig. 14 - The relationship between elevation and landslides in Gaoping riverwatershed

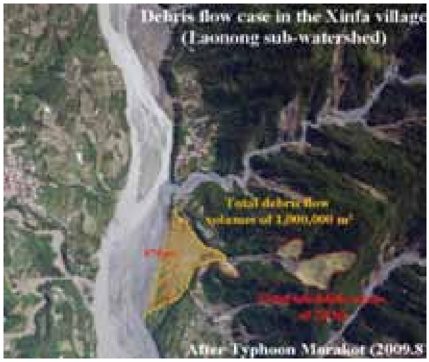

Fig. 15 - The debris flow hazard in Xinfa village in the Laonong river watershed in Gaoping watershed after Typhoon Morakot

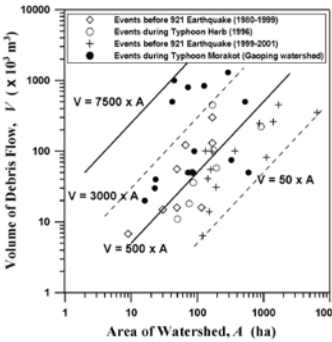

Fig. 16 - The relationship between watershed area and debris flows deposited volume in Chenyoulan and Gaoping river watershed

tershed, such as, Nanshalu, Xinfa, and Maya Villages. The positions and distributions of debris flow events after Typhoon Morakot were showed in Figure 2.

The debris flows were confirmed and documented after each single strong typhoon event hit Taiwan from 2004 to 2009 by Formosa Satellite II Image analyses and field surveys. The results showed that the number of severe debris flows in Gaoping river watershed was below 5 before 2009. However, the number increases up to 20 from 6 after Typhoon Morakot, see Table 1. According to the outcomes of SWCB, debris flow disasters in Gaoping river watershed were estimated and documented after Typhoon Morakot, as shown in Table 5. The locations, rainfall records, and damages of debris flow disasters adopted from rainfall stations have been described and calculated.

From the rainfall data brought by Typhoon Morakot in Fig. 9 or Tab.5, the record-breaking rainstorm mainly concentrated on the upper region of Gaoping river watershed (Laonong river watershed and Cishan river watershed), where 20 debris flow disasters occurred. The most wretched hazard of all debris flows is in Xinfa Village in the Laonong river watershed (see Figg. 10 and 15). The debris flows with 20 ha landslides and 1,000,000 sediments deposited which damaged 80 houses, destroyed 1 km roadway, 41deaths. Furthermore, Typhoon Morakot also brought significant debris flow hazards in other villages, see Tab.5. The running path and widespread sediment deposition volume of debris flows play an important role to endanger the habitants who live close to the debris flow potential streams, high probability of debris flow occurrence streams. In order to further understand the debris flow deposited volume, the catchment areas and the debris flow deposited volume are selected to analyze and estimate the relationship of catchment areas and deposited volume (Franzi & Bianco, 2001).

The debris flow deposited volume is roughly proportional to the catchment in Chenyoulan river watershed, and get the empirical functions at low limit

V= 50A and up limit V= 2,000A, as showed in Figure 16 (Jan & Chen, 2005). To comprehend the impact of Typhoon Morakot on debris flow deposited volume in Gaoping river watershed, the deposited volume events during Typhoon Morakot were plotted in Figure 13 .The results show that the low and up limits in Figure 13 have an increasing trend, which are V= 500A and V= 7,500A, respectively.

CONCLUSIONS

The sediment-related hazards have been more severe due to extreme rainfall events. On August 8, 2009, Typhoon Morakot stroke Taiwan and brought huge amounts of rainfall. The rainfall of Typhoon Morakot is found to be high-intensity and long-duration. All Taiwan was covered under the rainfall. Severe disasters, including landslides, debris flows, landslides dams, and floods, occurred in the Central and Southern Taiwan. Large amount of sediments and driftwoods have severe impacts on downstream rivers and reservoirs The heavy rains during Typhoon Morakot triggered 27 debris flows and 370 km^2 landslide areas in the central and southern Taiwan. The 60% debris flows and 50% landslide areas occurred in the Kaoping river watershed. Typhoon Morakot triggered 31 large cases of debris-flow and landslide hazards in the Kaoping river watershed. The most catastrophic landslide and debris flow hazard could be observed in Xinfa Village (Xinkai Community) and Xiaolin Village (Kaohsiung County).

Extreme rainfall events and recurrent debris flows have had significant socioeconomic consequences whose impacts on the wealth of Taiwan may eventually exhaust the available resources to cope with the aftermath of such disasters. Although the central government has been making efforts to develop debris flow and landslide countermeasures since Typhoon Herb, many debris flow and landslide mitigation measures and warning systems are still inadequate. For evacuation in the case of emergency, it will be necessary to enhance public awareness of many debris flow and landslide hazards and educate people on how to react to debris flow and landslide hazards.

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