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Paper:

An Overview of Disasters Resulted from Typhoon Morakot in Taiwan

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The purpose of this paper is to provide information on disasters caused by Typhoon Morakot in Taiwan. The torrential rainfall is regarded as the main cause, so information on the torrential rainfall is explored first. The maximum cumulative rainfall depth observed during Typhoon Morakot approached the world's greatest point rainfall record, and isohyets of cumulative rainfall depth are included, together with storm centers. Storm centers are important to disasters resulted from Typhoon Morakot, because these disasters occurred around or downstream from storm centers. Disasters triggered by Typhoon Morakot include floods, landslides, landslide dams, driftwood accumulation, and water supply disruption. Those occurring simultaneously or consecutively at one location are termed "compound hazards." Current warning systems for single disasters may not be sufficient to handle compound hazards, suggesting that we must develop new systems for issuing early warnings about compound hazards.

Keywords: Typhoon Morakot, compound hazard, rainfall, flood, sediment-related disaster

1. Introduction

A tropical depression formed on the sea 1,000 km northeast to Philippines on August 2, 2009. It then turned into a Typhoon on August 4 and was named as Morakot. Typhoon Morakot slowly moved westward toward Taiwan on the path shown in **Fig. 1** [1]. Typhoon Morakot's intensity was once equivalent to that of a Category 2 hurricane on the Saffir-Simpson Hurricane Scale, with maximum wind speed of 85 knots [2]. From August 7, 2009, the storm circle of Typhoon Morakot affected Taiwan when, at 17:00, the island came within the typhoon's storm circle. Typhoon Morakot made landfall at 23:50 the same day in eastern Taiwan's Hualien County, as shown in **Fig. 2**. Typhoon Morakot's intensity gradually decreased as it moved across the Central Mountains of Taiwan. Typhoon Morakot's storm circle left Taiwan at 18:30 on August 9, turned northward toward China, and weakened to a tropical depression on August 11 in China.

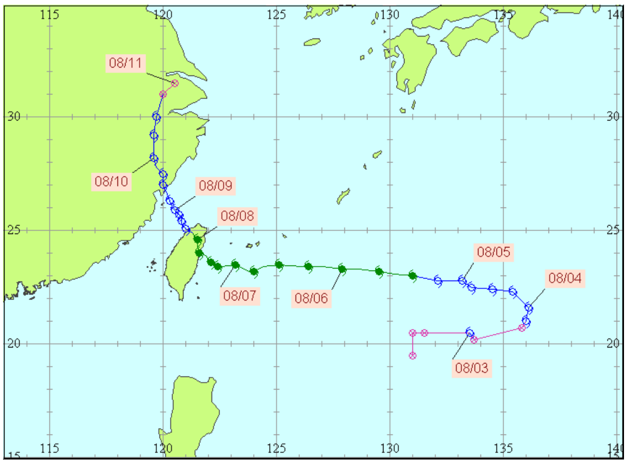

Fig. 1. Track of Typhoon Morakot [1].

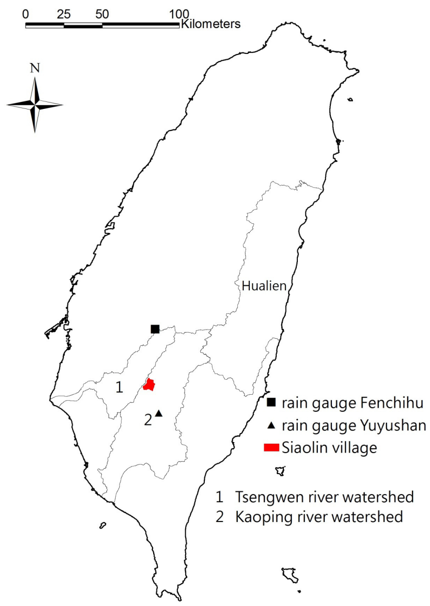

Fig. 2. Sites mentioned in this paper.

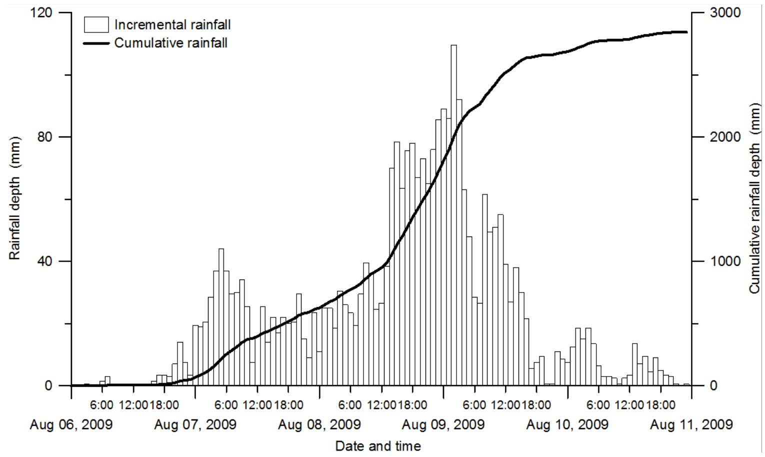

Fig. 3. Incremental and cumulative rainfall hyetographs at rain gauge Fenchihu during Typhoon Morakot.

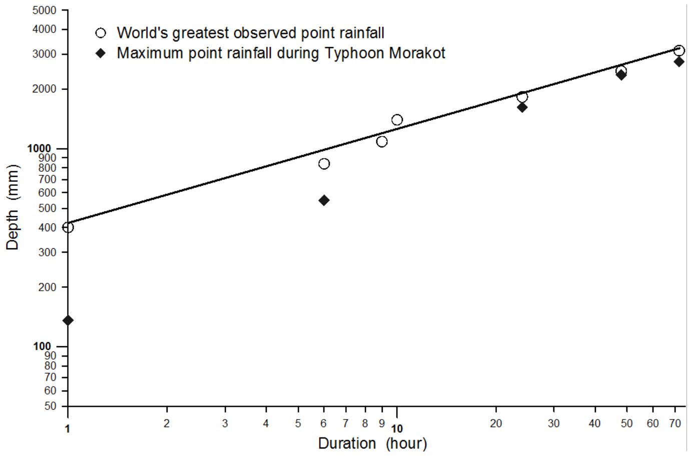

Fig. 4. World's greatest point rainfall record versus the maximum point rainfall record during Typhoon Morakot.

2. Rainfall

For Taiwan, Typhoon Morakot is probably the deadliest typhoon over the past fifty years. The purpose of this paper is thus to provide an overview of disasters due to Typhoon Morakot – disasters including floods, landslides, landslide dam formation, driftwood accumulation, and water supply disruption. Those occurring almost concurrently at certain sites are called "compound hazards." The sections that follow start with the characteristics of the heavy rainfall, followed by floods, the sediment-related disasters, and driftwood accumulation. An example of a compound hazard is also given. A possible measure to alleviate the losses caused by compound hazards is suggested as the conclusion of this paper.

The most critical feature of Typhoon Morakot is the rainfall, and the rainfall is generally regarded as the major cause of the disasters triggered by this typhoon. As stated by Shieh et al. [2], the characteristics of the rainfall of Typhoon Morakot are long-duration, large-extent, and high-

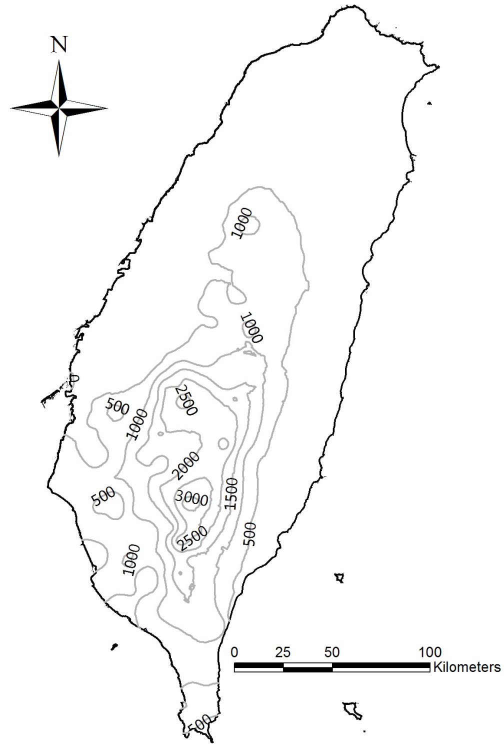

Fig. 5. Isohyets in Taiwan during Typhoon Morakot. Isohyets are in mm depth of total rainfall.

intensity. As seen in **Fig. 3**, for example, incremental and cumulative rainfall hyetographs at rain gauge Fenchihu (**Fig. 2**) show that observed rainfall lasted 118 hours and the cumulative rainfall depth is 2841.5 mm. The greatest 1-hour rainfall intensity is 109.5 mm/hour.

The maximum point rainfall depth records [3], extracted from Taiwan's rainfall records during Typhoon Morakot are shown in **Fig. 4**. Note that the values of the 24-hour, 48-hour and 72-hour cumulative rainfall depths approach those of the world's greatest point rainfall records [4], indicating the rainfall's high intensity.

2.1. Isohyets

Cumulative rainfall depth isohyets for Taiwan during Typhoon Morakot, shown in **Fig. 5**, demonstrate how rainfall covered all of Taiwan during the typhoon, showing the rainfall's large extent. Storm centers observed in southern Taiwan as shown in **Fig. 5** are strongly related to subsequent disasters, including floods, landslides, and landslide dam formation.

2.2. Frequency Analysis

In Taiwan, the design of water resource systems is based on rainfall frequency analysis. The design level of major rivers is different from that of minor rivers. For major rivers, the design level is determined using the design storm for a 200-year return period. For minor rivers, in contrast, the design level is determined using a 50-year storm return period. Once the loading of a system exceeds

Table 1. Frequency analysis result of the cumulative rainfall depths for different durations during Typhoon Morakot [3].

Watershed	Rain gague	Duration (hour)						Cumulative rainfall depth during Typhoon Morakot (mm)
		24		48		72		
		Depth (mm)	Return Period (year)	Depth (mm)	Return Period (year)	Depth (mm)	Return Period (year)	
Choushui river	Alisan	1624	> 2000	2361	> 2000	2748	> 2000	2884
Beigang river	Dapu	760	977	971	> 2000	1124	> 2000	1148
Puchi river	Zanniaoliao	650	21	1202	> 2000	1595	> 2000	1631
Bazhang river	Shipanlong	1583	90	2107	147	2504	238	2637
Chishui river	Dadonsan	759	> 2000	1181	> 2000	1467	> 2000	1522
Tsengwen river	Tsengwen	1089	489	1644	> 2000	1914	> 2000	1948
Yanshui river	Chidin	611	236	781	101	828	39	846
Erhjen river	Mucha	828	> 2000	1105	> 2000	1191	> 2000	1221
Kaoping river	Wueiliaosan	1415	> 2000	2216	> 2000	2564	> 2000	2701
Kaoping river	Chiasen	1078	> 2000	1601	> 2000	1856	> 2000	1916
Dongkong river	Laiyi	829	101	1168	1534	1289	> 2000	1339

its capacity, determined by the design level, the system may fail.

The frequency analysis of the cumulative rainfall depths of 24-hour, 48-hour, and 72-hour for many rain gauges during Typhoon Morakot is given in **Table 1** [3]. It can be seen that the return periods of many cumulative rainfall depths exceed 200 years, and some even exceed 2,000 years. Most such rainfall depths were observed at rain gauges near storm centers, indicating that the loadings of many water resource systems might exceed their capacity. Failures of these systems caused disasters.

3. Flood

During Typhoon Morakot, the torrential rainfall mainly fell on areas near storm centers and hence the corresponding downstream areas were flooded. As shown in **Fig. 6**, blue shaded areas downstream from storm centers flooded during Typhoon Morakot. The downstream areas of two watersheds, which are the Tsengwen River watershed and the Kaoping River watershed (**Fig. 2**), were severely damaged by the flood. The cause of the flood is that the loadings of flood-prevention systems were greatly larger than their capacities. The loadings came from the torrential rainfall.

3.1. Impact

Flood damage resulting from Typhoon Morakot is summarized in **Table 2** [3]. The most severely damaged area is in southwest Taiwan, where flooding breached levees. Levee breach statistics are given in **Table 3**. Following breaches, floodwaters flowed into areas originally protected by levees. In other places, flood damage causes were more complex, including a lack of levees, overtopping of levees, and unexpected flood discharge from reservoirs. Waters that could not drain in time via drainage systems caused further damage and flooding.

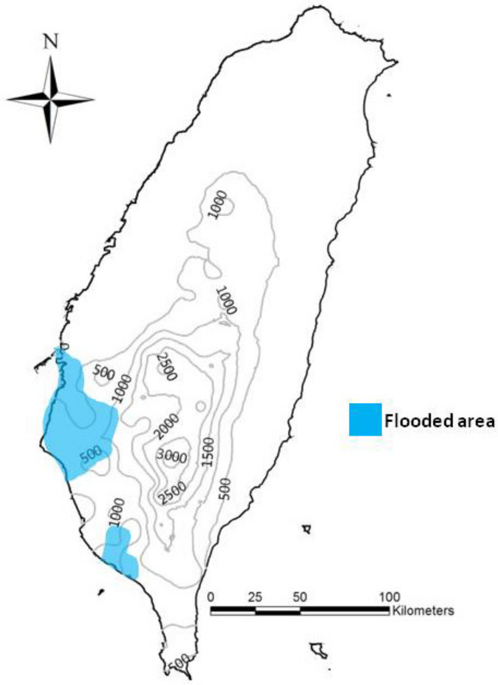

Fig. 6. Flooded areas during Typhoon Morakot [3].

3.2. An Example

One of the most severely flooded areas is the Tsengwen River watershed, shown in **Fig. 7**. Among the watershed's three reservoirs, the Tsengwen reservoir (reservoir

Table 2. Damage statistics [3].

Item	Amount
Casualties (person)	757 (698 died, 59 missing)
Road disruption (number of places)	100
Power supply failure (house)	1,595,419
Water supply failure(house)	769,159
Agricultural damage cost (NT dollars)	16,468,630,000
Water resource system failure (number of places)	174
Evacuated person	24,950
Persons received by shelters	5,990

Table 3. Statistics of levee breaches [3].

Item	Length of breaches (m)	Length of damaged (m)
Levee of major rivers	36,242	9,590
Levee of drainage systems	0	325
Sea wall	520	180

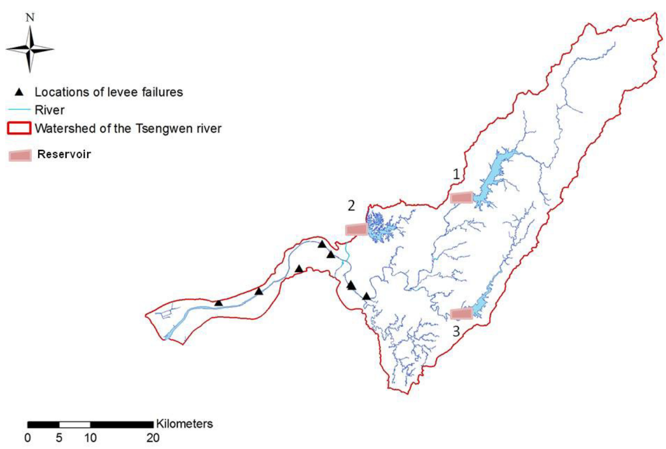

Fig. 7. Tesengwen River watershed.

1 in **Fig. 7**) is a main supplier of water to southern Taiwan and is, in addition, Taiwan's largest reservoir. During Typhoon Morakot, massive rainfall flooded this watershed and its densely populated downstream areas, e.g., as shown in **Fig. 8**.

Tsengwen reservoir inflow and outflow hydrographs during Typhoon Morakot are shown in **Fig. 9**. Regulation of the Tsengwen reservoir made the peak discharge of the outflow hydrograph discharge less than that of the inflow hydrograph. During Typhoon Morakot, the peak discharge of the inflow hydrograph was 11,729 m^3/s – the historical maximum. The peak discharge of the outflow hydrograph was 8,367 m^3/s. The capacity of the flood-prevention system immediately downstream from the Tsengwen reservoir is just 4,940 m^3/s [5]. The Tsengwen reservoir outflow rate exceeded the downstream flood-prevention system capacity from 00:00 to 16:00 on August 9, as shown in **Fig. 9**, causing the flood-prevention system to fail.

Fig. 8. The flood in the downstream area of the Tsengwen reservoir.

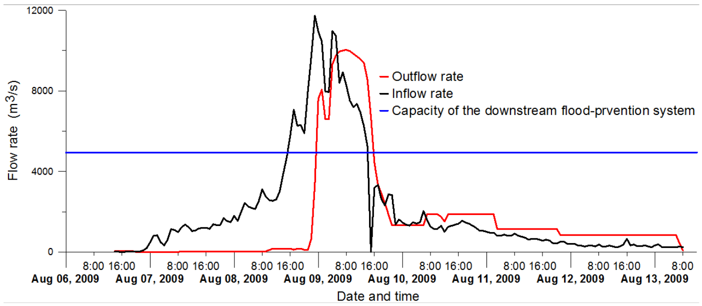

Fig. 9. Tsengwen reservoir inflow and outflow hydrographs during Typhoon Morakot.

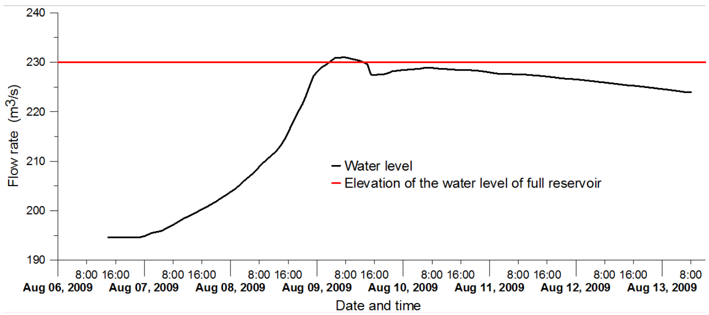

Fig. 10. Tsengwen reservoir water level hydrograph during Typhoon Morakot.

The hydrograph of the water level of the Tsengwen reservoir is shown in **Fig. 10**. The full reservoir level, 230 m, should not be exceeded if the reservoir is to remain safe. This level was actually exceeded, however, from 04:00 to 12:00 on August 9, as shown in **Fig. 10**. In attempts to maintain the reservoir safety and viability, the administrator had to release water which is unbearable to the downstream flood-prevention system. This was a compromise alternative between flooding and dam destruction.

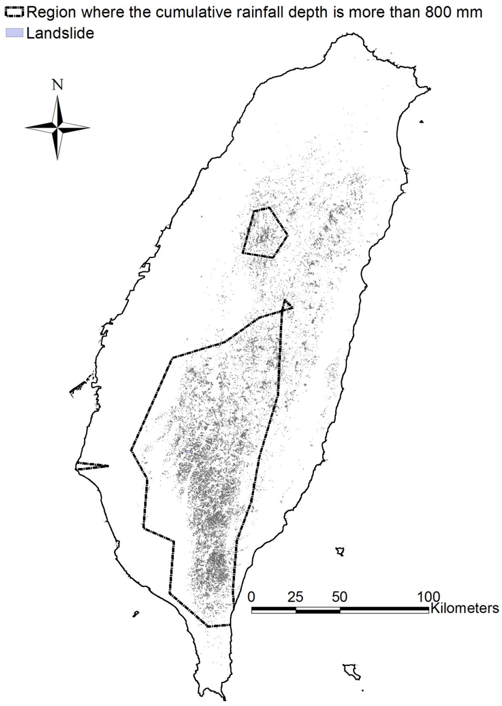

Fig. 11. Landslides within regions where the cumulative rainfall depths are more than 800 mm.

4. Sediment-Related Disasters

Rainfall is one driving force in landslides and slope erosion – two sources of sediment yield. Large landslides blocking river channels may form landslide dams, and sediment yield may contaminate water, disrupting water supplies. Landslides, landslide dams, and turbid water are thus regarded here as sediment-related disasters, as detailed in the sections that follow.

4.1. Landslides

Torrential rainfall during Typhoon Morakot triggered landslides all over Taiwan. One notorious example in Siaolin village (**Fig. 2**) killed over 400 persons. The cumulative rainfall depth observed at a nearby rain gauge was 2,583 mm and lasted 91 hours. Shieh et al. [2] provide details.

Landslides occurring during Typhoon Morakot are recognized using satellite imageries. Results are overlaid by isohyets of cumulative rainfall depth as shown in **Fig. 11**. Note that numerous landslides occurred within regions where cumulative rainfall depths exceeded 800 mm.

The landslide rate l is defined as:

$$l = \frac{A_L^r}{A^r} \quad \quad (1)$$

where A_L^r is the area of landslides within region r and A^r is the area of region r. Region r indicates a region within which observed cumulative rainfall depths fall in a specific interval.

Landslide rates for regions with different cumulative rainfall depths are in **Fig. 12**. (Triangles are landslide rates for landslides newly added during Typhoon Morakot. Circles are landslide rates for landslides occurring before Typhoon Morakot and being enlarged during the typhoon. Squares summarize newly added and enlarged landslide rates.)

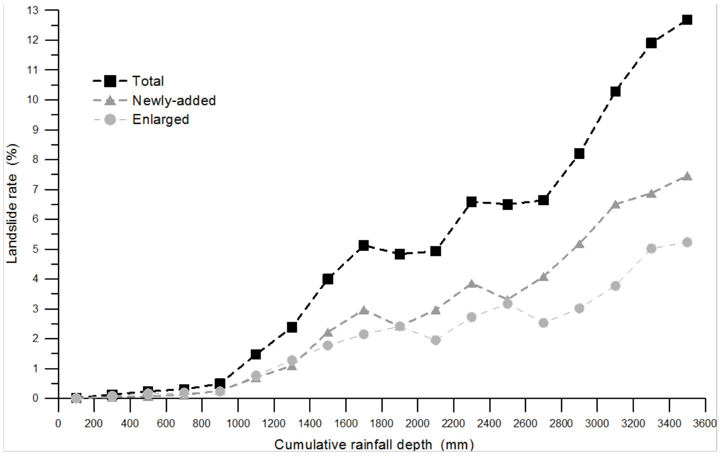

Fig. 12. Landslide rates in regions of different cumulative rainfall depths.

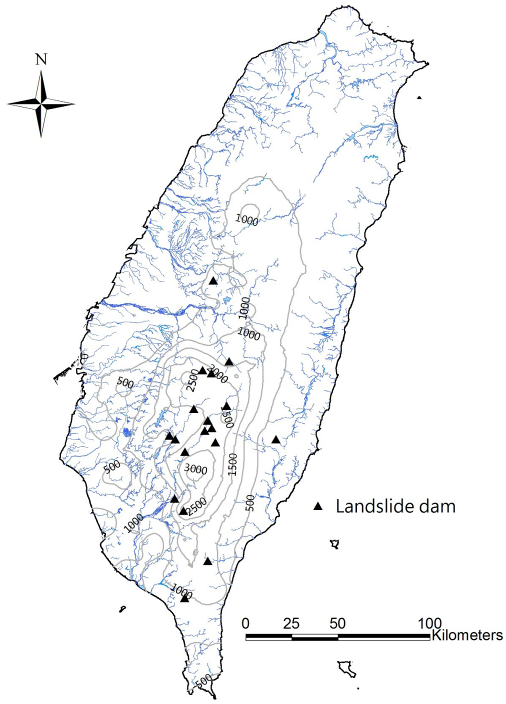

Fig. 13. Landslide dams formed during Typhoon Morakot.

Note that the landslide rates increase with the increasing of cumulative rainfall depth, and newly added landslide rates are generally larger than enlarged landslide rates, indicating that the area of landslides newly added during Typhoon Morakot exceeds that of existing landslides. This phenomenon may cause greater sediment yield from slopes of landslide after Typhoon Morakot than that from before.

Fig. 14. A landslide dam photographed from a helicopter.

Fig. 16. Turbid water observed in the Nanhua reservoir during Typhoon Morakot [4].

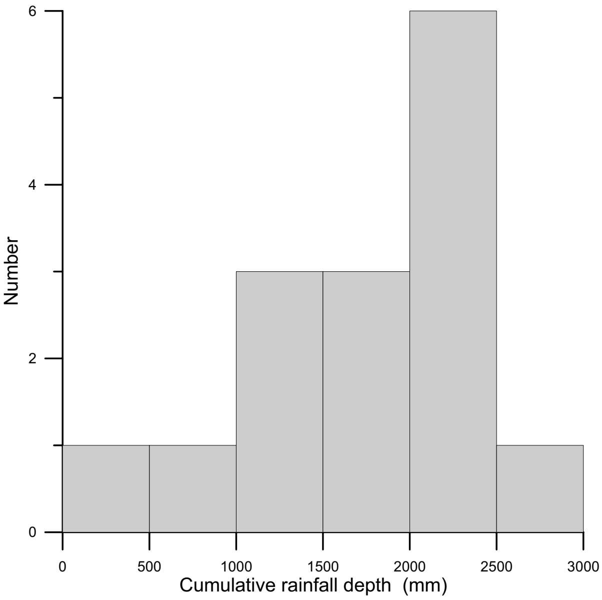

Fig. 15. Number of landslide dams in regions where the cumulative rainfall is different.

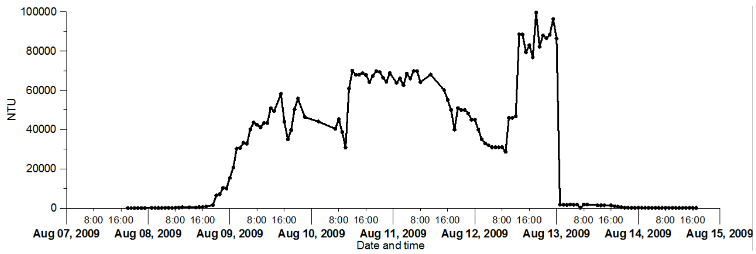

Fig. 17. Time series of the turbidity measured in nephelometric turbidity units (NTU) in the Nanhua reservoir during Typhoon Morakot [3].

4.2. Landslide Dams

The 15 landslide dams forming during Typhoon Morakot were observed using satellite imageries and are located as shown in **Fig. 13**. A landslide dam photographed from a helicopter is shown in **Fig. 14**. Most of the 15 landslide dams spread around storm centers, with some being downstream from storm centers. **Fig. 15** compares landslide dam locations to isohyets. Twelve landslide dams formed in the region within which the cumulative rainfall depth is between 1,000 mm and 2,500 mm.

4.3. Turbid Water

During Typhoon Morakot, turbid water was observed in reservoirs, for example, **Fig. 16** of the Nanhua reservoir (reservoir 3 in **Fig. 7**). The water treatment plant of the Nanhua reservoir is capable of handling the water whose turbidity in nephelometric turbidity units (NTU) not exceeding 100 NTU. Nanhua reservoir water turbidity, shown in **Fig. 17**, was at least 100 NTU until August 14, 2009, meaning that the water supply of the Nanhua reservoir ceased for almost one week.

5. Driftwood

Driftwood and its accumulation are a source of damage to facilities such as bridges, levees, and dams. Driftwoods in river channels may obstruct water flow and raise water levels to flood levels. Such increased water levels may also aggravate flood damage.

Satellite imageries taken afther Typhoon Morakot showed much bare land and the occurrence of many landslides, indicating the destruction of vegetation. Strong surface runoff may have carried driftwood down river channels, from which driftwood was then pushed downstream to the sea or caught upon dams, bridges, and other facilities.

Our field investigation found driftwood in areas downstream from storm centers. After floods receded, for example, driftwood caught on pipes downstream from storm centers is shown in **Fig. 18** and in the Tsengwen reservoir as shown in **Fig. 19**.

Fig. 18. Driftwood beside a pipe.

Fig. 20. Landslide in Siaolin village.

Fig. 19. Driftwood in the Tsengwen reservoir.

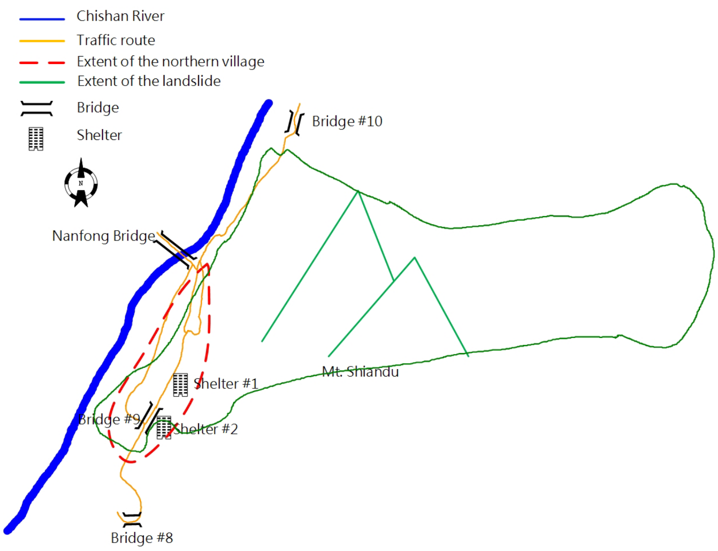

Fig. 21. A simplified map of Siaolin village.

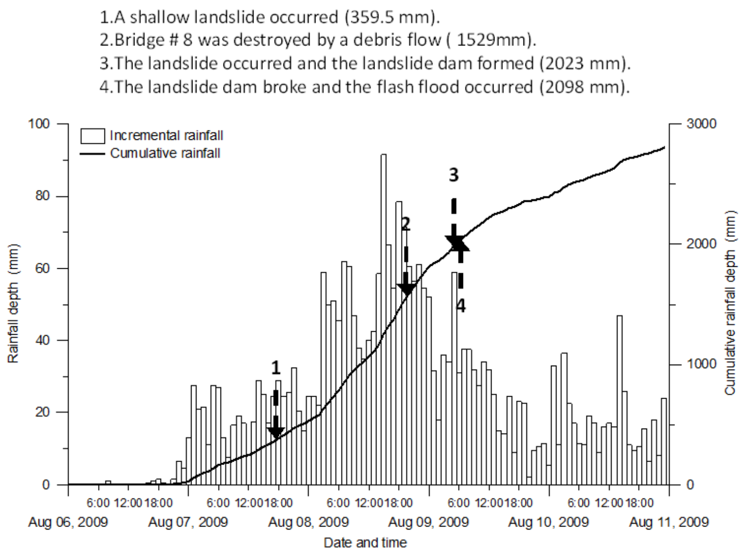

Fig. 22. Incremental and cumulative rainfall hyetographs of rain gauge Yuyushan.

6. Compound Hazards

As stated, a landslide in Siaolin village killing over 400 persons is one example of a compound hazard. This included a debris flow, a landslide, a landslide dam formation, and a landslide dam break which itself triggered a flash flood. The landslide is shown in **Fig. 20**. A simplified map of Siaolin village shown in **Fig. 21** is provided for readers to understand the compound hazard. The incremental and cumulative hyetographs observed at the rain gauge Yuyushan (**Fig. 2**) near Siaolin village are drawn in **Fig. 22**, together with important events and corresponding cumulative rainfall depths.

The first event was a shallow landslide followed by a debris flow. Bridge #8, shown in **Fig. 21**, was destroyed by the debris flow. At about 06:00 on August 9, the landslide occurred when cumulative rainfall depth was 2,023 mm. The landslide then formed a landslide dam that later broke, triggering a flash flood.

7. Conclusion

Torrential rainfall played an important role during Typhoon Morakot. As aforementioned, disasters of different types occurred around or downstream from storm centers, including compound hazards. The disasters occurred in Siaolin village [2] is one example of the compound hazard.

Compound hazards, such as the ones occurred during Typhoon Morakot, are often inevitable, but may be alleviated, for example, through use of early warning systems. Present warning systems are, however, often specialized for single hazards and are not sufficient to deal with the compound hazard. We must therefore develop early warning systems for the compound hazard.

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