Characteristics of Debris Flow in Taiwan - A Case Study in Shenmu Area

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Debris flow has become a common natural hazard in Taiwan. After several typhoons (Typhoon Mindule in 2004; Typhoon Haitang in 2005; and Typhoon Morakot in 2009), the increasing landslide in the middle Taiwan had resulted in abundant debris source at the upper streams, and therefore contributed to the higher potential of debris flow. The Soil and Water Conservation Bureau (SWCB) in Taiwan started to build debris flow monitoring stations since 2002 to observe and collect debris flow data. Sensors like rain gauge, soil moisture, and geophone, had been applied for observation. Among the cases, Shenmu was the location of frequent debris flows. The monitoring features and the debris flow history in Shenmu were described in this study. The correlation of effective rainfall and soil moisture is discussed using event results. The rainfall characteristics of debris flow in Shenmu area are summarized in the end.

Key words: debris flow, debris flow monitoring, landslide, rainfall warning, soil moisture

1. INTRODUCTION

Because of the climate change, the severe weather and extreme rainfalls have occurred more often in Taiwan, resulting in frequent natural hazards and disasters. Among the disasters, debris flow has become the major threat in Taiwan. To effectively monitor the debris flow and study its characteristics, the Soil and Water Conservation Bureau (SWCB) in Taiwan, the agency responsible for slopeland management, started to construct debris flow monitoring stations in 2002. The monitoring stations had applied sensors and instruments, such as the rain gauge, wire sensor, geophone, soil moisture sensor, and CCD camera, to observe and collect data from the areas susceptible to the debris flows. The data was further analyzed for understanding the behavior and mechanism of debris flows.

The monitoring stations had been established at high risk areas of debris flows all over Taiwan, providing 24-7 observation and real-time notices. Because of the frequent debris flows at the distant mountain areas, a brand new concept of basin-wide monitoring network had been adopted to extend the capability of debris flow observation and disaster response [*Lee, et al*., 2010]. **Fig. 1** illustrates the idea of basin-wide monitoring network. The traditional monitoring stations were connected to establish a network covering the potential debris flow area, including the debris source region. The network had greatly enhanced the monitoring system for debris flow in Taiwan.

Currently there are 1,671 potential debris flow torrents in Taiwan. To achieve the goal of basin-wide monitoring network, the SWCB worked with the research team of Feng Chia University to develop mobile stations and portable units for debris flow monitoring (**Fig. 2**). The mobile stations and portable units were event-oriented and designed for immediate response to an event. There are 19 in-situ stations, 3 mobile stations, and 14 portable units on duty for debris flow monitoring.

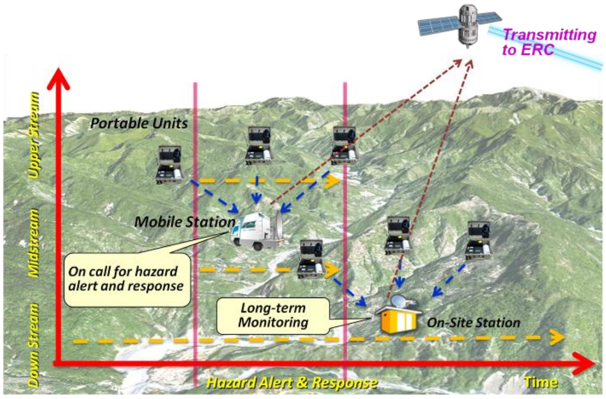

Fig. 1 The basin-wide monitoring network.

(a) The in-situ station

(b) The mobile station

(c) The portable units

Fig. 2 The monitoring stations in Taiwan.

In addition to the monitoring stations, the warning systems is also important. Most of the debris flow warning systems are based on the rainfall data [*Lee*, 2006]. However, the causes of a debris flow include the abundant source and appropriate slope of the riverbed. Therefore, the data like the soil moisture and geophone signals are potentially useful to develop an enhanced debris flow warning model [*Lee*, *et al*., 2012]. In this paper, the capability of gathering data and the types of sensors or instruments used to obtain the data are described in the next two sections, followed by the case study and analysis results.

2. SHENMU MONITORING STATION

The study area of Shenmu is located at the central Taiwan and a debris flow monitoring station had been established in 2002. The local village is adjacent to the confluence of three streams: Aiyuzi Stream (DF226), Huosa Stream (DF227) and Chushuei Stream (DF199). These streams are classified as potential debris flow torrents with high risk [*Lee, et al*., 2011, 2012].

After the debris flow occurred in Typhoon Herb 1996, the Chushuei Stream had become the location of frequent debris flows. In 2001 of Typhoon Toraji and heavy rainfalls, people living in Shenmu had suffered from several debris flows. To protect the residents, the SWCB finished the debris flow monitoring station at the Shenmu in 2002.

During the Typhoon Morakot in Aug. 2009, the record-high rainfall had brought serious disasters in the middle Taiwan, especially at the mountain regions. The accumulated rainfall in Shenmu was as high as 1,550 mm, resulting in catastrophic debris flows in Aiyuzi Stream. The debris flow had damaged the roads and the bridge, the only access to the Shenmu, and made the people of Shenmu in the life-threating situation. This event was the most serious typhoon in Taiwan (total of about 677 casualties).

Table 1 summarizes the environmental characteristics around the Shenmu Station. **Fig. 3** shows the layout of monitoring sensors and equipment, and **Fig. 4** shows the topographic map of Shenmu. The monitoring practice of Shemu Station includes instruments and sensors, such as rain gauge, soil moisture sensor, geophone, wire sensor and CCD camera. The station continuously collects the observation data of rainfall, soil moisture and geophone signals, and transmits data back to the emergency operation center. The data had been used for alert in response to the debris flow disaster and further analysis in advanced studies.

Table 2 and **Fig. 5** indicate the area and locations of landslides along these three streams after Typhoon Morakot. It should be noted that the landslide area (the green-yellow blocks) in **Fig. 5** was recognized by the satellite image taken after the Typhoon Morakot in 2009 and overlaid with the aerial photo of Shenmu. The landslide area extended and increased after the Typhoon Morakot because of its extremely heavy and record-high rainfall in the area.

3. DEBRIS FLOW OBSERVATION

A debris flow monitoring station can collect data of rainfall, ground vibration signals, soil moisture, and water level. The observed data is further used for debris flow researches, including the early warning models.

Table 1 Environment of Shenmu Station

Location	Shenmu Village, Nantou County	**Debris Flow No.**	DF199, DF227, DF226
Catchment	Zhuoshui River	**Tributary**	Chusuei, Huosa, Aiyuzi
Debris Flow Warning Threshold	250 mm (accumulated)	**Hazard Type**	Channelized debris flow
Monitored Length	5.518 km	**Catchment Area**	7,216.45 ha (Shenmu)
Geology	neogene sedimentary rock	**Slope at Source**	30~50°
Landslide area	Large, 1%≦ landslide ratio ≦5%	**Sediment**	Average debris material size: 3”-12” in diameter
Vegetation	Natural woods, medium sparse	**Damaged by**	debris, overflow
Engineering Practice	None	**Priority of Mitigation**	High
Station Elevation	1,187 m	**Coordinate (TWD97)**	X: 235367 Y: 2602749

Table 2 The landslide area in Shenmu (after 2009)

Debris Flow No.	Stream	Length (km)	Catchment Area (ha)	Landslide Area (ha)
DF199	Chusuei Stream	7.16	861	33.29
DF227	Huosa Stream	17.66	2,620	149.32
DF226	Aiyuzi Stream	3.30	400	99.85

Fig. 3 The monitoring layout of Shenmu Station.

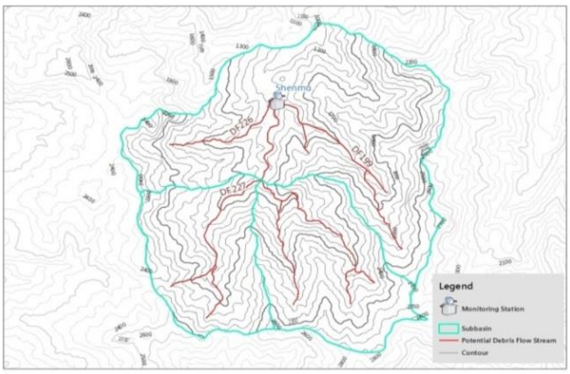

Fig. 4 The topographic map of Shemu.

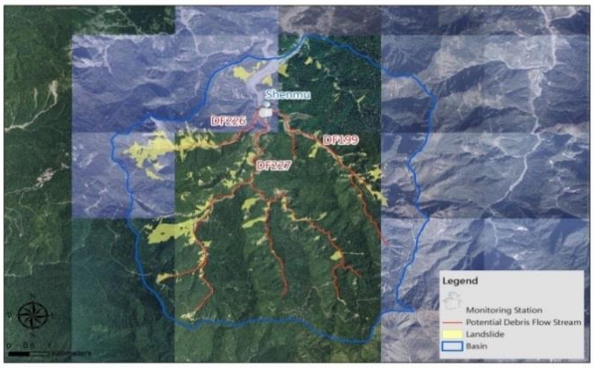

Fig. 5 The lanslide areas of Shenmu (image taken after Typhoon Morakot in 2009).

Therefore, the monitoring stations are very important in the disaster response to debris flows. According to the data features and purposes, the monitoring sensors can be classified into three approaches: direct, indirect, and other approaches. The sensors of direct and indirect approaches are usually used for debris flow warning, and the other sensors and instruments are used as information supplement.

3.1 Direct Approach

The direct approach refers to the sensors which can respond to the debris flow when it occurs. These sensors include the wire sensor and geophones. The wire sensor will transmit a signal when it is broken by a debris flow. Therefore, the monitoring system can record the time of debris flow passing through the location of wire sensors. Usually the wire sensors are installed at the upper sections of the stream, such that a time window can be created between the timing of wire broken and arrival of debris flow at the downstream. Evacuation can be conducted due to the time window of warning.

Geophones are sensors to measure the ground surface vibration. The vibration along the river or stream is caused by the rolling rocks, debris in a debris flow. Based on the recorded signal of vibration, the debris flow occurrence can be identified from the time series data [*Fang et al.*, 2008]. Because of the characteristic of wave propagation, the signals of ground surface vibration can be detected even when the debris flow is far from the sensors. Therefore, the geophones are usually installed with the wire sensors at the upper stream. When a debris flow occurs, the change of geophone signals can provide early warnings to the public. **Fig. 6** shows typical geophone signals of a debris flow.

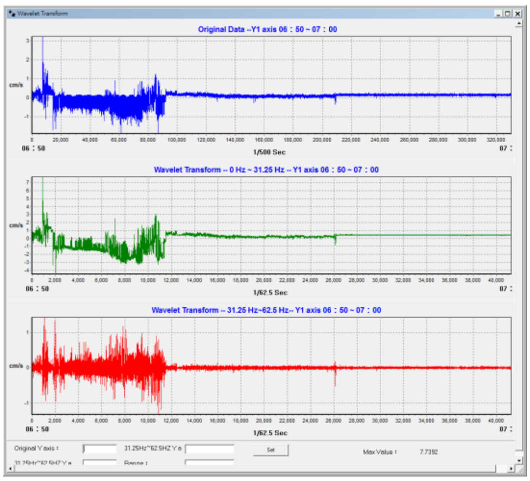

Fig. 6 Geophone results of Typhoon Soulik (06:50~07:00, July 13, 2013).

3.2 Indirect Approach

The indirect approach refers to the sensors which provide necessary information about the debris flow, but cannot record the timing of debris flow occurrence. These sensors are mainly the rain gauges. Rainfall is the major criteria used for debris flow early warning, and is the most common factor applied in the early warning models. The SWCB uses the rainfall to determine the announcement of evacuation.

3.3 Other Approach.

The other approach refers to sensors and instruments which are used as assistance. These sensors cannot provide information for debris flow warning, and include CCD camera, soil moisture sensors, and water level meters. The CCD camera is usually used to provide images of site conditions when a debris flow occurs. The images captured by the CCD can imply the environmental changes before and after the debris flows, and CCD is an important instrument in the monitoring system.

Soil moisture sensors and water level meters are used for long-term observation and provide research material for environmental studies about the debris flow. The water content of a site is measured by the soil moisture sensors, and the changes of soil moisture indicate the stability of slopes at the debris source areas. The data of water level meters is mainly used to understand the fluctuation of streams and the changes of water depth, to estimate the sediment volume generated from a debris flow. The information is then be used for the design of engineering practices. Data from soil moisture sensors and water level meters is significant to the analysis of debris flow.

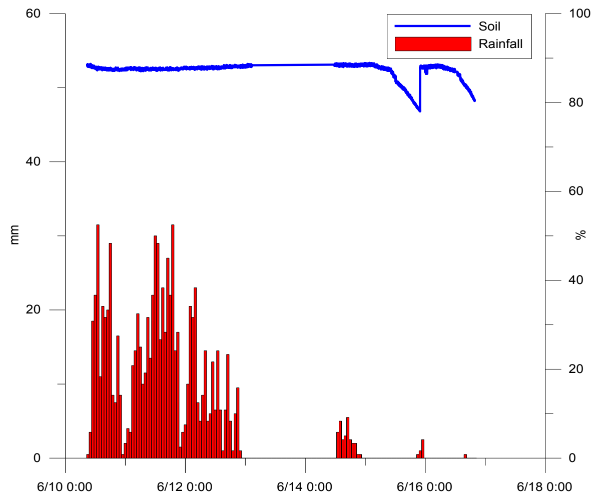

Fig. 7 Rainfall and soil moisture data.

4. DEBRIS FLOW CASE HISTORY IN SHENMU

The Shenmu Monitoring Station started operation since 2002, monitoring the region influenced by the three potential debris flow torrents. **Table 3** summarized the case history in Shenmu area.

After the Typhoon Morakot in 2009, the debris flow occurred almost every year, and all occurred at the Aiyuzi Stream. The reason of this phenomenon partly comes from the facts that Aiyuzi Stream is shorter than the other two streams and has the highest ratio of the landslide area (99.85 ha) to the entire catchment area at its upstream slopes after Typhoon Morakot. These factors contribute to the frequent occurrence of debris flow in Aiyuzi Stream. Until now, the Shenmu is still under the threat of debris flow during typhoons and heavy rainfalls.

Table 3 Debris flow case history of Shenmu

Date	Event	Location (stream)	Occurrence	Hazard Type
2004/5/20	-	Aiyuzi	14:53	debris flow
2004/5/21	-	Aiyuzi	16:08	debris flow
2004/5/29	-	Aiyuzi	16:19	debris flow
2004/6/11	-	Aiyuzi	16:42	debris flow
2004/7/2	Typhoon Mindulle	Aiyuzi	16:41	debris flow
2005/7/19	Typhoon Haitang	Chusuei, Aiyuzi	-	flood
2005/8/4	Typhoon Matsa	Chusuei, Aiyuzi	-	flood
2005/9/1	Typhoon Talim	Chusuei, Aiyuzi	-	flood
2006/6/9	0609 Rainfall	Chusuei, Aiyuzi	about 08:00	debris flow
2007/8/13	0809 Rainfall	Chusuei	-	flood
2007/8/18	Typhoon Sepat	Chusuei	-	flood
2007/10/6	Typhoon Krosa	Chusuei	-	flood
2008/7/17	Typhoon Kalmaegi	Chusuei	-	flood
2008/7/18	Typhoon Kalmaegi	Aiyuzi	-	flood
2009/8/8	Typhoon Morakot	Chusuei,Aiyuzi, Huosa	08:00 (landslide) 16:57 (debris flow)	landslide, debris flow
2010/9/19	Typhoon Fanapi	Huosa	-	flood
2011/11/10	-	Aiyuzi	13:17	debris flow
2011/7/13	-	Aiyuzi	14:33	debris flow
2011/7/19	0719 Rainfall	Aiyuzi	3:19	debris flow
2012/5/4	-	Aiyuzi	15:56 16:09	debris flow
2012/5/20	-	Aiyuzi	8:15	flood
2012/6/10	0610 Rainfall	Aiyuzi	10:34 15:14	debris flow
2012/6/11	0610 Rainfall	Chusuei	17:08	flood

5. RAINFALL CHARACTERISTICS IN SHENMU

The practical early-warning models for debris flow are mostly based on rainfall factors [*Lee*, 2006]. Application of a critical line to determine if the rainfall reaches the warning criteria was another model using rainfall data [*Osanai*, *N.*, *et al*., 2010]. These rainfall-based warning models usually consider rainfall factors of accumulated rainfall, antecedent rainfall, and intensity of rainfall.

The criteria of effective accumulated rainfall of 250 mm was used for the debris flow warning at Shenmu area. The effective accumulated rainfall (R) was defined as below [*Jan*, 2004; *Lee*, 2006].

$$R = R_o + \sum_{i=1}^{7} \alpha^i R_i = \sum_{i=0}^{7} \alpha^i R_i \qquad (1)$$

where R_o is the pre-debris flow rainfall of an event, R_i is the daily rainfall of previous i-th day before current event and α (=0.8) is the weighting factor of daily rainfall. **Fig. 8** illustrates the rainfall definitions in the equations.

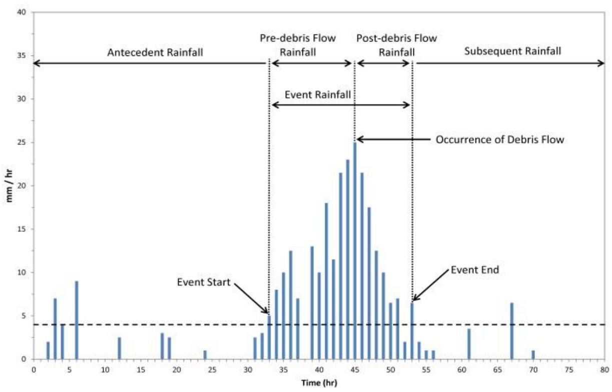

Fig. 8 Schematic diagram of a rainfall event definition [after *Jan*, 2004]

The effective accumulated rainfall (R) was computed using the 7-day antecedent rainfalls before the debris flow. The 7-day rule on estimating the antecedent rainfall was considered because the rainfall 7 days ago had insignificant effect to the present time [*Lee*, 2006]. In real-time operation, the value of R_o was not included because the occurrence time of debris flow was unpredicted. The SWCB had adopted the effective accumulated rainfall for debris flow early warning.

Huang et al. (2013) studied the debris flow case history in Shenmu and noted that the debris flow events after 2009 occurred while the effective accumulated rainfall didn't reach the warning level of 250 mm. **Fig. 9** shows the scatter plot of maximum hourly rainfall and effective accumulated rainfall.

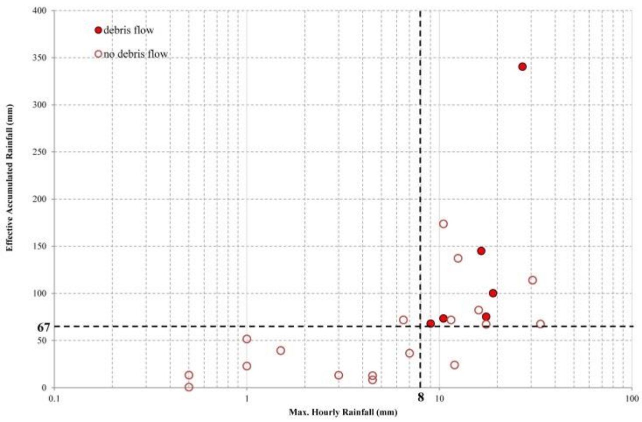

Fig. 9 The scatter plot of events in Shenmu since 2009. [*Huang et al*., 2013]

The debris flow occurred after 2009 had implied the increasing possibility of small-scaled event with much less rainfall [*Huang et al*., 2013].

The method of computing the effective accumulative rainfall was based on the empirical model, using the α of 0.8 [*Jan*, 2004]. It was necessary to discuss the usability of the rainfall warning estimation at the Shenmu area since the environment had changed significantly after years of typhoons and heavy rainfalls.

The debris flow was considered in somewhat relationship with the soil moisture at the sites [*Wei et al.*, 2005]. Wei et al. (2005) had proposed a method of estimating the effective rainfall from the soil moisture analysis. The method applied the following assumptions.

1. The decreasing process of the effective rainfall from a rainfall event is independent to others.
2. The decreasing process of the incremental soil moisture from a rainfall event is independent to others.
3. The decreasing of the incremental soil moisture and the effective rainfall follows the same numerical function.

Based on these assumptions, the effective antecedent rainfall and the decreasing function with time were derived from the site observation data [*Wei et al.*, 2005].

The method assumed that the function of describing the effective rainfall was the same as the one for soil moisture. The equation of the incremental soil moisture and the effective rainfall are expressed as below.

$$EF_i = f(F, i) \tag{2}$$

$$EW_i = g(W, i) = W \times \frac{i+a^k}{(i+a)^k} \tag{3}$$

$$\mathrm{EF} = EF_1 + EF_2 + \cdots + EF_n \tag{4}$$

$$\mathrm{EW} = EW_1 + EW_2 + \cdots + EW_n + c \tag{5}$$

where EF_i indicates the daily effective rainfall of i-th day before the present, F is the daily rainfall, EW_i is the soil moisture increment at i-th day, W is the soil moisture increment induced by F at the i-th day, a and k are the parameters to be determined, and c is a constant (the soil moisture in normal time). EF and EW are the effective accumulated rainfall and the total soil moisture, respectively. The functions f and g are assumed to follow the same type of equations. [*Wei et al.*, 2005].

Based on the method mentioned above, this study used the events of Typhoon Saola and Typhoon Tembin (**Table 4**) to analyze the variation of rainfall and soil moisture, and compared the results to the SWCB approach.

Table 4 The typhoons and tropical storms of 2012

Name	Period	Type
JELAWAT	09/27～09/28	Super Typhoon
TEMBIN	08/26～08/28	Typhoon
TEMBIN	08/21～08/25	Typhoon
KAI-TAK	08/14～08/15	Tropical Storm
HAIKUI	08/06～08/07	Typhoon
SAOLA	07/30～08/03	Typhoon
DOKSURI	06/28～06/29	Tropical Storm
TALIM	06/19～06/21	Tropical Storm

Debris flows occurred in Shenmu during these two events and the observed data were used for analysis. In order to capture the changing trend of soil moisture and rainfall, the data from the period of July 16 to Oct. 21 was applied in the analysis. **Fig. 10** shows the records of hourly rainfall and soil moisture at the Shenmu station. The data period of July 16 to Aug. 15 was used for the Typhoon Saola, and period of Aug. 15 to Sep. 13 was used for Typhoon Tembin. It should be noted that the daily rainfall and the average daily soil moisture, computed from the hourly observations, were used in the analysis and comparison.

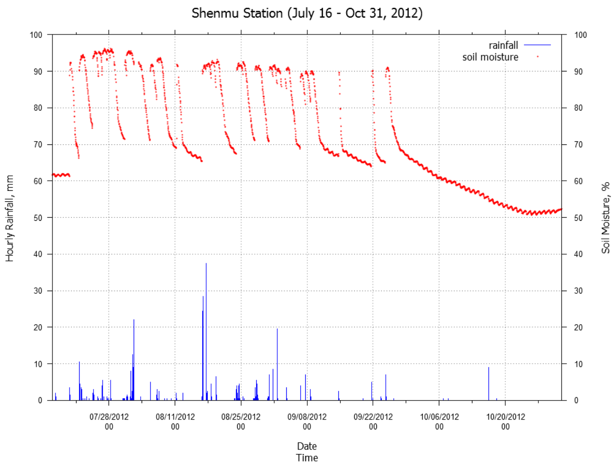

Fig. 10 Rainfall and soil moisture at Shenmu Station during July 16 to Oct. 31, 2012.

With the nonlinear least square optimization, the parameters of *a* (=290) and *k* (=2) was determined using the data of Typhoon Saola. The curve fitting results was shown in **Fig. 11**. The fitted line indicates a good estimation on soil moisture with a coefficient of determination (R^2) of 0.95. The verification of (*a*, *k)* had been conducted using the data of Typhoon Tembin (**Fig. 12**) and the records after the typhoon (**Fig. 13**). The results had implied that the parameters of *a* (=290) and *k* (=2) were suitable for soil moisture increment estimation in Shenmu.

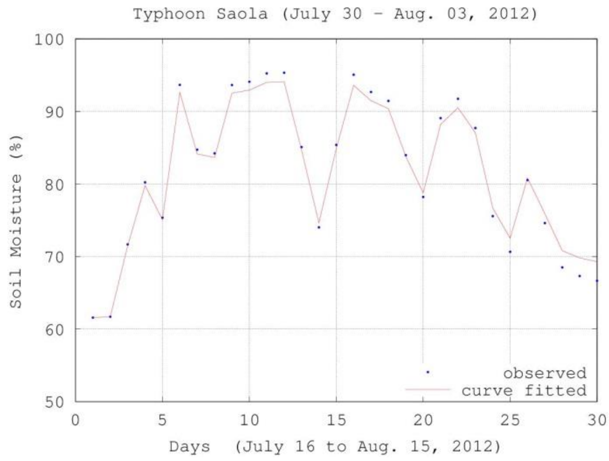

Fig. 11 Results of curve fitting using Typhoon Saola data.

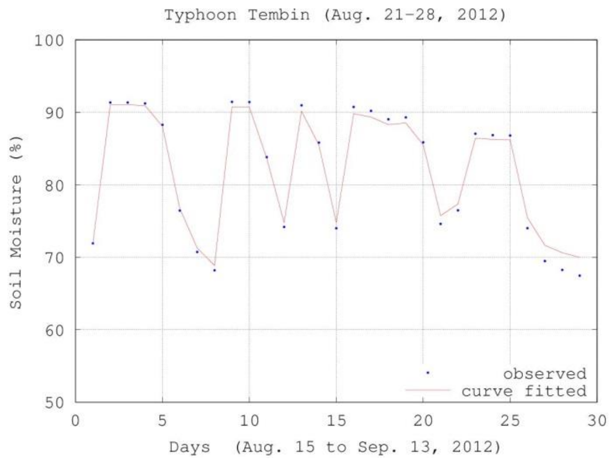

Fig. 12 Results of curve fitting using Typhoon Tembin data.

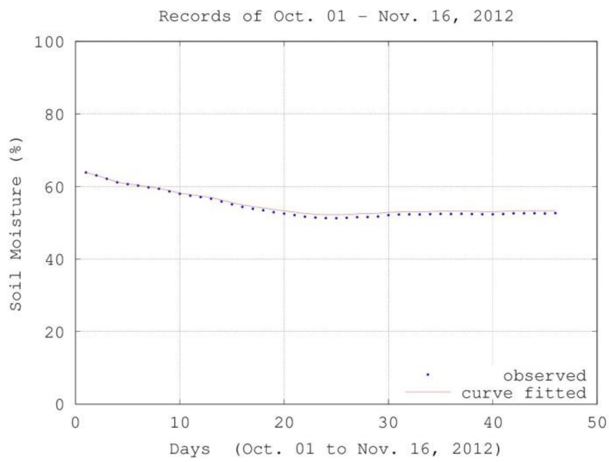

Fig. 13 Curve fitting using data after the typhoon.

After determining the function of soil moisture increment, the same parameters and function were used to compute the effective rainfall, as expressed below.

$$EF_i = F \times \frac{i+209^2}{(i+209)^2} \quad (6)$$

The warning rainfall used for the debris flow was determined based on the effective accumulated rainfall. The comparison between the observed and estimated effective accumulated rainfall were conducted using the typhoon events of interest. **Fig. 14** and **Fig. 15** show the analysis results of Typhoon Saola and Typhoon Tembin, respectively. The difference noted on the figures had indicated the effective rainfalls were in a certain percentage of the observed ones. Based on the estimation results, the effective accumulated rainfall by Eq.(4) was about 0.94 ~ 0.96, with an average of 0.95, of the observed rainfall.

Further comparison of effective accumulated rainfall was conducted to understand the difference between the approaches of SWCB and the *EF* (Eq. (4)). **Fig. 18** and **Fig. 19** show the analysis results. The figures implied that the effective accumulated rainfall estimated by the SWCB approach was much less than the estimated rainfall of *EF*, and decreased quickly when the daily rainfall decreased. The reason of this condition was because of the 7-day rule used in the SWCB method. It is also noted from the figures that the effective accumulated rainfalls of the first 2-3 days were close to the observed rainfalls, but decreased with time unless other daily rainfalls were added.

To better compare the approaches of *EF* and SWCB, the 7-day rule was adopted in the estimation using the *EF* function. The results were shown in **Fig. 14** and **Fig. 15**. The results had indicated that the estimation from *EF* and SWCB approaches had similar decreasing trend of rainfall with time. The values of both methods were close at the beginning few days, and then varied slightly due to the different estimation functions. Overall, the two curves had similar trend. However, the values estimated by the *EF* method were higher than the ones by the SWCB method. The ratio of rainfall by *EF* to SWCB was about 1.78 to 1.98, with an average of 1.88.

Overall, the higher estimated effective rainfall was obtained by the EF method, with an average ratio of 0.95 to the observed rainfalls. The value of 0.95 was higher than the weighting factor of 0.8 used in the SWCB approach. Therefore, the resulting effective accumulated rainfalls were different between the two methods. Generally, both the *EF* and SWCB methods predicted the effective rainfall in the similar decreasing trend with time. It was not clear at current status to determine which method was better than another. The *EF* method derived from the variation of observed soil moisture was expected to present better estimation on effective rainfall, because the soil moisture indicated the water content left on the ground. More cases and data were needed for further studies about both methods.

CONCLUSION

From this study, the following conclusions were made.

1. The debris flow warning was mainly based on the rainfall prediction. The effective accumulated rainfall was adopted in current debris flow monitoring system in Taiwan. The effective accumulated rainfall of 250 mm was set by SWCB for the rainfall warning in Shenmu area.

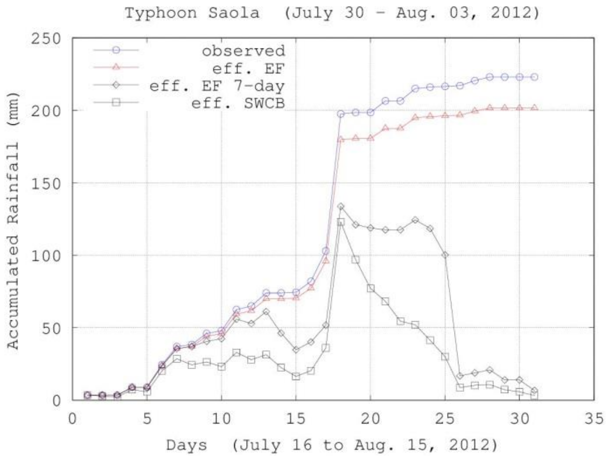

Fig. 14 Accumulated rainfall estimated using Typhoon Saola data.

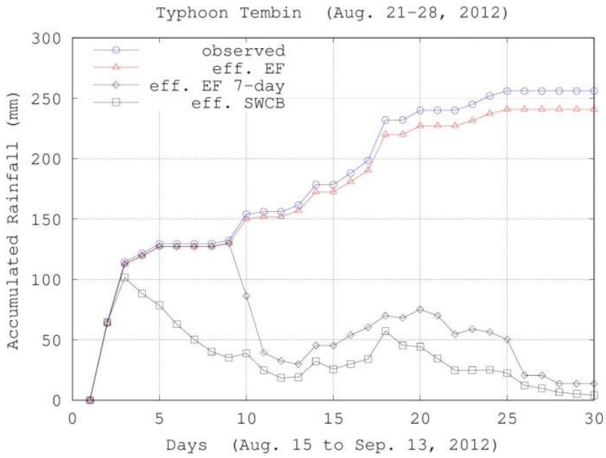

Fig. 15 Accumulated rainfall estimated using Typhoon Tembin data.

2. Before 2009, most debris flows occurred in the Chushuei Stream when the effective accumulated rainfall reached 250 mm. After Typhoon Morakot in 2009, the debris flows

frequently occurred in the Aiyuzi Stream, because of the increasing landslide areas at its upper streams. In recent debris flow cases, the rainfall warning had not reached 250 mm when a debris flow occurred in Shenmu. The rainfall warning of 250 mm had been considered to re-evaluated in response to the environmental changes in Shenmu.

3. The analysis of soil moisture in this study had indicated a reasonable method of estimating the effective accumulated rainfall directly from the site observations. The rainfall warning derived from the soil moisture analysis can be used in the debris flow monitoring system.
4. Both the *EF* (Eq.(4)) and SWCB methods had similar decreasing trend of effective rainfall, and were applicable in the debris flow monitoring and warning. More cases and data are needed for analysis, especially about the relationship of rainfall and soil moisture.

ACKNOWLEDGMENT: This research was partly supported by the Soil and Water Conservation Bureau, Council of Agriculture, Executive Yuan, Taiwan. Thanks to all people providing help on this study.

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