



A simple and feasible process for using multi-stage high-precision DTMs, field surveys and rainfall data to study debris flow occurrence factors of Shenmu area, Taiwan

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Abstract. The occurrence of typhoon Herb in 1996 caused massive landslides in the Shenmu area of Taiwan. Many people died and stream and river beds were covered by meters of debris. Debris flows almost always take place in the Shenmu area during the flood season, especially in the catchment areas around Tsushui river and Aiyuzih river. Anthropogenic and natural factors that cause debris flow occurrences are complex and numerous. The precise conditions of initiation are difficult to be identified, but three factors are generally considered to be the most important ones, i.e. rainfall characteristics, geologic conditions and topography. This study proposes a simple and feasible process that combines remote sensing technology and multi-stage high-precision DTMs from aerial orthoimages and airborne LiDAR with field surveys to establish a connection between three major occurrence factors that trigger debris flows in the Shenmu area.

reached substantial conclusions regarding the occurrence of debris flows, the flow characteristics of debris flows, the variations in debris flow occurrence, and debris flow disasters, even if more research is needed to improve the results obtained hitherto (Harris, 1977; Takahashi, 1978; Sidle et al., 1985; VanDine, 1985; Ashida et al., 1983; Anderson and Sitar, 1991; Arattano and Franzi, 2004; Imaizumi et al., 2008; Guzzetti et al., 2008; Passmore et al., 2008; Lin et al., 2011). According to the obtained results, a large number of both anthropogenic and natural factors are known to affect the occurrence of debris flows. Only field observation and repeated surveys can allow for good evidence about debris flow occurrence (Johnson, 1970; Pierson, 1986; Pierson and Costa, 1987; Arattano and Franzi, 2004; Jakob and Hungr, 2005; Arattano et al., 2010). Using remote sensing, field investigation, and other analysis techniques, this study evaluates debris flow occurrence and magnitude with respect to three general debris flow elements: rainfall characteristics, geologic conditions and topography.

1 Introduction

The Shenmu area, which is located in the central part of Taiwan, is generally affected by debris flows during the typhoon and flood seasons and has the highest debris flow frequency throughout Taiwan. Due to the high frequency of debris flows, and because approximately 1000 people live in this highly mountainous area, great damage potential exists. Resultantly, many researchers and considerable resources have been involved to study the lithology, hydrology as well as geomorphology of the Chen-yo-lan river basin, which includes the Shenmu area. It is well known that many authors have

2 Overview of environment

2.1 Study area

As illustrated in Fig. 1, the Shenmu area is located in the southwestern corner of Nantou County, in a fold-thrust belt that makes up the western foothills of Taiwan. Topography is characterized by tall mountains and steep slopes, with elevations ranging from 500 m a.s.l. to 2500 m a.s.l. The Shenmu area steeper than 28.8° represents 45 % of the total regional

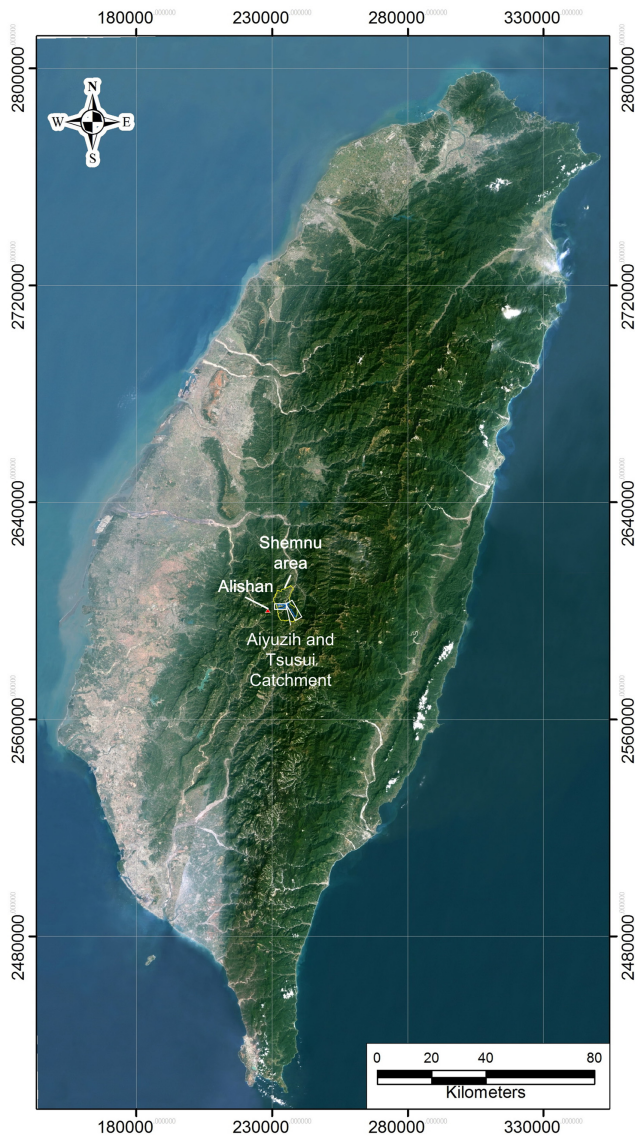


Fig. 1. Graphical location of Tsushui river and Aiyuzih river catchment in Taiwan.

extension (72.16 km²) and 47.75 % of the slopes are north-facing. The Shenmu area is crossed by three primary geologic structures: the northeast-southwest Hesse anticline and Tungfu syncline and the Chen-yo-lan fault. Densely forested mountain slopes are built up by the Nanchuang and Hesse formation (see Fig. 2). These formations consist mainly of hard, dark grey argillite and grey slate with thinly bedded muddy sandstone, which are prone to more severe weathering and become weak layers in the rock strata. These geologic conditions make the slope unstable under heavy rainfall and strong earthquake shaking. Hence, during the typhoon and flood season, the combination of huge rainfalls and local weak geological conditions easily permit the occurrence of debris flows. As a consequence, the debris flows

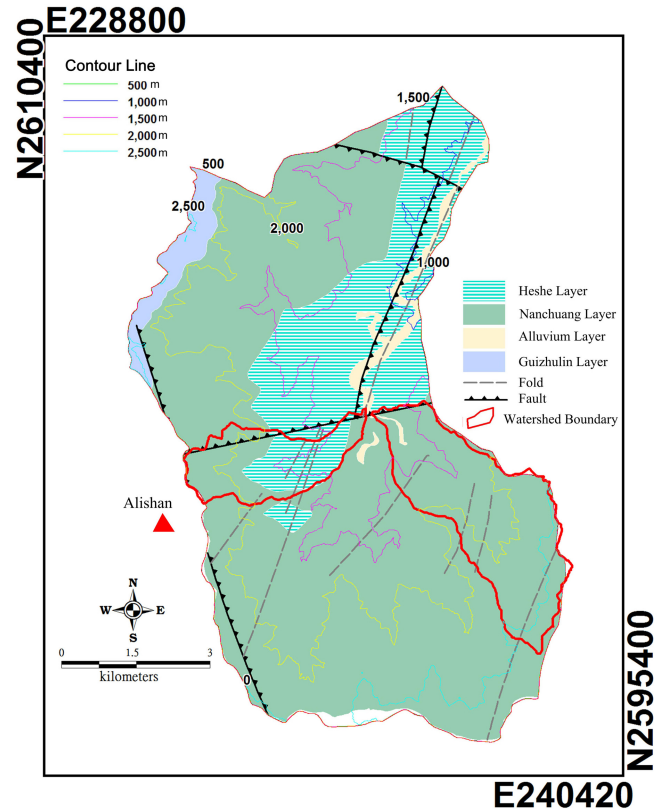


Fig. 2. Geological map of Shenmu area.

cause structural damages to the check dams located there (see Fig. 3) and endanger inhabited areas, properties and residents at risk (Franzi, 2012).

2.2 Hydrology

The Shenmu area is located in the Hesse river watershed, an upstream watershed of the Chen-yo-lan river. The Aiyuzih, Hossa and Tsushui rivers constitute the Hesse river watershed. Temperature ranges from 5.9° to 14.4°, averaging 10.9° annually. Average annual accumulated rainfall for three weather monitoring stations located at Alishan, Shenmu Village, and Hsinkaoko ranges from 1950 to 4980 mm. According to hydrologic analysis based on 1961 to 2000 typhoon rainfall data, the results indicate the rainfall center of Taiwan is close to Alishan Mountain (see Fig. 4). Recent extreme rainfalls have caused annual accumulated rainfall of Taiwan to increase, especially for Alishan, where, since 2005, annual rainfalls have exceeded 5000 mm (see Fig. 5). This rate is double the annual average precipitation (2500 mm) for Taiwan and over four times the world annual average precipitation.



(a)



(b)



(c)

Fig. 3. Photos of damage-induced debris flow in Shenmu area after typhoon Morakot. (a) Sediment disaster causes road closure at the confluence of Tsushui and Aiyuzih rivers. (b) Large amount of sediment material deposited in river bed. (c) Failure of check dam in Tsushui river.

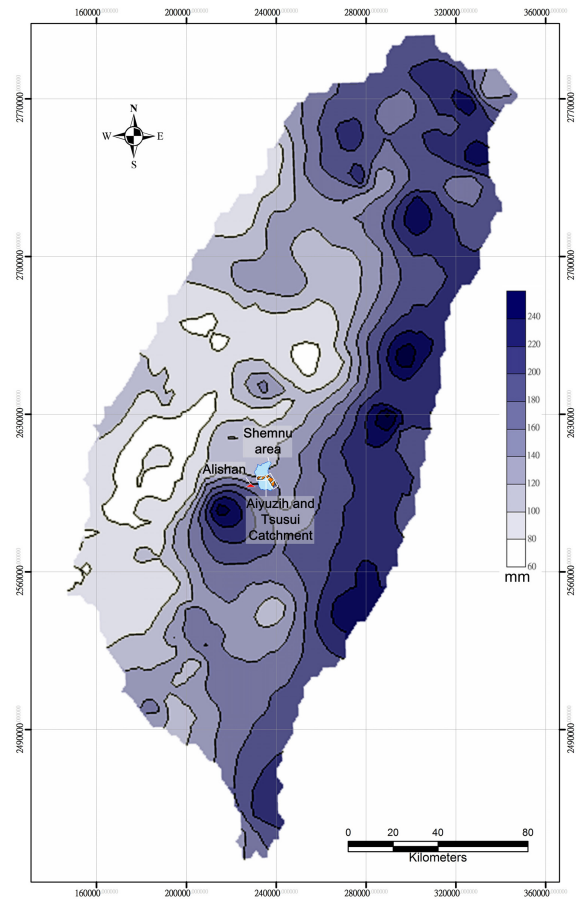


Fig. 4. Distribution of average annual rainfall 1961–2000 (Water Resources Agency, <http://wrb.gov.tw>).

2.3 Major typhoon events and subsequent suspended sediment

Under the effect of global climate change, the probability of extreme weather occurrence has increased. In the mountain area, it can be observed that the magnitude of disasters caused by water-sediment flows, induced by high intensity and long duration rainfall events, has increased. The mode of sediment transport can be classified in different ways (Einstein, 1964), according to the mechanics of sediment transport process, from suspended load to debris flow (Franzi, 2002). In general, measurements of sediment concentrations in a flow depend on accurate field instrumentation to identify the process of water-sediment flow (Arattano and Franzi, 2004). In particular, suspended loads of sediment can be measured by depth-integrating suspended-sediment sampling from water-sediment current (Nilsson, 1969). However, measurement of sediment concentration in debris flows is very difficult and often impracticable. The variations in time of the sediment, carried by water discharge, can represent the upstream hydrologic conditions in modeling the process (Vanoni, 2006). However, as far as hazard assessment

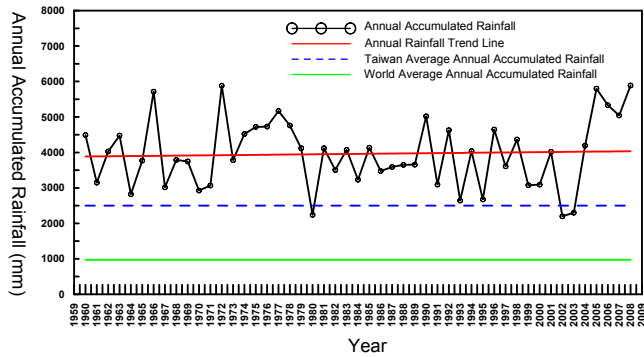


Fig. 5. Time series of annual rainfalls at Alishan.

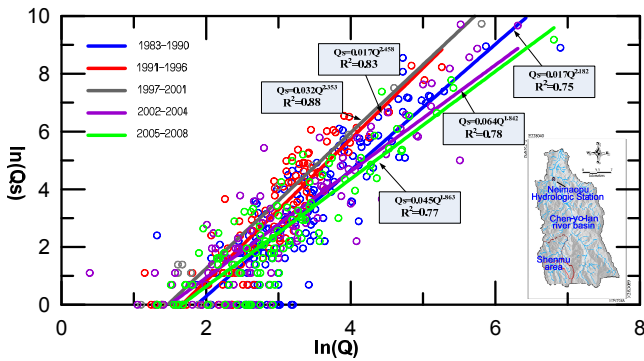


Fig. 6. The relationship of peak daily water discharges (Q) and suspended sediment (Q_s) at the Neimaopu hydrologic station in Shenmu area.

is concerned, forecasting the kind of water-sediment flows that originates during extreme rainfall is a very difficult task (Franzi, 2012).

For understanding sediment transport process triggered by major typhoon events, this study collected suspended sediment records from 1983 to 2008 obtained from the Taiwan Water Resources Agency Neimaopu Hydrologic Station downstream of the Shenmu area. A regression analysis has been carried out by referring to five time periods, for which the major typhoon events may be referred to in Table 1. Actually, in each period, from an empirical point of view, the sediment carried by the current seems to follow a different trend. For each period a relationship between the daily peak water discharge and the transported sediment has been obtained (see Fig. 6). Results of suspended sediment clearly varied for each of the five typhoon periods. It can be seen that from 2002 to 2004, the catchment sediment yields gradually seem to be close to the pre-1990-level. From 2004 to 2008, the catchment sediment yields dropped to pre-1990 levels. This decrease may be explained by measurement uncertainties, due to the fact that sediment volumes, transported by the current (during the 1999 Chi-Chi Earthquake which occurred in the period 1997–2001) bypassed the station.

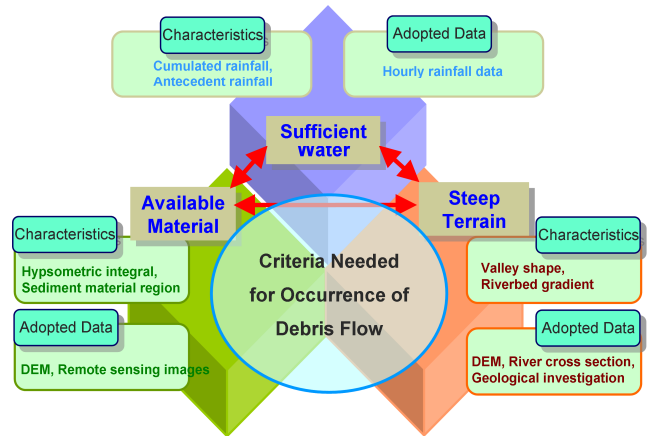


Fig. 7. Correlation among the three major debris flow occurrence factors.

3 Investigation methods

Conditions necessary for debris flow occurrence in the Tsushui and Aiyuzih rivers were evaluated using basic hydrologic, geologic and topographic characteristics (see Fig. 7). Effective rainfall and rainfall intensity records were correlated with real debris flow cases. High-precision digital terrain and airborne LiDAR DTM datasets were used to identify debris flow material sources and quantify the hypsometric integrals of the two catchment areas. Topographic changes of the river valley associated with debris flow scour and deposition were identified by means of multi-stage high-precision DTMs, in situ river cross section measurements obtained using a total station, and a geological survey.

3.1 Rainfall event analysis

In order to examine the relationship between rainfall distribution and debris flow occurrence, 27 rainfall events, recorded between 2002 and 2009, were collected for the Tsushui and Aiyuzih rivers. Pictures of damages caused by the debris flows show the evidence of debris flow occurrence (Soil and Water Conservation Bureau, <http://246.swcb.gov.tw/history/history-greatcase.asp>). For this study, the definition of *rainfall event* by the Taiwan Central Weather Bureau has been used, according to which rainfall event is “any rainfall in which hourly rainfall exceeded 4 mm h^{-1} ” as shown in Fig. 8 (Jan et al., 2003). The first hour in which hourly rainfall exceeded 4 mm h^{-1} is designated as the beginning time of the event. The final consecutive six hours of this event having an intensity less than 4 mm h^{-1} is designated as the ending time of the event. Regarding the correlation of rainfall characteristic and debris flow occurrence, the rainfall intensity equal to 4 mm h^{-1} may be considered the lower threshold for debris flows occurrence, while the time of occurrence is close to maximum rainfall intensity (Jan et al., 2003; Shieh et al., 2009). In addition to rainfall intensity, debris

Table 1. Rainfall parameters from heavy rains with debris flows.

Year	Event	Aiyuzih river catchment area		Tsushui river catchment area	
		effective accumulated rainfall (mm)	rainfall intensity (mm h ⁻¹)	effective accumulated rainfall (mm)	rainfall intensity (mm h ⁻¹)
2003	67 Heavy Rain	228.1	20.5	–	–
2004	521 Heavy Rain	143.1	40.5	–	–
2004	Mindulle	333.3	24.5	–	–
2005	Talim	–	–	204.6	25.0
2006	69 Heavy Rain	331.1	43.5	290.5	23.5
2007	89 Heavy Rain	–	–	333.0	23.5
2007	Sepat	–	–	186.1	39.5
2007	Krosa	217.0	53.5	–	–
2008	Kalmaegi	267.7	64.5	210.3	58.0
2009	Morakot	287.0	30.0	–	–

Note 1: “–” indicates no debris flow took place after the rainfall. Note 2: Rainfall calculation was based on Shieh et al. (2009). Note 3: Rain delay was based on the accumulated rainfall from 7 days before the effective rainfall. Note 4: Effective accumulated rainfall refers to the accumulated rainfall of a continuous rainfall from the beginning to the time of maximum rainfall intensity plus previous seven-day rainfall. Note 5: Limitation of rain gauge only measured rainfall per 30min with temporal resolution. Note 6: All of rainfall events are real cases that triggered debris flows as reported in SWCB (2010).

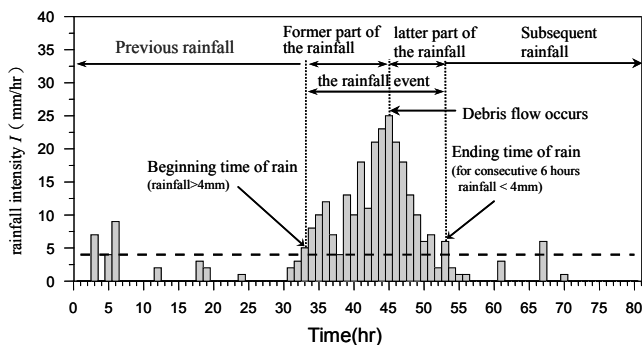


Fig. 8. Definition of rainfall events (after Jan et al., 2003).

flow occurrence has significant correlation with effective accumulated rainfall. Real case studies can be found in Jan et al. (2003). Effective accumulated rainfall refers to the “total rainfall calculated from the beginning of the event to the time of maximum intensity (see Fig. 8) plus previous seven days antecedent rainfalls” (Claine, 1980; Davies, 1997; Jan and Lee, 2004; Jakob et al., 2012). Of the 27 events, debris flows were recorded for 11 and did not occur during 16 listed in Tables 1 and 2. Rainfall events for both Aiyuzih river and the Tsushui river are plotted in Fig. 9. In the figure, rainfall intensity represents the maximum hourly rainfall. Events for which debris flows did occur are shaded black. The two diagonal lines represent minimum hydrologic conditions for debris flow occurrence. No debris flows occur at rainfall intensities less than 20 mm h⁻¹ and using the intersection of these two lines, approximately 200 mm of effective accumulated rainfall appears to be threshold value for debris flow occurrence in these two river catchments. However, the threshold value for rainfall intensity is different for each catchment.

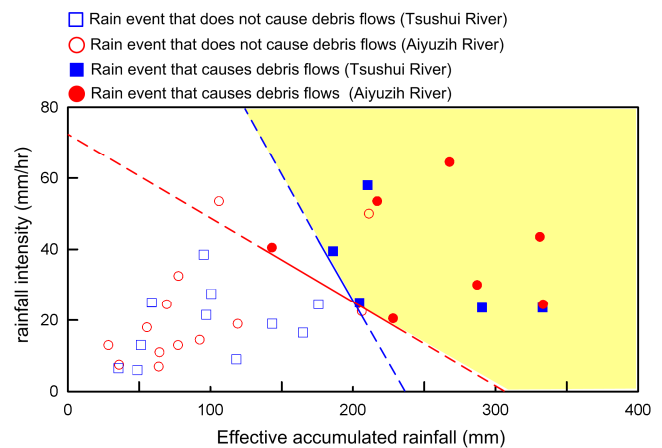


Fig. 9. Correlation between effective accumulated rainfalls and rainfall Intensity.

As shown in Fig. 9, for the same effective accumulated rainfalls, the rainfall intensity required to trigger debris flow in Aiyuzih river catchment area is smaller than the one of Tsushui river. This means that when the effective accumulated rainfall is less than 200 mm, the probability of debris flow occurrence for Aiyuzih river catchment area is higher than Tsushui river.

On the contrary, when the effective accumulated rainfall exceeds 200 mm, Tsushui river catchment area would get higher probability of debris flow occurrence than the other. This suggests when the effective accumulated rainfall is greater than 200 mm, debris flows are more likely to happen in the Tsushui river catchment area. Similar regular patterns of hydrological conditions in combination with accumulated rainfall and rainfall intensity to trigger debris flows

Table 2. Rainfall parameters from heavy rains without debris flow.

Year	Event	Aiyuzih river catchment area		Tsushui river catchment area	
		effective accumulated rainfall (mm)	rainfall intensity (mm h^{-1})	effective accumulated rainfall (mm)	rainfall intensity (mm h^{-1})
2002	Rammasun	119.1	19.0	–	–
2002	Nakri	77.3	13.0	–	–
2003	Dujuan	–	–	164.9	16.5
2004	Aere	–	–	95.3	38.5
2004	Haima	63.7	7.0	–	–
2004	Nanmadol	55.6	18.0	97.13	21.5
2005	Matsa	106.0	53.5	175.8	24.5
2005	Longwang	69.4	24.5	100.6	27.5
2006	Chanchu	92.5	14.5	51.2	13.0
2006	Kaemi	64.3	11.0	143.3	19.0
2006	Saomai	28.4	13.0	–	–
2006	Bopha	35.9	7.5	58.8	25.0
2007	Ewiniar	77.6	32.5	48.8	6.0
2007	Wipha	206.2	22.5	118.1	9.0
2007	Pabuk	–	–	35.4	6.5
2008	Fung-wong	211.2	50.0	–	–

Table 3. DEMs Used by this study.

Data period	Method	Source
2002	aerial orthophoto (DEM)	Ministry of Interior
2005	aerial orthophoto (DEM)	Soil and Water Conservation Bureau
2009	airborne LiDAR (DEM)	Soil and Water Conservation Bureau

Note: Each grid size of used DEMs is 5 m and its accuracy of these DEMs ranges between 30 cm to 50 cm.

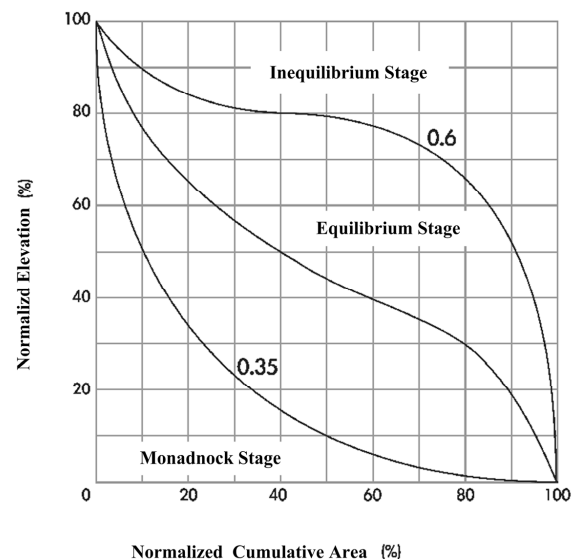
agree well with real cases reported by Jan et al. (2003, 2004), Shieh et al. (2009) and Arattano et al. (2010).

3.2 Analysis of sediment source

High-precision DTMs derived from aerial orthoimages and airborne LiDAR DTM data sets were used to calculate hypsometric integrals of the Tsushui river and Aiyuzih river catchments for the years 2002, 2005, and 2009 listed in Table 3. Subtraction of the 2005 and 2009 DTM data set from the 2002 data set allowed comparison of elevation data for those different periods and identification of slope and river changes in the catchment areas.

3.2.1 Hypsometric integral

The hypsometric integral is the area beneath the curve which relates the percentage of total relief to cumulative percent of area and is often used to indicate topographic development of a catchment. The hypsometric integrals from 2002, 2005, and 2009 for the Tsushui river and Aiyuzih river catchment are compiled in Table 4. The hypsometric integrals for

**Fig. 10.** Hypsometric integral analysis and terrain evolution classification (after Strahler, 1952).

both sub-catchment areas are greater than 0.6, which according to hypsometric integral analysis (Strahler, 1952; Benda et al., 2003, 2005), and terrain evolution classification (see Fig. 10), suggest a state of non-equilibrium and a developing terrain. Therefore, sediment production processes such as erosion and debris flows are expected.

Table 4. Annual hypsometric integrals in the two sub-catchment areas (after SWCB, 2010).

Catchment	Tsushui	Aiyuzih
Year	river	river
2002	0.709	0.698
2005	0.709	0.699
2009	0.716	0.712

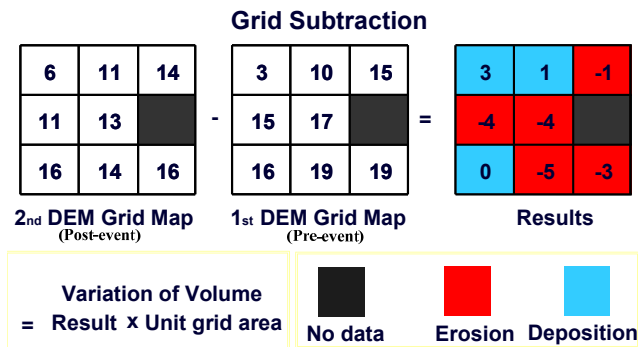


Fig. 11. Grid subtraction in post-event and pre-event digital terrain elevations (after Hsiao et al., 2011).

3.2.2 Differences in 2002, 2005 and 2009 digital terrain model

Direct grid subtraction of DTM data from years 2005 and 2009 from 2002 DTM data were used by ArcGIS 9.31 Spatial Analyst to quickly identify topographic changes in the Shenmu area. As shown in Fig. 11, a negative grid value of the subtracted DTMs means that the elevation of the terrain lowered and material was lost. Conversely, a positive value means material accumulation. The estimate of the total amount of sediment, eroded or deposited in the catchment area, is obtained by multiplying the obtained values for the grid unit area of the DTM (Hsiao et al., 2011; Lin et al., 2012).

Material loss and material accumulation relative to topographic location are illustrated in Fig. 12. It shows that the historical trend of overall terrain change is erosion. After typhoon Morakot in 2009, the total erosion in Tsushui and Aiyuzih river catchment area was respectively 6.56 and $19.14 \times 10^6 \text{ m}^3$ of sediment loss. Comparing the 2002–2005 and the 2005–2009 periods, it can be found that the sediment loss during 2005–2009 was over 4.4 to 167 times the sediment generated by the antecedent period. This change was more significant in the Aiyuzih river. In addition, as revealed by historical data shown in Table 1, rainfall events become more severe and prone to trigger the debris flow occurrence after 2005. For both of the river catchment areas, slopes were the main sources for sediment supply.

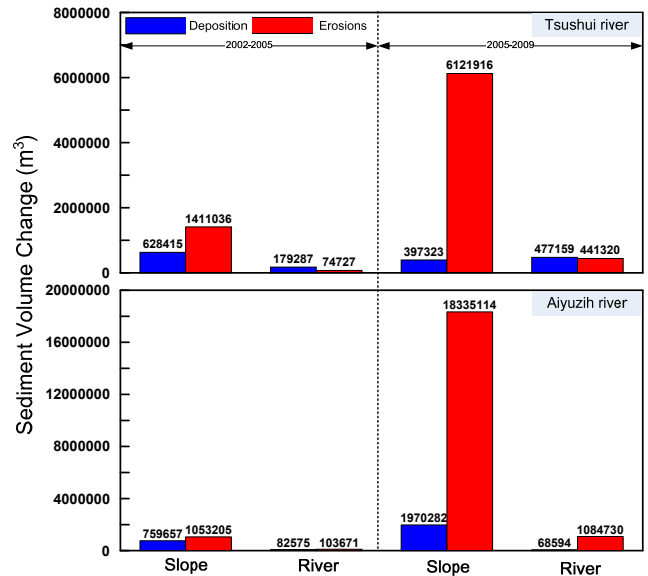


Fig. 12. Sediment volume changes in Tsushui river and Aiyuzih river catchment areas.

Results of DTM subtraction for the Shenmu area are plotted with aerial overlays from the same periods, as shown in Figs. 13 and 14. Red areas are areas of material erosion and blue area are areas of material deposition. According to these two figures, as far as Tsushui river catchment is concerned, during the 2009 typhoon Morakot, the primary collapse happened in the upstream East flank of the catchment. Scattered deposits are seen along the river with main deposits at the foot of slope failure on the downstream right flank and in the riverbed downstream of the Shenmu area. As far as Aiyuzih river catchment area is concerned, after typhoon Morakot, several large landslides occurred, the biggest one in the southwestern part (see Fig. 13). Several sediment deposits are still clearly visible at the source area. Moreover, field surveys confirm the above observations. It was documented that the two rivers have large volumes of sediment deposited on the river flanks and slopes, close to the catchment head (see Fig. 15).

3.3 Erosions, deposits, and valley shape analysis

Assessments of the erosion and deposition processes along the valley have been carried out by means of river cross section data from different periods to explore the erosion/deposits trends and valley changes associated with debris flows. The reason for this kind of analysis lays in the fact that, on average, V-shaped valleys are typical of the debris flow initiation segment, whereas U-shaped valleys represent debris flow movement (Chen and Su, 2001). According to the different available data sources, the assessments have been based on the historical DEMs and topographical surveys (see Table 5 and Fig. 16). Data accuracy and precision were very

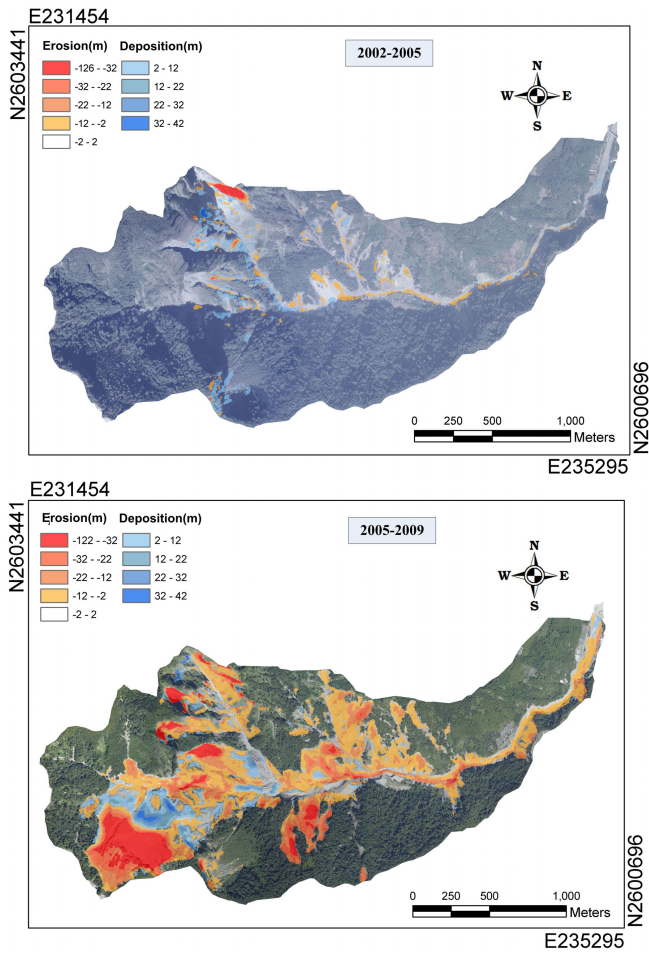


Fig. 13. Elevation changes (2002–2005 and 2005–2009 periods) after 2009 typhoon Morakot in Aiyuzih river catchment area.

rough, according to the different kinds of field measurement, and therefore only erosion and deposition trends and valley changes will be discussed and compared here.

3.3.1 Erosions/deposits

The analysis of erosion/deposition trends in both upstream and downstream sections of the Tsushui river and Aiyuzih river catchment areas are shown in Figs. 17 and 18. According to the figures, the two rivers constantly widened, especially after typhoon Morakot. Further, erosions happened to both upstream reaches while deposits occurred in downstream reaches.

3.3.2 Valley shape analysis

Valley shape changes in Shenmu area have been evaluated by means of in situ surveys. Chen and Su (2001) carried out some studies, based on field data, and tried to compare cross sections in different valley shapes. They found that if the river cross section changed from a V shape to a U shape

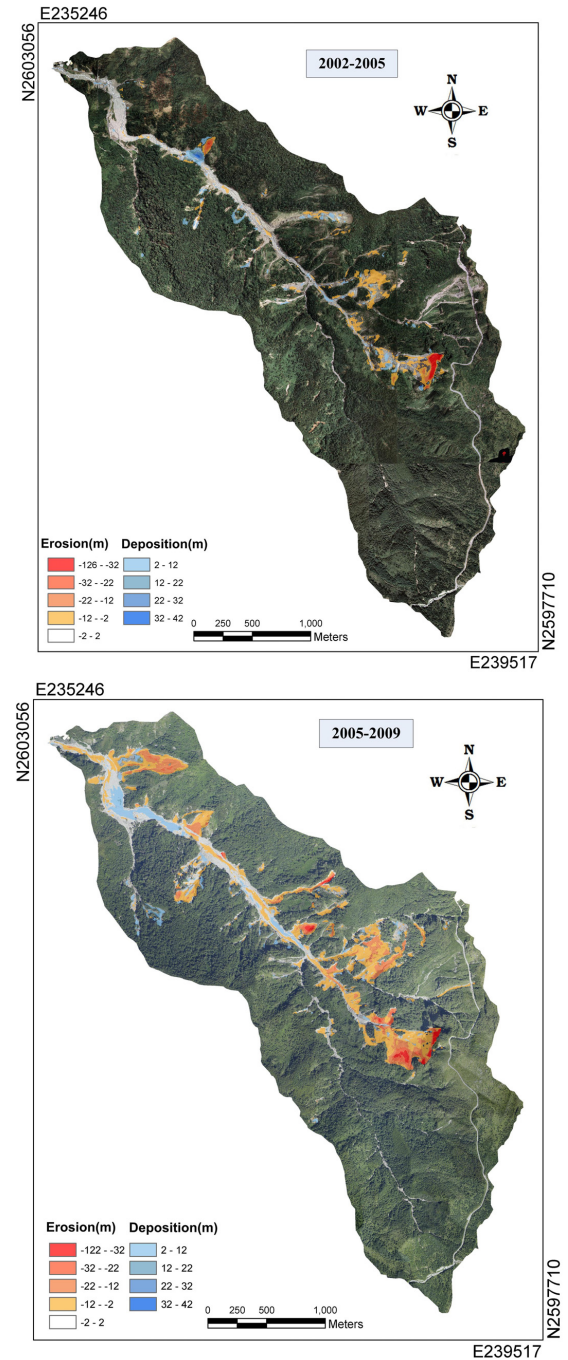


Fig. 14. Elevation changes (2002–2005 and 2005–2009 periods) after 2009 typhoon Morakot in Tsushui river catchment area.

after a debris flow, the V-U change would indicate a site for a debris flow occurrence. Figure 18 represents some cross sections of the Tsushui river, located approximately 900 m to 2500 m upstream of the downstream junction. In these figures, changes in the V and U-shapes, in the period from 2002 to 2009 (after typhoon Morakot), are indicated. The analysis of the DTMs can allow more precise quantification of

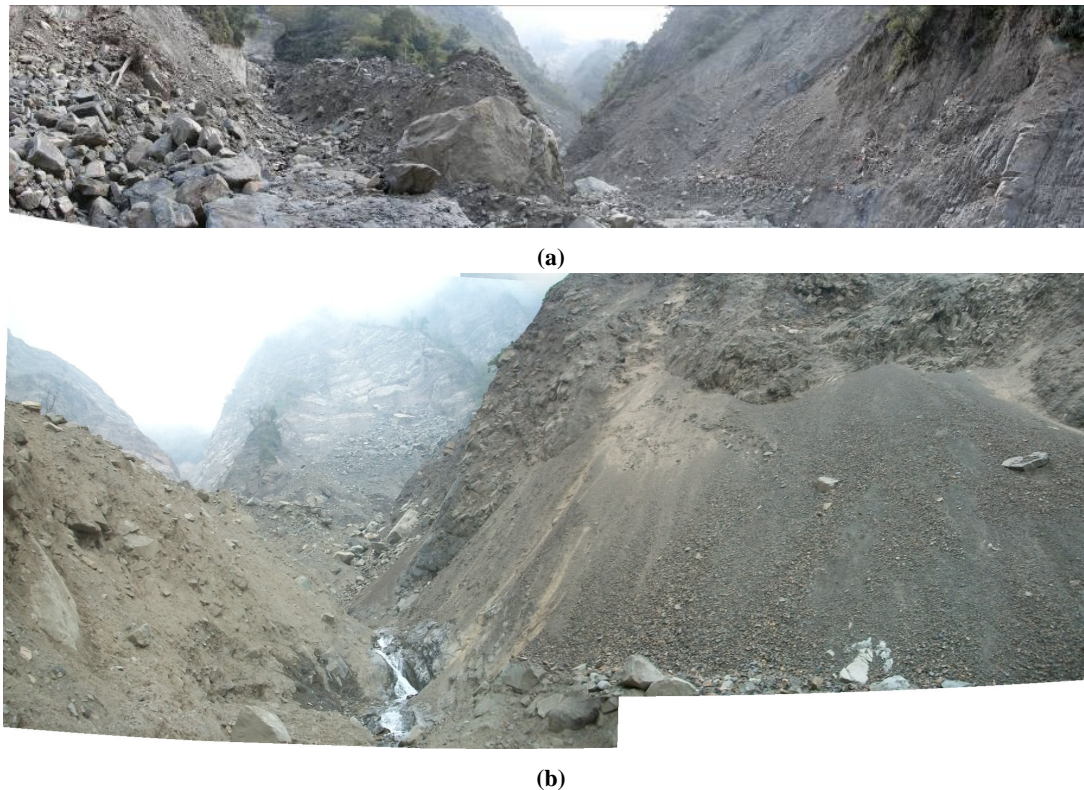


Fig. 15. Images of field observation along Tsushui river and Aiyuzih river in Shenmu area after typhoon Morakot (Date: 2009/12/04). (a) At location of 3193 m from the junction of Tsushui river, the valley is V shaped and well developed rock joint are clearly visible along the river flanks. Due to the approximately 10 m thick deposit of sediment material on the river flanks and slope, about 100 m downstream, the valley changes into a U shape. (b) At location of 2600 m from the junction of Aiyuzih river, the valley is V-shaped, slope turns exposed bedrock. A large volume of sediment material remains in the river and slope similar to the Tsushui river.

valley shape changes. Figure 19 contains some useful indications concerning landslides caused by typhoons in the past in Tsushui river. According to the figure, after typhoon Toraji in 2001, a significant collapse happened on the right-side flank, approximately 2500 m from the downstream junction. The total volumes involved in the collapse increased every year. Also after typhoon Mindulle in 2004, many landslides occurred in the upstream area. The debris was transported downstream by the surging water. The alternation in time of these landslides processes illustrates the transformation from V-shaped valleys to U-shaped valleys. Therefore, the upstream area of the Tsushui river is believed to be the sediment supply segment, that is the so-called “initiation segment”, i.e. the area where the erosions and landslides initiate, supplying sediment to debris flows. This natural process probably started in 2002, as it is evident in the comparison of 2002 and 2005 DTMs. The process is presently moving upstream.

Regarding the Aiyuzih river catchment area, valley analyses suggest the entire catchment area is U-shaped, as shown in Fig. 17. The V-U valley change cannot be deduced from the comparison of the cross sections. Consequently,

it is believed that the debris flow initiation segment is upstream the measured river section SEC20 shown in the figure (2300 m from downstream junction).

4 Discussion on debris flow triggering factors

As mentioned, the occurrence and magnitude of debris flows are influenced by three factors: rainfall characteristics, geologic conditions and topography. Below, these characteristics are summarized for each catchment.

4.1 General assessment

- a. From a geological point of view, most of the rocks in the upstream Shenmu catchment areas are sandstone and thin shale, with clear layers. Furthermore, a fault and anticline pass through the catchment area, both of which moved during the 1999 Chi-Chi Earthquake, and further fragmented the geologic structure of the area.
- b. In terms of topography, the shapes of the two catchment areas can be described as semi-circular, surrounded by mountains on three sides with an opening on one side.

Table 5. River section elevation data.

Data period	Source	Precision
2002	aerial orthophoto (DEM)	±30 to 50 cm
2005	aerial orthophoto (DEM)	
June 2009	airborne LiDAR(DEM)	
September 2009	airborne LiDAR(DEM)	
November 2009	on-site river cross section survey	±2 mm +2 ppm (Using Leica TS06 total station)
February 2010	on-site river cross section survey	

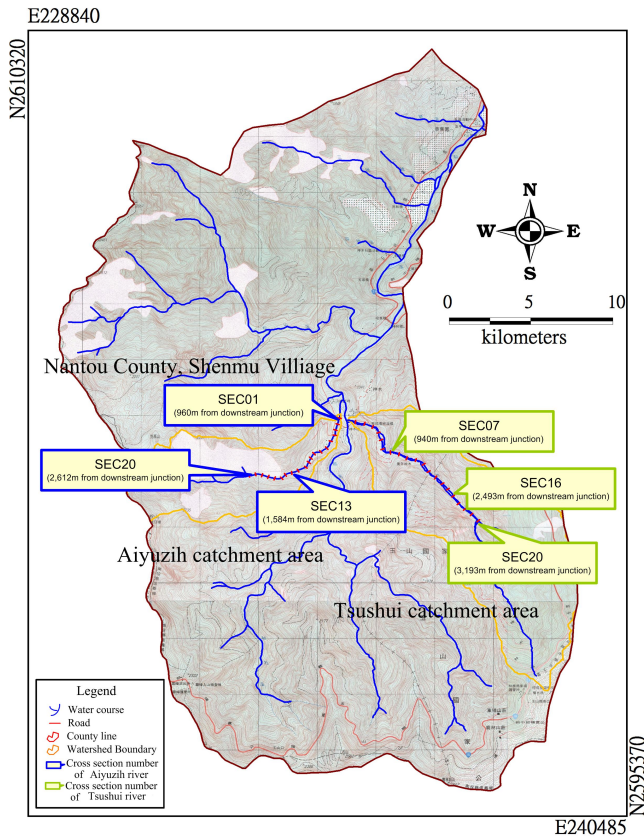


Fig. 16. Location of river cross sections.

This shape can easily develop gully erosions, landslides, and debris flows. Furthermore, the maximum elevation difference is more than 1500 m. Moreover, the catchment areas are still young and river erosion is intense. Larger amounts of sediment are washed downstream, and slopes are eroded at the toe, with a sedimentation in riverbeds. According to site surveys, the slope gradients of the two sub-catchment areas are 15° to 20° at Tsushui river and 20° to 26° at Aiyuzih river. Riverbed gradients of this magnitude can sustain fluid-like debris flows (Harris, 1977; Takahashi, 1978)

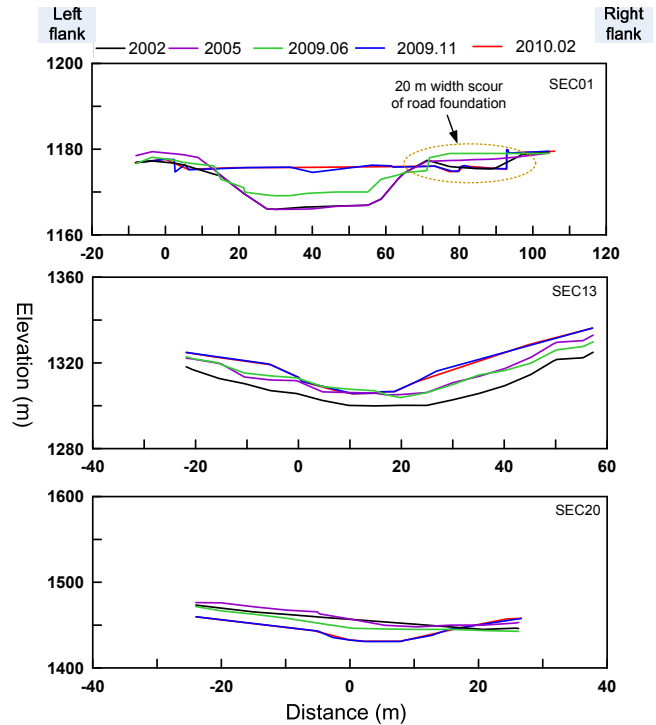


Fig. 17. River cross sections: SEC01, SEC13, SEC20 of Aiyuzih river catchment area.

c. Alishan has the heaviest rainfalls of all other sites in Taiwan. Affected by recent climate change, extreme and extended and heavy rainfalls are common. The annual average rainfall can reach 5000 mm. Large amounts of water replenish the groundwater and increase soil water content through joint cracks. This also causes shale to absorb water and to breakdown after expanding. When soil has been saturated with water for a long time, it becomes easily affected by gravity and transports the deposits out of catchment area in the form of debris flows.

Table 6. Debris flow occurring conditions.

	Catchment area	Tsushui river	Aiyuzih river
	Material supply	right flank collapse	collapse at source
Hydrological conditions	effective accumulated rainfall	200 mm	
	rainfall intensity	20 mm h ⁻¹	
	Initiation segment slope gradient	15° to 20°	20° to 26°
	Distance between initiation segment and downstream junction	2500 m or more	2300 m or more

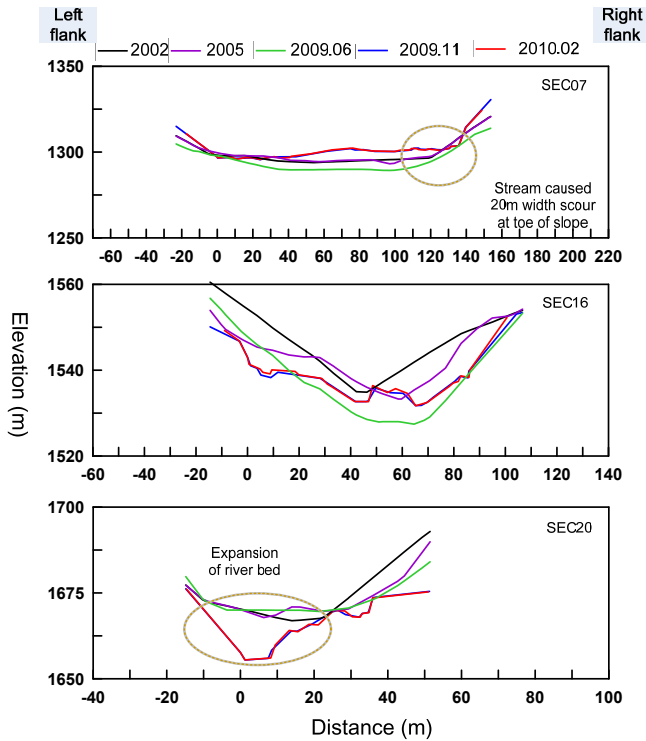


Fig. 18. River cross sections: SEC07, SEC16, SEC20 of Tsushui river catchment area

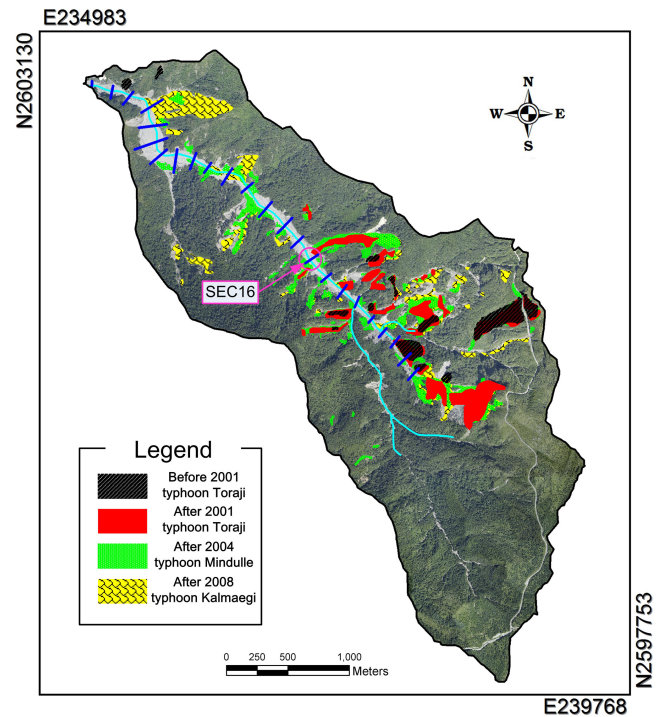


Fig. 19. Historical landslide distributions in Tsushui river catchment area.

4.2 Brief overview of debris flow occurring conditions

4.2.1 Tsushui river catchment area

In Tsushui river catchment area, the sediment collapse along the slopes of the two flanks is the main source of debris flow, especially on the right flank. According to the analysis which has been carried out in Tsushui river catchment area, when the effective accumulated rainfall in a single rainfall exceeds 200 mm, the sediment, located approximately at 2500 m (slope gradient between 15° to 20°) or more from downstream junction on the right flank, may become unstable. After 2009 typhoon Morakot, about 0.47 × 10⁶ m³ sediment volumes were deposited in upstream river bed reaches and near the junction of the river. Deposits near the junction

were more than 20 m thick. In addition, 0.39 × 10⁶ m³ sediment volumes were still lying on the slopes, especially on left-side tributary (see Figs. 12 and 14). In such a situation, the triggering mechanics can be easily predicted. As a consequence of rainfall intensities higher than 20 mm h⁻¹, the water pressure increases suddenly within the soil pores. This decreases the effective stress, filling the pores of unstable soil with water, and then makes huge amounts of soil drop into river to generate flowing movement. Eventually, it causes debris flow under the effect of slope gradient and water discharge. Following mechanics like this, the sediment volumes deposited in the riverbed and on slopes can be mobilized to debris flow.

4.2.2 Aiyuzih river catchment area

In the Aiyuzih river catchment area, the main material supply comes from the large collapse within the river source. If the effective accumulated rainfall in a single rainfall approaches 200 mm and rainfall intensity exceeds 20 mm h^{-1} , the collapsed sediment at 2300 m (slope gradient between 20° to 26°) or more from the downstream junction may transform into debris flows, moving downstream. These conditions are similar to Tsushui river. However, After 2009 typhoon Morakot, approximately $1.9 \times 10^6 \text{ m}^3$ of sediment is still concentrated and deposited in the upstream part of the catchment (see Figs. 12 and 13). The location of this mass of sediment creates a direct supply of material to the river and is prone to cause the next event of debris flow. The probability of debris flow occurrence for future rainfall event can heuristically be considered higher than Tsushui river.

From the above-named analysis and observations, debris flow occurrence conditions are compiled in Table 6. According to the table, when effective accumulated rainfall exceeds 200 mm, and rainfall intensity reaches 20 mm h^{-1} , the right flank of Tsushui river, more than 2500 m from the downstream junction, may develop large-scale collapses. The same applies to the slope more than 2300 m from downstream junction at Aiyuzih river. This supplies abundant material and increases the likelihood of debris flows (SWCB, 2010).

5 Conclusions

During the flood season, large-scale debris flow disasters frequently occurred in Shenmu area. From a risk assessment point of view, this threatens the security of downstream receptors, Highway 21, with the risk of interrupting the connections to many villages. It is one of the most disaster-prone areas in Taiwan. This study proposes a simple and feasible process to quantify basic hydrological and topological conditions (i.e. rainfall characteristics, geologic conditions and topography), using multi-stage DTMs and aerial images (before and after events), historical rainfall data and field survey. Through rainfall event analysis of real cases, the proposed approach helps to identify corresponding temporal and spatial patterns or trends of debris flow occurrence. Furthermore, a series of field surveys and in-site imaging of debris flow disasters confirmed the evidence of debris flow occurrence. The analysis suggests that both the Tsushui river and Aiyuzih river catchment areas have continuous geological activity. Riverbed movement is intense, and huge amounts of sediment, estimated by comparison of DTMs, have been recently deposited in the rivers and at mid-slopes. The main sediment supply comes from 2300 m (or more) from the downstream junction. Rainfall analysis suggests when the effective accumulated rainfall in a single rainfall reaches 200 mm, and when the rainfall intensity reaches 20 mm h^{-1} , the likelihood

for debris flow is high. Probably due to recent extreme climate changes, the average rainfall in the Shenmu area for the past five years has increased to approximately 5000 mm. This can facilitate the processes of debris flow formation and triggering.

As a result, debris flows are more frequent in the Shenmu area. Therefore, we recommend maintaining, monitoring and conducting comprehensive geotechnical surveys in this area. Furthermore, hydrological and geological surveys from upstream, midstream, and downstream areas should be consolidated to compile relevant information for future debris flow analysis and provide a reference for disaster prevention and evacuation of the residents by the government. This will improve the early warning system, prevention, and risk management and strengthen monitoring and prevention mechanisms.

Supplementary material related to this article is available online at:

<http://www.nat-hazards-earth-syst-sci.net/12/3407/2012/nhess-12-3407-2012-supplement.zip>.

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