Recognition of the Susceptibility of Hydrogeomorphic Processes in Mountainous Watersheds through Morphometric Indicators and Field Reconnaissance

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The morphometric parameters associated with hydrogeomorphic disasters such as debris flows, debris floods and floods in western Taiwan and Sichuan, China are analyzed in this study by employing the 5-m resolution digital terrain map and field studies. The drainage areas for debris-flow prone basins are within a wide range of 0.01-100 km^2. The morphometric parameters such as Melton Ratio (*MR*) and watershed length (*L*) are applicable to the identification of the debris-flow prone ravines. Through field reconnaissance, *MR*=0.3 can be regarded as the morphometric threshold for debris-flow basins in different regions, and their fan slopes are greater than 3 degrees. The debris-flow fan slope also increases with increasing *MR* values.

Key words: hydrogeomorphic processes, debris flows, fans, micro drainage, Melton Ratio

1. INTRODUCTION

Tremendous hydrogeomorphic disasters, including floods, debris floods, debris flows and landslides, often occur in Taiwan during the attack of severe typhoons or rainstorms. For the purpose of disaster prevention and response drills, there were 485 potential debris-flow torrents mapped island-widely by Soil and Water Conservation Bureau of Agriculture Council, Taiwan in 1990. The delineation criteria are based on both the risk of downstream protected targets and the topographic characteristics of the upstream catchments such as the drainage area exceeding 3 hectares at the channel slope of 10^o. In 2017, the total number of designated debris-flow torrents reached 1705, while only 986 torrents (58%) among them with debris-flow records. On the other hand, in Taiwan debris flows also occurred in non-designated torrents without protected targets. Thus, there is a need of an identification scheme of specific hazards associated with the hydrogeomorphic processes, which is beneficial not only for the proper design of countermeasures but also for land development and evacuation operation of the affected areas.

The drainage areas of debris flows cover a wide range of a few hectares to hundreds of kilometers [*Mizuyama*, 1982]. The dimensionless Melton ratio (*MR*, watershed relief (*H*, i.e., the difference between the highest and lowest elevations above the fan apex of a watershed) divided by the square root of watershed area (*A*)) is an indicator for watershed ruggedness, and it has been adopted to categorize debris-flow watersheds [*Melton*, 1965; *Jackson et al*., 1987; *Wilford et al*., 2004].

In this study, we evaluate the topographic information of debris-flow torrents in different watersheds of western Taiwan. The catchment geomorphic parameters such as Melton ratio and watershed length are used to categorize their hydrogeomorphic processes, and the identification scheme was verified by field reconnaissance and available debris-flow events in China.

2. STUDY AREAS

The study areas in this paper include three drainage basins in western Taiwan, i.e., the watersheds of Pingguang Creek, Chenyoulan River, and Chishan River. They are located in New Taipei City (northern Taiwan), Nantou County (central Taiwan), and Kaohsiung City (southern Taiwan), respectively (**Fig.1**). The detailed geomorphologic characteristics of the corresponding basins are shown in **Table 1**.

Typhoon and rainstorm events are the primary triggering factors to induce regional landslides, floods and debris flows. The annual mean precipitations in Pingguang Creek, Chenyoulan River, and Chishan River are 2,210 mm, 3,504 mm, and 2,645 mm, respectively. According to the historical record, Typhoon Morakot was the most critical event triggering the sediment-related disasters in both Chenyoulan River, and Chishan River watersheds in 2009. Furthermore, a severe Typhoon Soudelor brought heavy rainfall in northern Taiwan on 8th, August in 2015. The short-term rainfall intensity exceeded 80 mm/hr, and the accumulated precipitation had reached 769 mm in 24 hours and many landslides, debris flows, and debris floods occurred in Pingguang Creek basin (**Fig.2**).

Table 1 The geomorphologic characteristics of the study areas

Watershed	Pingguang Creek (PG)	Chenyoulan River (CYL)	Chishan River (CS)
Length	7.5 km	42.2 km	118 km
Area	19.4 km^2	447.3 km^2	736.2 km^2
Mean slope	9.85°	6.75 °	8.37°
Max. EL.	970 m	3,926 m	3,500 m
Min. EL.	45 m	301 m	43 m

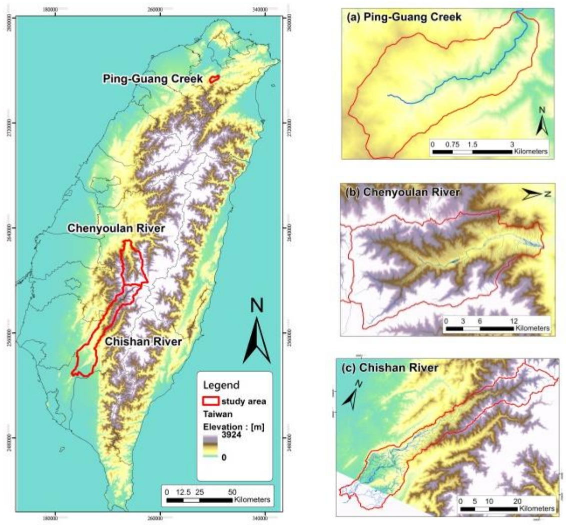


Fig. 1 Study areas in western Taiwan

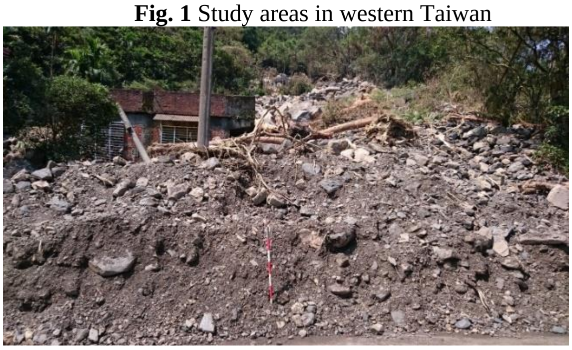


Fig. 2 Debris flow deposition in downstream reach in Ping-Guang Creek watershed (2015/08/13)

3. MATERIAL AND METHODOLOGY

3.1 High-resolution DEMs and micro-drainage classification

For the extraction of the geomorphologic feature, digital elevation models (DEMs) with two different resolutions are adopted in the study; one is 5m x 5m, and the other is 1m x 1m. The dataset was provided by Soil and Water Conservation Bureau, Taiwan. We utilized 5-m DEMs (2004 version) to divide micro-drainage basins and to construct streamlines through Geographic Information Systems (GIS) software. The airborne LiDAR (2009) can remove the surface vegetation and provides the 1-m high-resolution DEM, which is useful to enhance particular landscape features. After pre-processing, this data were transformed into visualization shading relief and applied to map old landslides, debris-flow and fluvial fans by their geomorphic features.

3.2 Micro-topography interpretation

The occurrence of landslides at the upper stream reaches usually contributes loose colluvium and material to trigger the subsequent debris flows. The topographic lineaments, scarps, landslide mass and debris-flow fans in three watersheds were characterized by visualization enhancement approach [*Lee et al*., 2017; *Lo et al*., 2017]. A powerful visualization technique, being referred to as sky-view factor (SVF) relief, is utilized in this study instead of traditional analytical hill shading from multiple directions. In brief, SVF can be regarded as a geophysical parameter that demonstrates the space of the sky visible from the given point on the ground surface [*Zakšek et al*., 2011]. SVF represents the largest range that can be encompassed over the observer or a certain point (the projected area of the hemisphere over the observer in a unit of space; [*Lo et al*., 2017]:

$$\Omega = \int_0^{2\pi} \int_0^{\pi/2} cos\varphi d\varphi d\lambda = 2\pi \qquad (1)$$

where, Ω, φ and λ denote the solid angle, latitude and longitude within the hemisphere, respectively. One can normalize the solid angle in Eq. (1) by using 2π, which gives the SVF:

$$\text{SVF} = 1 - (\textstyle\sum_{i=1}^{n} sinr_i)/n \qquad (2)$$

where γ_i and n represents the elevation angle from the horizontal surface and the selected number of azimuth directions, respectively. SVF=1 means that the entire hemisphere of sky is visible (such as on a plain or from a peak); SVF=0 means that virtually no sky can be seen from the observation point (canyon). **Table 2** lists the morphological features for manual mapping criteria in SVF relief maps. It is noted that some landscapes of landslides and debris-flow fans are affected by man-made countermeasures or training works. Once the micro-topography interpretation was performed, one can analyze the geometric parameters such as slope gradient (along with the centerline from the apex to the end of the broader fan) and area of debris-flow fans. Furthermore, the relationship between fan slope gradient and the drainage basin will be examined in the following section.

3.3 Melton's number(MR) assessment

The watershed boundaries, watershed lengths and stream orders were established by using DEM and GIS. The DEM has a cell size of 5 x 5 m and the lowest point of the feeding channel in a watershed was the apex of the fan. The Melton ratio (*MR*) and watershed length (*L*) is a suitable scheme for the differentiation of the hydrogeomorphic processes in mountainous watersheds [*Melton*, 1965; *Wilford et al*., 2004; *Chou et al*., 2017]. The watersheds in Pingguang Creek, Chenyulang River, and Chi-Shan River were derived based on DEM and GIS. The dominant hydrogeomorphic processes, including debris flows, debris floods, and floods, for each sub-basin are determined by their geomorphic parameters, *MR* and *L*, and verified by the depositional patterns in the fan areas through field reconnaissance.

Table 2 Micro-topography interpretation for recent landslides and debris-flow fans (summarized by *Lee et al*., 2016)

Feature	SVF relief map	Description
Landslide scarp		Most of the cliffs formed by slope slumps are scarps of slope top failure. The flanks are the result of the steep slumps and can be used to gauge the strain rate of the slope failure process
Landslide body		The original sliding body presents a dustpan-shaped depression with the upper section displaying subsidence, the middle section showing a gentle slope, and the lower section exhibiting hummocky relief
Debris-flow fan		It usually is formed at the gentle slope and broad downstream reach (deposition section: 3-6°). The shape of the fan is dominated by magnitude of debris flow, material, and geometrical condition of the channel. It could be symmetrical fan-shaped or lobe-shaped deposition.

4. RESULTS AND DISCUSSIONS

4.1 The geomorphologic characteristics of debris-flow fans

The formation process of an alluvial fan is dominated by the ratio between the power of the water discharge and the sediment supply from the upslope catchment [*Harvey et al*., 1999]. As shown in **Table 3**, this study identified and mapped 97 debris-flow fans over the watersheds of Ping-Guang Creek, Chenyoulan River, and Chishan River (**Fig. 3**). The area of debris-flow fans ranges from 0.05 to 25.47 ha depending on the scale of stream discharge

Table 3 The debris-flow/alluvial fans mapped in the study areas

Watershed	Pingguang Creek (PG)	Chenyoulan River (CYL)	Chishan River (CS)
Num. of fans	7	37	53
Area [ha.]	0.50- 2.76	0.05-25.47	0.57-21.58
Slope [deg.]	5.5-13.7	1.8-20.7	2.9-27.6

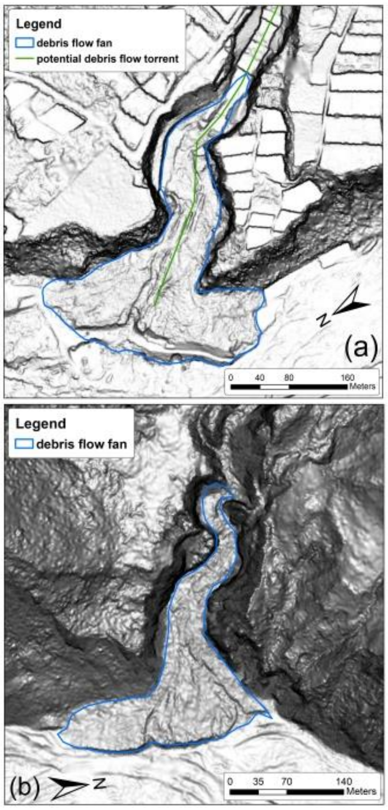


Fig. 3 Recent debris-flow fans mapped in (a) Chenyoulan River watershed and (b) Chishan River watershed.

and sediment yield via the feeding channel. Several geomorphologic characteristics in the study areas are summarized as follows. (1) The thickness and the area of deposition of the debris-flow fan increases in proportion to the number of the historical landslides in the upstream region (source area). The amount of in-channel sediment transportation may become more evident during the occurrence of a deep-seated landslide in the past. (2) The fan area at the upstream tributary is usually small, but the slope gradient is comparatively high. On the other hand, the slope gradient of debris-flow fan is gentle while it is located on the river terrace or adjacent to the main stream. (3) The landform of watershed predominates the slope gradient of debris-flow fan. Once the topography of upstream reach belongs to concave-typed depression, it will contribute rainfall transferring into surface runoff quickly. The classic fan-shaped deposition may be eroded and incised, and form a serval meandering channel at the distal end.

The Melton ratio ($\mathrm{MR} = \frac{H}{\sqrt{A}}$) is a critical morphometric variable related to the basin dynamics, and fan surface slope S_{fd} (in degrees) in general is a function of MR as follows [*Melton*, 1965].

$$S_{fd} = a(MR)^b \tag{3}$$

where *a* and *b* are site-specific coefficients.

The variations in coefficients *a* and *b* reflect the differences in climatic settings, sediment availability, tectonics and geological characteristics in the drainage basins. Greater values of *a* and *b* depict more active fans currently. The fan slopes in the study areas are closely related to the Melton ratio MR with *a* = 8.57 and *b* = 0.89) as shown in **Fig. 4**. The surface slopes of the alluvial fans are close to Melton's Group 1 for active tectonic regions or the regression with *a* = 8.51 and *b* = 1.065, which was proposed by *Kovanen and Slaymaker* [2008]. The Melton ratio is thus a morphometric variable reflecting the tectonics and the ratio of flood power to the sediment transport capacity. The Melton ratios for debris-flow dominated fans in the study areas have a value greater than 0.4 and the fan slopes are greater than 3 degrees.

4.2 The watershed hydrogeomorphic processes

The distributions of watershed areas for debris-flow basins in Japan [*Mizuyama*, 1982] and in the study areas are shown in **Fig. 5**. The drainage areas are within a wide range of 0.01-100 km^2, while most of them are small basins of less than a few square kilometers.

The debris-flow basins of Chenyoulan River (middle western Taiwan) are generally larger than those of Pingguan Creek (northwestern Taiwan), while those of Chishan River are in between. The Melton ratio (*MR*) and watershed length (*L*) form a suitable scheme for the differentiation of the hydrogeomorphic processes in Pingguan Creek with lower bound of MR of 0.5 and the upper bound of *L* of 2.2 km for debris-flow torrents (see **Fig. 6(a)**).

While the scatterplot of Melton ratio and watershed lengths for torrents in Chenyoulan River and Chishan River are shown in **Fig. 6(b)**, which depicts a lower bound of 0.43 for *MR* and an upper bound of 7 km for watershed length for debris-flow prone torrents. There is a buffer zone for the co-existence of debris flows and debris floods under the condition of *MR* > 0.43 with 7 < *L* <12 km, and 0.3 < *MR* <0.43 in watersheds of Chenyoulan River (CYL) and Chishan River (CS) through field

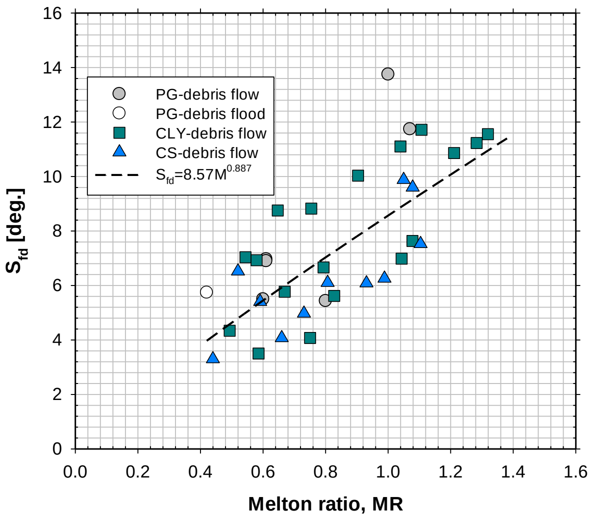


Fig. 4 Fan slopes as a function of the Melton ratios in the study areas as shown in Table 3.

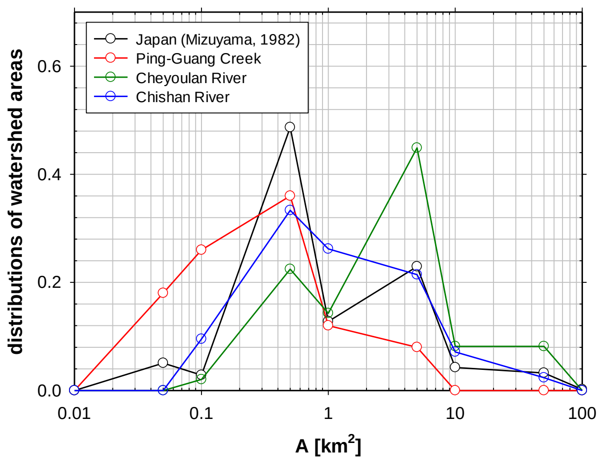
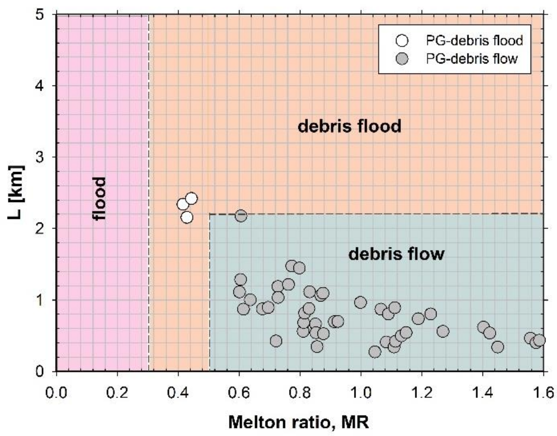


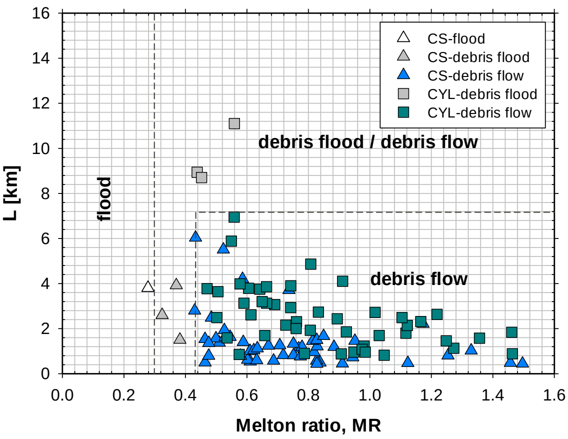
Fig. 5 The distributions of watershed areas for debris-flow basins in Japan and in western Taiwan

Table 4 Classification of sediment-related hazards in the study areas

Watershed	Pinggung Creek (PG)	Chenyoulan River (CYL)	Chishan River (CS)
Debris flows	50	47	50
Debris floods	3	3	4
Floods	0	0	1



(a) Pinggung Creek (PG) in Northwestern Taiwan



(b) Chenyoulan River (CYL)and Chishan River(CS)

Fig. 6 The relationship between watershed length (L) and Melton ratio (MR) for hydrogeomorphic hazards in western Taiwan

investigations. In accordance with analysis result and overlay by potential debris flow torrents, one may identify the sediment-related hazards occurred in three study areas (**Table 4**). For small Pingguang Creek watershed, fifty debris flows and three debris floods are clarified by integrating geomorphic factor and field investigation.

To verify the applicability of aforementioned morphometric parameters for hydrogeomorphic hazards in different regions, a data set of 147 debris-flow torrents in 5 counties (Ching-ping, Bai-chuan, Yin-shou, Long-tse and Der-chan) of

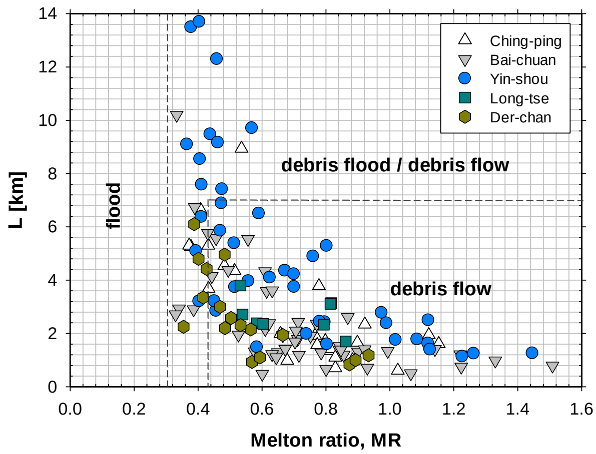


Fig. 7 The relationship between watershed length (L) and Melton ratio (MR) for hydrogeomorphic disasters in Sichuan, China.

Sichuan province, China was adopted for comparison (Dr. Bin Yu, personal communication). The results are shown in **Fig. 7**, which indicates a lower MR limit of 0.3 and a higher watershed length limit of 14 km for debris-flow prone torrents; so the scatting of debris-flow torrents in China covers both regimes of debris flow (DF) and debris flood (DFL) delineated in the study areas (**Fig. 6b**). As shown in **Fig. 7**, the maximum watershed length for debris-flow basins in Sichuan is about 13.7 km in Yin-shou region, and the corresponding drainage area is 48.7 km^2, which is within the range of 0.01-100 km^2 as shown in **Fig. 5**. Thus $MR>0.3$ and $L<14$ km should be the morphometric parameters for debris-flow basins in Sichuan, China.

The differences in their threshold values of *MR* and *L* for debris-flow prone watersheds among western Taiwan and China are mainly due to the differences of lithology, sediment supply, geological settings and climate. The zonation between debris flow and debris flood deserves further investigation. Above all, MR = 0.3 seems to be the lower bound for debris-flow basin as proposed by *Jackson et al*. [1987], and itself also serves as the upper bound for flood-related disasters.

5. CONCLUSION

The morphometric parameters, i.e., Melton Ratio and drainage length, are applicable to an identification scheme of hydrogeomorphic processes such as debris flows, debris floods and floods. Regarding the debris-flow torrents in the study areas, the lower bound of *MR* is about 0.3-0.5, while the upper bound of *L* is about 2.2 -14 km in different regions in western Taiwan and China due to their different lithology, sediment availability, geological and climate settings. MR=0.3 seems to be the lower bound for debris-flow basins as proposed by *Jackson et al*. [1987], and itself also serves as the upper bound for flood-related disasters. A buffer zone for the co-existence of debris flows and debris floods under the condition of $0.3 < MR < 0.43$, or $MR > 0.43$ with $7 < L < 12$ km deserves further research. The fan slope for debris-flow fans in this study areas generally exceed 3 degrees, and the fan slopes versus Melton Ratio are close to Melton's type Group 1 for active tectonic regions.

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