ARTICLE IN PRESS
GEOMOR-06222; No of Pages 9
Geomorphology xxx (2017) xxx–xxx
Contents lists available at ScienceDirect
Geomorphology
journal homepage: www.elsevier.com/locate/geomorph

# Sediment yield during typhoon events in relation to landslides, rainfall, and catchment areas in Taiwan

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ARTICLE INFO

*Article history:*
Received 3 July 2017
Received in revised form 13 November 2017
Accepted 13 November 2017
Available online xxxx

*Keywords:*
Sediment discharge
River catchment
Rainfall
Landslide
Typhoon event
Taiwan

ABSTRACT

Debris sourced from landslides will result in environmental problems such as increased sediment discharge in rivers. This study analyzed the sediment discharge of 17 main rivers in Taiwan during 14 typhoon events, selected from the catchment area and river length, that caused landslides according to government reports. The measured suspended sediment and water discharge, collected from hydrometric stations of the Water Resources Agency of Taiwan, were used to establish rating-curve relationships, a power-law relation between them. Then sediment discharge during typhoon events was estimated using the rating-curve method and the measured data of daily water discharge. Positive correlations between sediment discharge and rainfall conditions for each river indicate that sediment discharge increases when a greater amount of rainfall or a higher intensity of rainfall falls during a typhoon event. In addition, the amount of sediment discharge during a typhoon event is mainly controlled by the total amount of rainfall, not by peak rainfall. Differences in correlation equations among the rivers suggest that catchments with larger areas produce more sediment. Catchments with relatively low sediment discharge show more distinct increases in sediment discharge in response to increases in rainfall, owing to the little opportunity for deposition in small catchments with high connectivity to rivers and the transportation of the majority of landslide debris to rivers during typhoon events. Also, differences in geomorphic and geologic conditions among catchments around Taiwan lead to a variety of suspended sediment dynamics and the sediment budget. Positive correlation between average sediment discharge and average area of landslides during typhoon events indicates that when larger landslides are caused by heavier rainfall during a typhoon event, more loose materials from the most recent landslide debris are flushed into rivers, resulting in higher sediment discharge. The high proportion of large landslides in Taiwan contributes significantly to the high annual sediment yield, which is among the world's highest despite the small area of Taiwan.


## 1. Introduction

Landslides produce debris that will enter rivers and be transported to the ocean. Therefore, by analyzing sediment yields, we can identify not only the average exhumation rate of an area but also the effects of landslides on surface morphology (Chen et al., 2013). Landslides can directly or indirectly affect sediment discharge in rivers (Hovius et al., 1997, 2011; Dadson et al., 2004; Claessens et al., 2007; Vanmaercke et al., 2017). However, most studies on the linkage between landslides and sediment discharge have focused on a single or a few catchments (e.g., Pearce and Watson, 1986; Hovius et al., 1997; Dadson et al., 2004; Koi et al., 2008). Some studies have also pointed out that landslides can be highly relevant to sediment discharge even at regional or continental scales (de Vente et al., 2006, 2013; Delmas et al., 2009; Broeckx et al., 2016). Understanding geomorphic processes and contemporary sediment yields at regional and continental scales is important for a wide range of ecological, economic, and scientific reasons (Meybeck, 2003; Owens et al., 2005; Syvitski and Milliman, 2007; Vanmaercke et al., 2011; de Vente et al., 2013). Previous studies have found that spatial differences in sediment yield and contemporary erosion processes have been linked to differences in tectonics, topography, lithology, climate, and land use (e.g., Owens et al., 2005; Syvitski and Milliman, 2007; Korup et al., 2014).

Every year in Taiwan, about 384 Mt of sediment are transported into the ocean (Dadson et al., 2003). Of this amount, about 30–42% of the

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https://doi.org/10.1016/j.geomorph.2017.11.007
0169-555X/

Please cite this article as: Chen, C.-W., et al., Sediment yield during typhoon events in relation to landslides, rainfall, and catchment areas in Taiwan, Geomorphology (2017), https://doi.org/10.1016/j.geomorph.2017.11.007

sediment is discharged as hyperpycnal sediment concentrations, typically during typhoon events (Dadson et al., 2005; Lin and Chen, 2013). However, to estimate the proportion of the materials produced by the most recent landslides that enters rivers is difficult. Few previous studies have directly discussed the relationship between landslides and sediment discharge in Taiwan. Dadson et al. (2004) used the drainage area of the lowest point reached by each landslide to estimate the proportion of materials produced by the most recent landslides that entered a river. The results showed that when a landslide reaches a location with a drainage area of >1 km$^2$, the delivered sediment enters a river. In the Chenyoulan River catchment in Taiwan, about 80% of the materials produced by landslides induced by the 1999 Chi-Chi earthquake were not immediately delivered to rivers; they were successively delivered to rivers by subsequent typhoons (Dadson et al., 2004). The same phenomenon also has been observed in the epicentral area of the 2008 Wenchuan earthquake in China, where abundant materials from seismic shallow landslides rapidly evolved into debris flows caused by several extreme rainstorms after the earthquake (Zhang and Zhang, 2017). In addition, Lin et al. (2011) studied landslides in the upstream area of the Shihmen Reservoir, Taiwan, and pointed out that high landslide ratios do not correspond to high sediment discharge, probably because sediment discharge is controlled by water discharge and because landslide debris may remain on slopes.

Taiwan is an area extremely susceptible to landslides because of the steep mountainous topography, complex geological conditions, frequent heavy rainfall, and frequent earthquakes. Thus, many studies have been performed on landslides in Taiwan (Jan and Chen, 2005; Chang and Chiang, 2009; Lin and Chen, 2012; Chen et al., 2015b). Landslides triggered by rainfall and earthquakes are the major source of coarse and fine sediments in channels and rivers in Taiwan. These sediments are then transported and deposited in dams and reservoir downstream areas, where they reduce the storage capacity for drinking water and/or electricity production, and some move on to the ocean (Hovius et al., 2000; Claessens et al., 2006; Hilton et al., 2008). Exploration of the characteristics of sediment yields, especially the debris from landslides, is important because they are closely related to impacts on the facilities and environment of the downstream areas. The difficulty in quantifying the contribution of landslides to sediment yield in Taiwan is that not all landslides will effectively supply sediment to the river system. The contribution depends on sediment connectivity, which is influenced by a range of factors such as topography, geology, land use, distance to river, and catchment area. Therefore, this study analyzed the sediment discharge of 17 main rivers in Taiwan during 14 typhoon events and related the results to rainfall conditions, catchment areas, and landslides. We ruled out the impact of earthquakes by using the data from 2007, eight years after the Chi-Chi earthquake (the strongest earthquake in recent years in Taiwan).

## 2. Study area

Taiwan is located on an active subduction-collision region between the Eurasian Continental and Philippine Sea plates, with the Philippine Sea plate moving toward the Eurasian Continental plate at a rate of 80 mm/y (Yu et al., 1997). The subduction of the Philippine Sea plate beneath the Eurasian Continental plate resulted in the formation of an active mountain belt called the Central Range, which has over 200 peaks higher than 3000 m a.s.l. (Ho, 1986; Teng, 1990). It is also responsible for frequent large earthquakes and an orogenic uplift rate of about 5 to 7 mm/y (Li, 1976; Willett et al., 2003). About 70% of the island is either hilly or mountainous. The slope of the mountainous areas is mostly between 30° and 50° (Chen et al., 2015a). The landscape is characterized by small drainage basins (area of $<3.3 \times 10^9$ m$^2$), fractured rock formations, high relief, and steep stream gradients.

Taiwan is located approximately between 120°E and 122°E and between 22°N and 25°N, and the boundary between tropical and subtropical-monsoon climates is located in the southern part of Taiwan (Wang and Ho, 2002). Taiwan is also located on the major tracks of typhoons (tropical cyclones) in the northwest Pacific region, with an average of four typhoons every year (Wu and Kuo, 1999) causing heavy and concentrated rainfall. Annual rainfall over Taiwan averages 2500 mm. However, annual rainfall in mountainous regions can surpass 3000 mm (Shieh, 2000). Approximately 60% to 80% of the rain falls during the wet season (Chen et al., 2015a).

The shape of Taiwan is long and narrow, and most rivers originate from the Central Range and radially flow into the ocean in all directions. Among these rivers, 17 are the main representative rivers (Fig. 1). They include three rivers (the Xindian, Tahan, and Touchien rivers) in the northern part of Taiwan, four (the Taan, Tachia, Wu, and Choshui rivers) in the central part, five (the Tsengwen, Erhjen, Kaoping, Linpien, and Sihjhong rivers) in the southern part, and five (the Peinan, Hsiukuluan, Hualien, Hoping, and Lanyang rivers) in the eastern part.

### 2.1. Main rivers

Table 1 shows the lengths of the 17 main rivers, the average elevation and slope, and the main lithology of the catchments according to a 10-m digital terrain model from the Aerial Survey Office of Taiwan and the 1:500,000 Taiwan Geological Map from the Central Geological Survey of Taiwan. The central catchments have the highest average elevation, >1200 m. The average elevation of eastern catchments is over 1100 m and that of northern catchments is about 800 m. The southern catchments have the lowest average elevation and include the lowest three rivers (the Erhjen, Tsengwen, and Sihjhong rivers), with average elevations of 55.9, 323.8, and 470.4 m respectively. The eastern catchments have the highest average slope, about 30°. The average slope of northern and central catchments is over 27°. The average slope of southern catchments is much lower, at about 22°; the Erhjen River catchment has an average slope of only 10.4°.

The main lithology of the northern and central catchments is sedimentary rocks, such as sandstone, siltstone, and shale, with some metamorphic rocks such as slate and quartzite. The southern catchments consist mainly of mudstone of sedimentary rocks (e.g., the Tsengwen and Erhjen rivers). The eastern catchments are mostly composed of metamorphic rocks, such as slate and schist.

### 2.2. Typhoon events

On average, four typhoons strike Taiwan every year between summer and fall (Wu and Kuo, 1999), resulting in many geohazards such as landslides, debris flows, and floods. This study chose 14 typhoons during a 6-year period from 2007 to 2012 that caused landslides reported by the Soil and Water Conservation Bureau (SWCB) of Taiwan (Chen et al., 2015a). Most of these typhoons were generated east of Taiwan. Five of them passed through northern, four passed through central, and five passed through southern Taiwan (Fig. 2). Table 2 shows the period when each typhoon affected Taiwan, the maximum cumulative rainfall, and wind velocity observed. The information is from the Central Weather Bureau (CWB) of Taiwan (http://rdc28.cwb.gov.tw/TDB/ntdb/pageControl/ty_warning). The lowest value of the maximum cumulative rainfall, 394.0 mm, was observed during Typhoon Lionrock in 2010, but it still caused some landslides. The largest maximum cumulative rainfall, 3060.0 mm during Typhoon Morakot in 2009, caused a catastrophic landslide at Shiaolin Village in southern Taiwan that left 400 people dead or missing (Tsou et al., 2011). The maximum cumulative rainfall for most of these typhoons is near to or >1000 mm. Even some typhoons with tracks distant from Taiwan (e.g., Typhoons Parma and Megi) were accompanied by the northeast monsoon, bringing heavy rainfall in northern Taiwan with maximum hourly rainfall exceeding 100 mm. Typhoon events are also the main periods for the sediment yield of river catchments in Taiwan (Dadson et al., 2005; Lin and Chen, 2013).

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