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Average landslide erosion rate at the watershed scale in southern Taiwan estimated from magnitude and frequency of rainfall

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ABSTRACT

This study calculated the long-term average landslide erosion rate in the Kaoping River watershed in southern Taiwan and investigated the relative importance of extreme rainfall events on landslide erosion. The method followed three steps: first, calculating landslide volumes for 10 rainfall events from a multi-temporal, event-based landslide inventory; second, estimating the frequency of landslide-generating rainfall by using hydrologic frequency analyses; and third, combining the two sets of data to estimate the average landslide erosion rate. Results of the study showed that the average landslide erosion rate is 2.65–5.17 mm yr^{-1}, corresponding well to rates reported in other studies using other methods. The study also found that extreme-intensive rainfall events play a more important role on landslide erosion than frequent-moderate rainfall events. Extreme rainfall (maximum 24-h rainfall >600 mm) contributes 64–79% of the average landslide erosion rate. Moreover, the natural variation of landslide erosion magnitudes is extremely large and can cause significant uncertainty in estimating the landslide erosion rate from total landslide volume. This study found ±1.2 mm yr^{-1} of uncertainty based on simulation results involving a hypothetical 100-year landslide inventory. In summary, this study demonstrates the importance of extreme rainfall events on landslide erosion, and the method proposed in this study is capable of calculating a reliable estimate of average landslide erosion rate in areas with insufficient landslide records.

1. Introduction

In active mountainous regions, quantitative estimates of landslide erosion rate are important for understanding the evolution of landforms (Densmore and Hovius, 2000), the interaction between hillslopes and river processes (Larsen and Montgomery, 2012), the linkage between landsliding and its triggers (Chen et al., 2013), the mass transport from the terrestrial basins to the ocean (Hilton et al., 2008), and sedimentation in a river or a reservoir (Hovius et al., 2000; Claessens et al., 2006).

One of the approaches to estimating the long-term average rate of landslide erosion at watershed level is based on a multi-temporal event-based landslide inventory. For each event, landslide erosion can be estimated by mapping landslide areas and using a volume–area relation (e.g., Guzzetti et al., 2009; Parker et al., 2011; Larsen and Montgomery, 2012) to derive landslide volumes. A long-term average rate of landslide erosion can then be derived by dividing the total landslide volume by the number of years and the total area covered by the inventory. Chen et al. (2013) used this method and a multi-temporal inventory covering landslides triggered by 13 rainfall events in 2001–2009 to derive the average landslide erosion rates in three watersheds in Taiwan and correlate them with rainfall factors. However it is uncertain whether these rates represent long-term average rates. As pointed out by Reid (1998), to be valid estimates, the sampling period must represent an average distribution of landslide-producing events. This means that the sampling period must be long enough to cover not only frequent-moderate events but also extreme-intensive events to represent a reliable distribution. Moreover, the sampling interval must be shorter than the landslide recovery time so that frequent-moderate events are not under-represented in the sample (Claessens et al., 2006).

It is difficult to obtain a multi-temporal event-based inventory that can meet the above criteria for estimating a long-term average rate of landslide erosion. A solution is to construct the magnitude–frequency relation of the landslide trigger (e.g., rainfall or earthquake) and link it to an event-based landslide inventory for quantifying the long-term average erosion rate (e.g., Keefer, 1994; Reid, 1998; Malamud et al., 2004). The rational is that climatic records are typically available for longer periods than aerial photographs or satellite images for mapping landslides. The method was used by Reid (1998) for calculating average

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landslide frequency at a field site in central California, and by Reid and Page (2002) for estimating the magnitude and frequency of landsliding in a large New Zealand catchment.

An additional advantage of using climatic records for estimating landslide erosion rates is that it allows the opportunity to compare contribution of high-magnitude, low-frequency events versus low-magnitude, high-frequency events to landslide erosion. Several studies have documented the significant effects of extreme and catastrophic events on landslides (Wolman and Miller, 1960; Keefer, 1994; Goldsmith et al., 2008; Lin et al., 2008; Marriner et al., 2010; Chen et al., 2011). On the other hand, Reid (1998) has reported that, in a long run, the most effective landslide producer in central California is monthly rainfall of 280–300 mm, rather than that of over 350 mm. Thus the issue of comparing the effects of triggering events of different magnitudes on landslide erosion is still open for examination.

Taiwan is an island of 36,000 km^2 and is situated in the active subduction-collision region between the Eurasian Continent and the Philippine Sea plates (Huang et al., 1997), with frequent large earthquakes. About 70% of the island is either hilly or mountainous. The topography is characterized by small drainage basins, fractured rock formations, high relief, and steep stream gradients. Taiwan is also located on the major tracks of typhoons (tropical cyclones) in the northwest Pacific region, with an average of four typhoons per year (Wu and Kuo, 1999). Landslides triggered by typhoons and earthquakes act as major sources of both coarse and fine sediments in channels and rivers in Taiwan. These sediments are then transported and deposited in dams and reservoirs, reducing their storage capacity for drinking water and/or electricity production. Estimates of long-term average landslide erosion rates are therefore needed for sediment budget calculations as well as for the general purpose of watershed management in Taiwan.

In this study, we calculated the long-term average rate of landslide erosion by linking a multi-temporal event-based landslide inventory with rainfall data for a watershed in southern Taiwan. The inventory covered landslides triggered by 10 rainfall events in 2001–2009, the same as the inventory used by Chen et al. (2013). The rainfall data were compiled from gauging stations within the watershed with records spanning from 26 to 53 years. Besides calculating the average landslide erosion rate, this study also examined the contribution of different rainfall intensities to landslide erosion, the performance of different probability density functions for frequency analysis of rainfall events, and the accuracy of the estimated rate by comparing it with landslide erosion rates derived from sediment concentration data. We hope that this study can provide important information on landslide erosion and its trigger for watershed management in Taiwan.

2. Study area

The Kaoping River watershed, located on the south-western side of the Central Mountain Range of Taiwan, was selected as the study area (Fig. 1). The watershed has a drainage area of 2868 km^2, with elevations ranging from 25 to 3952 m and an average slope of 26.4° derived from a 40-m digital elevation model (DEM). The lithology is composed of metamorphosed and deformed rocks, including black and green schist, phyllite, and argillite, terrace deposits, and alluvium. About 76% of the study area is primary indigenous forest, with cultivated fields and built-up areas accounting for the remaining 24%. The suspended sediment discharge is about 49 Mt per year, mainly produced by typhoon- and earthquake-triggered landslides (Dadson et al., 2003).

Annual rainfall in the Kaoping River watershed ranges from 2300 mm in the downstream area to 4500 mm on the south-eastern side of the headwater area. Rainfall distribution is extremely uneven, with 90% of annual rainfall falling during the wet season of May to September (Water Resource Agency, 2013).

Rainfall during the wet season is mainly induced by typhoons. When a typhoon crosses northern Taiwan, it can bring heavy rainfall in southern Taiwan, including our study area, due to south-westerly wind flows (Wu and Kuo, 1999). Therefore, the Kaoping River watershed experiences frequent landslides and debris flows, which have been covered in several recent studies (Chiang and Chang, 2012; Mondini et al., 2013; Chang et al., 2014). In 2001–2009, there were nine typhoons and a heavy storm that caused extensive landslides in the study area (Chen et al., 2013). Hereafter these events are called landslide events. The basin-averaged, cumulative rainfall for the 10 landslide events ranged from 317 to 2232 mm. The most severe landslide event in this watershed was triggered by Typhoon Morakot (August 5–10, 2009), which brought an accumulated rainfall of over 2000 mm in many regions of southern Taiwan. The accumulated rainfall record of 3059 mm at the Mt. Ali station set a new rainfall record from a single typhoon event in Taiwan and the 48-hour rainfall record of 2361 mm at this station was close to the world record of 2467 mm (Quetelard et al., 2009).

3. Methods and materials

This study followed the work flow in Fig. 2. It estimated basin-averaged landslide erosion rates and frequencies of rainfall events separately, before linking them for the calculation of the long-term

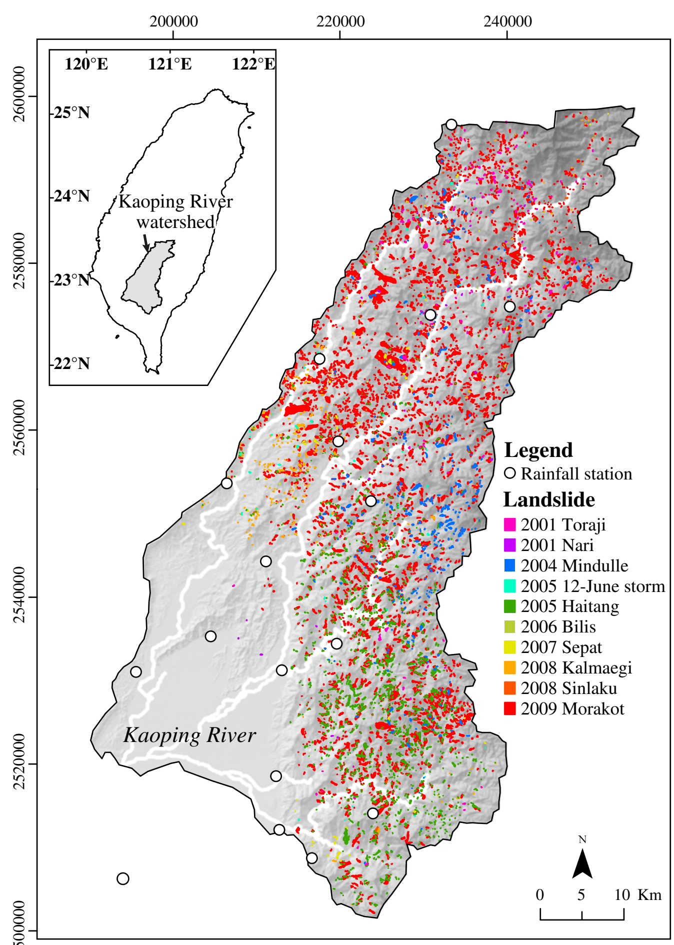

Fig. 1. The Kaoping River watershed and the multi-temporal, event-based landslide inventory from 2001 to 2009. The color polygons show new landslides triggered by rainfall events in the Kaoping River watershed. The circles are the rainfall stations maintained by the Water Resource Agency of Taiwan.