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Distributions of landslides, vegetation, and related sediment yields during typhoon events in northwestern Taiwan

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ABSTRACT

This study examined landslides caused by typhoon events in the upstream area of the Tao-Cheng River in northwestern Taiwan during a 13-year period, 1996 to 2008. Data from six typhoon events were compiled to analyze the relevant characteristics of landslides, vegetation, and changes in sediment discharge with particulate carbon in rivers in this area. The landslide ratio, the ratio of the landslide area to the total study area, was determined to be between 0.60% and 1.29%, and a high new generation ratio and low reactivated ratio of landslides were noted. Analysis of different bands of satellite images taken over a 10-year period disclosed that the Normalized Difference Vegetation Index (NDVI) in the upstream area of the Tao-Cheng River ranged from 0.47 to 0.63 before typhoon events and from 0.38 to 0.46 after typhoon events. The low landslide ratio and high new generation ratio in this area indicated that sporadic landslides tend to occur in new areas and do not have a great impact on vegetation conditions. Thus, the decrease in NDVI after typhoon events was caused by the seasonal effect with withering of vegetation. On the other hand, landslides in this area tend to occur on nonforest land because of the interventions of external forces, such as human developments and reclamation.

Geological materials produced by landslides and vegetation flushed by heavy rainfall during typhoon periods have a great effect on the amount of sediment discharge and particulate carbon discharge in the rivers. Furthermore, during typhoon periods, the amount of accumulated rainfall has a greater impact than the peak rainfall intensity on the increase of sediment and particulate carbon in rivers and on the decrease in the NDVI. Analysis of the particulate carbon from the rivers in this area revealed that in the rainy season, high strength and accumulated rainfall will lead to more sediment discharge and particulate carbon discharge in rivers. However, the particulate carbon is limited with further increases in rainfall because of the limited supply of particulate carbon in the upstream of the Tao-Cheng River.

1. Introduction

Taiwan frequently suffers loss of lives and property from landslides (Lin et al., 2001). Many studies have found that the most important factor causing landslides is rainfall (Aleotti and Chowdhury, 1999; Guzzetti et al., 1999; Dai et al., 2002; Chen et al., 2015). Wieczorek et al. (2000) pointed out that high intensities and long durations of rainfall are the important factors that induce landslides. Some studies have also used rainfall data to monitor and predict landslides (Keefer et al., 1987; Aleotti, 2004; Guzzetti et al., 2004). Given Taiwan's relatively steep terrain and the average of four typhoons per rainy season (Shieh, 2000), heavy concentrated rainfall frequently causes these geological hazards. When landslides occur, the sediment discharge of the river is affected because significant amounts of rocks, soil, and vegetation enter the river (Dadson et al., 2004). Since rocks, soil, and vegetation contain particulate carbon, they also affect the amount of particulate carbon in the rivers (Ludwig et al., 1996; Hilton et al., 2008). By analyzing sediment discharge and particulate carbon in rivers, we can estimate the output of particulate carbon and the movement of sediment. From this estimate, we can understand the distribution of particulate carbon flux in the surrounding environment, an important key for exploring the carbon cycle (Siegenthaler and Sarmiento, 1993; Stallard, 1998; Wu et al., 2007).

Lin et al. (2008) confirmed that surface erosion and landslides during the typhoon period are the main sources of surface material entering the river. Coynel et al. (2005) found that as the amount of suspended

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load in the river increases, the percentage of particulate organic carbon in the river decreases. This decrease is because of the reduction of the organic material supply caused by continual high flow erosions.

In this study, we compared the relationship between landslides and vegetation in order to discuss the effect of vegetation coverage on the possibility of landslide occurrence. In addition, to recognize changes in sediment and particulate carbon discharge after landslide materials and vegetation were flushed into rivers during different time periods, including typhoon periods, water samples from the rivers were collected and analyzed so as to monitor the overall changes in the river chemistry.

This study investigated six typhoon events that caused heavy rainfall in the study area around the catchment of the Tao-Cheng River from 1996 to 2008. These six events were: (i) Typhoon Herb (July 1996), (ii) Typhoon Toraji (July 2001), (iii) Typhoon Aere (August 2004), (iv) Typhoon Haitang (July 2005), (v) Typhoon Krosa (October 2007), and (vi) Typhoon Sinlaku (September 2008; Table 1). The landforms in this catchment were formed by the alluvial cutting of rivers. Most of the area is composed of hills, plateaus, and mountainous areas. The erosional cutting has produced a high-relief topography with various geological conditions. In addition, large differences in altitude in this area also create a vast vegetation landscape (Water Resources Agency, 1998). Therefore, this is a suitable area for discussing the distributions of landslides, vegetation, and related sediment yields during typhoon events.

2. Study area

The upstream area of the Tao-Cheng River is located on the northwest side of the Central Mountain Range in Taiwan (Fig. 1). The area is about 358 km^2. The topography slopes downward from southeast to northwest, and the difference in elevation is >2000 m. The average elevation of the study area is 1130 m, and the average slope is 31°. Because the slope is downward from southeast to northwest, the main slopes are west, northwest, north, and northeast faces. The study area has two main rivers: the Shang-ping River and the You-luo River. The Shang-ping River originates from Luchangda Mountain (elevation 2616 m) in the Hsuehshan Mountain Range. It is 44 km in length with an average slope of 1.17°. The You-luo River originates from Lidung Mountain (elevation 1913 m). It is 26 km in length with an average slope of 1.22°. These two rivers converge to become the Tao-Cheng River, and the slope decreases to 0.30°. The annual average temperature is 22.8 °C, and the annual average rainfall, mainly concentrated in May, is 2642 mm. During typhoon and rainstorm periods, the maximum flood volume can reach 4700 m^3/s, while during the dry season, the flow volume is <0.05 m^3/s (Water Resources Agency, 1998). Land use at elevations of 200 m to 2474 m in this area is mainly agriculture and forestry. The forests include bamboo groves, planted deciduous woods, planted coniferous woods, and wildwoods.

The three main formations in the study area are the Tatungshan Formation, the Shihti Formation, and the Nanchuang Formation. The Tatungshan Formation is composed of weak metamorphic thick sandstone, with a thickness mostly between 10 cm and 2 m and a uniaxial compressive strength of about 60.5 Mpa. The joint in this formation is not obvious. The lithology of the Shihti Formation is thick sandstone with thin shale and has a strength of about 46.6 Mpa. One or two joints exist in this formation. The lithology of the Nanchuang Formation is interbedded with sand and shale, and the ratio of shale is higher than that in the Shihti Formation. Its strength is about 39.3 Mpa. One joint exists in this formation.

3. Data and methods

3.1. Sediment discharge and particulate carbon analysis

The hydrological stations for observing sediment discharge and flow discharge in this study area, Shangping station (1300H014) and Neiwan station (1300H013), are located on the Shang-ping River and the You-luo River, respectively. The average flow discharge is obtained with an ultrasound device installed on a bridge over the river to automatically record the water level, and the rating curve relation between water level and flow discharge is used to obtain the flow discharge. Flow discharge and sediment concentration are measured irregularly, but roughly about twice per month. During the typhoon season (May to October), the data are measured three to four times per month. Sediment discharge is obtained by multiplying the measured flow discharge by the measured sediment concentration. Sediment concentration is calculated by processing water samples obtained by the DH-48 depth-integrated sediment sampler. When the sampler is dropped into and lifted from a river, it samples water so as to give the vertical profile of the water sample. After the sample is weighed, filtered, dried, and weighed again, the sediment concentration is calculated.

The rating curve estimation method (Walling, 1977) was used to estimate the sediment discharge from the measured flow discharge and sediment discharge data from 1990 to 2007. The formula used was:

$$E_{RC} = \frac{365}{n} \sum_{i=1}^{n} k Q_{wi}^{b} \tag{1}$$

where E_{RC} is sediment discharge (t), Q_{wi} is average daily flow discharge (m^3/s), k is constant, b is the exponential of the rating curve, and n is number of measurements.

Estimations include the following: (i) annual sediment discharge and (ii) sediment discharge during storm events. In this study, the annual sediment discharge was estimated from annual data taken from 1990 to 2007, and the sediment discharge during storm events was based on the data of five typhoon events from 1996 to 2007. As the stations in this area did not measure flow discharge or sediment discharge in 2008, we were unable to estimate the sediment discharge during Typhoon Sinlaku or the annual sediment discharge in 2008.

Water samples of 2 to 3 L were collected each time from the Shang-ping station (Shang-ping River) and the Neiwan station (You-luo River) from January 2008 to January 2009 (Table 2). Each water sample was filtered and dried to obtain the suspended load. The suspended load was then ground up to obtain a 0.25 g sample, which was then heated to 1350 °C to produce CO_2 gas. The wavelength of the CO_2 gas, measured by nondispersive infrared (NDIR), was then adjusted using the standard sample to estimate the sediment concentration, particulate carbon

Table 1
Typhoon events.

Typhoon	Dates	Maximum wind velocity (m/s)	Average daily rainfall (mm)	Maximum daily rainfall (mm)	Accumulated rainfall (mm)
Herb	1996 (07/29–08/01)	53	210.9	691.8	843.6
Toraji	2001 (07/28–07/31)	38	19.9	79.0	79.6
Aere	2004 (08/23–08/26)	48	276.9	570.3	1107.6
Haitang	2005 (07/16–07/20)	55	80.1	171.3	400.5
Krosa	2007 (10/04–10/07)	51	165.3	478.0	661.2
Sinlaku	2008 (09/11–09/16)	51	165.5	432.3	993.0