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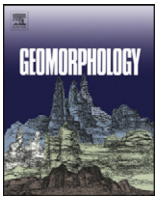

The influence of landscape configuration upon patterns of sediment storage in a highly connected river system

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ABSTRACT

Orthoimages are used to analyze the influence of valley width, channel slope, and the area of landslides that deliver sediment to valley floors upon the downstream pattern of sediment storage in the Liwu basin, eastern Taiwan. Confined valley settings dominate this steep, deeply dissected, uplifting mountainous basin. Although they occupy 82% of the whole channel network, sediment storage is limited in these reaches. Partly confined valley settings are restricted to relatively short reaches of two tributary systems. Over 95% of sediment storage in the Liwu River is found within the short alluvial section of laterally unconfined valley close to the river mouth. Lateral bars are the primary features associated with sediment storage in confined reaches (54% in total volume), while floodplains dominate the partly confined and laterally unconfined reaches (95% in total volume). Downstream patterns of sediment storage are controlled primarily by valley confinement (i.e., valley width) and landscape configuration. Channel slope and locations of contemporary landslides are not key determinants of sediment storage patterns. Sediment accumulation at confluence zones is not determined by the catchment area of tributaries or by landslide area; rather, it is determined by valley confinement of the trunk stream at the confluence and the associated downstream sequence of river types. Sediment conveyance is very effective within this highly connected river system.

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1. Introduction

Other than landscapes where solution processes are prominent, clastic sediment is the primary tool with which rivers perform erosion. The efficiency of erosion processes on the channel bed is related to the volume, caliber and hardness of sediments: if there is too much sediment, the bed is protected (buffered); if too few sediments are available, erosive activity is constrained. Hence, sediment availability and patterns of sediment storage are important determinants of the type and distribution of geomorphic process zones in river systems. Sediment availability, in turn, reflects the rate of sediment generation in any given landscape, the frequency with which sediments are mobilized and/or reworked, and the amount of sediments stored in accommodation spaces along the valley floor. Hence, sediment storage is a key component in the analysis of sediment budgets, as it is the critical link between erosion rate and sediment yield (Straumann and Korup, 2009). Quantifying the volume of sediment storage is an important issue in catchment-scale (e.g., Schrott et al., 2003; Houben et al., 2006; Otto et al., 2009; Straumann and Korup, 2009; Smith et al., 2011) and reach-scale analyses (e.g., Larsen and Santiago-Román, 2001; Kasai et al., 2005; Lancaster and Casebeer, 2007; Smith and Dragovich, 2008).

Patterns of sediment storage also influence the capacity of a river to adjust (i.e., sensitivity; see Brunsden, 2001; Fryirs et al., 2009) and transfer materials (i.e., connectivity; see Harvey, 2001; Hooke, 2003; Fryirs et al., 2007a,b). Connectivity reflects the way in which different landscape compartments fit together in a catchment (i.e., landscape configuration; see Brierley et al., 2006). Connectivity between compartments influences river responses to external factors (e.g., climate change, tectonic effects, and land use change) and associated patterns and rates of morphological adjustment within a catchment, thereby influencing the evolutionary trajectory of a river (Brierley and Fryirs, 2009; Fryirs et al., 2009; Surian et al., 2009; Jain and Tandon, 2010). Storage elements may buffer the effects of large runoff events, introducing lags into otherwise simple balances between sediment input and output (Marutani et al., 1999). Collectively, understandings of these relationships can be applied to sediment disaster mitigation and river management (see Brierley, 2010a).

Patterns of sediment storage vary markedly in differing landscape settings and catchments. In low relief, low drainage density terrains, extensive sediment storage may form impediments to sediment conveyance in 'disconnected' landscapes (see Fryirs et al., 2007b). In these low energy settings, sediment conveyance is restricted to episodic, infrequent, large magnitude events. Residence times of sediment stores may extend over tens or hundreds of thousands of years. By contrast, incision, accentuated relief, and dissected terrains that result from tectonic uplift generate highly connected landscapes, with effective and efficient sediment delivery from hillslopes to valley

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floors via landslides (lateral connectivity) and thence downstream along steep and narrow confined valleys (longitudinal connectivity) (Snyder et al., 2003; Brierley et al., 2011).

The eastern Central Range of Taiwan, located at the convergent plate boundary between the Philippine Sea oceanic plate and the Eurasian continental plate, is a typical highly connected landscape. Uplift rates are high, averaging 5–7 mm a^{-1} (Liew et al., 1990), while average erosion rates are approximately 3–7 mm a^{-1} (Dadson et al., 2003). The region has a subtropical climate with mean annual precipitation of 2500 mm and an average of 3.7 typhoons per year (Wu and Kuo, 1999). Recurrent seismic and typhoon events in these high relief terrains result in frequent landslides and extremely high sediment yield, extending beyond 10,000 t/km^2/yr for river systems in eastern Taiwan (Milliman and Syvitski, 1992). Landslides are the dominant source of sediment for rivers extending from the Central Range (Hovius et al., 2000). Inside the mountain belt, valley floors are narrow with limited space for alluviation. However, high rates of sediment supply from hillslopes cause extensive gravel mantling of channel beds, despite active incision through rock (Benda and Dunne, 1997; Whipple, 2004; Turowski et al., 2008a). In addition, poorly sorted gravels and boulders are stored in floodplain pockets, which are preserved behind bedrock spurs or accumulations of wood (Brierley and Fryirs, 2005). To date, understanding of controls upon these pockets of stored materials, and associated implications for connectivity of sediment flux, has received limited attention (Carling, 2006).

At the catchment scale, sediment storage increases as channel slope and stream power decrease (Church, 2002). However, Macnab et al. (2006) and Taylor and Kite (2006) showed that local controls such as variability in valley width and occurrence of confluence zones also influence patterns of sediment storage, as the spatial distribution of accommodation space disrupts systematic catchment-wide relations (see also Rice and Church, 1998; Benda et al., 2003; Rice et al., 2006). Besides, landslides are an additional control upon patterns of sediment storage in tectonically uplifting landscapes (Benda and Dunne, 1997), potentially creating a cascading sequence of intramontane storage units such as alluvial flats or debris terraces (Korup, 2005). Indeed, Hovius et al. (2000) considered that sediment flux of mountain ranges is controlled by the mode and rate of hillslope mass wasting and by the transport capacity of the channel network.

Systematic analysis of controls upon catchment-scale sediment storage and flux builds upon appraisals of bedrock and alluvial compartments of a river network (Wohl, 2010). The River Styles framework (Brierley and Fryirs, 2005) provides a geomorphic tool for appraising the influence of landscape setting upon catchment-scale patterns and linkages of river types. By extension, it can be used to appraise geomorphic controls on sediment flux (Fryirs and Brierley, 2001, 2010; Fryirs et al., 2007a, 2009; Brierley et al., 2011). The entry point into identification of a River Style is the valley setting. Valley confinement controls the capacity of the channel to adjust over the valley floor, determining patterns of sediment storage and reworking. It not only determines the size of accommodation space, it also influences variability in hillslope–channel relationships across a catchment. Building upon a hypothesis that valley confinement is a key control upon the spatial distribution of sediment storage in a catchment, and resulting connectivity relationships fashion the pattern and rate of sediment flux, this study applies the River Styles framework to interpret the influence of valley width, channel slope, and the area of landslides upon the downstream pattern of alluvial sediment storage in the Liwu basin, eastern Taiwan.

2. Regional setting

The Liwu River basin flanks the Central Range of Taiwan. It drains from the main divide (~3500 m asl) to the Pacific Ocean, with more than 90% of whole catchment area >1000 m (Chang et al., 2000). Given its very short length (~60 km), the river has a steep channel slope (~0.05). Mean annual precipitation is around 2200 mm. Precipitation rates as high as 600 mm/d have been reached during typhoon passage (Schaller et al., 2005). This ~616 km^2 of steep terrain is underlain mainly by schist, marble, and gneiss (see Fig. 1). These Palaeozoic and Mesozoic rocks underwent considerable deformation during the Cretaceous and Tertiary as a result of the complex tectonic settings (Petley, 1998). Preferential weathering of schist exerts a primary control upon drainage patterns. Permian marble (metamorphosed limestone) forms most of the extremely high cliffs found along the gorge. Considerable faulting and jointing induces many small rockfalls. High uplift rates and large magnitude climatic events have created the spectacular Taroko Gorge, a 600 m deep ravine carved into the high strength marble (Petley, 1998).

Based on fission track measurement, Brunsden and Lin (1991) proposed that the average rate of uplift has been approximately 5.5 mm a^{-1} over the last 500 ka in the Central Range. Subtracting the current rate of denudation of 5.0 mm a^{-1}, the net rate at which the gorge would be created is 0.5 mm a^{-1}. Short term geodetic surveying data showed the rate of contemporary uplift is 15.2 mm a^{-1} in the marble area but 3.2 mm a^{-1} in schistose area (Liou and Chang, 2009). Fission track estimates of rock exhumation showed an erosion rate of 3 to 5 mm a^{-1} over the last 2 Ma (Liu et al., 2001; Willett et al., 2003). Cosmogenic nuclide calculation revealed that the average incision rate of Taroko Gorge has been 26 mm a^{-1} over the last 6.5 ka, indicating that the Holocene incision rate was considerably faster than the Quaternary average (Schaller et al., 2005). Catchment-wide erosion rate derived from decadal sediment load gauge data is 12.5 mm a^{-1} (Dadson et al., 2003). Annual measurements of fluvial bedrock wear at selected sites showed an averaged wear rate of 3.4 mm a^{-1} in schists (Hartshorn et al., 2002).

Quaternary terraces with thick gravel deposits lie up to 200 m above the contemporary channel bed, upstream and downstream of the Taroko Gorge, attesting to episodic aggradation prior to rejuvenation in the late Holocene (Chyi, 1994; Petley and Reid, 1999). Incision has been accompanied by valley widening during large floods, while thalweg lowering is driven by intermediate discharges (Hartshorn et al., 2002). Turowski et al. (2008b) concluded that the partitioning of erosion in the channel is set by the balance between the sediment load and the transport capacity of the river. Hanging valleys in the Liwu River are considered to reflect a pulse of incision along the trunk stream that outpaced tributary responses, such that the gradients at tributary mouths pass a threshold value beyond which erosional efficiency declines, giving rise to a mismatch between trunk and tributary erosion rates (Wobus et al., 2006). Similar results have been found in other uplifting zones (e.g., Crosby and Whipple, 2006; Cook et al., 2009).

Most tributaries drain predominantly from schist terrains with slate, phyllite, and sandstone interbeds in the headwaters (Fig. 1). The biggest tributary Taosai originates from mountain >3000 m then merges with the Siaowaheier and Sikela, and joins the Liwu River at Tianxiang. The Shakadang is a unique tributary which drains from a lower elevation (~2000 m), flowing primarily within gneisses and marble, joining the Liwu trunk stream close to Taroko. The Liwu River can be differentiated into upper and lower gorges. The hillslopes downstream of Tianxiang are much steeper than upstream.

Flow discharge of the Liwu River at Lushui Station, about 1.5 km upstream of the entrance to the Taroko marble gorge, show a mean annual discharge of 2.33×10^6 m^3 km^{-2} from 1956 to 2009 (upstream drainage area is 435 km^2). Daily average discharge is 32.1 m^3 s^{-1}, ranging from 44 m^3 s^{-1} in the wet season (between 25 and 65 m^3 s^{-1}, from May to October) to 20 m^3 s^{-1} in the dry season (between 15 and 25 m^3 s^{-1}, from November to April). Discharge during typhoons can exceed the long-term daily average by an order of magnitude or more. Typhoon Andy in 1982, a 50 yr flood with a peak discharge of 2593 m^3 s^{-1}, is the largest event in recorded history. Another recent typhoon, Billis in 2000, had a peak discharge of

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