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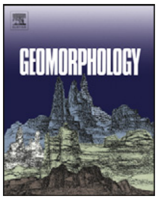

Monitoring channel responses to flood events of low to moderate magnitudes in a bedrock-dominated river using morphological budgeting by terrestrial laser scanning

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ABSTRACT

Changes to channel morphology reflect geomorphic work by flood events of differing magnitude and frequency. Advances in remote sensing and digital terrain processing now allow for sophisticated analysis of spatial and temporal changes in erosion and deposition. Although the morphological budgeting approach using digital elevation models of difference has been widely applied to track volume estimation of changes to erosion and deposition over time, appraisals of geomorphic effectiveness in high-energy confined and partly confined channels are still lacking. This study applied terrestrial laser scanning to monitor three reaches of the Liwu River, a bedrock-dominated river in eastern Taiwan, from 2009 to 2012, to investigate channel responses to flood events of low to moderate magnitude and appraise their geomorphic effectiveness. Variability in geomorphic effectiveness reflected valley confinement and the composition/configuration of geomorphic units on the channel bed. Annual low magnitude flood events reworked gravel and sand deposits, creating local scour and fill (<0.5 m in depth) in the confined and in the unconfined reaches. Lower unit stream power in the wider, less-confined reach resulted in longer intervals between phases of boulder reworking relative to the confined reach. Bedrock exposure and stable sediment storage units in the confined reach restricted changes to channel pattern. Successive moderate and low magnitude events in 2012 created an evident erosion of 7556 m^3 (~1 m in depth) and were able to modify channel configuration in partly confined and unconfined reaches. Frequent changes of scour/fill position on the channel bed indicate that the Liwu River is highly sensitive to flood events of low to moderate magnitude. This reflects an active orogenic river system that is characterized by a steep channel and narrow valley floors with limited accommodation space but abundant sediment.

1. Introduction

Changes to channel morphology reflect geomorphic work by flood events of differing magnitude and frequency. The original conceptualization proposed by Wolman and Miller (1960) suggested that channel morphology is determined predominantly by frequent discharge events (mean annual or bankfull stage, 2.33-year recurrence interval) rather than infrequent large events. Subsequent reappraisals indicated that the geomorphic effectiveness of flood events of a given magnitude varies markedly in differing environmental settings (Wolman and Gerson, 1978). Indeed, rivers in certain localities preferentially adapt their form to infrequent, high magnitude events: e.g., bedrock-dominated rivers (Baker, 1977) and some gravel-bed rivers (Heritage and Milan, 2004). Elsewhere, variability in flood magnitude (expressed using measures such as the coefficient of variability) is a critical determinant of geomorphic effectiveness as infrequent high magnitude events are able to rework large amounts of sediment bringing about dramatic changes to channel and floodplain features in some instances (Finlayson and McMahon, 1988; Nanson and Erskine, 1988). Materials transported and deposited during any given event are made available for entrainment and transport by subsequent floods. Hence, sequences of floods and the duration of the relaxation period between events may be critical determinants of geomorphic effectiveness (e.g., Nanson, 1986; Kochel, 1988). In supply-limited channels, the amount of work undertaken by a rare large flood and subsequent smaller floods during the relaxation phase may exceed the cumulative work undertaken by bankfull-stage floods (Milan, 2012).

The impact of floods on channel morphology is highly variable. While some major floods produce catastrophic change (e.g., Baker, 1977; Miller, 1995; Milan, 2012), other events of a similar magnitude have little geomorphic impact (e.g., Costa and O'Connor, 1995; Magilligan et al., 1998). In part this reflects preconditioning factors, such as the preceding history of flood events that may have scoured away or deposited large volumes of sediment in a given reach (e.g., Johnson and Warburton, 2002; Gray et al., 2014). Alternatively,

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changes to channel boundary conditions such as removal of riparian vegetation or wood may exert critical (threshold-induced) changes in the geomorphic effectiveness of flood events of a given magnitude (e.g., Brooks and Brierley, 1997; Brooks et al., 2003). Floods of similar magnitude and frequency may produce dissimilar morphological response, even within the same catchment (Nanson, 1986; Magilligan, 1992; Fuller, 2008; Thompson and Croke, 2013). Downstream patterns of river types and their connectivity influence sediment availability during any given event (see Hooke, 2003; Fryirs et al., 2009). Fuller (2008) concluded that the spatial discontinuity of channel transformation relates to valley floor and channel configurations. Similarly, Thompson and Croke (2013) found dramatic differences in geomorphic responses between two adjacent reaches of contrasting valley configuration. The confined reach was net erosional, while the unconfined reach was net depositional. Higher stream power in confined channels may produce greater geomorphic work than wider channels (see Fuller, 2007). In summary, geomorphic impacts of flood events are spatially discontinuous and reach specific.

Morphological budgeting using information gained from monitoring three-dimensional channel change provides an increasingly valuable tool in process-based evaluation of sediment flux (Ashmore and Church, 1998; Ham and Church, 2000). Advances in remote sensing and digital terrain processing and increased analytical capacity now allow for sophisticated appraisals of spatial and temporal changes in erosion and deposition. Digital elevation models (DEMs) of Difference (DoD) now support analyses of net landscape change for morphological budgeting across a range of spatial scales (Heritage and Hetherington, 2007; Croke et al., 2013). Reach-scale DEMs can be derived using various approaches, including photogrammetry (Lane et al., 1996; Heritage et al., 1998; Westaway et al., 2003), total station (Eaton and Lapointe, 2001; Fuller et al., 2003b), RTK-dGPS (Brasington et al., 2000; Milan, 2012; Fuller and Basher, 2013), airborne Lidar (Croke et al., 2013; Thompson and Croke, 2013), and terrestrial laser scanning (Heritage and Hetherington, 2007; Brasington et al., 2012; Rychkov et al., 2012; Williams et al., 2013). Advantages of terrestrial laser scanning (TLS) include its accuracy (subcentimeter- to centimeter-scale elevation error) and efficiency in terms of field data collection and post-processing (Heritage and Hetherington, 2007). The TLS has been applied to survey the Earth surface in a range of geomorphological settings such as sand dunes (Nagihara et al., 2004), karst landforms (Siart et al., 2013), cliff erosion rates (Gulyaev and Buckeridge, 2004), stream bank retreat (Resop and Hession, 2010), hydraulic biotope mapping (Milan et al., 2010), bedrock bedforms (Wilson et al., 2013), gravel bed roughness (Heritage and Milan, 2009), and braided river evolution (Wheaton et al., 2010; Williams et al., 2013).

Although the morphological budgeting approach using DoD has been widely applied to estimate volumes of erosion and deposition, the appraisal of geomorphic work in highly dynamic channels is still lacking. It is required to assess dynamics of high-energy, confined and partly confined channels. Rivers in Taiwan are subject to typhoon-induced flooding events that occur 3–4 times every year on average (Wu and Kuo, 1999). Recurrent typhoon and seismic events in these high relief terrains result in frequent landslides and extremely high sediment yield, extending beyond 10,000 t km^2 a^{-1} for river systems in eastern Taiwan (Milliman and Syvitski, 1992). High flow discharge and high sediment load during typhoon passage result in significant variability in channel bed morphology. Hence, in this setting, frequent annual flood events of low to moderate magnitude may play an important role in shaping the channel morphology. This study applied TLS to monitor three reaches in the Liwu River, a bedrock-dominated river in eastern Taiwan, from 2009 to 2012, to investigate channel responses in confined/unconfined reaches to flood events of low to moderate magnitude and appraise their geomorphic work and effectiveness.

2. Study sites

The Liwu basin drains from the Central Range of Taiwan (~3500 m asl) into the Pacific Ocean over a short distance of around 60 km with a very steep channel slope (~0.05 m m^{-1}) (Fig. 1). Over 90% of the catchment area of 616 km^2 lies at elevations above 1000 m asl (Chang et al., 2000). The regional lithology is comprised of Palaeozoic and Mesozoic schist, marble, and gneiss that underwent considerable deformation during the Cretaceous and Tertiary (Petley, 1998). Considerable faulting and jointing induces many small rockfalls. Permian marble forms most of the extremely high cliffs along the gorge. High uplift and incision rates have created the spectacular Taroko Gorge, a 600-m-deep ravine carved into the high strength marble (Petley, 1998) (Fig. 1). Taroko National Park was established in 1986 to protect the unique landscape and its ecological environment. This steep mountainous terrain is primarily covered by forest.

Mean annual precipitation in the area is ~2200 mm. Precipitation rates as high as 600 mm d^{-1} have been reached during typhoon passage (Schaller et al., 2005). Flow discharge of the Liwu River has been recorded at only one long-term gauge station (Lushui) since 1956 (Fig. 1, the upstream drainage area is 435 km^2). At Lushui the average daily 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) (Kuo and Brierley, 2013). Discharge during typhoons can exceed the long-term daily average by an order of magnitude or more. For example, Typhoon Billis in 2000 had a peak daily discharge of 2240 m^3 s^{-1}. Estimated data indicated that ~90% of the total sediment discharge and 15% of the total water discharge of that year occurred over 5 days during this flood event (Hartshorn et al., 2002). The index of variability of peak annual discharges (the standard deviation of the logarithms of flows) is 0.40, which is much higher than the world average of 0.15 (Finlayson and McMahon, 1988). This indicates a great variability in flood magnitude. Over the past 30 years, the frequency of flood events of low (100–500 m^3 s^{-1}), moderate (500–1000 m^3 s^{-1}), and high magnitude (>1000 m^3 s^{-1}) is 2.5, 0.6, and 0.3 times per year, respectively (Kuo and Brierley, 2014). Compared to the long-term average, the study period (2009–2013) had a lower frequency of floods (1.75, 0.25, and 0 times per year for low, moderate and, high magnitude events, respectively).

Most flood events in this area are induced by typhoons with a return period of 1–2 year(s). Fig. 2 shows the daily discharge and available sediment load data derived from the sediment concentration sampling record at Lushui station during the study period, with typhoon events labeled. The largest event during this period was Typhoon Saola, which had a return period of 3.5 years and a peak daily discharge of 853 m^3 s^{-1}. This event had a high sediment load of 0.16 MT d^{-1} (0.89 percentile based on a 16-year sampling record). Sediment load of similar magnitude was recorded in typhoon Fanapi in 2010, an event with a recurrence interval of 1.8 years.

Sipan Dam with a height of 15 m was constructed for hydroelectric power generation at the end of the gorge section in 1965 (Fig. 1). This regulates downstream flow discharge and forms a sediment trap (Chang et al., 2000).

Confined valley settings occupy over 80% of the whole channel network and dominate this steep, deeply dissected, uplifting mountainous basin. 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 (Kuo and Brierley, 2013). Thin, patchy mantles of alluvium persist along bedrock reaches despite active incision through rock (Whipple, 2004). Landslides are a major source of sediment in tectonically active mountain belts (Dadson et al., 2004). In the Liwu basin, steep terrain and fragile geology, along with frequent flood and seismic events, create significant landslide activity in the upper catchment. High hillslope–valley floor and longitudinal connectivity prompt efficient sediment transport to downstream reaches (Kuo and Brierley, 2014).