Invited Commentary

Towards an Understanding of Catchment-scale Sediment Dynamics: Cascades & Connectivity in Steepland Systems

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Steepland terrain is a characteristic of the Pacific Rim which must be better understood to mitigate and reduce risk associated with the cascade of sediment through short, steep, energetic catchments. The natural laboratory of New Zealand’s East Coast ranges provides examples to improve the understanding of linkages between slopes and channels in the upper part of steepland river systems at this critical point in the sediment cascade. These examples illustrate an array of processes contributing abundant sediment in concert with intrinsic and extrinsic controls conditioning catchment connectivity. Once generated from hillslopes, the residence time of alluvium is contingent upon the efficacy of erosion and transfer processes moving sediment along the conveyor. Impacts of point sources of sediment delivery may be long-lived.

Key words: gully erosion, slope-channel coupling, headwater stream, New Zealand

1. INTRODUCTION

Many Pacific Rim watersheds are characterised by steepland terrain. These short, steep catchments convey sediment very effectively in well-connected cascades from source to sink. The nature of these catchments means that processes such as landslides and flooding often happen very rapidly and with little warning. These environments render human populations occupying this terrain very vulnerable to sediment disasters. High population densities bring people directly into the pathway of high energy natural processes and extreme events. The results of such an intersection of people with these processes can be tragic: in 2009 a single landslide triggered by Cyclone Morakot at Shiaolin in Taiwan killed an estimated 450 people. Even in regions of low population density, deaths from such events occur: during preparation of this paper a fatality occurred in a sparsely populated region of New Zealand’s South Island as a much smaller landslide destroyed a house near the Abel Tasman National Park. New Zealand’s worst natural disaster (excluding earthquakes) occurred in 1953 when a lahar from Mt Ruapehu destroyed a railway bridge at Tangiwai, killing 151 people.

This paper uses examples from New Zealand’s steepland landscape as a natural laboratory to endeavour to better understand the sediment cascade and connectivity in this hazardous environment. Lessons learned in this part of the Pacific Rim can be applied elsewhere to mitigate the hazard in areas of greater population density and exposure to risk. In particular, this paper focuses on conditions in the upper parts of catchments that amplify or modulate sediment delivery in concert with climatic and tectonic drivers of erosion processes. Connectivity in the upper parts of steepland catchments along the eastern margin of New Zealand’s North Island is examined using annual to seasonal field-based measurements and aerial photo analysis. The objective of this research is to improve the understanding of linkages between slopes and channels in the upper part of steepland river systems at this critical point in the sediment cascade.

2. SEDIMENT CASCADES AND CONNECTIVITY IN STEEPLAND TERRAIN

Effective management of sediment transfers and mitigation of sediment disasters in steepland catchments requires an understanding of transport pathways, sources and sinks of this material as it is moved from slope to sea along the ‘jerky conveyor’ [sensu Ferguson, 1981]. This is an incredibly
complex task, given the array of factors controlling sediment sources, sinks and pathways within any single catchment [e.g. Fryirs, 2013]. Steepland catchments are no exception, although the opportunity for sediment storage may be more limited than in larger catchments, nevertheless the conveyance remains complex. Steepland has been defined by Gomez et al. [2010] as, “terrain in which hillslopes have a gradient >7° and are mantled by shallow, immature soils that support natural vegetation, forest or pasture”. These catchments are significant generators of sediment via processes including landsliding and gullyng [e.g. Parkner et al., 2007; Jones and Preston, 2012; Marden et al., 2012]. Sediment yield from these environments is among the highest on Earth per unit area, for example sediment yield from the Waiapu River in the East Coast Region of New Zealand equates to 20,520 t/km²/yr [Hicks et al., 2000]. The elevated erosion in these environments is attributed to their active tectonic setting and erodible terrain, as well as exposure to tropical and mid-latitude storms, and the compromise of catchment integrity by human activity, in particular deforestation [Nakamura et al., 2000; Gomez et al., 2010].

At the head of the steepland sediment cascade, gully erosion may be particularly significant [e.g. De Rose et al., 1998; Hicks et al., 2000; Kasai et al., 2001; Gomez et al., 2003a; Page et al., 2008; Marden et al., 2012]. Sediment supplied from gullies tends to be more persistent than material delivered by shallow landsliding in this terrain, since gullies, already established, are activated by small, frequent rainstorms, whilst landsliding is activated during less frequent, high magnitude events [Hicks et al., 2000; Jones and Preston, 2012]. Parkner et al. [2007] identified a range of processes operating in gully environments in the Waiapu catchment, distinguishing between slide complexes and gullies per se. These processes combine in large systems, such that gully erosion is enhanced by mass movement processes. In these systems, mass movements tend to comprise debris flows and both deep seated and shallow sliding, which may be (re)activated by gullyng within the complex as part of intrinsic feedback mechanisms (e.g., slope undercutting), as well as high magnitude rainstorms [Fuller and Marden, 2008]. Large amphitheatre-like features develop and the combined mechanisms give rise to gully-mass movement complexes, where sediment is generated both by fluvial incision and mass movement [Betts et al., 2003]. In the steepland East Coast Region of New Zealand’s North Island, which is prone to gullyng due to the underlying highly weathered and crushed Cretaceous shales and Tertiary sand/mudstones, more than half of the sediment load of the Waipaoa and Waiapu Rivers is derived from these gully-mass movement complexes [Marden et al., 2005; Page et al., 2008]. De Rose et al. [1998] suggest that ~3% of the annual sediment load of the Waipaoa River (15 Mt) is derived from a single gully mass movement complex known locally as Tarndale Slip (Fig. 1). The significance of this Tarndale gully complex to the Waipaoa sediment cascade has increased as other gully complexes have been shut down by reforestation since the 1960s [Gomez et al., 2003b; Marden et al., 2012]. Landscape components in this terrain are recognised as being strongly coupled [Fryirs et al., 2007]. However, connectivity may be disrupted by the presence of buffers, such as alluvial fans, which develop at the outlet of large gullies [e.g. Betts et al., 2003]. These features amplify or modulate sediment supply from the gully system to the trunk stream network as they are repeatedly cut and filled respectively [Fuller and Marden, 2010].

Fig.1 Tarndale gully-mass movement complex, Waipaoa catchment, New Zealand: catchment location in New Zealand (left), LiDAR derived terrain model of gully labelled T at left (middle), photograph of gully complex looking south across the headwall (right).
Elsewhere in the eastern ranges of New Zealand’s North Island gullying may be less significant in generating sediment at the head of the cascade. In the south-eastern Ruahines the bedrock is a more coherent Mesozoic greywacke and argillite of varying decomposition [Mosley, 1978] and the dominant forms of erosion identified by Marden [1984] are shallow debris avalanches and debris slides, which typically occur on slopes steeper than 20° [Riedler, 2012]. Deeper-seated slope failures occur in crush zones associated with faulting [Marden, 1984]. The steepness of this terrain ensures a high degree of slope-channel coupling, such that on-slope storage is minimal and the sediment cascade is therefore less effectively buffered at the slope-channel nexus in this environment. This has implications for sediment management at these sites which is discussed in this paper.

3. SITES AND METHODS

The first example in this paper focuses on connectivity between the Tarndale gully-mass movement complex and the stream network (Fig. 1). This focuses on very short term changes elucidated using high resolution surveys between 2004 and 2011. Detailed surveys of a large gully-mass movement complex and its associated fan in the upper Waipaoa catchment (Fig. 1) used a combination of ground survey, LiDAR and Terrestrial Laser Scanning between 2004 and 2011. These data were used to generate digital elevation models (DEMs) to assess morphological change and sediment transfers between successive survey dates, from which sediment delivery processes and connectivity were inferred and quantified within this low order catchment.

The second example assesses connectivity over a longer timeframe and at a lower resolution, but greater spatial extent, using headwater tributaries in the south-eastern Ruahine Range some 250 km farther south along the North Island’s axial ranges (Fig. 2). Here a series of small headwater catchments in the south-eastern Ruahines was investigated using aerial photo assessment to quantify the spatial extent of slope instability (Fig. 2). This in turn was compared with channel dynamics using morphological budgeting at the catchment outlet of selected systems.

4. WAIPAOA

Seasonal surveys of the fan emanating from the Tarndale Gully revealed complex behaviour which superficially appeared to be driven by overall wetness associated with rainstorm frequency and intensity, but subsequently also indicated a

![Fig. 2 Southeastern Ruahine catchments: location (left), example catchment: Tamaki (right), with stream dynamics at circled outlet indicated beneath (B & C), photograph looking northwest up Car Park Creek, tributary No.8 on map to right (middle).](image-url)
conditioning by intrinsic slope and gully dynamics [Fuller and Marden, 2011]. Enhanced resolution of the behaviour of the fan afforded by analysis of DEMs presents a picture of complex, rapid, a-seasonal cutting and filling (Fig. 3). Sediment generated from the Tarndale gully complex causes rapid infilling. This sediment is conveyed down-fan and most effectively delivered to the Te Weraroa Stream by trimming of the lower fan during high flows. This means the upper part of the fan may be infilled at the same time as the downstream portion incises, since trimming produces a headcut, which incises the downstream section of the fan, evacuating stored sediment to the mainstem stream network of the Waipaoa. This in turn steepens the profile of the fan, facilitating incision of the upper section and transfer of sediment through this system. The behaviour of the lower fan is thus conditioned both by interaction with the Te Weraroa Stream and sediment supplied from up-fan.

Of significance for connectivity in this landscape is the operation of two critical junction switches, (i) at the gully-fan nexus, (ii) at the fan-stream nexus. This has been described in detail by Fuller and Marden [2011]. During the period of study, the fan has acted as a buffer for sediment supplied by the gully, serving to alternately modulate and amplify sediment delivery according to inputs and outputs at its interface with the gully and stream respectively and the operation of these junction switches.

Overall, progressive aggradation of the fan surface [Fuller and Marden, 2010] indicates a measure of buffering between the gully and fan is taking place. In contrast with other systems in this environment studied by Marutani [1999], Kasai et al. [2001] and Kasai [2006], the Tarndale Fan is not showing any sign of longer-term degradation, primarily because the gully system remains extremely active. This activity was investigated further using Terrestrial Laser Scanning (TLS) and LiDAR surveys in an attempt to quantify the processes operating in the gully-mass movement complex itself. The key processes delivering sediment from the headwall of the gully to the fan are gullyling and rilling, which may be primed by larger-scale, deeper seated landsliding (Fig. 4). However, it is difficult to separate some of these processes, since sediment is conveyed into the gullies and rills by small-scale shallow slides sourced at the top of the slope. This material, accumulating in the rills cut into the fretted gully

headwall (cf. Fig. 1) is in turn a source of small scale debris flows and slurries conveying sediment directly from the gully to the fan. Similarly, larger scale, deep seated landslides from other parts of the gully-mass movement complex may yield debris flows directly to the fan, however such events are relatively rare in the study period and less significant in terms of volumetric contribution to the sediment cascade than smaller scale, but far more frequent processes [Taylor et al., in prep]. Inevitably, it is difficult to be precise about the processes operating in this environment. Quantification of gross volumetric change for the entire gully and fan system using TLS and LiDAR derived DEMs does however permit an assessment of the efficacy of the fan as a buffer. Results from Taylor et al. [in prep] suggest that in some years a maximum of 49% of the sediment supplied from the gully to the fan may be stored (buffered). These results also indicate that a volume of sediment equivalent to that delivered across the gully-fan junction may be yielded to the stream, implying a 100% connectivity and zero buffering. It is however likely that the volume of sediment crossing the fan-stream junction is in fact sourced from the lower fan, indeed in one period (2008-2010) more sediment was removed from the fan than was supplied by the gully. This demonstrates the complexity of sediment dynamics in steepland headwater environments on a seasonal and annual basis and emphasises the complex role played by buffers such as alluvial fans in these environments in terms of amplifying and modulating sediment supply. It is therefore important to take into account their presence and potential contribution to steepland sediment cascades.

5. RUAHINES

Analysis of aerial photographs in the south-eastern Ruahines combined with an appraisal of stream channel dynamics in five catchments (Fig. 2) assessed the extent of catchment connectivity and its impact on stream dynamics [Schwendel and Fuller, 2011]. A wide range of channel dynamics is observed in essentially adjacent catchments and the reasons for this diversity of behaviour were...
attributed to varying degrees of catchment erosion and connectivity [Schwendel et al., 2010]. However, the most active stream channels were not in those catchments with the greatest degree of coupled slope erosion. Connectivity was greatest in the upper Waipawa catchment, but while sediment transfers were not insignificant at this catchment outlet, higher quantities of sediment were eroded and deposited in apparently less-well connected systems, notably the Tamaki catchment. This may relate to the relative intrinsic sensitivity of these reaches to flood flows: if the Tamaki is more sensitive than the Waipawa it is likely to be more responsive and dynamic.

However, equally important, and often overlooked in New Zealand’s steepland sediment cascades is the role played by sediment stored in-channel. This is significant in many Ruahine catchments, which underwent severe aggradation in response to major catchment disturbance triggered by Cyclone Alison in 1975. It has been estimated that in the 1970s as a whole, ~2,807,426 m³ of sediment was delivered from landsliding to catchments in the SE Ruahines [Riedler, 2012]. More specifically, 322,000 m³ was delivered from landslides in the Tamaki catchment between 1974 and 1977 [Riedler et al., 2013]. Steep tributaries in the Tamaki catchment have substantial quantities of sediment stored in the steep valley floor upstream of the mapped channel sites. Reworking of this material, combined with strong reach-to-reach connectivity, means that this legacy sediment constitutes an important proportion of the contemporary sediment load in these systems. These catchments are therefore continuing to respond to an event that occurred some 40 years previously. Assessment of connectivity in these south-eastern Ruahine streams reveals the significance of system history for contemporary stream dynamics and reinforces the concept of landscape memory introduced by Brierley [2010].

6. DISCUSSION & IMPLICATIONS FOR MANAGEMENT OF STEEPLAND SEDIMENT CASCADES

To understand catchment-scale sediment dynamics in steepland systems, we must recognise the role played by both short-term, seasonal events and processes, as well as longer term extreme events in conditioning sediment delivery and transfer. This recognition of spatial and temporal variability in catchment connectivity is vital to grasp if management and mitigation is to be effective. Macklin et al. [2010] have argued that effective slope–channel coupling renders steepland rivers responsive to both short- and longer-term environmental changes that enhance sediment production in these catchments and the examples from the Waipaoa and Ruahines demonstrate this. The impact of sediment and flood-producing events in a catchment is conditioned by the degree of coupling between landscape units within that catchment, such that well-coupled systems effectively transmit sediment generated by these events from slopes to channels, generating a response to that event [Harvey, 2001]. Catchment connectivity may amplify or modulate the nature and spatial propagation of that response, with the operation of buffers, barriers, blankets, and boosters [Fryirs et al., 2007]. The Tarndale system demonstrates the complexity of this amplification and modulation via critical junction switches in a highly sensitive environment. Conversely, systems in the Ruahines were overwhelmed with sediment in the 1970s, which is still contributing to the sediment cascade in these catchments.

The question of residence time and legacy sediment in steepland systems therefore needs to be taken into account in managing the steepland sediment cascade. Phillips et al. [2007] suggest that in the Waipaoa the average residence time of alluvium exceeds 100 years. This might be surprising given the degree of activity observed at Tarndale, however, sediment supply from such components of the Waipaoa system exceeds transport capacity and the catchment regime is aggradational [Phillips et al., 2007]. This is seen in microcosm in the Tarndale system itself: while responding rapidly to sediment supply variability from the gully complex and knickpoint incision triggered by distal fan trimming, the fan has continued to aggrade. However, the efficiency of the Waipaoa in conveying suspended sediment should not be underestimated, since only ~2% of the total suspended sediment load is sequestered in the floodplain [Phillips et al., 2007]. Similarly, in the Ruahines, these systems have demonstrated an aggradational response. Residence time in these small, steep catchments appears to be longer than equivalent systems elsewhere. For example, Kasai et al. [2004] suggested that following major aggradation in response to a Typhoon in 1993, the channel system in Oyabu Creek had essentially recovered in ~7 years. The difference in catchments such as Tamaki in the Ruahines may simply be the extent of sediment delivered to the system, completely overwhelming the channel. In addition, landsliding in these catchments has continued post Cyclone Alison in 1975, such that sediment supply
is ongoing [Riedler et al., 2013] and not allowing system relaxation. This is similar to the situation observed by Kasai et al. [2005] in the Weraamaia catchment in the East Coast Region of New Zealand, where recovery to a 1938 storm was disrupted by Cyclone Bola (100 year ARI) in 1988. Here relaxation time is in the order of ~70 years. Inevitably, relaxation and recovery pathways are conditioned by subsequent disturbance events and adjacent (sub)catchments may demonstrate different pathways reflecting spatial and temporal variability in sediment transfer thresholds [Fryirs et al., 2007], thus Tarndale continues to aggrade, while Oil Springs, a few kilometres away, degrades [Marutani et al., 1999]. Ultimately, system configuration and connectivity determines system behaviour and response [Fryirs, 2013].

Steepland sediment cascades are rightly perceived as sensitive and responsive to disturbance [Macklin et al., 2010], rapidly conveying products of erosion through them at times in a highly destructive manner. Management of steepland sediment cascades therefore needs to account for complexity in behaviour of these systems, conditioned by unique threshold conditions in each catchment. In addition, longer-term residence of sediment and potentially long recovery pathways within these systems must also be recognised. The impacts of an extreme event, or major source of erosion in a catchment, may be enduring beyond the timeframe of a decade and potentially last far longer. To take proper account of this in management requires longer term planning, as well as recognition of the complexity of behaviour in these high energy systems, such that long-term projected recovery and system relaxation is also readily disturbed by the recurrence of an extreme event.

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