Conceptualization of sediment flux in the Tongariro catchment

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Abstract
To quantify sediment flux in river systems requires not only measurements (or estimates) of how much sediment moves through channel cross-sections or reaches over a given time period, but also consideration of how representative those measurements are and how long those rates of sediment movement will be sustained. Geomorphic analysis must accompany application of engineering principles to develop this understanding, explaining controls on sediment availability for a particular system. Geomorphic controls on sediment flux are discussed here in terms of four principles: landscape setting, landscape connectivity, reach sensitivity and sediment organization. These principles are applied in the Tongariro catchment. The landscape setting of this catchment is fashioned primarily by the volcanic history of the area, with abundant sediment supply. Landscape connectivity is limited, with many sediment stores in upland areas disconnected from the lower course of the river. Reach sensitivity downstream of the gorge is limited by the area of active channel inset within terraces. Significant channel adjustments have occurred in the braided reach beyond the terrace-confined reaches. This reach has acted as an efficient trap for gravel-sized materials, such that further downstream, the meandering and multi-channeled delta reaches comprise sand-sized materials. These latter reaches have shown negligible channel adjustments over the last 80 years. Collectively, these inter-related controls determine variability in sediment availability in the Tongariro catchment over time, thereby exerting a dominant influence upon sediment flux. Human disturbance is concluded to have had a negligible impact on sediment flux in this resilient system.

Key words
Landscape setting, landscape memory, landscape connectivity, river sensitivity, bed material organization, planform adjustment, River Style

Introduction
Explaining variability in sediment flux is a key aspect for evaluating river management applications with respect to habitat availability and viability, the sustainability of resource extraction, and concerns for erosion, sedimentation and flooding hazards (e.g., Sear, 1994; Sear et al., 1995). Understanding of controls on natural variability in sediment flux is important for determining how human disturbance has affected river adjustments (Richards, 2002). Approaches to analysis of sediment flux vary markedly depending on the purpose of the exercise (Reid and Dunne,
Sediment movement can be measured in the field with reasonable accuracy over short periods (hours/days) and modelling applications can be used to quantify long-term average rates of sediment flux under assumed sets of conditions. Indeed, we have good theoretical and experimental (flume-based) understanding of hydraulic controls on sediment flux in river channels. However, analyses of the landscape controls that determine sediment availability within a specific catchment, and the efficiency of sediment transfer to the channel itself, are poorly established. Spatial and temporal variability in sediment flux often confounds our ability to generate reliable sediment rating curves.

This paper outlines a conceptual approach to analysing geomorphic controls on movement of bedload materials at the catchment scale. Factors that determine sediment availability, the frequency with which sediment stores are reworked, and how readily stores are replenished are used to assess how representative sediment movement is at any given place over any given time interval. The approach developed here is qualitative, but future applications could quantify the relative importance of the primary controls upon sediment flux.

We first briefly summarize conventional approaches to analysis of sediment flux based upon cross-section-scale application of engineering principles. The geomorphic (landscape) approach to analysis of controls upon sediment flux is then documented (Fig. 1). This builds upon four components: landscape setting (geologic and climatic conditions), the inter-reach connectivity of a landscape (how readily sediments are conveyed from hillslopes to valley floors and from reach to reach along the river), reach-scale sensitivity to geomorphic adjustment, and the organization of sediments within reaches (their ease of mobility). These concepts are then used to outline controls on sediment flux within the Tongariro catchment. We then assess the effects of human disturbance in relation to 'natural' variability, and highlight implications for the management of sediment flux at the catchment scale.

**Geomorphologic aspects affecting sediment flux**

**Consideration of scale**

As indicated in many papers in this special issue, engineering analysis of sediment flux focuses on sediment continuity through erosion, transport, and deposition. This focus is typically at channel cross-section scales, and is scaled up to provide reach- and catchment-scale descriptions of sediment processes. This approach is inadequate to describe flux variations along reaches, as it focuses solely upon sediment moving through a cross-section, and fails to consider factors such as patches of armouring and bedrock that limit sediment supply, and local erosion at sub-reach scales. More importantly, if uniform upscaling is used, significant catchment-scale controls on sediment movement and storage will be overlooked or not addressed. Numerical models cannot capture the inherent complexity of the natural world, and unavoidable assumptions must be made to simplify model behaviour (Merritt et al., 2003). Equations and relations used in sediment transport models are typically one dimensional, and often reflect empirical relationships derived elsewhere (e.g., Brasington and Richards, 2007). Lumped simulation models are furthermore typically framed in relation to average flow and sediment conditions. It is thus unlikely that the mechanistic, one-dimensional reasoning behind conventional numerical modelling can be applied to anything beyond small-scale spatial and temporal processes. To compensate for this, various non-fluid properties that affect bedload transport must be incorporated into these modelling applications (Lane...
et al., 2008). These reframed applications must consider geomorphic properties such as landscape setting, landscape connectivity, planform geometry, and bed material organization.

A general picture of sediment flux through a catchment

Rivers can only move the sediments that are available to them. Sediment generation is determined primarily by the landscape setting, in particular tectonic controls and the erodibility of the prevailing lithology (Richards, 2002). These are interrelated, in that the conditions that create high availability of sediment via uplift also create significant relief via incision, thereby inducing high erosion rates via landscape dissection. Uplifting, dissected terrains are highly-connected landscapes, with effective and efficient sediment delivery from hillslopes to valley floors, and thence downstream along steep and narrow confined valleys. Rapid transfer of high volumes of material promotes further incision. Over time, and with distance downstream, valleys widen and sediment stores become more recurrent and permanent features. These bodies of sediment are themselves prone to reworking, with variable residence times. Channel planform and channel geometry reflect the way a channel adjusts and moves sediment on valley floors. Resulting patterns of sediment stores and sinks, and their material properties, influence the ease and frequency with which sediments are reworked and redistributed. These geomorphic principles are brought together in Figure 1 to provide a conceptual overview of geomorphic controls on sediment flux.

Landscape setting

Rivers must be viewed in their landscape context. Geological controls determine the relief, topography and erodibility of a landscape. The balance of uplift and erosion sets the boundary conditions for sediment generation and reworking. Across New Zealand, for example, there are profound differences in river types and sediment flux in landscapes such as the rapidly uplifting weak rocks of the East Coast region of the North Island, the volcanic landscapes of the central/northern part of the North Island, and the uplifting glaciated landscapes of the Southern Alps (cf., Adams, 1979; Griffiths, 1979; 1982; Hicks et al., 1996). Sediment availability, and associated patterns of sediment stores and sinks, vary markedly in these differing landscapes, in terms of both the volume and calibre of material. Lithology influences the hardness and size of breakdown products of these materials. The relationship between relief (slope) and valley width also determines the accommodation space for sediment storage.

Figure 1 – Cross-scalar relationships that determine sediment flux at the catchment scale
These considerations determine patterns of sediment source, transfer and accumulation zones in any given catchment (Schumm, 1977; Brierley and Fryirs, 2005).

The climate regime and vegetation cover affect the magnitude, frequency and ease with which materials are eroded from hillslopes, transferred to valley floors, and conveyed downstream. Regeneration of sediments upon hillslopes, determined largely by tectonic controls on uplift and lithologic/climatic controls upon weathering rates, determines how readily sediment stores can be replenished, making materials available to be eroded and/or reworked. Some landscapes are essentially stripped of readily-available sediments. In these supply-limited landscapes, sediments that do become available are readily flushed through the system. In contrast, transport-limited landscapes may become choked with sediment, promoting rapid and extensive aggradation on valley floors. Residence times for sediment reworking vary markedly for differing sediment storage units, whether on hillslopes or along the valley floor (both channel and floodplain compartments) (Brown, 1987; Phillips, 2003). As climate conditions and land use change over time, so too does the nature and distribution of vegetation and resulting patterns of sediment flux.

Landscape setting is a primary influence upon the sensitivity of landscapes to human disturbance. For example, removal of forest cover promoted extensive landslide and gully mass movement activity, which induced rapid accumulation of materials on valley floors in the East Coast region of New Zealand (Hicks et al., 2000; Page et al., 2007). Other than in areas with historical alluvial mining activities, such dramatic landscape responses to human disturbance are uncommon elsewhere in New Zealand. A significant proportion of the large volume of sediment liberated by human disturbance may be stored downstream (the so-called sediment delivery problem). These sediment stores have been referred to as ‘legacy sediments’ (e.g., James, 2010). Wilkinson and McElroy (2007: 140) contend that “(a)ccumulation of post-settlement alluvium on higher-order tributary channels and floodplains … is the most important geomorphic process in terms of the erosion and deposition of sediment that is currently shaping the landscape of Earth.” In some settings, human activities may result in decreased rates of sediment movement over time as sediment sources are depleted or exhausted (e.g., Brooks and Brierley, 2004; Fryirs and Brierley, 2001; Hudson, 2003). The impact of dams upon sediment flux is especially profound (Vörösmarty et al., 2003). Hence, human disturbance may enhance or suppress rates of sediment flux.

Contemporary human impacts upon sediment flux need to be placed in the context of the history (or memory) of any given landscape (Phillips, 2007; Brierley 2010 a, b). For example, earthquakes or volcanic eruptions may impart a persistent long-term imprint upon the landscape, generating and redistributing large volumes of materials (e.g., Simon, 1992; Montgomery et al., 1999). Many landscapes have an imprint of past climatic events. For example, the contemporary sediment load of many rivers flowing from glaciated areas has been greatly influenced by reworking of glacially-derived sediments (paraglacial materials), which create vast fan and terrace sequences along some rivers (see Ballantyne, 2002; Church and Slaymaker, 1989). Finally, past human actions may affect the contemporary behaviour of a system.

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. This approach to river classification uses reach-scale assemblages of geomorphic units (channel and floodplain features that reflect distinctive relationships between
process and form). Source, transfer and accumulation zones are differentiated on the basis of patterns of erosional and depositional landforms in differing valley settings. Confined valleys are predominantly erosional features in source zones. Partly confined valleys have discontinuous floodplain pockets in transfer zones. Laterally unconfined valleys have an array of sediment stores and sinks, typically acting as transfer or accumulation zones. The River Styles framework can be used to appraise geomorphic controls on sediment flux, relating the package of erosional and depositional features in any given reach to the pattern of river types in a catchment (and associated implications for sediment transfer from reach to reach).

The imprint of landscape connectivity between reaches on sediment flux
The manner and extent to which sediments are conveyed through a catchment reflects the connectivity or coupling of that particular system (Harvey, 2002; Hooke, 2003). Connectivity must be maintained throughout a system if inputs from headwater source zones are to become outputs at the basin mouth. Viewed in this way, the sediment delivery ratio provides a measure of the effectiveness of landscape connectivity. Forms and strengths of landscape connectivity can vary dramatically throughout a catchment and over time (Brierley et al., 2006; Jain and Tandon, 2010).

Two key components of landscape connectivity are the transfer of sediments from hillslopes to valley floors (a form of lateral connectivity), and reach-to-reach transfer of sediments along the valley floor itself (longitudinal connectivity). In highly coupled systems, water and sediment from hillslopes are delivered directly to the channel (Harvey, 2002; Fryirs et al., 2007). Moving downstream, slope flattens and valley floors widen, increasing accommodation space and the capacity for sediment storage (Lane and Richards, 1997). Various landforms may impede sediment conveyance, either within landscape compartments or within the catchment as a whole. Some landforms buffer sediment delivery from hillslopes to valley floors, while other landforms act as barriers that inhibit the efficiency of sediment transfer along valley floors (Fryirs et al., 2007). In some settings, slopes and channels are decoupled, as materials mobilized on slopes are re-stored down-slope or in fans at the base of slopes (Fryirs and Brierley, 1999; Harvey, 2001; Korup, 2005; Korup et al., 2004). Tributary systems may be disconnected from the trunk stream (Ferguson et al., 2006; Rice, 1999). Floodplain pockets and terraces may disconnect hillslope-derived sediments from within-channel sediment storage units such as mid-channel bars and benches (Brierley and Fryirs, 1999). Limited competence along a channel may inhibit the movement of coarse sediment from reach to reach (Hooke, 2003). Alternatively, channel incision may decouple channel and floodplain processes. These various forms of decoupling disconnect large parts of a catchment from the primary sediment conveyor along the trunk stream, reducing the catchment area from which sediments are delivered and transported in any given period. The position and breaching capacity of buffers and barriers can be considered analogous to a series of switches that determine which parts of the landscape contribute to the sedimentary cascade over different time intervals (Brierley and Fryirs, 2009; Fryirs et al., 2007, 2009). To date, these principles have not been meaningfully quantified, and they are largely overlooked in appraisals of catchment-scale sediment flux.

Reach-scale sensitivity to geomorphic adjustment
As noted from the Lane balance diagram (Lane, 1955), channels adjust their form in relation to their sediment loading (volume and calibre) and flow attributes (the
amount of water acting on a given slope). As such, channel form is determined by the balance between sediment characteristics and the ability of the energy regime to mobilize available materials. Alterations to these relationships induce aggradation or degradation along a reach. The nature and rate of channel adjustments, and associated sediment flux, vary markedly from bedrock rivers where erosional processes are dominant, to alluvial rivers with a mix of erosional and depositional processes. In essence, bedrock rivers are sediment-supply-limited systems, whereas alluvial rivers are typically transport-limited systems (Church, 2006). Alluvial channels rework sediment stores as they self-adjust along valley floors. As the sensitivity and capacity for geomorphic adjustment vary for bedload, mixed load and suspended load rivers, so too does their ability to store and rework sediments. The greater the proportion of readily-accessible stores in the active channel zone, the higher the likelihood that these materials will be reworked by subsequent high flow events.

**Sediment organization and roughness within reaches**

Sediment organisation and roughness within reaches influence sediment-flux at the sub-reach scale (Hoyle et al., 2008). The nature and distribution of material within a reach, along with delivery of sediment from upstream, determine the amount and calibre of material available to be transported by a channel. Sediment flux thus both reflects, and in turn determines, the nature of sediment stores and sinks within a reach, and how available materials are to be transported from one part of a river system to another. Local availability of sediment may vary during a given event, as materials are locally reworked and stored again at differing stages of flow events. This is one of many factors that induce hysteresis effects in sediment loads during floods, inhibiting our capacity to generate reliable sediment rating curves.

Elements creating resistance, such as vegetation, wood, bedforms and lagged gravels, along with channel alignment itself, further affect bedload mobility, where channels are presumed to adjust their form to maximize resistance to prevailing water and sediment fluxes (e.g., Nanson and Huang, 2008). Sediment mobility varies markedly for topographic surfaces with differing bed material attributes and roughness elements (Mao and Surian, 2010). Sediment sorting, packing, armour/paving and imbrication decrease surface sediment mobility, reducing the frequency of entrainment of bedload materials (e.g., Haschenburger and Wilcock, 2003). We can differentiate between primary sources of sediments on hillslopes, short term stores that are often reworked (e.g., mobile sediments that make up mid-channel bars) and long-term sinks that are spatially separated from reworking processes (e.g., floodplain and/or terrace deposits; Fryirs and Brierley 2001). The volume, calibre and cohesiveness/packing of sediments in sources, stores and sinks, and their positions on the valley floor (and heights relative to water level), affect the ease with which these materials are eroded and/or reworked (Brown, 1987; Davis, 2009; Heitmuller and Hudson, 2009). Clearly, the spatial distribution of bed material types and associated roughness elements exerts a primary control upon the frequency of sediment reworking across the valley floor at different flow stages. Just as importantly, these reach- and system-specific relationships change over time. The following section analyses interactions among these various controls upon sediment flux in the Tongariro catchment.

**The Tongariro catchment**

**The influence of landscape setting on sediment flux**

The Tongariro River is classified into nine River Styles (Fig. 2). Headwater zones of
the catchment are differentiated into two regions – the Kaimanawa Ranges in the east and Tongariro National Park to the west. In the Kaimanawa Ranges, actively uplifting, poorly consolidated greywacke has created a dissected landscape with countless steep and short ‘V’-shaped valleys. First-order streams are *Confined, low sinuosity, gravel-bed rivers*. This landscape unit has a dendritic drainage pattern. Many small streams drain into the

trunk streams of the Waipakihi River to the north and Whitikau Stream to the south. The lower gradient trunk streams flow within wider valleys with channel sediment stores such as lateral bars (these are *Confined, low sinuosity, gravel-bed rivers with lateral bars*).

In the sparsely vegetated landscapes of the active volcanic zone of Tongariro National Park, ephemeral streams driven by rainfall and snowmelt readily mobilize unconsolidated

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**Figure 2** – River Styles within the Tongariro Catchment. Grain-size analysis sites are indicated.
gravels. **Confined, volcanic headwater reaches** flow within gullies. Downstream, shallow confined valleys cut across the low slope of the volcanic plateau, with high sediment loads from lahars, lava flows and tephra deposits resulting in **Confined, low sinuosity, volcanic plateau cobble-bed rivers** (Fig. 2). The flat terrain disconnects sediment transfer from the very productive source zone upstream, acting as a sediment sink. This subcatchment has a parallel drainage pattern. Streams drain the volcanic slopes and flow across the central plateau prior to joining the Tongariro River. No major tributaries of the size and drainage area observed within the Kaimanawa Ranges are found within this subcatchment.

The trunk stream of the Tongariro River is transitional from a **Terrace confined, bedrock and cobble-bed river** to a **Partly confined, wandering cobble-bed river** once terraces widen (Fig. 2). The Tongariro River drains into Lake Taupo, within a caldera which erupted 1.8 ka (Manville et al., 2009). The Hatepe eruption covered the catchment with over 60 km$^3$ of material, of which >30 km$^3$ comprised ash and pumice tephra deposits (Wilson et al., 1980). Since then, the channel has incised into the tephra and underlying lahar materials (Cronin et al., 1997), resulting in channels that are partly confined by terraces. Reworked materials have created a lag deposit that lines the contemporary channel. Local gorges have formed in the upper reaches as the channel has incised into lava flows (Fig. 3). These rivers have limited accommodation space (indicated by discontinuous floodplain pockets), and a restricted range of adjustment. Alluvial sediment storage is restricted to localized wider sections between the terraces in this sediment transfer zone (Fig. 2).

Beyond the constraints imposed by terrace margins, the river becomes an **Unconfined, braided, gravel-bed river** (Fig. 2). This reach is transitional to an **Unconfined, meandering sand-bed river** and the **Unconfined, sand-bed delta**. This area acts as a sediment sink, as the delta progrades into Lake Taupo.

The primary impact of human disturbance upon landscape setting, and resulting sediment flux, is via changes to either sediment inputs (acceleration or suppression) or influences upon the rate of sediment movement (primarily induced by hydrological impacts). Vegetation cover may exert a significant influence on these controls. Although land-use changes have altered vegetation cover across much of the Tongariro catchment, there is no evidence to indicate marked changes to the transfer of coarse sediments (i.e., the bedload fraction) for most River Styles in the catchment. Other than localized adjustments along the lower course of the river (outlined below), the pattern of sediment source, transfer and accumulation zones has not been altered by human activity. Many landscapes that are sensitive to human disturbance are characterized by extensive sediment slugs triggered by human alterations to sediment stores on hillslopes and valley floors, however there are no significant human-induced ‘legacy’ sediments in the Tongariro catchment. This highly sediment-charged and dynamic volcanic landscape has been resilient to human-induced geomorphic changes.

Along with changes to sediment inputs, flux relationships are also influenced by factors that affect the rate of sediment movement. Two primary human impacts are evident in the Tongariro catchment. The impact of dams is discussed in the following section on landscape connectivity. The second primary impact is base-level control brought about by adjustments to the level of Lake Taupo. Control gates installed in 1941 on the outflow of Lake Taupo regulate the base level for the Tongariro River. Mean lake levels from 1906–1940 to 1942–1996 increased by 6.5 cm (Eser and Rosen, 2000), skewing the overall distribution of lake
levels towards higher levels (Smart, 1999). However, fluctuations in level are not evenly distributed across seasons. Mean monthly lake levels display greater differences during summer months of up to 20 cm higher after the control gates were installed, while winter levels are far more similar to those before artificial control. Lake level variation has also altered over time, with the mean level from 1942–1949 being 31 cm higher than 1906–1940. Eser and Rosen (2000) noted that the extent of the wetland adjacent to the lower Tongariro River increased notably from 1941 to 1958, increasing the length of the channel adjacent to wetland. Anecdotal evidence suggests an increase in flooding, with farming houses in the delta being abandoned (Smart, 2005). Alterations to the base level are inferred to have caused an increase in the rate of deposition and the active channel area as the channel expanded by over 1 km$^2$ in plan along a 2.5 km stretch of valley in the braided reach between 1928 and 1958 (discussed later). The operation of the Taupo Control
Gates also results in a greater capacity to convey water than the original natural outflow, however the level is managed in accord with seasonal patterns of power usage. Despite the increased capacity of the control gates, there are still periods when inflows exceed outflows, leading to higher lake levels. This contributed to the extent of flooding and deposition in the 2004 flood (Munro, 2005). The increase in flooding may also be influenced by natural subsidence in the delta (Genesis Power Limited (2000) estimate subsidence rates of 2 mm/year following earthquakes in 1983). These are essentially localized adjustments, and the volcanic history continues to exert the dominant imprint upon sediment flux.

**Landscape connectivity**

There is abundant sediment in the Tongariro catchment. Volcanic events generate irregular and dramatic influxes of sediment, and incised streams in upland areas rework these materials. Extensive accommodation space atop the Central Plateau acts as a major sediment sink in the middle-upper part of the basin. Downstream of various mid-catchment gorges, the lower course of the Tongariro River has incised into volcanic materials, creating a partly-confined valley that is inset between terraces (cf., Fryirs and Brierley, 2010; note that the terraces themselves are long-term sediment sinks). There is limited accommodation space for sediment storage in this part of the catchment, and the reach acts as a transfer zone. Beyond the terraces, however, contemporary sediment storage is high, marked by in-channel sediment stores (braid bars) and floodplain sinks.

Various landforms impede sediment conveyance through the Tongariro catchment (Fig. 4). Essentially, the upper and lower catchment are disconnected by base-level controls induced by the bedrock gorge in mid-catchment (Fig. 3). This acts as a barrier to sediment conveyance, with significant storage of materials in upstream sediment sinks. Although hillslope-channel coupling is highly effective in the steep, dissected terrain of the upper catchment, and large volumes of sediment are delivered to the valley floor, most of this material is retained within the flat terrain of the plateau landscape.

The marked discontinuity in sediment flux along the Tongariro River is reflected by downstream changes in bed material size. Above the terrace-constrained reach of the mid-lower catchment, the median bed material size ($D_{50}$) (Wolman count) in the Waipakihi Stream is 61 mm. There is significant in-channel sediment storage, with large areas of active gravel stored as lateral bars (the channel is 300 m at the widest point) (Fig. 3, photograph A). In contrast, the upper section of the terrace-constrained reach, where lahar materials are reworked within the incised channel trench, has a $D_{50}$ of 230 mm. Bars are not as large and continuous as in the Waipakihi Stream (Fig. 3, photograph E). Median bed material size in the braided reach is 85 mm. The volumes of gravel delivered and transported through the terrace sections are ultimately captured in the braided section, making this reach particularly sensitive to changes in sediment flux. There is limited conveyance of gravels beyond the braided reach, and sand-sized materials dominate the meandering sand-bed river and delta downstream (Fig. 3, photograph F). Sediment trapping within these lower reaches partially disconnects sediment transfer to Lake Taupo, which itself is the ultimate sediment trap on the Tongariro system. Average rates of sediment accumulation in the delta zone for the past 1850 years are estimated to be around 2.6 million tonnes a year (Smart, 2005). Contemporary rates are around 5% of this. This reflects a decrease in both sediment supply and catchment-wide connectivity.

Two dams have been constructed within the imposed, confined section of the Tongariro system. Average rates of sediment accumulation in the delta zone for the past 1850 years are estimated to be around 2.6 million tonnes a year (Smart, 2005). Contemporary rates are around 5% of this. This reflects a decrease in both sediment supply and catchment-wide connectivity.
structures is regulated, with the mean flow reduced by 40%. Sediment delivery through sluice gates occurs only during large events. Sluice gates on the Rangipo Dam are raised and the Poutu Intake is shut off (so all flow is delivered to the river) during high magnitude events (>100 m³s⁻¹), scouring up to 60,000 tons of sediment from the Rangipo Reservoir (Collier, 2002). The gates remain open until all the sediment has been scoured from the settling basin, which takes around 8 hours. Natural flows are retained in the river for a few days following dam flushing to allow continued transport of the sediment mobilized from the dam (Genesis Power Limited, 2000). The Poutu Intake (downstream of the Rangipo) allows suspended and bed sediment to be transported through a 200 mm screen into settling chambers which are scoured approximately once a week (Jowett, 1980). As such, sediment delivery and transport through the mid-catchment is irregular, with surges in supply following flood events > 100 m³s⁻¹ and reduced loads at normal flows. Despite these alterations to the delivery of material to the lower catchment, contemporary operation of the Tongariro Power Scheme appears to have had a minimal impact upon the contemporary bedload sediment flux and associated channel adjustment. The large bed material derived from lahars requires high magnitude events to mobilize and rework much of the channel within the terraces, creating a resilient system.

Stopbanks constructed in the lower reaches adjacent to Turangi artificially confine the river, which limits the capacity for geomorphic adjustment. Davies and McSaveney (2006) have linked stopbanks and flood-works to channel aggradation. However, stopbanks along the lower Tongariro River are located along
relatively narrow and straight reaches that have undergone little change in total channel area in the past 80 years (Fig. 4). This suggests these reaches are well connected, since sediment delivered to them is transported rather than stored in bars. The stopbanks may therefore maintain or improve a high degree of longitudinal connectivity in this section of the system, flushing sediment to the unconfined braided reach downstream.

Reach-scale sensitivity to geomorphic adjustment along the lower Tongariro River
Planform adjustments along the lower Tongariro River over the last 80 years are shown in Figure 5. The Partly-confined, wandering, cobble-bed reach has incised into tephra and lahar materials and has limited capacity for adjustment. A coarse basal lag inhibits further incision (Fig. 6). Terraces constrain channel migration, fixing bends
in place and forcing river morphology and bar turnover. Wider valley sections with floodplain pockets are more sensitive to adjustment, as they are prone to reworking by activation of flood channels and floodplain stripping. This creates lateral and mid-channel bars. This reach efficiently conveys materials delivered from upstream. The extent of incision and the height of terraces progressively but gradually decreases downstream. This reach has experienced negligible adjustments over the past 80 years, with no evidence for sustained aggradation or degradation over this period (Smart, 1999). No notable planform changes have occurred in response to flow adjustments associated with operation of the dams.

The Unconfined, braided, gravel-bed river that lies immediately beyond the terraces has formed through long-term deposition of sediments generated by the reworking of terrace materials. The unconfined nature of the reach and low slope results in unconstrained channel adjustment and aggradation. This bedload-dominated river is prone to rapid realignments of channels via thalweg shift or downstream and lateral migration of bars. Non-cohesive channel boundaries are readily reworked. Extensive sediment stores are reworked over annual or decadal timescales, as evidenced by recurrent planform adjustments (Fig. 5).

Despite their non-cohesive sandy boundaries, the Unconfined, meandering, sand-bed river and the multi-channelled delta at the lower reach of the Tongariro have shown limited planform adjustment over the past 80 years (Fig. 4). The low slope, unconfined valley setting and low channel capacity result in extensive sediment storage on the floodplain, delta and associated wetlands of this sediment sink. Palaeo-channels on the floodplain indicate a history of avulsion. Limited channel adjustments indicate a lack of lateral reworking of materials. Ongoing channel contraction has decreased channel capacity and infilled pools, with an average decrease in channel width of 26 m. Colonization by exotic willow species over the past 40 years has increased bank strength. Removal of these trees at isolated locations over recent years has led to bank erosion, although as yet little significant change in width and channel planform.

Variability in reach-scale geomorphic adjustment, and resulting reworking of valley floor materials and sediment flux, reflect the sensitivity of the reach to adjustments on the one hand, and the input of materials into that reach as determined by landscape connectivity on the other (see Fig. 1). Given its unconfined nature, the braided reach beyond the terraces is more prone to adjustment, while the meandering and delta reaches act as long-term sediment sinks.

In terms of human impacts on sensitivity to adjustment, gravel extraction in the braided reach in the 1960s and 1970s resulted in a single channel with low sinuosity, thereby controlling channel expansion. Subsequently, large floods transported more material into this reach, instigating a braided planform (Fig. 5). River responses to other management activities, including stopbank construction and control of Lake Taupo levels, are not easy to discern along the lower Tongariro River.

**Sediment organization and roughness along the lower Tongariro River**

Variability in channel planform, geometry, bed material and vegetation associations are shown for three reaches of the lower Tongariro River in Figure 6. Adjustments within the Partly confined, wandering cobble-bed reach are characterized by a cycle of mid-channel and lateral bar formation from reworking of floodplain surfaces, stabilization by vegetation and transition back to floodplain. The sediment distribution is heterogeneous and bimodal within this reach, reflecting the coarse lahar lag and the smaller-sized active fraction delivered from upstream. Large protruding
Figure 6 – Planform maps, cross-sections, reach-scale photographs (showing vegetation) and grain-size distribution (100 clast Wolman counts for the coarsest surface) for three River Styles within the Tongariro River. Distance bars on the cross-sections refer to horizontal distances only, as the vertical scale has been exaggerated. The Unconfined, meandering, sand-bed river has localised gravel accumulations on point bars.
clasts protect smaller materials, increasing the shear stress required to mobilize them and decreasing the frequency of reworking. These inherited materials are locally reworked, and patterns of bed material organization likely reflect downstream changes in the width of the active channel zone within terraces (cf., Cowie and Brierley, 2008).

Bed material size is notably finer and more homogenous (better sorted) in the braided reach that lies downstream of the terraces (Fig. 6). Mobile channels rework loosely consolidated, unpacked material on braid bars with little vegetation. Limited grain protrusion and hiding results in limited roughness. Adjacent floodplain sections act as sediment sinks. The uniform sand-sized material in the meandering and delta reaches limits grain resistance. However, sinuosity and channel multiplicity induce form resistance that promotes deposition. In addition, planted exotic willows provide instream roughness, locally trapping sediments.

Human disturbance has had a limited and localized impact upon bed material organization along the lower Tongariro River. Long-term incision into volcanic materials has been the primary determinant of available materials and their distribution, fashioning the pronounced downstream gradation from cobblelag material through well-sorted gravels to sand deposits. Dams have interrupted sediment conveyance, but there is a sufficient range of flows to ensure that disruption to sediment patterns is not significant. Local impacts are most pronounced in the braided reach, where stopbanks and gravel extraction have disturbed the channel bed and altered the ease of sediment conveyance. Also, clearance of riparian vegetation and an influx of willows have affected channel geometry along the meandering sand-bed and multi-channeled delta reaches. In longer-term perspective, these factors have exerted a negligible impact upon sediment flux in the catchment as a whole.

Summary and implications for river management

The nature and rate of sediment flux in the Tongariro Catchment are largely a product of the volcanic terrain. The legacy here is one of interrupted sediment availability, with volcanic eruptions and major reworking events such as lahars resetting the sediment balance in an irregular manner (i.e., landscape setting). River channels have adapted to this irregular sediment input. Incision through the tephra and lahar deposits has created a partly confined valley in which the channel is inset within terraces. Critically, the contemporary input of sediment into the lower course of the river is limited by the disconnected nature of the landscape upstream (i.e., landscape connectivity). The volcanic plateau acts as a major buffer to sediment conveyance. In addition, base-level control induced by gorges acts as a major barrier to downstream movement of sediment (Fig. 3).

Downstream changes in valley confinement and slope cause significant variability in river adjustment along the lower course of the Tongariro River. The channel is laterally constrained within terrace materials for much of the lower course. There is a marked transition in river type and associated patterns of sediment flux in the braided reach beyond the terraces. In contrast to all other reaches along the lower Tongariro River, this reach has been subjected to significant channel planform adjustments over the last 80 years (i.e., this reach is more sensitive to geomorphic adjustment). Interestingly, this reach has behaved as a sediment trap, limiting conveyance of gravel materials to the sand-bed meandering and multi-channel delta reaches downstream. The latter reaches have experienced negligible planform adjustments over the last 80 years, but palaeo-channels indicate an avulsive history for this area.

The inter-related larger-scale geomorphic controls affect bed material organization and the ease of sediment reworking along the
channel. As the channel incised to create the terraces within the partly confined reach, it selectively retained the coarsest fraction of lahar deposits as basal lag materials (cobbles) that are infrequently reworked. However, selectively entrained finer gravels have been flushed downstream, presenting a completely different set of uniformly sized, readily mobilized materials within the braided reach (Fig. 6). Braid bars are readily reworked, bringing about recurrent planform adjustments. Sediment trapping by this reach has seemingly inhibited the extent and rate of channel adjustments in the downstream sand-bed reaches.

The imprint of the volcanic setting upon sediment flux in the Tongariro Catchment is so prominent that system responses to human disturbance have been limited. High sediment availability, along with a naturally sparse vegetation cover across much of the catchment, have minimized responses to land-use change. Although dams have altered the flow regime of the river, impacts upon sediment flux have been well managed and no major changes to channel planform are evident. The increase in the frequency of high water levels in Lake Taupo causes a back-water effect, reported to extend 3 km upstream of the delta, enhancing landward movement of saturated soils and the area of wetland (Tonkin and Taylor, 1999; Eser and Rosen, 2000). Increased flooding and aggradation may have affected the extent of deposition and braiding, especially following the installation of the control gates in 1941 (Smart, 1999; Fig. 4). As a result, the primary sediment management issue in this catchment relates to ongoing adjustments in the braided reach, and associated management strategies via stopbanks and gravel extraction. In a sense, stopbanks can transfer problems downstream and require ongoing maintenance. Unless gravel extraction is undertaken in a sustainable manner, problems will ensue and channel adjustments are likely to be accelerated (with associated implications for aquatic habitat). Alternative approaches to river management apply 'space to move' or 'erodible corridor' concepts, striving to allow the river to self-adjust, thereby minimizing the need for direct management interventions and associated costs (see Rapp and Abbe, 2003; Piegay et al., 2005).

Conclusion

This study highlights the role of geomorphic controls on the spatial and temporal variability of sediment availability across a landscape, and the rate at which those materials move through river systems. Variability in sediment supply draws into question the applicability of modelling procedures that assess sediment flux under an assumed set of near constant (uniform) conditions. Unless geomorphic considerations are incorporated within engineering practices, management outcomes are likely to be compromised. Effective management of sediment flux cannot be undertaken at cross-section to reach scales. Instead, a landscape-scale view of sediment continuity is required. This must incorporate an understanding of sediment generation and movement on hillslopes, effectiveness of sediment transfer to valley floors, the efficiency of downstream conveyance of sediments and their storage along valley floors. These interactions are complex – some river systems are highly sensitive to change, and disturbance responses are readily conveyed through a catchment. Other systems are remarkably resilient; change seldom occurs, and any adjustments that do take place have negligible implications for other parts of that catchment (i.e., some landscapes are naturally connected; others not). The Tongariro catchment is quite resilient. Human disturbance has not had a profound impact upon sediment flux in this river system. The primary sediment management issue in this catchment relates to ongoing adjustments in the braided reach,
and associated management via stopbank construction and gravel extraction.

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