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Assessing geomorphic sensitivity in relation to river capacity for adjustment

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ABSTRACT

River sensitivity describes the nature and rate of channel adjustments. An approach to analysis of geomorphic river sensitivity outlined in this paper relates potential sensitivity based on the expected capacity of adjustment for a river type to the recent history of channel adjustment. This approach was trialled to assess low, moderate and high geomorphic sensitivity for four different types of river (10 reaches in total) along the Lower Tongariro River, North Island, New Zealand. Building upon the River Styles framework, river types were differentiated based upon valley setting (width and confinement), channel planform, geomorphic unit assemblages and bed material size. From this, the behavioural regime and potential for adjustment (type and extent) were determined. Historical maps and aerial photographs were geo-rectified and the channel planform digitised to assess channel adjustments for each reach from 1928 to 2007. Floodplain width controlled by terraces, exerted a strong influence upon reach scale sensitivity for the partly-confined, wandering, cobble-bed river. Although forced boundaries occur infrequently, the width of the active channel zone is constrained. An unconfined braided river reach directly downstream of the terrace-confined section was the most geomorphically sensitive reach. The channel in this reach adjusted recurrently to sediment inputs that were flushed through more confined, better connected upstream reaches. A meandering, sand-bed river in downstream reaches has exhibited negligible rates of channel migration. However, channel narrowing in this reach and the associated delta indicate that the system is approaching a threshold condition, beyond which channel avulsion is likely to occur. As this would trigger more rapid migration, this reach is considered to be more geomorphically sensitive than analysis of its low migration rate alone would indicate. This demonstrates how sensitivity is fashioned both by the behavioural regime of a reach and flow/sediment input from upstream. The approach to assess geomorphic river sensitivity outlined here could support 'room to move' or 'freedom space' approaches to river management by relating likely channel adjustments for the type of river under consideration to the area of land that is required to contain 'natural' patterns and rates of geomorphic functionality.

1. Introduction

Widespread recognition of human-induced damage to river systems, and disproportionately high extinctions of aquatic species, has resulted in a drive for river restoration activities across the world (Bernhardt et al., 2005). Legislation such as the European Water Framework Directive identifies hydromorphological deterioration as a key pressure upon river condition, alongside water quality concerns (e.g. www.reformrivers.eu). Among many factors, limited successes in restoration activities to date reflect efforts to recreate the form of systems, underplaying the regenerative role of formative processes and associated system dynamics (e.g. Clarke et al., 2003; Wohl et al., 2005; Beechie et al., 2010). However, appraising morphodynamic relationships in river systems is a challenging task, as differing types of river adjust in differing ways, at differing rates, in response to variability in flow and sediment regime, and differing forms of disturbance (including human activities). Beyond this, measuring processes such as bedload transport is inherently difficult, presenting a major source of uncertainty in analyses of channel adjustment (Brasington et al., 2003; Wilcock et al., 2009). As a consequence, emerging approaches to river restoration increasingly emphasise prospects for a river to self-adjust or self-heal whenever possible, rather than endeavouring to prescriptively determine what a river 'should do' (e.g. Darby and Sear, 2008; Kondolf, 2011). Key examples that highlight efforts to 'make space for the river' include Rapp and Abbe's (2003) 'room to move' approach, Piégay et al.'s (2005) erodible corridor concept, and associated 'freedom space' initiatives (e.g. Cals and van Drimmelen, 2001; Biron et al., 2014). Determining how much space is required to contain channel adjustment if the river is left to its own devices is a key consideration in these deliberations. Effective management of risks/hazards, alongside concerns for ecosystem services and river values, is contingent upon sound knowledge of the 'expected' (historical) range of variability for the type of river under consideration (Wohl, 2011; Rathburn et al., 2013; Rinaldi, in this issue. Understanding of the manner/rate of channel adjustment, and associated measures of geomorphic

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sensitivity, therefore provides key conceptual information to underpin management practices.

Brunsden and Thornes (1979) define sensitivity as "… the likelihood that a given change in the controls of a system will produce a sensible, recognisable and persistent response" involving "…the propensity for change and the capacity for the system to absorb change". Building on this definition, Downs and Gregory (1993) described sensitivity as a ratio between the magnitude of channel adjustment and the magnitude of change in the stimulus causing the adjustment. Despite long-standing recognition of the importance of sensitivity concepts in river science and management (e.g. Brunsden and Thornes, 1979; Thomas and Allison, 1993; Thomas, 2001;Werritty and Leys, 2001), there have been few attempts to develop a systematic and consistent approach to assess geomorphic river sensitivity. Significant guidance in the development of such an approach provided by Downs and Gregory (1993, 2004), Hooke and Redmond (1992) and Downs et al. (2013) points to the importance of considering forms of channel adjustment alongside the ease (recurrence) of adjustment. Here we build upon these principles to develop a generic set of procedures to assess geomorphic river sensitivity. We define geomorphic river sensitivity as a measure of how sensitively a channel responds to disturbance events. If the channel responds readily and recurrently it is considered sensitive; if responses are negligible and infrequent, the river is considered to be resilient to change (Brierley and Fryirs, 2005). In this sense, sensitive reaches are subject to high rates of adjustment in response to stimuli. In contrast, resilient reaches have the capacity to inhibit change by absorbing excess energy and minimising the extent of adjustment in response to stimuli. Sensitivity within this context relates observed 'rates and types of adjustment' to 1) the potential range of adjustment for a river type and 2) channel responses to stimuli (disturbance events) of differing magnitude/frequency. Thus, sensitivity has both temporal (change over time in response to different stimuli) and spatial (how boundary conditions interact to make some reaches/river types more responsive than others) components. In this framing, sensitivity is not inherently 'bad'; rather, it provides a guide to the likely form and rate of channel adjustment (cf., Florsheim et al., 2008; Fryirs and Brierley, 2009). Viewed in this way, appraisal of geomorphic river sensitivity provides a powerful tool to assess river adjustment and apply such understandings in a management context.

Building upon the River Styles framework, this paper frames analysis of the geomorphic sensitivity of rivers in relation to their 'capacity for adjustment' (Brierley and Fryirs, 2005). An important distinction is made between the form and the ease/rate of adjustment that is 'expected' for a given type of river, recognising the potential for change to another type of river that has a different behaviour regime/capacity for adjustment, such that different measures may be required to assess its geomorphic river sensitivity (Brierley et al., 2008). Hence, proximity to a threshold state is included as a critical factor in assessment of geomorphic river sensitivity. In this paper, geomorphic river sensitivity is appraised in relation to: 1) the specific types and rates of adjustment for the different components of the system (magnitude of change), 2) how changes in fluxes drive change within the system (magnitude of stimuli), and 3) placement of each reach along an evolutionary trajectory that assesses a) how that reach has adjusted in the past, and b) the likely nature/rate of adjustment into the future. Development and application of these principles are demonstrated for the Tongariro River on the North Island of New Zealand.

2. Study Area

The Tongariro Catchment (777 km^2) is located in the Central North Island of New Zealand (Fig. 1a). Catchment elevation ranges from 2797 m at the peak of Mt. Ruapehu to 329 m where the Tongariro River drains into the Lake Taupo caldera (lake surface area 616 km^2). The climate of the region is alpine in the headwaters, grading to more temperate conditions at lower elevations. Mean annual rainfall is as high as 3400 mm at the volcanic summits, decreasing to 1200 mm at Turangi (Fig. 1a; Genesis Energy, 2009). Mean total monthly rainfall at Turangi is lowest in February (109 mm) and peaks in July (180 mm). Mean monthly temperatures in the lower catchment range from 6.5 °C in July to 17.3 °C in February, with the yearly average being 11.8 °C (NIWA, 2009).

The eastern headwaters of the catchment comprise the Kaimanawa Ranges. Uplift of Torlesse greywacke at a rate of 3 mm/year generates high on-going sediment delivery into the lower catchment (Litchfield et al., 2007; GNS, 2009). The regional forest park is made up of native beech and podocarp forest.

The Tongariro National Park that makes up the western headwaters of the catchment is characterised by an active (last eruption in 2012) volcanic field underlain by andesitic material. Unstable, steep, high-altitude hillslopes are unable to sustain vegetation other than mosses. High sediment loads are readily conveyed to the volcanic plateau below, where vegetation comprises a wide range of alpine desert fauna. Although incised channels cross this zone, the low gradient plateau buffers the high sediment load from upstream. Infrequent, high magnitude lahar events range in date from 14.7 ka and recent events have provided pulses of unconsolidated volcanic material into the lower Tongariro River (Cronin et al., 1997).

In its upper reaches, the Tongariro River is pinched between the uplifting Kaimanawa Ranges and the sediment stores of the volcanic plateau. As a result of incision, the confined, high energy river has a straight alignment between these units and it transports sediment efficiently to the lower catchment.

The study reach, termed the lower Tongariro River (Fig. 1), comprises four River Styles (Fig. 2). Land use in this lower section of the catchment includes plantations of *Pinus radiata*, low density sheep farming and the town of Turangi (population 3240) (Statistics New Zealand, 2010). The Taupo eruption in 186 AD reshaped sections of the caldera of Lake Taupo, resetting the geomorphic process zones in the Tongariro catchment. It delivered extensive pumiceous pyroclastic debris which smothered the landscape up to 10 m thick (Wilson et al., 1980; Manville et al., 2009). The lower Tongariro River has incised through the pyroclastic and underlying lahar sediments to form terraces that reach 10–15 m high (Fig. 3). Lahar material has left a boulder bed lag deposit which lines the channel, limiting the capacity for vertical adjustment. However, the terraces never actively confine the river, as the accommodation space between them is greater than the channel width at any point in time. Thus, a partly-confined, wandering, cobble-bed river is evident (Reaches A – G Fig. 1a, Fig. 2).

The downstream terrace extent reflects the historic base level related to the lake shoreline in 186 AD. Immediately downstream of the terraces, deposition is high and unconfined conditions have resulted in the development of a braided gravel-bed channel (Reach H – Fig. 1a). Further downstream, gradient decreases, the channel narrows and bed material size becomes finer-grained as the river becomes an unconfined, meandering, sand-bed channel (Reach I – Fig. 1a) that grades into an unconfined, multi-channelled delta at the lake edge (Reach J – Fig. 1a, Fig. 2). The delta region comprises the largest remaining freshwater wetland in New Zealand.

3. Methods

Development of the nested framework to assess river sensitivity involved: i) classifying the sensitivity of each River Style based on its capacity for adjustment; and ii) classifying the reach-scale adjustment based on the magnitude and rate of response observed in aerial photographs. Analyses of channel adjustments were derived from a 1928 map and aerial photographs from 1941 to 2007. The protocol for assessing river sensitivity is outlined in Fig. 4.

Four River Styles were identified along the lower Tongariro based on valley confinement, channel planform, geomorphic units and bed material (Brierley and Fryirs, 2005; Fig. 2). Each River Style was qualitatively