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# Landslide-driven erosion and slope–channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011

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ABSTRACT

Landslides are an important means of conveying sediment from slopes to channels in steepland environments, but landsliding is a discontinuous process. This means that any single assessment in time of their contribution to the sediment cascade is of limited value. To better understand landscape dynamics and the contribution of landslides to slope–channel coupling over time, this paper quantifies connectivity over a time span of 65 years in small, steep headwater catchments in the southern Ruahine Range, New Zealand. Temporal variability in landsliding and slope–channel coupling was assessed using six sets of aerial photography flown between 1946 and 2011, from which over 6900 landslides were mapped in ArcGIS, of which up to 78% connected with the stream network. Estimates of the volume of material delivered by landslide erosion to headwater channels were based on ground survey measurements of selected landslide scars and suggest that between 1946 and 2011 over 5 million m$^3$ of sediment was delivered from slopes to channels in the 221 km$^2$ study area. Forest cover is not sufficient to prevent this erosion. These catchment systems are particularly vulnerable to high magnitude storm events, which significantly elevate landslide intensity and enhance sediment delivery, as occurred in the mid-1970s. The legacy of these events remains in these headwater channels, with ongoing consequences for stream and hazard management in and adjacent to the ranges.

## 1. Introduction

Steep, headwater catchments have long been recognised as being active geomorphic environments contributing a substantial proportion of material to the catchment sediment cascade from this ‘production zone’ (e.g. Schumm, 1977a, 2005; Dietrich and Dunne, 1978; Gomi and Sidle, 2003; Warburton, 2010). Landslides play an important role in this sediment delivery, especially in steepland terrain, where slope–channel coupling is typically strong (Harvey, 2001; Korup, 2004a; Parkner et al., 2007; Fryirs et al., 2007; Crozier, 2010a; Fuller and Marden, 2011; Jones and Preston, 2012; Marden et al., 2012; Fryirs, 2013) and connectivity is a key attribute in the sediment transfer process in mountainous terrain (Cavalli et al., 2013). Glade (2003) suggests sediment generation in New Zealand is particularly related to landslide erosion, which is defined as soil, debris and rock moving by sliding, flow and complex movement such as avalanching and spreading. Much attention on landsliding in New Zealand has been on the susceptibility of deforested slopes to landslides, particularly in New Zealand's soft-rock hill country (e.g. DeRose et al., 1993; DeRose, 1996; Page & Trustrum, 1997; Brooks et al., 2002; Reid and Page, 2002; Hennrich and Crozier, 2004; DeRose, 2013). Glade (2003) has reviewed the occurrence of landsliding in New Zealand following widespread land use change from indigenous forest to pasture. Considerable research has focussed on assessing the probability of slope failure across different vegetation types and at different stages of maturity (age) — particularly during storm events (e.g. Phillips et al., 1990; Marden and Rowan, 1993; Bergin et al., 1995; Marden, 2004, 2012; Dymond et al., 2006; Papathoma-Köhle and Glade, 2012). However, in New Zealand relatively little attention has been paid to landslide occurrence on forested slopes in hard-rock terrain although notable exceptions include the documentation of landslide incidence during pre-European periods of erosion and sedimentation (Grant, 1965, 1966) but more commonly during historic storm events (James, 1973; Stephens, 1975; Marden, 1984; Parkner et al., 2007; Korup, 2005).

Effective management of sediment transfers requires an understanding of transport pathways, sources and sinks of material derived from landslides as it is moved from slope to sea along the ‘jerky conveyor’ (sensu Ferguson, 1981), in which sediment is alternately eroded and transported from multiple sources and deposited and stored in multiple sinks as it moves discontinuously along the catchment transfer pathway. This is a complex task, given the array of factors controlling sediment sources, sinks and pathways within any single catchment (e.g. Brierley et al., 2006; Hoffmann et al., 2007; Fryirs, 2013). In order

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to understand the contribution of landslides in this sediment transfer, to date most work seeking to understand processes operating at the slope–channel nexus has focused on single, discrete failures or complexes contributing sediment over short timescales ranging from a single event to a few years (e.g. Betts et al., 2003; Johnson et al., 2007; Fuller and Marden, 2011), or the effects of a single storm event across a broader spatial area (e.g. Jones and Preston, 2012), or a small area over a longer time period (Harvey, 2001). More recently Cavalli et al. (2013) and Heckmann and Schwanghart (2013) have applied numerical modelling to the problem. While this has improved understanding of processes operating in these environments, a longer-term perspective across more than one catchment would also be valuable to assess broader landscape dynamics, particularly with a view to catchment management. Importantly in this regard, Korup (2004a, 2005) has quantified sediment generation and delivery in several westward-draining catchments in the Southern Alps using aerial photography spanning 65 years (1937–2002). Korup's work focused on identifying and quantifying sediment delivery from large landslides (>1 km$^2$) in particular, together with their influence on river systems (Korup, 2004b).

Catchments in the southern Ruahine Range, North Island, New Zealand, were the subject of intensive research in the 1970s and early 1980s in response to major stream aggradation in eastern piedmont areas (e.g. Stephens, 1975; Blakely, 1977; Mosley and Blakely, 1977; Schumm, 1977b; Grant, 1977; Mosley, 1977, 1978a; Grant et al., 1978; Grant, 1981; Marden, 1984). This aggradation was attributed to deforestation of foot-slopes in the ranges, at a point defined as the valley 'throat' by Mosley (1977), where channel slope abruptly declines and valley floor width increases. Blakely (1977) suggested that this disturbance resulted in retrograding incision upstream, scour of old in-channel deposits and slope failure induced by bank erosion. In response to such enhanced sediment inputs, widening and aggradation of river channels was observed in catchments between 1910 and 1940 (Hubbard, 1976), and in particular following major storm events such as cyclone Alison in 1975 (Grant et al., 1978). Cunningham (1966, 1977); Cunningham and Stribling (1978); James (1973); Stephens (1975) and Marden (1977; 1984) provide some of the first specific comments on erosion types and possible causative factors. In connection with this geomorphic activity, Stephens (1975) found a 120% increase in slope erosion between 1946 and 1974 in two catchments. For the same period Marden (1984) found there was a 91% increase in slope erosion within the entire southern Ruahine Range. Grant (1989) suggested that in some catchments in the southern Ruahines, vegetated area decreased by 2.8% between 1946 and 1974, which he attributed to storm-induced landsliding.

More recently, Schwendel et al. (2010) and Schwendel and Fuller (2011) assessed short-term channel dynamics and catchment connectivity in five headwater catchments in the Southeastern Ruahine Ranges. They found a high degree of variability in short-term reach-scale morphodynamics (Schwendel et al., 2010), which appeared to be driven mainly by differences in sediment supply rate, modulated or amplified by coupling characteristics (degree of connectivity) in the catchments (Schwendel and Fuller, 2011). Schwendel and Fuller (2011) concluded that sediment supply to the reaches examined had become increasingly dependent on re-working of material stored in-channel and on valley floors as a legacy of earlier episodes of intensive slope erosion, such as Cyclone Alison in 1975, rather than ongoing supply of material from slopes, suggesting that the valley floors in this landscape have a clear memory of past events (cf. Brierley, 2010). However, they also identified a need to provide an assessment of longer-term erosion rates in these catchments to better contextualise sediment flux. Furthermore, no attempt was made to assess volumes of sediment delivered from slopes to channels in this previous work.

This paper addresses the need for a longer-term (multi-decadal) assessment of erosion to better understand temporal variability and contextualise contemporary sediment flux. The Ruahine catchments have been selected as a study site. Estimation is made of sediment volumes supplied by landslide-driven erosion in these headwater slopes for comparison with earlier studies (Stephens, 1975; Mosley, 1977; Marden, 1984), which were conducted in the immediate aftermath of a major cyclone in 1975 (Cyclone Alison). We therefore assess the extent to which these catchments have recovered from 1970s erosion and quantify the extent of slope–channel coupling in this environment assessed over a multi-decadal timescale for the first time in this region. The research differs from that done more recently elsewhere in New Zealand by focusing on landslide erosion in forested mountainous terrain dominated by small, shallow landsliding processes, in contrast to the deeper seated mechanics observed in analogous terrain in south Westland (e.g. Korup, 2005). Hitherto, these shallower processes have mainly been studied in soft rock hill country (e.g. Reid and Page, 2002; Jones and Preston, 2012; DeRose, 2013). Korup (2005) recognised the visual dominance of these features in the forested hillslopes in south Westland, which he equated with features defined by Whitehouse (1986) as debris avalanches, but these were not the focus of his research in terms of neither landslide type nor magnitude. This paper thus reflects one of the first quantitative studies of shallow landsliding since Marden's work in 1984 in forested 'alpine' terrain in New Zealand, following Crozier (2010a, p.12) definition of 'alpine', as distinct from 'hill country' in terms of its relief (exceeding 1000 m), tectonic setting (axial tectonic belt), rock type (hard, with structural discontinuities) and uplift rate (>1 mm/year).

### *1.1. Site description*

The Ruahine Range trends NNE–SSW and forms part of New Zealand's North Island axial ranges. The summit of the range rises from 915 m in the south to >1700 m at its highest point further north. The highest terrain in the study area rises to 1258 m (Fig. 1). The range represents steep, fluvially dissected terrain, characterised by an abrupt and actively eroding scarp in the east, with less steep and longer valleys to the west (Whitehouse and Pearce, 1992, and cf. Fig. 1). The summit ridge comprises a gently domed surface (Kamp, 1992). The eastern slopes have been subject to extensive landsliding for many decades, reported since the 1940s.

### *1.2. Geology*

The prevailing geology of the southern Ruahines is Mesozoic Torlesse terrane, which is a, "heterogeneous assortment of structurally complex, poorly fossiliferous, relatively quartz-rich, flysch-like, non-schistose rocks" (Marden, 1984, p.24). Essentially this can be summarised as folded Mesozoic greywacke and argillite of varying decomposition (Mosley, 1978b). Marden (1984) identified two primary lithological types in the study area (Fig. 1): (i) the Tamaki, comprises undeformed beds of coherent units of sandstone, argillite, siltstone, intraformational conglomerate, chert, calcareous siltstone and pebbly mudstone of Ohauan age (Late Jurassic age, Late Oxfordian–Kimmeridgian). The sequence is graded-bedded, eastward dipping, westward younging and therefore overturned; and (ii) Wharite, which comprises a strongly deformed succession of lens-shaped clasts of competent lithologies including sandstone, conglomerate, fossiliferous limestone, chert and volcanics within an argillaceous matrix resembling a melange of Oretian age (Late Karnian–Early Norian). Stratigraphic and structural relationships between the two lithological types are uncertain, although generally conformable with signs of faulting observed at some locations. The Ruahine Range is actively uplifting at average rates of 0.8 to 2.5 mm per year (Mosley, 1977), and uplift is believed to have commenced within the last million years (Heerdegen and Shepherd, 1992). Uplift rates vary spatially and relate to differential warping and tilting and deformational history of individual fault blocks (Heerdegen and Shepherd, 1992). Along its abrupt eastern margin the range is