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Spatial and temporal patterns of off-slope sediment delivery for small catchments subject to shallow landslides within the Waipaoa catchment, New Zealand

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ABSTRACT

The Waipaoa catchment in New Zealand has one of the highest measured specific suspended sediment yields measured in New Zealand compared to basins of comparable size. A significant source of this sediment is from shallow landslides which are often triggered on a regional scale during large magnitude storm events, defined as ~200 mm rainfall within 72 h. The first step of this sediment cascade is removal of landslide material from the slope and into the fluvial system when the debris tail is in physical contact and hence considered connected. The difference between the volume of sediment liberated in the event and the volume remaining on the slope immediately following the event is termed the off-slope sediment delivery ratio. This value ranged from 0.12 to 0.28 for small sub-catchments within the Waipaoa catchment depending on catchment morphology, landslide and triggering event characteristics. In the Waipaoa catchment a decrease in the catchment sediment delivery ratio is observed as the sub-catchment size increased. A human induced process which may affect off-slope sediment delivery is regolith exhaustion, as scars move further upslope in response to removal of preferred weathered material during previous events on the lower sections of slope. However, it appears that temporal scar migration away from the channels is not prevalent. Therefore, the hypothesis that hillslope relaxation since deforestation is prevalent in this setting is considered null. Rather the temporal pattern to sediment delivery ratios supports the context of evolving catchment in response to deforestation in the Terrain Event Resistance Model.

1. Introduction

The concept of sediment delivery, as outlined by Roehl (1962), is important in terms of linking landscape form and process and is imperative for understanding sediment transfer through the fluvial system (Schumm, 1977). Based on the assumption that catchment sediment yield can be related to different catchment characteristics (for example, the characteristics of the triggering event, catchment relief, soil and vegetation cover, and conditions in stream channels), only a portion of the material eroded from a catchment contributes to the sediment yield over a given time (Glymp, 1954). The attempts to account for the different components of sediment flux are often framed in terms of a sediment budget (e.g. Dietrich et al., 1982). Viewed from the perspective of measurements of (suspended) sediment discharge, which are routinely made in many drainage basins, the pertinent question is: what is the relationship between the sediment yield at the measuring point (Y) and the total amount of sediment eroded from the basin upstream of that point (T) for a given period of time? Roehl (1962) termed this relationship the sediment delivery ratio (D) where $D = Y/T$ is often expressed as a percentage.

Sediment delivery is strongly scale dependent. At the hillslope scale, sediment delivery first increases and then decreases as catchment area increases (Parsons et al., 2006). Three explanations have been given for this scale dependency of the sediment yield. First, since hillslope runoff also exhibits the same scale characteristics, it may be attributed to spatial variations in infiltration or temporal variations in rainfall intensity. Second, the dependency arises because some of the eroded sediment is stored in hillslope sediment sinks. Third, it is possible that as area increases the proportion of the area that contributes sediment to the outlet decreases because individual particles travel a finite distance during storm events. Regardless, the clear implication is that erosion rates measured at one scale cannot be extrapolated to another (Parsons et al., 2006). The same effect is seen at the catchment scale and is commonly observed as an inverse relationship between specific suspended sediment yield and drainage basin area (Walling, 1983), which arises because either the high erosion rates recorded in small headwater catchments are not sustained across the whole basin and/or storage reduces the amount of sediment delivered to the basin outlet. Because sediment in most river systems appears to spend much more time in storage than in transport (Meade, 1982), the application of a delivery ratio is seen as an obvious way of resolving the disparity between rates of erosion on hillslopes and in-stream measurements of suspended sediment yield (Dickinson and Wall, 1977).

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Partly because of this spatial and also temporal variability, sediment delivery ratios are not easy to model or predict. Dickinson and Wall (1977) identified two apparent paradoxes that make it difficult to accurately estimate delivery ratios. First, there is the problem of spatial aggregation or lumping (the spatial paradox), which relates to the problem of attempting to represent the sediment delivery characteristics of a catchment in which topography and soils (and hence infiltration capacity, runoff and erosion potential) vary from place to place, with a single number. Burns (1979) suggested that each sediment source should be viewed as possessing a unique delivery potential, with a probability of sediment being exported from a particular source that is linked to its relative position (with respect to the stream and the catchment divide). Second, a temporal or frequency paradox arises — although sediment loads are closely linked to runoff, the frequency distribution of sediment peaks is not equivalent to the distribution of runoff peaks often due to sediment supply constraints. In the Waipaoa catchment, this means that there is a poor correlation between peak suspended sediment concentration and peak discharge (Hicks et al., 2004), and that very high suspended sediment concentrations can occur during relatively small discharge events. These issues are compounded because sediment delivery ratios are estimated at different spatial and temporal resolutions, which range from a single hillslope (m^2) to large catchments (km^2) and individual storm events (h) to the long-term (mean annual) suspended sediment yield, and the fact that sediment availability varies in time and in space is typically ignored (Pain and Hoskin, 1970; Walling, 1983).

The Waipaoa catchment is a dynamic and evolving large scale drainage basin. The naturally high sediment yield provides a catchment which is ideal to demonstrate the entire source to sink sediment progression over geological timescales (Hicks et al., 1996; Page et al., 1999; Litchfield et al., 2008). Additionally, the widespread conversion from the indigenous podocarp-broadleaf forest to pasture faming by European settlers in the late 19th and early 20th centuries has resulted in a profound and long term change to sediment pattern in the catchment (Kettner et al., 2007). While there is an understanding of the changes in the erosion processes active in the catchment, this does not necessarily translate to a similar understanding of their contribution to the overall sediment yield within the contemporary time scale (Litchfield et al., 2008), as the amount of sediment transferred from the hillslopes to the channels is not constant over time. In this paper, the focus is identifying patterns in off-slope delivery within the Waipaoa catchment which varies both spatially and temporally.

2. Regional setting

The 2205 km^2 Waipaoa catchment, located on the eastern coast of the North Island of New Zealand, is situated within a zone of active deformation in the forearc margin of the Hikurangi subduction trench, a convergent plate boundary between the Pacific and Australian plates. Catchment geology, structure and active tectonics are considered to predispose this landscape to high rates of geomorphic activity (Litchfield et al., 2008). The headwaters of the Mangatu and Waipaoa Rivers, representing ~8% of the Waipaoa catchment, are underlain by a structural complex of Cretaceous and early Tertiary sedimentary rocks sustaining highly unstable landforms that have been a major source of sediment throughout the Quaternary (Gage and Black, 1979). The mid to lower reaches of the Waipaoa catchment consist of mid-Quaternary lacustrine, fluvial and lagoonal deposits. Throughout the rest of the catchment, landsliding is a common erosional process on the Miocene to Pliocene interbedded sandstone, siltstone and mudstone cover sequences on the lower steeplands. Typically these landslides are initiated when the storm rainfall exceeds a threshold of ~200 mm in 72 h (Dymond et al., 1999; Reid and Page, 2002). These landslides are highly fluid planar failures that in general mobilise only the soil profile and surface of weathered bedrock to a depth of about 1 m (Page et al., 1999). Such landslide triggering episodes have been referred to as a multiple occurrence regional landslide events, as thousands to tens of thousands of landslides may occur over areas extending up to 20 000 km^2 (Crozier, 2005).

European settlement in the region began in the late 1830s (MacKay, 1982), with the main settlement on the alluvial plains to the north of the Waipaoa River and a scattered rural population throughout the surrounding hill country. Indigenous forest was cleared to make way for production pasture and by 1880 most of the lower reaches of the catchment had been cleared, and the headwaters were cleared by 1920 (Henderson and Ongley, 1920; MacKay, 1982). The establishment of pastoral farming on the hill country initially provided the basis of the Gisborne district economy. However, the decline in the economic viability of pastoral farming, associated with high erosion rates on hillslopes under pasture, led to the rapid growth of production forestry. In 2001, ~6% of the catchment is covered in indigenous forest and scrub, ~70% of the catchment was is in pasture, and ~20% was covered by exotic forest (Page et al., 2001). The removal of the indigenous forest cover, initially on a small scale by Maori settlement c. 650 years BP (Jones, 1988) and more significantly European settlement, has resulted in a profound increase in the suspended sediment yield of the catchment in response to local climatic conditions (Hicks et al., 2000). The region has a temperate maritime climate but can be subjected to weather and climatic extremes (Hessell, 1980).

While large magnitude multiple occurrence events within the study area, such as Cyclone Bola (300–900 mm of rain from 6th–9th March 1988, with a recurrence interval of 100 years), have a dramatic effect on the landscape, the overall contribution from event triggered shallow landslides to the total long term contemporary sediment yield of the Waiapoa Catchment is small, being estimated at between 10% and 25% (Trustrum et al., 1999; Hicks et al., 2000; Reid and Page, 2002). Surprisingly, despite the regional impact from large scale events, 75% of material sourced from landslides is generated during events with recurrence intervals of less than 27 years (Reid and Page, 2002). In larger catchments, much of the displaced material goes directly into storage and consequently landsliding makes a smaller direct relative contribution to sediment yield than in smaller catchments where connectivity between hillslopes and channels is enhanced and sediment delivery is greater, for example Lake Tutira in Hawkes Bay, New Zealand (Page et al., 1994). Sediment in temporary storage on hillslopes that is released by subsequent small events may increase the event magnitude frequency distribution of suspended sediment loads for up to three years if landslide scars and tails remain un-vegetated (Hicks et al., 2000).

Page et al. (1999) and Reid and Page (2002) used aerial photography in conjunction with rainfall data to derive relationships between storm magnitude and landslide density on different land systems in the Waipaoa catchment. Each land system has a unique combination of rock type, landforms, erosion processes and sediment supply capacity, drainage density and channel morphology and is locally named (Page, 1994). Based on field measurements of 95 landslide scars, average volumes for landslides in each land system were measured. The overall sediment delivery ratio was estimated to be 0.45 and the percentage of sediment contributed by shallow landslides to the suspended sediment load of the Waipaoa river at Kanakanaia is ~0.15 ± 0.5 (Reid and Page, 2002), which rises to ~0.48 during extreme events comparable to Cyclone Bola (Page et al., 1999). Thus, in the Waipaoa catchment, where gully, sheet and riverbank erosion have the potential to generate sediment whenever it rains, the cumulative effects of low magnitude, high frequency events dominate the long-term catchment sediment yield (Hicks et al., 2000).

For the entire Waipaoa catchment, Dymond et al. (1999) estimated 30 $(\pm 5) \times 10^6$ m^3 of soil were eroded during the largest storm on record (Cyclone Bola). 13 $(\pm 3) \times 10^6$ m^3 of soil was estimated to have reached stream channels, by using spatially variable sediment delivery ratios (from 0.20 to 0.54), derived from the simulation and across