Off-slope sediment delivery from landsliding during a storm, Muriwai Hills, North Island, New Zealand

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Abstract One of the critical aspects of regional sediment transport that must be addressed is the issue of sediment delivery. Although both the mechanics of, and systematic controls on, sediment transport are well understood, there is little data on sediment delivery available. In August 2002 a high intensity rainfall event induced widespread shallow landsliding on the coastal hills south of Gisborne in the North Island of New Zealand, presenting an opportunity to obtain first-hand estimates of sediment delivery from landslides. Many of the failures were shallow and extremely fluid in nature, suggesting that high pore water pressure was the triggering mechanism, and in some cases sub-surface flow was clearly a factor. Field estimates of off-slope sediment delivery to channels, including ephemeral channels that were thought to have been present during the peak of storm runoff, were made for 220 individual failures within three catchment areas of uniform lithology and vegetation cover. One of the more important controls on sediment delivery is the timing of landsliding relative to duration of storm runoff, and therefore transport capacity. Related to this are issues of slope/channel coupling and connectivity within the landscape, and the location of landslides relative to channels, which is a function of the erosional history in the catchment, is clearly important. The average estimated sediment delivery ratio was ~26%. Although this figure is low, it applies to a single event, and implies that landsliding produces considerably more sediment that will be available for attenuated delivery through the fluvial system.

Key words rainfall-triggered landsliding; fluid failure; sediment delivery ratio; slope-channel coupling

INTRODUCTION

Sediments generated by erosional processes play an important role in the flux of many nutrients and contaminants, as well as representing a management issue in their own right. Generation and transport of sediments and nutrients involves a range of geomorphic and hydrological processes, and these individual processes can be modelled with greater or lesser accuracy using a range of models from factorial approaches through to sophisticated physically-based deterministic process representation. Modelling sediment redistribution at a regional scale, however, requires that the interaction between these processes is able to be represented, or at least that the relative contribution of each to regional fluxes can be determined. Thus, for each process it is necessary to quantify both the sediment it generates, and the volume and nature of sediment that it contributes to the regional flux. One of the critical aspects of regional sediment redistribution that must be addressed, therefore, is that of sediment delivery and especially the extent to which hillslopes as sources of sediment are coupled with the fluvial network. Although both the mechanics of individual processes and the systematic controls on sediment transport are understood, there is little data on sediment delivery available for model validation.

One of the most important geomorphic processes in the New Zealand landscape is landsliding (Eyles, 1983; Crozier, 1986). There is a wealth of data available for modelling the *generation* of sediment through landsliding, both empirically and deterministically, but relatively little is known about the associated sediment *delivery*. In perhaps the best-known use of a sediment budget approach in New Zealand, Page *et al*. (1994) estimated that 89% of sediment generated at Tutira during Cyclone Bola (1988) was derived from shallow translational landsliding. This was based on aerial photography and field verification of landslide volumes. Delivery was inferred as the difference between generation and terrestrial storage. Similarly, Page *et al*. (1999) and Reid & Page (2002) used simple assumptions concerning delivery in estimating the relative proportions that landsliding contributes to the fluvial sediment flux in the Waipaoa catchment. Simplifying assumptions are justified as there are few alternatives, given the complex range of factors that influence sediment delivery, making it virtually impossible to generalise sediment delivery ratios (see Walling, 1983). Hence, there is very little empirical data for model validation, although this is one of the crucial elements that must be addressed if models of regional sediment redistribution are to be useful.

In early August 2002, high-intensity rainfall initiated extensive landsliding in the hills to the south of Gisborne, presenting an opportunity to obtain first hand estimates of sediment delivery from landslides.

THE MURIWAI/TE ARAI STORM OF AUGUST 2002

Flooding and landsliding associated with the rainfall of 5–7 August occurred in many parts of the East Coast and northern Hawke's Bay. In the vicinity of Gisborne, the highest rainfalls (>300 mm for the entire event) were recorded in the coastal hills between Muriwai and the Te Arai valley (Fig. 1), and landsliding was largely confined to this area. Hill country landowners reported that most of the landsliding occurred toward the end of the storm following a 12-h period of greatest rainfall intensity.

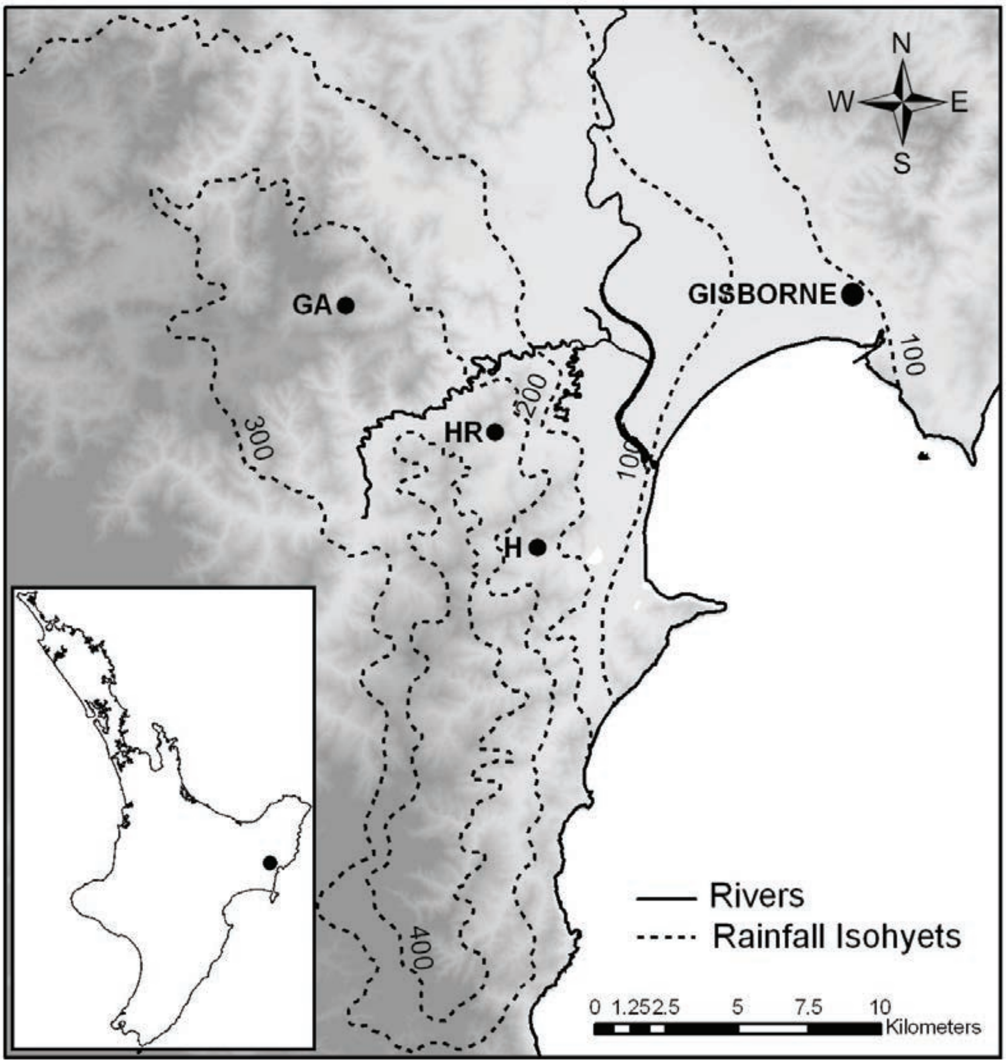

Fig. 1 Distribution of storm rainfall in the August 2002 event. The three study sites are indicated: H = Hinenui, HR = Harrington Road, GA = Gentle Annie. Rivers shown are the Waipaoa and its tributary the Te Arai which runs through the study area.

METHODS

Field reconnaissance occurred within days of the storm event, and evidence of ephemeral channelised flow on hillslopes and in sites of convergent topography was clearly evident. Following an initial regional reconnaissance, three sites with particularly high landslide densities were selected. The location of the Hinenui, Harrington Road and Gentle Annie sites is indicated in Fig. 1.

Dimensions of 220 landslide failure scars were assessed to derive an estimate of the volume of sediment generated. Initially the volumes of both scars and debris runout were measured for a number of failures using a technique described by Crozier (1973). The potential for inter-operator variability was addressed by involving all field workers in this exercise and calibrating their estimates against each other and subsequently working in pairs. Of the failure volume, visual estimates were made of the percentages that: (a) remained within the boundary of the failure scar itself; (b) remained in storage on the slope; and (c) that had been delivered off slope. This last value is considered to be the sediment delivery ratio (SDR) associated with each individual failure. It includes delivery to ephemeral channels that were thought, on the basis of physical evidence, to have been present during the peak of storm runoff. While no allowance was made for difference in density between *in situ* undisturbed soil and depositional material, previous evidence (Preston, 1999; Preston & Crozier, 1999) suggests that for these soils with a significant component of airfall-derived parent material (tephras and tephric loess) there is little difference in density between undisturbed and deposited material.

Fig. 2 Most of the failures were flows, with very little material rafted downslope as intact blocks. Note the difference in off-slope delivery associated with this single failure.

RESULTS

Many of the failures were shallow and extremely fluid in nature (Fig. 2), suggesting a fluid failure mechanism rather than a translational shear failure. Plasticity indices were measured for a small sample (n = 10) of soils from the Hinenui study site. Plastic limits are in the range 24–33%, and with liquid limits of 32–52% the range of moisture content in which plastic behaviour is possible is rather low (2–35%), suggesting that these soils readily behave as liquids when high rainfall intensity leads to rapid infiltration. Alternatively, high pore-water pressure may have provided the triggering mechanism, and in some cases sub-surface flow in pipes was clearly a factor. As a consequence of the important role played by water, many failures exhibited a high degree of evacuation, with 63% retaining 10% or less of the failed mass on the scar and 16% being fully evacuated. As a further indication of the fluid nature of runout, only 21% of failures exhibited no coupling whatsoever with the ephemeral drainage network. Summarised results for the three study sites are presented in Table 1. The average off-slope sediment delivery ratio for the 220 failures was 26.2%. This mean value conceals considerable variability, with estimates at all three sites covering the full range of possible delivery ratios from no coupling at all through to 6% of the failures exporting ≥90% of their material to an ephemeral channel. It should further be noted that of the 26.2% of generated sediment that was delivered off the primary slopes, a large proportion was subsequently deposited on the alluvial flats without reaching the permanent channel.

Table 1 Sediment delivery estimates for the three study sites.

Site	*n*	% on scar	% on slope	% Delivery off-slope
Hinenui	68	13.5	59.1	27.4
Harrington Road	42	21.2	55.4	23.4
Gentle Annie	110	16.8	55.5	27.7
Totals	220	17.1	56.7	26.2

DISCUSSION

Although the average sediment delivery ratio can be considered relatively low, given the small size of the catchments and the high drainage density during the storm event, a number of points regarding this figure should be kept in mind. Anecdotal evidence suggests that the majority of landslides occurred towards the end of the rainfall event, when the greater proportion of the total event transport capacity had already been expended. This is supported by the physical evidence, i.e. an absence of reworking of fresh debris and almost no evidence of sheet and rill erosion on bare landslide scars. This suggests that one of the more important controls on sediment delivery is the timing of landsliding relative to duration of storm runoff (and therefore transport capacity). Had rainfall continued at high levels for a longer duration following the occurrence of landsliding, it is reasonable to surmise that some proportion of the deposited mass would have been subject to reworking and that the average estimated delivery ratio associated with this event may have been greater.

The failure mechanism has clear implications for the behaviour of debris runout, and thus also for delivery of sediment off the slope. Once fluidised, internal friction is no longer present and the flowing regolith mass is typically able to travel considerably further than would be the case for an intact sliding mass. This implies that the potential for slope–channel coupling is likely to be enhanced. Indeed, not surprisingly, those failures that occurred adjacent to or nearby channels exhibited higher delivery ratios. However, many failures occurred higher on slopes, possibly indicating the zone on the slope where perched water tables had developed, but also clearly reflecting the catchment's erosional history. The lower and middle slopes comprise a mosaic of old failure scars and associated colluvial deposits. This material is in many instances more resistant to failure, being shallower and forming slopes of lower angles. It is principally on the spurs and crests of slopes that remnant undisturbed regolith material can be found, generally with only minimal lateral support as a result of the previous failures lower on the slope. The role of topography in landslide initiation is well known – not only in terms of slope angle, but also as a control on concentration of both surface and sub-surface flow and thus on pore water pressures or on water content more generally. Clearly, the topological arrangement of failure sites relative to channel location is also an important factor influencing delivery.

The high degree of evacuation, due to both the shallow regolith and the fluid nature of failure, has implications for the longer-term geomorphic development of these slopes; with regolith stripped, susceptibility to future failure is reduced (see Crozier, 1996; Crozier & Preston, 1999; Preston, 1999, 2000). At the same time, the relatively low degree of slope–channel coupling has implications for the regional sediment flux. Although the quantum of sediment supplied directly to the main channels some hundreds of metres distant from these small catchments was minimal during the storm event, where this material remains within the catchment, it is readily susceptible to remobilisation in subsequent, possibly lower-magnitude, rainfall events. Thus, while landsliding may be a minimal contributor to the regional sediment flux in a direct sense, as argued by Hicks *et al*. (2000), the sediment it generates will eventually be reworked in smaller events and by other processes. The effect is therefore attenuated sediment supply, and landsliding may be considered to be indirectly responsible for a substantial proportion of the sediment exported through the fluvial system in areas where it episodically generates large volumes of sediment.

CONCLUSION

The extent of mass movement failure generated in this storm event confirms that landsliding is a major sediment source. Nevertheless, these simple observations of landslide sediment delivery ratios demonstrate that mass movement processes are not necessarily very efficient in terms of supplying sediment to regional sediment flux, at least in the short term. This is dependent on various other locational factors; the spatial relationships between landscape units and the interaction between this and the frequency/magnitude characteristics of the particular erosional event introduce an element of contingency into sediment delivery. More importantly, the low event-related delivery ratios imply that substantial volumes of sediment remain in the catchment available for subsequent mobilisation by more frequent lower-magnitude processes.

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