The signature of an extreme erosion event on suspended sediment loads: Motueka River catchment, South Island, New Zealand

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Abstract Five years of continuously monitoring turbidity and suspended sediment (SS) at four sites in the Motueka River catchment, northern South Island, New Zealand, has characterised the downstream and temporal dispersion of high SS inputs from an extreme rainfall event. The rainstorm, of >50 year recurrence interval, was concentrated in the upper Motueka and Motupiko tributaries and delivered high sediment outputs from re-activated gully complexes and landslides. These only appear to activate when a rainfall threshold is exceeded. Monitoring stations in these tributaries captured a ~20- to 30-fold increase in SS concentrations and event sediment yields, whereas the monitoring station at the coast recorded only a 2- to 5-fold increase. The high concentrations and event yields decayed exponentially back towards normal levels over ~2–3 years at both upstream and downstream sites. Field observations suggest that this erosion recovery trend relates more to the exhaustion/stabilisation of transient riparian sediment storage than to "healing" of the primary erosion sites by surface-armouring and/or re-vegetation. The downstream decay relates both to dilution (from other tributaries carrying lower SS concentrations) and dispersion processes. Similar space–time patterns have been observed in other New Zealand catchments and have implications for the reliability of sediment yield estimates based on short monitoring records. A method is suggested for incorporating such extreme erosion events into estimates of long-term average sediment yield.

Key words erosion thresholds; suspended sediment ratings; event sediment yields; non-stationary yields; Motueka

INTRODUCTION

Sediment yields are notoriously variable in space and time, particularly as catchment size reduces and yields are controlled by a few discrete but intermittently-active erosion sites. This creates difficulty when it is necessary to compare yields from nearby basins with only short observation records, for example, to isolate the effects of contrasting land uses or natural controls such as lithology or rainfall, or to find the efficacy of erosion control measures.

The problem is compounded where the sediment yields from a series of runoff events are inter-dependent. For example, a landslide or gully activated by a rare, intense rainstorm and connecting with a water-course can elevate the supply of sediment to a stream for some years after the initial hillslope failure, thus the sediment yields during subsequent storms are linked to the primary event and are, for a period, greater than those from previous hydrologically-similar storms. Assuming no further slope instability, the period of elevated sediment supply relates to the "healing" time required for the landslide or gully to be stabilised by processes such as armouring and re-vegetation, and to the exhaustion or stabilisation of sediment transferred to riparian storage sites downstream. This raises the possibility that a catchment can experience cycles of "normal" and "abnormal" sediment yields if the healing/exhaustion time is shorter than the average recurrence interval of erosion processes that involve some erosion threshold.

Such extreme events therefore generate non-stationarity in response relationships, such as sediment rating relations (instantaneous discharge *vs* sediment concentration) or event sediment yield *vs* event hydrological magnitude (e.g. peak flow or total runoff). If this is not recognised, it can confuse estimates of long-term average sediment yield and comparisons among basins. In such situations it is arguably more edifying to look for the effect of controls such as land use in the response relationships rather than in short-term yields.

In this paper, we present results from five years of continuous suspended sediment monitoring at four sites in the Motueka catchment, South Island, New Zealand, that capture the signature of a localised extreme erosion event in the headwaters. We show how this event affected response relationships and tributary sediment yields, and suggest an approach for estimating long-term average yields from short-term records that capture the response to an extreme erosion event.

DATA COLLECTION

Study catchment

The 2075-km^2 Motueka River catchment drains into Tasman Bay at the northern end of New Zealand's South Island (Fig. 1). The mountainous western and southern tributaries drain Palaeozoic metasediments, ultramafic and igneous rocks, and Mesozoic weathered granites. The hilly eastern tributaries drain mainly Late-Tertiary-Quaternary gravels (Moutere Gravels). The western and southern headwaters tend to have a native forest cover, the mid-slopes are typically commercial exotic forest or pastoral farmland, while the valley floors are used for grazing, dairying, or horticulture.

Rainfall averages 1670 mm year^{-1} across the catchment and is greatest (up to 3500 mm year^{-1}) in the headwaters of the western tributaries. Storms can arrive from the north, west, or south, and the rainfall distribution over the catchment is typically patchy during these events.

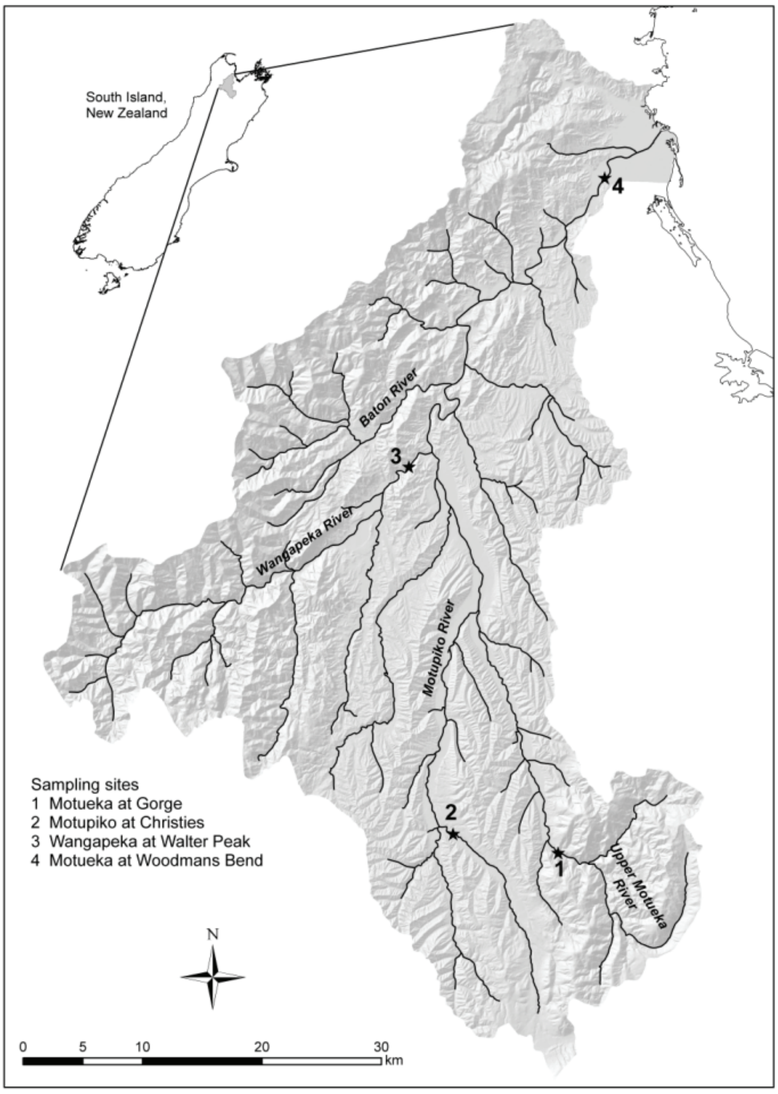

Fig. 1 Map of Motueka catchment, locating sediment monitoring stations.

Over the Easter weekend of 2005 (23–26 March), a heavy rainstorm (170 mm over 12 h with hourly intensities up to ~60 mm h^{-1}) was concentrated in the upper Motueka and Motupiko tributaries. A rainstorm of this magnitude has a >50 year return period over durations from 30 min to 24 h. The storm caused several landslips and re-activated gully complexes, both in the mountainous areas in the Motueka upstream of Motueka Gorge and in hilly terrain drained by the Motupiko River. These only activate infrequently when a rainfall threshold is exceeded.

Suspended sediment monitoring

Continuous suspended sediment monitoring has been undertaken at four sites in the Motueka catchment (Fig. 1, Table 1): on the mainstem Motueka at Woodman's Bend, capturing the discharge of sediment to the coast; on the Motupiko River at Christie's Bridge, representing the low rainfall hilly Moutere Gravel terrain; and on the Wangapeka River at Walter Peak and the Motueka headwaters at Motueka Gorge, representing the mountainous high rainfall terrain of the western and southern tributaries, respectively.

At each site, suspended sediment concentration (SSC) is proxied continuously (every 10 minutes) with nephelometric turbidity sensors (Greenspan TS300 or TS1200). Auto-samplers, activated on a stage-trigger and sampling flow-proportionally, are used during all high flow events to maintain a running field-based relationship between turbidity and SSC, to compile running sediment ratings, and to provide a backup SSC record in case of turbidity sensor failure. Occasional manual depth-integrated sampling is used to relate the point SSC at the sensor and auto-sampler intake to discharge-weighted cross-section mean SSC and also to collect samples for particle-size analysis. Micro-jets keep the turbidity sensors clear of algal growth. Gaps in the turbidity-generated record (due, for example, to sensors washing away during floods) are patched by preference with SSC data interpolated from the auto-samples, or otherwise using the current SSC-Q (water discharge) rating. Event sediment yields are integrated from the SSC and Q series records. Events are defined from the onset and ending of quickflow, which is separated from the hydrograph using the approach of Hewlett & Hibbert (1967).

RESULTS

Events over monitoring period

The flow record at the catchment outlet at Woodman's Bend over the sediment monitoring period (Fig. 2) showed a typical seasonal (winter-high) pattern, with freshes (up to 500 $m^3 s^{-1}$) occurring

Table 1 Catchment characteristics of suspended sediment monitoring sites.

Site	Catchment area (km^2)	Main lithologies	Main vegetation cover	Mean rainfall (mm $year^{-1}$)	Mean flow ($m^3 s^{-1}$)	Beginning of susp. sediment monitoring	Susp. sedt. yield over sediment monitoring period (t km^{-2} $year^{-1}$)
Motueka at Woodman's Bend	2050	Metasediments, igneous, Moutere Gravel	Native forest, plantation forest, pastoral grassland	1670	49.3	23/11/02	65
Wangapeka at Walter Peak	479	Metasediments, granite	Native forest	1980	19.2	19/11/02	60
Motueka at Gorge	163	Metasediments, ultramafics	Native forest and grassland	1790	6.7	6/4/04	610
Motupiko at Christie's Bridge	105	Moutere Gravel	Plantation forest, native forest	1460	1.6	18/11/02	111

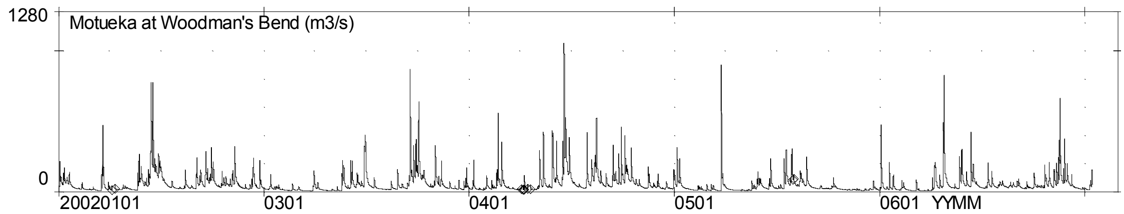

Fig. 2 Hydrograph (m^3 s^{-1}) from January 2002 through March 2007 for Motueka at Woodman's Bend.

on a quasi-monthly basis and quasi-annual events in the range 500–1050 m^3 s^{-1}. The tributaries show similar hydrograph patterns overall, but with the relative magnitude of flood peaks varying in response to the spatial distribution of rainfall. The Wangapeka patterns, with a higher baseflow, most closely matched those at Woodman's Bend, reflecting the greater rainfall and runoff from the western tributaries (Table 1). The highest flow at Woodman's Bend, in June 2004, was not exceptional at any of the tributary sites, indicating widespread but not extreme rainfall over the whole catchment. The highest flow event in the Wangapeka was not matched by similarly-sized events in the other two tributaries, indicating a westerly source for that event. The exceptional March (Easter) 2005 event in the upper Motueka (peaking at approx. 790 m^3 s^{-1}) and Motupiko (peaking at 166 m^3 s^{-1}) was focused in the south and caused only a minor fresh in the Wangapeka; however, as shown in the following sections, it had a major impact on the sediment yield response at the catchment outlet.

Suspended sediment rating relations

Rating relations between instantaneous (auto-sampled) SSC and water discharge for all four sites are shown in Fig. 3. Over the monitoring period, the scatter in SSC at given discharge ranged over

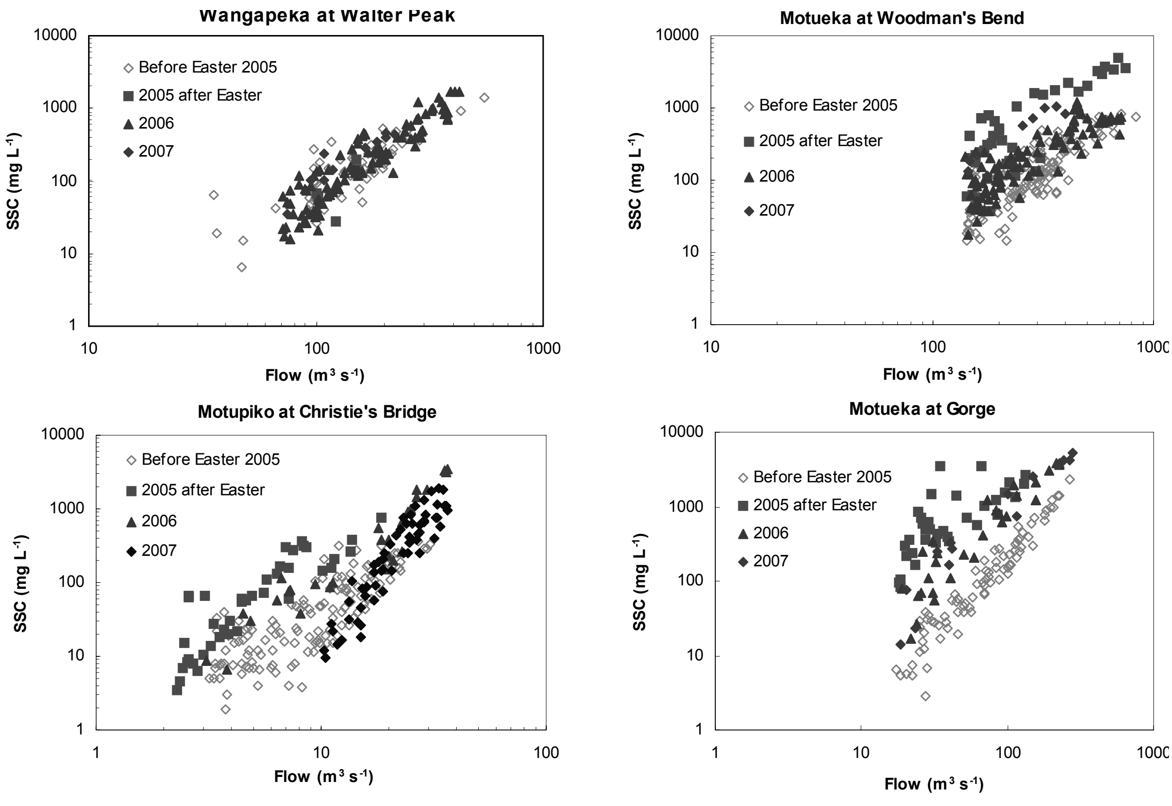

Fig. 3 Sediment rating relations for the four monitoring sites.

factors of 500, 100, 50 and 10 for the Motueka at Gorge, Motupiko, Motueka at Woodman's Bend, and Wangapeka sites, respectively. With the exception of the Wangapeka, time-coding the data (i.e. before the Easter 2005 event and in each year following that event) shows much less scatter (less than a factor of 10) in each period, and also a time-trend wherein SSC increased dramatically following the Easter 2005 event, then subsequently decayed back towards the pre-Easter 2005 range. Such temporal variability is not apparent in the Wangapeka data.

The non-stationary character of the sediment load responses of the Motueka mainstem at the Gorge and Woodman's Bend sites is shown in Fig. 4. This plots the ratio of the observed SSC to the SSC predicted from a power-law rating relation fitted to the pre-Easter 2005 data. The near-vertical stacks of points during individual events capture the 4- to 5-fold variability in SSC due to rising/falling stage hysteresis effects. Averaging-out this intra-event variability, at the Gorge the ratio of observed/predicted SSC increased by a factor of ~20–30 after the Easter 2005 event, then reduced exponentially. At Woodman's Bend, the ratio increased by only a factor of ~4–5, owing to the diluting effect of the relatively cleaner western tributaries (such as the Wangapeka) that were less affected by the Easter 2005 event.

Event sediment yield relations

The influence of the 2005 event also shows clearly in the relations between event sediment yield (SSY, t km^{-2}) and event hydrological magnitude, which we index using the event peak discharge (Q_p, m^3 s^{-1}). These event-yield ratings (Fig. 5) all show a power-law relation of the form SSY = $aQ_p^{2.45}$ and, with the exception of the Wangapeka, all show elevated event sediment yields for a given peak discharge after Easter 2005. Time-trends in the parameter a are captured in the ratio of observed event yield and yield predicted using a power law regression fit to the pre-Easter 2005 data (Fig. 6). This shows an event-yield increase by a factor of ~20 at Motueka Gorge, by 6–7 at the Motupiko, and by ~2–3 at Woodman's Bend, with a subsequent exponential reduction trend towards the "normal" range.

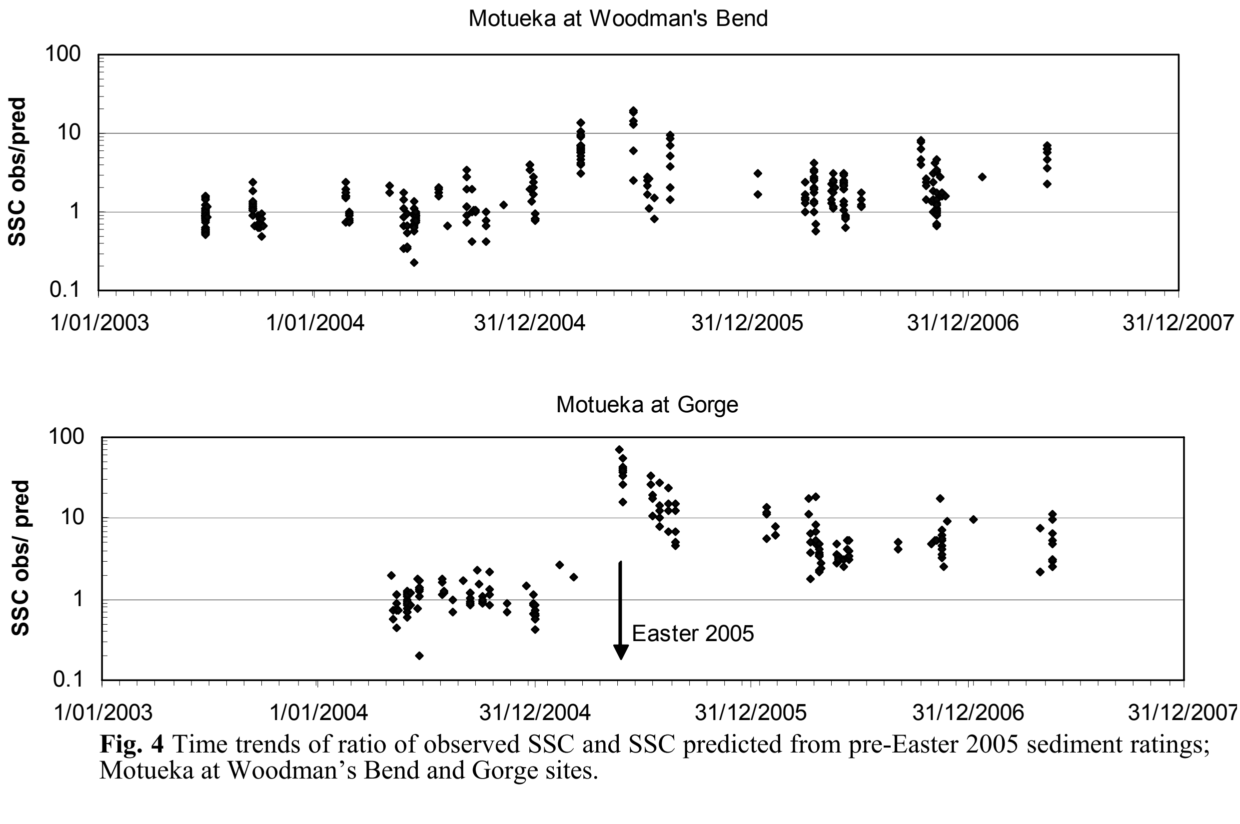

Fig. 4 Time trends of ratio of observed SSC and SSC predicted from pre-Easter 2005 sediment ratings; Motueka at Woodman's Bend and Gorge sites.

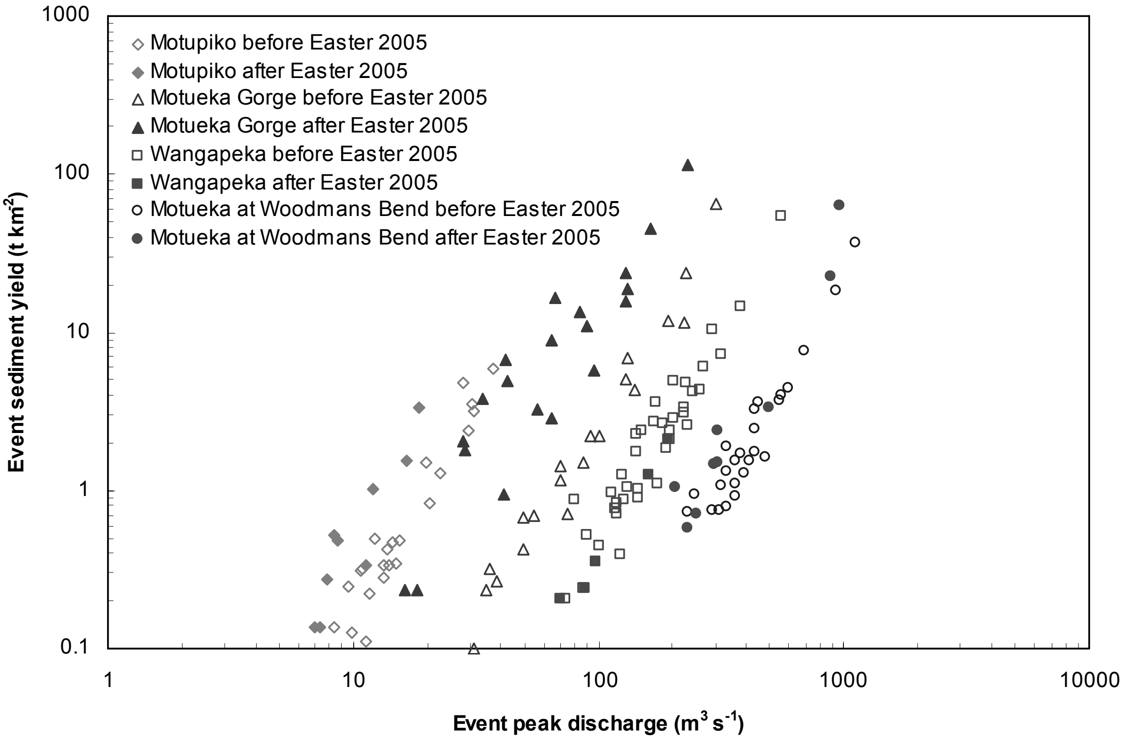

Fig. 5 Relations between event specific sediment yield and event peak discharge before and after Easter 2005.

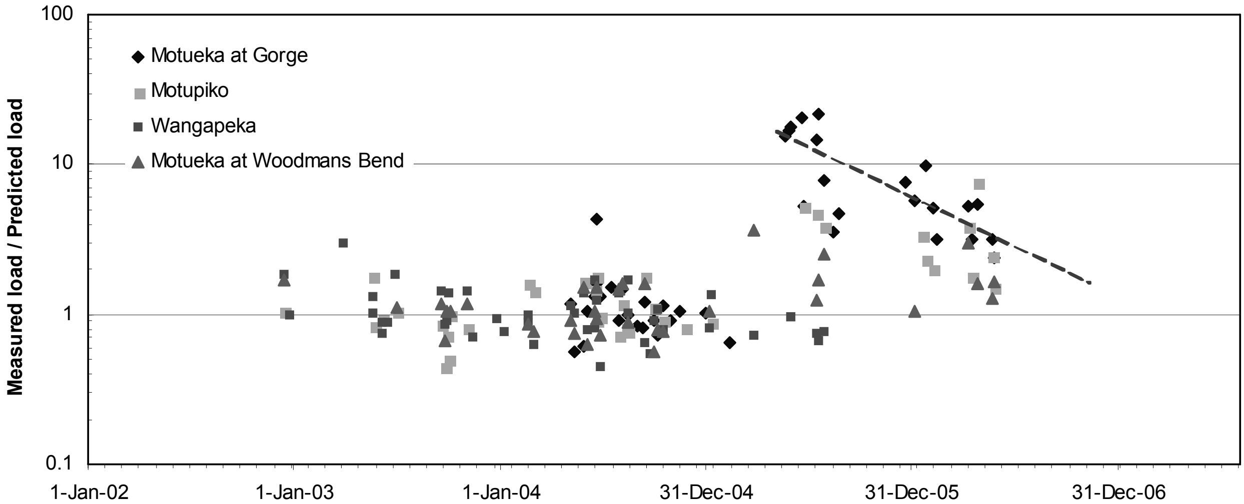

Fig. 6 Time trends of ratios of measured event sediment yield and event yield predicted from pre-Easter 2005 relations. Dashed line shows exponential decay trend at Motueka Gorge after Easter 2005.

Annual-average yield comparisons

Suspended sediment yields, integrated from the observed SSC and *Q* time-series for the periods of sediment monitoring (Table 1), suggest that while the upper Motueka and Motupiko clearly experienced more erosion during the monitoring period (as a result of the Easter 2005 event), the 5-year average catchment yield as captured at Woodman's Bend was moderated substantially by the larger western tributaries.

DISCUSSION

Non-stationary sediment yield response

Summarising the above results:

(a) An extreme rainfall event that was concentrated over the southern Motueka tributaries during March 2005 activated sediment sources that caused subsequent smaller, more common runoff events from these tributaries to carry sediment loads that were over an order of magnitude larger than those events would normally have carried.

(b) The increased yields (for events of the same peak discharge) declined exponentially with time. In the Motupiko, they had fallen into the range of normal event yields after 2–3 years, although in the upper Motueka the yields were still higher than normal after three years.

(c) While this extreme event did not significantly affect the western tributaries, the yields from the southern tributaries were sufficient to elevate sediment yields to the ocean by a factor of 2–3 over the following three years.

Similar non-stationary signals in sediment load response functions, due to the occurrence of "threshold" meteorological events that trigger erosion processes and a dramatic but transient increase in sediment supplies, have been described elsewhere (e.g. Hicks *et al.*, 2000; Nistor & Church, 2005). Hicks *et al.* (2000) noted factor of 1.4–2.2 increases in SSC at two sites in the Waipaoa catchment (North Island, New Zealand) for the three years after Cyclone Bola caused widespread landsliding and gullying (Reid & Page, 2002).

We suggest that the order 3-year time-scale for a return to (or to within a factor-of-two of) the normal range of SSC and sediment yields in landslide and gully prone terrain – such as the Motueka and Waipaoa catchments – may be set substantially by the exhaustion of in- and near-channel sources that had been "topped up" during the extreme events. While vegetation and armouring probably also help to close down the supply from riparian storage sites, field inspection in the upper Motueka showed that many of the gullies and landslides had not re-vegetated after three years. Thus the time to "heal" the sediment sources at the primary erosion sites may require longer than three years, and this would explain why the most recently measured event yields at Motueka Gorge remained above the normal range.

Estimating long-term average yields

The temporal and spatial variability in suspended sediment response exhibited in the Motueka data set complicates the task of relating differences in tributary sediment yields to factors such as lithology and land use. If the response functions (e.g. SSC-Q ratings, event yield-peak flow relations) were stationary, then these could be established over a relatively short monitoring period and then combined with the longer discharge records to derive long-term average yields. However, taking the example of the Motueka Gorge site, the estimated yield could vary over an order of magnitude depending on when the river was sampled. The ideal, but expensive, solution would be to continue monitoring long enough to reduce this sampling error.

An alternative approach is to embed in the sediment response function some dependence on recent erosion-triggering events. For example, event sediment yields may be predicted with the relation:

$$\mathrm{SSY} = a_t\, Q_p^{\,b} \quad \text{with } a_t = a_o\,(1 + (a_{max}/a_o - 1)\exp(kt)) \tag{1}$$

where a_t is the time-varying value of the coefficient to the SSY-Q_p response function, a_o is its value under normal conditions, a_{max} is its value immediately after an erosion-threshold-passing event, k is the exponential decay-rate constant for the ratio of SSY observed to normally-expected SSY following such an event, t is the time elapsed since such an event, and the exponent b is assumed independent of time. To estimate the long-term average yield, equation (1) can be combined with a long time-series of event peak flows, with t being re-set to zero whenever an event occurs that exceeds a given threshold. This would require monitoring sediment loads only long enough to: (a) identify the magnitude of hydrological event required to trigger significant erosion; (b) measure the relative increase in sediment load immediately after the threshold event; and (c) define the characteristic time for yields to return to the normal range.

Taking the example of the Motueka at Gorge, $a_o = 0.0000329$ and $b = 2.45$ from Fig. 5, and $a_{max}/a_o = 20$ and $k = -1.33$ (with units 1/years) from Fig. 6. The flow record, spanning 42 years from 1965 to 2007, contains two exceptional events, both peaking at ~800 m^3 s^{-1}, that occurred on 23 February 1995 and 23 March 2005 (i.e. the Easter 2005 event reported herein). Anecdotal accounts suggest that the 1995 event also triggered severe erosion in the upper Motueka catchment. The next biggest floods peaked below 600 m^3 s^{-1}. Thus, we might reasonably assume that floods greater than ~700 m^3 s^{-1} are associated with phases of "abnormal" erosion. With this assumption, application of equation (1) to the 42-year peak discharge record at Motueka Gorge gives a sediment yield of 519 t km^{-2} year^{-1}. A yield of only 94 t km^{-2} year^{-1} results if the "normal" response relation is applied over the entire 42-year period. This difference highlights the sensitivity of the long-term average sediment yield from a catchment to extreme events that perturb its erosion regime.

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