Geomorphology 305 (2018) 49–60

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

# State-shifting at the edge of resilience: River suspended sediment responses to land use change and extreme storms

Samantha Abbott [a], Jason P. Julian [a,*], Ioannis Kamarinas [a], Kimberly M. Meitzen [a], Ian C. Fuller [b], Samuel T. McColl [b], John R. Dymond [c]

[a] Department of Geography, Texas State University, San Marcos, TX 78666, USA
[b] Physical Geography Group, Institute of Agriculture & Environment, Massey University, Palmerston North, New Zealand
[c] Landcare Research, Palmerston North, New Zealand

ARTICLE INFO

Article history:
Received 27 March 2017
Received in revised form 1 September 2017
Accepted 4 September 2017
Available online 9 September 2017

Keywords:
Resilience
Landslides
Suspended sediment regimes
Land use change

ABSTRACT

The interaction of climate, geomorphology, and land use dictates catchment sediment production and associated river sediment loads. Accordingly, the resilience of catchments to disturbances can be assessed with suspended sediment regimes. This case study in the hill country of the lower North Island of New Zealand was a decade-long examination of the short- and long-term effects of an extreme storm event on sediment supply and exhaustion in the Oroua and Pohangina catchments, two catchments that have experienced intense land use changes and frequent broad-scale landslides. Indicators of Hydrologic Alteration, a program developed to characterize hydrologic regimes, was used to analyze daily suspended sediment records over a period of a decade in order to characterize sediment regimes of the Oroua and Pohangina. An aggregated data set of sediment-bearing events for the period of record was analyzed to examine the suspended sediment response of individual storms relative to runoff magnitudes. The findings of this study demonstrate that large storms that generate extreme landsliding and flooding have the ability to produce enough sediment to temporarily convert catchments from a supply-limited state to a transport-limited state. Landsliding and thus sediment supply was disproportionately high in locations where livestock grazing occurred on steep hillslopes. The timing and intensity of previous storms, or the antecedent catchment condition, was also shown to influence the response of the catchments. In both catchments, suspended sediment loads were elevated for a period of ~4 years following the landslide-generating February 2004 storm. The methods and findings we present are useful for assessing the resilience of catchments exposed to frequent disturbances such as land use changes and landslides.



## 1. Introduction

Sediment yield from a catchment is the result of many interacting environmental and anthropogenic factors and processes: geology, climate, tectonics, topography, soils, precipitation, vegetation, and land use (Knox, 1972; Milliman and Meade, 1983; Syvitski et al., 2000; Uriarte et al., 2011). Among these factors, disturbances in the form of extreme precipitation events and land use changes have disproportionate effects on river sediment regimes (Graf, 1977; Simon and Guzman-Rios, 1990; Gregory, 2006; Crozier, 2010). The resilience of a catchment to these disturbances—the ability of the catchment to 'absorb' the disturbance and retain its structure, function, and feedbacks (Walker and Salt, 2006)—depends on the relationships and cross-scale interactions of the aforementioned factors and processes (Julian et al., 2016; Reid and Dunne, 2016). One of the key tenets of resilience theory is that 'complex adaptive systems' like river catchments display emergent behavior, such that a change in one system component can cause the system to shift to a new regime or stable state (Walker and Salt, 2006, p. 35). Support for this concept has been demonstrated for catchment-scale sediment yield over millennial timescales as part of Knox's (1972) biogeomorphic response model, but could similar behavior occur over shorter timescales?

The biogeomorphic response model developed by Knox (1972) is a conceptual model that describes the relationships among precipitation, vegetative land cover, hillslope potential for erosion, and sediment yield (Fig. 1). Over millennial timescales, increased precipitation that follows a dry period will generate rainfall on relatively bare ground (or sparse vegetation) with a high hillslope potential for erosion, causing a spike in sediment yield. As vegetation cover becomes denser under a more humid climate, the hillslope potential for erosion decreases along with the sediment yield (Fig. 1A, left-half). A return to drier conditions results in vegetation cover dying back and the potential for erosion will increase again, but sediment yield will not increase until precipitation returns as an erosive force. In this model, land cover is dictated by precipitation regimes, and a negative feedback process occurs that

* Corresponding author.
E-mail address: jason.julian@txstate.edu (J.P. Julian).

http://dx.doi.org/10.1016/j.geomorph.2017.09.004
0169-555X/

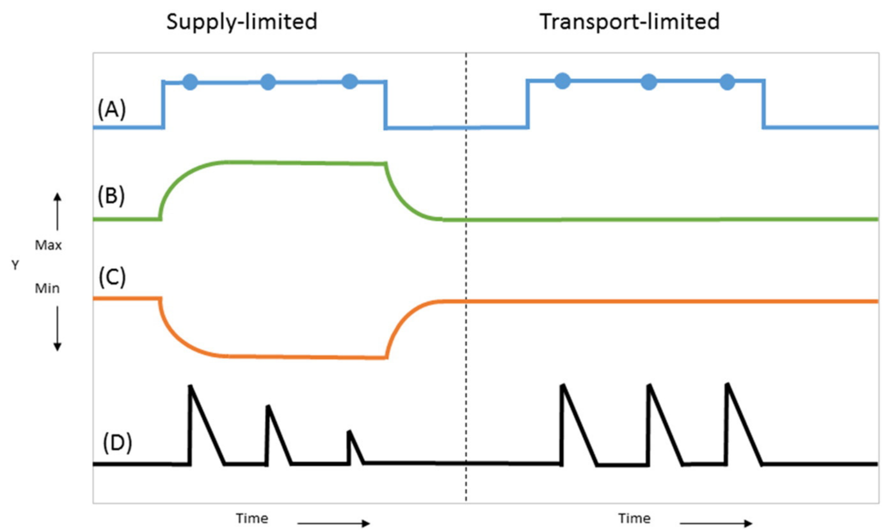


**Fig. 1.** Modified biogeomorphic response model. Seasonal interactions between (A) precipitation, (B) vegetative cover, (C) hillslope potential for erosion, and (D) suspended sediment yield response to individual storm events within a wet season. Lines (A-C) modified from Knox (1972). Line (D) contributed by authors. We added three dots on the precipitation line to indicate three storms of equal magnitude. The left half of the plot displays a supply-limited regime, where vegetative cover increases and hillslope potential for erosion decreases as the wet season progresses, creating a diminishing suspended sediment yield response over time to individual storm events of equal magnitude. The right half of the plot displays a transport-limited regime, where vegetation and hillslope potential for erosion are controlled by human land use (e.g., deforestation, overgrazing, etc.). In this scenario, available sediment in the landscape is abundant, therefore the suspended sediment yields to individual storm events would be proportional to the magnitude of the storm, regardless of when they occur in the wet season (i.e., early, middle, late).

maintains a sediment supply-limited state (Fig. 1D, left-half), where river loadings are limited by available sediment in the landscape. In a resilience context, the sediment supply-state-shifts of this long-term process-response model could be described as 'slow' variables operating within a cyclic framework of a resilient system that shifts between supply and transport limitation (Walker and Salt, 2006). However at shorter timescales, if land cover and sediment sources are instead dictated by human land use and discrete disturbances, which can both be viewed as 'fast' variables (e.g., deforestation, overgrazing, landslides), can enough sediment supply be created to shift the catchment to a sediment transport-limited state (Fig. 1D, right-half), where available sediment is abundant and river loadings are instead limited by runoff? And, if the 'fast' variables associated with land use change can force this state-shift, will the transport-limited state become persistent and force the system to permanently cross a threshold, or will the system shift back to supply-limited and operate within a boundary of resilience?

Land use practices such as intensive livestock grazing and plantation forestry can have significant impacts on river sediment regimes (Foley et al., 2005; Kamarinas et al., 2016; Julian et al., 2017). The relatively bare soil that remains after vegetation removal is susceptible to erosion during intense or sustained precipitation events, which leads to increased sediment loading that degrades river water quality (Milliman and Farnsworth, 2011). This temporary increase in available sediment can also shift a catchment from a supply-limited state to a transport-limited state over a relatively short time period (Fig. 1D). These terms were developed to describe aggrading and degrading river systems (Lane, 1955; Fryirs and Brierley, 2013) but can also describe sediment delivery to rivers from their drainage areas (Brierley et al., 2011). In terms of resilience, this change from a supply-limited to a transport-limited regime represents a new state. If this new state persists, the system would eventually cross a threshold toward channel aggradation; however, if it shifts back to supply-limited, then it would maintain a dynamic equilibrium between state-shifts, preserving the catchment's resilience to absorb land use disturbances.

In order to test the hypothesis that land use change can switch a catchment from a supply-limited state to a transport-limited state and the persistence of this state-shift for assessing resiliency, we used two catchments from New Zealand's North Island hill country. These catchments were ideal for this study because of the region's active geomorphology and relatively recent changes in land use; these factors provide a 'natural' experiment to examine the catchments responses to specific disturbances defined by spatial and temporal boundaries and cross-scale interactions, which is important for determining a system's resilience (Walker and Salt, 2006). Rainfall-induced landsliding is a dominant process of slope erosion and sediment delivery to rivers in this region (Hicks et al., 2000; Dymond et al., 2006; Basher et al., 2011, 2012; Basher, 2013). Landslide source areas and their debris tails can remain unvegetated for months to years, being prone to new erosion and remobilization in subsequent rainfall events (i.e., enhanced sediment supply). These landslide legacy effects have been documented in the East Coast region of New Zealand's North Island, where landsliding exposed slopes to subsequent gullying and high sediment yields (Gage and Black, 1979; Betts et al., 2003; Parkner et al., 2007; Fuller and Marden, 2011; Marden et al., 2012).

A number of studies have examined the impact of land cover/land use changes (LCLUC) on erosion rates and/or sediment yields in catchments throughout New Zealand (Fahey et al., 2003; Glade, 2003; Elliot and Basher, 2011; Kamarinas et al., 2016). The general findings show that converting indigenous vegetation to agricultural land uses results in increased soil erosion and higher sediment yields in rivers dominated by surface water runoff. In the steep, soft-rock terrain of the New Zealand hill country, which was virtually all forested before European settlement (ca. 1860; Fuller et al., 2015), these effects from forest-to-pasture conversions have been magnified because of a loss of rainfall interception and the removal of stabilizing root systems (Preston and Crozier, 1999; Quinn and Stroud, 2002; Reid and Page, 2002). While the effect of agricultural LCLUC on sediment yields is well founded, we lack an understanding of the long-term impacts of LCLUC on a catchment's resilience given the potential shifts between different sediment supply- and transport-limited states.

This study explored changes in the sediment-transport state of two catchments in response to two disturbances: forest-to-pasture conversion and an extreme precipitation event. In doing so, we examined spatial and temporal patterns, as well as geomorphic feedbacks and cross-scale interactions. Specific objectives were: (i) characterize fluvial suspended sediment regimes by using a previously developed hydrologic regime analysis technique; (ii) assess effects of land use on landslide occurrence and available sediment; (iii) identify landslides that are direct sediment sources to river channels and those that create legacy sediments for remobilization in later events; and (iv) determine when and why catchments switch from sediment supply limitation to transport limitation.

## 2. Methods

### 2.1. Study area and period

The Oroua and Pohangina river catchments are located in the southern part of the North Island of New Zealand (Lower North Island) (Fig. 2). Since European settlement ca. 1860, the Lower North Island's indigenous forest cover has increasingly been replaced with grassland for pastoral agriculture (Dymond et al., 2006; Vale et al., 2016). Present land cover (as of 2012) is dominated by shrub/grassland (mostly used as pasture), followed by indigenous and planted forests (Table 1). The climate in the region is temperate, with annual rainfall varying from 800 mm at the coast to 5000 mm at the top of the Ruahine Range, which runs north-south along the center of the Lower North Island. More rainfall typically occurs in winter than in summer, though weather in the region is generally variable (Fuller, 2005). In February 2004, the Lower North Island experienced an extreme precipitation event with an approximate recurrence interval of 150 years that resulted in extensive landsliding and flooding (Dymond et al., 2006; Fuller, 2007). The 15–16 February 2004 storm brought >20 h of consistent rainfall to the region and resulted in variable sediment responses between catchments (Fuller, 2007).

The most extensive landsliding during this event occurred in the Oroua and Pohangina river catchments, which are adjacent in the northwest portion of the Manawatu River basin and drain the mountainous Ruahine Range to the southwest (Fig. 2). The Ruahine Range comprises highly fractured greywacke (siltstone and sandstone) and is tectonically active, with uplift rates of up to 2.5 mm/y (Fuller et al., 2016). The Oroua and Pohangina catchments drain 308 and 489 $km^2$ respectively and have similar drainage densities, mean catchment slopes, relief ratios, and ruggedness (Table 1). Adjacent to and west of the greywacke Ruahine Range, the Oroua and Pohangina catchments are underlain by a thick succession (up to 4 km) of weakly lithified Plio-Pleistocene marine mudstones, sandstones, and gravels associated with the eastern Wanganui Basin (Abbott et al., 2005; Lee et al., 2011). These beds of poorly consolidated sandstones, mudstones, and gravels have been highly dissected in the Oroua and Pohangina catchments, producing highly erodible, short, steep hillslopes. Dominant soil orders include Brown soils and Pallic soils, which cover ~70% and 15% of the total land area respectively. The catchments are divided by the crest of an anticline, which is uplifting at an approximate rate of 1 mm/y (Fuller, 2007). This physiographic setting is conducive to high erosion rates, and specific sediment yields in the region are as high as 5809 t/$km^2$/y (Hicks et al., 2011). In addition to their active geomorphology and relatively recent land use changes, the Oroua and Pohangina catchments were chosen for analyses because they were heavily impacted by landsliding during the February 2004 storm (Hancox and Wright, 2005; Dymond et al., 2006) and because of their coincident availability of high-resolution discharge and turbidity/suspended sediment data sets.

### 2.2. Data

Environmental data utilized in this study included physiography, land cover/use, hydrology, and water quality. Physiographic data included a 15-m digital elevation model (DEM), local soil characteristics from the New Zealand Soils Database (Landcare Research, 2016), and hydrography from the River Environment Classification (REC, v2, National Institute of Water and Atmospheric Research (NIWA), 2016; Snelder et al., 2010). Land cover/use was obtained from the New

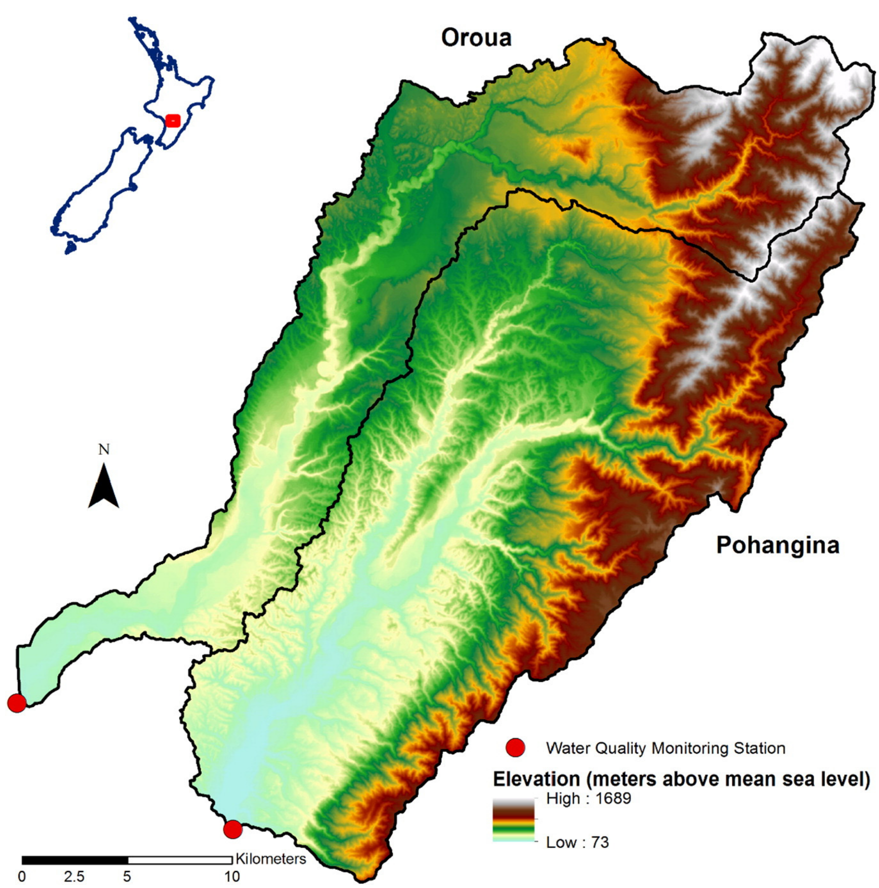


**Fig. 2.** The Oroua and Pohangina catchments, located on the Lower North Island of New Zealand.

**Table 1**
Physiographic characteristics of the Oroua and Pohangina catchments.

| | Oroua | Pohangina | Definition (units) |
|---|---|---|---|
| Area | 308.00 | 489.20 | Total catchment area above monitoring site ($km^2$) |
| Drainage density | 1.68 | 1.70 | Total length of streams per catchment area ($km/km^2$) |
| Mean catchment slope | 16.00 | 18.90 | Mean slope across entire catchment (%) |
| Relief ratio | 0.02 | 0.02 | The difference in elevation between the highest point in the catchment and the monitoring site divided by the total length of the catchment |
| Ruggedness | 13.40 | 11.30 | Standard deviation of catchment slope |
| Land cover (2012) | | | Catchment areal coverage of land cover (%) |
| Grassland/pasture | 72.60 | 64.90 | |
| Indigenous forest | 23.00 | 32.30 | |
| Plantation forest | 3.30 | 2.50 | |
| Other | 1.10 | 0.30 | |

Zealand Land Cover Database (LCDB, v4.1, Landcare Research, 2015). Hydrologic data included daily rainfall and daily water discharge obtained from Horizons Regional Council (HRC). Mean daily discharge values (in l/s) were used to calculate volumetric daily runoff magnitudes (in $m^3$). The water quality variable we used in this study was daily suspended sediment (SS) loads provided by HRC, with methods detailed in Basher et al. (2012). They collected these data at State of Environment (SoE) monitoring sites at the outlets of the Oroua and Pohangina catchments (see Fig. 2). Daily SS loads (in tonnes) were calculated for the two sites using turbidity and discharge data collected from the monitoring stations according to the following methods. In situ turbidity meters collected continuous-time-series turbidity data. Water samples collected during storm events were used to develop turbidity-suspended sediment concentration (SSC) rating relationships, which were then used to convert the turbidity data to an SSC time series. The SSC time series was integrated with the discharge time series to calculate daily SS loads. Daily data were available for the dates 9 November 2003–18 June 2014 for the Oroua and 14 April 2000–1 April 2014 for the Pohangina. About five months of data (23 May 2010–2 September 2010) were missing from the SS record in the Oroua catchment owing to a lapse in funding.

Landslide scars in our study area resulting from the February 2004 flood were previously mapped by Dymond et al. (2006) using SPOT5 10-m resolution data to develop a landslide susceptibility model for the Manawatu-Wanganui region. Landslides were identified by applying an unsupervised classification to the images and finding bright classes corresponding to bare ground on slopes >5°. A separation algorithm was used to separate landslide scars from debris tails. The map identified landslides with an accuracy of 80% and overestimated total landslide area by 2%. We used this data set to identify the locations of landsliding in the Oroua and Pohangina catchments and derive their slope, land cover, and connectivity to river channels. Soils data were too coarse (1:63,360) to differentiate soil characteristics among landslides.

A river-landscape connectivity layer (methods detailed in Kamarinas et al., 2016) was created by utilizing DEM derivatives. Flow direction and slope, in addition to river network and its floodplain, were modeled and each pixel's connectivity was evaluated based on slope and proximity to the floodplain thresholds. Floodplain extent was simulated by applying different buffer sizes on stream segments based on their stream order: 30-m buffer on third- and fourth-order order, 60-m buffer on fifth- and sixth-order, and 90-m on seventh-order streams. On the occasion that the next two pixels down the flowpath had a slope of >5° or that the next pixel was river/floodplain, then the originating pixel was labeled as connected; if the slope condition was not satisfied, then the pixel was labeled as disconnected. The resulting river-landscape connectivity layer was then used as a mask on the landslide occurrence map to assess which landslides were directly connected to the river channels.

Nonparametric statistical analyses were performed to test whether landslides on shrub/grasslands occurred on slopes that were significantly different from landslides that occurred on forests. The pairwise Wilcoxon rank sum test was chosen to compare the difference in slope between these two land cover groups, based on 2002 land cover (i.e., before the 2004 event). We used the Bonferroni correction to compensate for the increase in chances of getting significant *p*-values due to multiple comparisons.

### 2.3. Sediment regime analyses

Indicators of Hydrologic Alteration (IHA), software developed by The Nature Conservancy (2009), calculates the characteristics of natural and altered hydrologic regimes using daily discharge data. However, there is no reason why data in different units…could not also be used in the IHA (The Nature Conservancy, 2009). For this study, we used IHA to analyze daily discharge and daily SS records in order to characterize the flow- and sediment-regimes of the Oroua and Pohangina catchments. Sediment-bearing flood events were identified based on the daily SS record rather than the mean daily discharge record, using the environmental flow component (EFC) analysis in IHA. The IHA is commonly used to characterize hydrologic conditions and changes in a system, but application of this software to the suspended sediment record is a relatively novel method that to the best of our knowledge has only been used by one previous study (Yang et al., 2010). The >10-years availability of daily SS data allowed us to identify 'sediment events' and to characterize fluvial sediment regimes.

The IHA calculates 67 different metrics; of those, we focused on the monthly median values and a subset of the EFCs. The monthly median values were used to examine seasonal differences between winter and summer months. The EFCs classify the frequency and duration of five different flow components (extreme low flows, low flows, high flow pulses, small floods, and large floods), and we used these to classify sediment-bearing events. While specific magnitude, exceedance probability, or recurrence intervals can be set to characterize the EFCs, by default extreme low flows represent hydrological drought defined as <10% exceedance, low flows represent flows between 10 and 50% exceedance, high flow pulses represent flows that begin at 50% and increase to >75% exceedance, small floods represent high magnitude events with a return interval of at least 2 years, and large floods represent peak flow events with a return interval of 10 years or greater (The Nature Conservancy, 2009). For this study, we were interested only in the sediment-bearing events that include high flow pulses, small floods, and large floods. The duration of high flow pulse events are classified when the rising flow is >50% exceedance and increases by >25%/d up to a flow >75% exceedance, and the event ends when flows decrease by <10%/d back and down to <50% exceedance. If the peak of those events increases to a small flood or large flood, then the event is classified as such. With these parameters, individual events were defined as a period of continuous days classified as high flow pulses, small floods, or large floods based on the SS record. An aggregated data set of the daily flow and suspended sediment data was developed based on the results of the EFC analysis to look at the total runoff and event-based SS magnitude, intensity, duration, and sequencing of events for the period of record (sensu Julian and Torres, 2006).

The total runoff and SS magnitudes were calculated for each event by summing daily totals to create the event data set. Event peak values are the largest daily SS and runoff values within an event. Event SS magnitudes were normalized by event runoff magnitudes in JMP® Pro (v. 11.2.1) with a local polynomial regression (LOESS) using a quadratic fit, a tri-cube weighting function, a smoothing window ($\alpha$) of 0.67, and a zero-pass robustness to identify the mean condition, which represents the expected SS magnitude for a given runoff magnitude (Cleveland and Devlin, 1988). LOESS allows for an objective and empirical curve fit without making any assumptions about the form of the relationship. The difference between the expected and observed SS values for each event, referred to as the SS residuals, were plotted in a time series to analyze the relative SS response to flood events. One standard deviation of the population was used to identify events with significantly elevated or depleted SS magnitudes relative to their runoff magnitudes. These criteria were used to identify supply-limited (significantly depleted SS magnitudes over an extended period that exceeds seasonal fluxes; multiple years) and transport-limited states (significantly elevated SS magnitudes over an extended period that exceeds seasonal fluxes; multiple years) in the catchments within the period of record.

## 3. Results

### 3.1. Landslide occurrence within the context of physiography and land cover

Landslide scars triggered by the February 2004 storm covered 1.7% (5.22 km$^2$) of the Oroua catchment and 2.2% (10.34 km$^2$) of the Pohangina catchment. Aerial imagery from February 2005 revealed that many of these landslide scars remained unvegetated at least a year after the event (Fig. 3).

Shrub/grassland accounted for 77.4% and 84.4% of the land area of the Oroua and Pohangina catchments respectively (Fig. 3). Forest (mostly indigenous) occupied 21.3% of Oroua and 14.8% of Pohangina. No other land cover type exceeded 1% of total land area. The comparison of landslide occurrence between land cover classifications revealed that 94.2% of landslides in the Oroua and 97.9% of landslides in the Pohangina occurred on shrub/grassland (Fig. 3), with the vast majority of these being intensively managed pastures. When normalized by land cover (m$^2$ of scars/km$^2$ of land cover), landslide scar density was 16,000 m$^2$/km$^2$ for shrub/grasslands in Oroua yet only 700 m$^2$/km$^2$ for forests. Similarly for Pohangina, landslide scar density for shrub/grasslands was 20,700 m$^2$/km$^2$ but only 300 m$^2$/km$^2$ for forests.

Landslide patterns with hillslope angle were almost identical between the two catchments. Landslides in the Oroua occurred on slopes with a mean (±SD) slope angle of 19.2° ± 10.5°, and in the Pohangina landslides occurred on slopes with a mean slope angle of 19.3° ± 8.9°. When compared between land cover classes, the Wilcoxon rank sum test (with Bonferroni correction) showed that landslides on forests had significantly ($p$-value < 0.001) higher slope angles than landslides on shrub/grasslands. The mean slope angle for landslides under forest cover was 26.9° ± 12.1°, while for shrub/grasslands, it was 18.8° ± 9.2°.

The connectivity analysis (Fig. 4) revealed that 25% of landslides in the Oroua and 28% of landslides in the Pohangina were directly connected to the river channels and likely contributed to SS loads during the course of that runoff event.

### 3.2. Flow and sediment regimes

The median daily SS and discharge values for each month for the period of record show distinct seasonal patterns in the Oroua and in

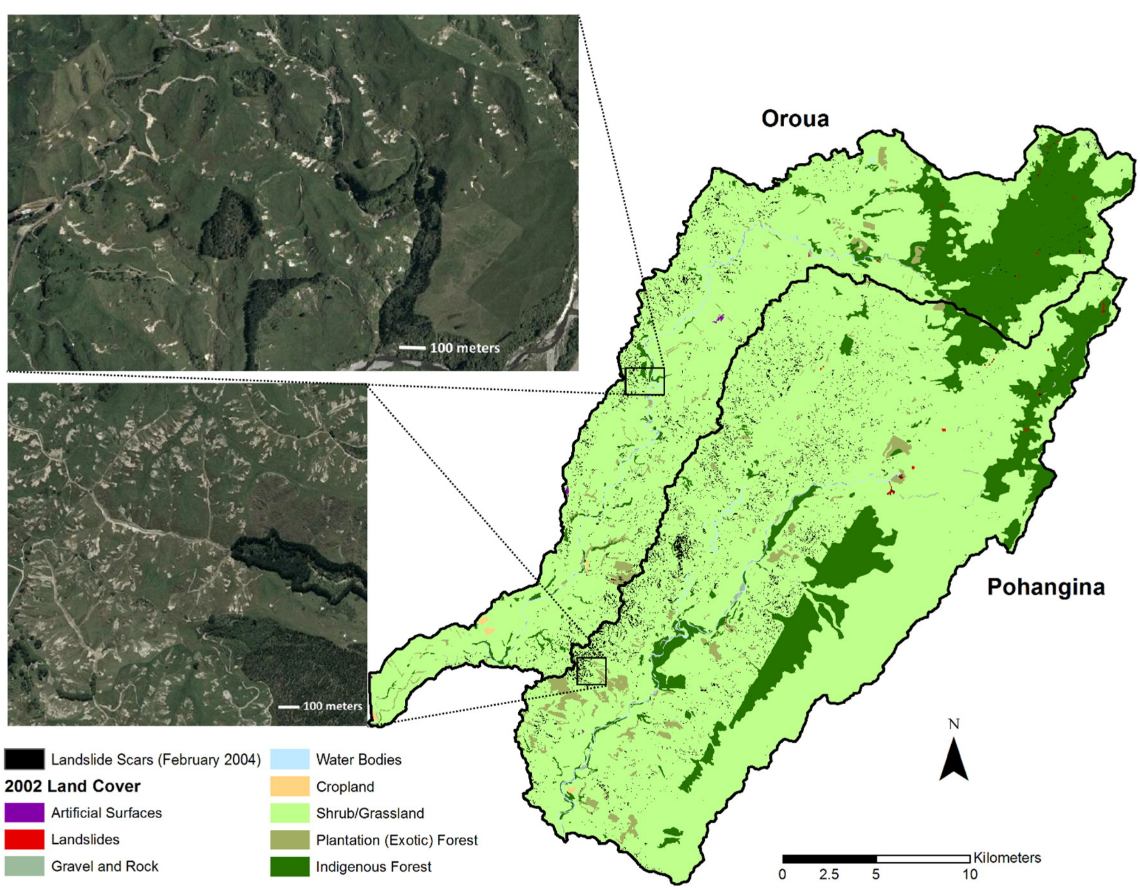


**Fig. 3.** Land cover in the Oroua and Pohangina subcatchments for the year 2002. Inset satellite imagery from nearly one year (January–February 2005) after the February 2004 storm shows landslide scars persisting on grassland and pasture. Forested areas show more resistance to landsliding.

the Pohangina, with higher SS loads and discharge rates occurring in winter months (June–October) than in summer months (November–May) (Fig. 5). The relative difference between SS and discharge also displayed a seasonal pattern where sediment loads were higher (for the same discharge) during winter months. Maximum daily discharge values for each month for the period of record were relatively consistent throughout the year, while maximum daily SS values for each month for the period of record were more variable because of the influence of large individual storm events. For example, the maximum daily SS value for the month of February for the period of record occurred during the February 2004 storm.

Results of the IHA flow and suspended sediment regime analyses revealed that a total of 265 sediment events in the Oroua and 403 sediment events in the Pohangina occurred during the period of record (Table 2). A greater number of these events occurred in winter months (57% and 61% for Oroua and Pohangina respectively) than in summer months. The longest sediment event in the Oroua was a 'small flood' that lasted 28 days and occurred in the summer, while the longest sediment event in the Pohangina was a 'high flood pulse' in the winter that lasted 24 days. The median sediment event duration in both catchments was 2 days. While the median runoff magnitudes and peaks were higher in sediment events that occurred in winter months than in summer months, the maximum runoff and peaks occurred in sediment events in summer months. The highest SS magnitudes and peaks for the sediment events also occurred in summer months. Suspended sediment–runoff relationships for the sediment events showed that for a given runoff magnitude, SS magnitudes were often higher in summer than in winter (Fig. 6). On average, summer sediment events in the Oroua had 86% higher SS magnitudes than winter sediment events. In the Pohangina, this difference was only 15%.

Time series analyses of the SS residuals for the identified sediment events are displayed as bubble charts along with rainfall in Figs. 7 and 8. In the Oroua catchment, 11 events had SS residuals elevated relative to the mean (greater than one standard deviation of the population), and these events carried 46.8% of the total sediment load for the period of record. In the Pohangina, 21 events had SS residuals elevated relative to the mean, and these events carried 58.1% of the total sediment load. With few exceptions for either catchment, events with SS loads significantly depleted relative to the mean tended to occur in winter months. In the Oroua, there were 14 such events with significantly depleted SS loads, with all but two of them occurring in winter. There were 19 such events in the Pohangina, 17 of which occurred during winter. The majority of sediment events were relatively small in magnitude and duration, and the SS residuals for these events tended to cluster about the mean condition.

The largest runoff event, the February 2004 flood, had SS magnitudes that were significantly elevated relative to the mean condition in both catchments, especially in the Oroua (Figs. 7 and 8). The largest events in the Pohangina in the following 4 years, up to 2008, had significantly elevated SS loads. From 2008 onward, there were fewer elevated SS events overall and none between 2008 and 2012, with the largest event during this period having an SS load significantly depleted relative to the mean. There were fewer large events in the Oroua closely following the February 2004 event, but two of the three largest post-2004 events were significantly elevated relative to the mean. As in the Pohangina, a period of depleted sediment began in Oroua in 2008. Another period of elevated SS followed this period of sediment exhaustion in the Oroua catchment beginning in mid-2010, but the same was absent from the Pohangina record. This period of elevated sediment loads in the Oroua occurred after a period of missing SS data, which

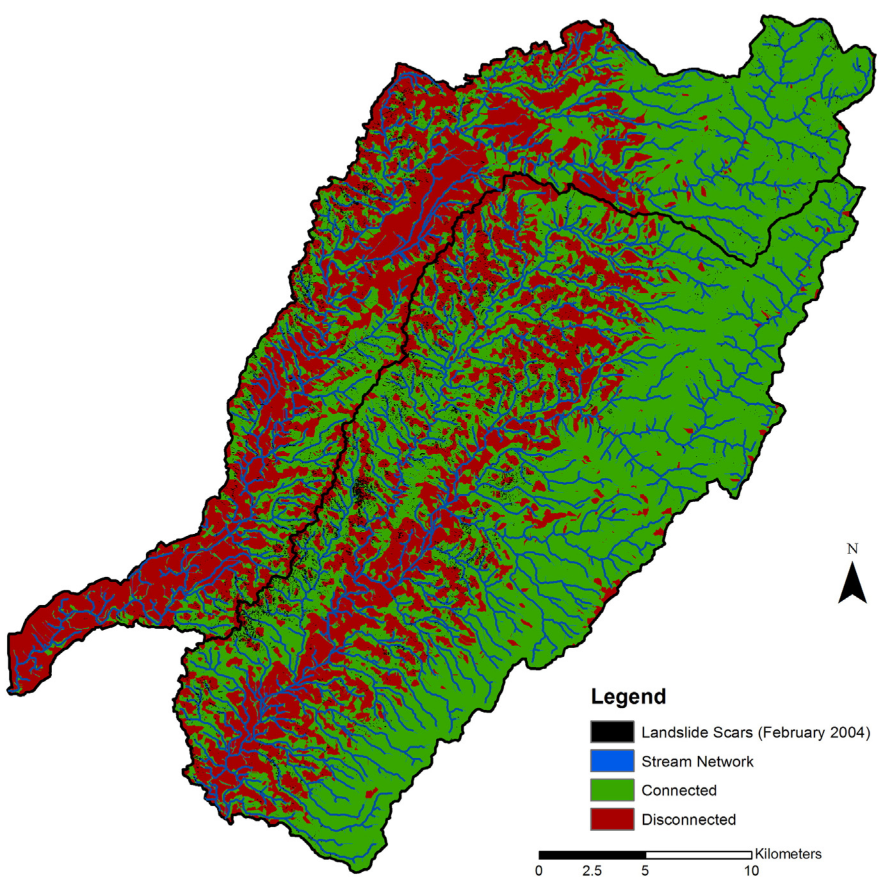


**Fig. 4.** The connectivity analysis identified 55% of the Oroua and 71% of the Pohangina as immediately connected to the river network. Of the landslides that resulted from the 2004 storm, 25% and 28% were connected to the river channels in the Oroua and Pohangina respectively.

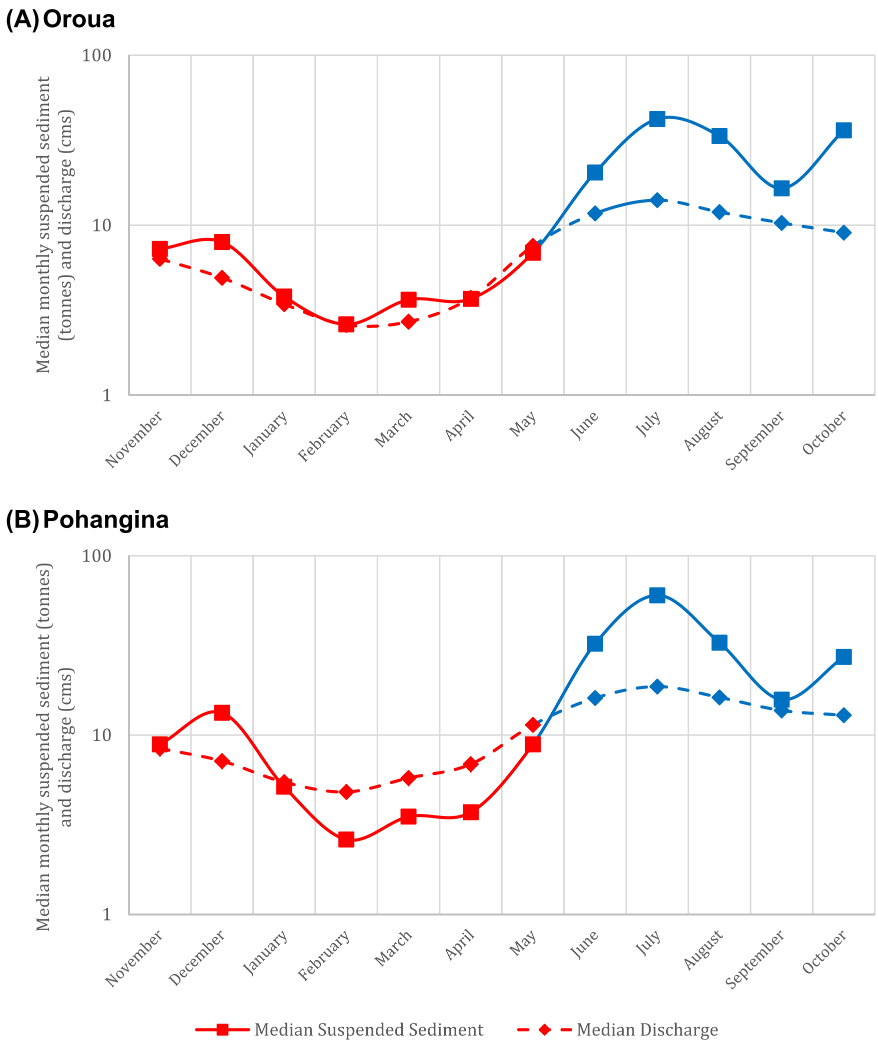


**Fig. 5.** Monthly median daily discharge (diamonds, dashed line) and suspended sediment (squares, solid line) for the period of record for Oroua (A) and Pohangina (B). Higher median discharge and suspended sediment magnitudes are observed in winter months (June–October; blue) than in summer months (red) in both subcatchments.

was missing owing to a lapse in funding, but during a period that included a large storm.

## 4. Discussion

### 4.1. Land use effects on catchment soil erosion

In the North Island of New Zealand, widespread shallow landsliding commonly occurs in the soft-rock hill country (Sparling et al., 2003; Crozier, 2010; De Rose, 2012), and this process can also be extensive in harder, fractured, greywacke terrain (Fuller et al., 2016). However, it is the soft-rock terrain that is the dominant sediment source in the wider Manawatu basin (Vale et al., 2016). In soft-rock terrain, removal of forests to increase pastoral land cover has led to an increased frequency and distribution of rainfall-induced landsliding because of a loss of rainfall interception and the removal of stabilizing root systems (Preston and Crozier, 1999). Landsliding in the Oroua and Pohangina catchments during the February 2004 event occurred disproportionately on pasture, corroborating other studies that found that removal of stabilizing tree root systems of native and exotic forests led to more frequent and widespread landslide occurrence in New Zealand (Fuller, 2005; Dymond et al., 2006; Crozier, 2010) and beyond (Allan, 2004; Foley et al., 2005; Milliman and Farnsworth, 2011). While the coarse resolution of soils data did not allow us to perform statistical tests, it is likely that landslides would occur disproportionately on Pallic soils, which have high bulk density and weak structure (Hewitt, 2013). As expected, steeper slopes (>19°) showed more susceptibility to landsliding overall. However, there was a significant difference between forested and pasture slopes, with pasture landslides occurring on considerably gentler slopes of 19° compared to 27° for forested slopes.

Results of the connectivity analysis suggest that 75% of landslides in the Oroua and 72% of landslides in the Pohangina were not directly connected to river channels (Fig. 4). The debris produced by these uncoupled landslides may contribute little in the way of suspended sediment (SS) loads in the rivers during the event in which they were triggered, but they likely create sediment sources across the catchment that are available for remobilization in subsequent events. In a similar type of study on the Hoteo River catchment in northern New Zealand, Kamarinas et al. (2016) found that large storms over large areas of disturbed land led to cyclical periods of above-normal suspended sediment yields for subsequent flow events.

The increased occurrence of landslides in response to changes in land use could potentially transform a catchment from a supply-limited system to a transport-limited system by decreasing vegetative cover and increasing erosion rates (Milliman and Meade, 1983; Allan, 2004). In terms of the biogeomorphic response model adapted to the timescale of these human-influenced disturbances, vegetation removal from pasture grazing, forest harvesting, and landsliding would result

**Table 2**
Seasonal and event-based flow and suspended sediment regimes for Oroua and Pohangina catchments (summer includes November–May, and winter includes June–October).

| | Oroua | | Pohangina | |
|---|---|---|---|---|
| | Summer | Winter | Summer | Winter |
| # of events | 115 | 150 | 157 | 246 |
| Duration (days) | | | | |
| Range | 1–28 | 1–22 | 1–20 | 1–24 |
| Median | 2 | 2 | 2 | 2 |
| *Water runoff ($m^3$)* | | | | |
| Magnitude | | | | |
| Min | 145,152 | 283,392 | 290,304 | 330,048 |
| Max | 84,110,400 | 65,543,040 | 140,927,040 | 88,674,912 |
| Median | 1,578,528 | 2,999,376 | 2,678,400 | 5,009,904 |
| Peak | | | | |
| Min | 145,152 | 283,392 | 290,304 | 330,048 |
| Max | 30,153,600 | 12,355,200 | 57,542,400 | 23,760,000 |
| Median | 1,313,280 | 1,542,240 | 1,987,200 | 2,730,240 |
| *Suspended sediment load (tonnes)* | | | | |
| Magnitude | | | | |
| Min | 49 | 49 | 84 | 84 |
| Max | 320,785 | 136,486 | 622,443 | 267,965 |
| Median | 672 | 580 | 1082 | 1008 |
| Peak | | | | |
| Min | 49 | 49 | 84 | 84 |
| Max | 195,008 | 90,544 | 406,034 | 173,910 |
| Median | 586 | 385 | 868 | 704 |

in an abrupt reduction of the vegetation cover line (Fig. 1B). Depending on the timing of precipitation, these abrupt changes, also viewed as 'fast' variables in a resilience context, could increase the potential for a catchment to become transport-limited. The February 2004 storm occurred in a summer that was unusually wet, with soils in the catchment at field capacity in January; the storm was the last in a sequence that occurred on 1–3, 4–5, 10–12, and 15–16 February (Fuller and Heerdegen, 2005). These conditions, along with the storm's intensity and duration, likely contributed to the extent and severity of landsliding during this event.

The Hoteo River catchment study by Kamarinas et al. (2016) also revealed a clear relationship between land use and river sediment loads. In that study, which focused on total land disturbance rather than landslide disturbance alone, plantation forest areas contributed more to sediment runoff (tonnes/y) than grassland and pasture areas for a period of up to 4 years after harvest events After forests recovered, however, pastures assumed the dominant role in sediment runoff contribution. Also noteworthy is that in the Hoteo catchment, forested areas were almost exclusively situated on steep slopes and were more connected than grassland areas. Landscape connectivity in the Hoteo catchment was higher than in Oroua and Pohangina. Thus, this discrepancy may be at least partially attributable to a more comprehensive river network data set used in the Hoteo. The national REC stream network utilized in this study is largely composed of perennial channels, while the Hoteo study expanded this data set to include intermittent and ephemeral streams, which are likely active during the large storms that were the focus of that study. Further investigations into land use effects on soil erosion in the Lower North Island should account for these intermittent and ephemeral channels.

Recovery of topsoil in landslide scars in New Zealand, even after decades, rarely reaches the level of noneroded sites (Sparling et al., 2003; Rosser and Ross, 2010). In addition to the impact to river sediment loads, the February 2004 storm caused widespread property damage and loss of productive pasturelands by removing fertile topsoil and reducing the soil column. Similar responses were observed in the Waipaoa catchment (Reid and Page, 2002). Subsequent to the storm, the Horizons Regional Council, the governing environmental authority for the region, implemented the Sustainable Land Use Initiative (SLUI) to target land management change in the highly erodible hill country. In the Oroua and Pohangina and the broader Manawatu basin, the purpose of SLUI was to identify critical source areas for sediment and to develop a model called SedNetNZ that represents all erosion, transportation, and sediment storage processes occurring within the catchment (Elliot and Basher, 2011; Basher et al., 2012). The SLUI seeks to reduce erosion in the NZ hill country by identifying highly erodible land and applying passive and active conservation measures, such as retiring certain pastures and planting trees (Dymond et al., 2016). Based on the findings from our study, these land use conversions could be effective at preventing enhanced river sediment loads that produce transport-limited states. Adaptive management practices such as these provide examples for how society can intervene to act as a driver contributing to a system's resilience (Folke, 2006; Meitzen et al., 2017).

### 4.2. Interactive biogeomorphic effects of land use, geomorphology, and climate

The February 2004 storm caused extensive landsliding across predominantly pastures in the Oroua and Pohangina catchments, which increased river sediment loads in both the short- and long-term. Sediment loads were elevated relative to the mean in both catchments during the storm and for approximately 4 years following (Figs. 7 and 8), indicating that these catchments became temporarily transport-limited because of a sudden increase in available sediment. Previous studies have demonstrated the influence of seasonal effects and event sequencing on event sediment loads (Hooke, 1979; Walling and Webb, 1982; Hudson, 2003; Kamarinas et al., 2016). Longer periods between storm events usually allow for the buildup of sediment supply and thus for more available sediment to be transported during subsequent storms (Walling and Webb, 1982). Walling and Webb (1982) also found that higher SSC-Q relationships occurred in seasons with lower base flow. Higher base flows lead to dilution of SS, as most SS was generated by runoff. This dilution effect might partly explain the observations here of a seasonal pattern of elevated SS residuals in summer events (when base flow is relatively low) and depleted SS residuals in winter events (when base flow is relatively high; Figs. 7 and 8). This multiyear pattern is distinct from the seasonal flux that was revealed by the monthly daily SS and discharge analysis (Fig. 5), in which higher SS loads are associated with winter months rather than summer months. Thus, this extended, multiyear pattern of sediment depletions and elevated fluxes is evidence (respectively) for the shifts between supply-limited and transport-limited states.

In other catchments throughout the world, greater SS values have been found during events with higher peak discharges, suggesting that peak flows provide the energy to directly erode and effectively transport sediment (Hooke, 1979; Simon and Guzman-Rios, 1990). In the Oroua and Pohangina, higher SS values were observed in summer events (November–May) and are likely resulting from the occurrence of higher peak flows (Fig. 1, Table 2). Higher SS and peak flows in summer may also be an indication that summer events involved higher intensity rainfall. This is assuming that lower antecedent soil-moisture conditions exist in summer, therefore necessitating higher intensity rainfall to produce the same or greater peak discharge and SS production (via landsliding; Glade et al., 2000) as a winter event.

The impact of event sequencing on event SS was evident in Pohangina where, despite transporting the largest SS magnitude, the February 2004 storm had an SS residual not much higher than the threshold of one standard deviation. This is possibly because of the occurrence of another sediment event with a large runoff magnitude in the Pohangina in January 2004 that depleted available sediment for the February 2004 storm. The Oroua did not have a comparable prior event, which is likely why the February 2004 storm had a much larger SS response than in the Pohangina. In addition, a principal tributary of the Oroua, the Kiwitea Stream, sustained extensive bank erosion associated with catastrophic channel change during the February 2004 storm event, which was estimated to contribute about 1 million $m^3$ of

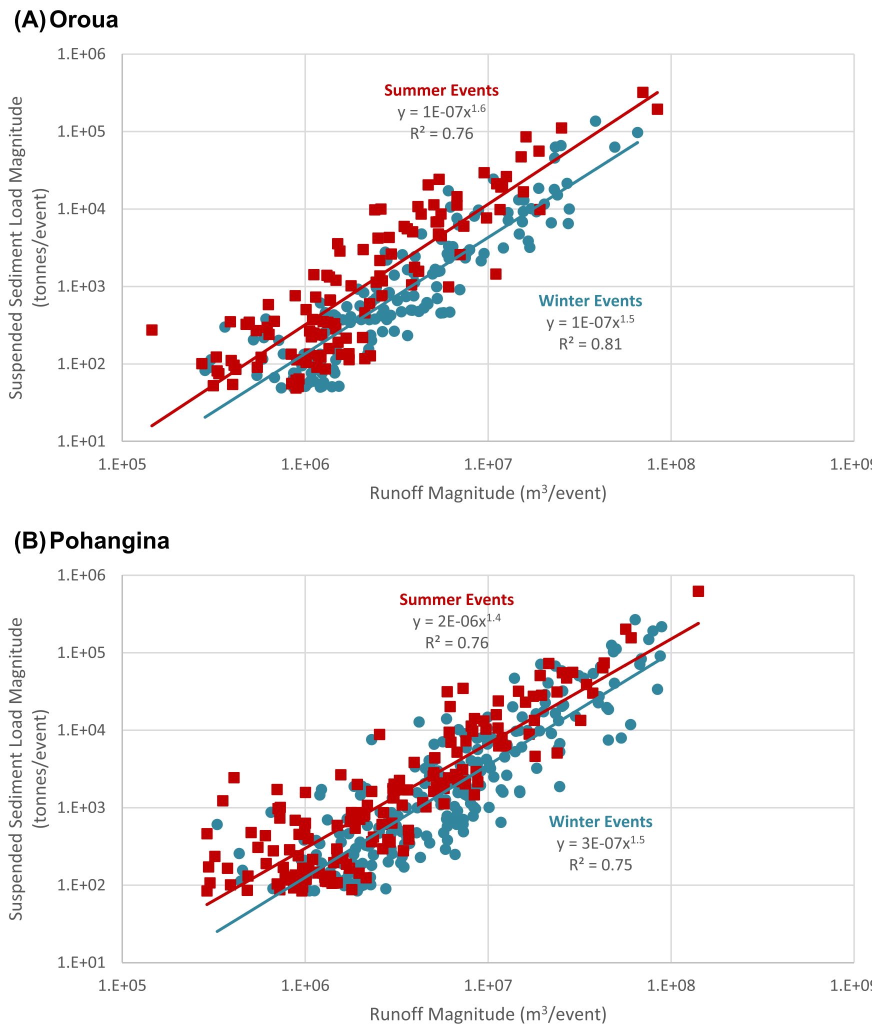


**Fig. 6.** Event suspended sediment load magnitude versus runoff magnitude for Oroua (A) and Pohangina (B). Squares represent summer events and circles represent winter events. For a given runoff magnitude, higher suspended sediment values were observed in summer months than in winter months.

sediment directly to the channel system (Fuller, 2008). Bank erosion in the main stems of the Pohangina and Oroua rivers was far less severe (Fuller, 2007). This is a reminder that sediment produced in storm events is not restricted to off-slope sediment delivery to the channel, and floodplain reworking may be a significant sediment source. The residual SS response to the February 2004 storm in the Pohangina was in fact quite muted compared with the residual SS response in the Oroua, although the SS magnitude was higher in the Pohangina for this event (Figs. 7 and 8). Subsequent storm events for the following four years likely continued to transport available sediment supply (e.g., remaining landslide debris) to the river channels and reworked sediment stored temporarily within the active river channel. These findings are consistent with previous studies of New Zealand catchments in which sediment supply is dictated by rainfall-triggered landsliding. For example, Hicks et al. (2000) found that in the Te Arai Basin, landslide scars and debris tails contributed sediment for a 1–2 year period following the storm in which the landslides were triggered. One possible explanation for longer lag times (~4 years) observed in the Oroua and Pohangina catchments in this study is that these catchments have larger drainage areas than the Te Arai (83 $km^2$), so sediment takes longer to move through these systems. Another possible explanation could be that there was greater connectivity and therefore less post-event sediment stored on the slopes in the smaller Te Arai Basin compared with the larger, less-connected Oroua and Pohangina catchments.

After 4 years, sediment loads were diminished relative to the mean condition, indicating that this available sediment in the landscape was becoming relatively exhausted and that the catchments had returned to a supply-limited state. Following an additional high flow event that occurred in the Oroua in 2010 but which was absent from the Pohangina, SS values were once again elevated in the Oroua (Fig. 7). One explanation for this observed SS response is that this event could have caused further landsliding in the Oroua, again increasing available sediment and switching the catchment back to a transport-limited landscape. Further remote sensing analyses similar to the work done by Dymond et al. (2006) on more recent images would be needed to confirm if there was in fact further landsliding. Another explanation is that this 2010 storm reactivated sediment that was produced during the 2004 storm but did not make it to the channel at the time (i.e., temporarily stored in floodplains, valley fills, valley margins, wetlands, ephemeral channels, or landslide debris tails). In field visits following the landslides, we did observe landslide debris tails stored on the hillslopes; Fryirs et al. (2007) described these sediment stores as 'buffers' disrupting sediment delivery in the landscape.

The findings of this study contribute to a larger body of literature, which demonstrates that the impact of an extreme precipitation event on river sediment loads is dependent on local geomorphology and land use, as well as antecedent weather conditions. Indeed, Simon and Guzman-Rios (1990) showed that dense grass, forest cover, gentler slopes, and rapid infiltration limited the availability of fine-grained

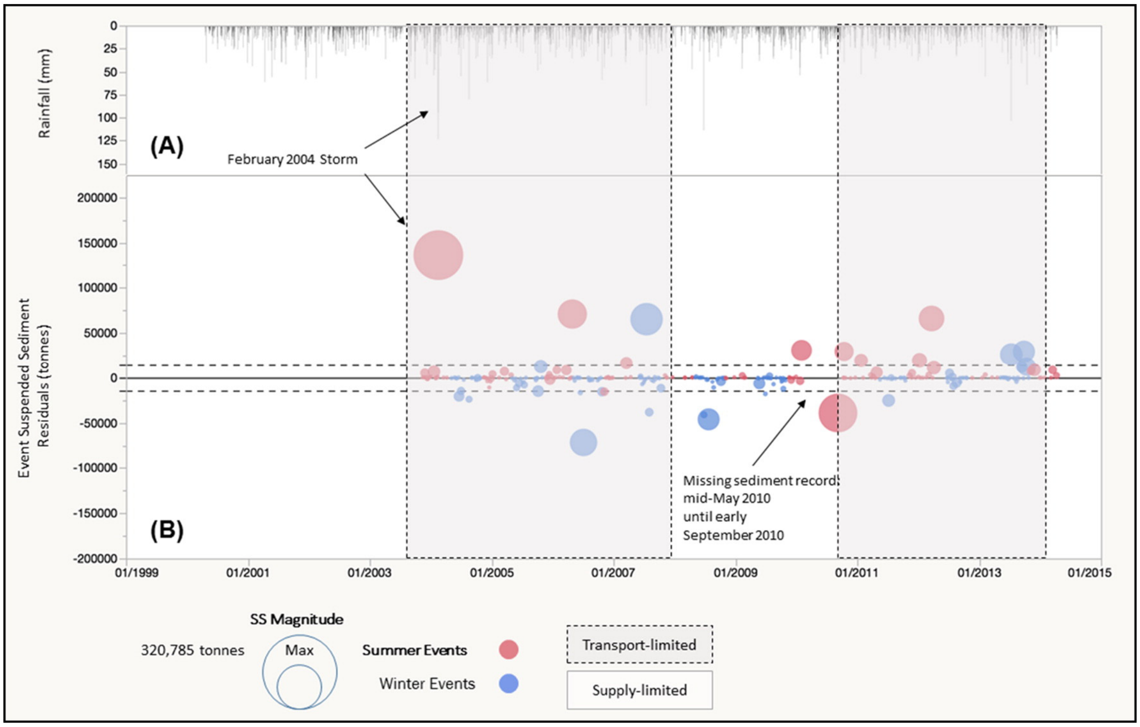


**Fig. 7.** Time series analyses of rainfall (A) and event SS residuals (B) in the Oroua catchment. The horizontal dotted lines are one standard deviation, representing the threshold for enhanced (positive) or depleted (negative) sediment loadings. The vertical dotted lines represent transitions between periods of transport-limitation (gray areas) and periods of supply-limitation.

material for transport. As the biogeomorphic response model illustrates and our study demonstrates, river sediment loads are generally highest when precipitation and hillslope potential for erosion is high and vegetation cover is low (Fig. 1). These same conditions create the potential for a landscape to become transport-limited by increasing available sediment. While Knox (1972) focused on geological timescales, our results provide empirical evidence that these interactions can also occur over seasonal and yearly timescales, although we acknowledge that our

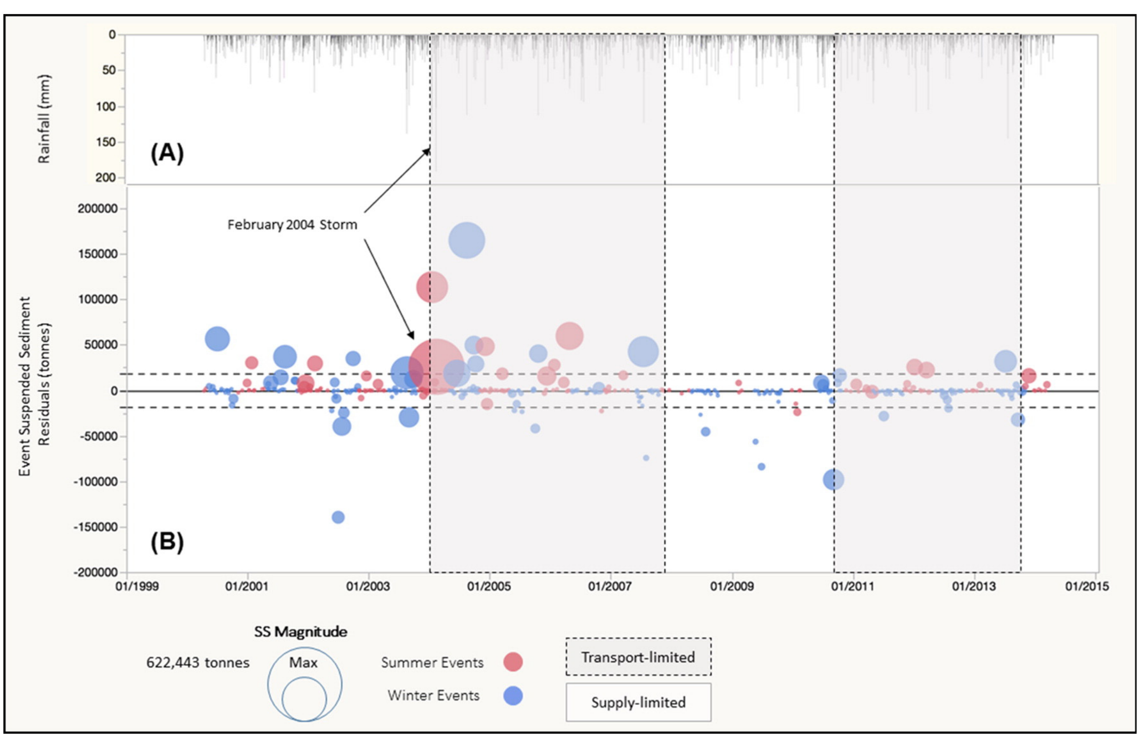


**Fig. 8.** Time series analyses of rainfall (A) and event SS residuals (B) in the Pohangina catchment. The horizontal dotted lines are one standard deviation, representing the threshold for enhanced (positive) or depleted (negative) sediment loadings. The vertical dotted lines represent transitions between periods of transport-limitation (gray areas) and periods of supply-limitation.

short period of data makes it difficult to determine whether these observed sediment flux patterns are consistent with geologic-scale patterns. At the seasonal scale, suspended sediment loads in the Oroua and Pohangina catchments were higher in winter months when runoff magnitudes were higher (Fig. 5), but large events that occurred in summer months also carried high suspended sediment loads (Table 2).

At longer timescales, the extreme storm in February 2004 removed vegetation cover and increased hillslope potential for erosion and the availability of sediment stores, resulting in elevated suspended sediment loads for a period of years. In the Oroua and Pohangina catchments, forest removal and livestock grazing on steep slopes likely exacerbated the impact of the February 2004 storm on landslide erosion and river sediment loads by removing stabilizing vegetation on land already prone to erosion. Other significant sediment sources, such as gully erosion and streambank (floodplain) erosion, were not quantified in this study but also contributed large amounts of sediment to the rivers (Fuller et al., 2016; Vale et al., 2016). Furthermore, although this study was limited to the suspended sediment component of total river sediment load, we should note that landslide disturbances also have a significant impact on bedload sediment production and transport. In a study of another high relief catchment in which landsliding is a significant geomorphic process delivering sediment to the channels, bedload was found to comprise between 34 and 92% of the total sediment yields (Simon and Guzman-Rios, 1990).

### 4.3. Catchment resilience

In the context of resilience, the observed patterns in suspended sediment in the Oroua and Pohangina catchments reveal shifts between two sediment transport states approximately every 3–4 years. The dynamic equilibrium of these state shifts prevents one state from being persistent within the system, demonstrating the capacity of the catchments to resist permanent threshold changes. These observed state changes are largely influenced by event sequencing, including the timing of events relative to prior and subsequent events, as well as the season in which they occur. Large storms such as the February 2004 storm have the ability to generate large amounts of sediment; however, our findings that these landslides occurred disproportionately on grazed pastures (even after normalizing by land cover area) suggests that it was land use change that shifted these catchments from a supply-limited state to a transport-limited state. By oscillating between states over seasonal, annual, and decadal timescales, the system maintains a similar structure, function, and set of feedbacks associated with its sediment regime. The recovery of catchment vegetation, and thus the period over which the catchment shifts back to a supply-limited state, is also influenced by land use, particularly livestock density and type (Julian et al., 2017). Accordingly, land management initiatives such as SLUI can improve catchment resilience by reducing the potential for hillslope erosion and ensuring that transport-limited states do not become more persistent.

The Oroua and Pohangina catchments are part of the larger Manawatu River basin, which Julian et al. (2017) revealed is one of the most turbid rivers in New Zealand. While agricultural land use has no doubt contributed to enhanced sediment runoff, another likely influence is the lack of vegetated wetlands in these catchments. Vegetated wetlands only accounted for 0.6 ha (<0.01%) of the Oroua catchment and 2.0 ha (<0.01%) of the Pohangina catchment. With such a miniscule coverage, these residual wetlands do not provide a detectable water quality improvement function at the catchment scale (Mitsch and Gosselink, 2000). Historically, wetlands covered ~10% of mainland New Zealand (Ausseil et al., 2011). This considerable loss (>90% of pre-European extent) of wetlands has deprived New Zealand rivers of many valuable ecosystem services, especially the filtration/processing of sediment (Clarkson et al., 2013). If some of these wetlands could be restored (particularly at the bottom of hillslopes prone to landsliding), a negative feedback would be introduced that would store/buffer this increased sediment supply and promote catchment resilience.

## 5. Conclusions

Conversion of forest to grassland/pasture on land already prone to landsliding in the New Zealand hill country has led to the increased occurrence and magnitude of storm-induced landsliding, which in turn has short- and long-term impacts on river suspended sediment loads. The results of this study have demonstrated that within the context of land use change, large storms have the ability to generate enough sediment via landsliding to temporarily convert catchments from a supply-limited state to a transport-limited state over relatively short timescales (<10 years). The timing and intensity of subsequent storms influence the duration of a transport-limited state. If vegetation has time to reestablish, sediment stores in the landscape may become less erodible and the catchment may switch back to a supply-limited state. If, however, another erosive storm occurs before this time, these stores may be reworked and contribute to elevated suspended sediment loads. This condition may remain until storms cease, vegetation reestablishes, or the sediment stores are exhausted.

Models have shown that soil conservation measures, such as revegetating and retiring highly erodible pasturelands, can significantly reduce erosion in the Lower North Island of New Zealand (Dymond et al., 2016). Additionally, wetlands and riparian buffers can serve as sediment sinks and buffers in intensively managed landscapes. Initiatives such as SLUI focus on where erosion occurs within a catchment, but further understanding of when shallow landsliding occurs in the lower North Island hill country and other areas with similar physiographic and land use characteristics is useful for targeting more effective land management. The availability of daily SS data at a decadal time period in the Oroua and Pohangina catchments allowed us to identify suspended sediment bearing events using IHA. Though developed and used extensively for characterizing hydrologic regimes, this study demonstrates that IHA can also be effectively utilized to characterize fluvial sediment regimes in a catchment, given the availability of daily SS data.

In response to growing concerns about the impact of land use activities on water quality, regional governing agencies in New Zealand increased their environmental monitoring in the 1990s with a focus on quantifying sediment and nutrient runoff. Water quality in New Zealand rivers since 1989 have shown declining trends for a number of constituents, particularly in catchments where land cover is dominated by pasture and forest harvesting (Larned et al., 2004; Basher et al., 2011; Ballantine and Davies-Colley, 2014; Julian et al., 2017). Monitoring the runoff and suspended sediment regimes should remain a priority for catchment management in New Zealand. This empirical information will continue to be critical for quantifying the impacts of land use changes and making adaptive management decisions geared toward sustaining the resilience of the nation's rivers.

## Acknowledgements

This work was funded by NSF GSS grant #1359970 and NASA LCLUC grant NNX14AB77G (PI Julian). Thanks to the staff of Horizons Regional Council for providing data, guidance, and feedback on this project and for hosting field visits to the Oroua and Pohangina catchments. Thanks to Massey University for providing a workspace as well as guidance and feedback on this project. Guidance and feedback was also provided by Landcare Research (including Les Basher) and is much appreciated. We also thank the two anonymous reviewers who helped us provide clarity and strengthen our manuscript.

## References

Abbott, S.T., Naish, T.R., Carter, R.M., Pillans, B.J., 2005. Sequence stratigraphy of the Nukumaruan Stratotype (Pliocene-Pleistocene, c. 2.08–1.63 Ma), Wanganui Basin, New Zealand. J. R. Soc. N. Z. 35, 123–150.

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. Annu. Rev. Ecol. Evol. Syst. 35, 257–284.

Ausseil, A.G.E., Chadderton, W.L., Gerbeaux, P., Stephens, R.T.T., Leathwick, J.R., 2011. Applying systematic conservation planning principles to palustrine and inland saline wetlands of New Zealand. Freshw. Biol. 56, 142–161.

Ballantine, D.J., Davies-Colley, R., 2014. Water quality trends in New Zealand rivers: 1989–2009. Environ. Monit. Assess. 186 (3), 1939–1950.

Basher, L.R., 2013. Erosion processes and their control in New Zealand. In: Dymond, J.R. (Ed.), Ecosystem Services in New Zealand – Conditions and Trends. Manaaki Whenua Press, Lincoln, New Zealand, pp. 363–374.

Basher, L.R., Hicks, D., Clapp, B., Hewitt, T., 2011. Sediment yield response to large storm events and forest harvesting, Motueka River, New Zealand. N. Z. J. Mar. Freshw. Res. 45 (3), 333–356.

Basher, L.R., Payne, J., Watson, B., 2012. Suspended Sediment Yields in the Manawatu Catchment: Analysis of Data Collected by Horizons Regional Council. Landcare Research Contract Report LC947 for AgResearch and Horizons Regional Council.

Betts, H.D., Trustrum, N.A., De Rose, R.C., 2003. Geomorphic changes in a complex gully system measured from sequential Digital Elevation Models, and implications for management. Earth Surf. Process. Landf. 28, 1043–1058.

Brierley, G.J., Reid, H.E., Coleman, S.E., 2011. Conceptualization of sediment flux in the Tongariro catchment. J. Hydrol. N. Z. 50 (1), 161–180.

Clarkson, B.R., Ausseil, A.G.E., Gerbeaux, P., 2013. Wetland ecosystem services. In: Dymond, J.R. (Ed.), Ecosystem Services in New Zealand - Conditions and Trends. Manaaki Whenua Press, Lincoln, New Zealand, pp. 192–202.

Cleveland, W.S., Devlin, S.J., 1988. Locally weighted regression: an approach to regression analysis by local fitting. J. Am. Stat. Assoc. 83, 596–610.

Crozier, M.J., 2010. Landslide geomorphology: an argument for recognition, with examples from New Zealand. Geomorphology 120, 3–15.

De Rose, R.C., 2012. Slope control of the frequency distribution of shallow landslides and associated soil properties, North Island, New Zealand. Earth Surf. Process. Landf. 38, 356–371.

Dymond, J.R., Ausseil, A.G., Shepherd, J.D., Buettner, L., 2006. Validation of a region-wide model of landslide susceptibility in the Manawatu–Wanganui region of New Zealand. Geomorphology 74 (1), 70–79.

Dymond, J.R., Herzig, A., Basher, L., Betts, H.D., Marden, M., Phillips, C.J., Ausseil, A.E., Palmer, D.J., Clark, M., Roygard, J., 2016. Development of a New Zealand SedNet model for assessment of catchment-wide soil-conservation works. Geomorphology 257, 85–93.

Elliot, A., Basher, L., 2011. Modelling sediment flux: a review of New Zealand catchment-scale approaches. J. Hydrol. N. Z. 50, 143–160.

Fahey, B.D., Marden, M., Phillips, C.J., 2003. Sediment yields from plantation forestry and pastoral farming, coastal Hawke's Bay, North Island, New Zealand. J. Hydrol. N. Z. 42, 27–38.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Folke, C., 2006. Resilience: the emergence of a perspective for social-ecological systems analyses. Glob. Environ. Chang. 16, 253–267.

Fryirs, K.A., Brierley, G.J., 2013. Geomorphic Analysis of River Systems: An Approach to Reading the Landscape. John Wiley and Sons, Chichester, p. 345.

Fryirs, K.A., Brierley, G.J., Preston, N.J., Kasai, M., 2007. Buffers, barriers, and blankets: the (dis)connectivity of catchment-scale sediment cascades. Catena 70, 49–67.

Fuller, I.C., 2005. February floods in the lower North Island, 2004: catastrophe – causes and consequences. N. Z. Geogr. 61, 40–50.

Fuller, I.C., 2007. Geomorphic work during a '150-Year' storm: contrasting behaviors of river channels in a New Zealand catchment. Ann. Assoc. Am. Geogr. 97 (4), 665–676.

Fuller, I.C., 2008. Geomorphic impacts of a 100-year flood: Kiwitea Stream, Manawatu Catchment, New Zealand. Geomorphology 98, 84–95.

Fuller, I.C., Heerdegen, R.G., 2005. The February 2004 floods in the Manawatu, New Zealand: hydrological significance and impact on channel morphology. J. Hydrol. N. Z. 44, 75–90.

Fuller, I.C., Macklin, M.G., Richardson, J.M., 2015. The geography of the Anthropocene in New Zealand: differential river catchment response to human impact. Geogr. Res. 53, 255–269.

Fuller, I.C., Marden, M., 2011. Slope-channel coupling in steepland terrain: a field-based conceptual model from the Tarndale gully and fan, Waipaoa catchment, New Zealand. Geomorphology 128, 105–115.

Fuller, I.C., Riedler, R.A., Bell, R., Marden, M., Glade, T., 2016. Landslide-driven erosion and slope-channel coupling in steep, forested terrain, Ruahine Ranges, New Zealand, 1946–2011. Catena 142, 252–268.

Gage, M., Black, R.D., 1979. Slope-stability and geological investigations at the Mangatu State Forest. Forest Research Institute Technical Paper, 66, 37. Wellington, New Zealand Forest Service.

Glade, T., 2003. Landslide occurrence as a response to land use change: a review of evidence from New Zealand. Catena 51 (3), 297–314.

Glade, T., Crozier, M., Smith, P., 2000. Applying probability determination to refine landslide-triggering rainfall thresholds using an empirical "antecedent daily rainfall model". Pure Appl. Geophys. 157 (6), 1059–1079.

Graf, W.L., 1977. The rate law in fluvial geomorphology. Am. J. Sci. 277, 178–191.

Gregory, K.J., 2006. The human role in changing river channels. Geomorphology 79 (3), 172–191.

Hancox, G.T., Wright, K., 2005. Analysis of Landsliding Caused by the 15–17 February 2004 Rainstorm in the Wanganui-Manawatu Hill Country, Southern North Island, New Zealand. Institute of Geological & Nuclear Sciences, science report 2005/11, p. 64.

Hewitt, A., 2013. Survey of New Zealand soil orders. Ecosystem Services in New Zealand: Conditions and Trends 1 (10), 121–131.

Hicks, D., Shankar, U., McKerchar, A.I., Basher, L., Lynn, I., Page, M., Jessen, M., 2011. Suspended sediment yields from New Zealand rivers. J. Hydrol. N. Z. 50 (1), 81–142.

Hicks, D.M., Gomez, B., Trustrum, N.A., 2000. Erosion thresholds and suspended sediment yields, Waipaoa River basin, New Zealand. Water Resour. Res. 36, 1129–1142.

Hooke, J., 1979. An analysis of the processes of river bank erosion. J. Hydrol. 42, 39–62.

Hudson, P.F., 2003. Event sequence and sediment exhaustion in the lower Panuco Basin, Mexico. Catena 52, 57–76.

Julian, J.P., De Beurs, K.M., Owsley, B.C., Davies-Colley, R.J., Ausseil, A.G.E., 2017. River water quality changes in New Zealand over 26 years: response to land use intensity. Hydrol. Earth Syst. Sci. 21, 1149–1171.

Julian, J.P., Podolak, C.J.P., Meitzen, K.M., Doyle, M.W., Manners, R.B., Hester, E.T., Ensign, S., Wilgruber, N.A., 2016. Shaping the physical template: biological, hydrological, and geomorphic connections in stream channels. In: Jones, J.B., Stanley, E.H. (Eds.), Stream Ecosystems in a Changing Environment. Elsevier, London, pp. 85–133.

Julian, J.P., Torres, R., 2006. Hydraulic erosion of cohesive riverbanks. Geomorphology 76 (1–2), 193–206.

Kamarinas, I., Julian, J.P., Hughes, A.O., Owsley, B.C., de Beurs, K.M., 2016. Nonlinear changes in land cover and sediment runoff in a New Zealand catchment dominated by plantation forestry and livestock grazing. Water 8 (10), 436.

Knox, J.C., 1972. Valley alluviation in Southwestern Wisconsin. Ann. Assoc. Am. Geogr. 62 (3), 401–410.

Landcare Research, 2015. New Zealand Land Cover Database (LCDB), v.4.1. http://www.lcdb.scinfo.org.nz/.

Landcare Research, 2016. National Soils Database. https://viewer-nsdr.landcareresearch.co.nz/search.

Lane, E.W., 1955. The Importance of Fluvial Morphology in Hydraulic Engineering. Proceedings, American Society of Civil Engineers, 81, paper no. 745, July.

Larned, S.T., Scarsbrook, M.R., Snelder, T.H., Norton, N.J., Biggs, B.J.F., 2004. Water quality in low-elevation streams and rivers of New Zealand: recent state and trends in contrasting land- cover classes. N. Z. J. Mar. Freshw. Res. 38, 347–366.

Lee, J.M., Bland, K.J., Townsend, D.B., Kamp, P.J.J., 2011. Geology of the Hawke's Bay area. Institute of Geological & Nuclear Sciences 1:250 000 Geological Map 8. 1 sheet + 93 p. Lower Hutt, New Zealand, GNS Science (Compilers).

Marden, M., Arnold, G., Seymour, A., Hambling, R., 2012. History and distribution of steepland gullies in response to land use change, East Coast region, North Island, New Zealand. Geomorphology 153, 81–90.

Meitzen, K.M., Phillips, J.N., Perkins, T., Manning, A., Julian, J.P., 2017. Catastrophic flood disturbance and a community's response to plant resilience in the heart of the Texas Hill Country. Geomorphology (In press).

Milliman, J.D., Farnsworth, K.L., 2011. River Discharge to the Coastal Ocean: A Global Synthesis. Cambridge University Press, Cambridge, United Kingdom.

Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. The J. Geol. 91 (1), 1–21.

Mitsch, W.J., Gosselink, J.G., 2000. The value of wetlands: importance of scale and landscape setting. Ecol. Econ. 35 (1), 25–33.

National Institute of Water and Atmospheric Research (NIWA), 2016. River Environment Classification, v.2. https://www.niwa.co.nz/freshwater-and-estuaries/management-tools/river-environment-classification-0.

Parkner, T., Page, M., Marden, M., Marutani, T., 2007. Gully systems under undisturbed indigenous forest, East Coast Region, New Zealand. Geomorphology 84, 241–253.

Preston, N.J., Crozier, M.J., 1999. Resistance to shallow landslide failure through root-derived cohesion in east coast hill country soils, North Island, New Zealand. Earth Surf. Process. Landf. 24 (8), 665–675.

Quinn, J.M., Stroud, M.J., 2002. Water quality and sediment and nutrient export from New Zealand hill-land catchments of contrasting land use. N. Z. J. Mar. Freshw. Res. 36, 409–429.

Reid, L.M., Dunne, T., 2016. Sediment budgets as an organizing framework in fluvial geomorphology. In: Kondolf, G.M., Piegay, H. (Eds.), Tools in Fluvial Geomorphology. Wiley Blackwell, pp. 357–375.

Reid, L.M., Page, M.J., 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49, 71–88.

Rosser, B.J., Ross, C.W., 2010. Recovery of pasture production and soil properties on soil slip scars in erodible siltstone hill country, Wairarapa, New Zealand. N. Z. J. Agric. Res. 54 (1), 23–44.

Simon, A., Guzman-Rios, S., 1990. Sediment discharge from a montane basin, Puerto Rico: implications of erosion processes and rates in the humid tropics. International Association Hydrological Sciences Publication 192, 35–47.

Snelder, T., Biggs, B., Weatherhead, M., 2010. New Zealand River Environment Classification User Guide. Produced for the Ministry for the Environment by the National Institute of Water and Atmospheric Research (NIWA). Publication number: ME 1026.

Sparling, G., Ross, D., Trustrum, N., Arnold, G., West, A., Speir, T., Schipper, L., 2003. Recovery of topsoil characteristics after landslip erosion in dry hill country of New Zealand, and a test of the space-for-time hypothesis. Soil Biol. Biochem. 35, 1575–1586.

Syvitski, J.P., Morehead, M.D., Bahr, D.B., Mulder, T., 2000. Estimating fluvial transport: the rating parameters. Water Resour. Res. 36 (9), 2747–2760.

The Nature Conservancy, 2009. Indicators of Hydrologic Alteration Version 7.1 User's Manual.

Uriarte, M., Yackulic, C.B., Lim, Y., Arce-Nazario, J.A., 2011. Influence of land use on water quality in a tropical landscape: a multi-scale analysis. Landsc. Ecol. 26 (8), 1151–1164.

Vale, S.S., Fuller, I.C., Procter, J.N., Basher, L., Smith, I., 2016. Characterization and quantification of suspended sediment sources to the Manawatu River, New Zealand. Sci. Total Environ. 543, 171–186.

Walker, B.J., Salt, B.A., 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press, Washington D.C.

Walling, D.E., Webb, B.W., 1982. Sediment Availability and the Prediction of Storm-period Sediment Yields. Recent Developments in the Explanation and Prediction of Erosion and Sediment Yield (Proceedings of the Exeter Symposium, July 1982), 137. pp. 327–337.

Yang, T., Xu, C.Y., Chen, X., Singh, V.P., Shao, Q.X., Hao, Z.C., Tao, X., 2010. Assessing the impact of human activities on hydrological and sediment changes (1953–2000) in nine major catchments of the loess plateau, China. River Res. Appl. 26 (3), 322–340.