CROSS-SCALE INTERACTIONS BETWEEN LAND COVER/LAND USE, CLIMATE, AND RIVER WATER QUALITY: A CASE STUDY OF THE MANAWATU RIVER CATCHMENT, NEW ZEALAND

by

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DEDICATION

To my parents and grandparents,

Who have shown overwhelming support of all of my academic and personal endeavors.

Thank you.

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LIST OF ABBREVIATIONS

Abbreviation	Description
DEM	Digital elevation model
DI	Disturbance index
EFC	Environmental flow component
HRC	Horizons Regional Council
IHA	Indicators of Hydrologic Alteration
LCDB	New Zealand Land Cover Database
LCLU	Land cover/land use
LOESS	Local polynomial regression
SLUI	Sustainable Land Use Initiative
SoE	State of Environment
SS	Suspended sediment
SSC	Suspended sediment concentration
TNC	The Nature Conservancy

ABSTRACT

The interaction of climate, geomorphology, and land use dictates catchment sediment production and associated river sediment loads. This case study in the Manawatu River catchment in 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 landslide-dominated Oroua and Pohangina subcatchments. Indicators of Hydrologic Alteration (IHA), 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 dataset of sediment-bearing events for the period of record was analyzed with a local polynomial regression (LOESS) to examine the suspended sediment response of individual storms relative to runoff magnitudes. The findings of this study demonstrate that large storms have the ability to generate enough sediment via landsliding to temporarily convert these catchments from a supply-limited state to a transport-limited state. Land use in the form of livestock grazing on steep hillslopes was an important control on the location of landslides and thus sediment supply. The timing and intensity of storms were also important influences on these state transitions. The suspended sediment response to the February 2004 storm (relative to the mean condition) was smaller in the Pohangina than in the Oroua. The occurrence of another large storm in the Pohangina that closely preceded the February 2004 storm likely depleted available sediment in the landscape. In both subcatchments, suspended sediment loads were elevated for a period of approximately four years following the landslide-generating February 2004 storm. The spatial and temporal interactions between land cover/land use and climate have important implications for land management strategies to reduce erosion and improve river water quality in landscapes dominated by storm-induced erosion.

I. INTRODUCTION

Sediment production is the result of all erosional processes that occur within a catchment. The rate of sediment production and transport is influenced by vegetative cover, geology, soil type, precipitation intensity, climatic variability, topographic relief, and land use (Knox 1972; Milliman and Meade 1983; Syvitski et al. 2000; Uriarte et al. 2011). Land use practices, such as livestock grazing and plantation forestry, can have significant impacts on river sediment regimes, acting to degrade river water quality over time (Foley et al. 2005). Land that is disturbed by grazing and plantation forestry activities becomes susceptible to erosion during intense precipitation events, which leads to increased sediment loading and impacts local and downstream river water quality (Milliman and Farnsworth 2011). This increase in available sediment can also shift a catchment from a supply-limited state (i.e., river loadings are limited by available sediment in the landscape) to a transport-limited state (i.e., available sediment is abundant, so river loadings are limited by runoff). The interactions between climate and land cover/land use (LCLU) control the occurrence and rate of these state transitions, and understanding the conditions under which these transitions occur can be critical for effective natural resource management and ecosystem restoration.

In the hill country of the North Island of New Zealand, storm-induced landsliding is a dominant geomorphic mechanism eroding and delivering sediment to rivers (Basher 2013; Basher et al. 2012; Basher et al. 2011; Dymond et al. 2006). Areas disturbed by landslide events can remain unvegetated for months to years, and are potentially persistent sources of erodible sediment that can have long-term impacts on local and downstream river water quality. Removal of forest cover to increase available pastoral land cover has led to an increased frequency and distribution of rainfall-induced landslide events due to the removal of stabilizing root systems (Preston and Crozier 1999). In February of 2004 a large storm hit the Lower North Island of New Zealand, resulting in over 62,000 individual landslides in the Manawatu River catchment that affected approximately 190 km^2, or three percent of the total catchment area (Dymond et al. 2006). Landsliding resulting from this storm removed productive soils from pasture hillslopes and elevated local and downstream river sediment loads both immediately and in the long-term. This study is an examination of the interactions between LCLU, climate, and river water quality in the Manawatu River catchment on the North Island of New Zealand, with a focus on the effects of an extreme precipitation event on river sediment regimes.

II. THEORETICAL FRAMEWORK AND PURPOSE STATEMENT

Many general and site-specific models have been developed to predict river sediment loads in order to identify drivers and mitigate impacts on soil erosion and water quality (Syvitski et al. 2000; Ausseil and Dymond 2008; Dymond et al. 2010; Hicks et al. 2011). The Biogeomorphic Response Model, developed by Knox (1972) and modified by Graf (1977), is a general model that describes the interactions between climate, vegetative cover, and hillslope potential for erosion and their impacts on sediment production (Figure 1a-d). The model predicts that a period of increased precipitation following a dry period will fall on sparsely vegetated or bare ground with a high hillslope potential for erosion, causing a spike in sediment production. As precipitation events increase in duration or frequency, vegetative cover becomes denser and the hillslope potential for erosion decreases along with the rate of sediment production. After precipitation events decrease or stop, vegetative cover will die back and the potential for erosion will increase again, but sediment production will not resume until precipitation returns as an erosive force. The model was based on geologic time scales (thousands of years), but could this same dynamic occur over shorter periods (months to years)?

The potential suspended sediment response to a significant storm event (Figure 1e) was appended to the Biogeomorphic Response Model, expanding the model to represent general trends expected in river sediment load response to an individual storm event under various climactic and LCLU scenarios. Late in a dry period when hillslope potential for erosion is high, and early in a wet period when sediment production is high, the potential suspended sediment response to a storm event would be relatively high. Late in a wet period and early in a dry period when hillslope potential for erosion is low, the potential suspended sediment response to a storm would be relatively low. The same conditions which would result in a high potential suspended sediment response to a storm event are also potential periods of sediment transport-limitation (gray bars, Figure 1).

This study is an examination of subcatchment-scale sediment regimes in the context of the Biogeomorphic Response Model and sediment supply/transport at intermediate timescales (i.e., months to years). The purpose of this study was to determine whether the Manawatu River catchment in New Zealand is a transport-limited or supply-limited landscape, and to identify what factors contribute to the temporal variability of this status. Specifically, how is this status influenced by LCLU and extreme precipitation events on the subcatchment scale?

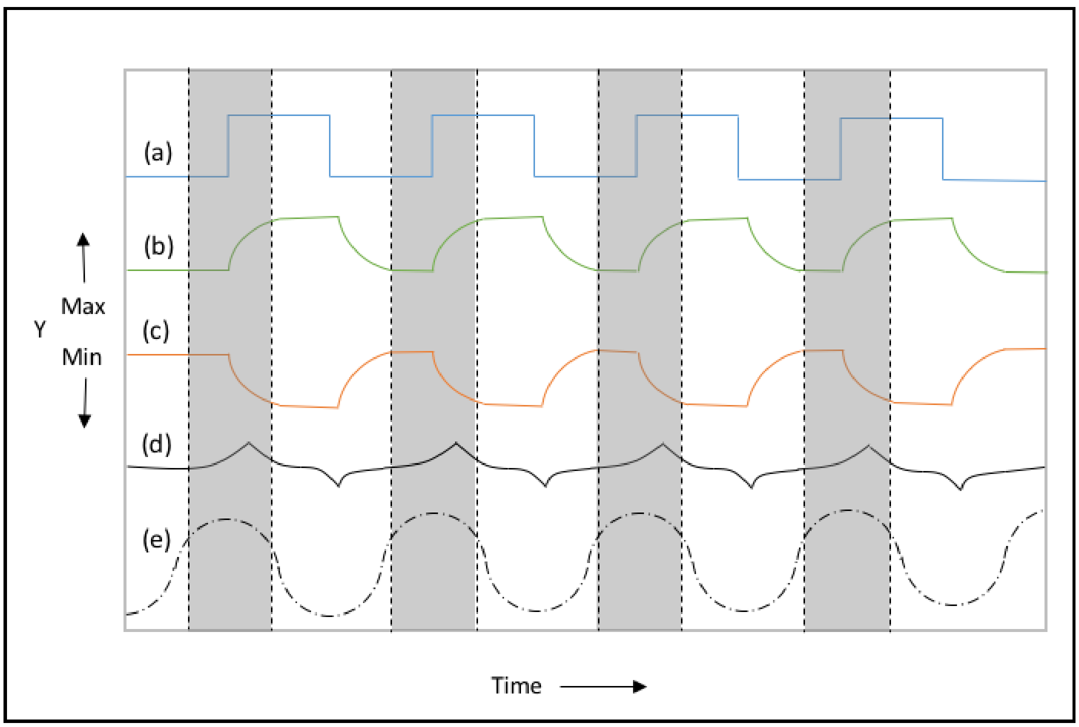


Figure 1. Modified Biogeomorphic Response Model. Seasonal interactions between precipitation (a), vegetation cover (b), hillslope potential for erosion (c), sediment production (d), and potential suspended sediment response to a significant storm event (e). Gray bars represent potential transport-limited states, while white areas represent potential supply-limited states. Lines (a-d) from Knox (1972); line (e) and gray bars by author.

The objectives of this research were to: (1) use a previously developed hydrologic regime analysis technique to characterize fluvial suspended sediment regimes; (2) assess effects of land use on landslide occurrence and available sediment; (3) identify landslides that are direct sediment sources to river channels; and (4) to determine when and why catchments switch from sediment supply-limitation to transport-limitation.

III. LITERATURE REVIEW

Interactions between land cover/land use, climate, and river water quality

The concentration, duration, and frequency of suspended sediment (SS) in a river are collectively known as SS regimes. Changes in SS regimes as a result of landscape disturbance from anthropogenic use can have detrimental effects on water resources, including aesthetic issues, higher costs of water treatment, and ecological degradation (Grove et al. 2015). The Biogemorphic Response Model introduced in Chapter II describes the general interactions between land cover/land use (LCLU), climate, and SS regimes (Figure 1). This model was developed to describe these interactions on geologic timescales, where climate (the long-term precipitation pattern) is the controlling variable. Precipitation is a primary sediment production control as an erosive force and because runoff is the primary transportation mechanism delivering sediment to rivers. Sediment yields are dependent on flow capacity, so lower sediment yields are generally observed in periods of low-flow (e.g. dry season). Alternatively, higher sediment yields are generally observed in periods of high-flow (e.g. floods or wet season) (Florsheim et al. 2011). On shorter timescales, factors other than precipitation can alter vegetative cover and hillslope potential for erosion and thus potential SS response to individual storm events. Anthropogenic land use practices such as agriculture, forestry, and urbanization have transformed a large percentage of the Earth's land surface cover and have contributed to the degradation of surface water quality (Allan 2004; Foley et al. 2005). Agricultural lands occupy approximately 40 percent of the Earth's surface, and land use practices such as agriculture and timber production have led to a net loss of approximately seven to eleven million km^2 of forest in the past 300 years (Foley et al. 2005; Milliman and Farnsworth 2011). LCLU changes associated with agriculture and forestry practices impact rivers both directly and indirectly by decreasing vegetative cover, increasing available sediment and nutrient loads, and altering the hydrologic regime by decreasing infiltration, increasing runoff, and altering channel network geometries (Milliman and Meade 1983; Allan 2004; Florsheim et al. 2011; Uriarte et al. 2011; Julian et al. 2013).

Previous studies have shown relationships between climate, LCLU, and water quality (Milliman and Meade 1983; Allan 2004; Florsheim et al. 2011; Uriarte et al. 2011), but few have considered these interactions at multiple temporal scales. Rather, land cover is generally treated as a static variable. However, various land use practices can result in highly variable, short-term landscape changes. Land cover change associated with one agricultural practice in particular called "intensive rotational grazing," or pasture strip grazing, can occur at weekly rates (Drewry 2006) dramatically increasing susceptibility of the land to erosion. Likewise, logging activities can transform a forest to bare ground in a similar timeframe. The timing, intensity, duration, and frequency of precipitation events can directly contribute to river suspended sediment responses following anthropogenic LCLU disturbances.

Models are continuously in development to predict soil erosion and transportation potential at the catchment-scale using sediment yield data, but many lack sufficient empirical validation (Syvitski et al. 2000; de Vente and Poesen 2005; Hicks et al. 2011). Factors such as local topography, geology, vegetation, and scale of analysis influence which geomorphic processes are dominant within a particular catchment, and as vegetation and other LCLU factors vary through time, so may the active erosion and sediment transport processes (Schumm and Lichty 1965; Fuller 2008). For example, landsliding is an important geomorphic process influencing landscape morphology and river water quality in landscapes with high relief (Crozier 2010). Significant issues can arise when models developed for one scale of analysis are used to describe sedimentation processes at other scales. That is, dominant sediment erosion and transportation processes that occur at one scale are not necessarily dominant at another scale of analysis. Consequently, the majority of current studies assessing LCLU effects on local and downstream water quality restrict their scope to small watersheds in order to minimize the spatial variability of factors such as climate and geology (Schumm and Lichty 1965; Sliva and Williams 2001; de Vente and Poesen 2005; Florsheim et al. 2011).

At short timescales (individual events), extreme precipitation events (large storms) significantly impact river sediment loads. For example, rainfall-induced landsliding has been shown to be an important factor controlling landscape morphology and a dominant contributor to river sediment loads (Crozier 2010). The areas of bare soil left by these landslide scars then become potentially persistent sediment sources for future precipitation events. Additionally, extreme precipitation events have been found to alter channel morphologies, and thus, sediment source connectivity to river channels, though these effects are highly variable and dependent on local geology, topography, and vegetation (Fuller 2007; Fuller 2008). The impact of extreme precipitation events on sediment yields is much greater than LCLU alone in terms of the time to recover and total area affected (Basher et al. 2011). What is less clear is how these extreme precipitation events, including their relative timing and intensities, interact with LCLU to influence long-term sediment source areas and river connectivity (Fuller 2008; Schwendel and Fuller 2011; Pechenick et al. 2014). Seasonal and decadal climatic variability at multiple spatial scales are important controls on the timing, frequency, and intensity of extreme precipitation events, and thus, river SS regimes.

Supply- and transport-limited landscapes

The terms "supply-limited" and "transport-limited" were developed to describe degrading and aggrading river systems (Lane 1955; Brierley and Fryirs 2005), but can also describe sediment delivery to rivers from their drainage areas (e.g. Brierley et al. 2011). Sediment yield at the catchment-scale is a result of all present and past erosion and sediment transportation processes occurring within a catchment (de Vente and Poesen 2005). Sediment loads in rivers are dictated by sediment supply from the landscape as well as flow transport capacity (Brierley and Fryirs 2005; Florsheim et al. 2011). Riverine landscapes can be identified as "supply-limited", in which river loadings are limited by available sediment in the landscape, or "transport-limited", in which available sediment is abundant, so river loadings are determined by runoff. In supply-limited landscapes, an extreme precipitation event has the capacity to deplete the sediment supply for subsequent precipitation events, thus the frequency, magnitude, and timing of precipitation influences available sediment in the landscape. In transport-limited landscapes, sediment loads will be proportional to runoff, regardless of the timing of storm events because of the availability of sediments exceeds the river transport capacity (Figure 2). Undisturbed catchments tend to be supply-limited, while catchments with areas of intensive agriculture and deforestation tend to be transport-limited because of the increased availability of sediment (Allan 2004; Milliman and Meade 1983). In addition to land use, climate, geology, and topography are major drivers affecting the supply-limited or transport-limited status within a particular landscape. The gray bars in Figure 1 represent the conditions that would be conducive to a transport-limited state.

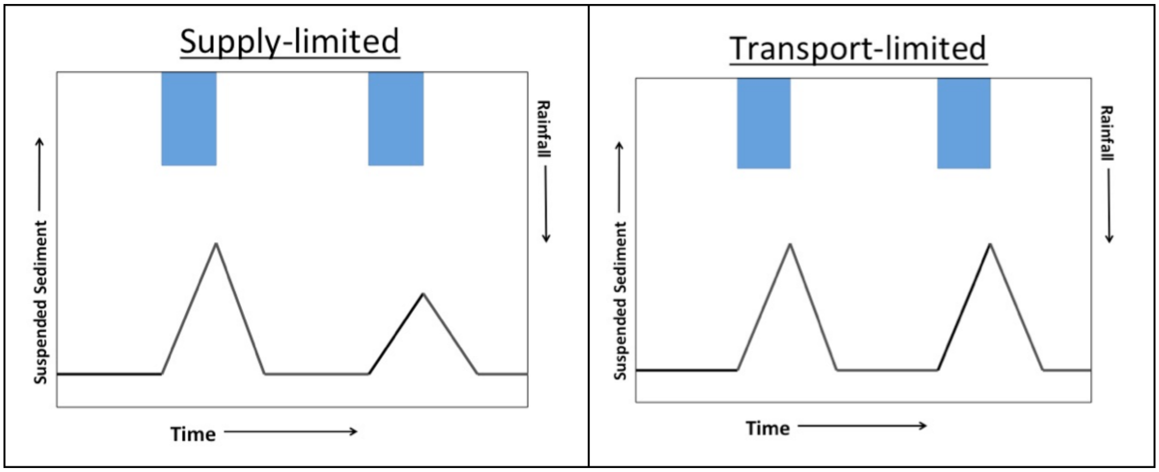


Figure 2. Supply- and transport-limited landscapes. In a supply-limited landscape, a heavy precipitation event can deplete the landscape of available sediment for subsequent precipitation events. In a transport-limited landscape, erodible sediment is abundant, so the suspended sediment load response to precipitation will be proportional to flow.

Sediment erosion and transport in New Zealand

Since the development of pastoral agriculture in New Zealand, sheep and cattle grazing has been the dominant land use in the lower catchment areas in most of the country (Allan 2004). Land use intensity in New Zealand has increased considerably in recent decades, particularly pastoral agriculture, which occupies approximately 40 percent of the country's land area (Fahey et al. 2003; Ballantine and Davies-Colley 2014). The importance of effective land management to sustain both human and natural ecological interests is widely recognized (Dodd et al. 2008; Davies-Colley et al. 2011). A number of studies have examined the impact of LCLU on erosion rates and sediment yields in catchments throughout New Zealand (Quinn and Stroud 2002; Reid and Page 2002; Fahey et al. 2003; Glade 2003; Elliot and Basher 2011). Recent assessments of the Manawatu River catchment have shown degrading trends in water quality. A positive correlation has been shown to exist between turbidity and pastoral land cover, indicating that increased pastoral land cover results in increased sediment loads (Fahey et al. 2003; Ballantine and Davies-Colley 2014).

Other studies have observed the enhanced impacts of forest harvesting on increased sediment yield in New Zealand's river systems, especially at the small catchment scale (Fahey et al. 2003; Basher et al. 2011). Previous studies which examined the effects of pastoral agriculture and plantation forestry on water quality in New Zealand have recognized limitations because of an insufficient understanding of feedback mechanisms and scales of analyses (Fahey et al. 2003; Larned et al. 2004; Dodd et al. 2008; Basher et al. 2011; Hicks et al. 2011; Ballantine and Davies-Colley 2014). Intense agricultural activities such as forest harvesting and intensive grazing can result in drastic LCLU changes at weekly rates. These "disturbed" areas can serve as direct and indirect sediment sources, and the relative timing and intensity of precipitation events will affect river SS responses to these LCLU disturbances.

On the North Island of New Zealand, widespread shallow landsliding commonly occurs on steep hillslopes of the soft rock hill country (Sparling et al. 2003; Crozier 2010; De Rose 2012). Removal of forest cover to increase pastoral land cover, especially since European settlement circa 1840, has led to an increased frequency and distribution of rainfall-induced landsliding because of the removal of stabilizing root systems which act to inhibit erosion (Preston and Crozier 1999). Various studies have found that river sediment loads in New Zealand hill country are dominated by landslide-triggering extreme precipitation events, which can increase both the supply and transport of sediments within a catchment (Dymond et al. 2006; Basher et al. 2011; Basher et al. 2012). Additionally, many have observed an increased occurrence of landsliding following storm events in New Zealand hillslopes as a result of LCLU practices, such as pastoral agriculture, which can remain unvegetated for months to years, creating persistent sediment source areas that have long-term impacts on river SS regimes (Hovius et al., 2000; Glade, 2003; Dymond et al., 2006; Fuller 2007; Fuller, 2008; Dymond et al., 2010).

In February of 2004, the southern portion of the North Island experienced an extreme precipitation event with an approximate recurrence interval of 150 y that resulted in extensive landsliding and flooding (Dymond et al. 2006; Fuller, 2007; Smith et al. 2011). The February 15-16 storm brought more than 20 h of consistent rainfall to the Manawatu River catchment and resulted in variable sediment responses between subcatchments (Fuller 2008). In addition to impacting river sediment loads, the storm caused widespread property damage and loss of productive pasture soil. Despite many studies of the impacts of individual storm events, few have considered the long-term impacts of landsliding on erosion rates and water quality (De Rose 2012). The increased occurrence of landslides in response to changes in LCLU could potentially transform a landscape from a supply-limited to a transport-limited by decreasing vegetative cover and increasing erosion rates (Milliman and Meade 1983; Allan 2004). This research examines the immediate- and long-term impact of this event on erosion and river SS regimes in two subcatchments of the Manawatu: the Oroua and the Pohangina, which were strongly affected by the February 2004 storm.

IV. STUDY AREA AND BACKGROUND

This Manawatu River catchment was a suitable candidate for this study because the region has made considerable increases in pasture grazing and plantation forestry practices in recent decades (Fahey et al. 2003; Ballantine and Davies-Colley 2014), and because high-resolution discharge and suspended sediment (daily) data spanning years to decades is available for multiple monitoring stations within the Manawatu River catchment (provided by Horizons Regional Council, New Zealand). The Manawatu River catchment is located in the southern part of the North Island of New Zealand (Figure 3), spanning an area of 5,885 km^2. Since European settlement circa 1840, its indigenous forest cover has been increasingly replaced with grassland for pastoral agriculture (Dymond et al. 2006). Present land use (as of 2012) is dominated by grassland and pasture, followed by natural and planted forest (Table 1). The climate in the Manawatu is temperate, with annual rainfall varying from 800 mm at the coast to 5000 mm at the top of the ranges. More rainfall occurs in winter than in summer, though weather in the Manawatu is generally variable (Fuller 2005).

The most extensive landsliding in the Manawatu during the February 2004 event was in the Oroua and Pohangina River subcatchments, which are adjacent in the northwest portion of the catchment and drain the mountainous Ruahine Range to the southwest (Figure 3). The Ruahine Range is comprised of highly fractured greywacke (siltstone and sandstone) and is tectonically active, with uplift rates of up to 3 mm/yr (Fuller 2007). The Oroua and Pohangina subcatchments drain 308 and 489 km^2, respectively, and have similar drainage densities, mean catchment slopes, relief ratios, and ruggedness values (Table 1). The topographic setting of the Oroua and Pohangina subcatchments is dominated by highly dissected hillslopes composed of up to 4000 m of poorly consolidated alluvial and marine sands and gravels above the underlying greywacke basement. Dominant soil orders include

Brown soils and Pallic soils, which cover approximately 70% and 15% of the total land area, respectively. The subcatchments are divided by the crest of an anticline, which is uplifting at an approximate rate of 1 mm/yr (Fuller 2007). This physiographic setting is conducive to high erosion rates, and specific sediment yields in the region are as high as 2000-5000 t/km^2/y (Fuller 2007). The Oroua and Pohangina subcatchments of the Manawatu were chosen for more detailed analyses because they were heavily impacted by landsliding during the February 2004 storm, and because of the availability of high-resolution LCLU and water quality datasets.

Table 1. Physical characteristics of the Oroua and Pohangina subcatchments.

	OROUA	**POHANGINA**	**Definition (Units)**
Area	308.0	489.2	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	16.0	18.9	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	13.4	11.3	Standard deviation of catchment slope
Land Cover			Catchment area of a particular land cover type (%)
Grassland/Pasture	72.6	64.9	
Native Forest	23	32.3	
Planted Forest	3.3	2.5	
Other	1.1	0.3	

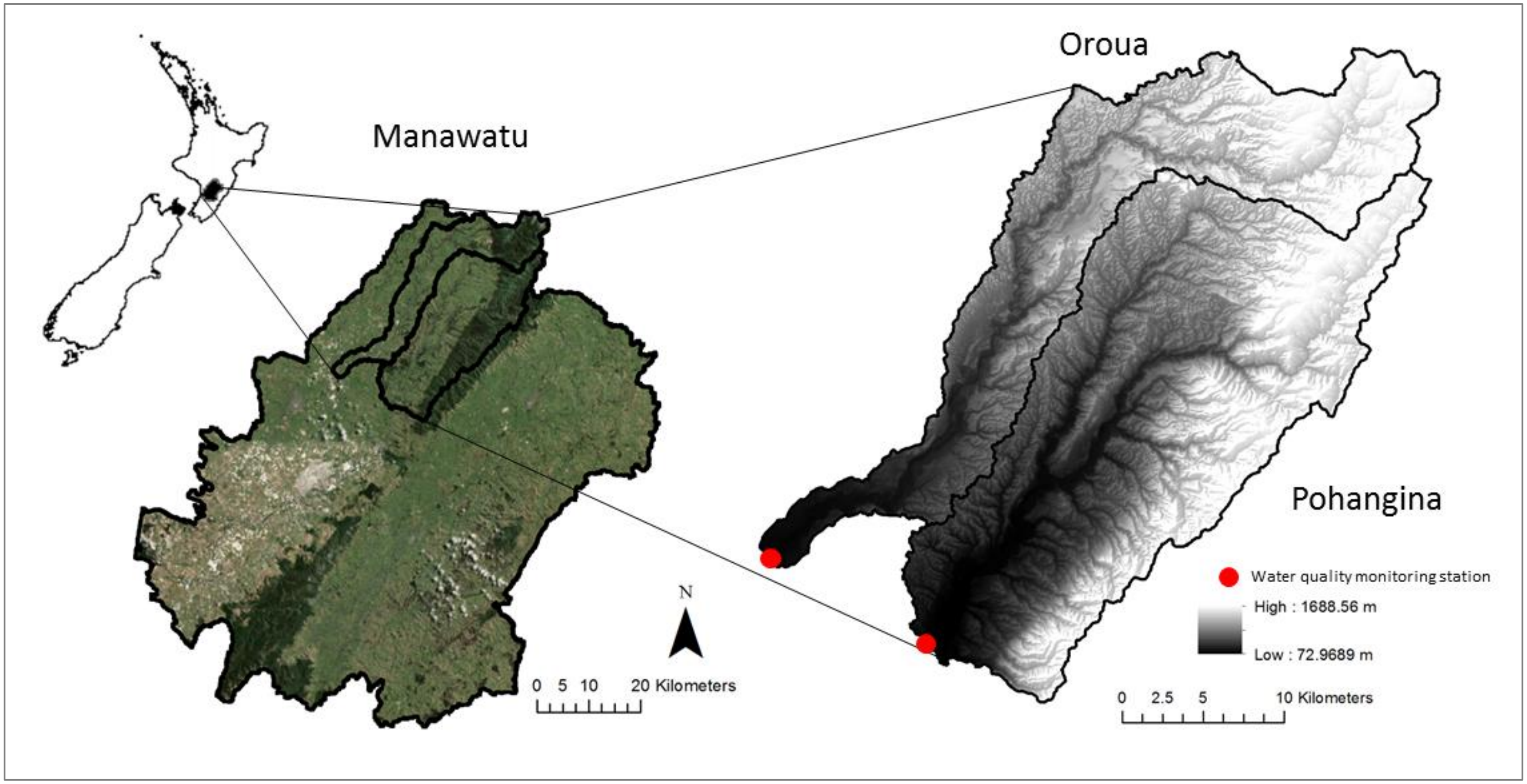


Figure 3. Site location map. The Manawatu River catchment is located on the Lower North Island of New Zealand. The Oroua and Pohangina subcatchments are located in the northwest portion of the Manawatu.

V. DATA AND METHODS

Data

Environmental data utilized in this study includes physiography, land cover/use, hydrology, and water quality. Physiographic data included a high-resolution (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; Snelder et al. 2010). Land cover/use was obtained from the New Zealand Land Cover Database (LCDB). 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 used in this study was daily suspended sediment (SS) loads provided by HRC. They collected these data at State of Environment (SoE) monitoring sites at the outlets of the Oroua and Pohangina subcatchments (see Figure 3).

Daily suspended sediment yields (in tonnes) were calculated for the two sites using turbidity and discharge data collected from the monitoring stations according to the following methods. 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 a SSC time series. The SSC time series were integrated with the discharge time series to calculate SS loads (sensu Basher et al. 2012). Daily data are available for the dates 11/9/2003-6/18/2014 in Oroua and 4/14/2000-4/1/2014 in Pohangina. Approximately five months of data (5/23/2010-9/2/2010) are missing from the SS record in the Oroua subcatchment due to a high flow event which displaced the turbidity meter in the channel.

Land use/land cover analyses

Landslide scars in the Manawatu River catchment created during 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 (Figure 4). Landslides were identified by applying an unsupervised classification to the images, and finding bright classes corresponding to bare ground on slopes greater than five degrees. 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 dataset to identify the locations of landsliding in the Oroua and Pohangina subcatchments and derive their slope, land cover, soil type, and connectivity to river channels.

A river-landscape connectivity layer was created by utilizing DEM derivatives based on a study by Palmer et al. (2013). 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. On the occasion that the next 2 pixels down the flowpath had a slope of >5 degrees or the next pixel was river/floodplain then the originating pixel was considered as connected; if the slope condition was not satisfied then the pixel was considered to be disconnected. The resulting river-landscape connectivity layer was then used as a mask on the landslide occurrence map to assess the percentage and location of landslides that are connected to the river channels.

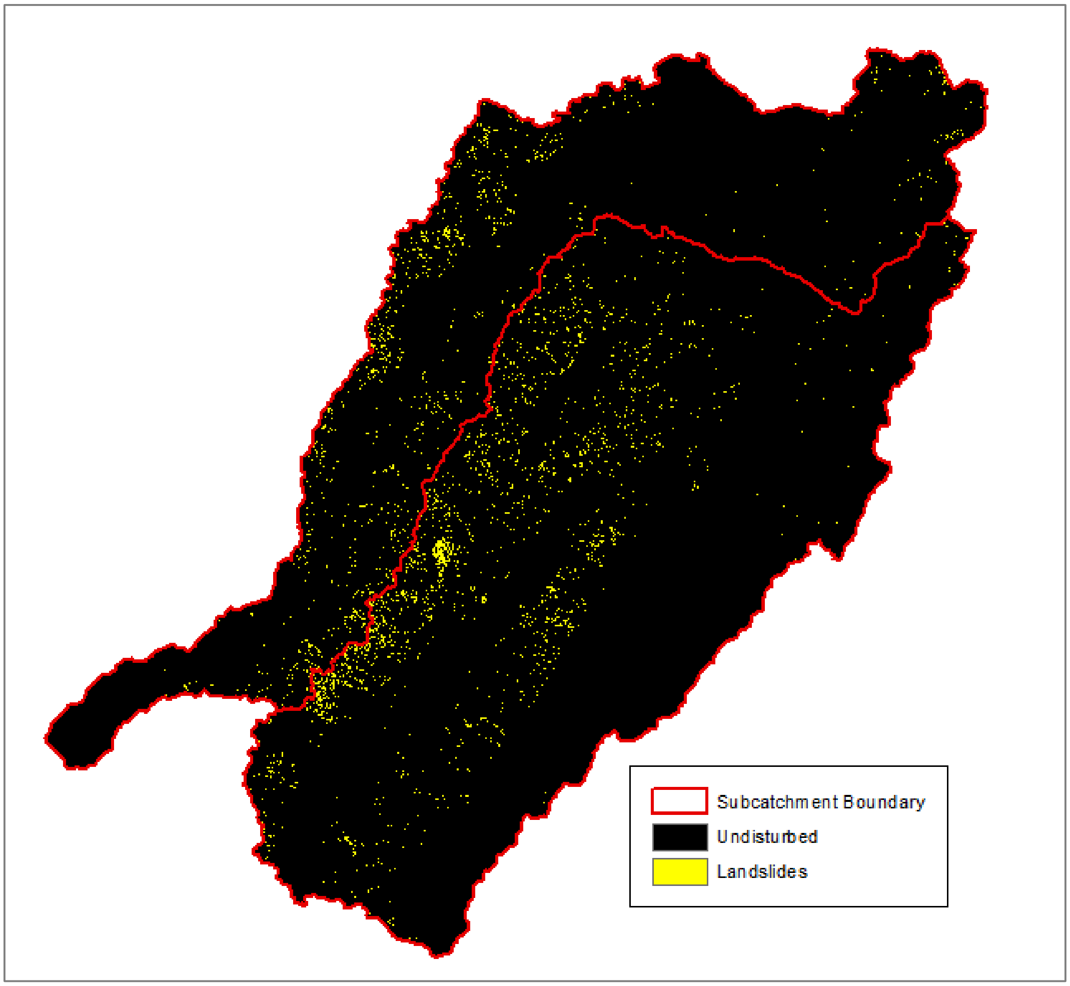


Figure 4. Landslide occurrence map. Landslides mapped from SPOT5-10 m resolution imagery (Dymond et al., 2006).

Sediment regime analyses

Indicators of Hydrologic Analysis (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" (TNC 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 subcatchments. 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. 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 has only been used by one study (to the best of our knowledge) prior to ours (eg. Yang et al. 2010). The availability of daily SS data on the decadal scale allowed us to identify 'sediment events' (hereafter 'events') and characterize fluvial sediment regimes.

IHA calculates parameters for five types of EFCs: extreme low flows, low flows, high flow pulses, small floods, and large floods. While specific magnitude or exceedance probability thresholds can be set to characterize the EFCs, in general extreme low flows represent drought conditions, low flows represent base flows, high flow pulses represent flows greater than low flows but which typically do not overtop channel banks, small floods represent high magnitude events often with a return interval of 2 years, and large floods represent peak flow events usually with a return interval of 10 years or greater (TNC 2009). For this study, all SS values that exceeded 75% of daily SS values for the period were classified as "high flow pulses," and all SS values below 50% of daily SS values for the period were classified as "low flows." High flow events begin when the SS value increases by more than 25% per day, and end when flow decreases by less than 10% per day. By using the daily SS record for the EFC analysis instead of the mean daily discharge record, we focused our analysis on sediment-bearing flow events. An aggregated dataset was developed based on the results of the IHA EFC analysis to look at the total runoff and SS magnitudes and peaks for individual events for the period of record. Individual events were defined as series of continuous days that IHA identified as high flow pulses, small floods, or large floods based on the SS record.

The total runoff and SS magnitudes were calculated for each event by summing daily totals to create the event dataset. 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 1979). LOESS allows for an objective and empirical curve fit without making any assumptions about the form of the fit. 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.

VI. RESULTS

Land use/land cover and landslide occurrence

Grassland/pasture accounted for 72.6% and 64.9% of the land area of the Oroua and Pohangina subcatchments, respectively (Figure 5). Forest occupied 26.4% of Oroua and 34.8% of Pohangina, while in both subcatchments all other land cover types account for the remaining <1%. Landslides triggered by the February 2004 storm affected 14.7% and 17.8% of the land area of the Oroua and Pohangina subcatchments, respectively. Aerial imagery from February 2005 shows many of these landslide scars remained unvegetated a year after the event (Figure 5). The comparison between landslide occurrence and land cover classifications revealed that 91% of landslides in the Oroua and 96% of landslides in the Pohangina occurred in grassland/pasture. Landslides occurred on slopes with an average steepness of 19.3 and 19.4 degrees in the Oroua and Pohangina subcatchments, respectively. The connectivity analysis revealed that only 25% of landslides in the Oroua and 28% of landslides in the Pohangina were connected to the river channels and likely contributed to SS loads during the course of that runoff event (Figure 6).

Hydrology and sediment regimes

Both water runoff and suspended sediment (SS) magnitudes were consistently higher in the Pohangina subcatchment than in the smaller Oroua (Table 2). The median daily SS and runoff magnitude values for each month for the period of record show distinct seasonal patterns in both the Oroua and Pohangina, with higher SS loads and discharge rates occurring in winter months (June-October) than in summer months (November-May) (Figure 7).

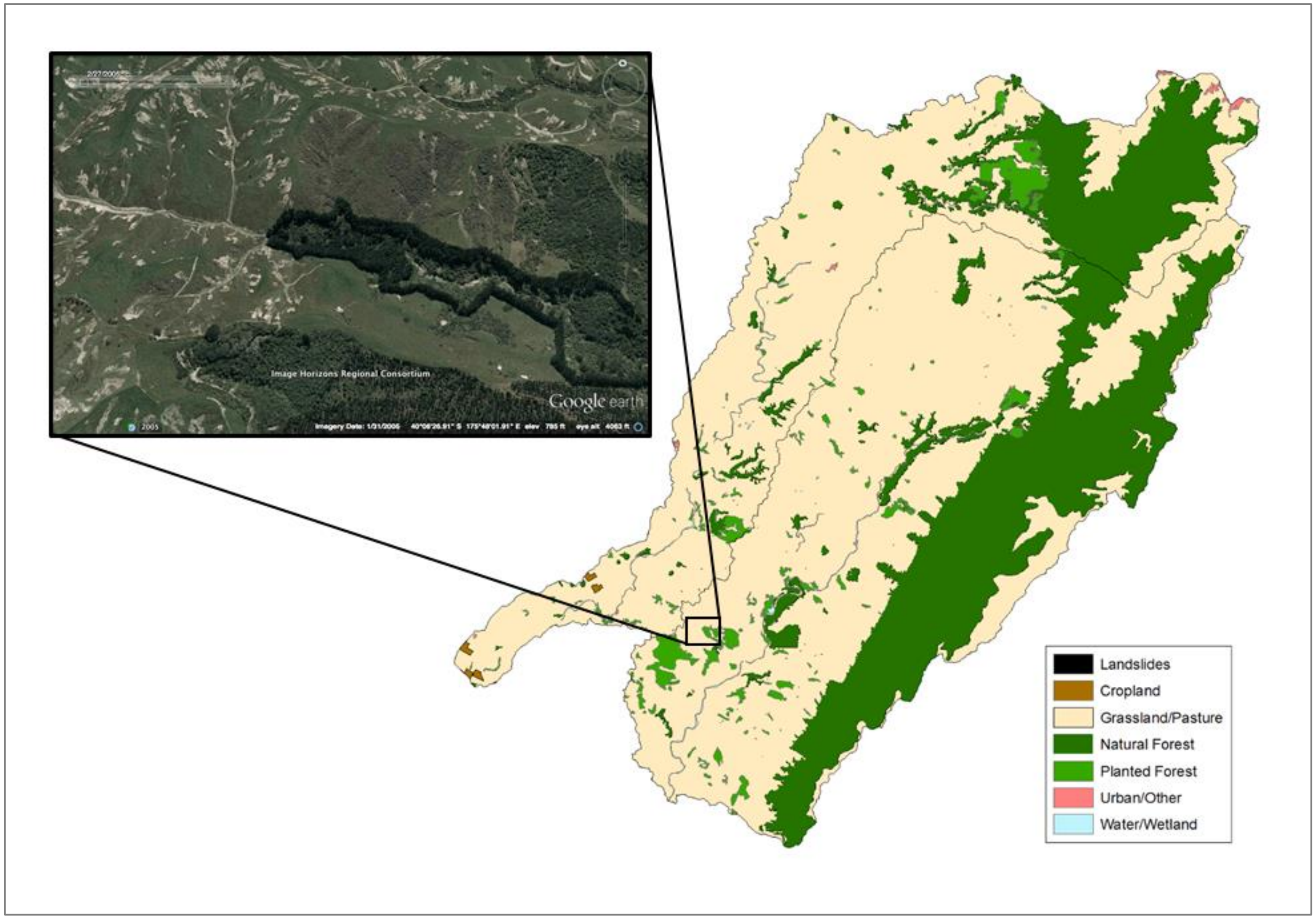


Figure 5. Land cover in the Oroua and Pohangina subcatchments. Satellite imagery from nearly one year (January 2005) after the February 2004 storm shows landslide scars persisting on grassland and pasture. Forested areas show more resistance to landsliding.

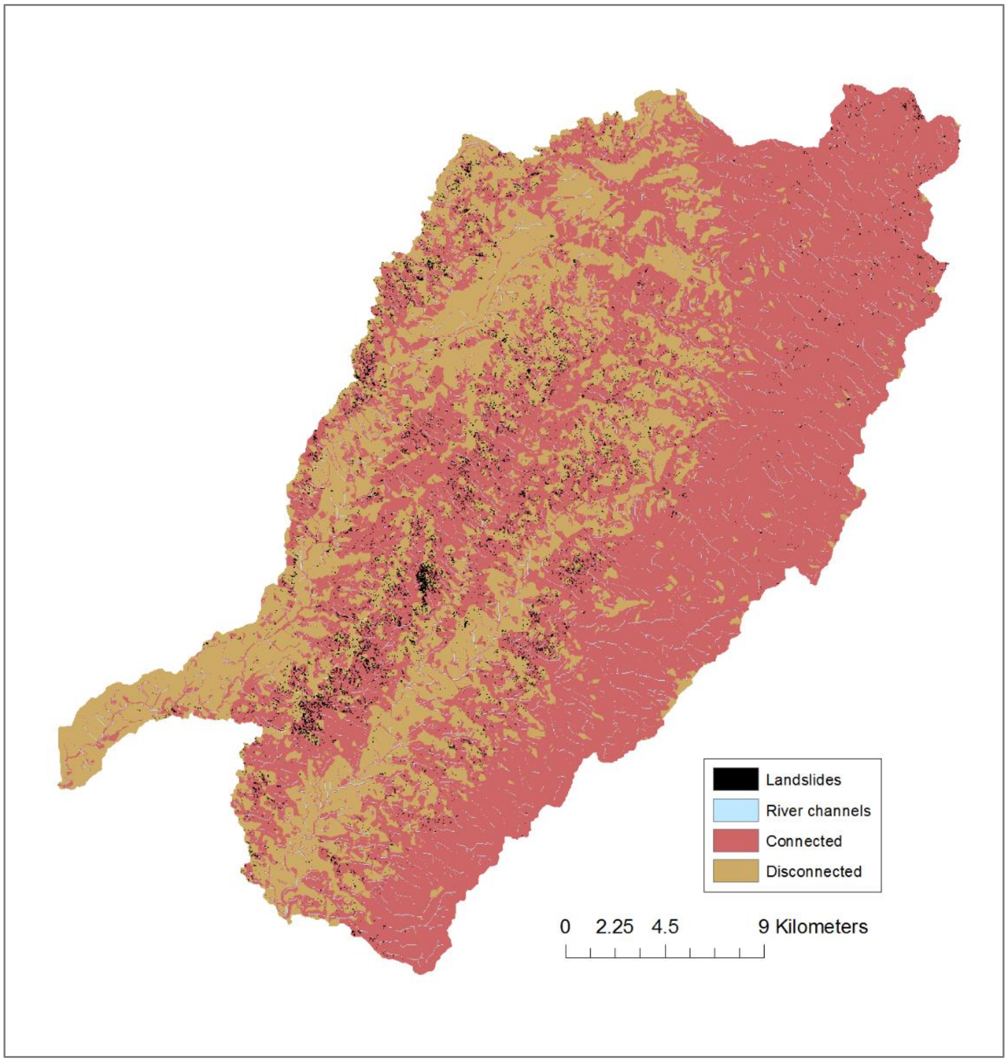


Figure 6. Connectivity map. The connectivity analysis identified 55% of the Oroua and 71% of the Pohangina as immediately connected to the river network. Of the landslides that resulted from the February 2004 storm, 25% and 28% occurred in the Oroua and Pohangina, respectively, on land that was immediately connected to the river network.

There were a total of 265 sediment events in the Oroua and 403 sediment events in the Pohangina for the period of record (Table 2). More events occurred in winter months (57% and 61% for Oroua and Pohangina, respectively) than in summer months. The longest event in the Oroua was 28 days and occurred in the summer, while the longest event in the Pohangina was in the winter and lasted 24 days. The median event duration in both subcatchments was 2 days. The median runoff magnitudes and event peaks in winter months were higher than in summer months, but higher maximum runoff and event peaks occurred in summer months. By contrast, higher SS magnitudes and peaks occurred in summer months than in winter months. Suspended sediment—runoff relationships show that for a given runoff magnitude, SS magnitudes are higher in summer than in winter (Figure 8).

Table 2. Seasonal suspended sediment regimes.

			OROUA		POHANGINA	
			Summer	**Winter**	**Summer**	**Winter**
Duration (days)		**# of Events**	115	150	157	246
		Range	1-28	1-22	1-20	1-24
		Median	2	2	2	2
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 (tonnes)	**Magnitude**	**Min**	49	49	84	84
		Max	320,785	136,486	622,443	267,965
		Median	672	580	1,082	1,008
	Peak	**Min**	49	49	84	84
		Max	195,008	90,544	406,034	173,910
		Median	586	385	868	704

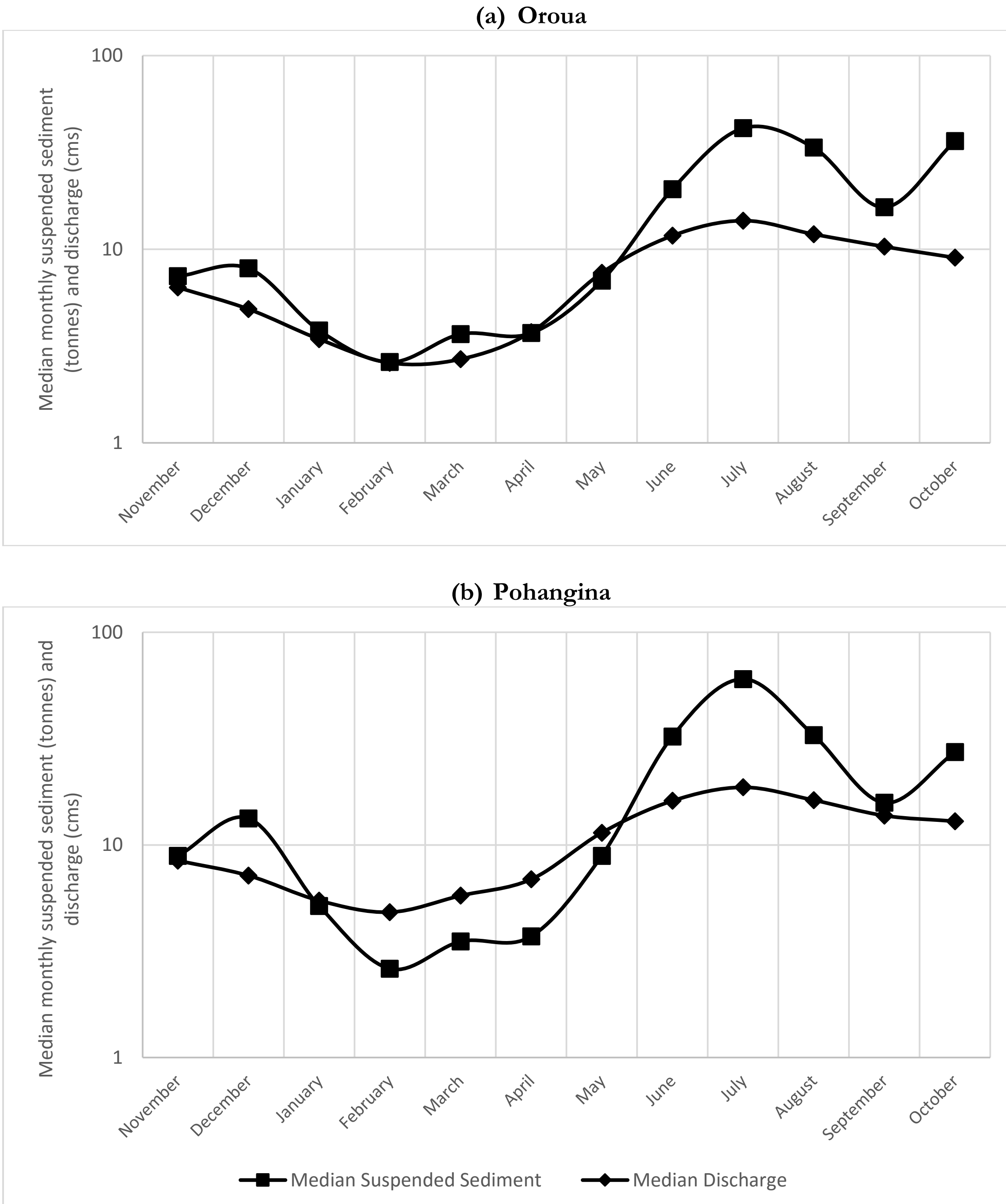
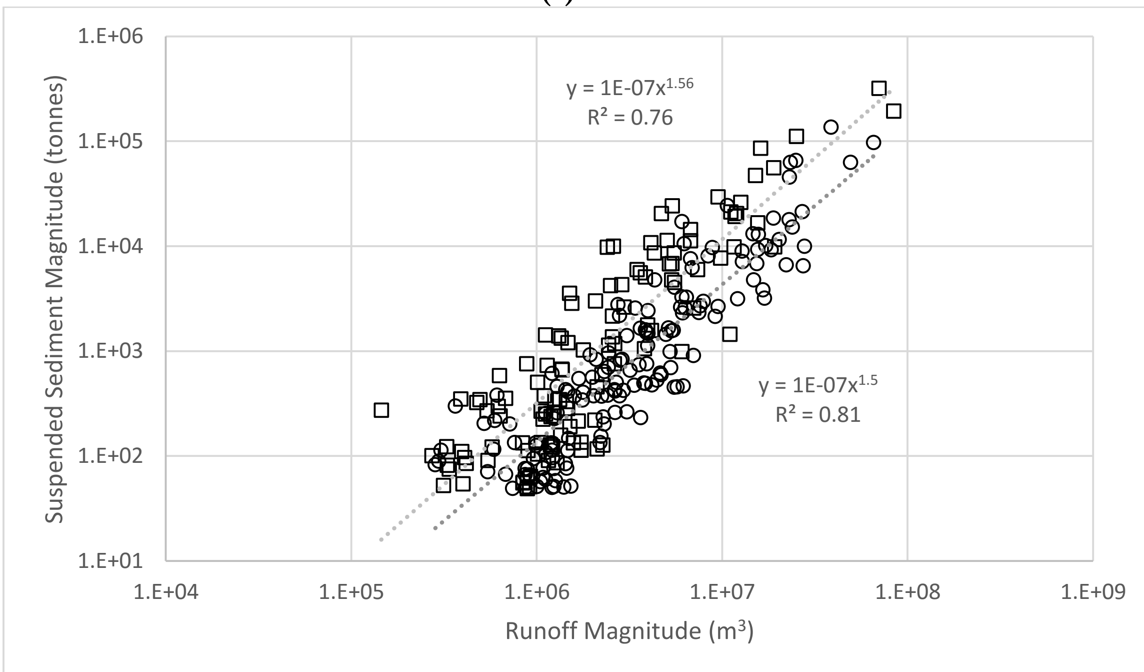


Figure 7. Monthly trends in discharge and suspended sediment. Monthly median daily discharge and suspended sediment for the period of record for Oroua (a) and Pohangina (b). Higher median discharge and suspended sediment magnitudes are observed in winter months (June-October) than in summer months in both subcatchments.

(a) Oroua



(b) Pohangina

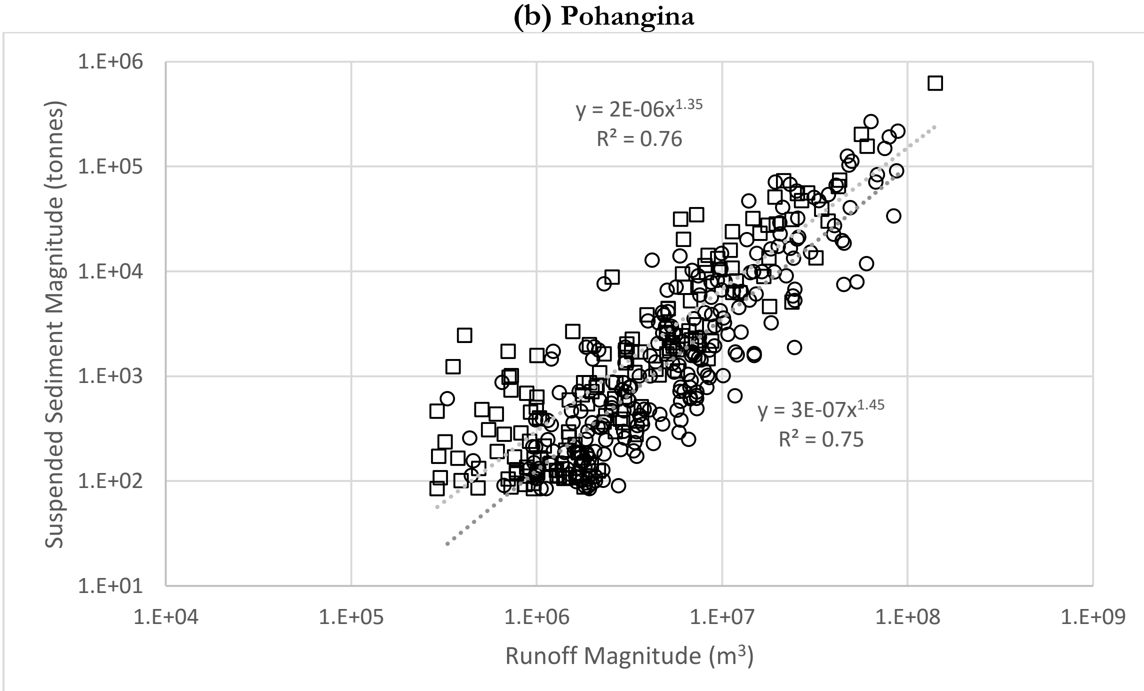
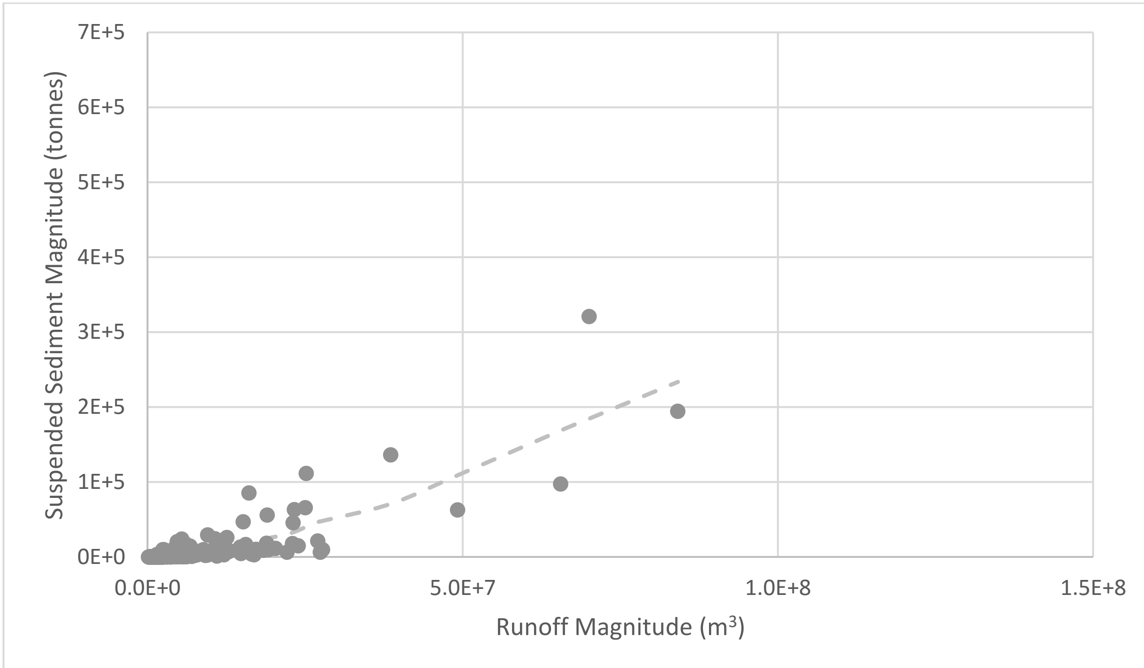


Figure 8. Suspended sediment—runoff relationships. Event suspended magnitude versus runoff magnitude for Oroua (a) and Pohangina (b). Squares represent summer events and circles represent winter events. For a given runoff magnitude, higher suspended sediment values were observed in summer months than in winter months.

Results of the local polynomial regression (LOESS) are displayed in Figure 9. Suspended sediment residuals derived from LOESS show a normal distribution, with the majority of events clustered around the mean condition. Residuals appear heteroscedastic relative to runoff magnitudes. Smaller events are clustered around the mean condition (residual=0), while larger events tend to have the largest residuals in both the positive and negative direction (Figure 10). In the Oroua subcatchment, eleven 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 event SS residuals elevated relative to the mean, and these events carried 58.1% of the total sediment load. With few exceptions, all events with SS loads that were depleted relative to the mean occurred in winter months. In the Oroua, 14 events had SS loads that were significantly depleted relative to the mean condition, with 12 of those events occurring in winter. There were 19 events with significantly depleted SS residuals in the Pohangina, with 17 of those occurring in winter. Time series analyses of the SS residuals are displayed as bubble charts along with rainfall in Figures 11 and 12.

The largest runoff event, the February 2004 flood, had SS magnitudes that were significantly elevated relative to the mean condition in both subcatchments, though not as high in the Pohangina as in the Oroua. The largest events in the Pohangina in the following four years had significantly elevated SS loads. From approximately 2008 until 2012, there were no events with SS loads significantly elevated, and the largest event had an SS load significantly depleted relative to the mean. Following this event, a small number of events again had elevated SS loads. There are fewer large events in the Oroua closely following the February 2004 event, but two of the three largest events following are significantly elevated relative to the mean. As in the Pohangina, a period of depleted sediment began in Oroua in

(a) Oroua



(b) Pohangina

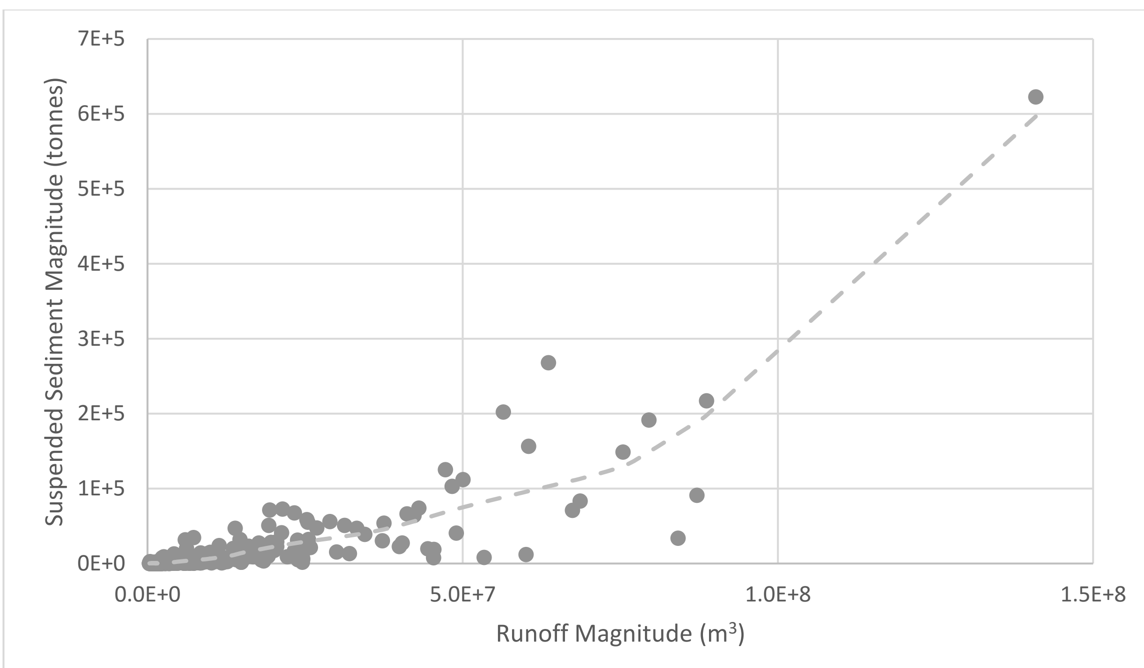
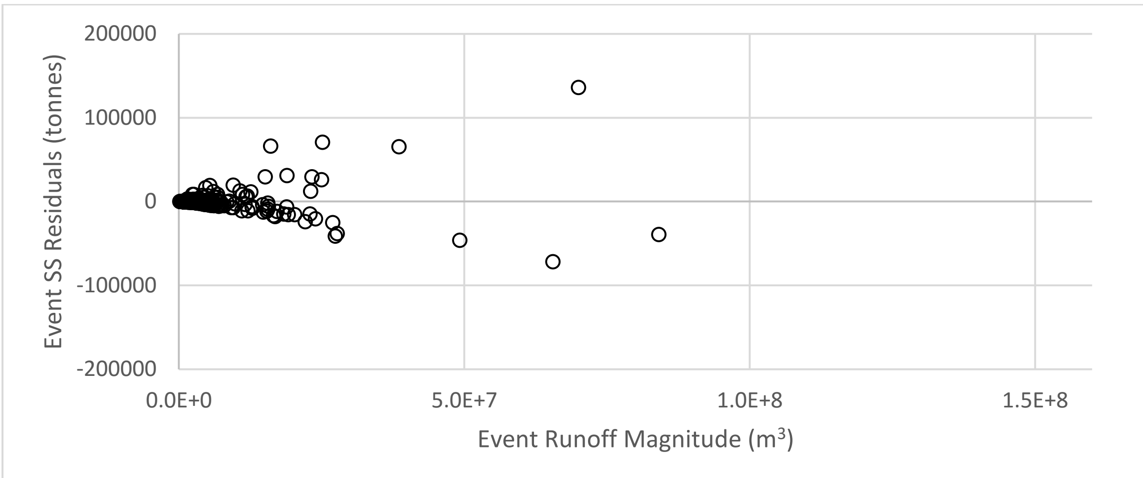


Figure 9. LOESS regression. Local polynomial regression (LOESS) based on event suspended sediment magnitude versus runoff magnitude for Oroua (a) and Pohangina (b). Circles represent all events identified from the IHA EFC analysis. The dashed line is the result of LOESS, and represents the mean expected SS response to a given runoff magnitude.

2008. Another period of elevated SS followed this period of sediment exhaustion in the Oroua subcatchment beginning in mid-2010, but was muted in the Pohangina record. This period of elevated sediment loads in the Oroua followed the period of missing SS data, which was due to a high flow event dislodging the turbidity meter.

(a) Oroua



(b) Pohangina

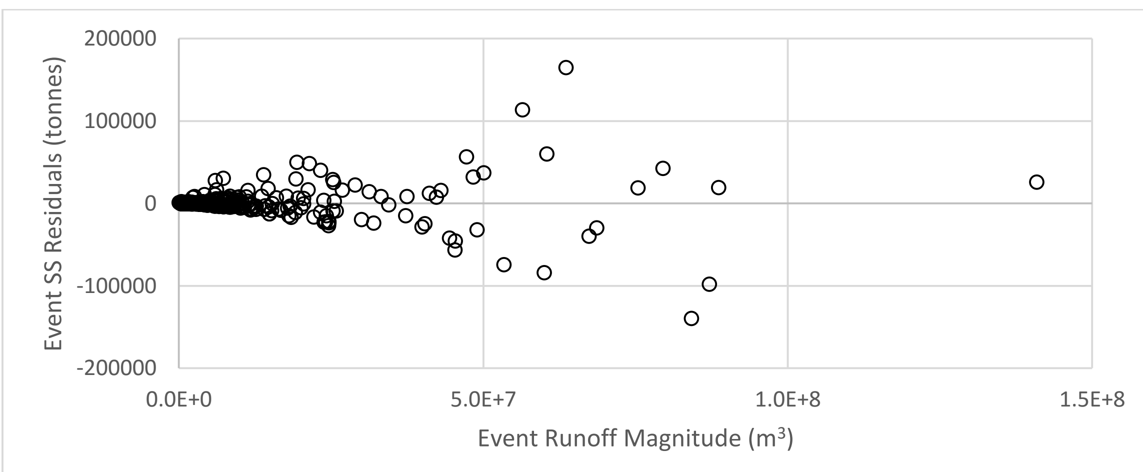


Figure 10. Event suspended sediment residuals versus event runoff magnitude. Suspended sediment residuals show heteroscedasticity relative to runoff magnitude. Smaller events are clustered around the mean condition (residual=0), while larger events have larger residuals.

VII. DISCUSSION

Land use effects on catchment soil erosion

Landsliding in the Oroua and Pohangina catchments occurred disproportionately on grassland and pasture, supporting previous studies which found that removal of stabilizing root systems has led to more frequent and widespread landslide occurrence in New Zealand (Fuller, 2005; Dymond et al. 2006; Basher et al. 2011). Landslides also occurred disproportionately on Pallic soils, which have high bulk density and weak structure, making them susceptible to erosion (Hewitt and Dymond 2013). Not unexpectedly, steeper slopes (>19 degrees) showed more susceptibility to landsliding than more level areas. 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, and likely produced colluvium stored in the hillslopes that did not immediately impact suspended sediment (SS) loads in the rivers.

The increased occurrence of landslides in response to changes in land cover/land use (LCLU) could potentially transform a landscape 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, vegetation removal from pasture grazing, forest harvesting, and landsliding would result in an abrupt decrease on the vegetation cover line (Figure 1b), making it more similar to the precipitation line (Figure 1a). Depending on the timing of precipitation, these abrupt changes could increase the potential for a catchment to become transport limited (conceptually, the gray bars in Figure 1 would widen). The February 2004 storm occurred in summer, which is the dry season when hillslope potential for erosion is high. These conditions, along with the storm's intensity and duration, likely contributed to the extent and severity of landsliding during this event.

Recovery of topsoil in landslide scars in New Zealand after decades rarely reaches the level of non-eroded sites (Sparling et al. 2003; Rosser and Ross 2010). In addition to impacting river sediment loads, the storm caused widespread property damage and loss of productive pasturelands by removing fertile topsoil and reducing the soil column (Reid and Page 2002). Prior to the storm, the Horizons Regional Council, the governing authority for the region, had already implemented the Sustainable Land Use Initiative (SLUI) to target land management change in the highly erodible hill country. In the Manawatu catchment, 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). SLUI seeks to reduce erosion in the Manawatu hill country by identifying highly erodible land and applying passive and active conservation measures, such as retiring pastureland and soil conservation planting (Dymond et al. 2016).

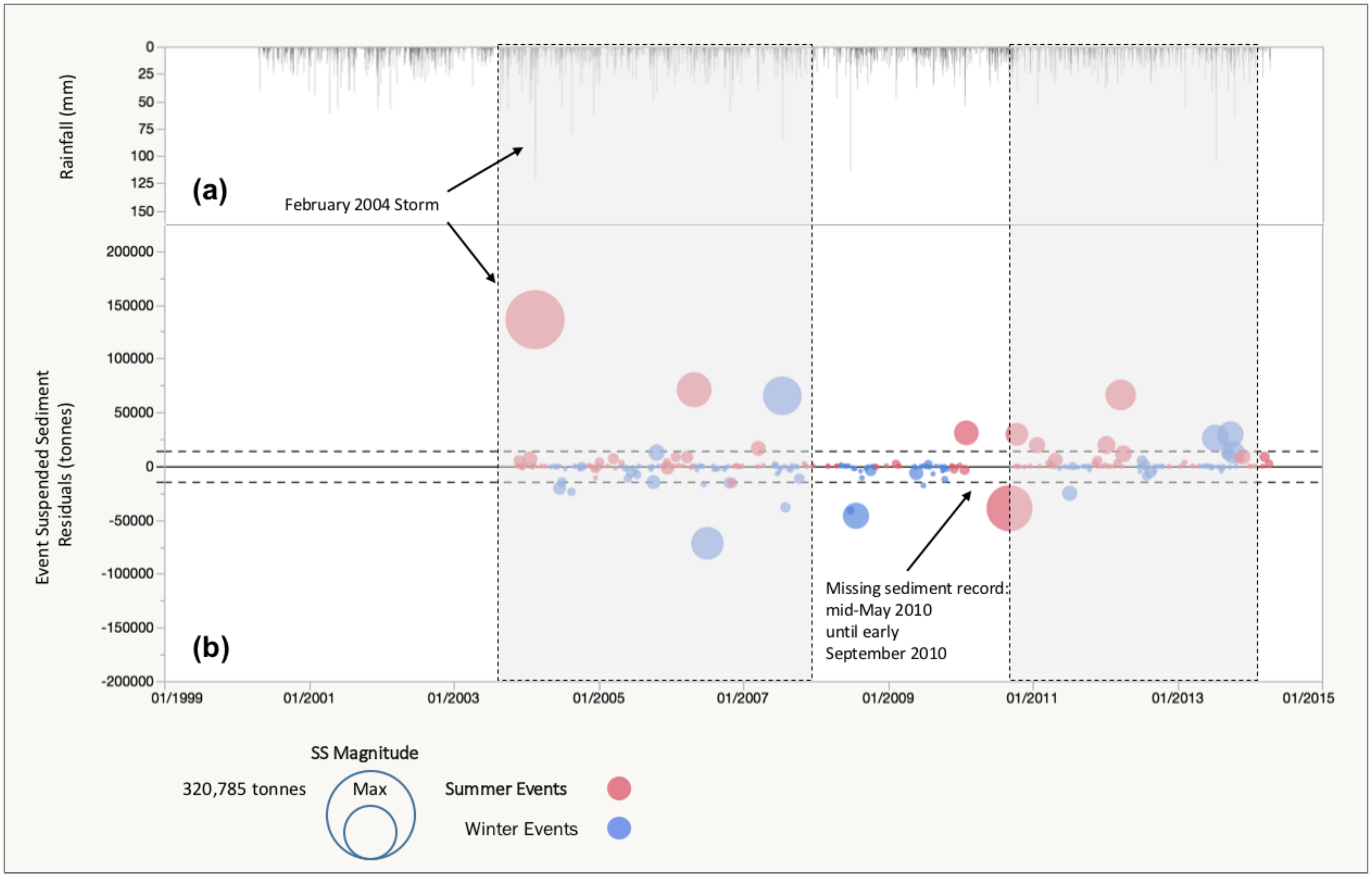


Figure 11. Oroua time series of suspended sediment residuals. Time series analysis of rainfall (a) and event suspended sediment residuals (b) in the Oroua subcatchment. Gay bars show periods of transport-limitation.

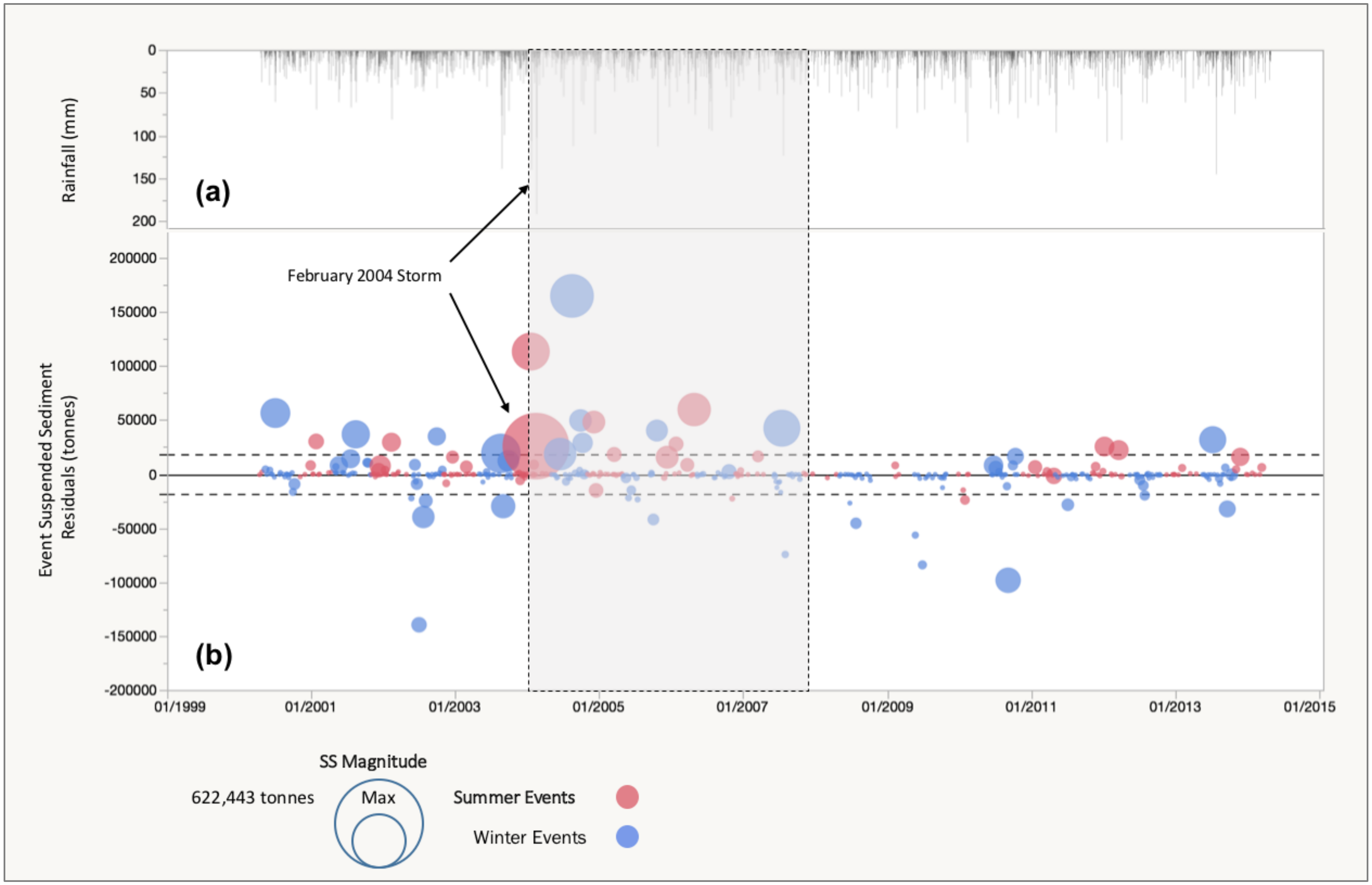


Figure 12. Pohangina time series of suspended sediment residuals. Time series analysis of rainfall (a) and event suspended sediment residuals (b) in the Pohangina subcatchment. Gay bar show period of transport-limitation.

country. In the Manawatu catchment, 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). SLUI seeks to reduce erosion in the Manawatu hill country by identifying highly erodible land and applying passive and active conservation measures, such as retiring pastureland and soil conservation planting (Dymond et al. 2016).

Interactive effects of land use, geomorphology, and climate

The February 2004 storm caused extensive landsliding in grassland and pasture in the Manawatu River catchment, which increased river sediment loads in both the short-term and the long-term. Sediment loads were elevated relative to the mean in both the Oroua and Pohangina subcatchments during the storm and for approximately four years following, indicating that these catchments became temporarily transport-limited due to a sudden increase in available sediment. Previous studies have demonstrated the influence of seasonal effects and event sequencing on event sediment loads (eg. Hooke 1979; Walling and Webb 1982; Hudson 2003). Longer recovery times between storm events allow for more available sediment to be transported during subsequent storms (Walling and Webb 1982). Higher SSC-Q relationships have been found in seasons with lower baseflow levels (Walling and Webb 1982). Higher baseflow levels lead to dilution of SSC, as most SS is generated by runoff. This relationship explains the observed seasonal pattern of elevated SS residuals in summer, when baseflow is relatively low, and depleted SS residuals in winter, when baseflow is relatively high. Greater SS values have also been found during events with higher peak discharge levels, suggesting that peak flows provide the energy to both directly erode and effectively transport sediment (Hooke 1979). In the Oroua and Pohangina, higher SS values

(a)

(b)

Figure 13. Photos of landslides in the Manawatu. Examples of landslides in the Manawatu from June 2015 that are directly connected to river channels (a) and examples of landslides that are disconnected (b), leaving sediment stored in debris tails in the landscape.

were observed in summer events (November-May), and are likely due to the occurrence of higher peak flows and high hillslope potential for erosion (Figure 1).

The impact of event sequencing on event SS was evident in the 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 likely due to the occurrence of another large runoff event in the Pohangina in January 2004 that depleted available sediment for the February 2004 storm. Oroua did not have a comparable prior event, which is why the February 2004 storm had a much larger SS response than in the Pohangina. Indeed, the Pohangina SS response to the February 2004 storm was muted compared to the Oroua SS response (Figures 11 & 12). Subsequent storm events for the following four years likely continued to transport available sediment stored to the river channels. These findings are consistent with previous studies of New Zealand catchments in which sediment supply is dictated by rainfall-triggered landsliding. 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 such storms. One possible explanation for longer lag times observed in the Oroua and Pohangina subcatchments in this study (approximately four years) is that these subcatchments have larger drainage areas than the Te Arai (83 km^3), so sediment takes longer to move through these systems.

After four years, sediment loads were diminished relative to the mean condition, indicating that this available sediment in the landscape was exhausted and the subcatchments had returned to a supply-limited status. 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 (Figure 11). One explanation for this observed SS response is that this event caused additional landsliding in the Oroua, again increasing available sediment and switching the sub-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 increased landslide activity. 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, wetlands, ephemeral channels, or landslide debris tails). In field visits following another landslide-triggering storm in the Manawatu in June 2015, we did observe debris tails associated with landslides stored in the hillslopes (Figure 13).

In response to growing concerns about the impact of anthropogenic activities on river water quality, regional governing agencies increased environmental monitoring in the 1990s with a focus on quantifying sediment and nutrient runoff. Water quality in New Zealand rivers for the period of 1989-2009 has 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). The findings of this study contribute to a larger body of literature which demonstrate 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. As this study has demonstrated, river sediment loads are generally highest when precipitation and hillslope potential for erosion is high and vegetation cover is low (Figure 1). These same conditions create the potential for a landscape to become transport-limited by increasing available sediment. These interactions occur over seasonal and longer timescales. At the seasonal scale, suspended sediment loads in the Oroua and Pohangina were higher in winter months, when runoff magnitudes were higher, but large events which occurred in summer months when vegetation cover was low and hillslope potential for erosion was high also carried large suspended sediment loads. At longer timescales, the extreme storm in February 2004 removed vegetation cover and increased hillslope potential for erosion, resulting in elevated suspended sediment loads for a period of years. In the Oroua and Pohangina subcatchments, livestock grazing on steep slopes 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, were not quantified in this study, but also contribute large amounts of sediment to the rivers.

Future work

Subsequent research on cross-scale interactions between climate, LCLU, and water quality will address how weekly land cover changes associated with livestock grazing and plantation forestry interact with precipitation to affect river sediment loads throughout the entire Manawatu River catchment. A high-resolution (8-day, 30-m) land disturbance index (DI) time series for the period 2000-2014, which is currently under development, will be used to represent weekly LCLU changes in terms of disturbance. To determine how weekly land cover changes interact with climate to influence river sediment loads, the climate and water quality time series for all water quality monitoring sites will be analyzed in conjunction with the DI maps and time series currently under development. In addition to the Oroua and Pohangina, seven more subcatchments of the Manawatu River catchment with characteristic climate and LCLU characteristics have an associated water quality monitoring site with a daily suspended sediment record spanning years (Figure 14). Weekly and monthly time series of water quality, climate, and land cover (in terms of disturbance) will be developed for each subcatchment, and empirical, regression-based models will be used to quantify the effects of LCLU changes on water quality. Though many have studied the effects of LCLU on sediment yield and other water quality parameters, few have accounted for weekly LCLU changes the way that these methods allow.

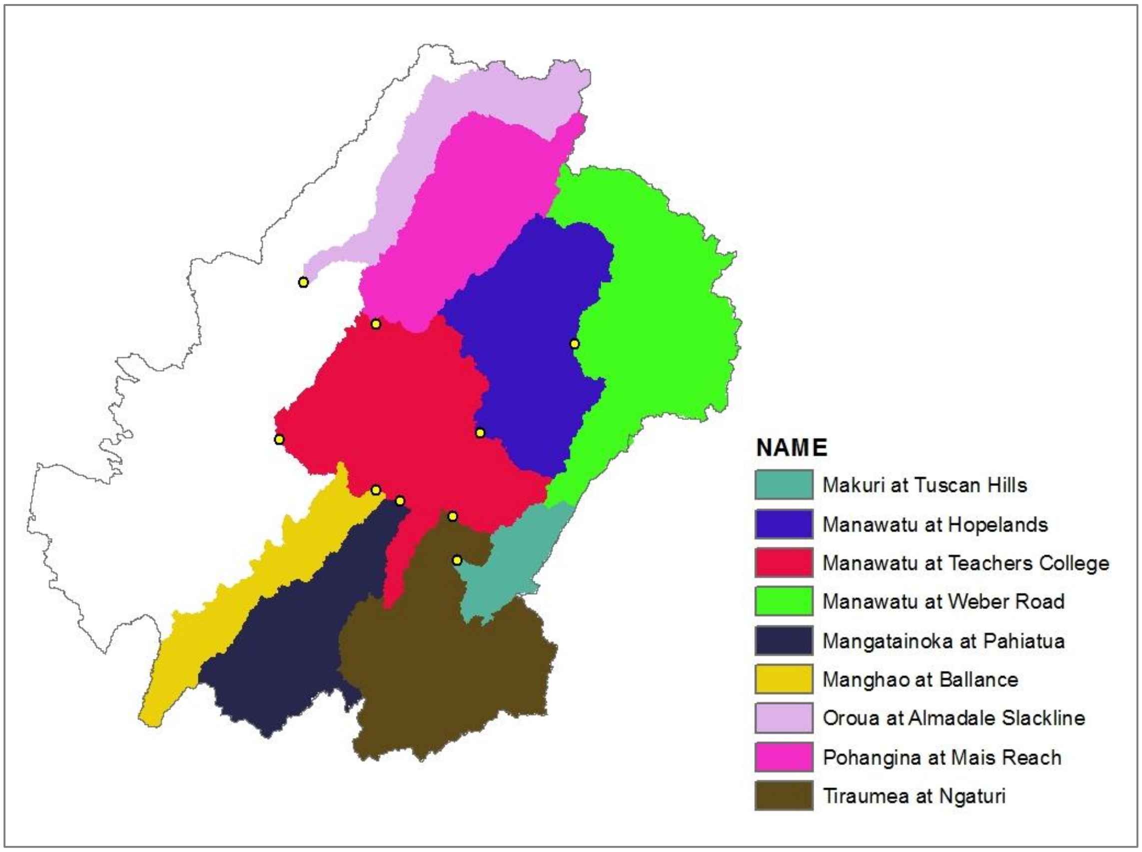


Figure 14. Manawatu subcatchments with suspended sediment records.

VIII. CONCLUSIONS

This thesis was a study of the cross-scale interactions between land cover/land use, climate, and river water quality in the Manawatu River catchment that explored the short-term and long-term effects of land use change on river sediment loads in the Oroua and Pohangina subcatchments in the context of an extreme precipitation event. Conversion of forest to grassland and pasture on land already prone to landsliding in the Manawatu River catchment on the Lower North Island of New Zealand has led to the increased occurrence of storm-induced landsliding, which in turn has short- and long-term impacts on river suspended sediment loads. A 150 y storm in February of 2004 caused extensive landsliding in the Manawatu, particularly in the Oroua and Pohangina subcatchments, and immediately transported large volumes of suspended sediment to the river channels. A sediment regime analysis using Indicators of Hydrologic Alteration revealed that the suspended sediment response to large storms was elevated relative to the mean condition for a period of approximately four years following the February 2004 storm due to the increase of available sediment caused by the landsliding.

The results of this study have demonstrated that large storms have the ability to generate enough sediment via landsliding to temporarily convert small catchments from a supply-limited status to a transport-limited status on short timescales (<10 y). The timing and intensity of prior and subsequent storms are important controls dictating how long a catchment remains in a transport-limited state. If vegetation has time to reestablish, available sediment in the landscape may become exhausted and the catchment may switch back to a supply-limited status. If, however, another landslide-triggering storm occurs before this time, suspended sediment loads may remain elevated for longer time periods. Seasonal weather conditions also influence river sediment regimes. In the Oroua and Pohangina subcatchments, periods of transport-limitation manifested in summer events, and would not have been observable over a time period shorter than a decade.

Models have shown that soil conservation measures, such as revegetating and retiring highly erodible pasturelands, can significantly reduce erosion in the Lower North Island (Dymond et al. 2016). Additionally, wetlands and riparian buffers can serve as sediment sinks 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 change. The availability of daily SS data on the decadal-scale in the Oroua and Pohangina subcatchments allowed us to identify 'sediment 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 that has daily suspended sediment data for period of years.

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