GEOSPATIAL ANALYSES OF TERRESTRIAL-AQUATIC CONNECTIONS ACROSS NEW ZEALAND AND THEIR INFLUENCE ON RIVER WATER QUALITY

by

Ioannis Kamarinas, M.Sc.

A dissertation submitted to the Graduate Council of
Texas State University in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
in Geographical Information Science
August 2018

Committee Members:

Jason P. Julian, Chair

Kimberly M. Meitzen

F. Benjamin Zhan

Kirsten M. de Beurs

ACKNOWLEDGEMENTS

First and foremost, I want to thank my advisor Dr. Jason Julian, Associate Professor at the Department of Geography. It has been an honor to be his Ph.D. student. I appreciate all his contributions of time, ideas, and funding to make my Ph.D. experience productive and stimulating. The joy and enthusiasm he has for his research was contagious and motivational for me, even during tough times in the Ph.D. pursuit.

For this dissertation I would like to thank my committee members: Dr. Kimberly Meitzen, Dr. Benjamin Zhan, and Dr. Kirsten de Beurs for their time, interest, and helpful comments. I am also grateful to our collaborators at NIWA, especially Dr. Andrew Hughes and Dr. Suzie Greenhalgh for providing datasets, scientific advice, and hosting me while I visited New Zealand.

Lastly, I would like to thank my family for all their love and encouragement. Their support has been unconditional all these years; they have given up many things for me to pursue my academic endeavors; they have cherished with me every great moment and supported me whenever I needed it.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iv

LIST OF TABLES viii

LIST OF FIGURES ix

ABSTRACT xi

CHAPTER

1. INTRODUCTION 1

Intense Land Use Practices and Stream Water Quality 1
The Need for More Accurate River Networks 2
The Importance of Headwaters in Sediment Conservation 3
Purposes and Methods 4
Structure of Dissertation 5
Papers Presented in Chapters 5
Manuscript Details 7

2. NONLINEAR CHANGES IN LAND COVER AND SEDIMENT RUNOFF IN A NEW ZEALAND CATCHMENT DOMINATED BY PLANTATION FORESTRY AND LIVESTOCK GRAZING 8

Abstract 8
Introduction 9
Methods 13
Study Area 13
Land Cover/Use and Disturbance Index 15
Physiographic Data 17
River Network and Connectivity 17
Hydrologic and Water Quality Data 18
Time-Series and Statistical Analyses 20
Results 21
Land Use and Disturbance at the Sub-Catchment Scale 21
Landscape Connectivity 22
Physiographic and Hydrologic Effects on Land Disturbance 22
TSS Spatiotemporal Dynamics 24

Discussion 25
Connections among Land Use, Climate, Disturbance, and Sediment Runoff 25
Landscape-River Connectivity..27
Nonlinear Changes..28
Conclusions 30
Tables 31
Figures 33

3. MAPPING STREAM NETWORKS USING PHYSIOGRAPHIC CHARACTERISTICS AND VARYING ACCUMULATION THRESHOLDS..42
Abstract 42
Introduction 43
Methods..45
Study Area 45
Hydrography Dataset and Physiographic Regions 46
Channel Head Mapping 47
Clustering and Stream Delineation 49
Validation..49
Results 50
Channel Head Mapping 50
Varying Accumulation Thresholds 50
Stream Delineation and Drainage Density..52
Modeled Stream Network Validation 53
Discussion 54
Channel Networks Within the Context of Physiographic Diversity....54
Study Limitations..58
Applications and Future Directions 58
Tables 60
Figures 63

4. PRIORITIZING UNMAPPED HEADWATER CHANNELS FOR PROTECTION IN NEW ZEALAND'S MOST SEDIMENT-IMPAIRED CATCHMENTS 70

Abstract 70
Introduction 70
Methods..74
Catchment Selection 74
Headwater Streams Prioritization 74
Results 76

Priority Headwaters 76
Headwaters in High-Producing Grasslands 76
Headwaters in Plantation Forests....................77
Headwaters in Croplands 77
Discussion 78
Prioritizing Protection....................78
Potential Effectiveness of Protection 79
Future Work 82
Tables 83
Figures....................86

5. CONCLUSIONS....................90

Nonlinear Changes in the Relationship Between Land Disturbance and Sediment Runoff....................90
Channel Networks Within the Context of Physiographic Diversity 91
Headwater Prioritization for Riparian Buffering/Fencing....................92
Future Work and Broader Impact....................93

APPENDIX....................95

REFERENCES 97

LIST OF TABLES

Table **Page**

2.1. Summary of landscape and water quality data used for this research 31

2.2. Physiographic characteristics of the study area (Hoteo) and its sub-catchments 31

2.3. Piecewise regression output 32

3.1. REC classification system used to differentiate physiographic regions 60

3.2. Mapped channel heads per attribute class..60

3.3. Mapped channel heads summary for physiographic classes across New Zealand, including the number (n) of all 3rd-order streams, the n of stratified randomly sampled streams, the n of channel heads mapped, and the mean density of channel heads per class (channel heads per square km) 61

3.4. Cluster center for each variable used on the k-means clustering................................62

3.5. Results from new channel head validation against the REC channels and the mapped channels from aerial imagery 63

4.1. Physiographic and water quality characteristics for the 15 sediment-impaired catchments used in this study...83

4.2. Datasets used to prioritize headwater reaches for protection.....................................84

LIST OF FIGURES

Figure **Page**

2.1. (a) The Hoteo catchment (located on the North Island, NZ) and its five sub-catchments (black lines) delineated based on the location of gaging stations 33

2.2. (a) Percent of time of every pixel being disturbed for the 2000–2013 period 34

2.3. (a) Relative contributions of exotic forest (orange) and pasture (blue) to overall watershed disturbance; (b) Disturbance contribution (%) of each sub-catchment relative to the total watershed disturbance 35

2.4. Landscape connectivity for the study area; connected areas (green color) are considered critical source areas of sediment (CSAS) and were used as a mask for land disturbance..36

2.5. Wilcoxon rank sum test (Bonferroni correction) on disturbance values for different slope (flat, undulating, rolling, strongly rolling, and steep) and land cover classes: (a) high-producing grasslands and (b) exotic forest 37

2.6. Monthly (a) percentage of catchment connected and disturbed; (b) water clarity (residuals from local polynomial regression (LOESS) + mean clarity; and (c) flow-adjusted TSS (residuals from loess + mean TSS) for the period 2000–2013...38

2.7. Seasonal variation of disturbance for (a) exotic forestry and (b) high-producing grasslands...39

2.8. Sub-catchment suspended sediment budgets for the 2012–2013 period 40

2.9. (a) Flow event magnitudes; (b) TSS residuals event (n = 60) analysis from the period 2012–2014 for the Hoteo catchment outlet in order of occurrence showing periods of higher amounts of sediment than expected followed by lower amounts of sediment than expected 41

3.1. Map showing the location of the NRWQN stations and the total drainage area 63

3.2. Climate, Geology and Source-of-flow from the modified REC attributes of the North (left) and South Island (right) for the 77 NRWQN catchment area 64

3.3. Channel head point kernel density showing frequency and extent of channel head mapping, with areas in red being more densely mapped compared to areas in blue....65

3.4. Boxplots of values of upstream area for each geology, source-of-flow, and climate class....66

3.5. AIC test for choosing the optimal number of clusters (shown in red)....66

3.6. Drainage density comparisons of REC and modeled stream network for the 77 NRWQN catchments: A) Drainage density of the REC dataset, B) drainage density of the modeled river network (km/km^2), and C) Percent change increase (%) in drainage density with modeled stream network....67

3.7. Channel head change (%) and drainage density change (%) between REC and the new network for each of the 77 NRWQN catchments....68

3.8. Comparisons between modeled and REC channel heads to mapped channel heads based on aerial imagery....69

4.1. Conditional analysis flow chart showing No-Priority, Level 1 (Priority) and Level 2 (High-Priority) prioritization scheme....86

4.2. Results from the analysis showing the different levels of prioritization....86

4.3. On the left, an example of steep slopes (>5˚) resulting in classification of these headwaters as high-priority....87

4.4. Recent forest harvest in Whanganui catchment....88

4.5. On the left, frequently disturbed land (DI>20%) caused channel heads to be labeled as high-priority....89

ABSTRACT

This dissertation presents new techniques for quantifying and mapping terrestrial-aquatic connections, as well as new approaches for assessing the effects of intensive land uses on river water quality. Chapter 1 describes the general format of the dissertation as well as the research questions that were the impetus for this research. Chapter 2 is a case-study that investigated the nonlinear changes in land cover and sediment runoff in a sub-tropical catchment in New Zealand. Sediment budgets and their analyses showed that exotic forests were the dominant source of sediment runoff in periods of forest harvesting, while grasslands assumed the dominant role once exotic forests recovered. Connected land disturbance and water clarity time-series exhibited similar temporal break points, suggesting that the former can be a good indicator of stream water quality. Last, the connectivity layer that was developed could serve as a guide for placing and prioritizing Best Management Practices. In Chapter 3, a more accurate nationwide stream network for New Zealand was developed, that included intermittent and ephemeral streams, based on physiographic characteristics and varying thresholds. Results showed that the use of 8 different thresholds produced a higher and wider range of drainage density values. The new modeled network performed very well and identified the mapped validation headwaters 83-95% of the time. In Chapter 4, a new prioritization scheme for the protection of unmapped headwater channels in the most sediment-impaired catchment was proposed. Results showed more than 8,000 km of headwater streams need prioritization, with around 60% of them being High-priority. These streams corresponded

to more than 34,000 channel heads with 55.6% of them being High-priority. Using a conservative 10-m buffer on these headwaters produced an area of 175.4 sq. km that would need to be buffered or excluded from livestock. Last, Chapter 5 discusses the future work and broader impacts of this dissertation.

1. INTRODUCTION

Intense Land Use Practices and Stream Water Quality

Water quality is defined as the physical, chemical, and biological properties of a water body. It is affected by multiple and interacting disturbances (Allan 2004), both natural and anthropogenic. Of all the landscape components, land use has had the greatest impact on water quality over the past couple centuries (Foley, et al. 2005; Vitousek, et al. 1997). Therefore, a principal point of focus on current investigations in water resources is how land cover use/land use change (LCLUC) affects water quality of freshwater ecosystems, such as streams and lakes. Landscape alteration, particularly in the form of agriculture, disturbs the land and leads to enhanced runoff of water, sediment, organics, and other materials (Julian, Stanley, and Doyle 2008; Knox 1972).

Plantation forestry, an intensive land use management practice, is a good example of how land use affects water quality. After forest harvesting, the soil, which typically lacks understory vegetation in forests with dense canopy, is left exposed. It is then readily available to be washed off on the first intense precipitation event, resulting in considerable amounts of sediment entering the stream. Similar effects, but at a much finer spatiotemporal scale, can take place with intensive grazing, where rotational paddocks are grazed to bare ground and left to recover. Depending on weather conditions (soil moisture, precipitation, and temperature) it may take 8 days or more to recover (de Beurs, Owsley, and Julian 2016). The likelihood of exposure to precipitation increases with recovery time; thus, the chances of transporting sediment to riverine systems increases as the application of strip grazing intensifies and paddock recovery times lengthen. Despite our understanding of water/nutrient cycles and sediment erosion/transportation, there is not always a linear relationship between optical water quality characteristics (e.g., clarity, turbidity) and intense land management practices such as strip grazing and plantation forestry. Instead, this relationship depends on additional landscape components like slope, aspect, drought, soil moisture, and landscape connectivity.

The Need for More Accurate River Networks

Accurate stream network delineation is necessary for identifying source areas of runoff and assessing fluxes of water, sediment, organics, and nutrients. Historically, the most common methodology employed by watershed models was the minimum area threshold method, a single flow accumulation value that represents the origin of streams. However, uniformly applying the same area threshold across physiographically diverse landscapes can result in considerable under- or over-estimation of stream density (Colson, et al. 2008; Fritz, et al. 2013). Channel heads are scattered across diverse environments and because of fine-scale differences in local conditions (landscape, micro-climate, vegetation) produce a variety of distinct sub-catchments (Meyer, et al. 2007).

There has been a consensus that diverse landscapes produce varying channel initiation thresholds (Wohl 2014), and any channel network modeling attempt should account for these variations (Montgomery and Dietrich 1992; Montgomery 1993; Tucker 1998; Tarolli 2014). Other methods include field surveying, remote sensing approaches, or a combination of the two (Vianello, Cavalli, and Tarolli 2009). Given that there is a limitation on the area that can be physically surveyed, field-mapped locations are typically used to extract topographic information which would be later used to locate headwaters on other locations displaying similar topographic characteristics (Henkle, Wohl, and Beckman 2011; Wrońska-Wałach, et al. 2018; Jaeger, Montgomery, and

Bolton 2007). While mapping the location of channel heads across physiographically diverse landscapes can be daunting task (Garrett and Wohl 2017), it is a necessary one for aquatic biology and water resources conservation.

The Importance of Headwaters in Sediment Conservation

In riparian buffer planning, the importance of protecting headwater streams is often overlooked (Parkyn, et al. 2006). Headwater streams are important because they constitute a direct connection between terrestrial-aquatic environments and provide downstream areas with water, sediment, organic matter, and nutrients (Wipfli, Richardson, and Naiman 2007; Alexander, et al. 2007). These largely intermittent/ephemeral streams tend to be excluded from perennial-biased riparian policies (McKergow, Matheson, and Quinn 2016), thus remaining unprotected against intense agricultural practices and other forms of diffuse pollution. In addition, headwater streams are usually more susceptible to impacts, and it has been proposed that it takes longer for them to recover from disturbance events (Baillie and Neary 2015).

There are many factors that inform the ideal placement of riparian buffers for sediment conservation. Land use plays a detrimental role in sediment productivity (Foley, et al. 2005; Vitousek, et al. 1997) and thus it must be considered when deciding the optimal placement for a buffer zone. Livestock grazing, croplands, and plantation forestry are intense agricultural practices that have been identified as significant sources of sediment pollution (Julian, et al. 2017; Vörösmarty, et al. 2010). Moreover, land disturbance (i.e., bare soil as a result of vegetation removal, such as from forest harvesting) is an additional factor that could potentially lead to increased sediment production (Ahearn, et al. 2005; Haan, et al. 2006; Kamarinas, et al. 2016; Turner and

Rabalais 2003). Intensive livestock grazing can also be another factor that may increase sediment runoff; it may also increase overland flow due to ground compaction or over-grazing to the point where the surface is devoid of vegetation (McDowell 2006; Nellesen, et al. 2011; Webber, et al. 2010). As a result of these practices, exposed sediment is readily available to be washed out and into the stream network with the next precipitation event of sufficient intensity. Last, terrain also influences sediment production, as steep slopes adjacent to the stream network lead to increased landscape connectivity, which in turn lead to larger areas actively contributing sediment runoff (Czuba and Foufoula-Georgiou 2015; Kamarinas, et al. 2016).

Purposes and Methods

The objective of this research was to use a suite of geospatial data and tools to (1) assess the spatiotemporal relationships between intense agricultural practices and stream water quality, (2) develop a more accurate stream network that considers physiographic diversity, and (3) develop a prioritization scheme to find which headwater channels should be protected for purposes of sediment conservation and enhanced river water quality. The fundamental questions addressed within this dissertation were:

1. How do intensive land uses—specifically livestock grazing and forest harvesting—affect temporal patterns of sediment runoff at the sub-catchment scale?
2. How can stream networks be accurately mapped across large, physiographically-diverse landscapes?
3. Which headwaters should be prioritized for protection purposes of sediment conservation and enhanced river water quality?

The above questions were answered using multiple scales/resolutions of geospatial data in combination with statistical analyses and geospatial model development. The first, more theoretical question was answered by using an intensively managed sub-tropical catchment in the northern part of the North Island, New Zealand as a case-study, while the other two questions were answered at the national scale of New Zealand. New Zealand was used for my study area because (1) it has extremely diverse physiography over a relatively small area (same area as the state of Colorado); (2) it has wealth of long-term, multi-resolution data for physiography, land use intensity, and river water quality; (3) it is experiencing agricultural intensification across large areas; (4) many of its catchments are sediment-impaired; and (5) most of its headwaters are unprotected.

Structure of Dissertation

Papers Presented in Chapters

This dissertation is organized in the form of 3 independent manuscripts for journal submission, followed by a Conclusions chapter.

Chapter 2 examines nonlinear effects of land cover change and sediment runoff in response to intensive agricultural practices such as livestock grazing and plantation forest harvesting. First, both spatial and time-series analyses of land disturbance and river water quality variables were conducted. Second, a new method for assessing landscape connectivity was developed based on terrain slope and proximity to the river floodplain. Third, event-based analyses were performed on daily Total Suspended Sediment (TSS) data. Fourth, sediment budgets were calculated to assess deposition/erosion processes across the stream network. Finally, all the above analyses were combined to assess the relative contribution of the aforementioned agricultural practices to sediment runoff in

Hoteo catchment, New Zealand.

Chapter 3 is dedicated to developing a methodology that maps more accurate stream networks based on physiographic characteristics and varying accumulation thresholds. First, it describes model development, detailing how channel heads were mapped based on different physiographic classes. Second, it uses physiographic clustering for stream delineation, and finally validation for assessing the performance of the new modeled stream network.

Chapter 4 demonstrates how the modeled stream network built in Chapter 3 can be combined with other geospatial datasets to prioritize headwater channel protection for sediment conservation and enhanced river water quality. The study areas for this chapter were the 15 most sediment-impaired catchments in the National Rivers Water Quality Network (NRWQN). Several geospatial layers were used that represent areas likely to contribute sediment runoff: (i) livestock density, (ii) land disturbance, (iii) terrain gradient, and (iv) land use. With these datasets, conditional analyses were performed based on the following criteria: (i) all lands that are classified either as high-producing grasslands, plantation forests, or croplands would be considered as Level 1 or Priority areas. Additionally, if any of these areas had steep slopes (slope > 5˚), frequent disturbance (DI > 20%), or high livestock density (SU/ha > 5), then they would be considered as Level 2 or High-Priority Areas. If none fell into any of these two levels, then they were classified as No Priority. All headwater streams that were developed in Chapter 3 and were not captured by the REC were classified according to the aforementioned criteria.

Manuscript Details

Chapter 2 has already been published in the journal *Water*. I plan to submit the other two chapters for publication in peer-reviewed journals shortly after my dissertation is approved.

Chapter 2: Kamarinas, I., J.P. Julian, A.O. Hughes, B.C. Owsley, K.M. de Beurs. 2016. Nonlinear Changes in Land Cover and Sediment Runoff in a New Zealand Catchment Dominated by Plantation Forestry and Livestock Grazing. *Water 8*, no. 10: 436.

Chapter 3: Kamarinas, I., J.P. Julian. Mapping Stream Networks across New Zealand Using Physiographic Characteristics and Varying Accumulation Thresholds. *New Zealand Journal of Marine and Freshwater Research*.

Chapter 4: Kamarinas, I., J.P. Julian, K.M. de Beurs, B.C. Owsley, S. Greenhalgh. Headwater stream protection prioritization for sediment conservation practices and enhanced river water quality. *Sustainability*.

2. NONLINEAR CHANGES IN LAND COVER AND SEDIMENT RUNOFF IN A NEW ZEALAND CATCHMENT DOMINATED BY PLANTATION FORESTRY AND LIVESTOCK GRAZING

Abstract

Land cover can change frequently on intensively managed landscapes, affecting water quality across different spatiotemporal scales. Multi-resolution datasets are necessary in order to assess the extent and trends of these changes, as well as potential cross-scale interactions. In this study, both spatial and temporal analyses of land disturbance (i.e., soil exposure from vegetation removal) and water quality were performed on datasets ranging from daily to yearly time scales. Time-series analyses of land disturbance were compared against the water quality variables of total suspended solids (TSS), turbidity, and visual clarity for the Hoteo River catchment on the North Island of New Zealand for the 2000–2013 period. During forest harvest and recovery phases, exotic forests were the dominant disturbance, up to five times the area of grassland disturbance; while after recovery, grasslands assumed the dominant role, for up to 16 times the area of forest disturbance. Time-series of TSS from field sampling (2000–2013) and TSS-event analyses (2012–2014) displayed distinct nonlinear patterns, suggesting that after major events, sediment that is stored in the landscape is exhausted and a period of sediment build-up follows until the next major event. Time-series analyses also showed a connection between trends in connected land disturbance and visual water clarity, with connected disturbance having the potential to be a water quality indicator. Future research should be conducted at even finer spatiotemporal scales over longer periods in order to identify effects of localized land disturbances on downstream

water quality.

Introduction

Of all the landscape components, land use has had the greatest impact on water quality over the past couple of centuries (Foley, et al. 2005; Vitousek, et al. 1997). Accordingly, a principal point of focus in water resources and fluvial geomorphic investigations is how land cover/land use change (LCLUC) affects water quality of freshwater ecosystems, particularly suspended sediment dynamics. Understanding how LCLUC affects sediment runoff requires three pieces of information: (1) how the land use affects available sediment for runoff; (2) how the land use interacts with other landscape components to mitigate or enhance sediment runoff; and (3) connectivity between available sediment from land use and the drainage network. When all three of these processes are considered together, the relationships between LCLUC and fluvial sediment regimes are likely to be nonlinear over both space and time (Allan 2004; Tong and Chen 2002).

While these nonlinearities have been theorized for geomorphic systems (Phillips 2003), rarely (if ever) have nonlinearities in suspended sediment (other than event-scale hysteresis effects) been empirically connected to LCLUC. The reasons are twofold. First, most studies only consider one—or at most two—of the “three pieces of information” mentioned above (Quinn, et al. 1997; Schilling, et al. 2011). Second, the required data to capture these phenomena are usually not available at the appropriate spatio-temporal resolution. For example, temporal resolution of readily-available land cover datasets usually limits researchers to assessing land cover/use on decadal or semi-decadal time-scales (New Zealand Land Cover Database 2015; Homer, et al. 2015), when in reality, it can change on a weekly to monthly scale (de Beurs, Owsley, and Julian 2016; Lambin, Rounsevell, and Geist 2000). Spatially, suspended sediment or the related optical water quality variables of turbidity and visual water clarity are usually measured only at the catchment outlet, which can hide the effects of specific land–water relationships (Julian, et al. 2013), although there are exceptions where sub-catchment analyses were conducted (Abbaspour, et al. 2007; Hunter and Walton 2008). Further, only a few monitoring programs worldwide have consistently measured fluvial sediment in short intervals over long periods.

Sediment production from the drainage basin occurs when the force of water (via precipitation or flow) encounters available sediment. If vegetation is removed from the soil surface, it is more likely to be eroded (Knox 1972; Milliman and Syvitski 1992). Two common land uses that remove vegetation are plantation forestry harvesting and livestock grazing. After harvesting in plantation forestry, the soil (which typically lacks understory vegetation in forests with dense canopy) is left exposed. It is then readily available to be washed off during the next high precipitation event, resulting in considerable amounts of sediment and other materials entering the stream (Croke and Hairsine 2006; Kreutzweiser and Capell 2001; Neal, et al. 1998). Other major sources of erosion/runoff in plantation forests include roads (and their sidecast), landing sites, shallow landslides, and channel scouring/gullying (Fahey, Marden, and Phillips 2003; Fransen, Phillips, and Fahey 2001; Motha, et al. 2003). Similar processes, but at a finer spatial scale, can take place with intensive grazing (Bartley, et al. 2010; Daniel, Phillips, and Northup 2006; Quinn and Stroud 2002), particularly where rotational paddocks are cyclically grazed to bare ground and left to recover. The recovery time depends on weather conditions and soil moisture/fertility (McDowell 2008). The likelihood of exposure to precipitation increases with recovery time; thus, the chances of transporting sediment to riverine systems increases as management-intensive grazing expands and intensifies.

The relationship between LCLUC and sediment production depends on additional landscape characteristics such as slope, aspect, drought, soil properties, and vegetation. The relationship between hillslope erosion potential and vegetation, in particular, is complex and likely involves cross-scale interactions (i.e., when processes at one spatial or temporal scale interact with processes at finer or broader scales (Peters, Bestelmeyer, and Turner 2007)) because of their inherent interdependency (Marston 2010). However, in general, when vegetation cover increases, hillslope erosion potential decreases, and vice versa (Knox 1972; Marston 2010). Aspect affects vegetation vigor and recovery time, as south-facing slopes receive less sunshine than north-facing slopes in the southern hemisphere (opposite for the northern hemisphere). Prolonged periods of drought may also increase hillslope erosion potential by causing vegetation die-off or slowing recovery times. Soil properties such as texture dictate fertility and moisture, with loamy soils usually being the most beneficial. However, loamy soils can be more erodible compared to sandy and clayey soils (Wischmeier and Mannering 1969).

In order to understand the interaction between LCLUC and sediment production, river–landscape connectivity must be established, which requires an accurate stream channel network that includes even intermittent and ephemeral channels (Elmore, et al. 2013). Once the stream channel network is properly characterized, critical source areas of sediment (CSAS) can be derived. The most common stream delineation methodology employed by watershed/catchment models is the minimum area threshold method; however, different landscape characteristics produce different channel initiation thresholds (Montgomery and Dietrich 1992; Wohl 2014). Uniformly applying the same area threshold across physiographically diverse landscapes can result in considerable under- or over-estimation of stream density (Elmore, et al. 2013; Julian, Elmore, and Guinn 2012). After mapping an accurate channel network, landscape connectivity (via CSAS) is then determined by adjacent surface runoff from hillslopes and floodplains (Gergel, et al. 2002; Montgomery and Dietrich 1992; Wohl 2014). Previous attempts to assess landscape connectivity included computer- and field-based numerical assessments (Borselli, Cassi, and Torri 2008) and elaborate conceptual frameworks of hydrological and sediment connectivity (Bracken and Croke 2007; Bracken, et al. 2015). However, there are simpler procedures to determine connectivity, such as the one from Palmer et al. (Palmer, Dymond, and Basher 2013) that is based on slope thresholds, flow direction, and proximity to the drainage network. When a connected area is disturbed, it is considered to be a CSAS. These catchment-scale hydrographic methods allow us to assess the impact of landscape disturbances on long-term trends in river water quality; specifically, total suspended solids (TSS), turbidity, and visual water clarity.

Our understanding of water cycles and sediment erosion/transportation has demonstrated that there is not always a linear relationship between water quality and land management practices (Gergel, et al. 2002; Allan 2004). For example, in order for elevated turbidity values to be recorded at a monitoring site, “adequate” amounts of precipitation must mobilize readily available sediment throughout the landscape. Not only is there variation in precipitation across the catchment, but also in antecedent soil moisture conditions, in water abstraction for irrigation, and in the spatiotemporal scale of the data analyzed (Uriarte, et al. 2011). Even after all the aforementioned are taken into consideration, not all available sediment is delivered to the channel immediately (i.e., it can be stored and released at a later time) (Fryirs, et al. 2007; Walling 1983). These lag and legacy effects can further enhance nonlinear LCLUC–sediment runoff relationships. In order to capture these potentially nonlinear changes, high-resolution spatiotemporal data is needed.

In this study, we take advantage of a high temporal-resolution (8 day) land cover dataset over 14 years (2000–2014) and multiple water quality datasets with multiple sampling intervals (5 minute to monthly) over the same period, distributed throughout the catchment in order to examine connections among LCLUC, connectivity, and sediment runoff. The aim of this paper is fourfold: (1) understand how different land uses—specifically livestock grazing and forest harvesting—affect sediment runoff at the sub-catchment scale; (2) assess how land cover interactions with other landscape components influence sediment runoff regimes; (3) determine landscape connectivity between available sediment and the drainage network; and (4) characterize long-term trends in suspended sediment at the catchment scale. Suspended sediment data (interpolated from continuous turbidity records) was used to create time-series, derive suspended sediment budgets, and locate the sources and land uses responsible for increased sediment yields to the river system. Statistical analysis (i.e., piecewise regression) of water quality and land disturbance time-series at a monthly scale was then performed to assess the nonlinear trends and connections between landscape changes and river sediment regimes.

Methods

Study Area

For this study we selected a catchment with all of the previously described data requirements, in addition to having large areas of both plantation forestry and livestock grazing. The Hoteo River catchment is located in the northern part of New Zealand's North Island, approximately 60 km north of Auckland (Figure 2.1), and drains to the Kaipara Harbor, which is a valuable and sensitive estuarine ecosystem that is experiencing considerable sediment infilling and associated environmental degradation. The climate of the region is "sub-tropical", characterized by warm, humid summers and mild winters. Maximum and minimum daily air temperature averages 18.5 °C and 10.1 °C, respectively, with an average of 2129 sunshine hours/year. Most rainfall occurs in sustained events during the winter months of June (155 mm), July (180 mm), and August (152 mm), with an annual total rainfall of 1454 mm (1981–2010, The National Climate Database). Significant differences in precipitation patterns may occur within the catchment due to topography. Buikema (2012) reported variations (±100 mm) in recorded precipitation between the Dome Ranges in the southeastern part of the catchment to the rolling hills in the northwest.

The study area has three distinct landscape units as defined by Buikema (2012): the uplands (with steep slopes, >26°), foothills/rolling foothills, and alluvial floodplains. The dominant soil type is silt- or clay-loams, with the rest silt/sands and silt/clay loams in the river valleys. The original land cover of the catchment has been highly modified since broad-scale European settlement/agriculture in the mid-1800s, with clearings of native forests and draining of wetlands. These clearings have resulted in an increase in gully/channel formation and thus greater landscape connectivity (Buikema 2012).

Present-day land use is characterized by three distinctive classes: (1) grasslands for livestock grazing (dairy/beef cattle, sheep); (2) plantation (exotic) forests; and (3) native forests. Plantation forests are exclusively Monterey pine (Pinus radiata), which are mechanically clear-cut every 28 years, on average. There are a variety of grasses, such as perennial ryegrass, cocksfoot, tall fescue, and kikuyu. Native forests are predominantly podocarp/broad leaf forest (Buikema 2012). Wildfires in the Hoteo catchment are rare. Land use and other physiographic data for Hoteo and its sub-catchments examined here are summarized in Table 2.1 and described in detail below.

We divided Hoteo into five sub-catchments based on the locations of monitoring sites within the catchment, resulting in different elevation, slope, and land cover characteristics: Waiteitei, Whangaripo, Waiwhiu, Wayby Valley, and Saunders (Table 2.2). Waiteitei and Wayby Valley have flat-to-gentle slopes with grasslands being the dominant land cover (>90%). Whangaripo and Waiwhiu have steeper mean slopes (23.2° and 30.3°, respectively), but with different dominant land cover (grassland vs. exotic/native forest). Last, Saunders is also very steep, with an average slope of 28.1° and exotic forestry dominating the land cover.

Land Cover/Use and Disturbance Index

Land cover and use was characterized with the New Zealand Land Cover Database (LCDB) (New Zealand Land Cover Database 2015), which we also used to mask out areas other than forests and grasslands. In order to assess land disturbance (times and areas of bare ground), we used an 8-day, 450 meter land cover dataset developed by de Beurs et al. (2016) [10]. Details of the methodology can be found in their paper, but briefly, for each Moderate Resolution Imaging Spectroradiometer (MODIS) image, the Tasseled Cap transformation was calculated; by using the brightness, greenness, and wetness components based on the coefficients from Lobser and Cohen (2007) (Lobser and Cohen 2007), a disturbance index (DI) (Table 2.1) was calculated for every pixel. Each component is associated with a landscape property:

brightness is linked to albedo, greenness is linked to vegetation vigor, and wetness to the amount of water retained by vegetation. Next, the mean and standard deviation of each landcover and climatic region was calculated to standardize the DI values. The forest DI was calculated as the brightness minus the greenness and wetness; disturbed forests appear brighter but less green and wet compared to undisturbed forests. The grassland index was calculated by taking the negative sum of brightness, greenness, and wetness; disturbed grasslands appear less dark, green, and wet compared to healthy grasslands. The higher the DI, the more sparsely vegetated the pixel was, with a threshold value of three or higher indicating bare ground. We aggregated this dataset by sub-catchment so that our final product was an 8-day time-series (2000–2013) with the percentage of each sub-catchment disturbed (DI > 3).

The 8-day temporal and 450 m spatial resolution over 14 years resulted in a highly detailed land use/cover dataset adequate for the detection of weekly to monthly changes, particularly useful for assessing landscape changes associated with an intensively managed landscape. The index was calculated only on areas that were designated as high-producing grasslands or exotic forestry. Native forests were not assessed, because they were mixed in type and density, and thus displayed false disturbances. The rest of the classes—wetland/open water (0.30%), urban (0.25%), cropland (0.12%), and other (0.07%)—were masked out and not taken into account in DI calculations. For each exotic forest pixel, the time of harvest was identified based on an iterative script that recorded the first date that DI > 3, the sum of dates while DI > 3, and the first date after harvesting that DI < 3. This process resulted in a dataset that showed the year of first harvest, duration of recovery, and year of recovery.

Physiographic Data

A 15 m DEM was acquired from Landcare Research from which slope, direction of flow, and flow accumulation were derived to model catchment connectivity. The DEM was resampled at 450 m to match the DI data. Soils data was obtained from the 1:63,360 Fundamental Soils Layers (FSL), which is maintained by Landcare Research (Webb and Wilson 1995). Soil variables that we included in our analysis were texture and soil moisture.

River Network and Connectivity

The River Environment Classification (REC) is a national-scale (for New Zealand) synthetic stream network derived from a hydrologically corrected DEM (Snelder, Biggs, and Weatherhead 2004). Utilizing "fixed" thresholds on flow accumulation layers to identify the location of channel heads (like REC) is computationally efficient over large areas, but with limitations on the accuracy of the headwater locations (Elmore, et al. 2013). For that reason, we identified all channel heads of the Hoteo catchment using 0.5 m rural aerial photos from 2010–2012 (Land Information New Zealand; LINZ) as reference. Then, using a modified stream delineation algorithm (based on flow direction), we were able to delineate streams from their mapped headwaters to the watershed outlet. The newly-created stream network was used as input to inform the variables of our landscape connectivity model, described below.

We developed a landscape connectivity model in an effort to identify critical source areas of sediment (CSAS). The distinction between CSAS (connected) and areas not contributing to sediment runoff (disconnected) was made based on a sediment runoff model that utilized slope thresholds to allow for sediment movement (Palmer, Dymond, and Basher 2013). Below, we provide a description of the rules applied to each 15 m pixel in order to derive the landscape connectivity mask:

a) Pixels with slope >5° along the flow direction were assigned a "connected" value.

b) If slope <5° for at least two 15 m pixels along the flow direction, then a "non-connected" value was assigned.

c) Pixels immediately adjacent to the river (within the floodplain buffer) were assigned a "connected" value, regardless of slope.

The floodplain buffer was simulated based on the Strahler stream order and was defined as 30 m for 1st and 2nd stream orders, 60 m for 3rd and 4th stream orders, and 90 m for 5th and 6th stream order, on each side. These buffers were estimated based on the geomorphic mapping of rivers in the catchment by Buikema (Buikema 2012).

Hydrologic and Water Quality Data

Multiple water quality variables were assessed to estimate total suspended solids (TSS) loads. Monthly visual water clarity at the catchment outlet (Hoteo station) from the National River Water Quality Network (NRWQN) (Davies-Colley, et al. 2011) was used because of its consistency and long record (1989–2014), and because it has been proven to be the best estimator of TSS in the absence of TSS samples (Ballantine, Hughes, and Davies-Colley 2015). Turbidity was used because it is conveniently monitored with in situ sensors that can estimate TSS with high temporal resolution. Although less correlated to TSS than visual water clarity, it is still strongly correlated (Ballantine, Hughes, and Davies-Colley 2015). Turbidity (in NTU) was monitored at three sites within the catchment (Waiteitei, Waiwhiu, Hoteo) with 5 min resolution for the period 2012–2014. Time-stamped turbidity values were averaged to daily values and converted to TSS based on turbidity–TSS relationships (Gubbs: n = 33, R2 = 0.96, SE = 29.7; Waiteitei: n = 142, R2 = 0.95, SE = 31.0; Waiwhiu: n = 47, R2 = 0.99, SE = 34.3) to ensure consistency and compatibility between datasets of different sources (Gray and Simões 2008). The turbidity–TSS relationships used here were derived from 2nd degree polynomial equations, and their performances (p-values) were comparable to the ones used in Hughes et al. (2014) (Hughes, Davies-Colley, and Elliott 2014). Moreover, nine monthly TSS measurements collected at each of seven locations across the catchment (n = 63) were converted to daily loads (in t/day) by applying the concentration interpolation equation, which is described by Gray and Simões (Gray and Simões 2008).

Monthly water clarity (2000–2013, National Institute of Water and Atmospheric Research, NIWA) was flow-adjusted to remove the effects of flow before its trend was assessed; this was achieved by applying local polynomial regression (LOESS) to the clarity time-series (Cleveland and Devlin 1988). The lab method used for TSS was APHA 2540D (Eaton, et al. 2005), while the turbidity sensor was a Hach Solitax t-line SC, which is ISO7027 compliant. The flow data was obtained from the Auckland Council hydrometric sites.

Event-based analysis was performed on the daily TSS data, which were derived from the 5 min turbidity data. Indicators of Hydrologic Alteration (IHA) software was used to identify high flow pulses, small floods, and large floods for both daily TSS and flow. An event started whenever a daily TSS or flow value was classified as one of the three above classes and lasted until both returned to baseflow values. For each event, the duration (count of consecutive days), event peak (max value), and event magnitude (sum value) was calculated. The residuals from the relationship of TSS magnitude–flow magnitude were plotted against time to assess TSS response to different flows.

In order to assess the effects of drought on land cover and disturbance, the Standardized Precipitation Index (SPI) (Moore, Spittlehouse, and Story) was calculated. SPI was designed to show precipitation deficits over multiple scales (McKee, Doesken, and Kleist 1993), and is comparable between regions across the world. We used the 12-month timescale because it reflects long-term precipitation patterns, is tied to streamflow, and exhibits similar results with Palmer's Drought Index (WMO 2012). The precipitation data were drawn from the Warkworth EWS climate station (NIWA, 1922–2014).

Time-Series and Statistical Analyses

Time-series analyses were performed on three monthly datasets for the 2000–2013 period: percentage of disturbed and connected watershed (% DI), visual water clarity, and total suspended solids (TSS). Changes in their trend were assessed using segmented (piece-wise) linear regression. Piece-wise regression using the "segmented" package in R (Muggeo 2008) was chosen in order to assess the nonlinear changes in trend within the study period; evaluating the monotonic trend would have not yielded important findings on changes at a fine temporal scale. Initially, breakpoints (or points with an abrupt change in slope) were estimated from visual examination of the time series. Then, during the iterative phase of the process, were recalculated in order to minimize the mean squared error (MSE). The new breakpoint values may or may not have matched the ones initially provided and solely depended on minimized MSE, thus improving the fit.

Last, because the DI dataset did not exhibit normal distribution, a nonparametric test was chosen to test if DI varied significantly between land cover and slope classes. The Wilcoxon rank sum test, with the Bonferroni correction, was run for different land cover (exotic forest and grasslands) and slope classes (flat, undulating, rolling, strongly rolling, and steep). The latter were defined in the same way as in the Land Use Capability Handbook (Lynn, et al. 2009).

Results

Land Use and Disturbance at the Sub-Catchment Scale

The spatial distribution of disturbances among high-producing grasslands and exotic forests was variable across the catchment (Figure 2.2a). Individual pixels were disturbed from 0–83% of the time. Moderate-to-high disturbance frequency (yellow-orange color) was found in Waiwhiu, Whangaripo, and Saunders, as well as near the Hoteo watershed outlet. Some very disturbed pixels (red color) were spread across the watershed and are results of areas with mixed land cover (e.g., human structures like houses and roads in grassland pixels). By deriving the time of harvest of the exotic forests (Figure 2.2b), we found that most of the harvesting occurred from 2000–2004 (blue-green color), with 65% of that class being disturbed during the first four years of the record. Most of the exotic forestry was located in Waiwhiu, Saunders, and Whangaripo. The latest harvests occurred along the border of Waiwhiu–Whangaripo. Overall, the percentage of the Hoteo catchment disturbed ranged from 2.0%–13.7% at any given time with a mean of 7.3% for the 2000–2013 period.

The relative contribution to disturbance by land cover also varied over our study period (Figure 2.3a). Exotic forestry contributed most of the observed land disturbance from 2000–2010 and decreased significantly after 2012. In general, exotic forests were more disturbed, with a mean of 14.9% of the class being disturbed (max of 38% at 14 September 2003 and min of 0.4% on 19/12/2013). Grasslands were less disturbed with a mean of 4% (max of 11.2% at 1 May 2002 and min of 0.7% on 17 November 2001).

Sub-catchment contributions to overall DI formed 2 distinct groups (Figure 2.3b). Forested catchments such as Waiwhiu and Saunders displayed periods of high disturbance (harvest phase) followed by periods of low disturbance (recovery phase) and appear to be more disturbed (maximum values of 23.4% and 72.2%) at any given time. Pasture-dominated catchments such as Waiteitei and Wayby Valley, on the other hand, displayed a more seasonal pattern and appear less disturbed (maximum values of 17.9% and 13.9%) for a shorter time period (means of 3.9% and 1%). Whangaripo—with a 2-to-1 grassland-to-forest ratio—appears significantly disturbed with a max of 27% and a mean of 9.7%.

Landscape Connectivity

From the landscape connectivity model (Figure 2.4), 32% of Hoteo's catchment was not connected to its stream channels, while 68% was connected either through hillslope runoff (54%) or adjacent floodplain (14%). Most of the connected areas were on the hilly uplands (Whangaripo, Waiwhiu, and Saunders), while the disconnected areas were located on the flat grasslands (Waiteitei and Wayby Valley). More specifically, the percentage of connected areas for each sub-catchment were: Waiteitei 49.6%, Whangaripo 78.4%, Waiwhiu 95.7%, Wayby Valley 45.6%, and Saunders 93.7%. Exotic forests were almost exclusively situated on areas of high elevation/steep slope and thus were more connected than grasslands (79% and 40.4%, respectively).

Physiographic and Hydrologic Effects on Land Disturbance

Results of pairwise comparison using the Wilcoxon rank sum test with the Bonferroni correction showed that areas with exotic forestry had significantly more disturbance than high-producing grasslands ($p < 0.001$). Steep slopes (≥8°) overall (including both grass and forest) had significantly higher disturbance than gentle slopes (0–8°; $p < 0.001$). Grasslands on steep slopes also had higher disturbance compared to grasslands on gentle slopes (p-value < 0.001; Figure 2.5).

There was not much variation in soil type across the catchment. Except for the recent soils in the alluvial floodplain, the vast majority of the catchment was composed of Ultic soils, which are strongly weathered, well-structured clayey soils. Accordingly, they have moderate-high soil moisture, but are poor-draining and susceptible to erosion. Forested areas were dominated by clay loams, whereas pastures had a mix of clay/clay loams.

The connection of long-term precipitation patterns was shown on the SPI vs. monthly connected disturbance time-series (Figure 2.6a). Drought occurs when SPI falls below −1 and continues until SPI becomes positive. The timing of DI breakpoints coincided with the occurrence of extended periods of drought; more specifically in 2005, 2010, and 2013, the latter being the most severe drought for Hoteo on record.

The percentage of grasslands disturbed varied seasonally, with typically higher values during Winter/Spring and lower during Summer/Fall (Figure 2.7). Exceptions occurred during extended droughts (2000–2001, 2005–2008, 2010, and 2013), when disturbance was highest during Summer/Fall. Exotic forests exhibited similar seasonal behavior, but disturbance increases or decreases (Figure 2.6) were mostly influenced by forest harvests (Figure 2.3b) or recovery, respectively—especially during the 2002–2005 period.

TSS Spatiotemporal Dynamics

The connected disturbance vs. flow-adjusted clarity time-series had a stronger relationship than connected disturbance vs. TSS (Figure 2.6). A piecewise regression analysis (Arthur, Coltharp, and Brown 1998; Swank, Vose, and Elliott 2001) was performed to identify the breakpoints of change in the trend on this set of time series. The regression breakpoints occurred at approximately the same time (2005, 2010, and 2013) for both connected disturbance and water clarity, with diverging trends. The piecewise regression for water clarity had an R2 of 0.55, while the connected disturbance regression had an R2 of 0.59. Breakpoints for TSS did not line up with breakpoints for connected disturbance and water clarity during 2002, 2007, and 2008, but did in 2010. Note that the regression fit for TSS was relatively weak, with an R2 of 0.26. All breakpoints and standard errors are summarized in Table 2.3.

When relative contributions of TSS by sub-catchment for a relatively normal year in terms of precipitation (2012) were analyzed, an interesting pattern emerged (Figure 2.8). Net loss erosion (more sediment coming from the main channel or lower catchment than delivered by the sub-catchments) occurred during the Winter (July–October), while net storage deposition (more sediment coming out of the sub-catchments than delivered to the catchment outlet) occurred during the Summer (December–February).

Ranking sub-catchments by their mean TSS daily loads resulted in Waiteitei (2.4 t/d) being the largest contributor, followed by Whangaripo (1.7 t/d), Waiwhiu (0.8 t/d), Wayby Valley (0.2 t/d), and Saunders (0.1 t/d). However, when normalized by area and expressed as specific sediment yields, Whangaripo ranked first, with $3.7 \times 10-4$ t/ha/d, followed by Waiteitei ($3 \times 10-4$ t/ha/d), Waiwhiu ($2.1 \times 10-4$ t/ha/d), Wayby Valley ($0.9 \times 10-4$ t/ha/d), and Saunders ($0.8 \times 10-4$ t/ha/d).

Event-scale TSS data at the Hoteo catchment outlet from 2012–2014 (via a continuously monitoring turbidity sensor) showed a distinct nonlinear pattern (Figure 2.9) where relative TSS (via LOESS residuals) declined after sediment-laden floods, but eventually recovered and increased until the next large flood. This sine-like wave with sediment pulses (peaks) and sediment exhaustion (troughs) had almost four cycles over this 3-year period.

Discussion

Connections among Land Use, Climate, Disturbance, and Sediment Runoff

While many studies have investigated sediment runoff effects of land uses such as forest harvesting (Arthur, Coltharp, and Brown 1998; Swank, Vose, and Elliott 2001) and livestock grazing (McDowell 2006; Monaghan, et al. 2007) at the catchment scale over coarse time-scales, here we examined the more direct link to sediment runoff of connected disturbance (with 8-day resolution) at the sub-catchment scale. When comparing land use, connected disturbance, and sediment runoff, a clear pattern emerged: plantation forest areas were significantly more disturbed and more connected than high-producing grasslands, with correspondingly high TSS loads. Whangaripo and Waiwhiu contributed most of the landscape disturbance (Figure 2.2a), with an average of 23.5% and 17.2%, due to forest clearings on the area along their border that mainly occurred after 2006 (Figure 2.2b). They also both ranked very high on TSS, being the 1st and 3rd sediment runoff contributors in terms of t/year. Saunders was almost completely cleared during 2000–2002 (Figure 2.2b), an area that has since been reforested and now has relatively low specific sediment yields. On the contrary, Waiteitei, which is 94% pasture, consistently contributes 16.7% of the disturbance, on average, along with having the 2nd-highest specific sediment yield. Lastly, Wayby Valley (which is 97% pasture land) contributes only 0.7% of the disturbance on average with very low specific sediment yields. In summary, different land uses in the Hoteo catchment produced varying amounts of available sediment, and when land disturbance changed (from forest harvests, droughts, and possibly over-grazing), the magnitude and timing of sediment delivery to rivers also changed.

Climate and land cover are intricately connected with both positive and negative feedbacks affecting their relationship (Bonan 2008; Knox 1972). Extended periods of drought are expected to have a detrimental effect on vegetation, with significant vegetation die-off and increased areas of exposed soil (Anderegg, Kane, and Anderegg 2013). This would result in an increase in land disturbance (measured as connected disturbance in this study) unless mitigated by management responses such as fertilization, irrigation, supplemental feed, and reduced grazing. While we were not able to thoroughly assess all of these management practices across the entire catchment, numerous field observations and discussions with local farmers indicate that some of these practices were occurring at various times in our study period. However, management intensity in this region is relatively minor compared to other parts of New Zealand (Julian, et al. 2016), and thus most of the land–water relationships we observed were likely from biophysical processes. The main exception was plantation forest harvests. The connected disturbance increased up to 2004 can mostly be explained by forest clearings over relatively steep areas of the catchment (Figures 2.2, 2.3, and 2.6), especially Waiwhiu, Saunders, and Whangaripo. The drought—which began in late in 2004 and lasted until the start of 2008—kept land disturbance at moderate levels (Figure 2.6a), with 7.6% of the catchment being disturbed on average. Further, in January 2013, disturbed area doubled in response to a severe drought, which in turn led to a sharp decrease in water clarity (Figure 2.6a,b).

Landscape–River Connectivity

Determining landscape–river connectivity is crucial in the evaluation of whether land use changes have the potential to affect river water quality. Since the broad-scale European settlement of New Zealand, landscape connectivity has increased with the clearings of native vegetation, the addition of millions of sheep and cattle, and the consequent channel erosion and extensive gully formation (Glade 2003). The landscape connectivity model developed here is similar to the Highly Erodible Land (HEL) model (Dymond, et al. 2006) which used the largely perennial REC stream network. In order to advance this model and concept, we mapped the intermittent and ephemeral channels and thus accounted for the higher degree of connectivity present on the landscape. Given that most of a catchment's sediment yield occurs during large storms (Basher, et al. 2011; Milliman and Meade 1983; Reid and Page 2003) when ephemeral channels are active, it is important to account for these connected channels.

A more representative channel network map and a corresponding connectivity dataset is also useful for the identification and prioritization of sites for best management practices (BMPs) that improve water quality. Vegetation buffers, in particular, have been shown to filter sediment, nutrient, and other pollutant runoff before entering streams (Dosskey, Eisenhauer, and Helmers 2005; Lee, Isenhart, and Schultz 2003; Lowrance, et al. 1997); however, there is no consensus on the most effective location or size of these vegetation buffers (Fischer and Fischenich 2000). Our connectivity map and land disturbance analyses could provide insight on ideal buffer placement, which would be between stream channels and connected areas that are frequently disturbed (Figures 2.2 and 2.4). The size of these vegetation buffers could be determined based on contributing drainage area, slope, and amount of connected disturbance. Properly characterizing land disturbance and its connectivity to stream channels at the catchment scale is important for siting other BMPs, such as rain gardens and detention/retention ponds (Martin-Mikle, et al. 2015).

Nonlinear Changes

Using multiple resolutions of data at multiple scales, we found clear nonlinear changes in land disturbance, climate, and consequently sediment runoff (Figures 2.3, 2.6, and 2.8–2.9). The nonlinear patterns in TSS and water clarity appear to be the combined result of: (1) high sediment loadings to rivers from connected disturbed areas, which change in location and extent over time (Figures 2.2 and 2.3); (2) sediment supply limitation following sediment-laden floods (Figure 2.9); and (3) shifts between erosion and deposition in the channels (Figure 2.8). From several years of observation by us and others (Buikema 2012), there are large stores of sediment along the mainstem Hoteo River, which change from flood to flood. While it is this in-channel sediment that makes the Hoteo River one of the most turbid rivers in all of New Zealand (Julian, et al. 2016), this sediment has been derived from major landscape disturbances over the past 150 years (Buikema 2012). These legacy effects also contribute to nonlinear changes in water quality and a level of complexity that was beyond the temporal scope of this study.

For the assessment of nonlinear water quality trends, the disturbance index (DI) demonstrated the potential to be a water quality indicator. The breakpoint analyses (Figure 2.6) showed that significant changes/trends of connected disturbance and water clarity coincide, suggesting a cause-and-effect relationship between them on the temporal dimension. TSS time-series showed weak connection with connected disturbance; however, suspended sediment budgets were very useful for connecting sediment runoff to specific sub-catchments on the space dimension. The suspended sediment budgets also provided insight on depositional/erosional processes in the river channel/floodplain (Figure 2.8). For the latter, it is very important to consider the value of riparian fencing that can greatly affect these erosional/depositional process along the channel. While some of the perennial channels on dairy farms (a small percentage of the drainage network) were fenced, the majority of the intermittent and ephemeral tributaries were unfenced, and thus are likely to be significantly contributing to sediment runoff during high-flow events.

The location and timing of forest harvests, coupled with TSS/water clarity data suggest that exotic forestry is the major contributor of disturbance and sediment to the rivers. On average, exotic forests are more disturbed than grasslands (18 months vs 3.8 months) (de Beurs, Owsley, and Julian 2016), because the latter recover much faster. Connected disturbance increased significantly during the 2000–2004 period, where 65% of the forests in the Hoteo catchment were harvested. On the contrary, suspended sediment samples taken from all sub-catchments suggest that during periods of low disturbance (2012–2013), pasture watersheds contribute more sediment—anywhere from 25%–50% of the total suspended sediment measured. Over the course of seasons (Figures 2.8 and 2.9) and years (Figures 2.3, 2.6, and 2.7), all of these cross-scale interactions among land cover/use, climate, and land disturbance (over both space and time) described throughout this Discussion have produced unique nonlinear patterns in sediment runoff that need to be explored further.

Conclusions

The purpose of this study was to assess nonlinear LCLUC–water quality relationships and locate the sources of sediment runoff across the Hoteo catchment in New Zealand. Suspended sediment budget analyses showed that exotic forests were the dominant sediment source in periods of forest harvesting, while grasslands assumed the dominant role once exotic forests recover. Further analyses showed that connected land disturbance and water clarity time-series exhibited similar breakpoints on their trends, suggesting a cause-and-effect relationship. When the sequence of flood events was assessed, these changes in supply and transport of sediment resulted in a cyclical pattern of sediment runoff. Future investigations on water quality changes would benefit from an assessment of connected land disturbance. It has definitely been a useful water quality indicator in this study, especially when combined with climate data. The connectivity layer developed here could also serve as a guide to place and prioritize BMPs, especially in the form of vegetation buffers to reduce sediment runoff into rivers. Reducing suspended sediment in impacted rivers such as the Hoteo would further benefit downstream receiving waters with sedimentation or water quality problems. Indeed, the Kaipara Harbour (in which the Hoteo River drains) is a valuable and sensitive estuarine ecosystem that is experiencing considerable sediment infilling and associated environmental degradation. The focus of this study was seasonal and yearly changes in sediment runoff. The next step in this line of research would be to investigate the changes and relationships among land cover/use, climate, land disturbance, and other water quality variables at even finer spatiotemporal scales over longer periods.

Tables

Table 2.1. Summary of landscape and water quality data used for this research.			
Dataset	**Variable(s)/type**	**Scale, Period**	**Source**
Disturbance Index (DI)	%DI > 3/raster	[a]MODIS (8-day, 450 m), 2000–2014	de Beurs et al., 2016 [10]
Land Cover v3.3	Vector polygon	1:50,000, 2001–2008	Landcare Research
New Zealand Fundamental Soils Layers	Silt-clay%/ Vector polygon	1:50,000, 2000	Landcare Research
National Climate Database	Monthly precipitation totals	station, 1922–2014	[b]NIWA
Water quality data	Clarity, Turbidity, [d]TSS	Monthly, 2000–2014	[c]NRWQN, [b]NIWA
	[d]TSS	nine monthly samples, 2012–2013	Present study
	Discharge, Turbidity	5 min data, 2011–2014	Auckland Council
River Environment Classification v2.0	Stream segments/ Vector line	1:24,000, 2014	[b]NIWA
[e]DEM	Elevation/ raster	15 m, 2012	Landcare Research
Auckland 0.5 m rural aerial photos	Ortho-photography	0.5 m, 2010–2012	[e]LINZ

[a]Moderate Resolution Imaging Spectroradiometer
[b]National Institute of Water and Atmospheric Research
[c]National River Water Quality Network
[d]Total Suspended Solids
[e]Digital Elevation Model
[f]Land Information New Zealand

Table 2.2. Physiographic characteristics of the study area (Hoteo) and its sub-catchments. Land covers are native forest (NF), exotic forest (EX), high-producing grasslands (HG), and Rest (RE). Landscape connectivity refers to Connected (C), River and floodplain buffer (R), and Disconnected (D).						
Catch-ment	**Drainage density (km/km^2)**	**Area (km^2)**	**Elevation (m) Min/Max Mean/SD**	**Slope (degrees) Min/Max Mean/SD**	**Land Cover (%) NF/EX HG/RE**	**Landscape connectivity (%) C/R/D**
Hoteo	1.6	264.6	16.9/439.2 118.4/59.1	3.1×10^{-3}/110.0 19.8/14.8	15.2/21.1 60.8/2.9	54.0/14.0/32.0
Waiteitei	1.5	78.9	42.1/264.9 95.2/26.8	6.3×10^{-3}/80.0 12.3/9.2	4.4/0.3 94.0/1.3	36.4/13.2/50.4
Whangaripo	1.5	45.7	23.8/439.2 141.3/66.1	9.8×10^{-3}/102.2 23.2/14.8	23.0/9.2 61.0/6.8	63.4/15.0/21.6

Table 2.2. Continued.						
Catch-ment	**Drainage density (km/km^2)**	**Area (km^2)**	**Elevation (m) Min/Max Mean/SD**	**Slope (degrees) Min/Max Mean/SD**	**Land Cover (%) NF/EX HG/RE**	**Landscape connectivity (%) C/R/D**
Waiwhiu	1.5	38.8	33.9/401.9 194.7/72.2	13.4×10^{-3}/110.0 30.3/14.6	40.4/55.8 2.8/1.3	79.0/16.7/4.3
Wayby Valley	1.6	20.4	21.7/244.7 67.5/32.1	14.0×10^{-3}/103.4 12.6/11.3	0.0/2.2 96.8/1.0	33.1/12.5/54.4
Saunders	1.6	14.3	28.3/301.7 131.0/53.3	3.1×10^{-3}/93.9 28.1/13.7	27.3/63.6 4.5/4.6	77.3/16.4/6.3

Table 2.3. Piecewise regression output.		
Variable	$\boldsymbol{R^2}$	**Breakpoints (SE in months)**
Connected disturbance	0.59	Mar 2000 (±2), Apr 2005 (±3) May 2010 (±5), Aug 2012 (±6)
Clarity	0.55	Jun 2000 (±2), Feb 2005 (±17) Jun 2010 (±4), Apr 2013 (±2)
TSS	0.26	Aug 2002 (±6), Oct 2007 (±10) Jul 2008 (±8), Aug 2010 (±18)

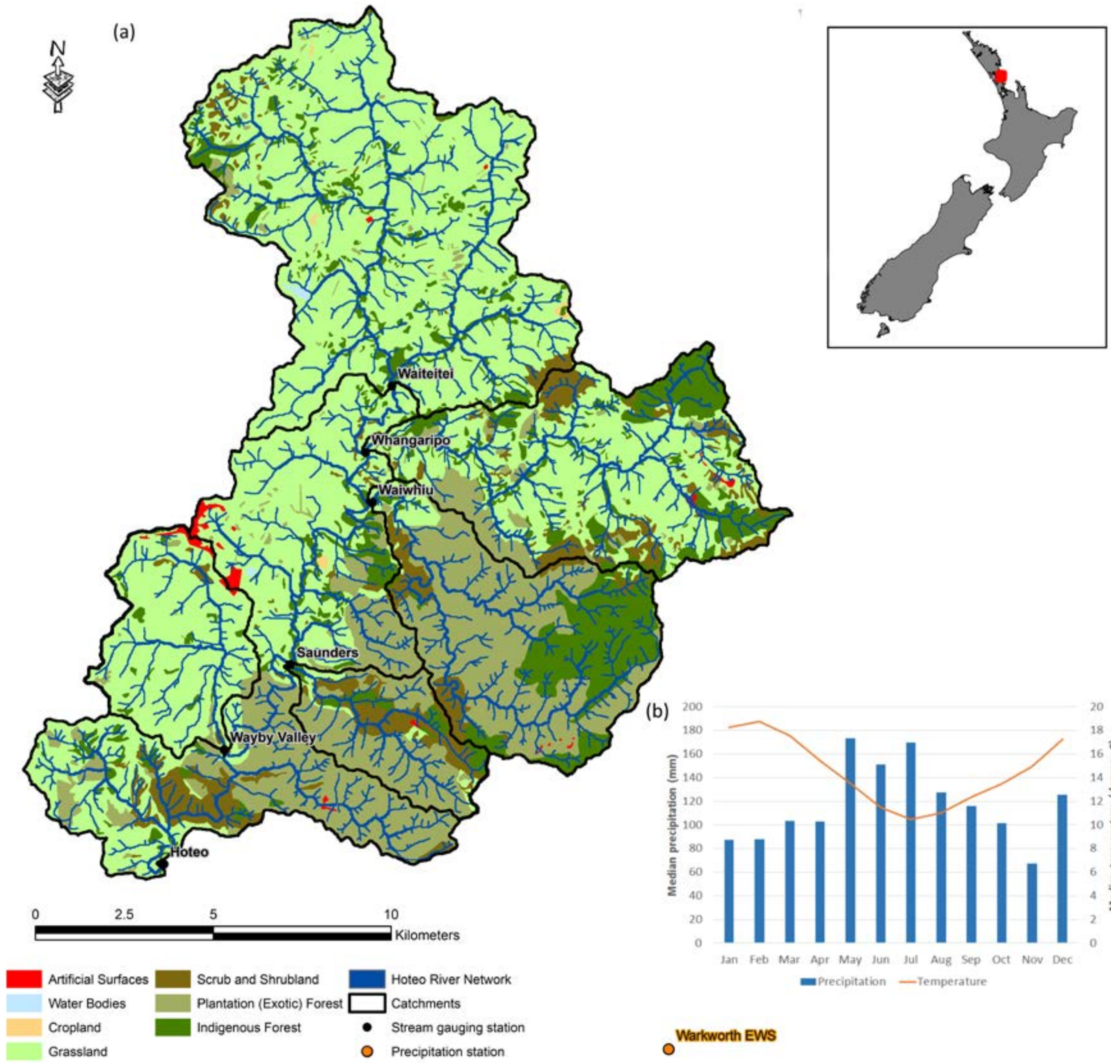

Figure 2.1. (a) The Hoteo catchment (located on the North Island, NZ) and its five sub-catchments (black lines) delineated based on the location of gaging stations. Land cover (LCDB v3.3) is shown for reference. Precipitation data were drawn from Warkworth EWS climate station, located 8 km south-east of Hoteo; (b) Climograph created from data drawn from Warkworth EWS climate station for the period 2000–2013.

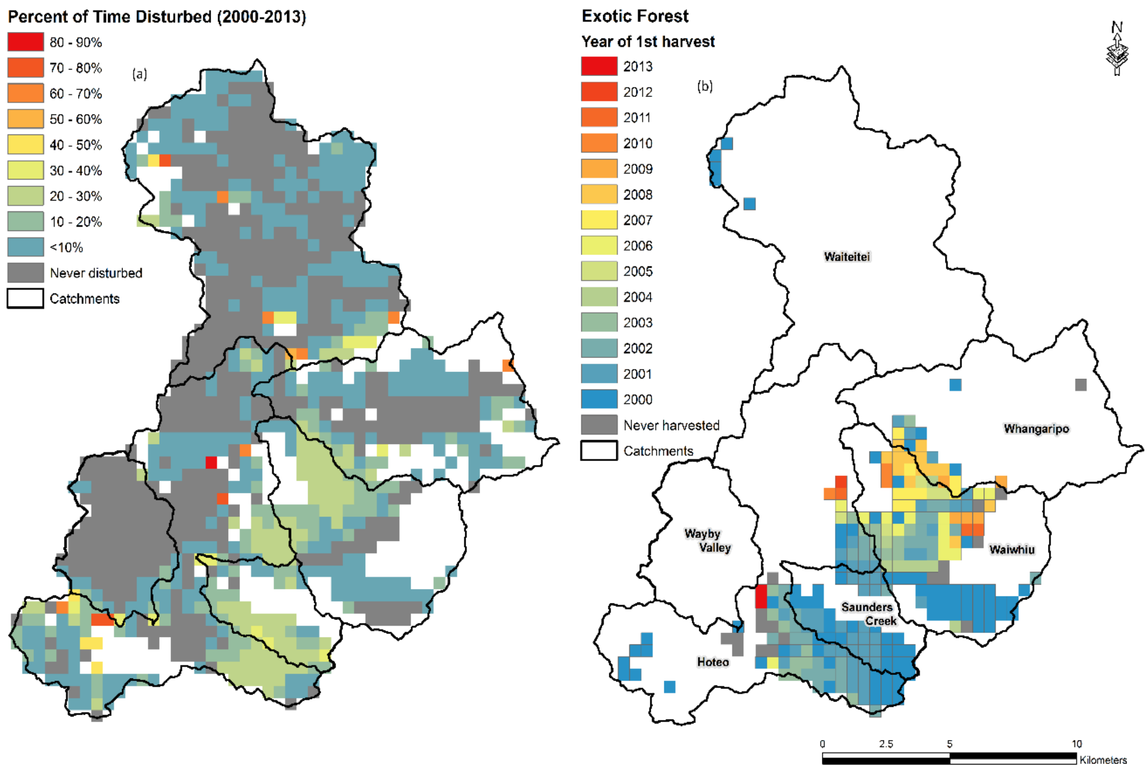

Figure 2.2. (a) Percent of time of every pixel being disturbed for the 2000–2013 period. White pixels were native forests, which were not assessed for disturbance. (b) The year of first harvest for each one of the exotic forestry pixels. Forests that were not harvested during the study period are shown as grey.

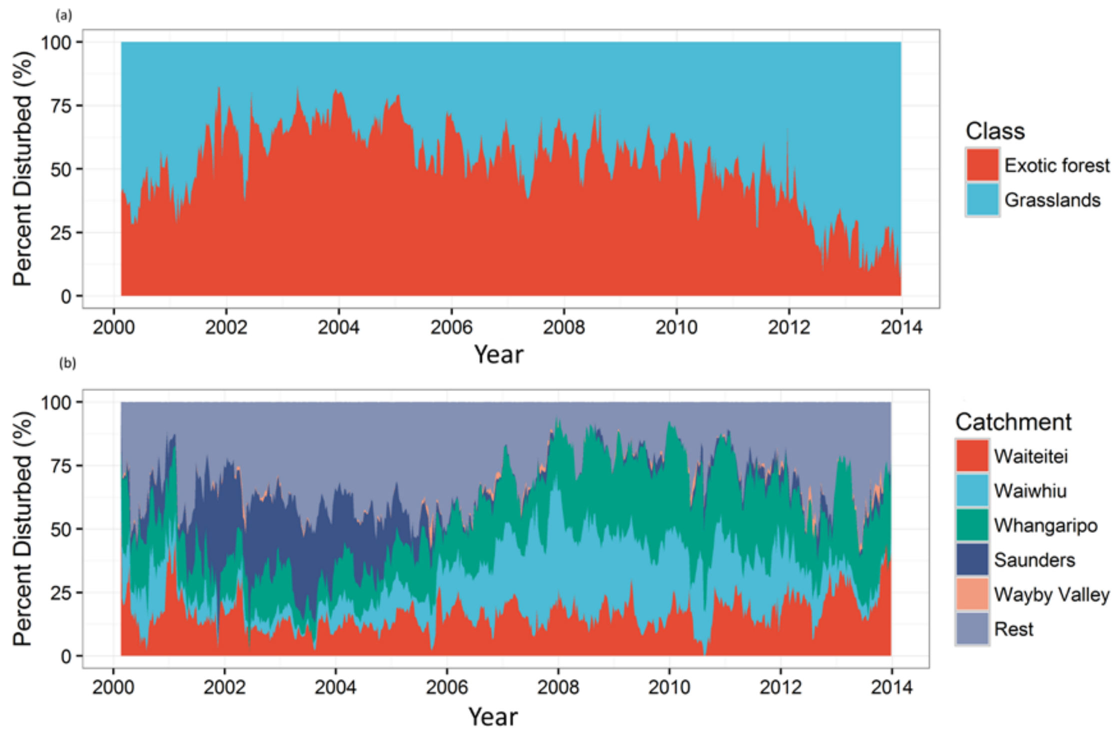

Figure 2.3. (a) Relative contributions of exotic forest (orange) and pasture (blue) to overall watershed disturbance; (b) Disturbance contribution (%) of each sub-catchment relative to the total watershed disturbance.

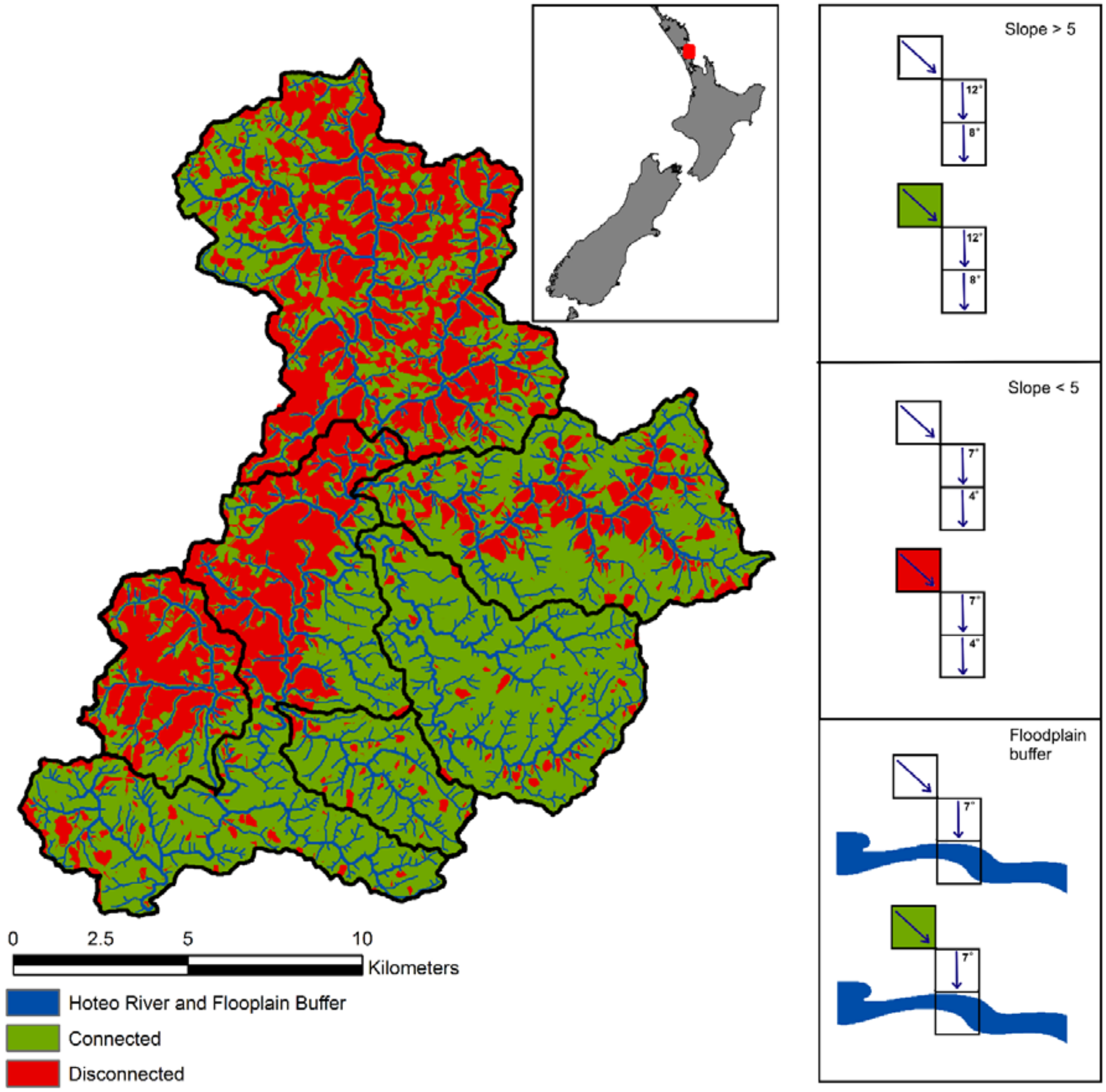

Figure 2.4. Landscape connectivity for the study area; connected areas (green color) are considered critical source areas of sediment (CSAS) and were used as a mask for land disturbance. A schematic of the rules (as described in Section 2.4) for developing the model are shown on the right-side panel. The 1st pixel (upper left corner) is the one being evaluated for connectivity; the next two pixels down the flowpath must both have slope values >5° for the 1st pixel to be considered as connected (green color). If either one of the next two pixels has a slope value <5°, then the pixel being evaluated is considered disconnected (red color). Lastly, if either one of the next two pixels are classified as floodplain, then the pixel is connected (green color).

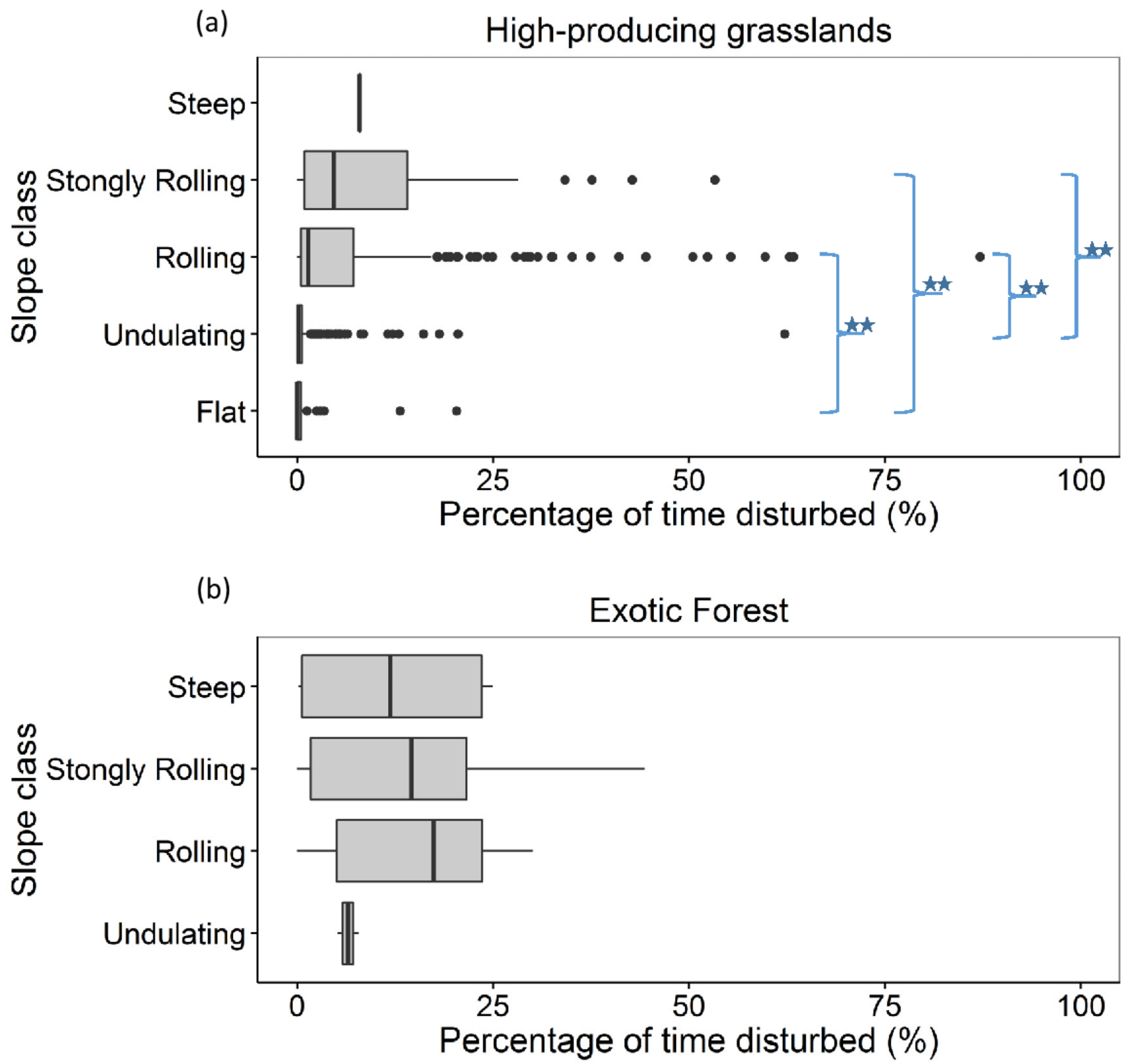

Figure 2.5. Wilcoxon rank sum test (Bonferroni correction) on disturbance values for different slope (flat, undulating, rolling, strongly rolling, and steep) and land cover classes: (a) high-producing grasslands and (b) exotic forest. Statistical significance between classes is shown with blue stars (p-value<0.001) on the boxplots.

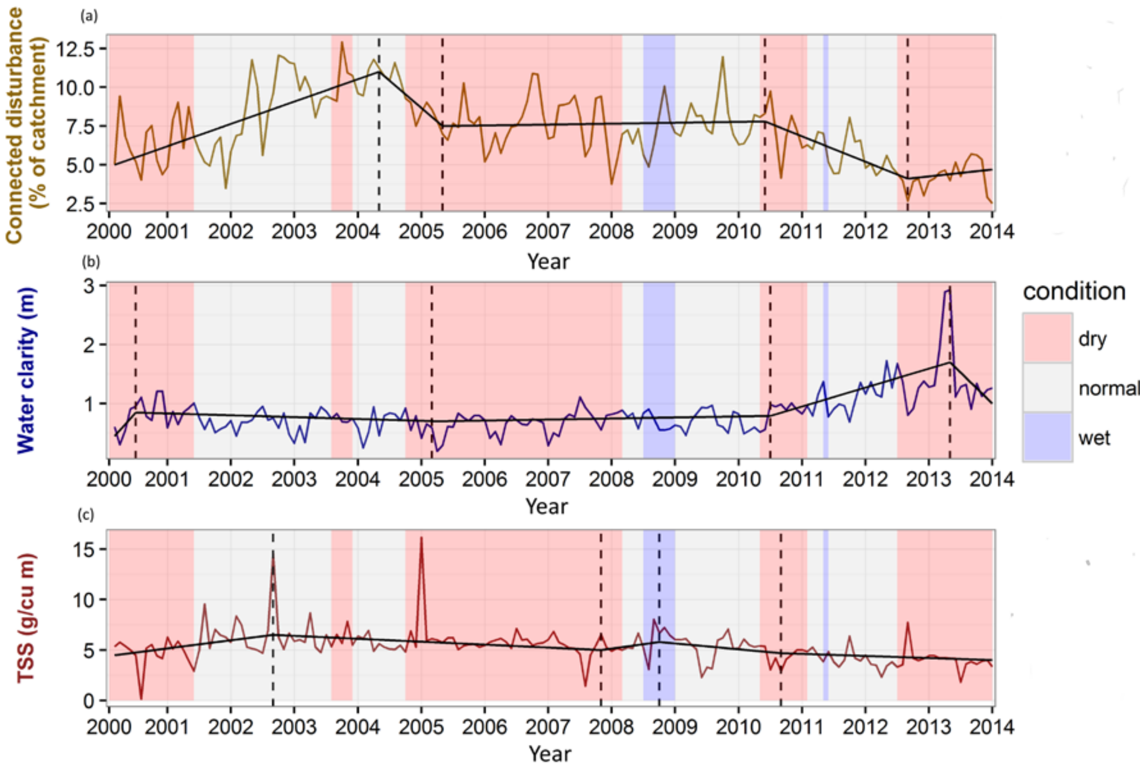

Figure 2.6. Monthly (a) percentage of catchment connected and disturbed; (b) water clarity (residuals from local polynomial regression (LOESS) + mean clarity; and (c) flow-adjusted TSS (residuals from loess + mean TSS) for the period 2000–2013. The timing of breakpoints (dashed lines) between connected disturbance and water clarity from 2005–2013 seem to coincide, suggesting a cause and effect relationship between the two. Wet (blue), normal (grey), and dry (red) periods were calculated from a 12-month standardized precipitation index (SPI). The segmented regression lines are shown in black.

Figure 2.7. Seasonal variation of disturbance for (a) exotic forestry and (b) high-producing grasslands. Exotic forestry appears to be significantly more disturbed than grasslands from 2000–2010 and even three times more disturbed than grasslands from 2002–2005.

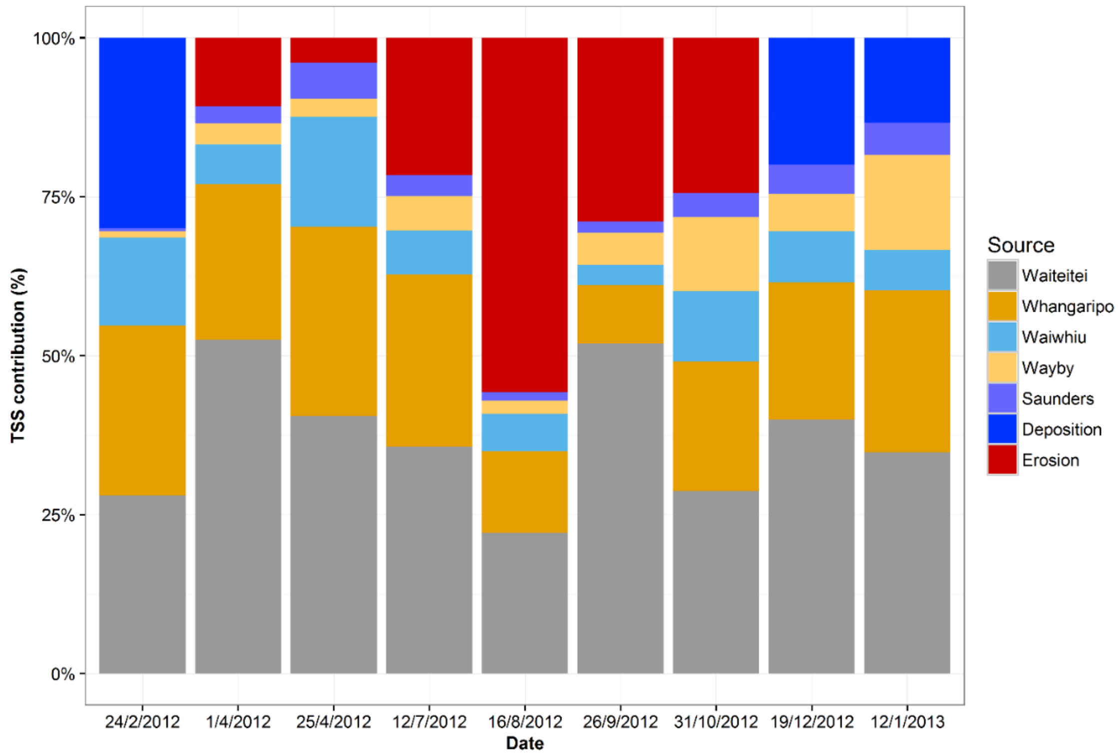

Figure 2.8. Sub-catchment suspended sediment budgets for the 2012–2013 period. Total suspended solids (TSS) contributions were calculated in t/day and are expressed as percentage of total exiting the Hoteo catchment. Net storage (deposition) occurred when the sum of TSS of all sub-catchments exceeded TSS exiting the catchment outlet, while net loss (erosion) occurred when more TSS exited the catchment outlet than was delivered by the sub-catchments.

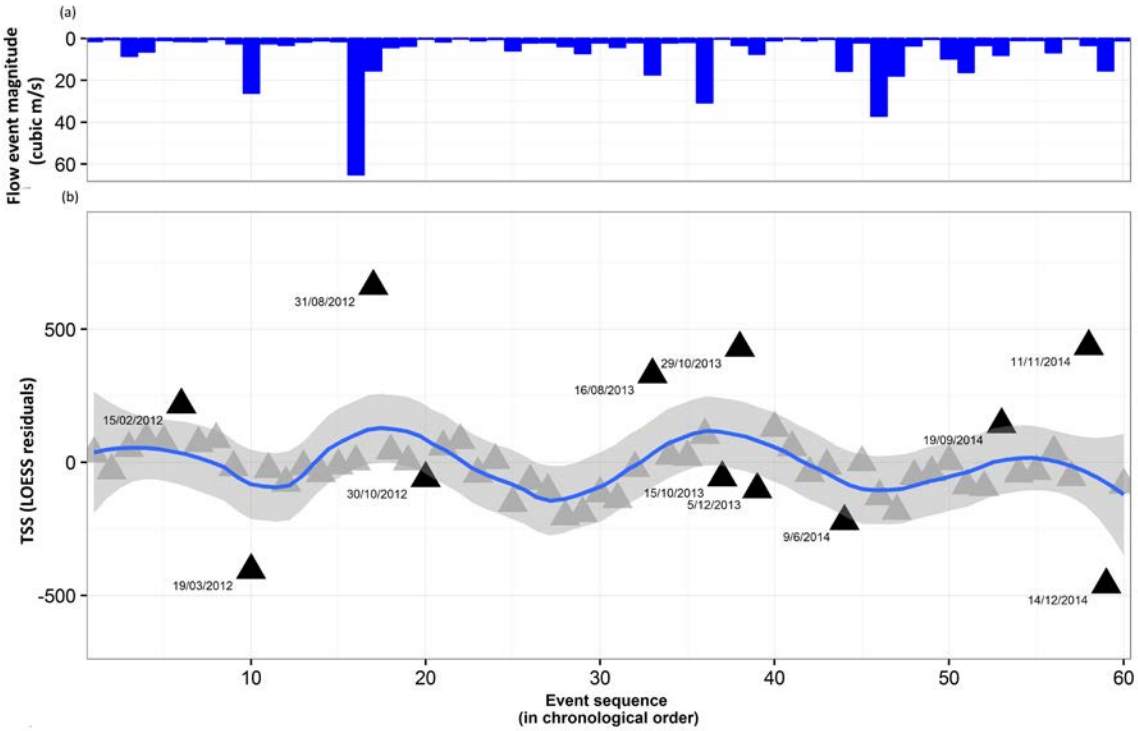

Figure 2.9. (a) Flow event magnitudes; (b) TSS residuals event (n = 60) analysis from the period 2012–2014 for the Hoteo catchment outlet in order of occurrence showing periods of higher amounts of sediment than expected followed by lower amounts of sediment than expected. The sine-like wave (blue LOESS line with 95% confidence intervals) suggests that after major TSS events (concave), sediment in the landscape is exhausted (convex). Similar patterns were described in Knox's (1972) [15] seminal paper occurring over thousand years or millennia. Our results show that these processes also take place on yearly or monthly time scales. The date (dd/mm/yyyy) is shown on extreme events.

3. MAPPING STREAM NETWORKS USING PHYSIOGRAPHIC CHARACTERISTICS AND VARYING ACCUMULATION THRESHOLDS

Abstract

Channel heads and their headwaters are important links between terrestrial and aquatic environments, particularly during high precipitation events; however, they are often overlooked and unmapped. In this study, I mapped channel heads and stream networks using varying accumulation thresholds based on physiographic characteristics (geology, source of flow, climate). The aim was to build more accurate stream networks that incorporate headwaters that are missing from existing national hydrography datasets. This study area encompasses the 77 National River Water Quality Network (NRWQN) catchments of New Zealand, with catchments representing different physiographic regions. Using satellite/aerial imagery, I mapped 10,323 channel heads across 43 physiographic classes to determine flow accumulation area thresholds for channel initiation. K-means clustering defined 8 unique physiographic area groups and the cluster centers were used as representative accumulation thresholds for each class. Using these 8 different flow accumulation thresholds, I modeled stream networks for all 77 NRWQN catchments. Model validation revealed that the new modeled network performed better than the existing national; hydrography dataset by capturing more channel heads that were closer to visually mapped channel heads. The new modeled stream network increased drainage density from 17-78%. Results showed that on average, a 1-fold increase in channel heads produced a 38% increase of drainage density. By having a more accurate and extensive channel network, river water quality issues can be better addressed.

Introduction

Channel heads are the beginning of river systems and their headwater reaches compose up to 80% of the total stream network (Benda, et al. 2005; Elmore and Kaushal 2008). Headwater streams are important because they provide downstream areas with water, sediment, organic matter, and nutrients (Wipfli, Richardson, and Naiman 2007; Alexander, et al. 2007). Channel heads, often being confused with stream heads which are the beginning of the perennial flow, may coincide with erosion hotspots (Wohl 2014) and thus their location with respect to land use activities can dictate the water quality of rivers and their receiving waters. Despite their broad importance, headwater streams are often overlooked due to their lack of perennial flow, small size, and nonexistence in hydrography datasets/maps (Gomi, Sidle, and Richardson 2002).

The total length of all streams (divided by drainage area) determines a catchment's drainage density, which is a useful metric in watershed characterization and planning (Elmore, et al. 2013). Many studies have shown that by not including headwater streams, drainage density is greatly underestimated when compared with nationwide datasets, such as the National Hydrography Dataset (NHD) (Colson, et al. 2008; Fritz, et al. 2013; Montgomery and Foufoula-Georgiou 1993; Heine, Lant, and Sengupta 2004). A study done by Hansen et al. concluded that only up to 21% of the actual stream network, validated by stream surveys on the field, appeared on 1:24,000 topographic maps (Hansen 2001). Another study conducted on different physiographic provinces across the mid-Atlantic US compared stream channels delineated based on field data with the NHD flowlines and found that not only were many headwater streams not present in the NHD dataset, but a few 2^{nd} and one 3^{rd} order channel as well (Julian, Elmore, and Guinn 2012), which resulted in considerable underestimation of drainage density. The common denominator across all these studies was the inaccurate mapping of channel head locations (Wohl 2014).

Channel heads occur in diverse environments as miniscule differences in local conditions (topography, micro-climate, vegetation) produce a variety of heterogeneous sub-catchments (Meyer, et al. 2007). Mapping the location of channel heads can be a difficult task (Garrett and Wohl 2017) and the most common stream delineation method calls for using a singular minimum accumulation threshold. However, studies have found that diverse landscapes produce different channel initiation thresholds (Montgomery and Dietrich 1992; Montgomery 1993; Tucker 1998; Tarolli 2014). Other methods include field surveying, remote sensing approaches, or a combination of the two (Vianello, Cavalli, and Tarolli 2009). Given that there is a limitation on the area that can be surveyed by foot, field-mapped locations are typically used to extract topographic information which can then be used to locate headwaters elsewhere sharing similar topographic characteristics (Henkle, Wohl, and Beckman 2011; Wrońska-Wałach, et al. 2018; Jaeger, Montgomery, and Bolton 2007).

Field surveying and subsequent topographic information extraction performs well on small to moderate size catchments; however, it is not as applicable over large, diverse landscapes. Physiographic variables such as climate, hydrology, and geology affect runoff characteristics and thus the location of headwaters. For example, relationships between headwater location and topographic parameters differ significantly between dry and wet regions (Garrett and Wohl 2017; Nicholas A. Sutfin, et al. 2014), and between piedmont and bedrock landscapes (Jaeger, Montgomery, and Bolton 2007; Julian, Elmore, and Guinn 2012). Therefore, it is imperative to incorporate these parameters into models that predict headwater locations.

The aim of this study was to assess and map channel heads and stream networks across a large, diverse landscape. I used New Zealand as my study area because it is one of the most physiographically-diverse nations on Earth for its size, but also because it is experiencing river water quality issues that have been linked to land use changes and improperly mapped source areas (Julian, et al. 2017; Kamarinas, et al. 2016). The product from this research is a dataset that better captures drainage density across New Zealand, which provides useful information on critical source areas of sediment and other pollutants relevant to river water quality. This proposed river network could potentially inform New Zealand's national stream dataset. Channel heads were located using aerial imagery for multiple physiographic regions across New Zealand. I then used these locations to calculate representative accumulation thresholds for different runoff regions based on climate, geology, and source-of-flow classes. Statistical analyses on various topographic characteristics were performed to assess the validity of the mapped headwaters and drainage density calculations, as well as to compare the proposed network to the existing national dataset.

Methods

Study Area

The study area included the 77 National River Water Quality Network (NRWQN) catchments, which collectively enclose approximately half of New Zealand's area (Figure 3.1). These NRWQN catchments have been the focus of many river water quality studies, particularly within the context of spatiotemporal changes in climate, hydrology, geology, and land use (Ballantine and Davies-Colley 2014; Davies-Colley, et al. 2011; Julian, et al. 2017). The NRWQN sites are located on 35 large river systems that are distributed across the two main islands of New Zealand (Ballantine and Davies-Colley 2014).

New Zealand has a diverse climate with 12 distinct climate zones (Figure 3.1): from warm subtropical in the north and the to the cool temperate on the south with mean temperatures ranging from 10° C to 16° C and ranging from 600 to 1600 mm of rainfall. The northeastern orientation of the Southern Alps constitute a barrier for the westerly winds carrying moisture from the ocean, resulting in areas in the west being very wet while areas in the east are semi-arid (Salinger 1979). New Zealand is geologically active with high mountains, rolling hills, active volcanoes, and coastal plains. New Zealand's diverse terrain adds extreme complexity to the hydrological cycle: steep slopes, the abundance of lakes, and glaciers being some examples of different sources of flow. Land cover has been highly altered over a relatively short time since human settlement with dense forests and tussock grasslands being converted to intensely managed landscapes, particularly for agricultural purposes (Weeks, Jmc, and Walker 2012). Indeed, agricultural and horticultural use make up nearly 1/2 of the nation's total area (Zealand).

Hydrography Dataset and Physiographic Regions

The existing national hydrography dataset is the River Environment Classification v.2 (REC v.2), which is a geospatial database containing attributes for each segment of New Zealand's perennial rivers. It also contains attributes for climate, source-of-flow, geology, land-cover, network position, and valley-landform, with each attribute categorized with different classes (Figure 3.2). Using this dataset, I selected the following attributes and classes to differentiate physiographic regions: climate (dry, wet and extra wet), source-of-flow (glacial-mountain, mountain, hill, low-elevation) and geology (alluvium, hard-sedimentary, soft-sedimentary, volcanic, plutonic and miscellaneous), resulting in 72 different physiographic combinations (Table 3.1). Given that the REC has more than 593,000 segments I selected a sample (1%) of all the 3rd order stream segments (n = 76,363) in the REC to make channel head mapping manageable and ensure that the workload could be completed within a reasonable time frame. For the selection, a stratified random sampling was performed on the segments based on the size of each class; those that had less than 100 segments were excluded from further analysis. The final selection included 764 3rd order stream catchments from 43 unique physiographic levels.

Channel Head Mapping

For channel head mapping, I used the 3rd-order catchments obtained from the previous exercise in combination with one meter or better satellite (GeoEye-1, WorldView-2, WorldView-3, Digital Globe; 2014-2016) and aerial imagery (Land Information New Zealand 2012-2015, accessed through ArcGIS basemaps, ESRI). I mapped all visible headwaters within the 3rd-order catchment, starting at the catchment outlet and following all stream segments in a clockwise manner. Channel heads were identified by breaks in slope, defined channel banks (using lower limit of permanent vegetation or ordinary high-water mark), and evidence of fluvial processes. Erosional features such as rills and gullies were not included; only what I interpreted to be active stream channels using criteria set forth by previous studies (Dietrich and Dunne 1993; Julian 2018). Accordingly, the confluence of multiple gullies was interpreted to be a channel head. In forested areas where channel banks were not visible, I mapped channel heads that were at breaks in slope with different vegetation. A maximum zoom-in scale was set to 1:3,000 to avoid over-zooming and misidentifying headwater locations based on terrain features.

Due to differences in spatial resolution and alignment errors between the aerial imagery and the DEM, the headwater location may not lay on the pixel of the highest accumulated upstream area, but on a neighboring pixel that has a very low accumulation value. To account for these potential errors, a script was written in Python to (1) identify the pixel location with the highest accumulation value around the mapped headwater and (2) move the point to that location. A 4-cell radius was chosen to compensate for errors associated with the creation of the DEM, the georeferencing of aerial imagery, and the manual headwater placement based on visual interpretation of imagery. Then, using the 15-m DEM that covered the entire New Zealand, 764 catchments were delineated using the 3^{rd}-order stream nodes as outlets to minimize processing area and time. For each mapped channel head, I calculated five topographic variables from the DEM, which have been found to be spatial explanatory variables for channel heads (Heine, Lant, and Sengupta 2004; Julian, Elmore, and Guinn 2012):

a) Area: Total catchment area above channel head (km^2).

b) Local slope: Average slope of a 3 x 3 cell window at the channel head location.

c) Plan curvature: perpendicular to the direction of the maximum slope.

d) Profile curvature: parallel to the direction of the maximum slope.

e) Standard curvature: a combination of the plan and profile curvature.

All spatial analyses were performed on the ArcGIS environment and scripting with Python programming language.

Clustering and Stream Delineation

Mapping stream networks using 43 different drainage thresholds (from 43 different physiographic regions) would be computationally inefficient. Therefore, I investigated different clustering techniques to derive fewer collective groups that still explained a high amount of the variance. Firstly, I used the Akaike information criterion (AIC) on upstrean area, curvature, and slope to identify the number of clusters that had the minimum total within-cluster sum of squares. Secondly, the results of AIC analysis were used to inform the k-means analysis that followed; all statistical analyses were performed in R environment (R Development Core Team 2013) and stream delineation was performed with the Soil and Water Assessment Tool (Arnold, et al. 1998). Lastly, drainage density of the modeled-derived streams and the REC streams (km/km^2) were calculated at the NRWQN catchment level, and then compared.

Validation

Three physiographically-dissimilar catchments were selected for assessing the performance of the new, modeled stream network: Hoteo (NRWQN code = AK1), Pohangina (subcatchment of WA8), and Monowai (DN10). The headwater dataset for Hoteo (n = 651) was previously mapped by Kamarinas et al., (Kamarinas, et al. 2016) and the headwater dataset for Pohangina (n = 1,205) was previously mapped by Abbot et al., (Abbott, et al. 2018). All the headwaters of Monowai (n = 157) were mapped based on visual inspection of the aerial imagery; the same method that was used for mapping the headwaters of all the randomly selected 3rd-order streams. These 2,013 channel heads were compared to the modeled and the REC channel head locations to characterize potential positional errors and assess the accuracy of the modeled heads.

Results

Channel Head Mapping

From the 764 3rd-order catchments, I mapped a total of 10,323 channel heads (Figure 3.3). 4,518 were located on the North Island and 5,805 were located on the South Island. The percentages of channel heads that belonged in each attribute class were: (a) Climate: Wet=49.3%, Extremely Wet=26.9%, and Dry=23.8%, (b) Geology: Hard-sedimentary=51.3%, Soft-sedimentary=17.5%, Volcanic=14.3%, Plutonic=7%, Alluvium=5%, and Miscellaneous=4.9%, and (c) Source-of-flow: Low-elevation=39%, Hill=35%, Mountain=22.9%, and Glacial-mountain=5%; exact channel head numbers are shown in Table 3.2.

The number of channel heads varied by physiographic class (Table 3.3). Some classes had less channel heads mapped, based on their size or due to limitations stemming from the satellite/aerial imagery. Agricultural areas were the most common obstacle in identifying all head channel locations (WHVO, DLAI, DLVO, EWLPI). Other challenges were caused by: (i) dense, native and exotic forests (WHVO, EWHSS, EWLSS, WLAI), (ii) city/urban setting (DLM, EWLSS) and (iii) snow-capped mountains (EWLHS, EWGMPI). The classes with the highest number of mapped channel heads were: WMHS (n=1256), WLSS (n=1076), EWMHS (n=1073), DHHS (n=809), and WLVO (n=809). Classes with the lowest number of channel heads were: WMM (n=6), WMSS (n=3), WLAI (n=3), DMSS (n=3), and WMPI (n=1).

Varying Accumulation Thresholds

Using topographic variables that have been previously shown to have a relationship with drainage area of channel heads, I investigated accumulation area-relationships with local slope, plan curvature, profile curvature, and standard curvature (Appendix A). Correlation coefficients for almost all plots were low, with the maximum being 0.25 and the mean being 0.06. Because of these lacks relationships, I instead relied on varying accumulation thresholds based on key physiographic characteristics.

Statistical analyses of the upstream accumulation area of channel heads showed differences between class means at each level (Geology, Climate and Source-of-flow). More specifically, at the Geology level, pairwise comparison using the Kruskal-Wallis method with the Bonferroni correction revealed that the mean of the dominant class HS (46.1% of the study area) was significantly different ($p < 0.001$) than the means of the V class (17.4% of the area), the SS class (14.6% of the area) and the M class (4.6% of the area). Moreover, the V class mean was significantly different than the Al (11.9% of the area) and the Pl (5.4% of the area). For the Source-of-flow level, pairwise comparison showed no difference on the means between M and H, with all other pairwise comparisons being significantly different ($p < 0.001$). At the Climate level, significant difference ($p < 0.001$) was shown between D-W and W-EW classes. All the relationships between classes are shown on Figure 3.4.

The Akaike information criterion (AIC) estimated the optimal number of clusters at 8 with an adjusted R^2 of 0.91 (Figure 3.5). This optimal clustering selection method was preferred among others because it estimated a sufficient number of clusters, for the size of the study area, with a very high value of adjusted R^2 calculated from the total variance in the data and the sum of within group variance. Other cluster number selection methods, such as the elbow and the silhouette, suggested 3-4 clusters, but without being able to account for a large part of the data variance (i.e., low R^2 scores). The 8 physiographic clusters are presented in Table 3.4 with their mean accumulation thresholds.

Stream Delineation and Drainage Density

Using the 8 physiographic clusters (Table 3.4), stream networks were modeled for all 77 NRWQN catchments. Each of the 77 NRWQN catchments were divided according to which cluster they fell into and the stream network was delineated by using the cluster center value as the flow accumulation threshold for that area. Cluster membership ranged from 1, for the very small catchments, to 8 for the larger catchments. The modeled stream network was assessed for two metrics: drainage density change (%) and channel head change (%) compared to the REC stream network. Figure 3.6a shows the REC drainage density being relatively uniform across the study area (~ 1.59 km/km^2), possibly due to one accumulation threshold being used for the entire country. My modeled stream network (Figure 3.6b), which takes into account physiographic differences, varied considerably among the 77 catchments, ranging from 1.67 km/km2 (RO1) to 3.19 km/km2 (WA2). For all catchments, the modeled stream network had a higher drainage density (Figure 3.6c), anywhere from a 16.6% increase (TK4) to a 77.9% increase (GS2). The most notable changes occurred in the south-central North Island and in the southeastern South Island.

The modeled stream network had many more than double the channel heads of the REC stream network, 2.4 channel heads/sq. km compared to per 1.1 channel heads/sq. km for the REC. On average, a one-fold increase on the number of channel heads, led to a 38% increase in stream length. The highest channel head change (187-195%) took place on TK1-TK3 catchments resulting in a significant increase in drainage density (64-65%, see red colored areas on Figure 3.6c). GS2 had the highest drainage density increase with

77%, but with one of the lowest channel head increases with 66.7%. Some of the smallest drainage density increases took place on WA2, TK4, TK6, and TU2 catchments (16.6-20%). These catchments also had low channel head changes (74.5-84.1%). The number of different clusters used to delineate each catchment did not play a factor in the resulting drainage density, but rather the combination of clusters with lower accumulation thresholds did. Clusters 3, 4, 5, and 7 had lower thresholds and their combination likely affected catchments more than cluster combinations with both low and high thresholds.

The relationship between channel head change and drainage density change was generally directly proportional (Figure 3.7). In the upper right quarter, catchments with high-high changes are situated, while catchments with low-low changes are situated on the lower left quarter. On the upper left quarter, catchments with lower than the average drainage density change but with higher than the average channel head change are displayed. The exact opposite (low channel head-high drainage density change) is shown on the lower right quarter. Most of the catchments were clustered at or near the center of the mean channel heads and drainage density change.

Modeled Stream Network Validation

For validation, I compared distances between modeled channel heads and mapped channel heads for three catchments (Table 3.5). For each catchment, a suite of standard descriptive statistics of the distance between channel heads (modeled and REC) to the mapped channel heads were calculated. Most importantly, the last column shows the number channel heads (modeled or REC) that are closest to the mapped channel heads (based on the Euclidean distance). Overall, the modeled Pohangina stream network performed very well, with the modeled channel heads having a mean distance of 199.9 m from the mapped heads while the REC channel heads were 234.6 m from the mapped channel heads. In all, 85% of the mapped heads were closest to the modeled channel heads. For the AK1 and the DN10, the REC had lower mean distance from mapped heads, but the modeled heads were closer to the mapped heads and had lower standard deviation than the REC.

Examples of good vs. bad modeled stream network performance is shown on Figure 3.8. The first column has imagery along with the mapped channel head, modeled head, and REC head locations for each one of the 3 validation catchments. On these, it is evident that the modeled channel heads are closer to the mapped ones. In some cases, there were no REC heads close to the mapped ones. The second column shows examples were the modeled stream network did not perform well, possibly due to difficulties associated with mapping channel heads in densely forested areas or in flat areas where intense agricultural activities may distort the landscape and make channel head identification practically impossible.

Discussion

Channel Networks Within the Context of Physiographic Diversity

Physiographic diversity makes identifying the exact locus of channel initiation a difficult task (Garrett and Wohl 2017; Clubb, et al. 2014; Heine, Lant, and Sengupta 2004). While field-mapping is the most accurate method of locating channel heads, it is not practical over large areas. One common approach on identifying the location of channel heads is by using the slope-area curves (Appendix A). However, there was not a strong correlation between local slope and drainage area, nor other topographic variables that have been shown to be related to drainage area of channel heads (Julian, Elmore, and

Guinn 2012). I believe this lack of relationships is due to the physiographic diversity of the catchments, which is supported by Jaeger, Montgomery, and Bolton (2007). Therefore, we have to rely on remote sensing and modeling techniques in order to capture the true locations of direct linkages between the terrestrial landscape and downstream environments. In this study, I developed a model with varying accumulation thresholds, based on physiographic attributes, in an effort to account for differences in landscape characteristics between channel heads that were created under different processes. From statistical analyses, I found that these different channel head physiographic regions fell into 8 clusters, which I used to assign 8 different accumulation thresholds across New Zealand, as opposed to the one accumulation threshold that was likely used in the REC national hydrography dataset.

Using my modeled stream network, I found that there were twice as many channel heads than were represented in the REC, which means there are twice as many terrestrial-aquatic connections than previously thought. From model validation in three physiographically-dissimilar catchments, the modeled channel heads were found to be closer to the actual channel head for 71-85% of all occurrences compared to the REC. In sum, the modeled stream network better characterized channel head numbers and locations, which accords with previous channel mapping models that used varying accumulation thresholds (Heine, Lant, and Sengupta 2004; Elmore, et al. 2013).

The modeled stream network increased drainage density across the 77 NRWQN catchments by 36%, with some catchments experiencing an increase as high 78%. In general, catchments in the North Island had a mean channel head increase of 105.3% with a mean drainage density increase of 38.4%; catchments in the South Island had increases of 107.7% and 36.5%, respectively. When normalized by area, the highest drainage density change was observed in the smaller catchments (GS2, WA2, WN5, AK2), suggesting that larger catchments are less sensitive to changes relative to their size.

Some of the highest increases were for the Canterbury catchments, specifically TK1, TK2, and TK3, which increased by 64-65%. These catchments are on the east side of the Southern Alps, an area characterized as relatively flat and semi-arid with alluvium soils. Such a sharp increase in stream density over those areas is in agreement with results from N. A. Sutfin, et al. (2014) who concluded that perennial stream classifications, in this case REC, that were extended to ephemeral channels, failed to capture differences in characteristics of the latter. On the other hand, TK6 which is adjacent to TK1, TK2, and TK3, shares some of the same characteristics, but showed an increase of only 18%. A possible explanation would be that the steep slopes with the high mountain peaks and the existence of large lakes, synthesize a landscape on which headwater development is restricted; dominant source of flow was mountain/hill compared to low elevation for TK1, TK2, and TK3.

Channel heads, even within small areas, can have very different flow accumulation thresholds (Wohl 2017). And in this study, the use of 8 different thresholds, based on the k-means clustering, resulted in larger and more heterogeneous stream networks. Although the majority of the 77 catchments are congregated around the mean values, some are displaying nonlinear trends where a sharp increase in channel heads was not followed by an increase of similar magnitude of drainage density (HM5, GY4, WA3). The common characteristics of these catchments are plutonic soils, on hills/low elevation over wet areas (Figure 3.2). What is more interesting is the fact that another set of catchments with similar physiographic characteristics (GS2, GS3, WA4), are showing the exact opposite head-to-density relationship: low channel head channel increase with a high drainage density increase. Geology could be the explanatory factor because while the 1st group sits on generally harder, less erodible plutonic soils, the 2nd group is dominated by soft-sedimentary soils, which has higher potential erodibility that is conducive to the creation of ephemeral and intermittent channels.

Figure 3.6 shows an important improvement of the new modeled network. Drainage density of the existing REC appeared to be uniform with values ranging from 1.2-1.9 km/km^2 (with the exception of the very small catchment WA2 with a value of 2.7 km/km^2). The new modeled drainage density, however, is both higher and with a wider range of values (1.7-3.2 km/km^2), which I believe accounts for physiographic differences between the catchments. REC is a synthetic river network which was likely created with one accumulation threshold, using the blue topo lines to correct for stream channel location, and with periodic additions/corrections. It's intended to capture all the perennial streams, but it is obviously not representing all the intermittent/ephemeral streams. However, intermittent/ephemeral streams are very important because they deliver sediment and pollutants during large storms playing a major factor in river water quality degradation (Abbott, et al. 2018; Julian, et al. 2017).

The relationship between the number of channel heads and drainage density was generally directly proportional, with an $r = 0.23$ (Figure 3.7); however, there were some notable outliers such as GS2, WN5, and WA2. The main reason these outliers appear can be attributed to their size; these are among the smaller catchments in the study area and even modest changes in stream length could have great impact on stream density measurements. Thus, while physiographic diversity shapes the general relationship between channel head number and drainage density, catchment size can create outliers.

Study Limitations

In this study, I mapped channel head locations using satellite/aerial imagery interpretation across an entire nation that was physiographically diverse. Although the mapped channel head sample was large (n=10,323), issues with imagery such as cloud cover, different sensors with varying resolutions affected the process of locating the channel head location. Moreover, dense exotic/native forests, intensive agricultural practices on flat areas (hard to distinguish ditches from channels), and urban development also affected the final number of channel heads mapped. To compensate for the positional errors of placing the headwaters based on high resolution imagery (often <1 m) while delineating streams on a 15-m DEM, a positional adjustment was made on all mapped channel heads resulting them to be moved on an average distance of 65.5 m around their neighborhood to the pixel with the greatest flow accumulation.

Although the clustering of the 43 different physiographic regions resulted in a stream network with increased and varying drainage density, it would be ideal if all classes were delineated based on their respective threshold. It is a matter of scale: using stream networks over large catchments will attenuate the effect of the missing unique threshold per class but it may be important on studies that focus on small catchments when the most accurate stream network is needed. Also, there were some classes (n=13) that did not make the 1% cutoff (i.e., less than 100 3rd-order stream segments) for the stratified random sampling and thus were assigned the average threshold of the class that was closest to them. Future models could be more comprehensive in this regard.

Applications and Future Directions

New technologies have emerged that allow for more accurate and detailed Digital

Elevation Models (DEM), and therefore potentially more accurate river networks. Light Detection and Ranging technology (LIDAR) has been found to be more accurate compared to the traditional DEM models (Murphy, et al. 2008; Degetto, Gregoretti, and Bernard 2015; James, Watson, and Hansen 2007), and can be effectively used for hydrography change detection (Poppenga, Gesch, and Worstell 2013) and locating channel heads (Orlandini, et al. 2011). Unmanned Aerial Vehicles (UAV) produce DEMs with minimal horizontal and vertical errors (Ajayi, et al. 2017) which can be extremely useful when delineating stream networks. Last, structure-from-motion-photogrammetry can derive survey quality terrain models which can be even used for higher dimensional hydrodynamic modeling (Javernick, et al. 2016).

Given the broad and multi-faceted importance of headwater streams (Wohl 2017), there are many applications for this improved stream network dataset. First, it could inform the existing national dataset (REC) which is available to researchers and the public and is used for many scientific studies and applications (Snelder, et al. 2004; Brosse, Arbuckle, and Townsend 2003; Kilroy, et al. 2008). Second, it could help answer research questions that require knowledge of the exact location of head channels such as targeting areas for water quality improvement through Best Management Practices (BMPs). BMPs are incorporated in Integrated Catchment Management Plans for issues such as reducing flood risks, reducing the effects of climate change, and improving water quality (Fenemor, et al. 2011; McKergow, Matheson, and Quinn 2016; Monaghan, et al. 2007). Indeed, channel head location knowledge is paramount for protecting downstream water quality, and when combined with other environmental data, could provide hotspots for targeted conservation efforts. Ultimately, the methods used in this study should be applied to the entire New Zealand so that a new and improved nationwide hydrography dataset is available.

Tables

Table 3.1. REC classification system used to differentiate physiographic regions. Some of the original classes were grouped (Volcanic) and others had very small spatial representation and were excluded from analysis (Spring, Regulated, Wetland).

Level	**Class**	**Symbol**	**Description**
Climate	Extremely Wet	EW	Mean annual effective precipitation ≥ 1500 mm
	Wet	W	Mean annual effective precipitation 500-1500 mm
	Dry	D	Mean annual effective precipitation 1500 mm
Source-of-flow	Glacial-Mountain	GM	Mountain and % permanent ice >1.5%
	Mountain	M	>50% annual rainfall volume above 1000 m ASL
	Hill	H	50% annual rainfall volume between 400 and 1000 m ASL
	Low-Elevation	L	50% annual rainfall volume below 400 m ASL
Geology	Alluvium	AI	Spatially dominant class unless Soft-Sedimentary class ≥ 25%, then SS.
	Hard-Sedimentary	HS	
	Low-Sedimentary	SS	
	Volcanic	VO	
	Plutonic	PI	
	Miscellaneous	M	

Table 3.2. Mapped channel heads per attribute class.

Level	**Class**	**Mapped channel heads (n)**
Climate	Extremely Wet	2,777
	Wet	5,087
	Dry	2,454
Source-of-flow	Glacial-Mountain	316
	Mountain	2,365
	Hill	3,616
	Low-Elevation	4,026
Geology	Alluvium	514
	Hard-Sedimentary	5,298
	Low-Sedimentary	1,811
	Volcanic	1,476
	Plutonic	718
	Miscellaneous	506
	TOTAL	**10,323**

Table 3.3. Mapped channel heads summary for physiographic classes across New Zealand, including the number (n) of all 3rd-order streams, the n of stratified randomly sampled streams, the n of channel heads mapped, and the mean density of channel heads per class (channel heads per square km). Refer to Table 3.1 for physiographic class descriptions.

Class	3rd-Order streams	Random sample	Channel heads mapped	Channel heads mean density (x10^{-2} heads/km^2)
WLSS	8350	84	967	4.2
WMHS	5679	57	947	7.2
WLVO	5401	54	602	3.3
WHVO	5164	52	362	2.5
EWMHS	4401	44	688	7.7
DHHS	4184	42	722	5.4
WHHS	4192	42	581	3.6
DLSS	4028	40	495	3
DLAl	3581	36	190	0.7
WLHS	3424	34	425	4.2
EWHHS	3120	31	608	5.3
EWHPl	2875	29	431	3.5
EWGMHS	2471	25	333	4.7
DLHS	2052	21	474	4.8
WHSS	1961	20	230	4.4
WLM	1320	13	240	5.5
EWMPl	1202	12	242	7.9
DLM	1022	10	117	3.4
EWHVO	959	10	72	3.1
DMHS	891	9	150	5.1
EWLAl	906	9	79	1
DHAl	837	8	135	1.7
EWHSS	757	8	75	3.6
EWLSS	728	7	85	2.8
DHSS	611	6	73	2.1
WHAl	554	6	53	0.8
WHM	599	6	104	3.7
WLAl	461	5	54	0.1
WLPl	456	5	68	3.2
DLVO	438	4	41	0.8
EWLHS	385	4	62	2.9
EWLVO	412	4	81	2.7
EWMVO	447	4	75	7.9
WHPl	323	3	56	4.6
DHM	214	2	48	6
DHVO	232	2	35	2.9
EWGMPl	224	2	18	3.8

Table 3.3. Continued.				
Class	**3rd-Order streams**	**Random sample**	**Channel heads mapped**	**Channel heads mean density (x10^{-2} heads/km^2)**
EWLPl	169	2	12	1.7
EWMSS	230	2	88	12.1
WMAl	237	2	36	6.7
EWHAl	147	1	10	3.6
EWMAl	105	1	6	6.5
TOTAL	**76,383**	**764**	**10,323**	

Table 3.4. Cluster center for each variable used on the k-means clustering. Upstream area cluster center was used for stream delineations.			
Cluster	**Slope (degrees)**	**Curvature**	**Upstream area (ha)**
1	34.99	-1.91	39.59
2	24.47	-1.66	32.44
3	19.94	-1.76	14.84
4	26.23	-1.88	20.72
5	33.21	-2.69	20.89
6	13.56	-1.36	21.54
7	12.43	-1.29	14.41
8	17.48	-1.55	27.06

Table 3.5. Results from new channel head validation against the REC channels and the mapped channels from aerial imagery. Number in parenthesis shows how many channel heads were mapped from visual inspection of imagery.							
Catchment	**Network**	**Min.**	**Median**	**Mean**	**Max.**	**Stdv.**	**Closest to mapped**
Hoteo (n=651)	Modeled	7.5	103.1	125.8	652.3	101.4	460
	REC	0.1	68.1	105.5	609.2	118.1	191
Pohangina (n=1205)	Modeled	2.8	182	199.9	697.3	139.9	1024
	REC	5	223.5	234.6	661	149.2	181
Monowai (n=157)	Modeled	7.5	159.1	194.9	629	155.6	119
	REC	4	101.2	170.3	621.7	164.2	38

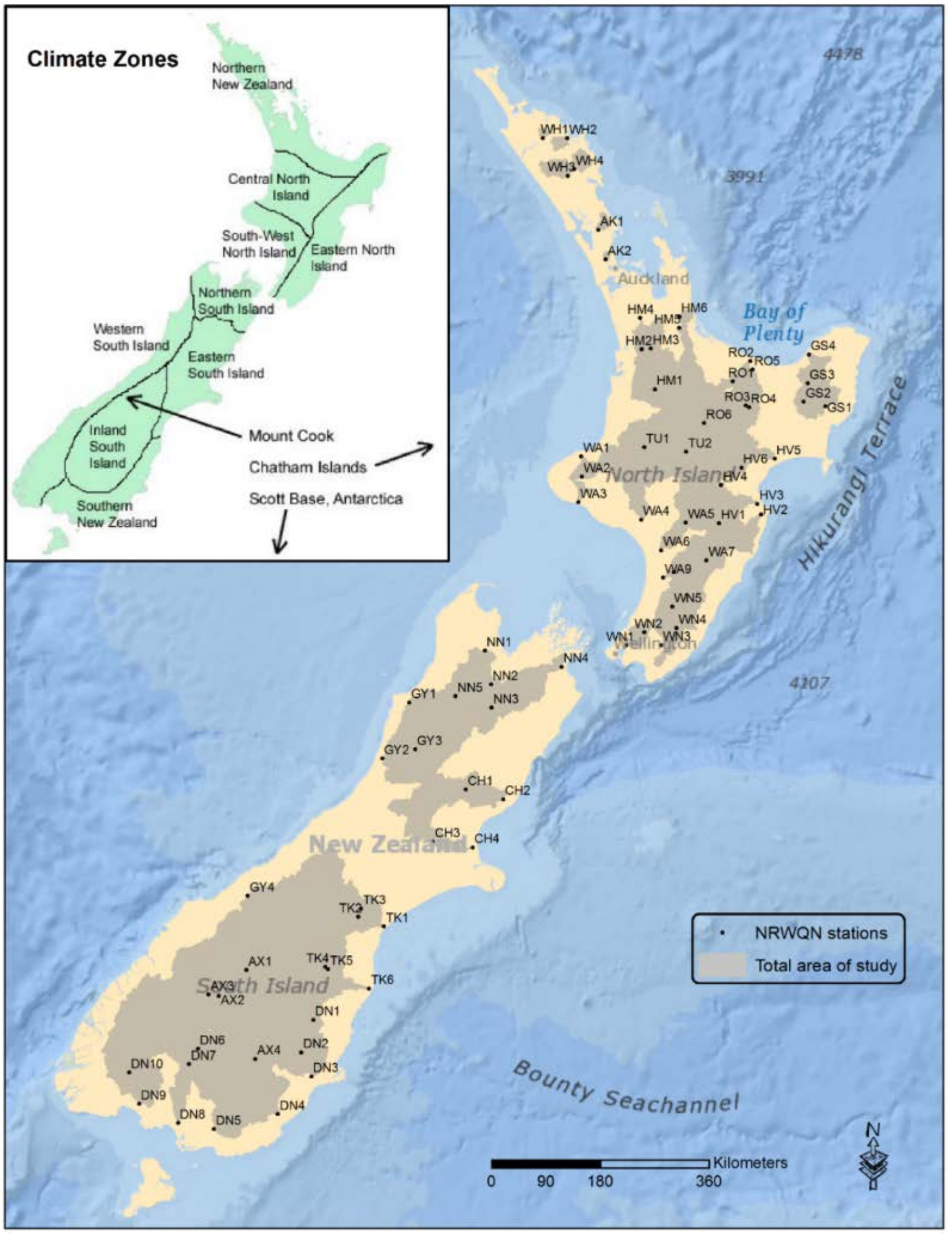

Figure 3.1. Map showing the location of the NRWQN stations and the total drainage area. Inset shows the different climatic regions of New Zealand.

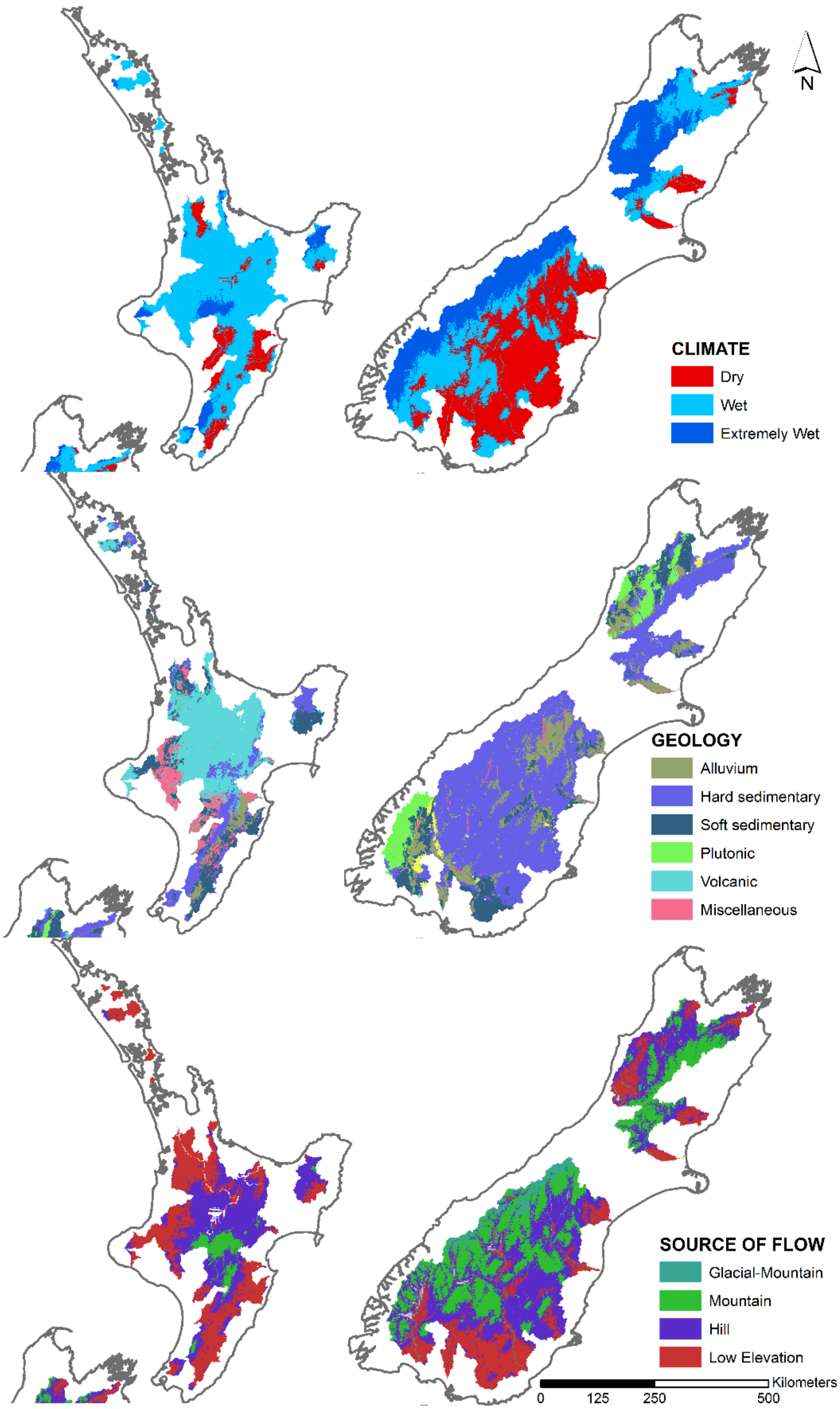

Figure 3.2. Climate, Geology and Source-of-flow from the modified REC attributes of the North (left) and South Island (right) for the 77 NRWQN catchment area.

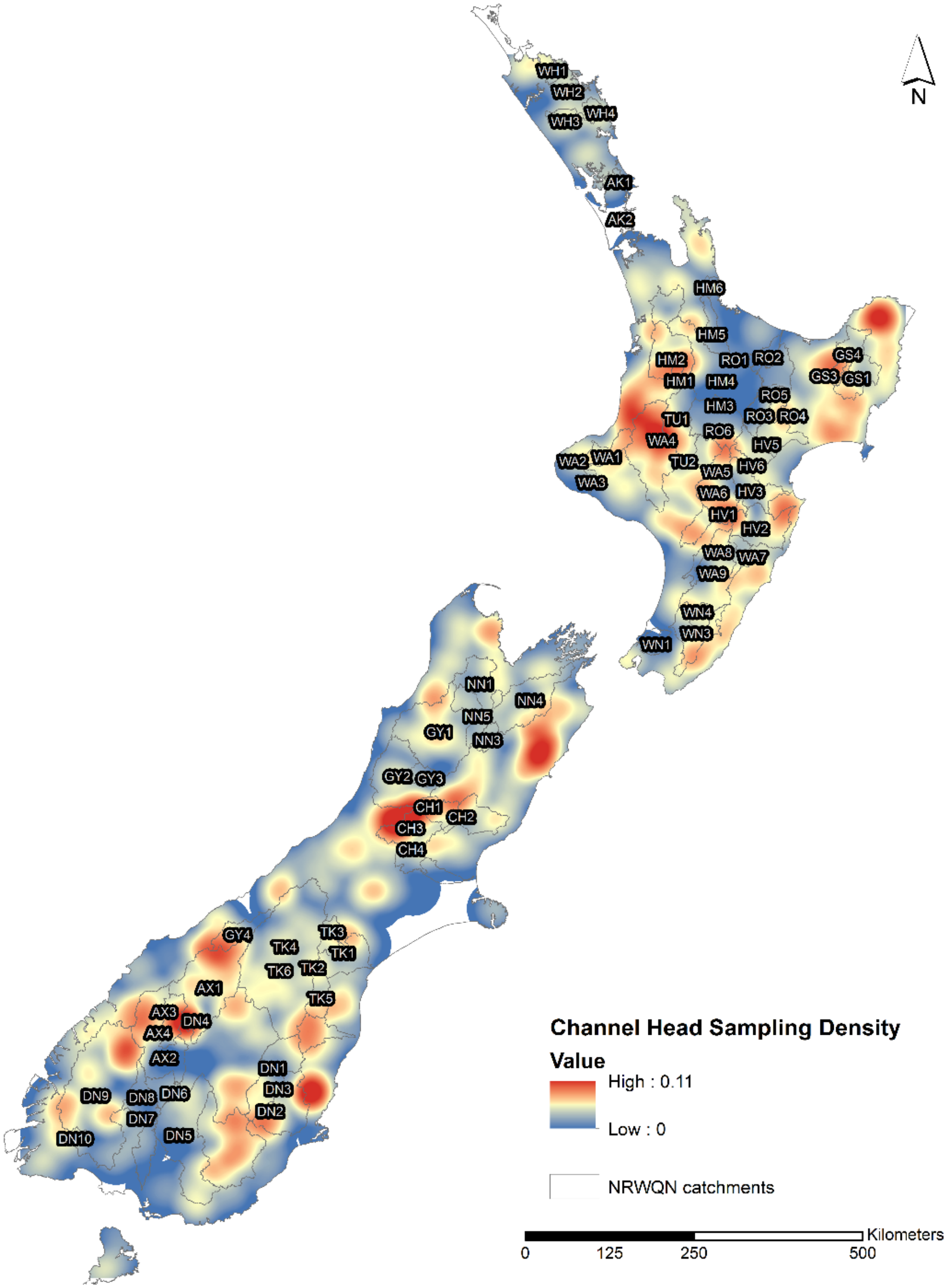

Figure 3.3. Channel head point kernel density showing frequency and extent of channel head mapping, with areas in red being more densely mapped compared to areas in blue. Units are in heads/km^2 with a search radius of 40,000 m.

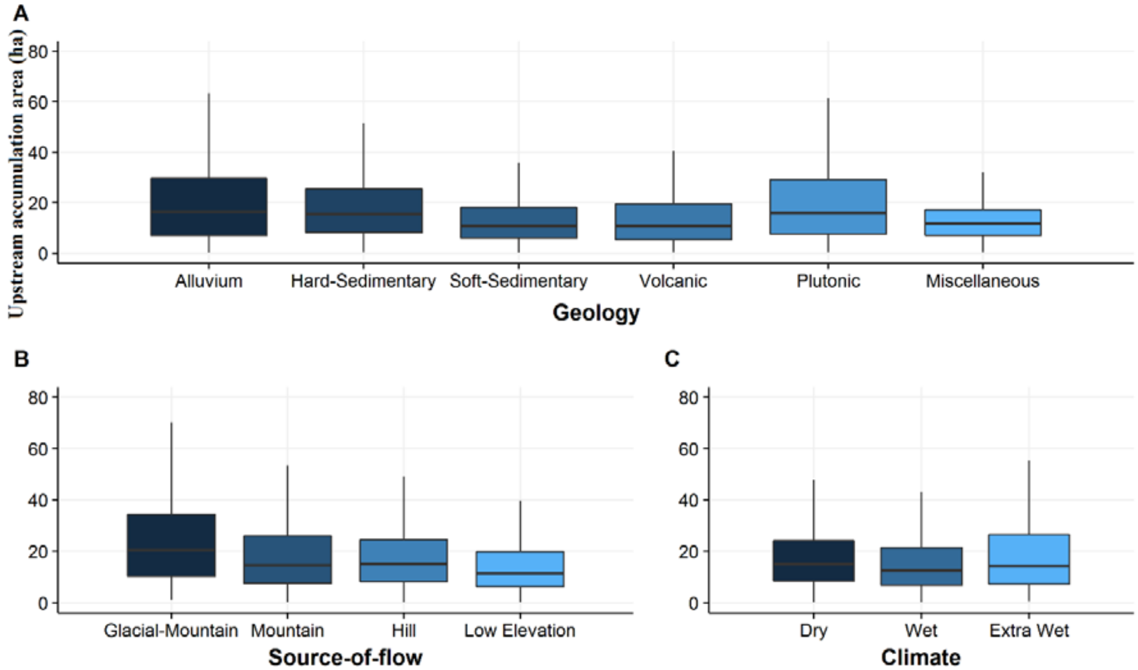

Figure 3.4. Boxplots of values of upstream area for each geology, source-of-flow, and climate class. Outliers are omitted for better visualization.

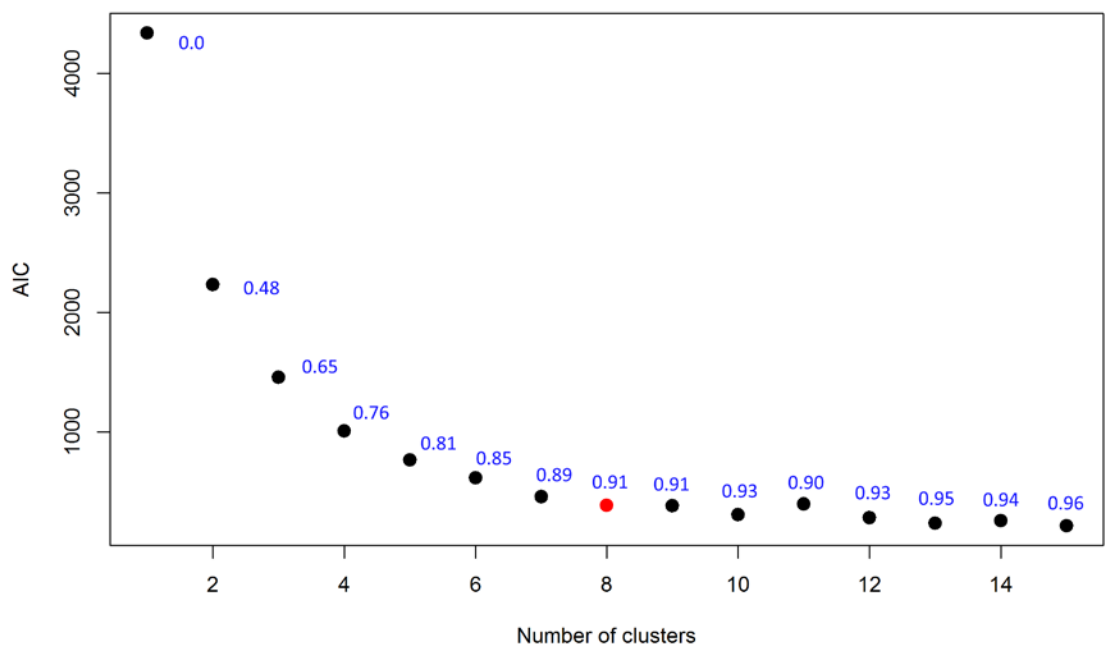

Figure 3.5. AIC test for choosing the optimal number of clusters (shown in red). Adjusted-R^2 values (blue numbers) are calculated based on the formula *rsq = 1-(totwss*(n-1)) / (totwss[1] *(n-seq(1,kmax)))*, where totwss=total within-cluster sum of squares, n=number of clusters, kmax=max number of clusters.

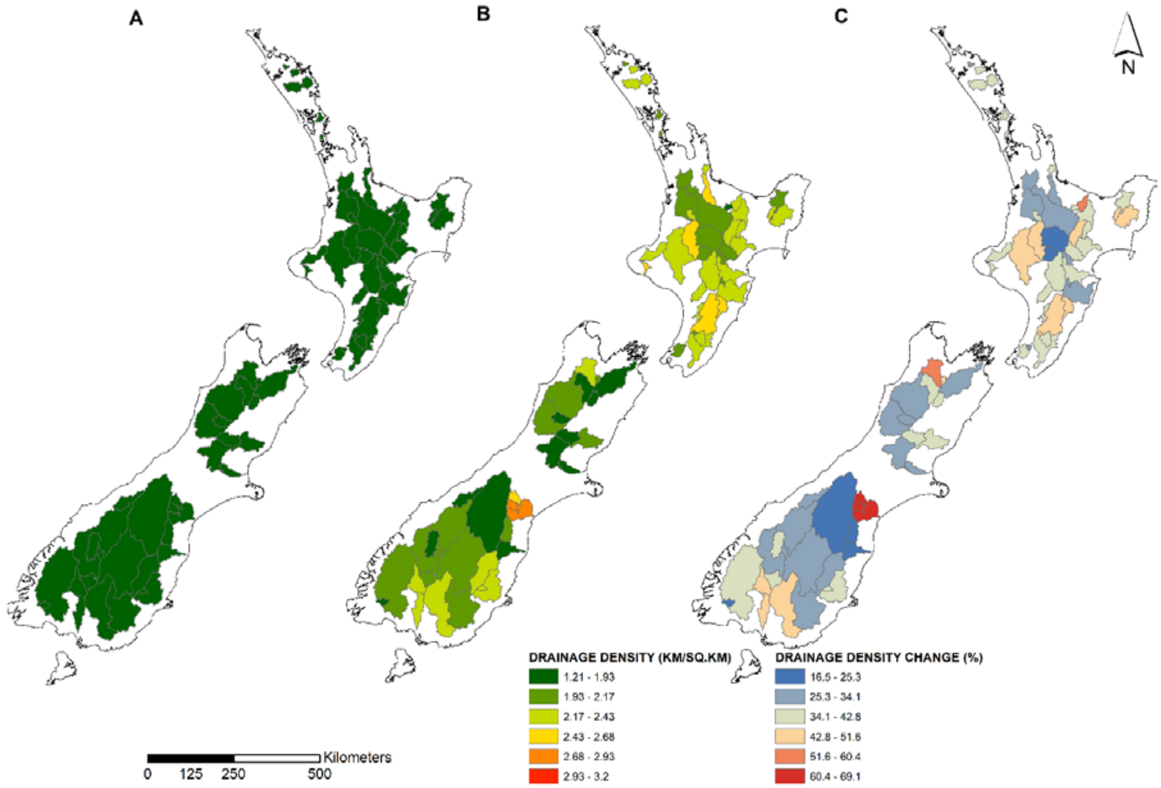

Figure 3.6. Drainage density comparisons of REC and modeled stream network for the 77 NRWQN catchments: A) Drainage density of the REC dataset, B) drainage density of the modeled river network (km/km^2), and C) Percent change increase (%) in drainage density with modeled stream network.

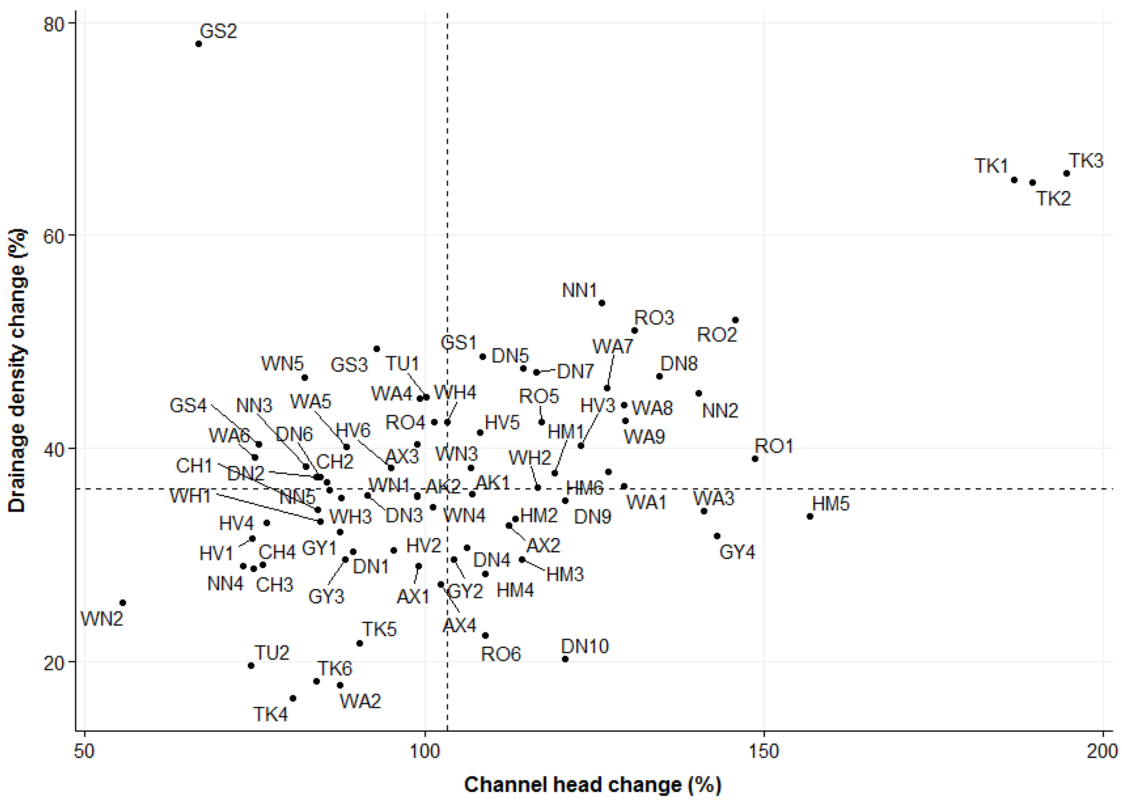

Figure 3.7. Channel head change (%) and drainage density change (%) between REC and the new network for each of the 77 NRWQN catchments. The upper-right and lower-left sections show catchments with high-high or low-low percent change. The upper left shows catchments with less channel head increase while the lower right less drainage density increase than expected. Dashed lines show the mean value between the catchments.

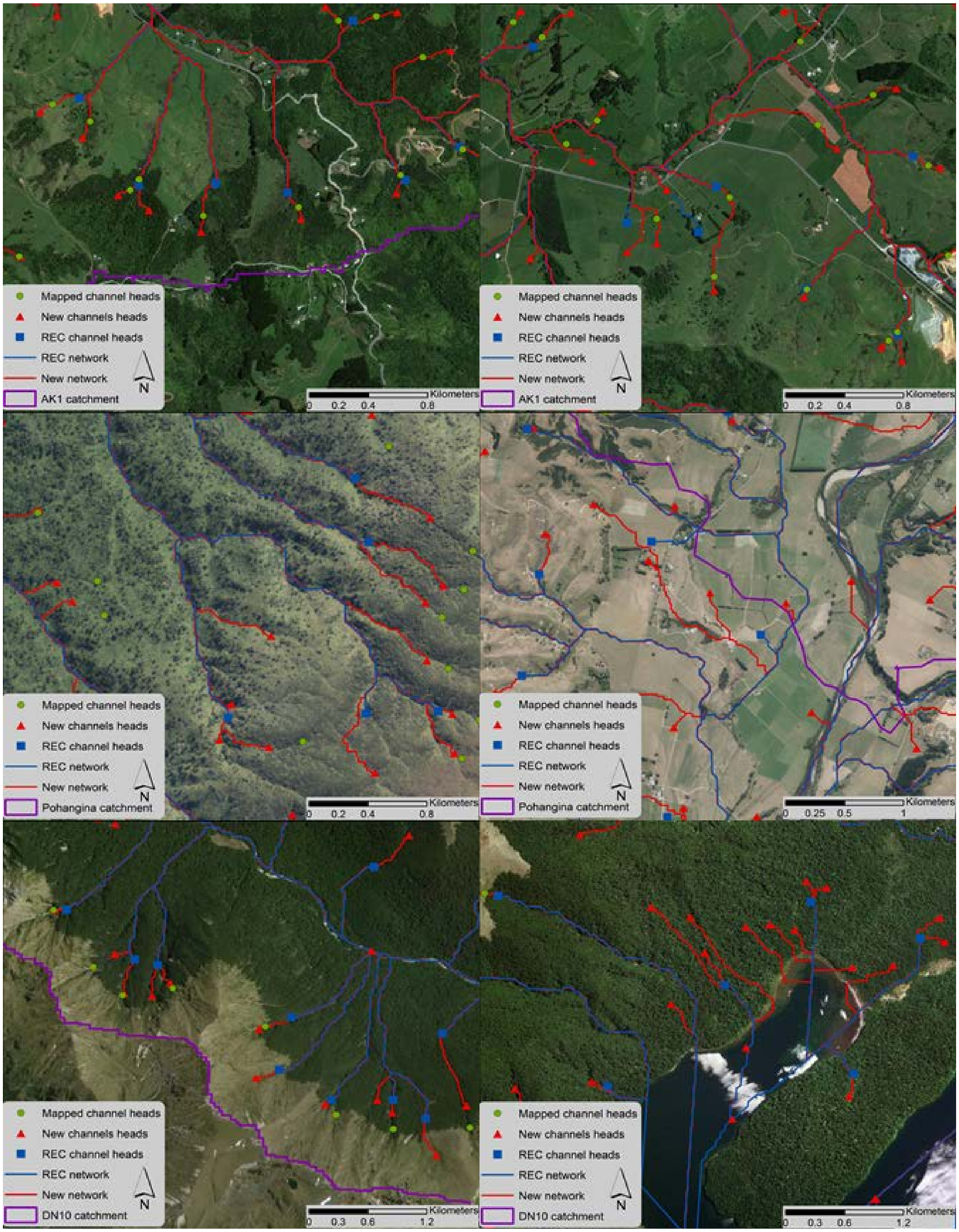

Figure 3.8. Comparisons between modeled and REC channel heads to mapped channel heads based on aerial imagery. On the left side are examples of the new stream network performing well compared to the actual location of channel heads. On the right side are examples where the modeled stream network under-performed.

4. PRIORITIZING UNMAPPED HEADWATER CHANNELS FOR PROTECTION IN NEW ZEALAND'S MOST SEDIMENT-IMPAIRED CATCHMENTS

Abstract

Riparian buffers have been successfully used to mitigate elevated river sediment concentrations in intensely managed agricultural landscapes. Their effectiveness, however, depends on their location and extent. Most policies have targeted perennial streams, ignoring the intermittent and ephemeral headwaters that provide the direct links for pollutants to enter the river network. In this study, I used a modeled stream network that incorporated intermittent and ephemeral headwater streams to prioritize locations for purposes of sediment conservation and enhanced water quality. I used a hierarchical approach where land use was the primary variable to identify "Priority" sites and secondary variables such as livestock intensity, landscape disturbance, and slope were used to identify "High-priority" sites. Using fifteen of New Zealand's most sediment-impaired catchments, I found that 19,108.1 km of headwater streams should be prioritized for protection. Most High-priority sites occurred on High-producing grasslands with increased livestock density (3,61.5 km). The results from this analysis informs national and local policies aimed at reducing suspended sediment concentrations in New Zealand's sediment-impaired rivers.

Introduction

The vast majority of pollution to non-urban rivers is diffuse pollution that enters the stream network at terrestrial-aquatic boundaries, specifically at channel heads and along channel banks. Protecting these riparian zones has long been a priority as a strategy to reduce diffuse pollution and improve river water quality, particularly for sediment runoff (Cooper, et al. 1987; Sweeney and Newbold 2014). Riparian buffers are effective sediment filters which slow down terrestrial sediment runoff and immobilize most coarse particles and some fines, preventing them from entering the stream network (Lowrance, et al. 1997; Quinn, et al. 1997; Fischer and Fischenich 2000). Riparian buffers can also receive floodwaters and trap some of the suspended sediment, further reducing downstream sediment loads (Webber, et al. 2010; Aarons and Gourley 2013). However, studies on the efficiency of the riparian buffers have reported varying levels of effectiveness, stemming from the limited knowledge on what is the appropriate buffer width and finding the optimum placement location (Sweeney and Newbold 2014; Tomer, James, and Isenhart 2003).

Studies have experimented with different buffer sizes and in general it was shown that sediment removal rates increased with increased buffer width (Young, Huntrods, and Anderson 1980; Dillaha, et al. 1988; Lena, et al. 1994). More specifically, Tate, et al. (2000) assessed the effectiveness of 10-m buffer strips on removing sediment runoff from different schemes of irrigated pastures and found that they significantly reduced Total Suspended Solids (TSS). These results were supported by similar studies on agricultural areas which reported sediment removal efficiencies from 82-99% for widths ranging from 12-19 m (Borin, et al. 2005; Lee, Isenhart, and Schultz 2003; Mankin, et al. 2007; Schoonover, et al. 2006). Another study by Clinton (2011) tested various buffer widths after forest harvest and concluded that stream quality was unaffected by harvesting for buffer widths greater than 10 m.

When planning riparian buffers at the catchment or watershed scale, one aspect that is often neglected is the importance of protecting headwater streams (Parkyn, et al. 2006). Headwater streams are important because they are the links between terrestrial and aquatic environments and provide downstream areas with water, sediment, organic matter, and nutrients (Wipfli, Richardson, and Naiman 2007; Alexander, et al. 2007). Yet, it is very common that intermittent/ephemeral streams are excluded from riparian policies (McKergow, Matheson, and Quinn 2016), thus remaining unprotected from erosion; unlike perennial streams which are usually the focus of such policies. Moreover, headwater streams are more sensitive to land use impacts, and it has been argued that it takes longer to recover from harvesting activities (Baillie and Neary 2015).

An integral part of the riparian buffer design is placement optimization, with a focus on locations that vegetation could intercept runoff from contributing upslope areas (Tomer, James, and Isenhart 2003; Martin-Mikle, et al. 2015). With methods such as the one developed by McGlynn and Seibert (2003), a combination of field measurements and terrain analysis of a digital elevation model (DEM) can produce varying riparian zone widths based on the upstream accumulation area. Moreover, precision conservation utilizes even more information in the form of datasets, such as topography, soils, farming practices, and stream location to account for non-uniformly distributed runoff flows in order to plan variable-width buffer designs (Dosskey, Eisenhauer, and Helmers 2005).

There are many factors that inform the ideal placement of riparian buffers for sediment conservation. Land use is the primary factor as it sets the environment from which sediment is produced (Foley, et al. 2005; Vitousek, et al. 1997). Agriculture in the form of livestock grazing, croplands, and plantation forestry has been identified as the main culprit for most sediment pollution worldwide (Julian, et al. 2017; Vörösmarty, et al. 2010). Accordingly, land disturbance (i.e., bare soil as a result of vegetation removal, such as from forest clear-cuts) is a secondary factor that can lead to increased sediment production (Ahearn, et al. 2005; Haan, et al. 2006; Kamarinas, et al. 2016; Turner and Rabalais 2003). Intensive livestock grazing can also be a secondary factor that potentially increases sediment runoff entering the stream through enhanced overland runoff from ground compaction, trampling of channel banks, or over-grazing to the point where bare soil is exposed (McDowell 2006; Nellesen, et al. 2011; Webber, et al. 2010). In all these scenarios, exposed sediment is readily available to be washed out and into the stream network with the next precipitation event. Another secondary factor is terrain, specifically steep slopes adjacent to the stream network that lead to increased terrain-stream connectivity, which in turn lead to larger areas actively contributing sediment runoff (Czuba and Foufoula-Georgiou 2015; Kamarinas, et al. 2016).

Considering these primary and secondary factors of sediment contributions to streams, this study develops a hierarchical strategy for identifying and prioritizing locations for protective riparian buffers around headwaters that are susceptible to sediment erosion and are currently unprotected. The study takes place in New Zealand (NZ) because (1) it is experiencing agricultural intensification across large areas, (2) many of its catchments are sediment-impaired, and (3) most of its headwaters are unprotected. A novel analysis was conducted on fifteen of NZ's most sediment-impaired catchments by overlaying modeled channel heads based on physiographic characteristics (from Chapter 3) onto data layers that represented terrain (slope), pressure from agricultural practices (livestock densities), and land disturbance (frequency and extent of bare soil following vegetation removal) The results from this study will assist in prioritizing areas for riparian protection and sediment conservation.

Methods

Catchment Selection

Fifteen sediment-impaired (Class II) catchments (Table 4.1) from New Zealand's National Rivers Water Quality Network (NRWQN) long-term monitoring program were selected based on analyses done by Julian, et al. (2017a). These catchments are sediment-impaired because their median values for monthly water clarity over a 26-year period were lower than the ANZECC (2000) trigger value of 0.8 m for lowland catchments or 0.6 m for upland catchments, distinguished by the 150 m elevation threshold. There were an additional four sediment- and nutrient-impaired catchments (Class IV) which also had exceptionally high median values for oxidized nitrogen (NO_x); however, these four catchments were not included in analyses because solely managing for sediment erosion could result in other complications like the development of harmful algal blooms if water clarity was increased in nutrient-rich waters (Julian, et al. 2017).

Headwater Streams Prioritization

The headwater streams used for analyses here are previously unmapped 1st-order channels for the 77 NRWQN catchments (Chapter 2). Briefly, this dataset was created by using a varying threshold stream delineation method by mapping headwaters foreach distinct physiographic region and assign unique upstream accumulation areas for each region.; these modeled headwaters that were not being captured by the REC were used in this research.

In order to prioritize reaches of headwaters for protection, I used several geospatial layers (Table 4.2) that represent likely areas of sediment production: (i) livestock density, (ii) land disturbance, (iii) terrain gradient, and (iv) land use. The livestock density dataset was calculated based on the amount of stock units (su) for each species: sheep =0.95S su, deer, 1.9 su, beef cattle = 5.3 su, and dairy cattle = 6.65 su per hectare. Land disturbance is defined as an index with a value> 20% which reflects areas that shown as having bare soil on Landsat imagery. The Digital Elevation Model (DEM) used here had a 15-m resolution and it was developed with high vertical accuracy, resulting in optimal terrain gradient calculations. Last, the most updated Land Cover Database (v4.1) was used but with a focus on only three classes: high-producing grasslands, plantation forestry, and croplands. The timestamp for this analysis is the 2011-2012 period where all the data chronologically coincide. All data layers were resampled to 450 m to match the coarsest spatial dataset (land disturbance) for subsequent overlay analyses.

Using the above datasets, I developed a prioritization scheme based on the following conditional analyses (Figure 4.1). First, the land uses of High-producing grasslands, Croplands, and Plantation forests were identified as "Priority" areas (value = 1) because they are intensive land uses that typically generate sediment available for runoff (Stott and Mount 2004; Basher, et al. 2011; Kreutzweiser and Capell 2001). From these areas, I then assessed for "High-Priority" (value = 2) if they met any of the following additional criteria:

a) Livestock densities greater than 5 su/ha, OR

b) Disturbance Index (DI) greater than 20%, OR

c) Local slope > 5 degrees.

When these criteria were applied, headwaters with increased connectivity (slope > 5˚, see Chapter 2 for connectivity definition), high livestock pressure (more than 5 livestock units per ha), on significantly disturbed areas (DI > 20%, at least 10 weeks per year disturbed) on sediment-impaired catchments (decreased CLAR/decreased NO_x) were identified. In the end, every 450-m pixel had a value of either Zero (No Priority), One (Priority), or Two (High-Priority). The modeled stream network from Chapter 3 was then overlaid on this dataset to extract stream reaches (linear features) that should be prioritized for protection.

Results

Priority Headwaters

Using the 15 sediment-impaired catchments (Table 4.1), a total of 86,491.8 km of streams were assessed, but for the rest of this study I only analyzed headwater 1st-order stream lengths (19,108.1 km) not included in New Zealand's River Environment Classification, under the assumption that these perennial streams are already protected and also to focus on the unmapped intermittent/ephemeral stream channels that likely contribute sediment to the river network. Overall for the 15 catchments studied here, there were 10,742.2 km of No-priority, 8,365.9 km of Priority, and 5,214.6 km of High-priority headwaters channels not captured by the REC. In terms of channel heads (point features) resulting from this new dataset, there were 50,901 No-priority, 34,639 Priority, and 19,264 High-priority channel heads.

Headwaters in High-Producing Grasslands

Most Priority channel heads occurred on high-producing grasslands (n = 29,626), with a total stream length of 8,365.9 km (Figure 4.2). Of these, 16,357 channel heads were High-priority with a total stream length of 4931.7 km. Most of these High-priority channel heads occurred on high livestock density (n = 12,080), followed by steep (> 5°)

land (n = 6,881), and frequently disturbed areas (n = 2,347); there were cases were a channel head was both in high density and steep, or disturbed area.

Slopes greater than 5˚ are very common on the rolling hills of New Zealand. Figure 4.3 (left) shows some headwater channels of the Rangitikei River that are classified as high-priority. Although the main stem of the river has riparian buffer composed of a combination of trees and grass, and it is fenced off so livestock don't have access, some of the smaller ephemeral/intermittent head channels are not protected. High livestock density values (Figure 4.3, right), on high-producing grasslands are also high-priority sites (red color). In contrast, forested parts of Whanganui River tributaries (bottom center) do not need to be prioritized (grey color) since trees act as riparian buffers and protect headwater channels.

Headwaters in Plantation Forests

A large number of channel heads occurred on plantation forests (n = 1,147), with a total stream length of 376.3 km (Figure 4.2). Of these, 671 channel heads were High-priority with a total stream length of 220.1 km. Most of these High-priority channel heads occurred on frequently disturbed areas (n = 455), followed by steep (> 5°) (n = 330), and high livestock density land (n = 34). Figure 4.4 below shows a recent harvest plantation forest area; notice the difference between the forested area that remained intact on the right (grey values for no priority) compared to the harvested area which is highlighted as priority (green) or high-priority (red).

Headwaters in Croplands

Few channel heads occurred on croplands (n = 583), with a total stream length of

195.4 km (Figure 4.2). Of these, 194 channel heads were High-priority with a total stream length of 62.8 km. Most of these High-priority channel heads occurred on frequently disturbed areas (n = 88), followed by steep (> 5°) (n = 80), and high livestock density land (n = 47).

Highly disturbed areas (Figure 4.5, left) are also a focus of prioritization. Disturbed headwaters (red color) from intense agricultural practices, are more likely to contribute sediment in the river and are prioritized for protection. In that site (bottom left), trees were harvested, and vegetation starts to slowly recover; but until it recovers it is a critical source area of sediment runoff. On Waikohu River (Figure 4.5, right), apparent erosion processes (abundance of gullies) along with the combination of steep slopes, high livestock densities and disturbance, suggests that these headwater streams should be protected.

Discussion

Prioritizing Protection

The aim of this study was to assess the status of headwater channels in some of New Zealand’s most sediment-impaired catchments (from Julian et al. 2017) for purposes of sediment conservation and enhanced water quality. To achieve this end, a new modeled stream network based on physiographic characteristics (Chapter 3) was used to find the true location of headwater channels which by nature are intermittent/ephemeral compared to the predominantly perennial streams of the existing REC national hydrography dataset. In order to develop a prioritization scheme for headwaters protection, additional datasets used, including a livestock density (from Ausseil, et al.

(2013)), a novel nationwide disturbance index dataset (from de Beurs, Owsley, and Julian (2016)), national elevation data (ref), and land use (NZ LCDB v4.1 (2015)). When combined, all of these datasets allowed me to develop a hierarchical classification for protection of headwaters.

The study area covered 15 relatively large catchments with a mean drainage area of 2747.6 km^2 and a mean drainage density of 2.15 km/km^2. In these catchments, there were 8,365.9 km of headwater streams that were prioritized for protection, with 59.7% being High-priority. These streams corresponded to 34,639 Priority channel heads, with 55.6% of them classified as High-priority. In all, this amounts to 43.8% of the streams that should be prioritized for protection, or 23% given High-priority.

It is estimated that with a conservative 10-m buffer (Clinton 2011), 175.4 km^2 of riparian area would need to be buffered or excluded from livestock accessing it. From these, 149.9 km^2 would be in high-producing grasslands, 23.8 km^2 on plantation forestry, and 1.7 km^2on croplands; however, croplands have usually livestock rotated and it would be more challenging establishing permanent riparian buffers when livestock is not present because of the area of arable land the farmer would lose. For cases like these maybe electric fencing, which can be temporary, would be a better alternative to traditional fencing.

Potential Effectiveness of Protection

The purpose of this study was to inform decision making on the location of headwaters needing prioritization for sediment conservation, along with keeping livestock out of streams and preventing cuttings in the riparian zones of active streams. Although protecting headwater stream channels with restrictive buffers and fencing can potentially reduce sediment inputs, there are still other sources of sediment to the river including downstream bank erosion (Murray, et al. 2011; de Vente and Poesen 2005) and upslope gullies (Gomez, et al. 2003; Kasai, et al. 2005). In fact, many of the mapped channels here begin at the confluence of multiple gullies and more extensive mitigation will likely be needed to make drastic improvements in water clarity and quality (Ayele, et al. 2018; Hambling 2008; Marden, et al. 2005). Indeed, several of the focus catchments used here, such as Awakaponga (RO2) and Whanganui (WA4), have frequent landslides that produce large, productive gullies (Glade 2003; Korup 2005) . These gullies can contribute sediment to rivers for many years following the initial landslide and convert catchments from sediment supply-limited to transport-limited (Abbott, et al. 2018). Moreover, many of the catchments examined here such as Hoteo (Hughes 2016), Waikohu (Marden 2011), and Manawatu (Fuller 2008) experience significant bank erosion that produces considerable suspended sediment loads.

There have been several NZ policies in the past decade aimed to improve river water quality by protecting streams from direct impacts, including Waikato Regional Council's Clean Streams strategy (Campbell 2002), Horizons Regional Council's One Plan (2014), and the nationwide Dairying and Clean Streams Accord (DCSA 2012). The DCSA has been the most effective policy with its focus on soil conservation, bank erosion reduction, and riparian management. In the most recent progress report, it is stated that 97.2% of the waterways have dairy cattle excluded, but only 27% of dairy farms with waterways had a riparian management plan and are expected to complete 50% of their riparian commitments by 2020 (DairyNZ 2017). Undoubtably, an agreement across so many stakeholders is a very important step towards minimizing stream sediment influx, however their stream definition as: "deeper than 30 cm, wider than a meter and permanently flowing", is not sufficient and does not cover the many intermittent/ephemeral headwater channels that produce fluvial sediment. Further, the DCSA only covers dairy cattle and thus does not take into consideration the potential effects from other livestock such as beef cattle and sheep. The effect of sheep on sediment production in NZ rivers is an issue that has been largely ignored, yet likely has a significant effect on river sediment loads, especially in steep headwater catchments (Julian, et al. 2017).

While this study focused on protecting headwaters to reduce river sediment loads, there will no doubt be benefits in reducing river nutrient loads as well. It has been estimated that headwaters contribute approximately 65% of the nitrogen flux in 2nd- and 55% in 4th-order streams (Alexander, et al. 2007). Thus, protecting the headwaters might be an important step in decreasing nutrient loads (Saunders, Meeuwig, and Vincent 2002; Dodds and Oakes 2008). Manawatu catchment, although not studied here, is a both nutrient- and sediment-impaired catchment (Class IV) that could benefit from headwater protection. Especially if the added effect of landslides is considered; sources of sediment production which usually occur in steep, unstable headwater areas. Considering all the above conditions, it is possible that by protecting the headwaters, either by riparian buffering, or by fencing, both sediment and nutrients loads can be effectively reduced.

The prioritization scheme presented here is primarily a reactionary approach for sediment-impaired catchments that considers impacts over the past decade. A longer-term approach would be ideal in order to observe the effectiveness of such efforts on water quality. The benefits of stream restoration and best management practices can take a long time to be observable (Bernhardt, et al. 2005). For example, extensive restoration of Chesapeake Bay streams in USA has been going on for decades; yet, a study on water quality parameters from 1986-2008 showed little improvement in water clarity from these efforts (Williams, et al. 2010). Diffuse pollution and legacy effects (Kronvang, et al. 2008; Boesch 2002) may extend the time needed for significant water quality improvement (Julian, et al. 2017). It must be noted that a broader approach would be more suitable for long-term sustainability, where protection should not only be narrowed down to the most impaired headwaters, but also to the ones that are not disturbed and are contributing clean water to the system. This more holistic approach would also prevent further sediment impairments.

Future work

Prioritizing best management practices (BMPs) is not an easy task because monetizing processes and specific targets (e.g. 50% reduction in sediment runoff) can be daunting. Several studies have examined methods for cost-effective prioritization (Feng, et al. 2006; Hruby, Cesanek, and Miller 1995; Machado, et al. 2006). This is an aspect missing from this study and which is necessary to draw attention from policy makers. Jang, et al. (2013) created a model of prioritizing BMPs using a synoptic approach to calculate indices for different area units and then rank these units. A modified synoptic approach could be incorporated in my study where instead of evaluating different BMPs, I could evaluate different scenarios or degrees of riparian fencing extent with their associated implementation costs and expected results.

Additionally, the inclusion of more variables in conditional analysis could potentially refine the results of this study. For example, Adhami and Sadeghi (2016) used several topographic, physiographic, and hydrological variables to prioritize subwatersheds with game theory. By reviewing their list of variables, I believe that rainfall intensity and frequency should be incorporated in future work because they provide feedbacks on the driver behind sediment runoff. It can be hypothesized that not only the location of these sensitive headwaters is important, but also whether these critical source areas are exposed to intense or frequent precipitation events that would mobilize available sediment.

Tables

Table 4.1. Physiographic and water quality characteristics for the 15 sediment-impaired catchments used in this study.

NRWQN ID	**Main river**	**Drainage area (km^2)**	**Drainage density (km/km^2)**	**Climate Class[1]**	**Dominant land use**	**Median clarity (m)**	**Median oxidized nitrogen (mg/m^3)**
AK1	Hoteo	264	2.15	A1	High-producing Grassland (50.9%)	0.8	347
AK2	Rangito-puni	81	2.09	A1	High-producing Grassland (58.6%)	0.6	215
AX3	Shotover	1,066	1.91	F2	Low-producing Grassland (75.25%)	0.4	16
CH3	Waimakariri at Gorge	2,381	1.84	F2	Low-producing Grassland (46.9%)	0.5	65
CH4	Waimakariri	3,017	1.88	F2	Low-producing Grassland (39.4%)	0.3	81
GS1	Waikohu	1,576	2.25	C1	Low-producing Grassland (47.8%)	0.1	80
GS4	Motu	1,385	2.08	M	Indigenous Forest (75.3%)	0.7	62
HM4	Waikato	12,381	2.15	B2	High-producing Grassland (40.2%)	0.7	332

Table 4.1. Continued.							
NRWQN ID	**Main river**	**Drainage area (km^2)**	**Drainage density (km/km^2)**	**Climate Class[1]**	**Dominant land use**	**Median clarity (m)**	**Median oxidized nitrogen (mg/m^3)**
HV5	Raupunga	2371	2.20	M	Indigenous Forest (65.1%)	0.6	107
RO2	Awakaponga	714	2.19	B1	Plantation Forest (42%)	0.7	358
WA1	Waitara	1114	2.43	A2	Indigenous Forest (37.5%)	0.5	294
WA4	Whanganui	6624	2.33	A2	Indigenous Forest (52.2)	0.4	189
WA6	Rangitikei	3461	2.24	C3	Low-producing Grassland (46.6%)	0.8	83
WH3	Mangakahia	810	2.18	A2	Indigenous Forest (32.8%)	0.8	70
WH4	Wairua	543	2.36	A2	High-producing Grassland (57.6%)	0.7	402

[1]Land Environments of New Zealand (Leathwick, et al. 2003(b))

Table 4.2. Datasets used to prioritize headwater reaches for protection.				
Dataset	**Type (resolution)**	**Value Range**	**Description**	**Source**
Livestock Density	Raster (100 m)	0 - 186.69 su/ha	Units of livestock per hectare. Livestock categories included: dairy, beef, deer, and sheep.	Ausseil, et al. (2013)
Land Disturbance	Raster (463 m, 8-day)	0 - 95% of time	Describes how many 8-day periods from 2000-2013 each pixel was "disturbed" (devoid of vegetation).	de Beurs et al. (2016)
Terrain Gradient	Raster (15 m)	0 - 3752.09 m	Slope derived from a 15-m digital elevation model (DEM)	National Elevation Dataset (2014)
Land Cover	Feature (1 ha)	33 different classes	Nationwide land cover for 2012	Landcare Research (2015)

Table 4.2. Continued.				
Dataset	**Type (resolution)**	**Value Range**	**Description**	**Source**
Modeled Streams Network	Feature		Stream network delineated by employing a varying accumulation threshold model based on the physiographic characteristics of each stream segment.	Chapter 3

Figures

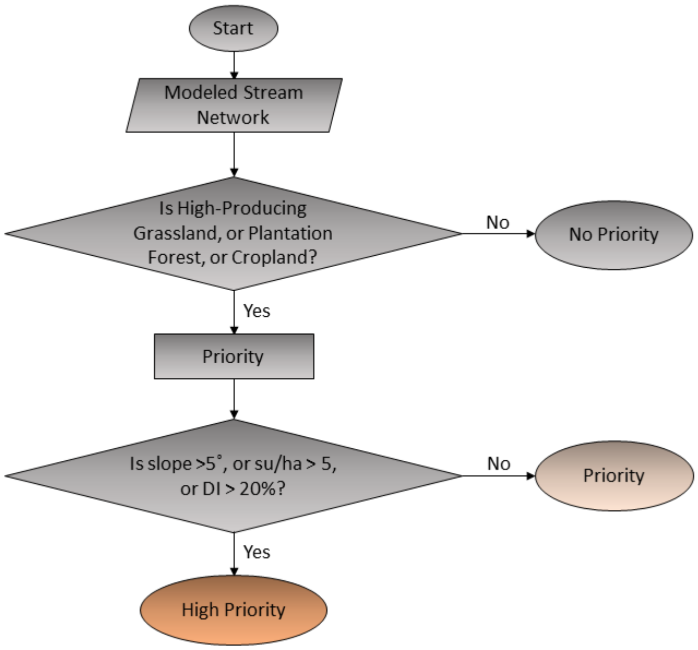

Figure 4.1. Conditional analysis flow chart showing No-Priority, Level 1 (Priority) and Level 2 (High-Priority) prioritization scheme.

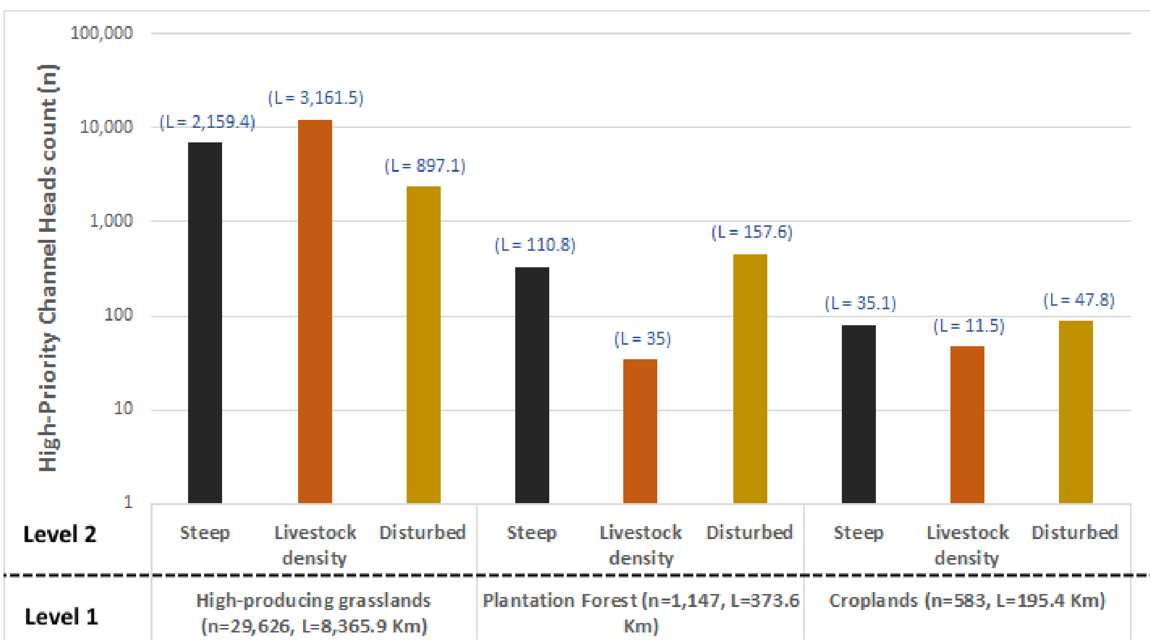

Figure 4.2. Results from the analysis showing the different levels of prioritization. Area below the dashed line summarizes Level 1 Priority channel heads count (n) and headwater stream length (L) of each land cover class. The bar plot shows the log of the Level 2 High-Priority channel heads count (y-axis) and headwater stream length (in km, blue). Level 2 classes: steep (slope >5˚); intensely managed (su/ha > 5); and disturbed (DI > 20%).

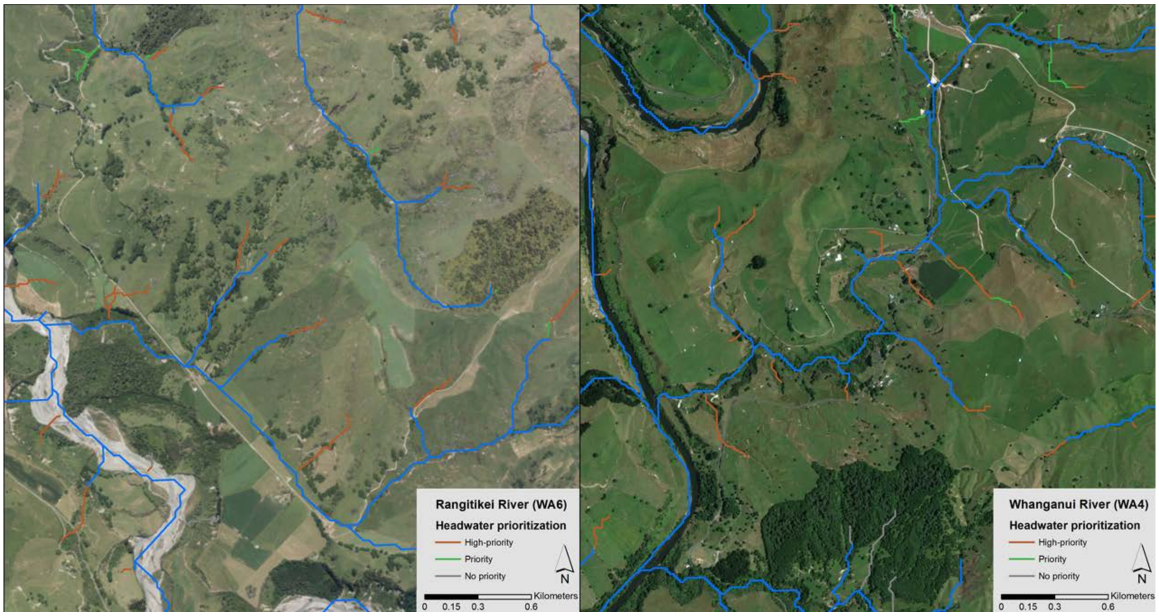

Figure 4.3. On the left, an example of steep slopes (>5˚) resulting in classification of these headwaters as high-priority. On the right, prioritization was dictated by high livestock density values (>5 SU/ha).

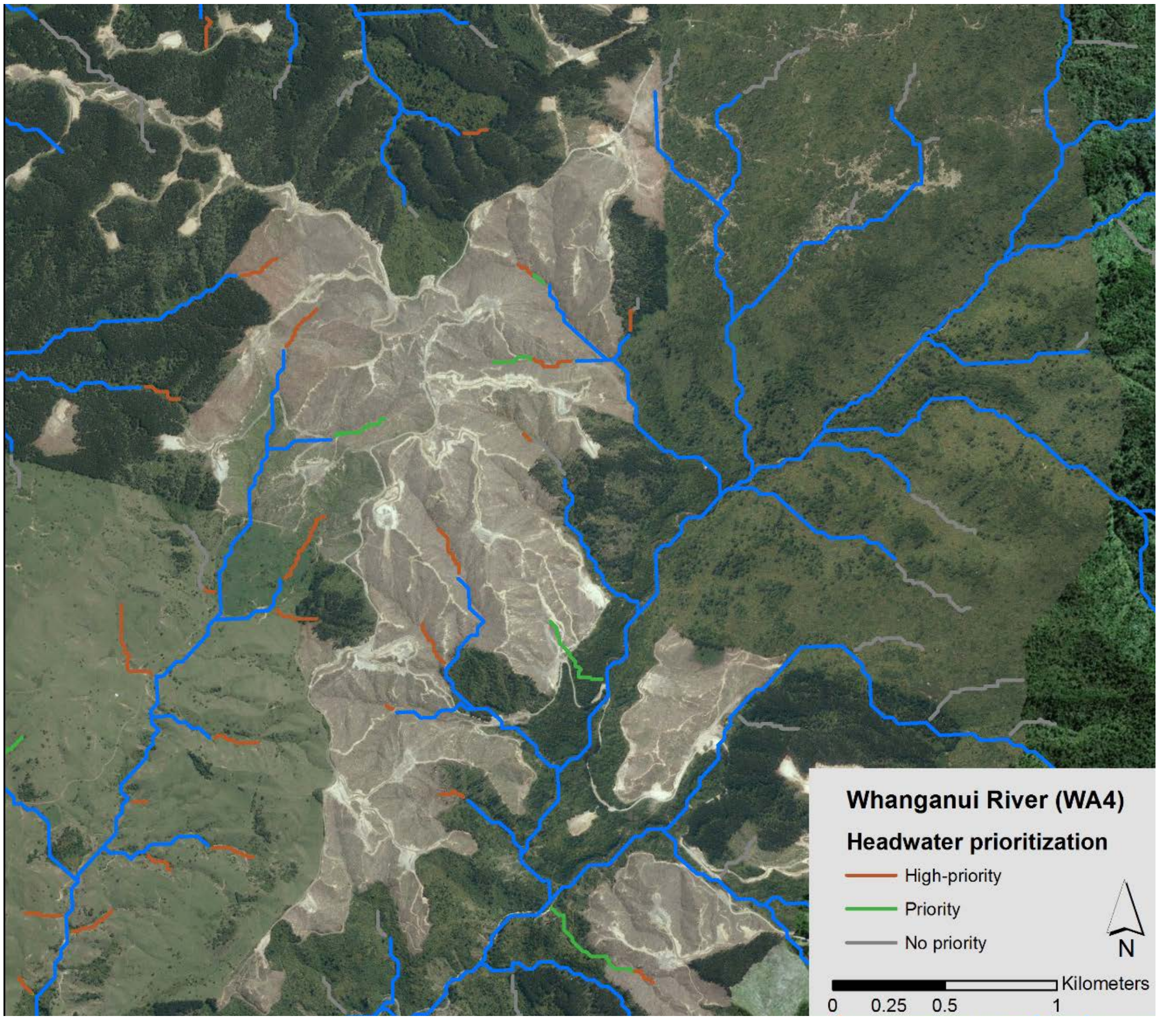

Figure 4.4. Recent forest harvest in Whanganui catchment.

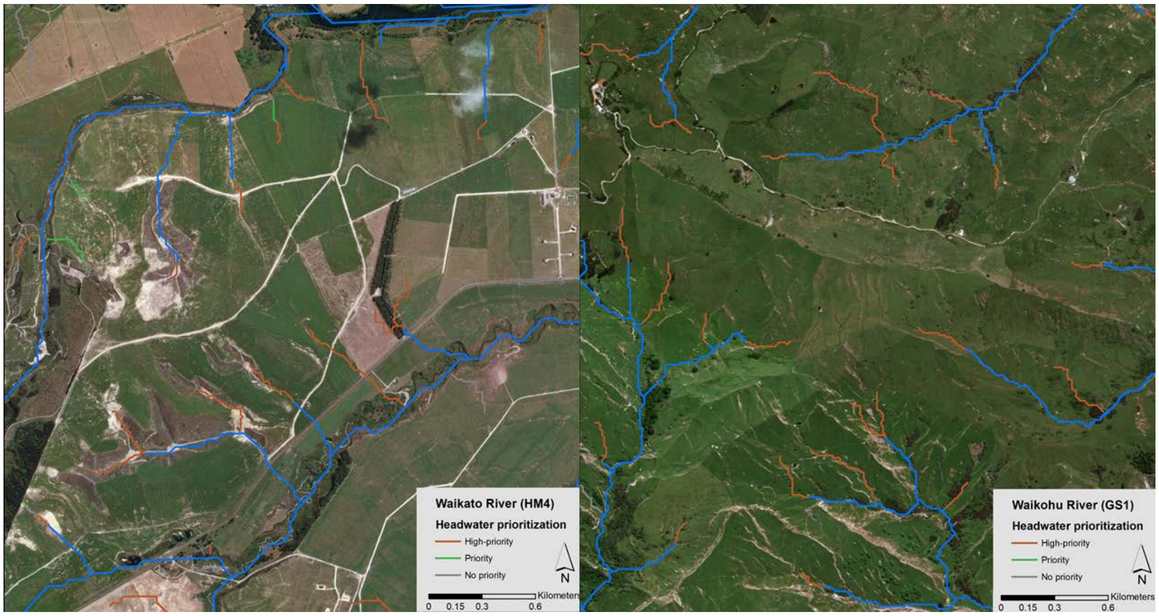

Figure 4.5. On the left, frequently disturbed land (DI>20%) caused channel heads to be labeled as high-priority. On the right, a combination of steep slopes, high stocking density and disturbed land resulted in high-priority channels.

5. CONCLUSIONS

The fundamental questions answered by this research were:

1. How do intense land uses—specifically livestock grazing and forest harvesting—affect temporal patterns of sediment runoff at the sub-catchment scale?
2. How can stream networks be accurately mapped across large, physiographically diverse landscapes?
3. Which headwaters should be prioritized for protection purposes of sediment conservation and enhanced river water quality?

These questions were addressed separately in individual chapters, with each Chapter answering questions that arose from the previous ones. Chapter 2 investigated the effects of land use on sediment runoff, but in the process, I came to the realization that in order to locate the critical source areas of sediment and their proximity to the stream network, I would need a stream network that not only captures mapped perennial streams, but also unmapped intermittent/ephemeral streams. This revelation led me to map all the headwaters of Hoteo catchment, producing a comprehensive and accurate hydrography dataset. In Chapter 3, I developed a more sophisticated methodology to create a nationwide hydrography dataset that accounts for physiographic diversity when modeling headwater stream locations, such that intermittent/ephemeral channels are captured. Last, in Chapter 4 I utilized the modeled stream network from Chapter 3 to locate and prioritize potential headwater locations for riparian protection applications in some of New Zealand's most sediment-impaired catchments.

Nonlinear Changes in the Relationship Between Land Disturbance and Sediment Runoff

Statistical analyses of multi-resolution datasets showed clear nonlinear changes in land disturbance, climate, and sediment runoff. The following processes occurring individually or concurrently were proposed to be affecting these relationships: (1) disturbed and connected areas are the sources of high sediment loadings, (2) readily available sediment is exhausted after floods (supply limitation), and (3) shifts between erosional and depositional processes across both space (along the channels) and time (between seasons). The in-channel sediment sources make Hoteo one of the most turbid rivers in New Zealand, but legacy effects from previous landscape disturbances also contribute sediment loads. Moreover, a novel disturbance index developed by de Beurs, Owsley, and Julian (2016) was useful in predicting stream water clarity changes in response to environmental changes. Land cover change analysis coupled with water quality analysis showed that forest harvested areas within the catchment are the dominant sources of sediment runoff until the forests recover, after which intensely-used grasslands resume the dominant role.

Channel Networks Within the Context of Physiographic Diversity

Using the stream delineation methodology with varying thresholds for different physiographic classes, I found that there were twice as many channel heads as previously captured by New Zealand's REC national hydrography dataset. Model validation, based on satellite/aerial imagery interpretation, showed that the model performed very well with the modeled channel heads being closer than the REC heads to the manually mapped channel heads. Moreover, drainage density increased by 36% and number of channel heads increased one-fold, on average, across the 77 NRWQN catchments. Last, the range of values of drainage density was wider, reflecting the contrast in environmental drivers among the different physiographic regions.

Headwater Prioritization for Riparian Buffering/Fencing

In Chapter 4, the hydrography dataset developed in the previous chapter was used to identify headwaters sensitive to increased sediment runoff. Combined with the use of livestock intensity, landscape disturbance, and slope layers, headwaters were prioritized in regard to applying BMP's to reduce sediment runoff entering the streams. The analysis was conducted on high-producing grasslands, croplands, and plantation forests; and only on that part of the modeled stream network that was not included in the REC under the assumption that REC streams are already protected. Results showed that there is a very high number of channel heads (>34,000) that should be prioritized for protection with a length of these headwater reaches totaling more than 8,000 km.

Validating the effects of headwater protection prioritization is extremely difficult and may take a long time to demonstrate effectiveness. In New Zealand, environmental policy, research funding, and performance assessments are developed over short periods, usually 5-year cycles. It is unlikely that dramatic improvements will take place over these time frames. Although we may not be able to prove if best management practices and restoration efforts actually improve stream health over observable time-scales, Chapter 2 showed us what does not work. The Hoteo River case-study demonstrated that by not protecting headwaters in intensively used areas, water quality degrades quickly and is difficult to remedy. Indeed, the Hoteo River is one of the most turbid and degraded rivers in all of New Zealand (Bernhardt, et al. 2005). This conclusion is corroborated by a recent study conducted on Kaipara Harbour which argued that despite the sediment erosion control measures taken, sediment runoff is still a significant issue for Hoteo (Green and Daigneault 2018).

Future Work and Broader Impact

Future work on Chapter 1 would include applying the methodology and lessons learned from the interactions between land use and river water quality to the entire 77 NRWQN catchments. Indeed, using a novel landscape disturbance dataset along with a vast suite of water quality variables, and applying the methods developed for assessing connectivity, could potentially lead to interesting findings related to terrain and climate heterogeneity that exist within and among these catchments. Hoteo, a small catchment compared to other NRWQN catchments, showed that sediment sources were located on the disturbed and connected areas (through connectivity analysis) and along the main river channel (through sediment budgets). However, other factors not present in Hoteo, such as differences in relief, geology, climate, and anthropogenic activity could potentially distort these nonlinear relationships, resulting in other linear and nonlinear linkages. Studies of sediment transport dynamics need to be conducted at catchment (and sometimes sub-catchment) extents across different temporal scales.

Sediment erosion control has been a focus of New Zeeland environmental policy for the last couple of decades, and riparian cattle fencing is usually the first line of defense for such efforts. However, uniformly applying these restrictions to only perennial streams using coarse criteria that do not take into consideration the variability in sediment sources will not likely yield significant water quality improvements. Thus, it is clear that the methods developed in Chapter 2 combined with the more accurate stream network developed in Chapter 3 could inform such policies to target areas of significant sediment production. Moreover, it can be more cost-effective to apply BMP's only where they are actually needed. For example, building standard-width riparian buffers along the entire perennial stream network could be costlier than building fewer wider buffer zones in specific locations that would intercept sediment runoff from critical source areas of sediment production.

Further, the benefits of such targeted conservation efforts may extend outside the boundaries of the catchment and can be multi-fold. Hoteo drains into the Kaipara Harbour, which is a valuable and sensitive estuarine ecosystem. It has been estimated that up to 70% of the sediment that ends up in Kaipara Harbour is due to agricultural practices on highly erodible lands, which may cost up to $331 million a year to remedy (Green and Daigneault 2018). The report also concludes that sources of sediment are split between land-based erosion and streambank erosion, which is in agreement with my findings in Chapter 2 (also Kamarinas, et al. (2016). However, they state that targeting mitigation is necessary and that further fine-grained analysis is required. The tools developed, data products, and findings from this dissertation are particularly useful for these types of environmental problems.

Once critical source areas of sediment are located, we can then prioritize the selection of areas for conservation by using the methodology developed in Chapter 4. An initial round of funding can be approved to target headwaters of High-Priority. This prioritization scheme can be also applied to perennial streams that have not been yet buffered/fenced. Results from first round of prioritization can then be assessed, and a second round of funding can be approved for areas labeled as Priority. As with the Kaipara Harbour example above, this dissertation shows that the path toward solving complex environmental problems requires a suite of geospatial data of multiple resolutions and analyses performed across multiple spatio-temporal scales.

APPENDIX

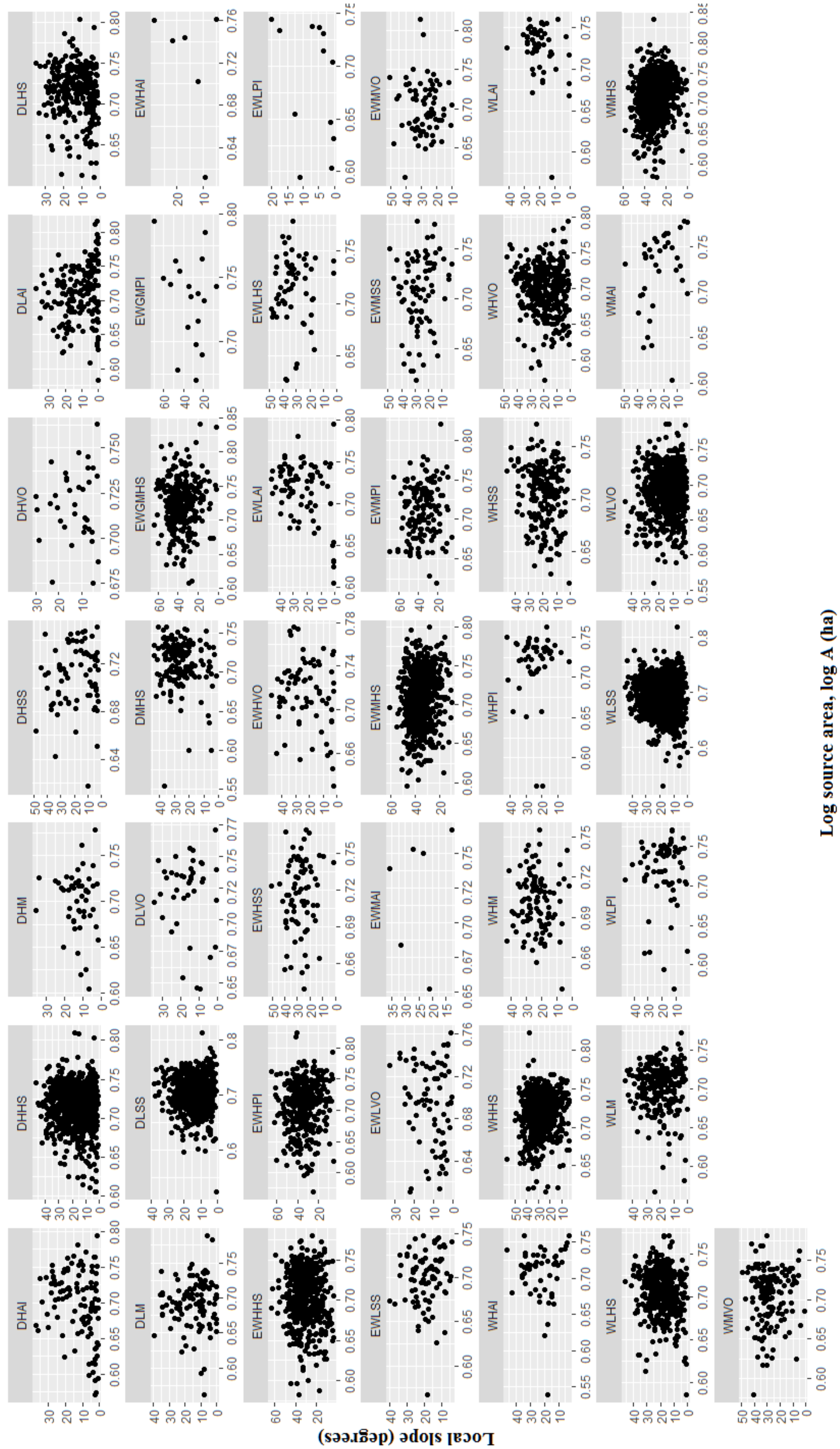

Figure 1. Local slope vs. Log source area plots for the 43 physiographic classes.

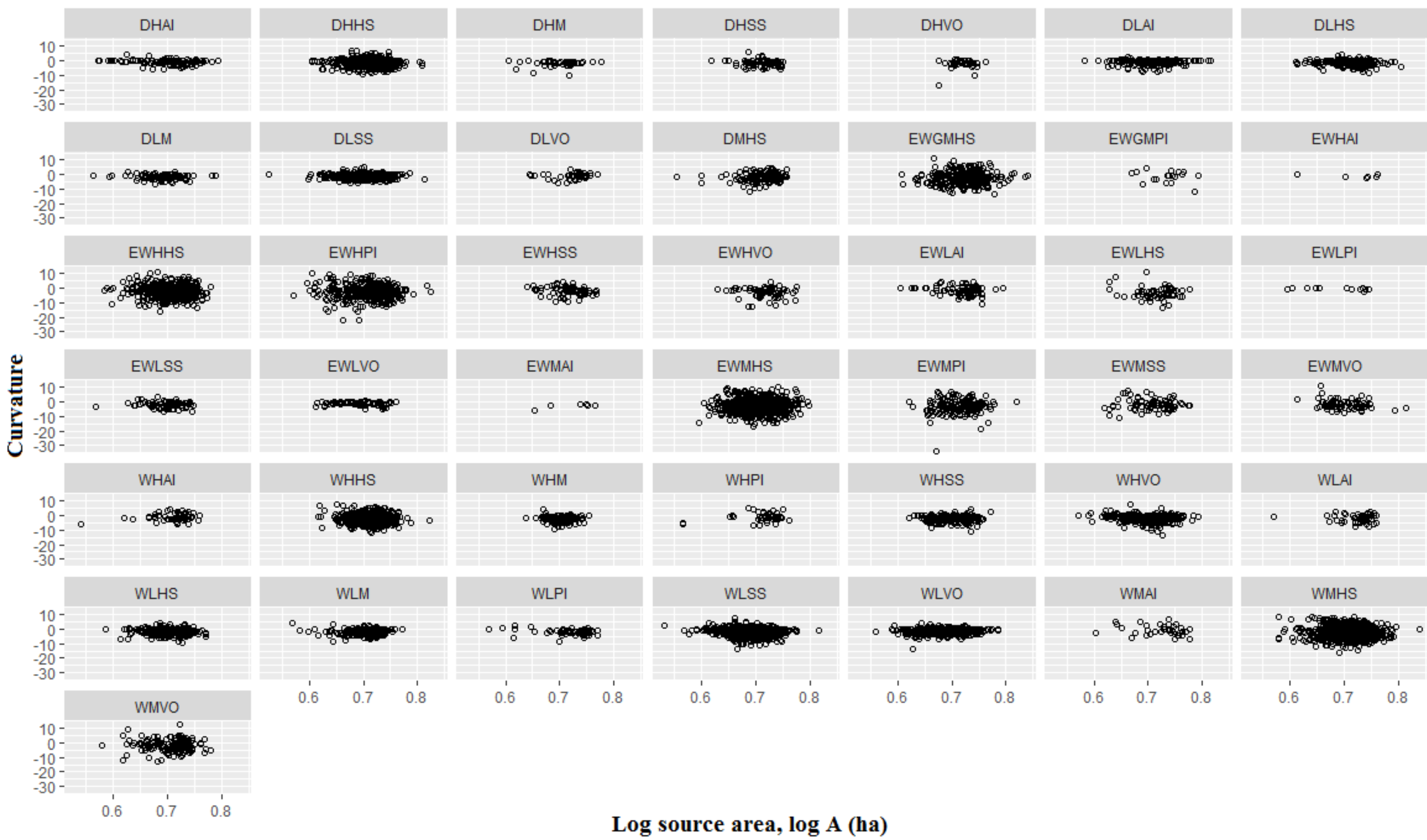

Figure 2. Curvature vs. Log source area plots for the 43 physiographic classes.

REFERENCES

Aarons, S. R., and C. JP. Gourley. 2013. "The Role of Riparian Buffer Management in Reducing Off-Site Impacts from Grazed Dairy Systems." *Renewable Agriculture and Food Systems* 28, no. 1: 1-16.

Abbott, S., J. P. Julian, I. Kamarinas, K. M. Meitzen, I. C. Fuller, S. T. McColl, and J. R. Dymond. 2018. "State-Shifting at the Edge of Resilience: River Suspended Sediment Responses to Land Use Change and Extreme Storms." *Geomorphology* 305 (2018/03/15/): 49-60. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2017.09.004.

Adhami, M., and S. H. Sadeghi. 2016. "Sub-Watershed Prioritization Based on Sediment Yield Using Game Theory." *Journal of Hydrology* 541 (2016/10/01/): 977-987. http://dx.doi.org/https://doi.org/10.1016/j.jhydrol.2016.08.008.

Ahearn, D. S., R. W. Sheibley, R. A. Dahlgren, M. Anderson, J. Johnson, and K. W. Tate. 2005. "Land Use and Land Cover Influence on Water Quality in the Last Free-Flowing River Draining the Western Sierra Nevada, California." *Journal of Hydrology* 313, no. 3-4 (Nov): 234-247. http://dx.doi.org/10.1016/j.jhydrol.2005.02.038.

Ajayi, O. G., A. A. Salubi, A. F. Angbas, and M. G. Odigure. 2017. "Generation of Accurate Digital Elevation Models from Uav Acquired Low Percentage Overlapping Images." *International Journal of Remote Sensing* 38, no. 8-10 (2017/05/19): 3113-3134. http://dx.doi.org/10.1080/01431161.2017.1285085.

Alexander, R. B., E. W. Boyer, R. A. Smith, G. E. Schwarz, and R. B. Moore. 2007. "The Role of Headwater Streams in Downstream Water Quality." *JAWRA Journal of the American Water Resources Association* 43, no. 1: 41-59. http://dx.doi.org/doi:10.1111/j.1752-1688.2007.00005.x.

Allan, J. D. 2004. "Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems." *Annual Review of Ecology Evolution and Systematics* 35: 257-284. http://dx.doi.org/10.1146/annurev.ecolsys.35.120202.110122.

ANZECC, ARMCANZ. 2000. "Australian and New Zealand Guidelines for Fresh and Marine Water Quality." *Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra*: 1-103.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. "Large Area Hydrologic Modeling and Assessment Part I: Model Development." *JAWRA Journal of the American Water Resources Association* 34, no. 1: 73-89. http://dx.doi.org/10.1111/j.1752-1688.1998.tb05961.x.

Ausseil, AG. E., J. R. Dymond, M. U. F. Kirschbaum, R. M. Andrew, and R. L. Parfitt. 2013. "Assessment of Multiple Ecosystem Services in New Zealand at the Catchment Scale." *Environmental Modelling & Software* 43 (2013/05/01/): 37-48. http://dx.doi.org/https://doi.org/10.1016/j.envsoft.2013.01.006.

Ayele, G. K., M. B. Addisie, E. J. Langendoen, N. H. Tegegne, S. A. Tilahun, M.A. Moges, C. F. Nicholson, and T. S. Steenhuis. 2018. "Evaluating Erosion Control Practices in an Actively Gullying Watershed in the Highlands of Ethiopia." *Earth Surface Processes and Landforms* 0, no. ja. http://dx.doi.org/doi:10.1002/esp.4436.

Baillie, B. R., and D. G. Neary. 2015. "Water Quality in New Zealand's Planted Forests: A Review." *New Zealand Journal of Forestry Science* 45 (May): 18. http://dx.doi.org/10.1186/s40490-015-0040-0.

Ballantine, D. J., and R. J. Davies-Colley. 2014. "Water Quality Trends in New Zealand Rivers: 1989–2009." *Environmental Monitoring and Assessment* 186, no. 3 (2014/03/01): 1939-1950. http://dx.doi.org/10.1007/s10661-013-3508-5.

Basher, L. R., D. M. Hicks, B. Clapp, and T. Hewitt. 2011. "Sediment Yield Response to Large Storm Events and Forest Harvesting, Motueka River, New Zealand." *New Zealand Journal of Marine and Freshwater Research* 45, no. 3 (2011/09/01): 333-356. http://dx.doi.org/10.1080/00288330.2011.570350.

Benda, L., M. A. Hassan, M. Church, and C. L. May. 2005. "Geomorphology of Steepland Headwaters: The Transition from Hillslopes to Channels." *Journal of the American Water Resources Association* 41, no. 4 (Aug): 835-851. <Go to ISI>://WOS:000231549900005.

Bernhardt, E. S., M. A. Palmer, J. D. Allan, G. Alexander, K. Barnas, S. Brooks, J. Carr, S. Clayton, C. Dahm, J. Follstad-Shah, D. Galat, S. Gloss, P. Goodwin, D. Hart, B. Hassett, R. Jenkinson, S. Katz, G. M. Kondolf, P. S. Lake, R. Lave, J. L. Meyer, T. K. O'Donnell, L. Pagano, B. Powell, and E. Sudduth. 2005. "Synthesizing U.S. River Restoration Efforts." *Science* 308, no. 5722: 636-637. http://dx.doi.org/10.1126/science.1109769.

Boesch, D. F. 2002. "Challenges and Opportunities for Science in Reducing Nutrient over-Enrichment of Coastal Ecosystems." *Estuaries* 25, no. 4 (August 01): 886-900. http://dx.doi.org/10.1007/bf02804914.

Borin, M., M. Vianello, F. Morari, and G. Zanin. 2005. "Effectiveness of Buffer Strips in Removing Pollutants in Runoff from a Cultivated Field in North-East Italy." *Agriculture, Ecosystems & Environment* 105, no. 1 (2005/01/01/): 101-114. http://dx.doi.org/https://doi.org/10.1016/j.agee.2004.05.011.

Brosse, S., C. J. Arbuckle, and C. R. Townsend. 2003. "Habitat Scale and Biodiversity: Influence of Catchment, Stream Reach and Bedform Scales on Local Invertebrate Diversity." *Biodiversity & Conservation* 12, no. 10 (October 01): 2057-2075. http://dx.doi.org/10.1023/a:1024107915183.

Campbell, A. 2002. *Clean Streams: A Water Body Enhancement Strategy for Environment Waikato*. Hamilton East: Environment Waikato.

Clinton, B. D. 2011. "Stream Water Responses to Timber Harvest: Riparian Buffer Width Effectiveness." *Forest Ecology and Management* 261, no. 6 (Mar): 979-988. http://dx.doi.org/10.1016/j.foreco.2010.12.012.

Clubb, F. J., S. M. Mudd, D. T. Milodowski, M. D. Hurst, and L. J. Slater. 2014. "Objective Extraction of Channel Heads from High-Resolution Topographic Data." *Water Resources Research* 50, no. 5: 4283-4304. http://dx.doi.org/doi:10.1002/2013WR015167.

Colson, T., J. Gregory, J. Dorney, and P. Russell. 2008. *Topographic and Soil Maps Do Not Accurately Depict Headwater Stream Networks*. Vol. 30, National Wetlands Newsletter.

Cooper, J. R., J. W. Gilliam, R. B. Daniels, and W. P. Robarge. 1987. "Riparian Areas as Filters for Agricultural Sediment." *Soil Science Society of America Journal* 51, no. 2 (Mar-Apr): 416-420. <Go to ISI>://WOS:A1987H024500029.

Council, Horizons Regional. 2014. *One Plan*. *Manawaru-Wanganui Regional Council*.

Czuba, J. A., and E. Foufoula-Georgiou. 2015. "Dynamic Connectivity in a Fluvial Network for Identifying Hotspots of Geomorphic Change." *Water Resources Research* 51, no. 3: 1401-1421. http://dx.doi.org/10.1002/2014WR016139.

DairyNZ. 2017. *Sustainable Dairying Water Accord: Three Years On...* Hamilton, NZ.

Davies-Colley, R. J., D. G. Smith, R. C. Ward, G. G. Bryers, G. B. McBride, J. M. Quinn, and M. R. Scarsbrook. 2011. "Twenty Years of New Zealand's National Rivers Water Quality Network: Benefits of Careful Design and Consistent Operation." *JAWRA Journal of the American Water Resources Association* 47, no. 4: 750-771. http://dx.doi.org/10.1111/j.1752-1688.2011.00554.x.

de Beurs, K. M., B. C. Owsley, and J. P. Julian. 2016. "Disturbance Analyses of Forests and Grasslands with Modis and Landsat in New Zealand." *International Journal of Applied Earth Observation and Geoinformation* 45, Part A (3//): 42-54. http://dx.doi.org/http://dx.doi.org/10.1016/j.jag.2015.10.009.

de Vente, J., and J. Poesen. 2005. "Predicting Soil Erosion and Sediment Yield at the Basin Scale: Scale Issues and Semi-Quantitative Models." *Earth-Science Reviews* 71, no. 1 (2005/06/01/): 95-125. http://dx.doi.org/https://doi.org/10.1016/j.earscirev.2005.02.002.

Degetto, M., C. Gregoretti, and M. Bernard. 2015. "Comparative Analysis of the Differences between Using Lidar and Contour-Based Dems for Hydrological Generating Debris Flows in the Dolomites." *Frontiers in Earth Science* 3: 15. http://dx.doi.org/10.3389/feart.2015.00021.

Dietrich, W.E., and T. Dunne. 1993. "The Channel Head." In *Channel Network Hydrology*, edited by K.J. Beven, Kirkby, M.J. , 175-219. Chichester, UK: John Wiley & Sons.

Dillaha, T. A., J. H. Sherrard, D. Lee, S. Mostaghimi, and V. O. Shanholtz. 1988. "Evaluation of Vegetative Filter Strips as a Best Management Practice for Feed Lots." *Journal (Water Pollution Control Federation)* 60, no. 7: 1231-1238. http://www.jstor.org/stable/25043629.

Dodds, W. K., and R. M. Oakes. 2008. "Headwater Influences on Downstream Water Quality." *Environmental Management* 41, no. 3 (March 01): 367-377. http://dx.doi.org/10.1007/s00267-007-9033-y.

Dosskey, M. G., D. E. Eisenhauer, and M. J. Helmers. 2005. "Establishing Conservation Buffers Using Precision Information." *Journal of Soil and Water Conservation* 60, no. 6 (Nov-Dec): 349-354. <Go to ISI>://WOS:000233893300016.

Elmore, A. J., J. P. Julian, S. M. Guinn, and M. C. Fitzpatrick. 2013. "Potential Stream Density in Mid-Atlantic U.S. Watersheds." *PLoS ONE* 8, no. 8: e74819. http://dx.doi.org/10.1371/journal.pone.0074819.

Elmore, A. J., and S. S. Kaushal. 2008. "Disappearing Headwaters: Patterns of Stream Burial Due to Urbanization." *Frontiers in Ecology and the Environment* 6, no. 6 (Aug): 308-312. http://dx.doi.org/10.1890/070101.

Fenemor, A., R. G. Young, B. Bowden, C. Phillips, and W. Allen. 2011. "Integrated Catchment Management—a Decade of Research in the Motueka River Catchment." *New Zealand Journal of Marine and Freshwater Research* 45, no. 3 (2011/09/01): 307-311. http://dx.doi.org/10.1080/00288330.2011.593183.

Feng, H., L. A. Kurkalova, C. L. Kling, and P. W. Gassman. 2006. "Environmental Conservation in Agriculture: Land Retirement Vs. Changing Practices on Working Land." *Journal of Environmental Economics and Management* 52, no. 2 (2006/09/01/): 600-614. http://dx.doi.org/https://doi.org/10.1016/j.jeem.2006.03.004.

Fischer, R. A., and J. C. Fischenich. 2000. *Design Recommendations for Riparian Corridors and Vegetated Buffer Strips*: DTIC Document.

Foley, J. A., R. DeFries, G. P. Asner, C. Barford, G. B. Bonan, S. R. Carpenter, F. S. Chapin, M.T. Coe, G. C. Daily, H. K. Gibbs, J. H. Helkowski, T. Holloway, E. A. Howard, C. J. Kucharik, C. Monfreda, J. A. Patz, I. C. Prentice, N. Ramankutty, and P. K. Snyder. 2005. "Global Consequences of Land Use." *Science* 309, no. 5734 (July 22, 2005): 570-574. http://dx.doi.org/10.1126/science.1111772.

Fritz, K. M., E. Hagenbuch, E. D'Amico, M. Reif, P. J. Wigington, S. G. Leibowitz, R. L. Comeleo, J. L. Ebersole, and T. L. Nadeau. 2013. "Comparing the Extent and Permanence of Headwater Streams from Two Field Surveys to Values from Hydrographic Databases and Maps." *JAWRA Journal of the American Water Resources Association* 49, no. 4 (2013/08/01): 867-882. Accessed 2018/05/18. http://dx.doi.org/10.1111/jawr.12040.

Fuller, I. C. 2008. "Geomorphic Impacts of a 100-Year Flood: Kiwitea Stream, Manawatu Catchment, New Zealand." *Geomorphology* 98, no. 1 (2008/06/01/): 84-95. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2007.02.026.

Garrett, K., and E. Wohl. 2017. "Climate-Invariant Area–Slope Relations in Channel Heads Initiated by Surface Runoff." *Earth Surface Processes and Landforms* 42, no. 11: 1745-1751. http://dx.doi.org/doi:10.1002/esp.4148.

Glade, T. 2003. "Landslide Occurrence as a Response to Land Use Change: A Review of Evidence from New Zealand." *CATENA* 51, no. 3–4 (4/1/): 297-314. http://dx.doi.org/http://dx.doi.org/10.1016/S0341-8162(02)00170-4.

Gomez, B., K. Banbury, M. Marden, N. A. Trustrum, D.H. Peacock, and P. J. Hoskin. 2003. "Gully Erosion and Sediment Production: Te Weraroa Stream, New Zealand." *Water Resources Research* 39, no. 7. http://dx.doi.org/doi:10.1029/2002WR001342.

Gomi, T., R. C. Sidle, and J. S. Richardson. 2002. "Understanding Processes and Downstream Linkages of Headwater Systems." *BioScience* 52, no. 10: 905-916. http://dx.doi.org/10.1641/0006-3568(2002)052[0905:UPADLO]2.0.CO;2.

Green, M. O., and A. Daigneault. 2018. *Kaipara Harbour Sediment Mitigation Study: Summary*. Hamilton, New Zealand: Streamlined Environmental.

Haan, M. M., J. R. Russell, W. J. Powers, J. L. Kovar, and J. L. Benning. 2006. "Grazing Management Effects on Sediment and Phosphorus in Surface Runoff." *Rangeland Ecology & Management* 59, no. 6 (Nov): 607-615. http://dx.doi.org/10.2111/05-152r2.1.

Hambling, R. 2008. "Gully Erosion and Sediment Load: Waipaoa, Waiapu and Uawa Rivers, Eastern North Island, New Zealand." *Sediment dynamics in changing environments*, no. 325: 339.

Hansen, W. F. 2001. "Identifying Stream Types and Management Implications." *Forest Ecology and Management* 143, no. 1 (2001/04/01/): 39-46. http://dx.doi.org/https://doi.org/10.1016/S0378-1127(00)00503-X.

Heine, R. A., C. L. Lant, and R. R. Sengupta. 2004. "Development and Comparison of Approaches for Automated Mapping of Stream Channel Networks." *Annals of the Association of American Geographers* 94, no. 3: 477-490. http://dx.doi.org/doi:10.1111/j.1467-8306.2004.00409.x.

Henkle, J. E., E. Wohl, and N. Beckman. 2011. "Locations of Channel Heads in the Semiarid Colorado Front Range, USA." *Geomorphology* 129, no. 3-4 (Jun): 309-319. http://dx.doi.org/10.1016/j.geomorph.2011.02.026.

Hruby, T., W. E. Cesanek, and K. E. Miller. 1995. "Estimating Relative Wetland Values for Regional Planning." *Wetlands* 15, no. 2 (June 01): 93-107. http://dx.doi.org/10.1007/bf03160663.

Hughes, A. O. 2016. "Riparian Management and Stream Bank Erosion in New Zealand." *New Zealand Journal of Marine and Freshwater Research* 50, no. 2 (2016/04/02): 277-290. http://dx.doi.org/10.1080/00288330.2015.1116449.

Jaeger, K. L., D. R. Montgomery, and S. M. Bolton. 2007. "Channel and Perennial Flow Initiation in Headwater Streams: Management Implications of Variability in Source-Area Size." *Environmental Management* 40, no. 5 (Nov): 775-786. http://dx.doi.org/10.1007/s00267-005-0311-2.

James, L. A., D. G. Watson, and W. F. Hansen. 2007. "Using Lidar Data to Map Gullies and Headwater Streams under Forest Canopy: South Carolina, USA." *CATENA* 71, no. 1 (2007/09/01/): 132-144. http://dx.doi.org/https://doi.org/10.1016/j.catena.2006.10.010.

Jang, T., G. Vellidis, J. B. Hyman, E. Brooks, L. A. Kurkalova, J. Boll, and J. Cho. 2013. "Model for Prioritizing Best Management Practice Implementation: Sediment Load Reduction." *Environmental Management* 51, no. 1 (January 01): 209-224. http://dx.doi.org/10.1007/s00267-012-9977-4.

Javernick, L., D. M. Hicks, R. Measures, B. Caruso, and J. Brasington. 2016. "Numerical Modelling of Braided Rivers with Structure-from-Motion-Derived Terrain Models." *River Research and Applications* 32, no. 5 (Jun): 1071-1081. http://dx.doi.org/10.1002/rra.2918.

Julian, J. P. 2018. *In Review. Channel Heads*. *Reference Module in Earth Systems and Environmental Sciences*: Elsevier.

Julian, J. P., K. M. de Beurs, B. Owsley, R. J. Davies-Colley, and AG. E. Ausseil. 2017. "River Water Quality Changes in New Zealand over 26 Years: Response to Land Use Intensity." *Hydrology and Earth System Sciences* 21, no. 2: 1149.

Julian, J. P., A. J. Elmore, and S. M. Guinn. 2012. "Channel Head Locations in Forested Watersheds across the Mid-Atlantic United States: A Physiographic Analysis." *Geomorphology* 177–178, no. 0 (12/1/): 194-203. http://dx.doi.org/http://dx.doi.org/10.1016/j.geomorph.2012.07.029.

Julian, J. P., E. H. Stanley, and M. W. Doyle. 2008. "Basin-Scale Consequences of Agricultural Land Use on Benthic Light Availability and Primary Production Along a Sixth-Order Temperate River." *Ecosystems* 11, no. 7 (2008/11/01): 1091-1105. http://dx.doi.org/10.1007/s10021-008-9181-9.

Kamarinas, I., J. P. Julian, A. O. Hughes, B. Owsley, and K. M. de Beurs. 2016. "Nonlinear Changes in Land Cover and Sediment Runoff in a New Zealand Catchment Dominated by Plantation Forestry and Livestock Grazing." *Water* 8, no. 10: 436. http://www.mdpi.com/2073-4441/8/10/436.

Kasai, M., G. J. Brierley, M. J. Page, T. Marutani, and N. A. Trustrum. 2005. "Impacts of Land Use Change on Patterns of Sediment Flux in Weraamaia Catchment, New Zealand." *CATENA* 64, no. 1 (2005/11/30/): 27-60. http://dx.doi.org/https://doi.org/10.1016/j.catena.2005.06.014.

Kilroy, C., T. H. Snelder, O. Floerl, C. C. Vieglais, and K. L. Dey. 2008. "A Rapid Technique for Assessing the Suitability of Areas for Invasive Species Applied to New Zealand's Rivers." *Diversity and Distributions* 14, no. 2: 262-272. http://dx.doi.org/doi:10.1111/j.1472-4642.2007.00406.x.

Knox, J. C. 1972. "Valley Alluviation in Southwestern Wisconsin." *Annals of the Association of American Geographers* 62, no. 3: 401-410. http://dx.doi.org/10.1111/j.1467-8306.1972.tb00872.x.

Korup, O. 2005. "Large Landslides and Their Effect on Sediment Flux in South Westland, New Zealand." *Earth Surface Processes and Landforms* 30, no. 3: 305-323.

Kreutzweiser, D. P., and S. S. Capell. 2001. "Fine Sediment Deposition in Streams after Selective Forest Harvesting without Riparian Buffers." *Canadian Journal of Forest Research* 31, no. 12 (2001/12/01): 2134-2142. Accessed 2018/06/18. http://dx.doi.org/10.1139/x01-155.

Kronvang, B., H. E. Andersen, C. Børgesen, T. Dalgaard, S. E. Larsen, J. Bøgestrand, and G. Blicher-Mathiasen. 2008. "Effects of Policy Measures Implemented in Denmark on Nitrogen Pollution of the Aquatic Environment." *Environmental Science & Policy* 11, no. 2 (2008/04/01/): 144-152. http://dx.doi.org/https://doi.org/10.1016/j.envsci.2007.10.007.

Leathwick, J. R., G. Wilson, D. Rutledge, P. Wardle, F. Morgan, K. Johnston, M. MdLeod, and R. Kirkpatrick. 2003(b). *Land Environments of New Zealand*. Auckland: David Bateman.

Lee, K. H., T. M. Isenhart, and R. C. Schultz. 2003. "Sediment and Nutrient Removal in an Established Multi-Species Riparian Buffer." *Journal of Soil and Water Conservation* 58, no. 1 (January 1, 2003): 1-8. http://www.jswconline.org/content/58/1/1.abstract.

Lena, B. M. Vought, Jonas Dahl, Pedersen Carsten Lauge, O. Lacoursi Jean, xe, and re. 1994. "Nutrient Retention in Riparian Ecotones." *Ambio* 23, no. 6: 342-348. http://www.jstor.org/stable/4314234.

Lowrance, R., L. S. Altier, J. D. Newbold, R. R. Schnabel, P. M. Groffman, J. M. Denver, D. L. Correll, J. W. Gilliam, J. L. Robinson, R. B. Brinsfield, K. W. Staver, W. Lucas, and A. H. Todd. 1997. "Water Quality Functions of Riparian Forest Buffers in Chesapeake Bay Watersheds." *Environmental Management* 21, no. 5 (Sep-Oct): 687-712. http://dx.doi.org/10.1007/s002679900060.

Machado, E. A., D. M. Stoms, F. W. Davis, and J. Kreitler. 2006. "Prioritizing Farmland Preservation Cost-Effectively for Multiple Objectives." *Journal of soil and water conservation* 61, no. 5: 250-258.

Mankin, K. R., D. M. Ngandu, C. J. Barden, S. L. Hutchinson, and W. A. Geyer. 2007. "Grass-Shrub Riparian Buffer Removal of Sediment, Phosphorus, and Nitrogen from Simulated Runoff." *JAWRA Journal of the American Water Resources Association* 43, no. 5 (2007/10/01): 1108-1116. Accessed 2018/06/12. http://dx.doi.org/10.1111/j.1752-1688.2007.00090.x.

Marden, M. 2011. *Sedimentation History of Waipaoa Catchment*. Gisborn: Landcare Research.

Marden, M., G. Arnold, B. Gomez, and D. Rowan. 2005. "Pre- and Post-Reforestation Gully Development in Mangatu Forest, East Coast, North Island, New Zealand." *River Research and Applications* 21, no. 7: 757-771. http://dx.doi.org/doi:10.1002/rra.882.

Martin-Mikle, C. J., K. M. de Beurs, J. P. Julian, and P. M. Mayer. 2015. "Identifying Priority Sites for Low Impact Development (Lid) in a Mixed-Use Watershed." *Landscape and Urban Planning* 140 (8//): 29-41. http://dx.doi.org/http://dx.doi.org/10.1016/j.landurbplan.2015.04.002.

McDowell, R. W. 2006. "Phosphorus and Sediment Loss in a Catchment with Winter Forage Grazing Off Cropland by Dairy Cattle." *Journal of Environmental Quality* 35, no. 2 (Mar-Apr): 575-583. http://dx.doi.org/10.2134/jeq2005.0364.

McGlynn, B. L., and J. Seibert. 2003. "Distributed Assessment of Contributing Area and Riparian Buffering Along Stream Networks." *Water Resources Research* 39, no. 4 (Apr): 7. http://dx.doi.org/10.1029/2002wr001521.

McKergow, L. A., F. E. Matheson, and J. M. Quinn. 2016. "Riparian Management: A Restoration Tool for New Zealand Streams." *Ecological Management & Restoration* 17, no. 3: 218-227. http://dx.doi.org/doi:10.1111/emr.12232.

Meyer, J. L., D. L. Strayer, J. B. Wallace, S. L. Eggert, G. S. Helfman, and N. E. Leonard. 2007. "The Contribution of Headwater Streams to Biodiversity in River Networks." *JAWRA Journal of the American Water Resources Association* 43, no. 1: 86-103. http://dx.doi.org/doi:10.1111/j.1752-1688.2007.00008.x.

Monaghan, R. M., R. J. Wilcock, L. C. Smith, B. Tikkisetty, B. S. Thorrold, and D. Costall. 2007. "Linkages between Land Management Activities and Water Quality in an Intensively Farmed Catchment in Southern New Zealand." *Agriculture Ecosystems & Environment* 118, no. 1-4 (Jan): 211-222. http://dx.doi.org/10.1016/j.agee.2006.05.016.

Montgomery, D. R. 1993. "Channel Network Source Representation Using Digital Elevation Models." *Water Resources Research* 29, no. 12: 3925-3934. http://dx.doi.org/doi:10.1029/93WR02463.

Montgomery, D. R., and W. E. Dietrich. 1992. "Channel Initiation and the Problem of Landscape Scale." *Science* 255, no. 5046 (Feb): 826-830. http://dx.doi.org/10.1126/science.255.5046.826.

Montgomery, D. R., and E. Foufoula-Georgiou. 1993. "Channel Network Source Representation Using Digital Elevation Models." *Water Resources Research* 29, no. 12: 3925-3934. http://dx.doi.org/10.1029/93WR02463.

Murphy, P. N. C., J. Ogilvie, FR. Meng, and P. Arp. 2008. "Stream Network Modelling Using Lidar and Photogrammetric Digital Elevation Models: A Comparison and Field Verification." *Hydrological Processes* 22, no. 12: 1747-1754. http://dx.doi.org/doi:10.1002/hyp.6770.

Murray, H. D., U. Shankar, A. I. McKerchar, L. Basher, I. Lynn, M. Page, and M. Jessen. 2011. "Suspended Sediment Yields from New Zealand Rivers." *Journal of Hydrology (00221708)* 50, no. 1: 81-142. http://libproxy.txstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=64840555&site=ehost-live.

Nellesen, S. L., J. L. Kovar, M. M. Haan, and J. R. Russell. 2011. "Grazing Management Effects on Stream Bank Erosion and Phosphorus Delivery to a Pasture Stream." *Canadian Journal of Soil Science* 91, no. 3 (Jun): 385-395. http://dx.doi.org/10.4141/cjss10006.

New Zealand Land Cover Database. 2015. Landcare Research (LCR).

Orlandini, S., P. Tarolli, G. Moretti, and F. G. Dalla. 2011. "On the Prediction of Channel Heads in a Complex Alpine Terrain Using Gridded Elevation Data." *Water Resources Research* 47, no. 2. http://dx.doi.org/doi:10.1029/2010WR009648.

Parkyn, S. M., R. J. Davies-Colley, M. R. Scarsbrook, N. J. Halliday, J. W. Nagels, M. Marden, and D. Rowan. 2006. "Pine Afforestation and Stream Health: A Comparison of Land-Use in Two Soft Rock Catchments, East Cape, New Zealand." *New Zealand Natural Sciences* 31 (2006): 113-135. <Go to ISI>://BCI:BCI200700389108.

Poppenga, S. K., D. B. Gesch, and B. B. Worstell. 2013. "Hydrography Change Detection: The Usefulness of Surface Channels Derived from Lidar Dems for Updating Mapped Hydrography." *JAWRA Journal of the American Water Resources Association* 49, no. 2: 371-389. http://dx.doi.org/doi:10.1111/jawr.12027.

Quinn, J. M., A. B. Cooper, R. J. Davies-Colley, J. C. Rutherford, and R. B. Williamson. 1997. "Land Use Effects on Habitat, Water Quality, Periphyton, and Benthic Invertebrates in Waikato, New Zealand, Hill-Country Streams." *New Zealand Journal of Marine and Freshwater Research* 31, no. 5 (1997/12/01): 579-597. http://dx.doi.org/10.1080/00288330.1997.9516791.

R Development Core Team. 2013. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing.

Salinger, M. J. 1979. "New Zealand Climate: The Temperature Record, Historical Data and Some Agricultural Implications." *Climatic Change* 2, no. 2 (June 01): 109-126. http://dx.doi.org/10.1007/bf00133218.

Saunders, D. L., J. J. Meeuwig, and A. C. J. Vincent. 2002. "Freshwater Protected Areas: Strategies for Conservation." *Conservation Biology* 16, no. 1: 30-41. http://dx.doi.org/doi:10.1046/j.1523-1739.2002.99562.x.

Schoonover, J. E., K. W. J. Williard, J. J. Zaczek, J. C. Mangun, and A. D. Carver. 2006. "Agricultural Sediment Reduction by Giant Cane and Forest Riparian Buffers." *Water, Air, and Soil Pollution* 169, no. 1 (January 01): 303-315. http://dx.doi.org/10.1007/s11270-006-3111-2.

Snelder, T. H., F. Cattanéo, A.M. Suren, and B. J. F. Biggs. 2004. "Is the River Environment Classification an Improved Landscape-Scale Classification of Rivers?" *Journal of the North American Benthological Society* 23, no. 3 (2004/09/01): 580-598. Accessed 2016/03/10. http://dx.doi.org/10.1899/0887-3593(2004)023<0580:ITRECA>2.0.CO;2.

Stott, T., and N. Mount. 2004. "Plantation Forestry Impacts on Sediment Yields and Downstream Channel Dynamics in the Uk: A Review." *Progress in Physical Geography: Earth and Environment* 28, no. 2: 197-240. http://dx.doi.org/10.1191/0309133304pp410ra.

Sutfin, N. A., J. R. Shaw, E. Wohl, and D. J. Cooper. 2014. "A Geomorphic Classification of Ephemeral Channels in a Mountainous, Arid Region, Southwestern Arizona, USA." *Geomorphology* 221 (2014/09/15/): 164-175. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2014.06.005.

Sutfin, Nicholas A., Jeremy R. Shaw, Ellen E. Wohl, and David J. Cooper. 2014. "A Geomorphic Classification of Ephemeral Channels in a Mountainous, Arid Region, Southwestern Arizona, USA." *Geomorphology* 221 (2014/09/15/): 164-175. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2014.06.005.

Sweeney, B.W., and J. D. Newbold. 2014. "Streamside Forest Buffer Width Needed to Protect Stream Water Quality, Habitat, and Organisms: A Literature Review." *JAWRA Journal of the American Water Resources Association* 50, no. 3: 560-584. http://dx.doi.org/doi:10.1111/jawr.12203.

Tarolli, P. 2014. "High-Resolution Topography for Understanding Earth Surface Processes: Opportunities and Challenges." *Geomorphology* 216 (2014/07/01/): 295-312. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2014.03.008.

Tate, K. W., G. A. Nader, D. J. Lewis, E. R. Atwill, and J. M. Connor. 2000. "Evaluation of Buffers to Improve the Quality of Runoff from Irrigated Pastures." *Journal of Soil and Water Conservation* 55, no. 4 (2000): 473-478. <Go to ISI>://WOS:000166458600009.

Tomer, M. D., D. E. James, and T. M. Isenhart. 2003. "Optimizing the Placement of Riparian Practices in a Watershed Using Terrain Analysis." *Journal of Soil and Water Conservation* 58, no. 4: 198-206.

Tucker, G. E. 1998. "Hillslope Processes, Drainage Density, and Landscape Morphology." *Water Resources Research* 34, no. 10: 2751-2764. http://dx.doi.org/doi:10.1029/98WR01474.

Turner, R. E., and N. N. Rabalais. 2003. "Linking Landscape and Water Quality in the Mississippi River Basin for 200 Years." *BioScience* 53, no. 6 (06//): 563. http://libproxy.txstate.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=syh&AN=9988980&site=ehost-live.

Vianello, A., M. Cavalli, and P. Tarolli. 2009. "Lidar-Derived Slopes for Headwater Channel Network Analysis." *CATENA* 76, no. 2 (2009/01/15/): 97-106. http://dx.doi.org/https://doi.org/10.1016/j.catena.2008.09.012.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. "Human Domination of Earth's Ecosystems." *Science* 277, no. 5325 (July 25, 1997): 494-499. http://dx.doi.org/10.1126/science.277.5325.494.

Vörösmarty, C. J., P. B. McIntyre, M. O. Gessner, D. Dudgeon, A. Prusevich, P. Green, S. Glidden, S. E. Bunn, C. A. Sullivan, C. Reidy Liermann, and P. M. Davies. 2010. "Global Threats to Human Water Security and River Biodiversity." *Nature* 467 (09/29/online): 555. http://dx.doi.org/10.1038/nature09440

https://www.nature.com/articles/nature09440#supplementary-information.

Webber, D. F., S. K. Mickelson, S. I. Ahmed, J. R. Russell, W. J. Powers, R. C. Schultz, and J. L. Kovar. 2010. "Livestock Grazing and Vegetative Filter Strip Buffer Effects on Runoff Sediment, Nitrate, and Phosphorus Losses." *Journal of Soil and Water Conservation* 65, no. 1 (Jan-Feb): 34-41. http://dx.doi.org/10.2489/jswc.65.1.34.

Weeks, E., O. Jmc, and S. Walker. 2012. *Estimating Patterns of Vulnerability in a Changing Landscape: A Case Study of New Zealand's Indigenous Grasslands*. Vol. 40.

Williams, M. R., S. Filoso, B. J. Longstaff, and W. C. Dennison. 2010. "Long-Term Trends of Water Quality and Biotic Metrics in Chesapeake Bay: 1986 to 2008." *Estuaries and Coasts* 33, no. 6 (November 01): 1279-1299. http://dx.doi.org/10.1007/s12237-010-9333-y.

Wipfli, M. S., J. S. Richardson, and R. J. Naiman. 2007. "Ecological Linkages between Headwaters and Downstream Ecosystems: Transport of Organic Matter, Invertebrates, and Wood Down Headwater Channels." *Journal of the American Water Resources Association* 43, no. 1 (Feb): 72-85. http://dx.doi.org/10.1111/j.1752-1688.2007.00007.x.

Wohl, E. 2014. *Rivers in the Landscape*, Science and Management. Oxford, UK: Wiley Blackwell.

Wohl, E. 2017. "The Significance of Small Streams." *Frontiers of Earth Science* 11, no. 3 (September 01): 447-456. http://dx.doi.org/10.1007/s11707-017-0647-y.

Wrońska-Wałach, D., M. Żelazny, S. Małek, K. Krakowian, and N. Dąbek. 2018. "Channel Heads in Mountain Catchments Subject to Human Impact – the Skrzyczne Range in Southern Poland." *Geomorphology* 308 (2018/05/01): 190-203. http://dx.doi.org/https://doi.org/10.1016/j.geomorph.2018.02.005.

Young, R. A., T. Huntrods, and W. Anderson. 1980. "Effectiveness of Vegetated Buffer Strips in Controlling Pollution from Feedlot Runoff." *Journal of environmental quality* 9, no. 3: 483-487.

Zealand, Stats New. "Agricultural and Horticultural Land Use." Last modified 4/19/2018. Accessed 6/2/2018, http://archive.stats.govt.nz/browse_for_stats/environment/environmental-reporting-series/environmental-indicators/Home/Land/land-use.aspx.