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DIPLOMARBEIT

Titel der Diplomarbeit

**„Landslide driven erosion in the Southern Ruahines, New Zealand:
An assessment of its spatial and temporal variability“**

Verfasser

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angestrebter akademischer Grad

Magister der Naturwissenschaften (Mag.rer.nat.)

Wien, 2012

Studienkennzahl lt. Studienblatt: A 453

Studienrichtung lt. Studienblatt: Diplomstudium Theoretische und Angewandte Geographie

Betreuer: Univ. Prof. Dr. Thomas Glade



Frontispiece: Picture of the Ruahine Forest Park, looking towards Dry creek and Car Park creek.

Declaration of academic honesty

I hereby declare that the present work was written on my own and that no material other than the cited literature and sources was used.

This work or parts of it have never before been handed in for any other degree or diploma and it is entirely congruent with the work handed in to my supervisor.

Signature:

Date:

Acknowledgments

First of all I want to thank my family, especially my parents Maria and Alois for the enduring support and motivation, making it possible to study my passion, geography.

Special thanks goes to my supervisor, Thomas Glade who accompanied me throughout the whole project and who also made it possible for me to go to New Zealand for my research stay. The necessary talks about this thesis shaping my ideas and the support with the two grants I successfully applied for was very motivating!

Ian Fuller was my first contact at Massey University in New Zealand. Besides the many hours in the field, especially your open office door and the resulting variety of talks about the project will always stay in my mind. Thank you very much for our cooperation and all the important tips as well as ongoing support after my return to Austria!

Two more really important scientist whom I want to thank are Mike Marden and Chris Phillips from Landcare Research who joined us for some intense discussions as well as for field work. Mike, special thanks for introducing me to Ian and proposing our cooperation.

One very appreciated person at the University of Vienna throughout my whole studies and of course also during my diploma theses is Rainer Bell. Ongoing talks about my thesis and consistently support per mail and trough talks helped me to keep track.

My brother Jonathan also played a crucial role as moral support. Thanks for that especially challenging task! Besides he worked on the layout concept with me and proofread parts of this work.

I also want to thank Angelika Riegler for encouraging me to take the initial step for going to New Zealand. She also helped me to structure my work and of course the meetings with her in New Zealand during my stay were fabulous!

My busy proofreaders Jenn Fowler, Nuzhat Enver, Senka Grossauer, Luna Riedler and Christine Ornetsmüller provided me with crucial grammar and expression tips. Especially Christine read the whole document and supported me with prized comments. Thank you all for your patient work.

Karin Aistleitner and Vivian Siegl were continuously supporting me with positive comments and encouraging talks during my writing phase easing this task.

During my time at Massey University, I was continuously supported by Matthew Irvin who is an excellent GIS professional, Martin Brooks explaining and testing the whole georadar gear with me, Jane Richardson, my excellent general support, Anja Moebis who guided me through geological challenges, Alan Palmer, literature and geology knowledge support and Jonas Haag joining us in the field and working next to me.

Generous data supply from several persons and institutions made this work as magnificent as it is right now. Besides Ian who shared all necessary available data from Massey University, I want to thank Brent Watson from the Horizons Regional Council for rainfall data, Harley Betts from Landcare Research Palmerston North for providing elevation data and Andrew Steffert also from the Horizons Regional Council for aerial picture sets. All of them also supported me with metadata and helped with troubleshooting via mail when I was back in Austria.

And of course I want to thank all the people who made my stay in New Zealand one of the greatest experiences in my life! First to my flatmates Daniel Farley and John Howard for some excellent dinners and relaxed spare time, my dance colleagues at the Ceroc studio in Palmerston North, my climbing partners at “the wall” at Massey and all my other friends I found there and of which I hopefully will keep some for the rest of my life.

Generously founded by the University of Vienna with two Grants.

Abstract

In mountainous regions which are used agriculturally or are adjacent to densely populated areas, mass movements strongly influence human activity and infrastructure. This also happens at a high rate in New Zealand, where mass movements occur throughout all the country. Shallow slides are the most abundant within them and also cause the majority of problems and damage. For example, starting in August 2011, NZ state highway number three was closed for nine months due to severe landsliding in the Manawatu Gorge (NZ Transport Agency 2012). Moreover in the Manawatu catchment 24.300 to 28.300 hectares of flood free, fertile fields are threatened to be buried by fluvial gravels (Hubbard 1978).

The Southern Ruahine Range is such an environment. While detailed investigations were carried out in the 1970's and 1980's no extensive investigations were accomplished since then. Here the aim is to better understand the erosion patterns through landslides and their material input into streams throughout this mountain range using aerial picture interpretation.

One aim of this work was to create a continuous record of the landslide affected area in the Southern Ruahines for more than 65 years ranging from 1946 until 2011 and to understand the potential material contribution to river systems through shallow landslides. The degree of hillslope-channel coupled debris slides and material provided by them is analysed within a selected catchment in the ranges.

Methods applied include aerial picture interpretation of landslides using GIS and determining their connectivity to the channel system. In addition detailed surface surveillance in the field applying differential GPS and a robotic total station was carried out and finally these measurements were combined to derive landslide volumes.

Employing up to six different aerial picture sets, more than 8900 individual features were mapped in the study area and detailed information about temporal and spatial landslide distribution was gathered. Four landslides were surveyed in the field to derive accurate digital elevation models for volume calculations. These values were used to derive

potential material contribution to the channel-system by coupled debris slides. As an example, in the 11,3 km² big Tamaki West catchment the minimum observed volume was 41.853 m³ in 1946, the maximum 322.000 m³ in 1977 and 144.837 m³ is the average volume of six obtained sets from 1946 to 2011.

Through the received data the landslide coverage available in the 1970's and 1980's could be completed until 2011. Furthermore the understanding of the relation between the number of hillslope-channel-coupled debris slides, their size and their affected area is greatly enhanced by the data provided in this study. This leads to an improved comprehension of the processes within the Southern Ruahine Ranges and their influence on the rivers system. To extend the knowledge further, regular investigations monitoring the landslide extent should be carried out in this fragile environment.

Kurzfassung

Besonders in Bergregionen, welche teilweise landwirtschaftlich genutzt werden oder sich in unmittelbarer Nähe von dicht besiedelten Gebieten befinden, haben Hangrutschungen einen starken Einfluss auf die Menschen und von ihnen genutzte Infrastruktur. Hangrutschungen treten in ganz Neuseeland in hohem Maße auf. Unter diesen sind besonders flachgründige Rutschungen am verbreitetsten, welche auch für den Großteil der Schäden sowie Probleme verantwortlich sind. Als Beispiel kann der durch zwei großflächige Rutschungen ab August 2011 für neun Monate gesperrte Highway Nummer drei im Manawatu Gorge angeführt werden (NZ Transport Agency 2012). Ferner laufen im Manawatu Einzugsgebiet 24.300 bis 28.300 Hektar hochwassersicherer fruchtbarer Ackerboden Gefahr, von Flussschottern begraben zu werden (Hubbard 1978).

Bei den Südlichen Ruahines handelt es sich um ein derartiges Gebiet. Nach intensiver Forschungstätigkeit im Bereich des Erosionsverhaltens der Südlichen Ruahines in den 1970er und frühen 1980er Jahren wurden bis 2011 keine zufriedenstellenden Untersuchungen durchgeführt. Es wird angestrebt, die Abtragungsprozesse durch Hangrutschungen sowie deren Materialeintrag in Flüsse innerhalb dieser Gebirgskette durch Luftbildinterpretation zu erforschen.

Ein Ziel dieser Arbeit war es, einen durchgehenden Datensatz für die von Hangrutschungen betroffene Fläche für mehr als 65 Jahre, nämlich von 1946 bis 2011, zu erstellen. Ferner soll der Anteil von Hangrutschungen, welche in direkter physischer Verbindung mit dem Flussbett in einem Einzugsgebiet in den Ruahines stehen, und das von ihnen zur Verfügung gestellte Material identifiziert werden. Daraus sollen Erkenntnisse zum potenziell von Hangrutschungen für Flusssediment zur Verfügung gestelltem Material gewonnen werden.

Angewendete Methoden beinhalten Luftbildinterpretation in einem GIS, wobei ebenfalls deren Konnektivität eruiert wurde. Weiters wurde detaillierte Geländevermessung unter Nutzung eines differentiellen GPS Systems und einer automatischen Totalstation

durchgeführt. Schließlich wurden die dadurch erhaltenen Ergebnisse kombiniert um die gekoppelten Hangrutschungsvolumina zu berechnen.

Unter Verwendung von bis zu sechs verschiedenen Luftbilddatensätzen konnte die räumliche und zeitliche Verteilung von Hangrutschungen detailliert mit über 8900 einzelnen Einträgen dokumentiert werden. Durch die detaillierte Oberflächenerkundung von vier Hangrutschungen konnten digitale Höhenmodelle für die Volumsberechnung erstellt werden. Diese Berechnungen wiederum wurden genutzt um den potenziellen Materialeintrag ins Flusssystem durch Hangrutschungen zu berechnen. Zum Beispiel wurde im 11,3 km² großen Tamaki West Einzugsgebiet im schwächsten Jahr 1946 Volumen von 41.853 m³ berechnet. Das Maximum von 322.000 m³ wurde in 1977 eruiert und der Durchschnittswert aller sechs untersuchten Zeitpunkte beläuft sich auf 144.837 m³.

Durch die vorliegende Untersuchung konnten die für die 70er und 80er des vorigen Jahrhunderts vorliegenden flächendeckenden Hangrutschungsanalysen bis 2011 weitergeführt werden. Weiters konnten der Zusammenhang zwischen der Anzahl, der individuellen Größe sowie der durch sie betroffenen Fläche von Hang-Gerinne-gekoppelte Rutschungen hergestellt und erläutert werden. Aus diesen Erkenntnissen ergibt sich ein besseres Prozessverständnis sowie ein klareres Bild der Auswirkungen auf das Flusssystem und sie zeigen auch die Notwendigkeit einer fortlaufenden Beobachtung der Hangrutschungsausdehnung in einem sensiblen Gebiet wie den Südlichen Ruahines.

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List of symbols

DEM – Digital elevation model

DOC – Department of Conservation

GIMP – GNU Image Manipulation Program

GIS – Geographical Information System

GPR – Ground Penetrating Radar

GPS – Global Positioning System

HRC – Horizons Regional Council

LINZ – Land Information New Zealand

m.s.l – Meters above sea level

NIWA – National Institute of Water and Atmospheric Research

NZ – New Zealand

RTK – Real Time Kinematic

TLI – Triangulation with Linear Interpolation

Topo 50 – Topographic Map, Scale 1:50000

1 Introduction

Landslides occur through all regions of the world. They are unavoidable natural phenomena and thus impact the human sphere, as they are closely interrelated. Landslides are threatening human lives and livelihoods as well as altering the landscapes in various ways. They have been studied since a long time not only by scientists but also by all different kind of people like farmers, property owners or just engineers.

But what exactly is a landslide? Cruden stated this in his journal article "A Simple Definition of a Landslide" in 1991 as following: "A landslide is the movement of a mass of rock, earth or debris down a slope." And yet it is clear that the availability of abundant literature on landslide investigation and the multiple definitions of that term indicate, that it is **not** that simple. In chapter 2 the topic of landslide and their properties will be further elaborated.

Some landslide have even more severe direct influences on the anthroposphere than others. For example the New Zealand State Highway number three, a regional traffic artery through the Manawatu gorge just south of the study area was blocked from August 19th 2011 until the 31st of May 2012 by two landslide slowing the traffic connections in the entire area (NZ Transport Agency 2012). Casualties due to landslide or their indirect impacts have been reported for many centuries. For example, Dai et al. (2005) described a landslide that occurred in 1767 B.C. in China and formed a landslide dam which blocked the Dadu River for 10 days. The resulting flood killed approximately 10,000 people in the downstream area, and this disastrous event is to be considered as one of the most severe ever.

However, not all of the landslide consequences are as fatal as the previous example. There are abundant indirect consequences of landslides not only for humans but also for the landscape itself. These ranges from economical losses in industry, tourist sector, agriculture and forestry due to damaged land or cut infrastructure supply to negative consequences in water quality for surface waters thus decreasing habitat quality and size

of fishes and land animals and increases the emotional stress of all of the affected parties (Schuster 1996, Burke et al. 2003).

So it is clear that negative consequences can arise even if the actual event happens in a remote area and human beings are only impacted through secondary effects. These indirect consequences will be further elaborated in the next chapter.

1.1 Background

Due to the intensive use of the plains adjacent to the Southern Ruahine Range for agricultural practices as well as for settlements and other infrastructural purposes, the influence of the physical processes happening in the ranges has always been an issue since European settlement started 165 years ago. However, this development has especially been an issue since the beginning of the 20th century along with the extensive deforestation of the steep and high elevated parts of the range, which is explained in more detail in chapter 3.5 - Landcover and vegetation. These critical vegetation changes as well as climatic events and changing conditions resulted in an altered erosion pattern throughout the entire Ruahine Range (Cunningham 1979, Grant 1991, Dymond 2006).

The threats, which originated in the range mainly from flooding and increased sediment transportation through the streams and torrents, are the root of the problem. Sediment hereby is defined by Mosley (1977, page 3): “[...] *the term sediment refers herein to all the solid material, irrespective of grain size, carried by a stream. It therefore encompasses terms such as metal and shingle.*” The first documented flooding incident occurred near Woodville in 1914, and increasing landslide activity in the range also threatened human created infrastructure and fertile land starting in 1949 and becoming more severe in 1965 (Grant 1977, Blakely 1984).

Within these previously mentioned consequences due to increased gravel input from the range, the most severe indirect economical problems derive from submerged agricultural areas which become infertile when being covered with a gravel-layer that is several centimetres thick, as well as from increased flooding due to diminished bridge discharge

capacity by aggregated sediments. Additionally the increased sediment charge in the stream beds pollute the waterways and decrease the water quality both for aquatic organisms and humans. (Hubbard 1978, Schuster 1996).

Stephens (1975) suspects that even the regional water supply could be affected by serious landsliding in the range and not only communication but also commuting connections could be interrupted.

The increased concerns about the worsening erosion in the Ruahine Range accompanied by the increased gravel input and transportation through the waterways has led to more in-depth research done by scientists and campaigns investigating the situation in mainly dense shrub, tree or tussock vegetation regions covering steep and elevated parts of the Ruahine Range. More details about the vegetation are given in chapter 3.5, Landcover and vegetation. The research focus was concentrated in these areas because erosion rates in the range started to rise noticeably around 1950 and then became even more severe due to an increasing number of visible landslides around 1965 (Grant 1981, Blakely 1981).

Starting in the 1970's until the mid 1980's extensive effort was put into the research of the Ruahine Range in order to understand the underlying reasons and processes leading to the erosion features encountered by a multitude of scientists (e.g. James 1973, Stephens 1975 and 1981, Mosley 1977, Schumm 1977, Grant 1977, 1981, 1983, 1991, Hubbard 1978, Cunningham 1979, Blakely 1984, Marden 1984).

During this intense investigation period several findings about the erosion behaviour in the Ruahine Range have been discovered. This included mapping of the soils in parts of the area as well as several region-wide erosion investigations, and mapping which covered a variety of processes like mass movements and sediment storage. Last but not least investigations on sediment remobilization (e.g. Grant 1977, 1983, Stephens 1981, Marden 1984). Especially Grant (1977, 1981, 1983) clearly recognized an increase in erosion and channel activity since 1949 until the peak of his investigations in 1983. He mentioned that in the Ruahine Range several states of different geomorphological

activities, so called "*erosion periods*" and "*tranquil intervals*" are common and he identified five of them since the 13th century which are shown in Figure 1.1.

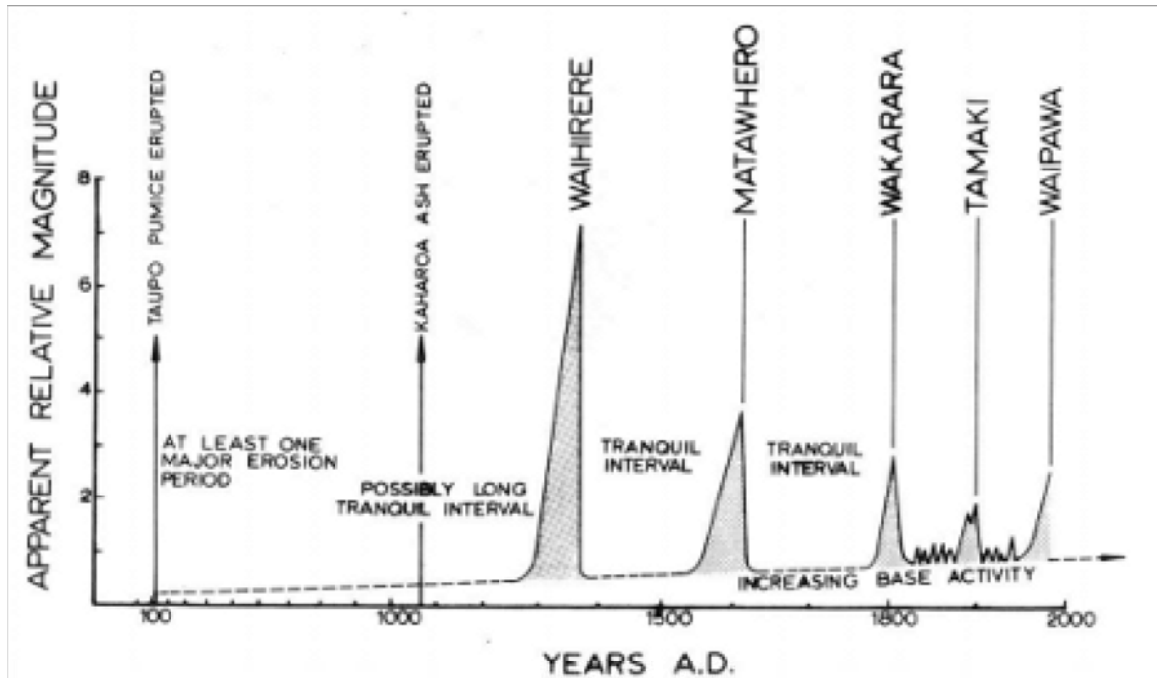


Figure 1.1: Erosion periods in the Ruahine Range after the 13th century. Two ash layers used for dating are included. The rising base activity is simplified, Grant 1981.

Grant (1983) concludes that the driving factors for his identified erosion cycles are of climatic nature only, and do not match with settlement and burning impacts. He also postulates that animals that have been introduced do have only very little or no influence on the process dynamics. Hubbard and Neall (1980) are supporting this theory by adding that besides storm events also earthquakes can be a triggering mechanism for mass movements and increased erosion.

Elder (1965), James (1973) and Mosley (1977) suggest that there was a variety of mammals introduced (see also chapter 3.5, Landcover and vegetation) which severely influenced and deteriorated the vegetation cover in the range. Considering this animal-induced deterioration in contrast to Grants (1983) hypotheses, James (1973), Mosley (1977) and Blakely (1981) stated that shallow mass movement rates coincide with

decreasing vegetation cover which is shown by Glade (1998) in another case in New Zealand.

Stephens (1981) and Marden (1984) agreed with Grant that there is an increase of erosion going on in the range between the 1940's and the late 1970's. The focus of their investigation was in the Southern Ruahine which correlates with the study area of this work (See chapter 3, Study area). Both of them used mirror stereoscopes to analyse aerial pictures and map both contemporary and historical ones. Erosion processes such as mass movements and fluvial erosion features were studied with this method especially by Marden (1984). In Marden's work the whole study area of this work is covered by the maps. Marden's investigations are covering a broader spectrum of processes including deep seated mass movements and focuses stronger on the geological background.

In association with these studies several management schemes were established to mitigate the erosion consequences in the Range. Namely by the Ruahine Range Control Scheme Committee, another plan by the Manawatu Catchment Board, and one by the New Zealand Forest Services (Marden 1984).

Since this very intense investigation period only two journal articles were found. One article analysing smaller catchments within the Southern Ruahine Range by Schwendel and Fuller (2011) and the unpublished *"Erosion and Revegetation in Car Park Creek"* investigating a small sub-catchment of the Tamaki West River by Dallmaier and Gross (1996). Even though a thorough literary search was carried out to find more information. Besides this, the approach of implementing large scale models assessing the erosion susceptibility by digital data processing is assessing the problem from another perspective (e.g. Dymond et al. 2006).

As discussed above there is abundant knowledge available concerning the condition of the Ruahine Range beginning in the 1950's until the early 1980's. After this period only scarce information for parts of the Range are available.

-> The current existing information about the ongoing erosion processes since the end of Marden's (1984) investigation are insufficient for this thesis. Until then the erosion rates have been on the rise, and simultaneously measures to mitigate the erosion using several

approaches have been taken. Certain questions remain as for instance: How have the erosion rates and distributions evolved since then, and can a trend of erosion patterns be identified?

These questions need to be answered in order to compare past results with new insights, and to get a clearer picture about the situation in the Ranges today. Recently released data as well as different analysis tools and methods allow a new approach and have the advantage of being able to compare former insight from other authors with newly gained results. The exact procedure how this is achieved will be explained in chapter 4, Methods.

A second important facet of the investigations done in the past were the assumptions made for calculations of eroded volumes by different kinds of mass movements in the Ruahine Ranges. Through new surveillance techniques it is possible to reassess this issue with the use of modern equipment. Besides this, the sediment input into rivers is crucial for the consequences of mass movements in the Ranges for downstream structures and areas. Both of these issues will be addressed in this work, and new findings concerning an activity period extending 65 years of observation will be presented in the following chapters.

1.2 Aim of the study

The basic framework for this diploma thesis will be outlined in more detail in this chapter. As the central investigated data consists of aerial pictures their availability constraints also the analysed time period. The investigatable time span is of course expanded by reviewing literature. However, the main results in this study are derived from three main sources. Aerial picture interpretation is one, detailed field survey is the second and digital elevation data is the third. Referring to the aerial imagery the **first aim** of the study is to broaden the insight of work carried out concerning the erosion history in the Southern Ruahines, and to clarify the extent of fresh landslides (this term will be explained in the

Landslides chapter 2.1) in the Southern Ruahines in more than last 65 years before the starting point of this investigation in 2011.

Furthermore the question remains how much material has been relocated by fresh landslides in a certain period of time. Therefore the **second aim** is to calculate the landslide volume for the observed actively eroding areas.

As one of the main concerns regarding the erosion activity in the Southern Ruahines is the sediment transported out of the Ranges to the plains. The **third aim** addressed here is the ratio of hillslope-channel coupling within the assessed area.

Based upon these aims certain hypotheses and questions arises which will be explained in the next chapter, Hypotheses and research questions.

1.3 Hypotheses and research questions

The research approach will be outlined by the research questions explained in this chapter as well as by the main hypotheses presupposing these questions.

The crucial basis of this work are the two main hypotheses which were elaborated to develop the researched topic towards a possible theory. These two will be assessed and reviewed within this work, and could provide the basis for further scientific analysis.

The main hypotheses are:

Hypothesis I: Stronger landslide activity in the research area results in a higher percentage of hillslope-channel connectivity.

Hypothesis II: The landslide extent of fresh landslides for the whole Southern Ruahines can be derived from the landslide cover in the Tamaki West catchment.

These presumptions will be investigated throughout the paper and finally appraised in the conclusion. The key factor to understanding both hypotheses and thus being able to

falsify or verify them is to have accurate values of the spatial extent for the respective facet.

Derived from these hypotheses as well as considering other aspects of interest for this study several research questions arise. These guiding questions which subsequently will be presented in the following chapters are as follows:

1. In which extent is the area in the Southern Ruahines affected by fresh landslides between 1946 and 2011?
2. How has the spatial landslide pattern in the Southern Ruahines evolved since 1946?
3. What is the volume of eroded material from characteristic landslides within the research area?
4. What is the volume of eroded material from characteristic landslides within the research area?
5. What is the volume of eroded material from all landslides within the research area?
6. What is the total material contribution by landslides to the river-system?

These questions are substantially underlying the research which is carried out through this whole work. Additionally, this issues underpin the analysis approach which guided not only the field work but also further investigations concerning the data processing and literature research.

2 Landslides

This chapter is a general introduction to the terms used relating to landslides and the underlying mechanisms as well as to the specific characteristics of the mass movements occurring in the study area. This includes the explanation of the terminology as well as it

is referring to the different potential triggering mechanisms. Since there were two main approaches used to determine the landslide activity in the study area: aerial picture interpretation and field work they are considered in this chapter as well. They will be explained in greater detail in chapter 4.

Landslides are not only a natural phenomena. They also have severe direct and indirect influences on the human infrastructure and their lives which has already been described in the first chapter. In New Zealand this is mainly caused by two types of landslides. On one hand these are deep seated rock and debris slides, and on the other shallow regolith slides. If the focus is drawn to the problematic aspects of landslides in New Zealand the latter category is responsible for the majority of incidents and problems connected to landsliding (Crozier et al. 1992). This includes direct consequences such as cut infrastructure connections or even in the worst case casualties. The indirect consequences are visible through the altered landscapes at the failure site as well as caused by the dispatched landslide material on other sites.

There are several preconditions influencing the hillslope stability as well as the failure process itself. Within these the most important in the study area is the climate and the resulting wet weather explained in chapter 3.4, Hydrology and climate. Furthermore, rock strength, geological configuration, earthquakes and resulting landscape characteristics which will be further explained in chapter 3.2 and 3.3 have an important impact on the landslide pattern. Landcover (chapter 3.5, Landcover and vegetation) is a more recent, externally changeable factor affecting mass movement processes.

Besides the elements preconditioning the landslide occurrence, also certain triggering factors play a major role in the Ruahine Range. Intense rainfall events are responsible for the majority of landslide events. Here, single events can occur as well as major events, including hundreds of landslides, depending on the intensity of the rainfall (Schumm 1977, Grant 1983, Marden 1984, Brooks et al. 2004).

Earthquakes also play an important role as a landslide mobilizing factor in different regions of New Zealand. Their relevance for this particular study is elaborated in chapter 3.3, Geomorphological state.

One more important factor for hillslope stability is the vegetation cover. Here evapotranspiration by the plants and increased mechanical cohesion through the tree-root system are the main influencing factors (Crozier et al. 1992). Hence, differences in the vegetation cover influence the resilience of slopes to triggering forces. Mosley 1977, Marden 1984, Crozier et al. 1992 and Glade 1998 agree that shallow landsliding is more common on slopes covered with pasture than on forested slopes. This is underpinned by Selby's (1976) work carried out on the North Island of New Zealand, where rainfall triggered landslides are investigated. One of the key findings in that article is, that when a storm event of a 30 year return period causes landsliding on pasture, an event with a 100 year return period is necessary to cause similar damage to a forest covered slope. Vegetation again is also influenced by different factors like climate change, lumbering or noxious animals. Further details referring to the condition of these elements in the study area are presented in the vegetation chapter, 3.5 where also the general landcover distribution is presented.

2.1 Definition of used terms

The word landslide covers a large variety of possible processes determined by a multitude of different definitions. In this work only a specific segment of landslides is investigated. To be more precise in the study area the most abundant, and thus investigated process consists of shallow landslides. Mostly not deeper eroded than two or three meters. This means other mass movements like deep seated landslides occur but were not considered in the mapping and field work for this diploma thesis.

Combining the insight of field work, mapping and data evaluation, a precise definition for the investigated process could be found.

From the divers definitions the one elaborated by Cruden and Varne's (1996) was chosen because of it's high accuracy concerning the inclusion of material attributes and it's grain size, the type of movement, the actual state of the process as well as the distribution, the water content, the movement rate and the subsequent conditions.

The landslides are thus defined as: retrogressing, multiple, very rapid, wet debris slide which was recently initiated or active and is thus also referred to as fresh landslide. With recently active, a period of maximum 12 years before the current state is indicated (the procedure to determine activity period for fresh landslides is explained in the methods chapter 4.2.1). This can also refer to a reactivated part of a landslide whereas only this part is included in the current work then. Further on, this definition will be referred to in short with **debris slide**, also including the state of activity.

3 Study area

In the following chapter the area of investigation is constituted. This will include the physical boundaries and location as well as the selection criteria for the study area.

Furthermore, the geological, geomorphological and soil parameters as well as the climate conditions will be elucidated. An overview of the vegetation in the region will be given and the chosen investigated field sites will conclude this chapter.

3.1 Location

The study area is situated in the Ruahine Range which is part of the northern axial ranges (Figure 3.2a) on New Zealand's North Island and trends SSW to NNE. The elevation of the Ruahine Range reaches from around 150 m.s.l. up to 1733 m.s.l. at the location of its highest peak, Mt. Mangaweka (Heerdegen and Sheperd 1992, Kamp 1992).

Within that mountain range this work focuses on an approximately 221 km² big territory which forms the southern end of the ranges, referred to as Southern Ruahines in this work. Elevation within the study area reaches from 165 m.s.l. until 1258 m.s.l. at Takapari Peak (LINZ 2012). The geographic extent of the investigated area spans from 40° 3' 45" south in the most northern part to 40° 17' 34" south in the southern reach. Within that section the Southern Ruahines are approximately 30 km in their extent from SW to NE.

Widthwise the most eastern extent is 176° 5' 16" east and the most western part reaches until 175° 48' 44" east. In its northern part where the Southern Ruahines are expanding the maximum broadness of the study area accounts to approx. 12 km.

The delimitation of the study area is determined by several factors. The main criterion of demarcation is the geological setting of the ranges. The whole investigated area lies in differently composed greywacke sandstone units surrounded by plio-pleistocene marine sediments (Marden 1984). In the east, the south, and the west the borders are directly deduced by these lithological units. In chapter 3.2, a detailed explanation of the geological setting is given and the extent of the lithological units based upon which the boundaries were chosen are shown in Figure 3.4 along with the boundaries confining the study area.

In the north, the study region is limited by two different features. On the north-western side, where the Takapari Road enters the ranges and the Wharite Lithotype (Figure 3.4 - point A) until point B, this gravel track determines the northern border. Starting at the intersection of the Takapari Road with the Tamaki-River catchment (point B) the boundary follows the northern line of the Tamaki-River catchment until the changeover from greywacke bedrock to tertiary sediments (point C) in the north-east whereas the boundary of the study area towards south is determined by the lithological setting again. The intersection points A, B and C are shown in Figure 3.1 along with the extent and location of the study area investigated in this work.

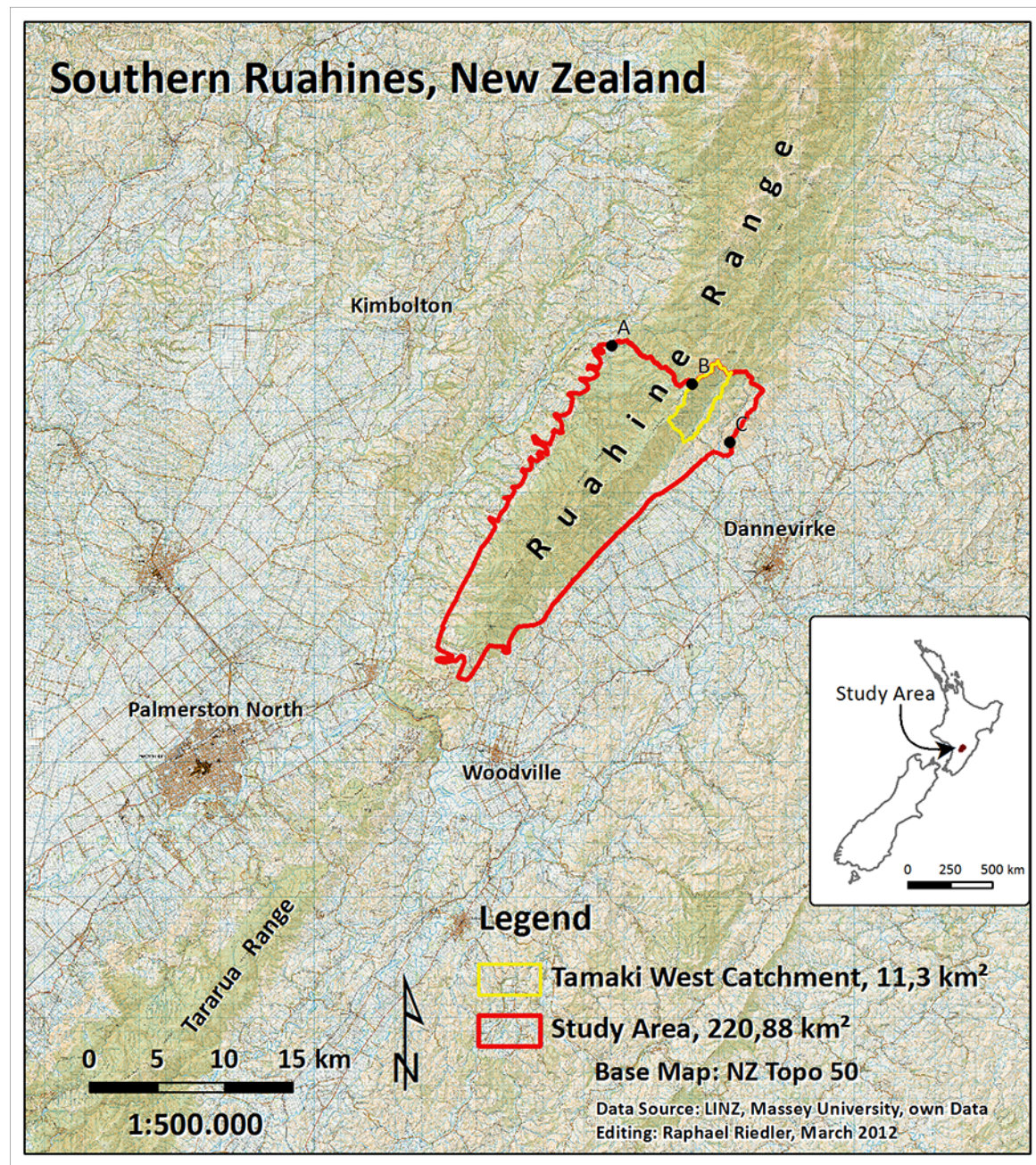


Figure 3.1: Study area of this work located within the Ruahine Range, North Island, New Zealand. The boundaries of the study area as well as of Tamaki West catchment including their area calculated in GIS are shown. The points A, B and C indicate changes in the criteria determining the accurate boundaries of the study area.

3.2 Geology and tectonics

Generally, almost all of the North Islands mountain ranges consists of Jurassic-Triassic (150 – 180 million years old) aged greywacke. Basically, the sole exception are mountains of volcanic origin. Still, this bedrock material is only accessible at sparse locations due to widespread younger sediments or volcanics submerging the greywacke (Kingma 1974, Heerdegen and Sheperd 1992).

Driven by forces involved in the convergent movements of the Australian and Pacific Plate there was an accelerated rate of uplift of the axial ranges starting about 5 million years ago. Most of the uplift happened in the last 2 million years (Winkworth 2005, McDowall 2010).

The Ruahine Ranges are part of the axial ranges of the North Island, New Zealand. A schematic map depicted in Figure 3.2 shows the rough course of the axial ranges on the North Island.

The uplift rates for the Southern Ruahines vary in number in different studies. Mosley (1977) states that they vary between 0,8 and 2,5 mm per year depending on the location within the ranges. More distinct, Marden (1984) proclaims that minimum vertical displacement since Ohakean (10000 – 25000 years B.P.) times is at least 1 mm per year. Supporting this finding Heerdegen and Sheperd (1992) are assuming that the uplift rates exceed 1 mm per year also in recent times although they also mention regional differences. This is supported by Brook and Hutchinson (2008), who are suggesting that the annual uplift rates even comprises 2-3mm. Anyhow, uplift rates are still on a high level compared to other regions in the world (e.g. they are comparable or exceeding the highest rates in the Alps, where the maximum rates are around 1,4 mm per year but in large portion, areas rates are much lower and even subsidence is present) (Pfiffner 2009). The formation of the Ruahine Ranges as we know them today with it's current landforms went trough a multitude of cycles starting mainly after the Oligocene where almost all of New Zealand was submerged by oceans (McDowall 2010). During Miocene times parts of the ranges and especially adjacent areas were partially submerged by oceans due to

changing water levels and tectonic uplift as well as depression (Kingma 1974, Marden 1984). According to Mosley (1977) virtually the whole Ruahine Ranges were still submerged three million years ago, and thick layers of silt and other sediments were deposited.

The rocks forming the Ruahine-Rimutaka Range are mainly composed of graded beds of Jurassic-Triassic age. The Ruahine Range can be classified as a horst bringing Mesozoic rocks to the surface (Kingma 1959). This situation is schematically illustrated in Figure 3.2b, where the present lithological classes can be seen as well as the context of relief and tectonic uplift.

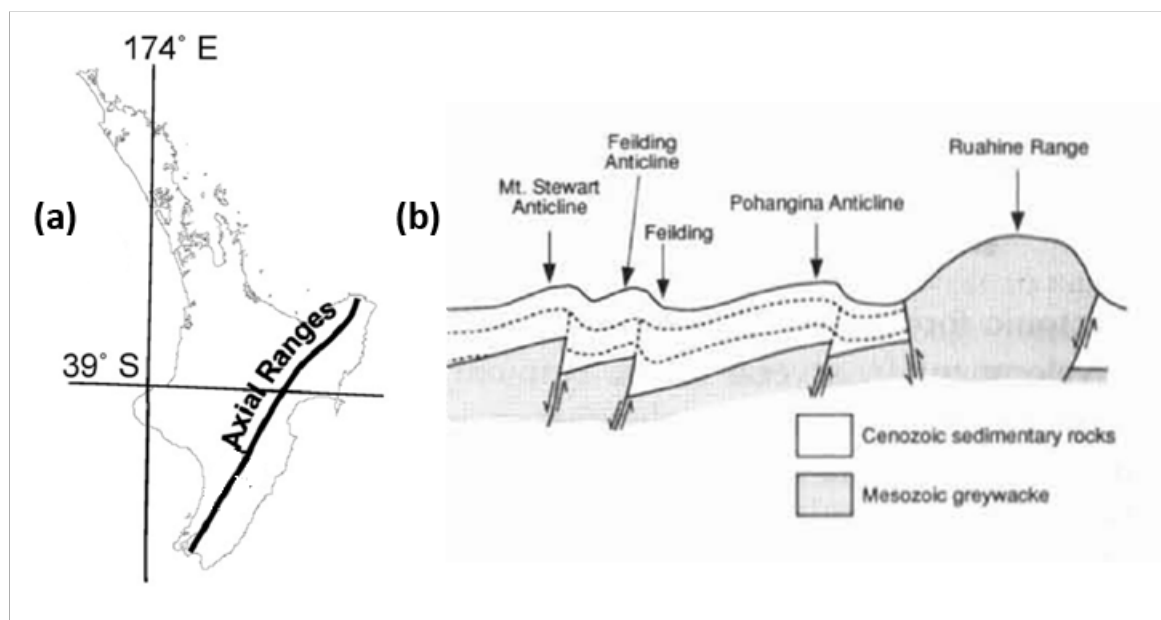


Figure 3.2: General overview of the Axial Ranges, North Island. In a) the schematic geographical extent of the Axial Ranges is shown. In b) the relation of structure and relief are sketched in the cross-section of the Ruahine Range ranging from Tangimoana to the ranges. After Fuller 2008, Heerdegen and Sheperd 1992.

A more precise definition of the rocks comprising the Ruahine Range is given in Marden (1984), where they are described as part of a rock unit called Torlesse terrane also referred to as Torlesse Supergroup. These rocks are defined as “heterogeneous

assortment of structurally complex, poorly fossiliferous, relatively quartz-rich, flysch-like, non-schistose rocks of the New Zealand Geosyncline forming the ranges of the south island of New Zealand [...] [and] comparable rocks in the main ranges in the North Island.”
(Marden 1984, page 24)

Within the Torlesse terrane, the most abundant rocks in the southern Ruahines are highly fractured and jointed sequences of sandstones and argillite sometimes including interbedded thinner siltstones of low metamorphic rank as shown in Figure 3.3. Less frequent also pebbly mudstone, conglomerate, breccia, limestone, chert and different volcanics as well as some other minor components are present (Marden 1984).



Figure 3.3: Sequence of alternating, westward younging Sandstone (grey) – argillite (dark grey, black and red) bedrock in the Tamaki West catchment. Person acts as scale. Note the more abundant, thicker sandstone units reaching from approximately eight cm to 25 cm compared to the argillite parts which range from approximately one cm to 13 cm. Fracturing and cleavages are present as well. The unit is located in the Tamaki lithotype. The picture direction is SW, parallel to the striking direction. Photo by Jonas Haag, 2011.

Concerning the stratigraphy, Marden (1981, p.12) concludes it as: “consisting of a linear sequence of NE- to NW- striking greywacke lithotypes lying sub-parallel to the NE trend of the axis of the Range.”

Marden (1984) determined three lithotypes shown in Figure 3.4. The main differences between them is the lithological composition as well as their strata properties. In the following text the three identified units are summarised.

The Tamaki Lithotype is characterised by mainly undeformed beds of coherent lithological units which are comprising of seven lithological components. These components are sandstone, argillite, siltstone, intraformational conglomerate, chert, calcereous siltstone and pebbly mudstone. It is represented by a high regularity of alternating bedded units respective to it's strata. *"The strata are predominantly eastward-dipping, westward-younging and hence are overturned"* (Marden 1984, page 30) as partially can be seen in Figure 3.3.

In contrast to the Tamaki Lithotype the Wharite Lithotype is determined by a multitude of different lithologies and also a less consistent strata, where bedding often is indistinct. This situation is referred to as 'Melange' to describe the overall condition of the rock body, describing a rock association which was formed under a mixture of sedimentary sliding or tectonic movement. The planar arrangements identifiable within the Wharite Lithotype are similar to the adjacent Tamaki Lithotype regarding strike and dip patterns. Because of the chaotic character of this Lithotype, no solid younging direction was established (Marden 1984).

The Western Lithotype which is represented by a small area west of the Wharite Lithotype consists of only three lithologies. Mainly sandstone, argillite and siltstone. Most of it's attributes are comparable to the Western Lithotype. The main differences are that argillite is less abundant in the bedded sequences and as already mentioned, all additional lithologies are absent (Marden 1984). For more detailed explanations of the herein used lithotypes, please consult Marden 1984.

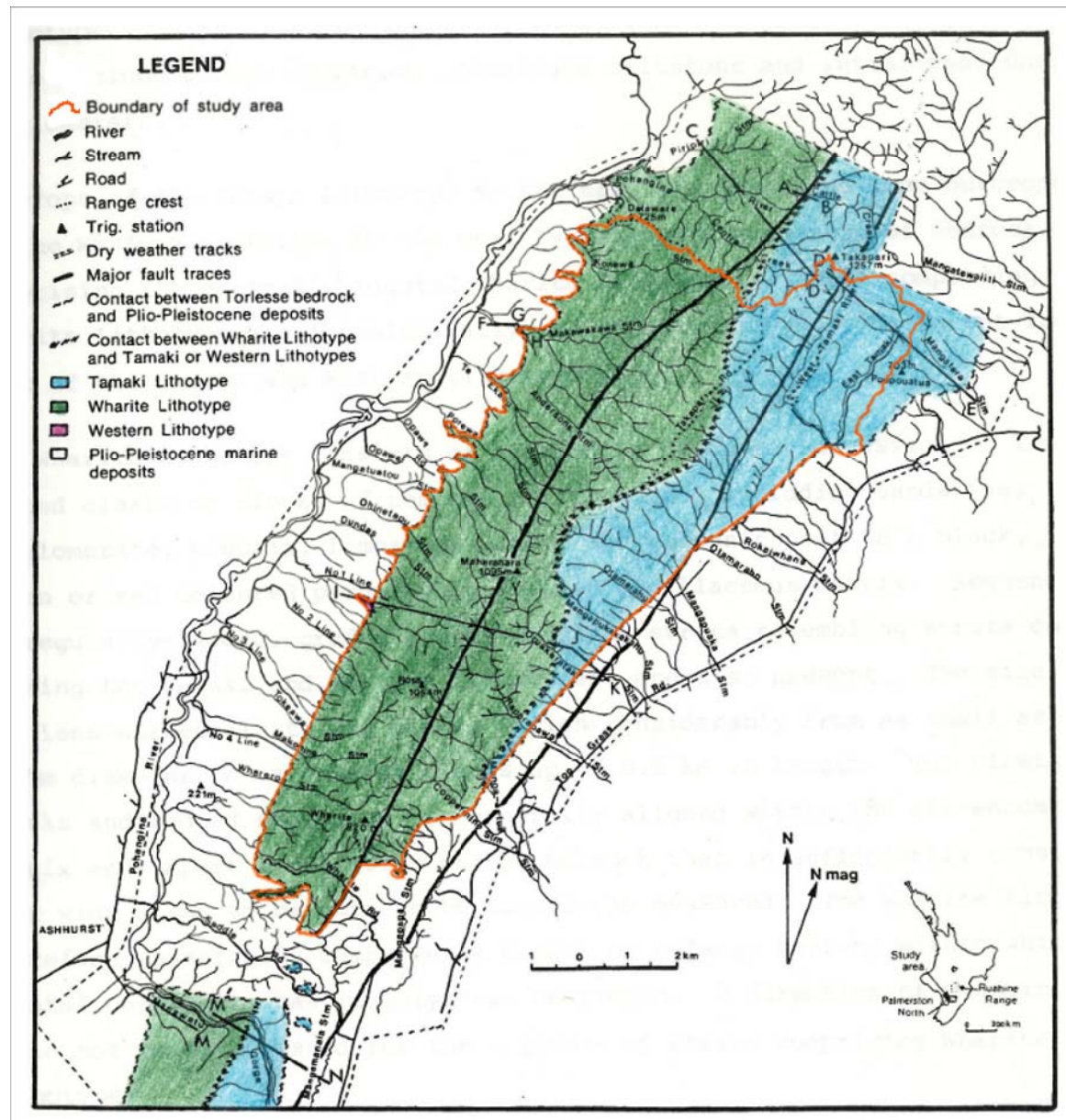


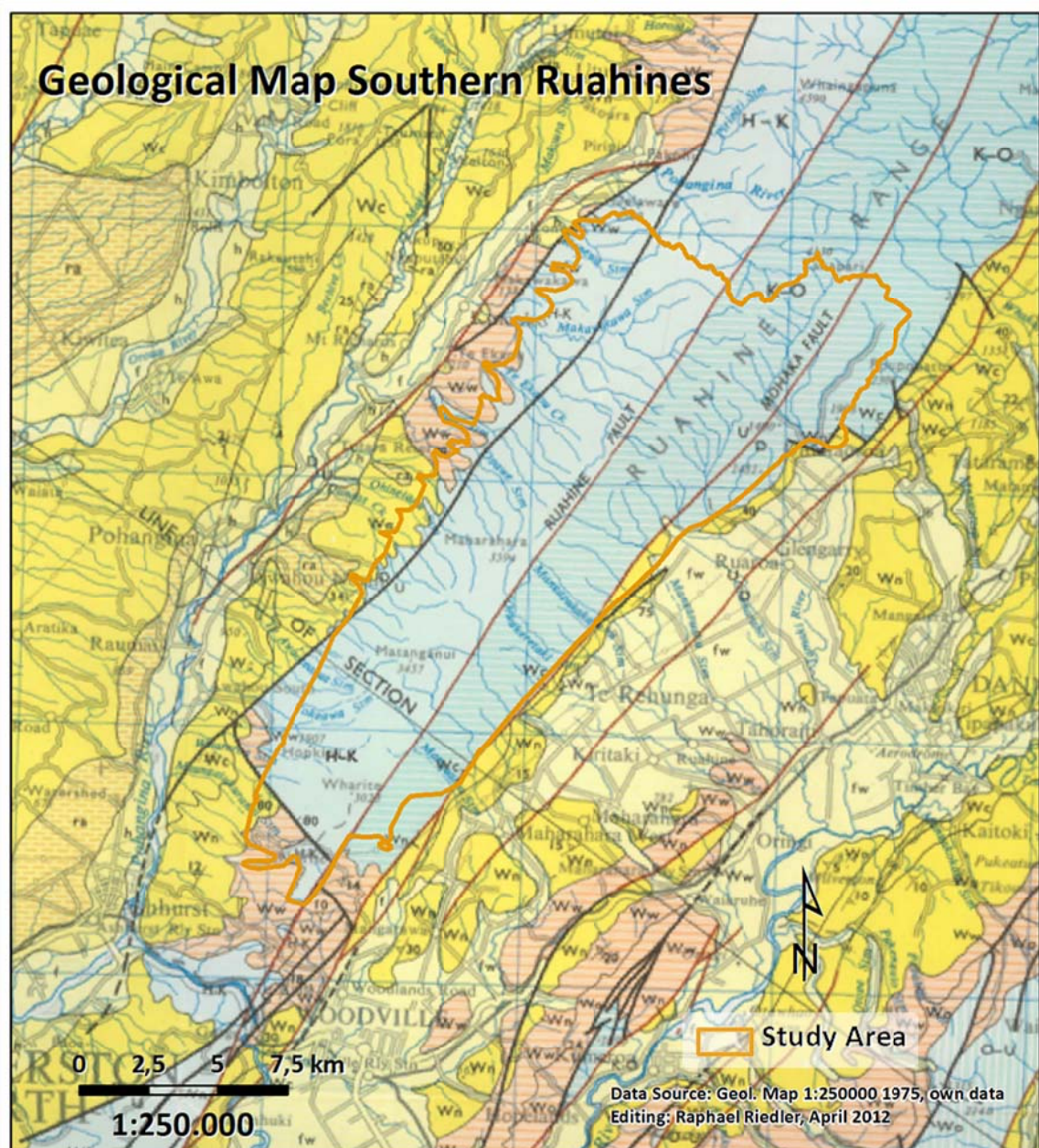
Figure 3.4: Map showing the Torlesse bedrock lithotypes in the Southern Ruahines as well as the study area that partially was derived from these lithological parameters adapted after Marden 1984

The geological map of the Southern Ruahines is pictured in Figure 3.5 and shows the geological units on a rather small scale of 1:250000. The Southern Ruahines and circumjacent lowland areas depicted on this map are represented by ten different lithological units. The two main bodies comprising the elevated parts of the horst

structure forming the Southern Ruahines are two different greywacke sandstone units both of Jurassic age separated by the Ruahine fault line. On this map the age difference towards the adjacent plains can be seen. The maximum age gap between these range-forming rock and the surrounding sediments counts up to 145 million years (Heerdegen and Sheperd 1992, Walker and Geissman 2009). This pronounced difference in material and age is connected to the tectonic movements which includes subduction and rise of the North Island as well as degradational processes (Kingma 1974).

Especially near the main streams in the area the Oroua, the Pohangina, and the Manawatu very young Holocene sediments are dominating.

The NE orientation of the ranges in general is also reflected by the trend of the two main greywacke units. The geology is also apparent in the landscape and relief of the area. The harder, older greywacke sandstones generally are higher elevated and develop steeper flanks than the other units. Besides bedrock outcrops, mainly at cut road sides, incised river banks and slope failures, these features help to orientate in the geological setting of the region (Marden 1984).



GEOLOGICAL REFERENCE

Lithology		HOLOCENE PLEISTOCENE
f	Undifferentiated alluvium in estuarine, swamp fluvial, or beach deposits; and in lowest terrace systems.	
h	Medium height terraces; Non-marine, undifferentiated, sandy gravels, sands, silts (tuffaceous).	
ra	Rapanui Formation; Basal conglomerate, dune sands, volcanic and marine sands, lignite bands.	
Wn	Marine, fossiliferous sands and silts with thin limestone horizons. Limestone usually recrystallised with sporadic greywacke pebbles.	HOLOCENE PLEISTOCENE
Ww	Coquina limestones, with or without greywacke pebbles in upper part of stage. Conglomerates, calcareous sandstones and siltstones in lower part.	
K - O	Alternating argillites and sandstones. Massive sandstones. Spillites. Spores.	PLIOCENE
fw	Woodville Alluvium; Fluvial deposits in Woodville area, laid down by Manawatu river system and locally accumulated through damming up of Manawatu Gorge.	
Wc	Gravels, sands and silts with or without pumice bands, either in marine sequences or in much dissected high terraces. Terrace gravels strongly weathered.	PLIOCENE
Wo	Light blue grey, fossiliferous, calcareous sandy siltstones with occasional sandstone bands and lines of concretions.	
H - K	Alternating dark grey argillites and sandstones. Intricately folded. Spillites. Some conglomeratic bands.	JURASSIC

Figure 3.5: Geological Map showing the geological setting in the study area and its surrounding. The legend shows all present geological features. adapted from: Geological map of New Zealand, Dannevirke, 1975, 1:250,000.

The most important features in the tectonic setting of the Southern Ruahines are the two dominant fault lines, the Ruahine Fault and Mohaka fault, stretching through the entire study area. Their orientation runs subparallel to the general trend of the Southern Ruahines separating the two greywacke units from each other, and are also forming a natural boundary to the Quaternary and Pliocene sediments in the SE. They are plotted in the geological map depicted in Figure 3.5 and prolong the Wellington fault which splits further south, barely visible in the SW corner of the geological map. Another major fault neighbouring the study area in the SE is the Woodville Fault which commences NE of Woodville and reaches until the Mahuraunui Stream. One more NE trending major fault borders the Southern Ruahines in the NW and stretches from the village Pohangina until it reaches the confluence of the Piripiri Stream with the Pohangina River. Both main fault lines passing within the Southern Ruahines are dextral faults whereas the two bordering faults are reverse faults. The former type characterises a strike-slip fault, where the fault movement proceeds mainly horizontal and is right-lateral, although most strike-slip faults in New Zealand also comprise some vertical movement. The latter classification refers to dip-slip faults, which have a vertical movement, and the surface which is above the fault is moved up. Additionally, there are abundant smaller faults that will not be further explained in this work but have a major influence on the fracturing and small scale structure of the complex bedrock in the study area (Marden 1984, GNS – NZ active faults database 2012).

Some of the fault lines in the Southern Ruahines are quite distinct and thus clearly visible in the field as well as on aerial pictures. The Mohaka Fault is shown on a picture in Figure 3.6 near Maharahara village. It is clearly identifiable by the physical displacement forming a ridge.



Figure 3.6: aerial picture of the Mohaka Fault on the eastern flank of the Ruahine Range, near Maharahara, GNS 2012

3.3 Geomorphological state

The preconditions for the prevalent geomorphological setting in the study area are mainly of geological and tectonic origin. Of course, climatic and anthropogenic influences are prevailing as well. The resulting relief in the Southern Ruahines is rough and comprises steep slopes as well as a pronounced partially deep incised river-system. As Van Westen (2004) states topography is one of the major factors influencing landslide behaviour, and the most up-to-date way to access spatial information on topography is through analysing DEM data. A good way to illustrate topography is by looking at the slope angle. The prevalent topography within the study area is thus presented in Figure 3.7. The inclination values are derived from a DEM raster file with a resolution of 15 m and range from 0° to 58°. Because of the raster cell size this map only gives a crude overview of the situation. Still the SE flank of the ranges can be identified as steeper than the more gentle NW side which is attributed to tectonic reasons (Heerdegen and Sheperd 1992).

The plateau in the centre of the ranges can also be distinguished by the green colour indicating a flat area. Split in 10° classes the biggest area is located between 20 and 30 degrees closely followed by the next class comprised of areas between 30 and 40 degrees. The accurate percentage and area of the respective classes is shown in Table 3.1. In total about two thirds of the research area have an inclination of at least 20° or higher.

Slope class (°)	pixel count	area (m ²)	area (km ²)	% study area
1: 0 - <10	109517	24641325	24,64	11,16
2: 10 - <20	219785	49451625	49,45	22,39
3: 20 - <30	320370	72083250	72,08	32,64
4: 30 - <40	286346	64427850	64,43	29,17
5: 40 - <50	45342	10201950	10,20	4,62
6: >50	244	54900	0,05	0,02
Sum:	981604	220860900	220,86	100,00

Table 3.1: Slope classes for the Southern Ruahines. The pixel size is 15 x 15m and equals 225m², calculated using Massey University data.

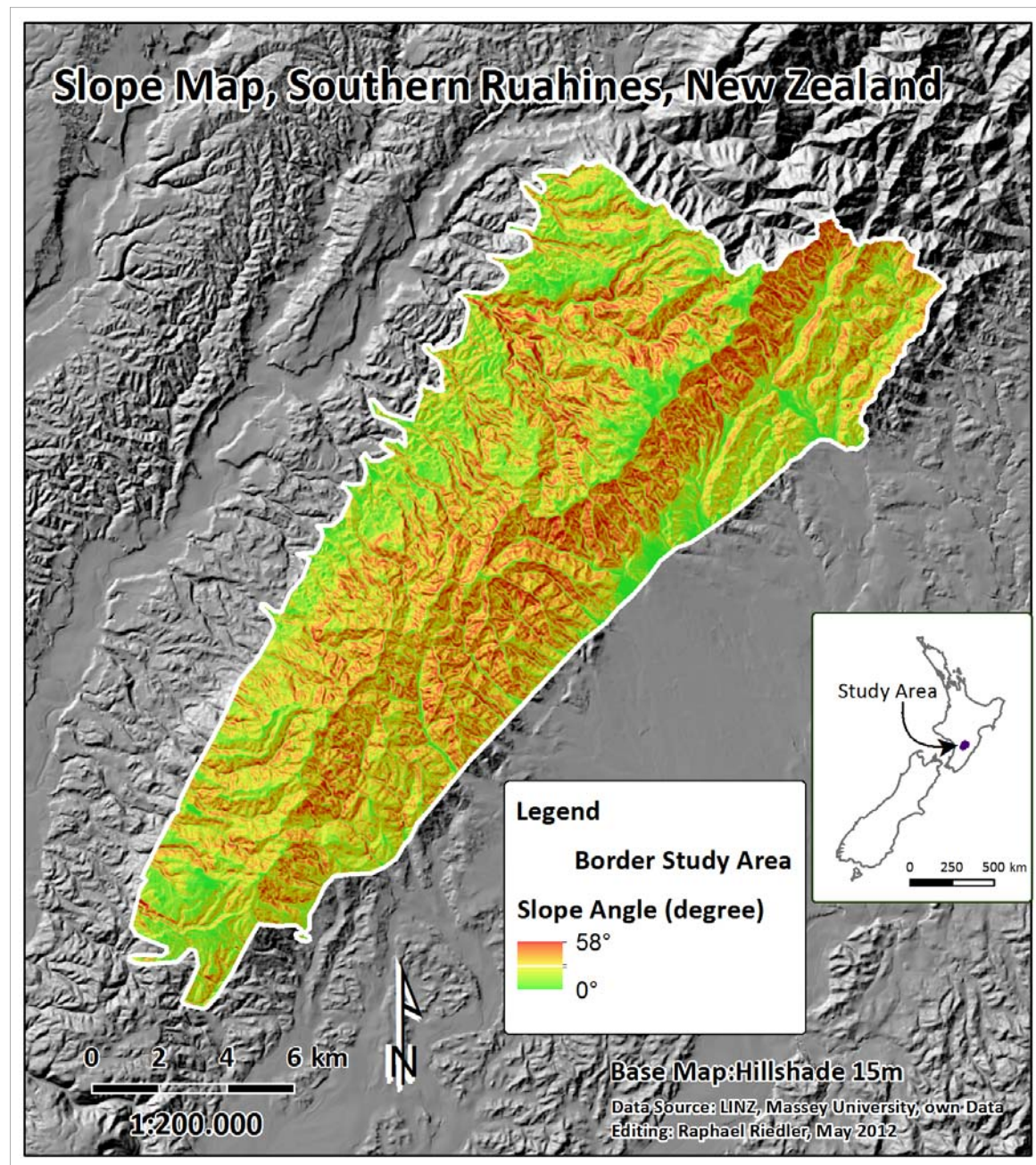


Figure 3.7: Slope map of the Southern Ruahines. Slope layer is set to 30% transparency and has a raster cell size of 15m.

Of course, valley flanks can exceed the slope value of 58° in the study area, and also do at various locations as revalidated during my field observation. At some places mainly at freshly eroded features they can reach up to a gradient of 90° for small parts of the hillside. At some locations undercutting due to gravitational mass movements also

produce small patches of overhanging soils. This is connected to the stabilisation of the top layers by vegetation and the accompanying root system.

This steep relief which was formed by fast tectonical uplift and subsequent rapid incision of rivers and streams resulting in oversteepened valley slopes is an important precondition for further physical processes going on in the region (Grant 1983). Additionally, the length of the individual slopes is another preconditioning factor for slope stability (Marden 1984). Further details concerning the relation of slope and landslides will be discussed in chapter 6.1.3.

In accordance to the tectonic activities, earthquakes are common in and around the Southern Ruahines influencing the appearance of the landscape in the study area (Stephens 1975). The displacement along the fault lines is only one consequence. Also slope failure can be triggered by them. Stephens (1975) did some more detailed investigations concerning the influence of earthquakes on the ranges. Even though these activities definitely have an influence on hillslope stability, accordingly to Grant (1983) these impacts are minor.

3.4 Hydrology and climate

The whole study area drains into the Manawatu which starts on the eastern side of the Ruahines some eight km NE of the study area, and has a catchment area of 5947 km² (Te Ara encyclopedia, 2012). On the western side of the Southern Ruahines all waterways first flow in the Pohangina which joins the Manawatu just after the Manawatu Gorge near Ashurst. In the study area itself there are multiple small rivers and torrents draining the ranges. On the eastern side of the range the rivers are steeper and shorter while they are more gentle and longer on the western side. Their flow is alternating because of the changing precipitation regime across the year (see Figure 3.8 and Figure 3.9) and in particular due to high intensity rainfall events (Marden 1984). Generally, there is a high density of rivers and streams prevalent due to the average rainfall amount that is high in the ranges. They are rising up to 3168 mm per year in the most elevated parts of the

study area as shown in Figure 3.10. Most of the bigger rivers flow perennially while some small torrents in the more elevated part of the Southern Ruahines are only activated during short periods. Some of the streams disappear at the range front because they are percolating into unconsolidated gravel (Marden 1984).

The climate diagram for Palmerston North shown in Figure 3.8 was compiled by using the monthly mean temperature and precipitation from the 30 year period between 1981 and 2010. It gives a representative example of the prevailing climate in the lowlands adjacent to the Southern Ruahines showing the low seasonal temperature variety. The difference comprises only 9,7°C between the coldest month of July with an average air temperature of 8,5°C and the warmest month, February where the average temperature rises up to 18,2°C. These conditions can be defined as maritime climate (Wright et al. 1993). This goes along with the visible rainfall patterns showing rather high activity throughout the whole year with an indistinct maximum in summer (December - February). More precisely in December with 95,6 mm immediately followed by the minimal rainfall per month measured in January accounting 55,1 mm and thus comprising a difference of 40,1 mm. There is no strong seasonal variability relating to the constant moist airflow arriving from the coastline which is located about 33 km east of Palmerston North. Instead, three mild peaks in June, September – October and December can be identified. Both, the mean annual temperature of 13,2 °C and the total annual precipitation of 899,7 mm are moderate.

Generally, it has to be kept in mind that the climate in the Southern Ruahines is not only colder but also wetter than in the surrounding lowlands and plains (Mosley 1977, Marden 1984, MacDonald-Creevey 2011). This can be seen in the climate chart for Wharite Peak (Figure 3.9) which is situated in the study area (for exact location see Figure 3.10) and is representative for the Southern Ruahines. At Wharite Peak the crest running along the ranges has its first summit and can be considered to start here. Concerning the precipitation patterns this trend is supported by the map shown in Figure 3.10 where a rising amount of rainfall is occurring towards the centre of the range correlating with an increased altitude.

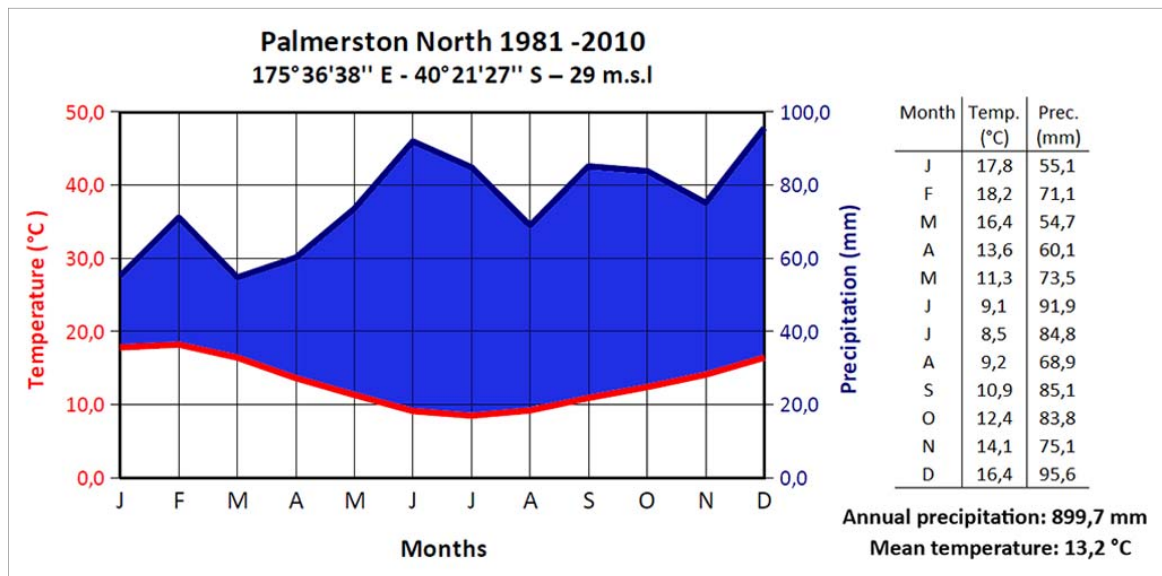


Figure 3.8: Walter-Lieth diagram for Palmerston North. The relation between the y-axis for air temperature (red line) and precipitation (blue line) is 1:2 and the blue colored surface indicates a humid climate. Own illustration based on NIWA data, received online from the National Climate Database (May 2012).

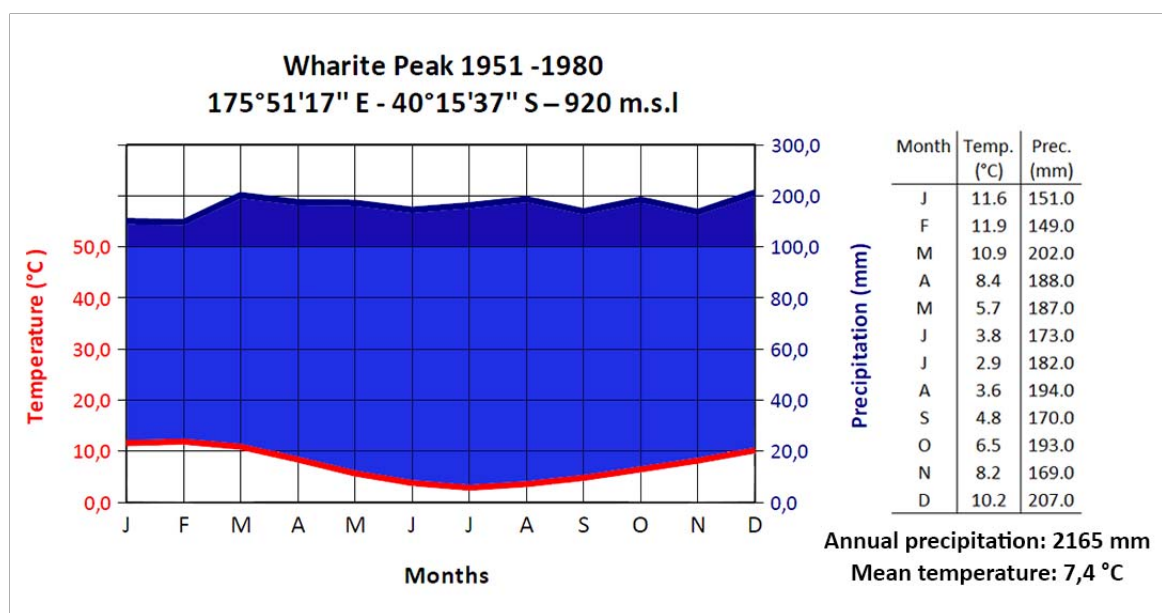


Figure 3.9: Walter-Lieth diagram for Wharite Peak. The relation between the y-axis for air temperature (red line) and precipitation (blue line) is 1:2 and the blue colored surface indicates a humid climate. Note, that the axis interval for precipitation changes after the value 100 from 20 to 100 units per segment. Own illustration based on NIWA data, received online from the National Climate Database (May 2012).

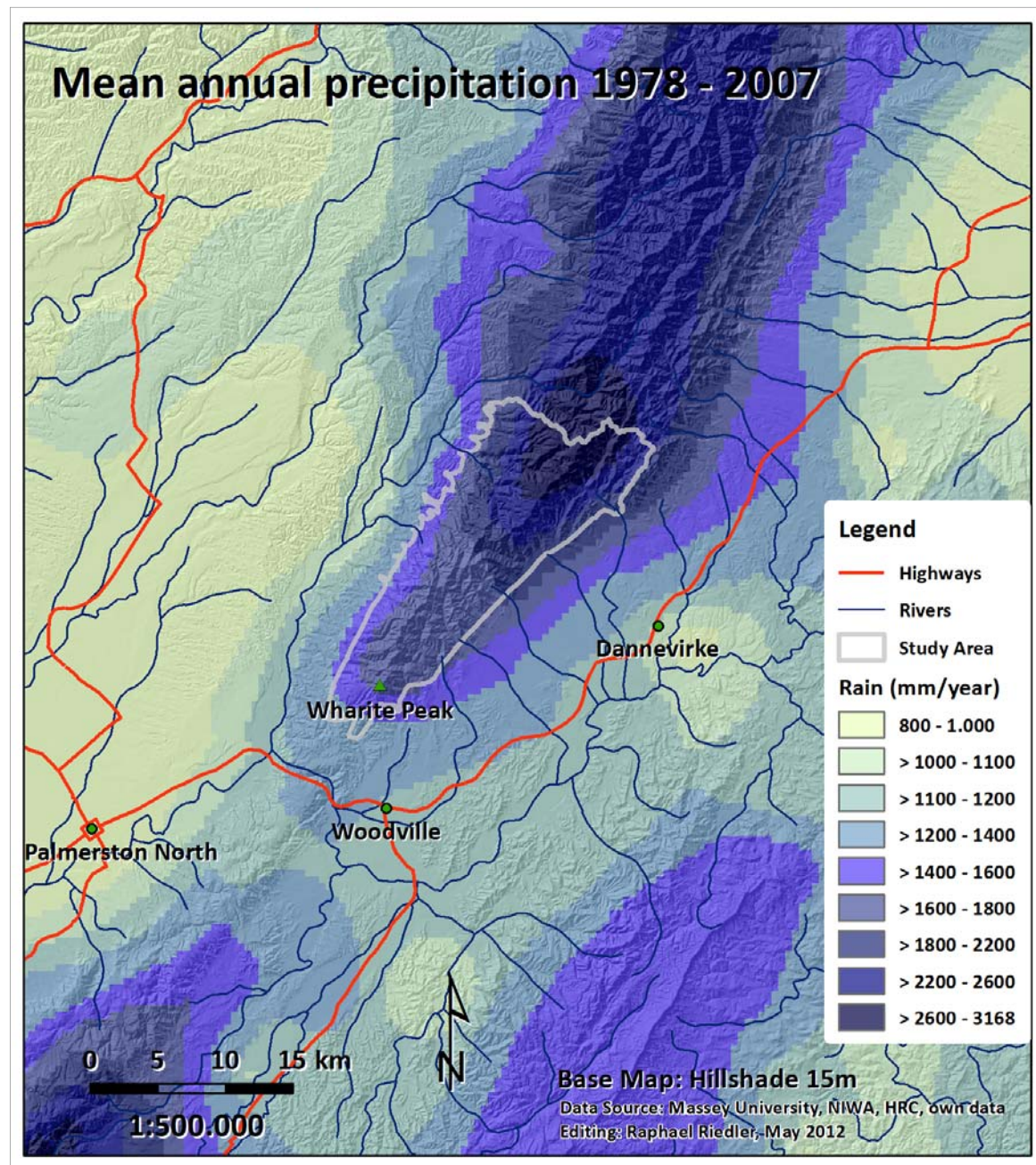


Figure 3.10: Precipitation map of the Southern Ruahines. The mean annual rainfall amount in mm is calculated from the periode 1978 – 2007 and displayed in a 500m resolution raster file.

The precipitation map in Figure 3.10 is derived from a raster file with 500 m grid size compiled by NIWA. The classification thresholds for the illustration were chosen manually to account for the big differences in mean annual precipitation between the lowlands and

the crest of the Ruahine Ranges. In the lowlands adjacent to the ranges values just over 800 mm per year are widespread rising up to the maximum of 3168 mm near Takapari peak comprising a difference of more than 2300 mm between the lowlands and the highest parts in the Southern Ruahines. Thus, it can be concluded that the Ruahine Range and the Tararua Range are acting as a meteorological divide. The simplified river drainage network shows a multitude of rivers draining the ranges towards SE and W/SW.

Wind speed as well as cloud cover, rainy days and solid precipitation such as snow are also greater and more variable in the Southern Ruahines than in the adjacent lowlands (Elder 1965, Mosley 1977, Cunningham 1981, Marden 1984).

One aspect which has to be emphasized is the increased cyclone intensity in the Ruahine Range mainly in summer and autumn. By cyclones, intense rainfall events which last up to 5 days are included. In this short period severe amounts of precipitation, often over 300 mm were recorded. For example during the cyclone Alison the largest three-day rainfall in the Ruahine Ranges accounted up to 612 mm (Grant 1978, Marden 1984).

Grant (1983) also stated that the cyclone frequency correlates with the air temperature, and that in warmer periods stronger cyclone activity is registered.

In total it can be concluded that weather extremes are more distinct in the ranges and climate generally gets colder and wetter with higher elevation.

3.5 Landcover and vegetation

Most of the study area is covered by woody vegetation or tussocks. The variety ranges from native species to introduced plants as well as human planted breeds comprising both native as well as exotic species. One of the noticeable features concerning the vegetation distribution is that there are altitudinal belts with distinct plant composition. In the highest altitudes tussock grass dominates. In the Southern Ruahines, snowgrass (*Chionochloa pallens*) and red tussock (*Chionochloa rubra*) can be found but are only growing in the most elevated parts of the ranges and thus therefore are spatially limited. The dominant species above 900 m.s.l. is leatherwood (most dominant: *Olearia colensoi*

and *Senecio elaeagnifolius*), a dense scrub which is widely spread in the whole study area. Below this altitude kamahi (*Weinmannia racemosa*) together with rimu (*Dacrydium cupressinum*) and rata (*Metrosideros robusta*) which all are broad-leaf trees are most abundant (Elder 1965). This fact also helps orienting in the field because the approximate elevation can be estimated by observing the vegetation.

Besides these plants that are all native (Elder 1965, Te Ara encyclopedia 2012) a multitude of introduced plants are present in the study area. The most abundant are introduced exotic grasses which cover the farmland in the lower parts of the Southern Ruahines and are used for livestock. Within the ranges different exotic species were planted by the New Zealand forest service after 1965 especially in the 1970's in the steeper parts of the ranges to stabilize fresh landslide scarps (Cunningham 1979, Strand 1981). Therefore different pine trees were used, but mainly radiata pine (*Pinus radiata*). In the lower parts of the Southern Ruahines especially in the crossover zone between the woody vegetation covering most of the steeper slopes and the fertile farmland they have planted willows (*Salix incana*) and poplars (*Populus alba*) from 1965 on to act as gravel reserves to stabilize the river bed and absorb transported sediments. Both aerial seeding as well as manual planting was applied (Cunningham 1979, Strand 1981).

The present vegetation cover in the study area roughly can be described by two classes comprising forest, shrub and tussock grass in one category and exotic grassland for pasture in the second class. As an example, the difference between these two classes is shown in Figure 3.11a. In 2005, 176,59 km² or 79,95 % of the area reside in the first class – woody vegetation, where 44,29 km² or 20,05 % can be found in the other class - pasture. This is a rise of 0,1% in comparison with the 1999 value where 176,38 km² were covered by woody vegetation. These results were obtained by aerial picture interpretation of the 2005 and 1999 aerial pictures received from Horizons regional council. Most of the area comprising woody vegetation is part of the Ruahine Forest Park administered by the DOC and set up in 1976 to protect plants and create recreation space (DOC 2012).

An important aspect in connection with this work, which is also explained in 2 - Landslides, is the stabilizing effect of vegetation on the hillslopes. Thus many authors discussed the changes of the vegetation in the study area including the involved factors altering the system.

The first severe change was human-induced and occurred when the European settlers cleared wide parts of the native forest on the North Island to set up farmland and pastures. Most of the forest on the foothills of the Southern Ruahines was felled in this clearance. In the period of the 1870s and 1880s most of the native forest in the lower parts of the Southern Ruahines has been cut down (Cunningham 1979). Besides this full clearance in the lowlands the forest within the ranges was severely influenced by milling. Here mainly big adult trees were lumbered, thus leaving mainly younger and medium high trees as well as dense shrubland behind (Marden 1984).

The second main impact occurred because of the release and invasion of exotic animals. The first animal which was introduced to the ranges in 1880s was the Opossum (*Trichosurus vulpecula*) followed by the red deer (*Cervus elaphus*) around 1900. Also goats (*Capra hircus*) were present in the Southern Ruahines after the 1920's even though their numbers were limited (Elder 1965, Cunningham 1979).

At the beginning the numbers of introduced animals were small and thus didn't influence the vegetation structures in the higher elevated parts of the Southern Ruahines. However, the amount of exotic animals, especially deer and opossums, increased significantly in the early 20th century. They started to alter the vegetation composition and deteriorate the forest cover in several areas. Deer seriously harmed undergrowth vegetation, seedlings and scrub, whereas opossums were mainly responsible for canopy defoliation where rata and kamahi trees were damaged most. Under this influence the vegetation cover got seriously harmed, and in some areas the forest died and was replaced by tussocks and shrubland. Another negative effect caused mainly by deers and goats is the delayed revegetation of landslide surfaces (Elder 1965, James 1973, Mosley 1977, Schumm 1977, Cunningham 1979, Marden 1984, Bellingham and Lee 2006).

Due to the massive influence of the newly introduced animals on the vegetation in the Southern Ruahines the department of internal affairs started to take countermeasures against the present mammals in 1938 including hunting and trapping. In 1956 this task was forwarded to the New Zealand Forest Service responsible for such work after that date. Their efforts were even intensified and after 1959 also aerial poisoning using 1080 coated carrot pieces was included. Despite the noxious animal control also revegetation measures, were taken (Elder 1965, Strand 1981).

Although all these studies show a relation between animal introduced vegetation deterioration and increased erosion processes there are further arguments appearing in the literature. Mosley (1977) points out that vegetation deterioration can be one of the most severe reasons for the increase of shallow debris avalanches in steep terrain. However, the exact relation between introduced animals the loss of vegetation, and the increased erosion rates in the Ruahine Range is still to be investigated and further data needs to be collected. Grant (1983) even completely contradicts the theory that introduced animals have an influence on the erosion processes in the Ruahine Ranges. He states that all changes of material supply and active erosion scars is due to climatic fluctuations and climate change. This is objected by Cunningham (1979) who states that before 1920 apart from localized storm and fire damage there was no sign of unhealthiness in the forest cover.

The argument of the strong influence of storms and climate change is also brought up in the work of Mosley (1977) where it is stated, that changing weather conditions could generally have weakened the resistivity of the forest whereas the animal damages could act as a triggering mechanism. Also Marden (1984) describes that wind damages are visible, especially within larger trees that often stand alone.

Another component altering vegetation composition are forest fires. These occurred at times within the study area even before the European settlement and sometimes happened close to known Maori routes (Cunningham 1979). These fires have been responsible for patchy vegetation patterns in some areas throughout the ranges but seems to have had little effect on the forest cover in the ranges (Elder 1965).

The state of the forest in the Southern Ruahines at the time of the field investigation in 2011 varies significantly. In some areas the zonal distribution of plant associations as described in the most detailed publication by Elder (1965) still are existing and intact like on parts of the western flank shown in Figure 3.11b.

In other parts though, the deterioration of the vegetation seems to have continued since 1965 and is now dominated by shrubland and small trees including some scattered clusters of pine trees as shown in Figure 3.11c. The area shown in the latter figure was still covered by more medium and high trees in the beginning of the 1980s (pers. communication M. Marden 2011). The dense leatherwood, dominant on the ridge of the Southern Ruahines seems to be in good condition.

a



b



c



Figure 3.11: Documentation showing current (2011) state of the vegetation in the Southern Ruahines. The picture shown in (a) was taken at the ridge on the Takapari road overlooking the Dry Creek catchment towards SE, also shown in the field site map, Figure 3.12. The green, round bush in the left bottom corner is part of the healthy leatherwood cover. In the valley woody vegetation, with scarce tree groups as well as single trees can be seen. Some landslide scars as well as the river bed is clearly visible between the vegetation. The light green area in the back of the picture is pasture, mixed with pine tree patches in dark green. In (b) dense, intact forest, mainly consisting of native plants can be seen. The location is at the entrance of the Takapari road into the Ruahine Forest Park on the western side of the Southern Ruahines. The picture shown in (c) was taken from the left lateral side of Dry Creek valley looking towards SSW also shown in the field site map, Figure 3.12. The human planted pine trees in the starting zones of debris slides for stabilization measures could develop in some areas. There is a significant size different visible between the introduced pines and the native forest cover, signaling a difference in resilience towards external factors.

Nevertheless which reason underlies the deterioration of the vegetation cover in the Southern Ruahines, it still is present and its influence on the hillslope stability as discussed in chapter 2 - Landslides is evident and therefore has to be considered.

3.6 Choice of field sites

Even though landslides are apparent throughout the whole research area they are unevenly distributed. This occurs due to different conditions of the specific sites which can be attributed to a multitude of factors explained earlier in this chapter. At the time when fieldwork was carried out, in summer 2011, there were only a few small catchments where no fresh landslides were present.

So within this large range of possible field sites subsequent factors needed to be considered and led to the present decision.

First of all, the purpose of the field work was to obtain accurate surface data for landslide scars of fresh landslides to be able to calculate their volume. Secondly, the mapped features obtained during the aerial picture interpretation had to be verified in the field.

Slightly different types of fresh landslides concerning their shape and depth were identified in the stud area. For a better representation of later calculated landslide volume these differences should be covered during the field work. To account for this differences, four landslides were chosen for accurate ground surveillance.

Another crucial factor for the choice of field sites is the accessibility. The major landcover in the Southern Ruahines is dense scrubs and trees, which are not very accessible without additional tools. What is more the bulky survey gear needs to be carried to the respective site by foot. As the path network within the Southern Ruahines is limited, mainly the river system is serving as walkways. Therefore, accessibility to the landslides from as well as a reasonable road connection to the stream bed or available trails has to be provided. In many cases the fresh landslides are situated in the steep valley heads making them badly accessible and hence are inappropriate for investigations.

One factor which is important but complex to determine during preparations or decision finding process is the GPS reception in the field. Accordingly to steep topography, and the different technical factors explained in chapter 4.1.1 - GPS and tachymeter field survey the reception can be limited. Due to the complexity and the accompanying high uncertainties this aspect was only marginally considered in the decision process. The intensely analysed field sites are now depicted in the following map, shown in Figure 3.12 and will further on be referred to as landslide one to four.

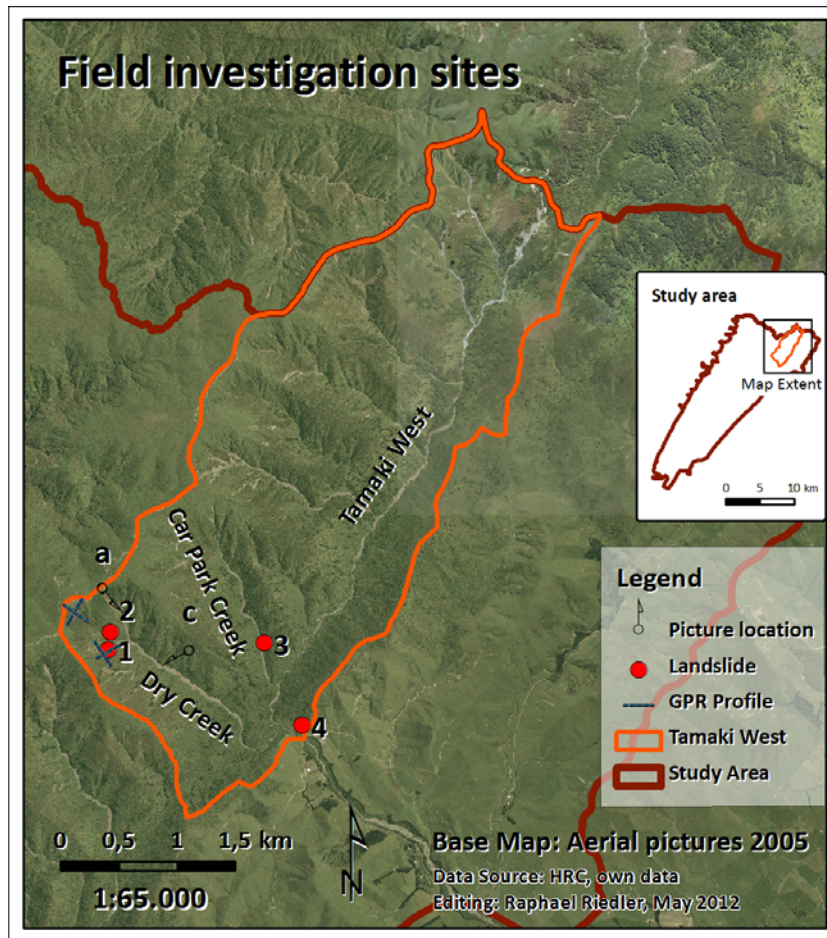


Figure 3.12: Location of landslides investigated by accurate surface surveillance. The two picture locations for vegetation identification present in the Tamaki West catchment and their line of sight are included.

Furthermore, field surveys in different locations throughout the whole Southern Ruahines were carried out to validate the landslide mapping results as well as to get an impression of the condition of the vegetation and the stability of the hillslopes. The parent material comprising the regolith and the form and character of the slope failures was inspected in different locations throughout the study area.

4 Methods

In the following chapter the used methods will be stated to get a better understanding of the processes leading to the results of this work. By documenting the specific methodical steps, it is intended to make the results transparent and replicable.

Throughout the thesis, different field methods as well as distinct digital data processing tools and methods were applied. Within the former, the surface survey procedure, using differential GPS and a robotic total station will be explained. Moreover, a set of different software programs were used to process the obtained data as well as provided additional data. This was mainly done in different GIS (Geographic Information System) programs such as ArcGIS 9.3, later version 10 or Surfer 9. For graphic refinement Photoshop CS6 and GIMP 2.8 were used and LibreOffice Calc 3.5 was applied to generate charts and graphs.

The purpose of the used techniques is to gather physical data of the investigated landslides and to make a comparison between them in the first step. In the second step, the processed field data and digitally computed data are compared by applying GIS programs to get an overview of the relevant processes in the research area.

Because of German software versions, in the entire work commas (,) are used to divide numbers and their decimals. Points (.) are used as a thousands separator to subdivide numbers bigger than 1000 to facilitate reading in this way: 1.000

4.1 Surface surveillance

An important part of the work was to determine the volume of the landslide-transferred material. Therefore, an accurate surface survey of characteristic landslides in the Southern Ruahines was an essential approach to derive digital elevation models. Using the DEMs, volume values for the analysed landslides could be derived and moreover, potential values for the research area could be deduced.

At the investigated landslides the fresh failure rupture was measured. This means the whole area that can be related to the landslide scar until the beginning of the transition or deposition area.

4.1.1 GPS and tachymeter field survey

During the field work the actual data generation was carried out. For this survey a differential GPS system as well as a robotic total station was used to register the wanted information.

Under the limiting conditions regarding the GPS satellite reception mainly due to a combination of steep and rough topography as well as due to limited satellite availability, the relative surveillance method using a tachymeter was necessary to complement the georeferenced data acquisition by the GPS device. Due to this advantage, features or points which are collected with the GPS system always can be located absolutely on a map or in a GIS program. However, this advanced recording method is only available if enough satellites are in the reception radius of the GPS antenna. Tachymeter received data also can be georeferenced if the reception position of the device is known.

In the present study three out of four surveyed landslides were entirely measured using the robotic total station. Within these three, two device positions were determined by triangulation of known GPS locations (for landslide number two and four, Figure 3.12, map field investigation sites) and thus the measured points could be determined absolutely. In one valley there was no GPS reception in the entire valley, and the effort to get the position using the tachymeter for a point to point measurement throughout the entire valley would have exceeded the benefit. So landslide number three (Figure 3.12) was only measured relatively. For the largest landslide, number one (Figure 3.12), both GPS, and the total station were used because of visibility and reception reasons. This particular landslide scar has a very irregular shape which can be seen in Figure 4.3 and at one spot in the very south of the landslide the affected area disappeared behind a bend referring to the tachymeter position. Because of the ragged terrain the suitable spots to

set up the total station were limited and so climbing up the landslide to use the GPS to gather additional points was considered the best solution.

The used GPS device is a Trimble R8 GNSS receiver (rover) as well as a Trimble R8 base station (base) equipped with a radio system for signal transmission between the rover and the base (Figure 4.1). The data acquisition was carried out using the real time kinematic (RTK) mode where the transmission of the base station signal to the rover in real time allows to record precisely located GPS data points. All taken points were stored in the New Zealand map grid. For further explanation concerning the geographic coordinate system, see chapter 4.2 referring to the mapping procedure in GIS and chapter 5 referring to the Data properties.

The initial setup of the GPS system is crucial to get accurate positions in the research area. First, the base station is set up at a well accessible position with good satellite reception. This setup includes the Trimble antenna and the radio with antenna. Both fixed in a tripod as shown in Figure 4.1. It has to be assured that the satellite reception at the base is adequate for the entire analysis period. Generally, four satellites are the minimum requirement to receive an accurate position using a GPS system. Depending on the current satellite constellations and technical limitations of used gear, the number of necessary satellites can rise (Czerniak and Richard 2002). In some cases it has been observed that a maximum of six satellites are required to achieve a satisfactory accurate result at the rover position. This can be explained by the fact that the constellation of satellites around the globe is focused on an optimized coverage of the higher populated northern hemisphere. In addition, the orientation of the subcatchments containing the investigated landslides is SO to SSO. As a result, some of the satellites in coverage are received from a very low angle above the horizon, and therefore are not ideal for an accurate positioning. Another problem can result from poor geometric configuration when some satellites are received in an acute angle and thus provide poor accuracy (Czerniak and Richard 2002). These factors are further influenced by the changing satellite constellations throughout the day, and the fact that most valleys narrow towards

the ridge. As a consequence, the signal can be lost because of a changing satellite constellation or topographic setting.



Figure 4.1: Left picture: Trimble R8 base station with radio device on a long metal pole on the left side, set up at the ridge above Tamaki West Catchment. Right picture: Trimble rover consisting of the antenna (white) and the data logger (yellow) fixed on a 2m carbon fiber pole including the spirit level on the small black triangle.(own picture 2011 and online rataling site azannunci 2012)

The rover consists of an antenna which is mounted on top of a two meter carbon fiber pole and a data logger (Figure 4.1). This flexible setup enables easy handling of the device even in rugged terrain. For higher accuracy a circular spirit level is installed at the crank holding the data logger. For data acquisition, the rod is placed upon the wanted location in straight vertical position, and after entering the point name the easting and northing values as well as the elevation in meters are saved on the data logger by pressing the enter button.

If there is restricted GPS reception or the accessibility to the measured features is limited due to topography or vegetation, a robotic total station is used to obtain data points. The used model is the Trimble S6 DR300+, which is shown in Figure 4.2. In the best case, the location at which the tachymeter is set up for measurements on a tripod can be surveyed

by the differential GPS device. In that case a second known point is necessary, and the S6 can be accurately located by triangulation between these two spots resulting in the possibility to obtain georeferenced data points. If that is not the case the survey marks are stored in a relative system and can only be used for calculation purposes.

There are two options for data acquisition after the setup and adjustment of the total station on the designated position. The first option includes a highly reflective prism similar to the one shown in Figure 4.2 on a height adjustable rod with a spirit level. This prism is stopped over sections to be measured and levelled using the bubble. If there are two surveyors present the data logger can stay at the total station. Alternatively, it can be attached to the prism which has the advantage that the survey can also be carried out by a single person as the S6 is able to auto-detect the prism and has a “follow prism” function. By pressing enter at the logger after successfully adjusting the total station points can also be stored remotely. However, it is faster to have a second scientist working at the tachymeter because the auto detect process can be time consuming and obstacles like trees or topographic features can cut the contact between the prism and the station. In this case the manual adjustment can speed up the auto detect process significantly because the tachymeter starts the detection process prism near it's current fix.



Figure 4.2: Left picture: Installed Trimble S6 DR300+ robotic total station at work. The data logger in the scientists left hand is remotely connected to the station. Right picture: Highly reflecteable 360° prism used as physical target for point measurent. (own picture 2011 and flickr picture database 2012)

The second option to receive point data using the total station is to use the reflectance of the operating laser. For the surveyed debris slides the time of flight – pulsed laser technology was used. This option is favourable if an area of interest is difficultly or not at all accessible by foot to measure the points by GPS or to place the prism as a target. The precondition is that no obstacles occur between the total station and the sections to be measured and that the maximum range of 300m for light rock is not exceeded (Trimble data sheet 2012). A good option is to install the surveillance position in a manner that the landslide is measured from the opposed valley side or on another point where the majority of the landslide area is visible (Höglund and Large 2005).

Once the data points are collected by any of that means and saved on the logger, the storage device is connected to a laptop where the information can be downloaded. This was done using Trimble Geomatics Office. Trough that procedures the accurate position of more than 3000 surveyed points was acquired.

4.1.2 DEM derivation

For further usage the raw point data obtained during the field work needs to be processed and converted. One important step for further calculations and subsequent GIS analysis is to produce a planar Dataset. For the needed purposes a DEM is most suitable. The DEM raster is produced using the Golden Software Surfer version 9 program.

As a first step the raw data quality was examined to determine exclusion criteria and to get an adequately accurate result. In the imported raw data all information as shown in Table 4.1 is included. The most important information for this survey are the northing, easting and elevation values because they determine the position and mean sea level of the recorded point. Furthermore the feature code is useful because it is entered during the survey and provides additional information about the investigated site. The name field contains an automatically continued point-number which clearly identifies each point and aids in temporal orientation.

Name	Code	Northing	Easting	Elevation	Start_Time	Stop_Time	Hz_Prec	Vt_Prec	Min_Sats
1016	peg15	6116873,64	2766758,77	772,46	31 Oct 2011 12:55:44	31 Oct 2011 12:55:44	0,022	0,052	5
1017	spot	6116873,94	2766758,30	772,31	31 Oct 2011 12:56:09	31 Oct 2011 12:56:09	0,016	0,038	6
1018	spot	6116872,40	2766755,33	773,87	31 Oct 2011 12:56:27	31 Oct 2011 12:56:27	0,018	0,044	6
...	...	...	...	...	...	...	...	...	...

Table 4.1: Data properties of field data after transferring them on a computer device. Hz_Prec refers to horizontal and Vt_prec to the vertical precision of the GPS data. Min_Sats refers to the minimal number of satellites at the rover position at the data aquisition time. Start and stop time resemble because point data was recorded. For the points received by the total station only the first 5 fields contain values. Northing, easting and elevation as well as the accuracy values Hz_Prec and Vt_prec are displayd in meters.

For revalidation the exclusion criteria are defined by the horizontal and vertical precision values. The different values arise because of the satellite constellations at the moment of data acquisition as explained more detailed in 4.1.1. For the data points acquired using

the total station there are no values in that field because the precision is not dependent on external factors like satellites, but only on the technical accuracy of the device and the exactness of measurement (e.g. the fit of the spirit level, the penetration depth of the rod into the ground). The device accuracy for distance measurements of the S6 system in standard mode is $\pm 3\text{mm} + 2\text{ppm (mm/km)}$ and $\pm 10\text{mm} + 2\text{ppm (mm/km)}$ in tracking mode which is negligible for this approach (Trimble S6 Datasheet 2012) The maximum distance at which points were obtained using the reflectance setup of the totalstation was 245 m.

Generally, by using a GPS system horizontal is higher than vertical precision which is also apparent in the present study (Kaplan and Hegarty 2006). Before the measured points get converted to a DEM, they get reassessed. All important values included in the original dataset are displayed in Figure Table 4.1.

For further use, all data exceeding the thresholds of 0,13 m for horizontal precision as well as 0,13 m for vertical precision are excluded. These thresholds are chosen empirically with regard to keep as much information included in the calculations as possible, as well as considering the data accuracy. Out of 1272 surveyed data points for landslide one, 585 points were obtained using GPS measurements. From these 585 points 10 points excess these thresholds in one of the two values, and were thus excluded from further calculations. The mean accuracy for the 575 GPS-surveyed points which reside within the thresholds is 0,015 m for horizontal precision and 0,034 m for vertical precision. Considering the rough surface conditions of the surveyed landslides shown in Figure 6.18 these values are very good. The valid GPS points as well as the 687 tachymeter obtained points are shown in Figure 4.3 including the position of the robotic total station.

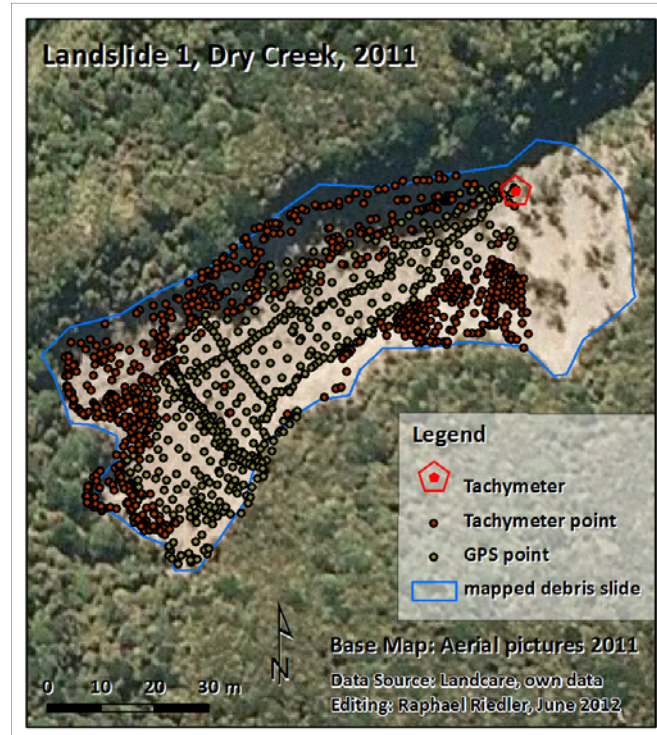


Figure 4.3: Example of investigated landslide including mapped and field data as well as the tachymeter position for this survey. Only valid data points are illustrated.

After the refinement, the data was available in processable form. The next step was to generate the DEMs for the respective landslides using the Surfer software.

First, the obtained field data had to be converted to a grid file with the wanted properties. The spatial information for each point was given in easting and northing values as well as the specific elevation value in meters for each point. The chosen grid size for the processed DEMs is 1 or 0,25 m. To determine the accurate DEM extent, the landslide-boundary, which functions as the calculation limit was digitised separately. The used gridding method to calculate the raster is triangulation with linear interpolation (TLI).

After compiling the grid file, several options to process and display the data in Surfer are available. The best way to get an overview of the DEM properties is to create a contour line map for the processed grid as done for the map shown in Figure 4.4.

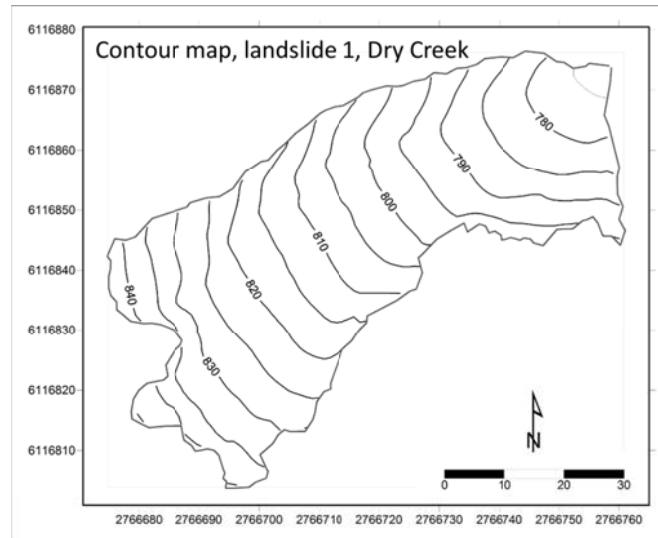


Figure 4.4: Contour map compiled from DEM derived from GPS and tachymeter points.

The compiled grids can be exported to other software like ArcGIS or processed directly in Surfer.

4.1.3 Volume calculation

One major step to derive an approximate volume for all the fresh landslides in the Southern Ruahines was to calculate the volume of the eroded material for the surveyed landslides. Using the already computed DEMs the volumes for the landslide were also calculated using Surfer 9 software.

To get the volume values, the known surface of the surveyed landslides was taken as the erosion base. As the missing material is not present any more at that location, the former slope surface of the undisturbed condition has to be reconstructed. For simplicity reasons, this is done by interpolating the slope surface through extracting the measured points which are located at the landslide boundary and interpolating a potential surface using the TLI method. Thereby, a second DEM for this plot is derived equally like in 4.1.2

explained. Through this approach, two clearly defined surfaces exist, one representing the potential state before the landslide appeared, and one representing the current state. Now, the surface representing the actual condition can be subtracted from the interpolated surface to obtain the volume eroded by the landslide. The calculation is carried out by an algorithm provided by the Surfer software for grid processing and the output file presents the results in text format. These individual values can also be applied to all mapped features in the study area. Therefore the area of the debris slide in a respective year just has to be multiplied with the calculated volume in m^3 for every m^2 .

4.2 Landslide mapping using aerial pictures and GIS

To get a broad dataset which covers the whole study area and shows its condition at different dates multiple sets of orthorectified aerial pictures were used to map landslides in the Southern Ruahines. Aerial picture interpretation still is one of the key elements of extensive landslide analysis and thus chosen for this approach. One of the biggest advantages of aerial picture interpretation is the long existence of aerial photography and long available time series (Van Westen 2004).

Further specifications about the data especially referring to their resolution, scale, date, extent and data provider will be elaborated in chapter 5.1.

The general process is the same for all the datasets, though there are slight differences in the chosen mapping scale due to the different resolutions and quality of the pictures. Another factor which distinguishes the mapping approach is the coloration, as some of the picture-sets are chromatic and some are in black and white.

Additionally the generated data was plotted on field maps which were overlaid by aerial pictures for field orientation similar to a map in Figure 6.4 but including a different element composition. With the aid of these maps further data could be obtained in the field and the mapped features could be revalidated. During the outdoor work in November and December 2011 the state of activity, the mapping extent and the connectivity of selected landslides were the main parameters investigated.

4.2.1 Mapping

The mapping was carried out manually utilizing the software ArcMap 9.3 and 10 which is part of the ESRI ArcGIS package. The advantage using this software is that also DEM treatment as well as further geoprocessing methods can be applied. The reason why the features were mapped manually instead of using an algorithm to detect the landslides automatically, is that expert knowledge still is more accurate than automated mapping procedures and thus preferable. Due to aspect and different vegetation and surface conditions, the spectral conditions of the aerial pictures change slightly within the dataset, what can be accounted for by the expert (van Westen 2004).

As the majority of data is available in the GCS New Zealand 1949 projection, this geographic coordinate system, New Zealand Map grid, is used for mapping purposes. Therefore data delivered in the Transverse Mercator – GCS_NZGD_2000 projection is transformed to New Zealand map grid using the “New_Zealand_1949_to_NZGD_2000_3_NZv2” command in ArcGIS. All processed data is available in one of these two coordinate systems.

Before the actual mapping process started, all available aerial picture sets were examined to get an overview of their quality (further discussed in chapter 4.2.4 and 5.1) and the extent of different visible features.

For an effective mapping procedure, Soeters and van Westen (1996 p. 142) state that *“The interpretation of slope movements from remote-sensing images is based in recognition or identification of elements associated with slope instability process.”* So in aerial picture interpretation differences between the actual investigated feature and the environment are used to identify the wanted features.

This is further underpinned by van Westen (2004) who points out that the spectral differences of slope failures and the vegetation is a crucial factor for landslide interpretation. All in such way identified debris slides are mapped in ArcGIS.

The vegetation cover is not only useful in identifying landslides, but also aids in determining the activity state of debris slide in the Southern Ruahines. The time span of

activity is determined by the following procedure, where it is taken into account how long a landslide scar needs to recover its vegetation cover in a way it is clearly identifiable on an aerial picture.

The maximum activity period of a fresh landslide determined in this study was calculated by a comparison of the mapping results from 1999, 2005 and 2011 in the Tamaki West catchment. These years were chosen because while including three sets, the time difference between the two external values is the shortest of all available pictures. The assumption is, that landslides which are not active in 1999, but are clearly identifiable as active in 2005 and are covered by an identifiable vegetation cover in 2011 again, show the maximum activity period. So a landslide fulfilling these criteria could have failed at any moment after 1999. Thus, it could exist for a maximum of 6 years until it got identified in 2005. After it was received, it had another 6 years time to establish a distinguishable vegetation cover until 2011. In total, this results in a maximum possible activity period of 12 years, where a landslide can be identified as recently active on an aerial picture. No information is included at which moment the landslide occurred or is noticeable vegetated again, only that it is not older than 12 years. Whenever results for the mapped landslides are presented for a single year, these refer to fresh landslides, which means that all values stated or illustrated appeared in a maximum time period of 12 years before the aerial picture was shot. There is no information about the exact date of occurrence included. Aerial picture mappings including all features appeared in the subsequent 12 years are further on referred to as time slice.

Within these fresh landslides, all the landslide affected area was mapped. This includes the scar, the transition area and parts of the deposition area, although the deposition area very often lies below existing vegetation which could withstand the physical forces and thus was not included in the mapped area. Within landslides which end in a stream bed, the material often was transported away, and thus also no deposition area is included in the data set. Due to the focus on the actively eroded area, a slight overestimation of the planar landslide surface is expected.

In order to have equal mapping conditions for each entire data set a mapping scale is chosen. During the whole digitising process, this scale is kept constant, and thereby all the recorded landslides are registered under the same conditions. The mapping scale for all years is 1:1.500, where a high detail grade can be identified and the landslide extent is precisely captured. The only exception is the year 1999, where due to the coarse picture resolution 1:3.000 was chosen as most appropriate scale.

After determining these criteria, the systematic mapping for the study area was carried out. Therefore a shapefile for each time slices is created and configured. The configuration parameters include the geographic coordinate system and necessary data fields included in the attribute table. An example for the included fields of the created shapefiles is shown in Figure 4.5. Within the allocated attributes, the fields Connected, referring to the possible material exchange, no_forest which is used to determine the attribution to the respective vegetation class determined in chapter 3.5 Landcover and vegetation, 08_09_pic identifying the few features mapped one the basis of the 2008/09 season imagery and Metadata are compiled manually. The other fields are generated automatically except the field area which gets computed using the calculate geometry command.

FID	Shape *	Id	Connected	no forest	08_09_pic	Area	Metadata
0	Polygon	1	1	0	0	378,26	connected: 1 = yes 0 = no
1	Polygon	2	1	0	0	68,04	no_forest: 0 = is in forest, 1 = out of forest
2	Polygon	3	0	0	0	79,62	08_09_pic: 0 = 2005, 1 = 2008
3	Polygon	4	0	1	0	372,91	
4	Polygon	5	1	0	0	551,47	
5	Polygon	6	0	1	0	765,66	

Figure 4.5: Section of the attribute table of the ArcGIS file for the 2005 debris slide mapping. The connected, no_forest and 08_09_pic values were entered manually for each individual feature. The area in m² was computed using the "calculate geometry" command.

These values are included in the shapefiles for the mapped landslides of all years. On the base of the included values the actual mapping process can start. The mapping is carried out manually by digitising polygons which circumscribe the landslide area.

During the mapping procedure, in the Tamaki West catchment also the connectivity between the landslide scars and the river system was investigated for all years. Therefore each landslide which was physically connected to a channel was classified as connected due to the fact that gravitationally eroded material can be discharged to the river. This physical connection has to be detectable visually, namely there has to be a direct connection between the gravel covered river channel and the bare landslide scar identifiable at the aerial picture. For the Southern Ruahines this was also accomplished for the 1999 and 2005 mapping but not for the other two dates due to missing image material.

Resulting in the changing data quality of each aerial picture set, the mapping approach has to be adapted individually for each. Problematic aspects include resolution, shading and changing image properties with different slope aspect which are elaborated in more detail in chapter 4.2.4, Mapping uncertainties.

4.2.2 Landslide-slope calculation

As mentioned in chapter 2 and 3.3 the inclination of the hill slopes is an important factor for landslide occurrence. As a 15 m DEM for the study area and a more accurate 2 m DEM for Dry and Car Park creek is available, more detailed analysis could be carried out. Obviously there are differences in the data accuracy which will be elaborated more precisely together with the results and their discussion.

The aim of the slope calculation is to obtain slope values for the zones where landslides occur. By doing this, the slope-spectrum within which debris slides appear as well as its distribution can be derived.

To obtain the elevation values, first the landslides mapped in vector format have to be converted to a raster set. For maximum accuracy the cell size of all ls-raster sets is equal

to the most accurate DEM of two m. This also enables easy comparability between the different sets. The conversion is carried out using the “feature to raster” order in the ArcToolbox, whereas the extent of the new landslide grid is aligned to the one of the two m DEM. Next, the slope values of a slope raster compiled out of the DEM have to be assigned to the landslide raster files. This is obtained using the “raster calculator” Toolbox. The output raster spatially represents the landslide extent and contains the respective slope value for each landslide pixel for further statistical interpretation. The two m grid can be used directly, whereas the 15 m raster first needs to be converted to a two m grid using the “resample” order in the Toolbox.

4.2.3 Reassessment of landslide mapping by Marden (1984)

Besides the available aerial picture sets, a second important data source was used to obtain information about the erosion patterns in the Southern Ruahines. This information was derived interpreting the mapped landslides for the 1940's and 1970's by Marden (1984). The data was provided in the form of georeferenced maps by M. Marden, Landcare Research. In this maps, shallow mass movements as well as deep seated failures are included, where only the shallow features were considered. Both used maps are attached in appendix I and appendix II.

After importing the two maps in ArcGIS, the mapped features were redigitised within the research area in the same way as the new debris slides were mapped.

Amongst the original map and the new shapefiles representing them, there are several possible error sources. The aerial pictures have a bigger scale than Marden's (1984) maps. This accounts for the problem, that after the generalisation which was done by Marden (1984) to derive the two surface erosion maps in a scale of 1:25000 from aerial pictures of a scale between 1:10000 and 1:24000 (see Table 4.1 for further details), the mapping on a larger scale for this work produces more detailed shapefiles again. Another problem can occur from the scanning and georeferencing procedure, where distortion can occur. More errors can result from the different perception of the processors. In the

mapping carried out by Marden (1984) virtually all hillslope areas which could be identified as bare ground were mapped (pers. communication M. Marden 2011). As this work focuses on fresh landslides and thus only landslides in a maximum time window of 12 years before the aerial picture is gathered are mapped, this could result in further differences in the mapping extent.

As a data source of that extent is very valuable for this work, a solution how to harmonize the different data was found. Therefore further aerial picture sets for the Tamaki West catchment were granted by Landcare Research, allowing a more detailed investigation of that region. This enables more findings for the whole work, and makes it possible to compare Marden's (1984) mapping with the current mapping for 1999 and 2005 carried out for the whole Southern Ruahines.

The actual procedure to reassess the two mapping approaches was carried out using the erosion extent from Marden (1984) and the debris slide mapping for the Tamaki West catchment carried out using aerial picture sets. As their dates resemble, and the same aerial picture sets were used to obtain the results a direct comparison of the extent shows the differences in the perceived landslide dimensions.

Next, these differences were set in relation, to obtain a revalidation coefficient. The used calculation values are shown in Table 4.2 and the revalidation coefficient R_A for area and R_N for the differences in the number of feature count can be derived. The formula to calculate the coefficient for area is: $R_A = A_{\text{Marden1984}} / A_{\text{Riedler2011}}$ and for feature count respectively using the mapped feature values.

	1946 Marden	1946 Riedler	difference M – R	1974 Marden	1974 Riedler	difference M – R
Erosion feature count (N)	129	90	39	211	157	54
Min. feature area - m ²	222,09	18,9		110,51	10,87	
Max. feature area - m ²	14044,57	17974,22		26814,557	18420,21	
Mean feature area – m ²	1460,112	972,77		2415,88	1393,62	
Erosion area – m ² (A)	188355,61	87549,36	100806,25	509750,54	218797,72	290952,82
Erosion area - km ²	0,19	0,09		0,51	0,22	
% of Tamaki West area	1,67	0,77	0,89	4,51	1,94	2,58
Reassessment factor area (R_A):			0,46481			0,42923
Reassessment factor feature count (R_N):			0,69767			0,74408

Table 4.2: Comparison of Marden's (1984) and own mapping for the calculation of the reassessment factors R_A and R_N .

For further comparison between the mapping obtained by Marden (1984) and the actual aerial picture mapped features, the two coefficients R_A and R_N are used to reassess the results by Marden (1984) in a way they are comparable to the mapping done in this work. Therefore the area and landslide numbers are multiplied with the respective coefficients to obtain values which resemble the interpretation mechanisms for the current work in a more desirable way.

4.2.4 Mapping uncertainties

During the mapping procedure, several difficulties were encountered. Some of them refer to the picture quality, others to the extent of vegetation which is the threshold to distinguish between fresh landslides and older features. The vegetation problem was solved individually for every landslide.

Most problems were referred to aerial picture quality and include picture resolution, shading effect and changing image properties due to changing slope aspect and other factors.

Shading is considered as the most severe problem. It occurs due to different factors, like high vegetation and topographic obstacles which casts shadows on the ground. The time of the day during the flight at which the pictures were taken is responsible for the direction and extent of a possible shadow. If the flight is timed ideal and carried out near the moment when the sun is at its highest point, it is possible to minimize shading influences.

The picture quality can be compared in Figure 5.1, where the same image section of each aerial picture data set is shown. The shading extent as well as the resolution are visible and problems can be explained by that example. Only at two dates, in 1977 and 2005 the shading extent is considered as little and thus good for mapping. In 1946 the shading only moderately influences the picture quality whereas in the other three years, considerable limitations are apparent. Here, the mapping uncertainties are increased, and more skilful interpretation is needed. In case of doubt, the area covered by shadow can not be mapped. Sometimes the topographic map can help to better understand the terrain

conditions and to work precisely even though the picture properties are not ideal. A good example can be seen in Figure 4.3 where the mapped debris slide and the underlain picture is shown parallel to the points investigated during the field work. By interpolating the extent of the landslide from the point data, the difference between the visible and the actual landslide can be derived. The digitally mapped feature was obtained under the fact, that the abrupt vegetation change indicates a sharp edge which represents the landslide scar boundary.

The picture resolution generally is good, with the only exception of 1999 where a 2,5 m grid is present. This is taken into account by choosing a smaller mapping scale of 1:3.000 compared to the other years.

Due to alternating light intensities, the colour or brightness of slopes with a different aspect can change within one picture set. This is considered during the mapping, and equally aligned areas are used for comparison among themselves.

The mapped results were evaluated during fieldwork, raising the awareness for difficulties during the mapping procedure. After the fieldwork was carried out, the mapped landslides were reviewed and if necessary edited.

These examples show, that the data quality differs and this has to be kept in mind when the results are interpreted.

5 Data acquisition and properties

As multiple data sources were used within this study, the different data origins as well as their properties will be elucidated in this chapter. Supplemental to the considerable amount of collected data, multiple external information sources account for the available material. Miscellaneous data sources result in different data types and changing properties. These differences will be investigated and possibilities as well as limitations will be discussed in this chapter. Well understood data characteristics are most important for accurate scientific work and this chapter should show the potential and restrictions of the available data and consequently also the prospects.

First of all in Table Table 5.1 an overview of all used datasets and their properties is given. Within the range of these 24 different entries it is visible, that multiple data types with different attributes are used. Although similarities as well as differences in certain aspects can be identified within the listing, it is not always possible to make a statement about the data quality, which is a crucial information. The latter aspect will be elaborated in the following sub-chapters, each dealing with the properties of a specific data type.

Data type	Scale/Resolution	Geometry	Base Data	Provider
External data				
Aerial pictures Tamaki West C. 2011	0,4 x 0,4m	Raster	-	Landcare Research
Aerial pictures Southern Ruahines 2005	0,75 x 0,75m	Raster	-	HRC
Aerial pictures Southern Ruahines 1999	2,5 x 2,5m	Raster	-	HRC
Aerial pictures Tamaki West C. 1977	1:10.000	Raster	-	Landcare Research
Aerial pictures Tamaki West C. 1974	1:24000	Raster	-	Landcare Research
Aerial pictures Tamaki West C. 1946	1:13.600	Raster	-	Landcare Research
DEM Southern Ruahines	15 x 15m	Raster	20m contours, spotheight LINZ, 2000	Massey University/ Landcare Research
DEM Dry Creek and Car Park Creek	2 x 2m	Raster	Aerial pictures 2011 0,4 x 0,4m	Landcare Research
Rainfall data NZ	500 x 500m	Raster	Rain data 1978-2007	HRC/NIWA
MM erosion map 1974-77	1:25.000	Raster	Aerial Pictures 1974,1977	Marden M. (1984)
MM erosion map 1946-49	1:25.000	Raster	Aerial Pictures 1946, 1949	Marden M. (1984)
Torless Supergroup map	~1:143.000	Raster	Marden M. (1984)	Marden M. (1984)
Geological map – region	1:250.000	Raster	Kingma J.T. (1962)	Kingma J.T. (1962)
New Zealand Topographic Map	1:50.000	Raster	-	Massey Univ./LINZ
Catchment division NZ, 3 rd order	-	Vector	30m catchment raster	Massey Univ./DOC
Precipitation and Temperature data Palmerston North, Wharite Peak	-	point	Data period: 1981-2010, 1951-1980 respectively	NIWA
Compiled data				
Landslide DEM, four locations	0,25 x 0,25m	Raster	GPS/tachymeter survey	Own data
Landslide mapping 2011	-	Vector	Aerial pictures 2011	Own data
Landslide mapping 2005	-	Vector	Aerial pictures 2005	Own data
Landslide mapping 1999	-	Vector	Aerial pictures 1999	Own data
Landslide mapping 1977	-	Vector	Aerial pictures 1977	Own data
Landslide mapping 1974	-	Vector	Aerial pictures 1974	Own data
Landslide mapping 1946	-	Vector	Aerial pictures 1946	Own data
Landslide elevation data	-	Point	Field work	Own data

Table 5.1: Properties of all used data material.

One special case concerning the aerial pictures is the picture set from 2005. Due to bad weather conditions in 2005 not all the region could be recorded on the 16th of January 2005. Due to continuing bad weather conditions and trouble between the remote sensing company and HRC, the client, the picture set finally was completed in 2008 (pers.

communication A. Steffert 2011) This fact influences a small patch in the north-eastern part of the study area. This part covers approximately 1,45% of the study area. Due to simplicity the data set is referred to as aerial picture set 2005. The detailed flight plan is attached as Appendix III.

Besides specific quality criteria, including possible errors and acquisition conditions, spatial data has the advantage, that through its spatial resolution there is one criteria present which allows a comparison for all items belonging to that category.

Within this study a wide variety concerning the resolution is used. The Landslide DEMs, which were produced from field data have the highest accuracy with a cell size of 0,25 m. On the contrary, the geological map covering the Southern Ruahines has a small scale of 1:250.000. The different scope also reflects different data purposes and the possible processing opportunities. This issue has to be kept in mind during the analysis and certain aspects of the analysis have to be adjusted to the data base.

5.1 Aerial pictures

As the temporal and spatial coverage by aerial pictures in the Southern Ruahines is good, this data source represents the most important base for this work. Due to the long existence of recordings and the mostly high accuracy, ortho-images provide a good basis for landslide mapping in general and also in this case.

Within the accuracy criteria, resolution and data acquisition time are the most important. Resolution gets especially important if small objects and precise limits should be identified. The latter quality facet is already more delicate. Ideally the different aerial picture sets are acquired during the same time of the year, because the vegetation conditions under similar climate properties normally should behave similarly. As the vegetation cover very often determines the visibility of certain features, especially in forested areas, this aspect is most important. The second factor is the time of the day at which the survey flight was carried out. This element influences the picture quality by different shading properties. Ideally, the photos should be taken when the sun has

reached its position in the zenith where shading can be reduced to a minimum, and the majority of the landscape is clearly recognizable. Additionally there can also be differences within one flight series, because during data generation the altitude of the sun is changing. Within an area of as large as the study area this aspect normally is neglectable, but it still has to be considered, as the flight plan might include surrounding areas, and thus takes longer, which was the case for the used aerial images (pers. comm. A. Steffert 2011, M. Marden 2012).

Both aspects are especially important for this study, because the main parts of the study area are situated in forested area as well as in rough terrain with strong relief differences. Especially the terrain situation can hinder the image interpretation at multiple spots in the study area if the picture attributes are not ideal. Clouds can also be a problem for interpretation issues, but with all six obtained datasets no clouds are present which can be attributed to the person in charge for the data acquisition. Further details to the actual mapping procedure influenced by image quality can be found in 4.2.4, Mapping uncertainties. For a detailed quality comparison of the different aerial picture sets refer to Figure 5.1.

Aerial picture quality comparison

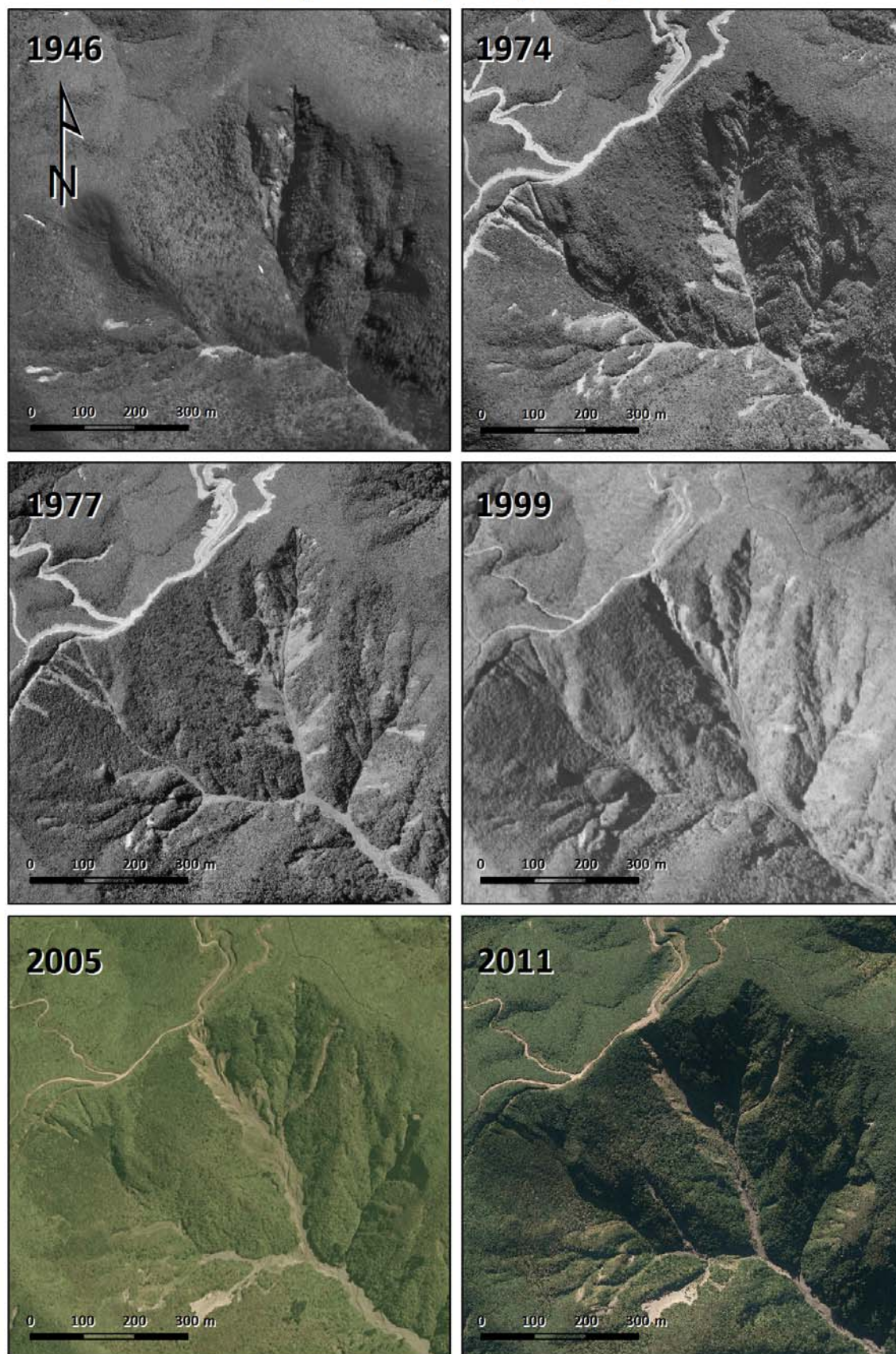


Figure 5.1: Comparison of the different aerial picture sets. The display detail shown is the same in all six sections. Note the construction of the Takapari Road between 1946 and 1974. (HRC 2011, Landcare Research 2012)

Regarding the image-quality, the most obvious difference is that pictures recorded before 2005 are in black and white and the sets of 2005 and 2011 are chromatic. Therefore differences in the interpretation procedure arise, because it is easier to distinguish differences in the vegetation cover as well as the soil regeneration state in the coloured pictures.

5.2 DEM

Digital elevation models can be used for a multitude of purposes. Depending on the needed attributes, the requirements differ greatly. In the case of this study, the quality of the DEMs which were derived from the field data relies on two factors, the density of field recorded spot-heights and the interpolation method. As interpolation method TLI was used and the data points obtained per landslide varied between 215 and 1262. Detailed specification about the particular results for the derived DEMs are presented in chapter 6.2.1 where also the point density is given for each debris slide.

For the two DEMs which were obtained externally, the level of detail varies considerably which mainly can be attributed to the compilation method and the data availability. Whereas the detailed two m DEM was derived from a highly accurate aerial picture recorded in 2011 the coarse 15 m DEM was derived from digitised 20 m contour lines and spot heights provided by LINZ of the years 2000 and later. This is not only resulting in a different accuracy, but also in the different resolution seen in the grid size varying from four m² in the former to 225 m² in the latter case. For a rough overview the coarse elevation model is still very useful, however detailed calculation are only partially reasonable.

5.3 Elevation data

For the manually acquired elevation data, two aspects are crucial for data quality. First, the accuracy of the used technical devices and secondly the precise execution and documentation of the field survey. Whereas the technical devices are up to date and thus mostly reliable and the acquired data can be post-processed, the initial correct setup for data reception is crucial. Therefore the setup was always double checked before the survey was started, and professional handling of the gear was understood.

For the calculation of raster files derived from the field data, arbitrary grid size can be chosen. Still a reasonable relation between the dimensions of the investigated feature and the point frequency has to be kept in mind. This is in favour of the meaningful result accuracy and the compilation time for digital processing.

The device accuracy and exclusion criteria for the GPS points exceeding the fixed threshold were already explained in chapter 4.1.2 and will thus not be repeated.

The crucial factor concerning the elevation data is the correct processing to obtain satisfactory results. Here, it has to be taken care, that the DEMs compiled from the field data are compatible to the received digital elevation models.

6 Results

The following chapter is the centrepiece of this work, where the results are presented in detail and also discussed at the end of each sub-chapter. The general discussion follows in a separate chapter.

The two cornerstones of this investigation are the field work which was carried out and the data processing. Here, both field data as well as additional external sources were analysed. Of course these external data sources were chosen and handled in a way that all obtained information complements the surveyed data and new insight through innovative combinations were gained.

Field work was split into several parts, where an initial field inspection in October 2011 was the takeoff to get a broad overview of the study area. The detailed landslide investigation was carried out in several single field days during November and December 2011.

6.1 Temporal variation of the erosion extent

The interpretation of up to six aerial picture sets, spanning over a period of 65 years between their recording dates, is the base for the landslide mapping presented in this chapter. Due to data disposability, the number of available image sets differs spatially. The digital results were underpinned by field validation, where the mapped features were checked for their accuracy.

For a greater time resolution in the whole study area, the detailed mapping carried out by Marden (1984) in the 1940's and 1970's will be included in the analysis.

The aerial picture interpretations aims at the analysis of the landslide patterns. An additional aim would be to identify a possible trend in the landslide extent as well as its possible future development.

There is a clear influence of the landcover on landslide patterns and the study area is covered by woody vegetation as well as pasture. Consequently the different landslide distribution under these vegetation covers is investigated as well.

6.1.1 Erosion extent between 1946 and 2011 in the Tamaki West Catchment

Besides the investigation of the Southern Ruahines using different data sources for four dates, the Tamaki West catchment was investigated in higher temporal resolution. Here, six aerial picture sets, including the records of the years 1946, 1974, 1977, 1999, 2005 and 2011 are available and were used to obtain information about landslide patterns. Due to its higher temporal resolution, the analysis of the Tamaki West catchment is

crucial for further calculations in the study area, and thus presented first. The Tamaki West catchment is covered mainly by woody vegetation, which comprises 99,86 % of its area. Thereby it differs from the rest of the study area which features a higher percentage of pasture, namely 20,05 %.

In addition, an accurate DEM with a resolution of two m is available for two subcatchments, Dry Creek and Car-Park creek, both situated in Tamaki West (shown in Figure 3.12 and Figure 6.1), which is used for additional calculations presented later.

First the erosion extent of each investigated year will be shown on a single map to display the characteristics and divergences between the different dates. Because detailed topographic information for the Tamaki West catchment is useful for the further interpretation of the landslide distribution, a map depicting the valley names within the catchment is shown in Figure 6.1.

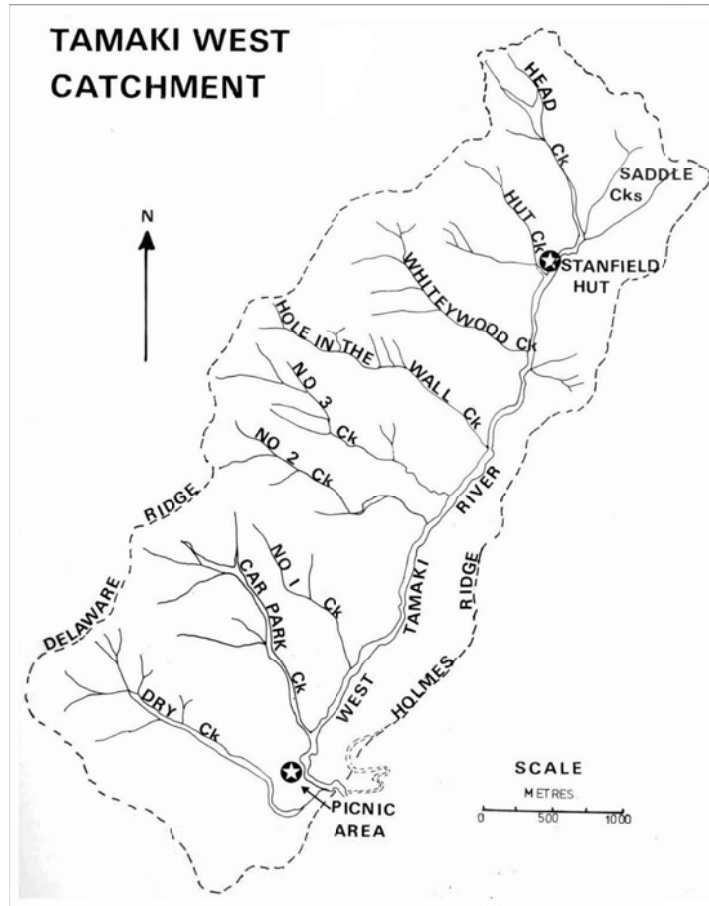


*Figure 6.1: Detailed map of Tamaki West catchment.
(adapted after Neall 1981)*

As only two aerial picture sets are available for the whole study area, and the data received particularly for the Tamaki West catchment just covers its exact extent, for illustration purposes in the maps showing the 1946, 1974 and 1977 erosion extent the margins are covered by the 1999 images and for 2011 by the 2005 pictures.

The first map showing the landslides which occurred before and in 1946 is depicted in Figure 6.2. It shows only little erosion activity compared to the other years, covering an area of 87.549 m² where only in 1999 less erosion was present. Debris slides occur in all subcatchments even though in No. 1 creek and Saddle creeks there are only very little features present. A denser appearance is identified in Car Park creek, No. 2 creek and Head creek and generally in the valley-heads.

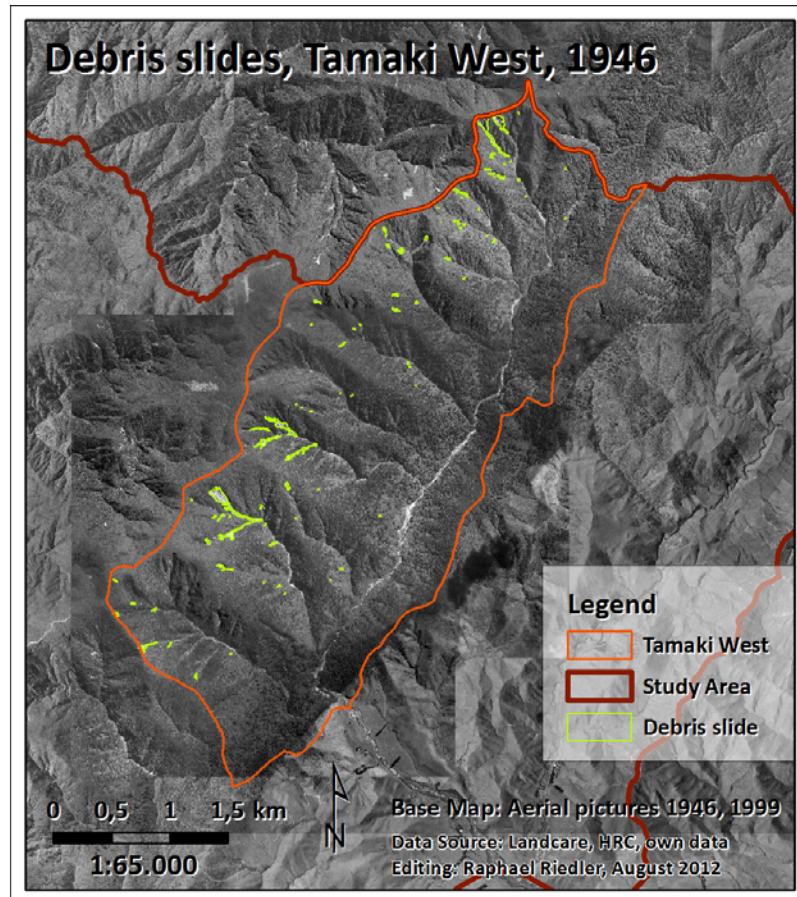


Figure 6.2: Erosion extent due to debris slides in the Tamaki West catchment, 1946. 1999 aerial pictures complement the base map at edges.

Between the first and the next investigated time slice of 1974, shown in Figure 6.3 there is a difference of 28 years. This means that only parts of this period can be analysed by the mapping approach chosen in this study because it exceeds the 12 years within fresh landslides are identifiable. In 1974 landslides are abundant and thus also found in all subcatchments of Tamaki West, where they are quite evenly distributed. Nevertheless, Whiteywood creek and Hole in the Wall creek show less debris slides than other branches. Single landslides can also be identified on the true left valley flank of Tamaki West river. The location of the debris slides within the subcatchments tends to be at higher elevations, even though there are also erosion features present at the valley flanks

closer to the confluence of the side-branches with Tamaki River. In total with a landslide area of 218.798 m² it is the second most affected year recorded in Tamaki West.

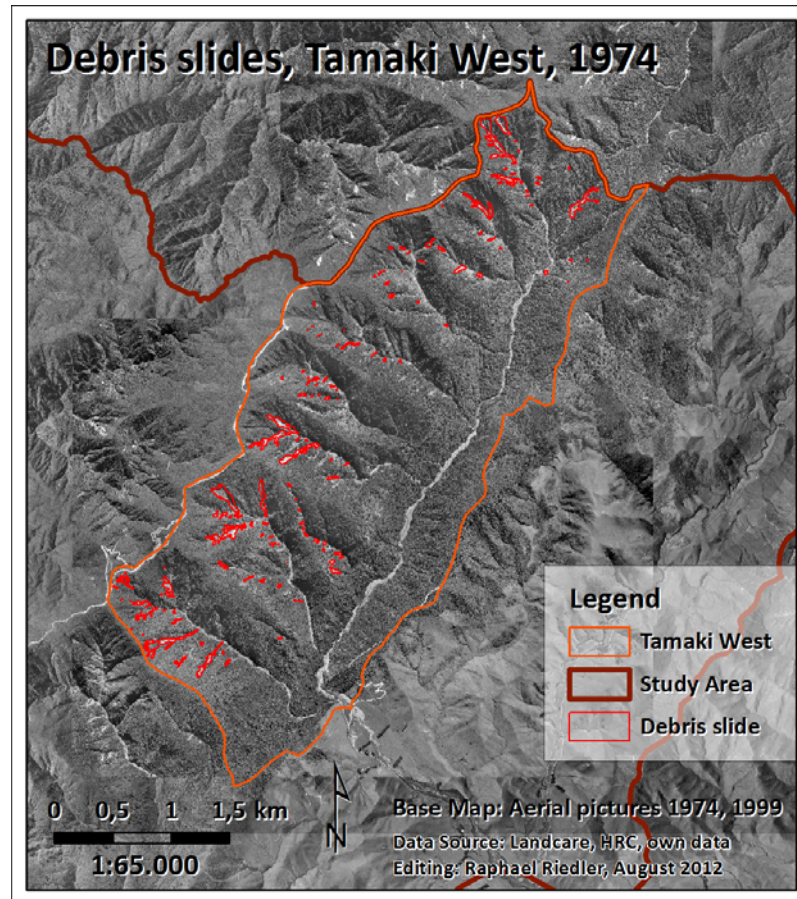


Figure 6.3: Erosion extent due to debris slides in the Tamaki West catchment, 1974. 1999 aerial pictures complement the base map at edges.

In the year 1977 (Figure 6.4) the by far most severe landslide extent is recorded of all six dates investigated. The affected area comprises 348.990 m² and every subcatchment is seriously concerned. Even on the true left valley flank of the Tamaki West river reaching up to the Holmes ridge, several debris slides can be identified. Still, most landslides are in the steeper, upper half of the subcatchments, except for Head creek and Saddle creeks, which generally have a higher elevation and landslides are spread all over these

subcatchment. The two creeks No. 1 and Hole in the Wall are a bit more tranquil than the other branches.

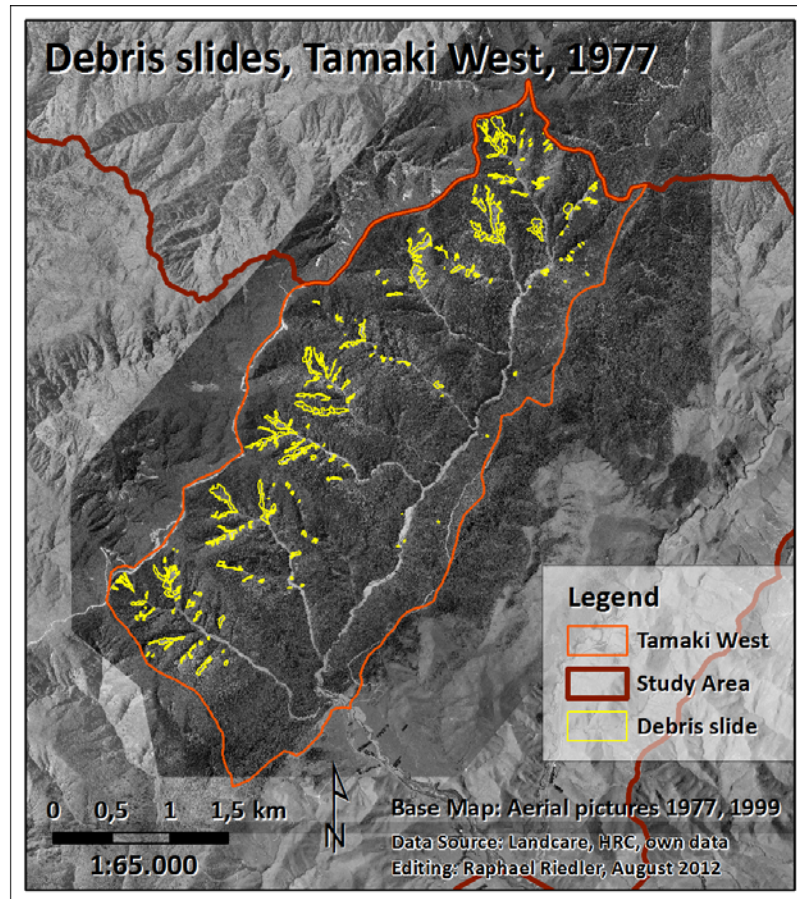


Figure 6.4: Erosion extent due to debris slides in the Tamaki West catchment, 1977. 1999 aerial pictures complement the base map at edges.

All subcatchments are only slightly affected in 1999 which can also be seen in the map depicted in Figure 6.5. Only in Dry creek, Car Park creek and No 2 creek a little more landslide activity can be identified. This is also evident in the landslide area of 86.275 m² which comprises for the lowest value of all investigated years. All landslides are located at the very end of the subcatchments and there are no landslides present in the true left valley flank of Tamaki West river. Dry Creek is an exception here, because debris slides are also apparent in lower parts of the branch. Again it should be pointed out that the time

span between the 1999 and 1977 aerial pictures exceeds the 12 year period of detectable landslides and thus not all debris slides which occurred between these two dates could be identified.

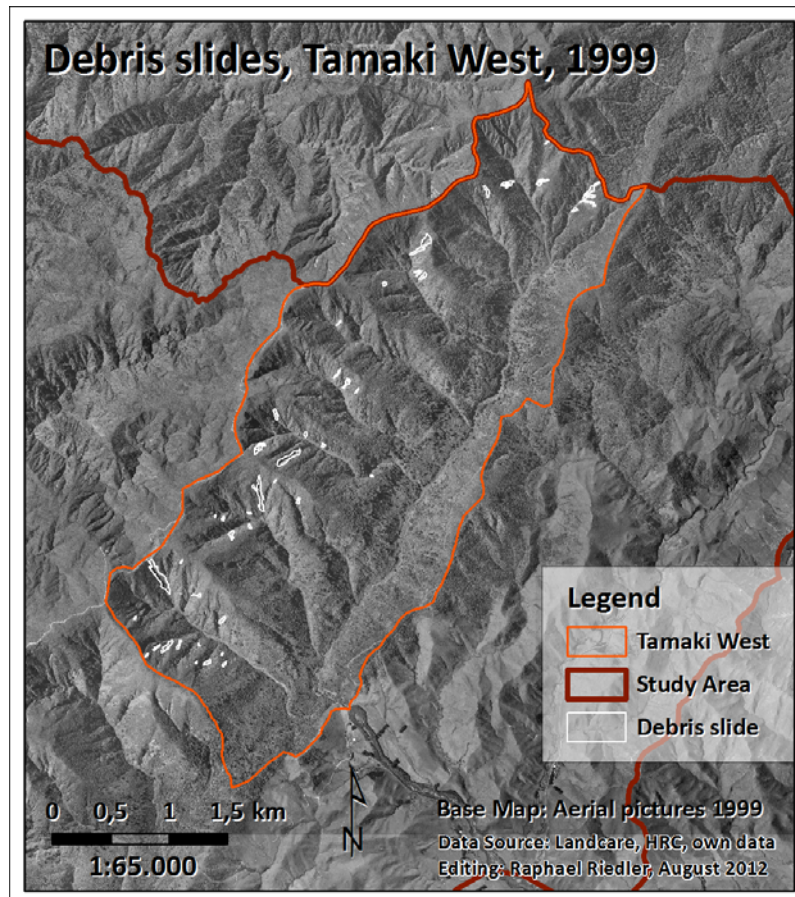


Figure 6.5: Erosion extent due to debris slides in the Tamaki West catchment, 1999.

The first mapping results based on a chromatic picture are shown in Figure 6.6, where the extent of the landslides apparent in 2005 can be seen. In total, it is the third most affected year after 1977 and 1974 with an extent of 143.509m². The landslides appear mostly at the more elevated parts of the subcatchments but compared to the number of features present more than in other years can also be identified in lower parts. One single debris slide can also be identified at the true left valley flank of Tamaki West river.

Generally, the landslides are equally distributed throughout all subcatchments with the exception of No. 1 creek, Hole in the Wall creek and Hut creek where less features are present.

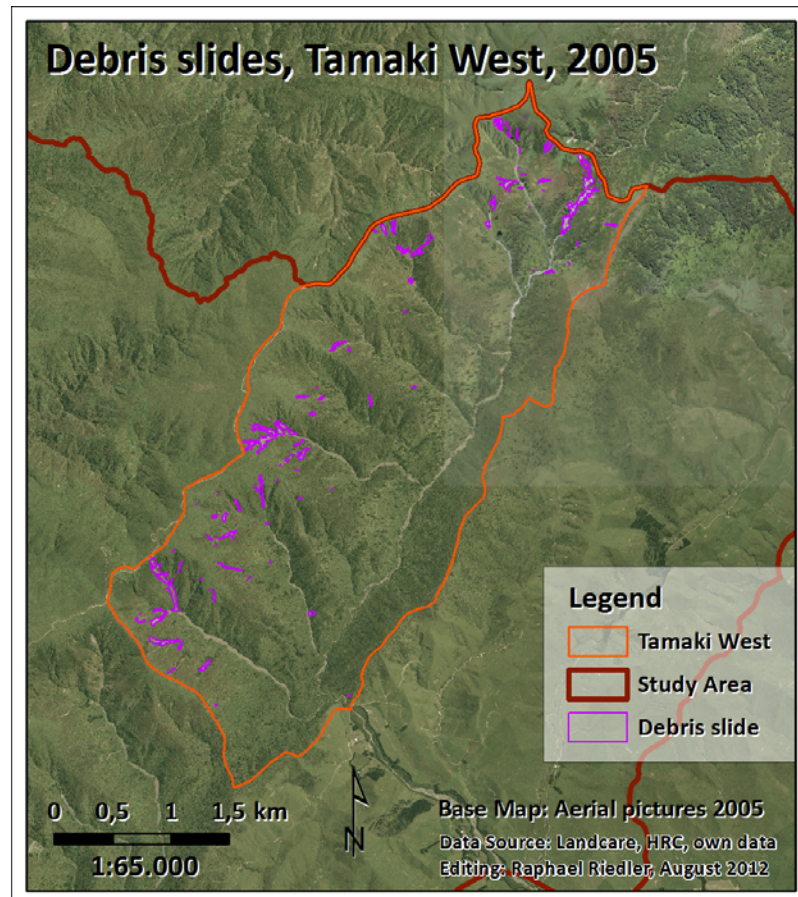


Figure 6.6: Erosion extent due to debris slides in the Tamaki West catchment, 2005

In 2011, with an extent of 129.864m², slightly less area is affected by debris slides than in 2005. Similar to 2005 only one isolated landslide is present between the Tamaki West river and Holmes Ridge which can be seen in the map in Figure 6.7. Again the tendency that identified features appear closer to the valley-heads is present through some progress a little further down towards the confluence of the side-branches and Tamaki

West river. No features at all are found in No. 1 creek and only little are present in Whiteywood and Hut creek. In contrast No. 2 creek is densely covered by debris slides.

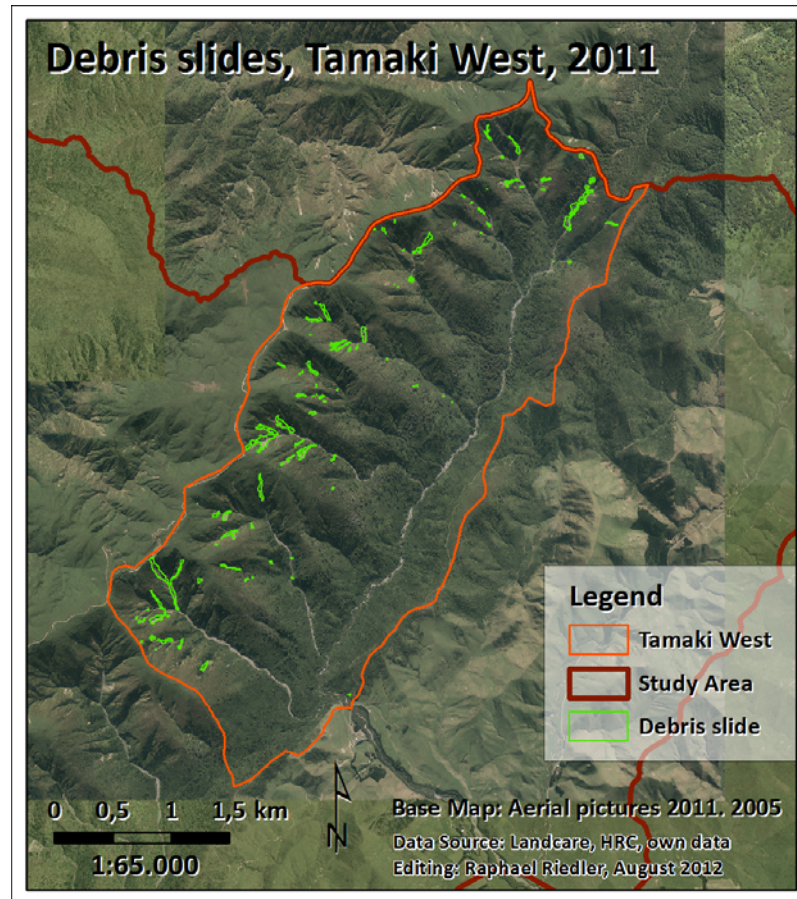


Figure 6.7: Erosion extent due to debris slides in the Tamaki West catchment, 2011. 2005 aerial pictures complement the base map at edges.

The summary of the mapped features for all years is presented in Table Table 6.1 where the total landslide affected area in meters and kilometers as well as the number of mapped debris slides is shown. To give an impression within which size-range the identified debris slides reside, their minimum, maximum and mean area is given for all years.

For better comparability, the area of the landslides is also displayed as the percentage covering the Tamaki West catchment.

	1946	1974	1977	1999	2005	2011
Erosion feature count	90	157	176	50	110	102
Min feature area – m ²	18,9	10,87	22,73	59,17	20,47	11,48
Max feature area – m ²	17.974,22	18.420,21	16.267,59	14.529,04	24.097,78	17.161,06
Mean feature area – m ²	972,77	1.393,62	1.982,9	1.971,53	1.304,63	1.262,14
Erosion area – m ²	87.549,36	218.797,72	348.990,91	86.275,43	143.509,36	129.864,72
Erosion area – km ²	0,09	0,22	0,35	0,09	0,14	0,13
% of Tamaki West catch.	0,77	1,94	3,09	0,76	1,27	1,15

Table 6.1: The mapped debris slides in the respective years for Tamaki West. The catchment area is 11,3 km². The individual numbers of single failures as well as their total inflicted area in absolute values as well as a percentge of the catchment surface are depicted.

For a clearer illustration, the different erosion values in percent are also depicted as a diagram shown in Figure 6.8. The supplemental information gained by this representation is, that it accounts for the temporal variations between the analysed dates because the years are accounted for on the x-axis. The steeper the graph connecting two data points, the more rapid a change between two dates occurred.

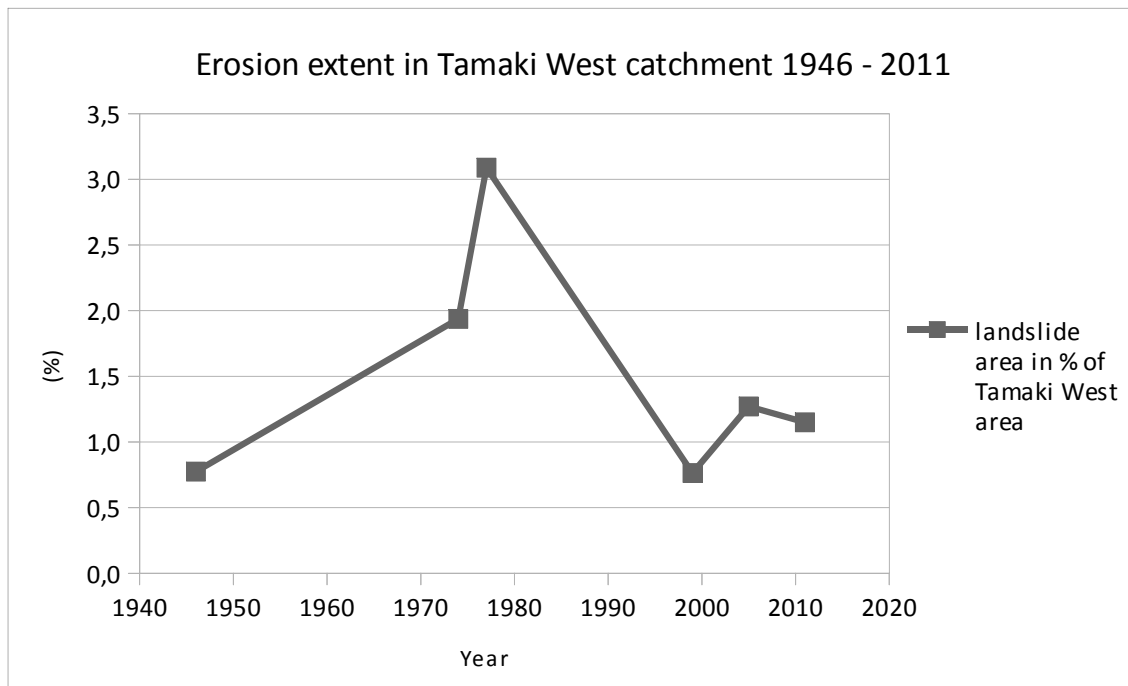


Figure 6.8: In the diagram, the temporal variability of the erosion extent in the Tamaki West catchment is shown. The exact data for the figure can be seen in Table 6.1. Note the different dates of data generation.

By including the percentage of the landslide-affected area the results for the Tamaki West catchment and the Southern Ruahines can be analysed and compared easier in the discussion, concluding this subchapter.

6.1.2 Erosion extent between 1946 and 2005 in the Southern Ruahines

Two aerial picture sets shot in 1999 and 2005 which cover the whole Southern Ruahines were analysed. Additional two erosion maps for the 1940's and the 1970's compiled by Marden (1984) were reassessed for this work and are included in the results.

Within the study area 79,05 % is covered by woody vegetation and 20,05 % by pasture. This is considered within the landslide analysis and the respective erosion values in each landcover class will be presented.

The first date for which data is provided is 1946, where the erosion extent present at that time is shown in Figure 6.9. The data presented on the map is the original data redigitised

after Marden (1984) and accounts for 2.362.330 m². In the map, landslides are clustered in the centre. Besides, along the steep eastern side of the Southern Ruahines a higher density of debris slides is visible. At the foothills, less features are present.

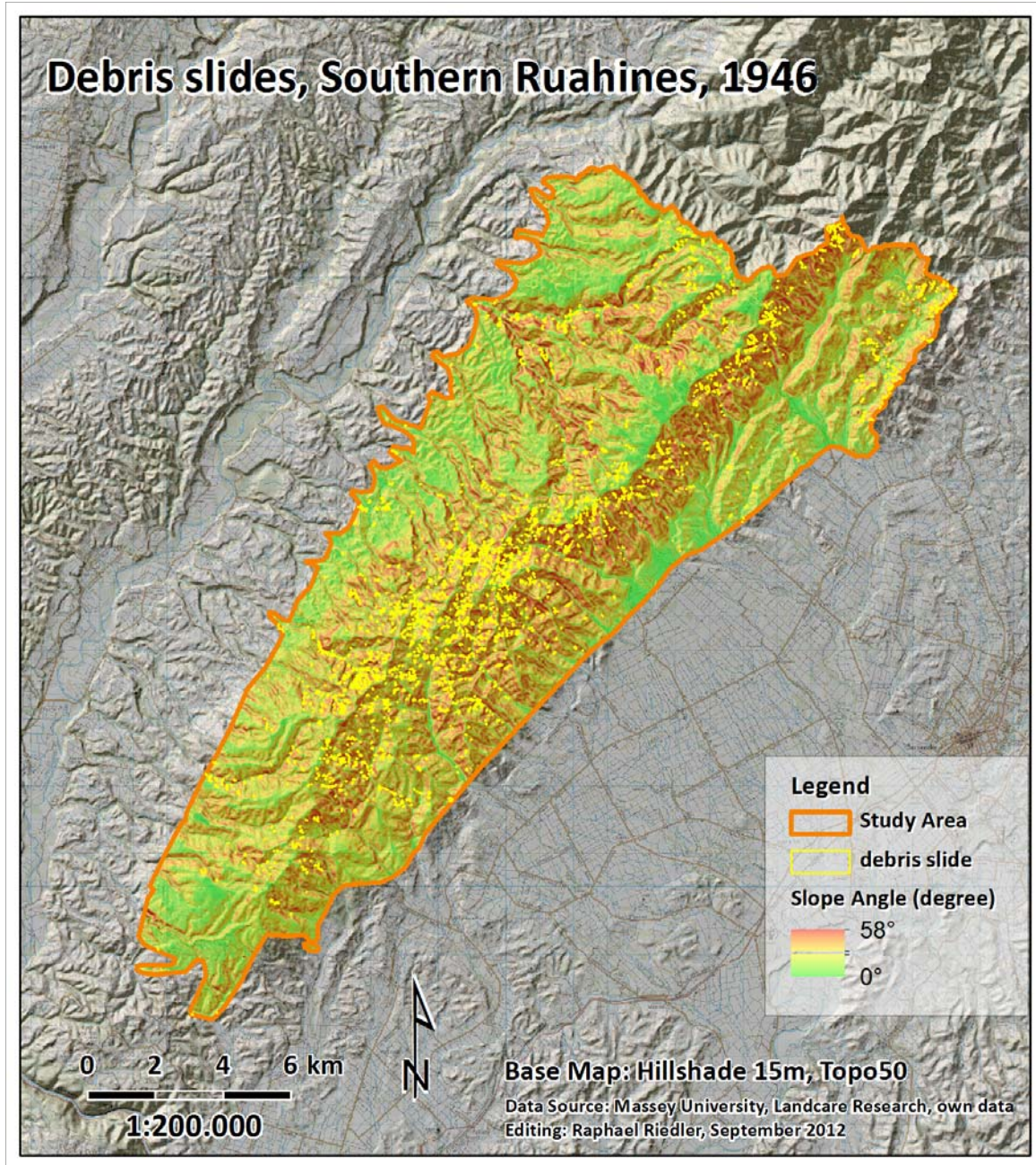


Figure 6.9: Erosion extent due to debris slides in the Southern Ruahines, 1946. Remapped after Marden (1984).

In 1974 the landslides shown in Figure 6.10 cover by far the largest extent accounting for an area of 5.244.076 m². Virtually in all regions of the study area shallow translational

slides can be found. Only three regions in the foothills in the south, east and west as well as the central plateau are mostly undisturbed. Within the dense landslide cover, in the central zone on both sides of the ridge an aggregation is found. Also on the steep NE flank more features are present as well as in the opposite Makawakawa catchment.

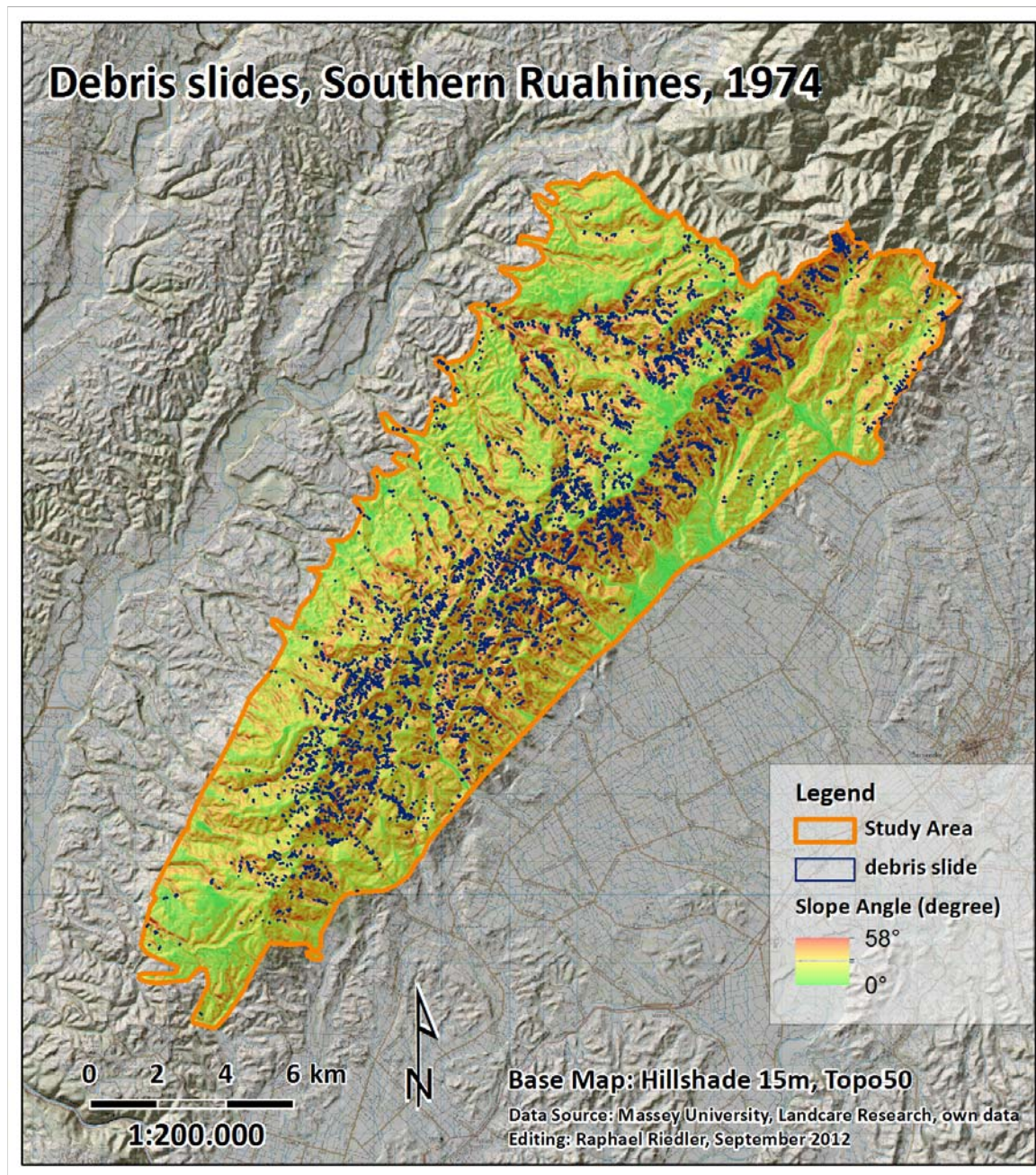


Figure 6.10: Erosion extent due to debris slides in the Southern Ruahines, 1974. Remapped after Marden (1984).

The map illustrated in Figure 6.11 shows the landslide extent in 1999 which is derived directly from aerial picture interpretation. No distinct distribution pattern can be identified for the present debris slides covering 241.304 m². Only at the steep valley flank in the NE a slight concentration of landslides can be remarked. The forest boundary derived from the aerial pictures is shown in green. All the area within the polygon is covered by woody vegetation whereas the rest is mainly pasture. Individual patches of forest outside this area are neglectable.

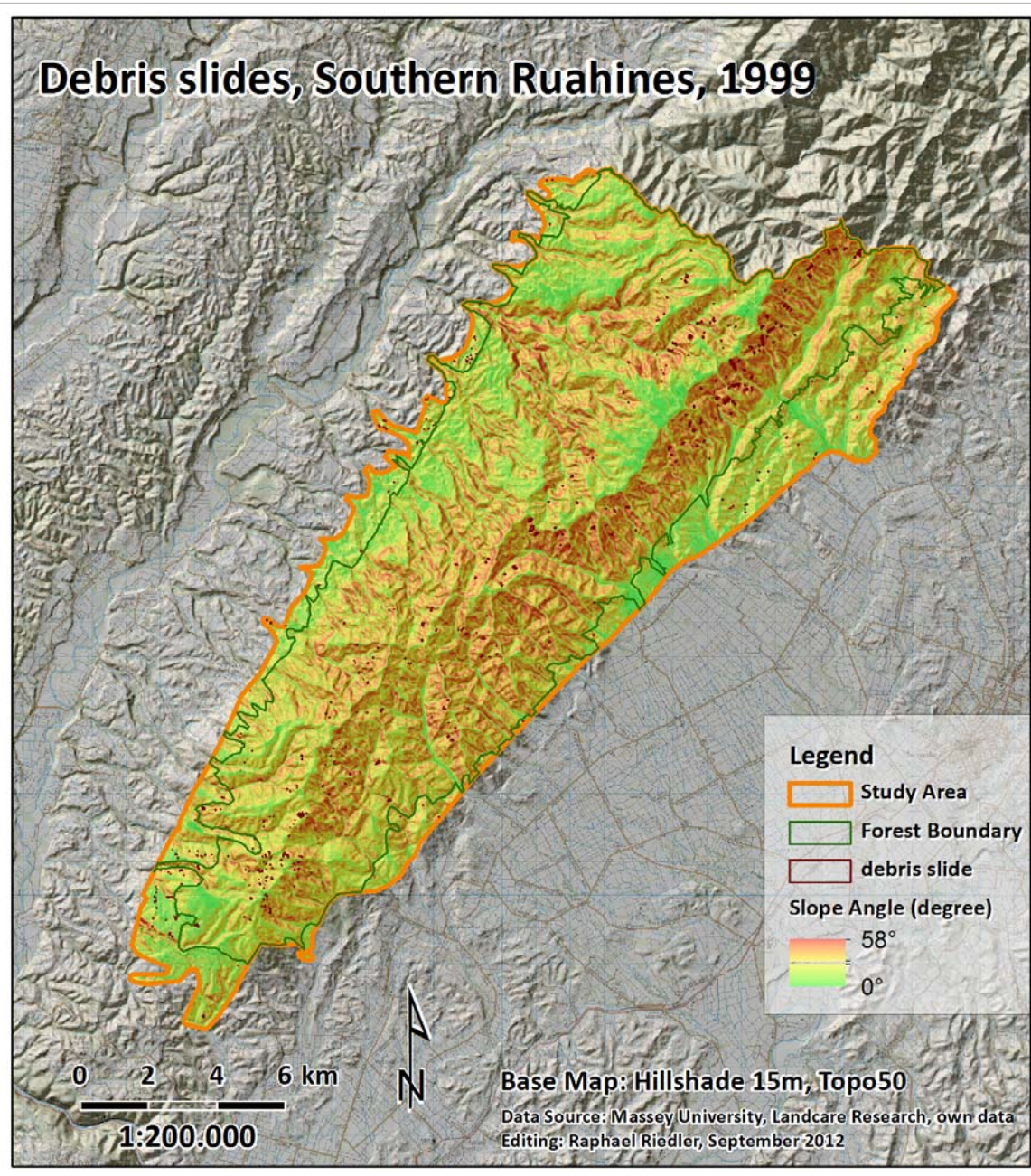


Figure 6.11: Erosion extent due to debris slides in the Southern Ruahines, 1999.

The most recent mapping for 2005 is shown in Figure 6.12 and the detected landslides cover an area of 483.640 m². Within this map an interesting pattern is visible because two clusters of debris slides can be identified at places where they wouldn't be expected due to the prevalent slope. One is situated just outside the forest boundary in the NW and the second one in the most southern corner of the study area. Besides that a denser

occurrence of landslides is visible at the steep eastern flank, the valley-head of Makawakawa stream and the centre.

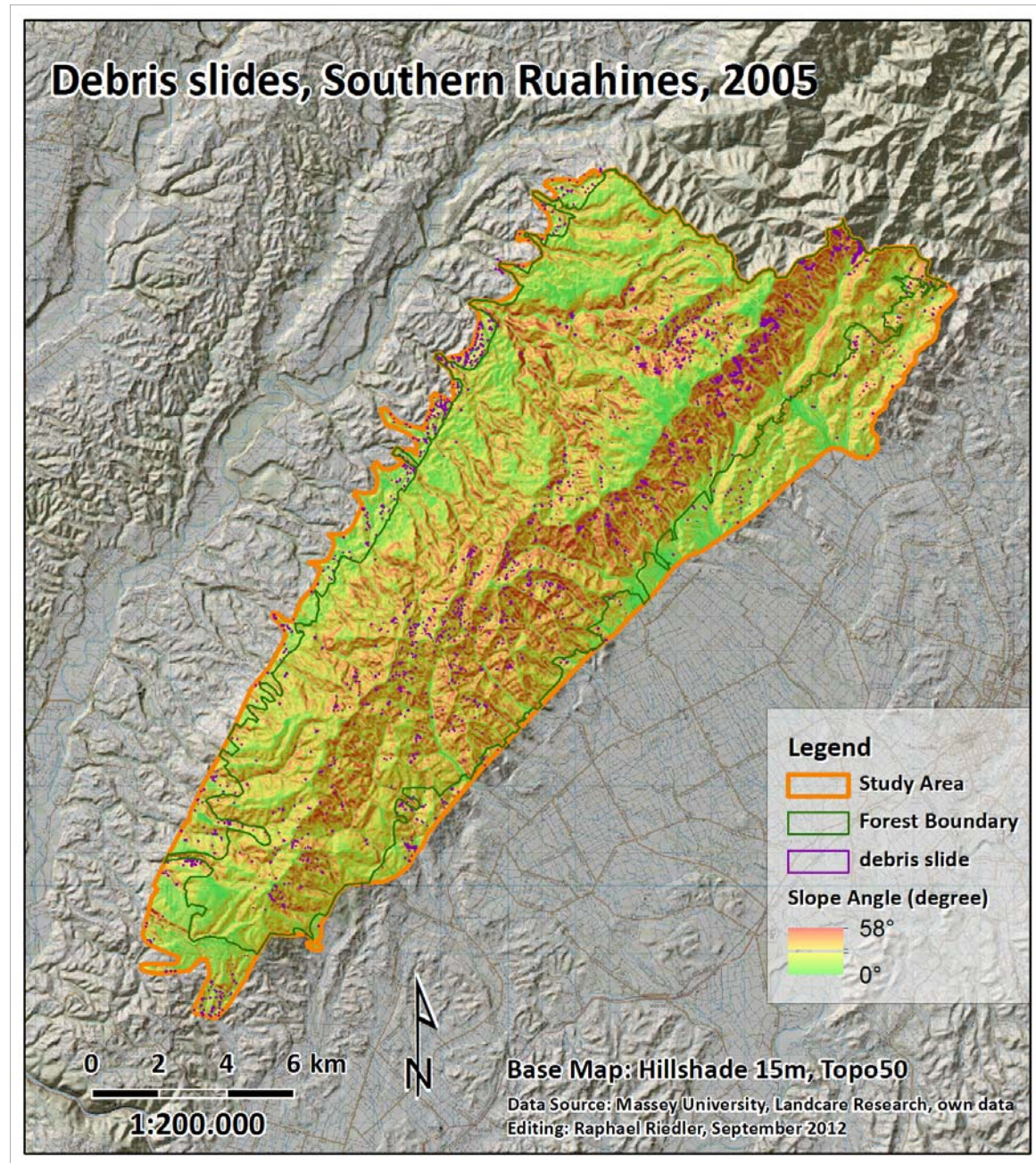


Figure 6.12: Erosion extent due to debris slides in the Southern Ruahines, 2005.

Hitherto shown maps give a crude overview of the temporal development for the distribution patterns of the landslides within the Southern Ruahines. Through the

combination of the hillshade image, which represents the relief with the slope grid as map base, a visual interpretation of the spatial landslide distribution is facilitated and a first impression of the landslide slope can be derived. Detailed values for erosion feature count number as well as their areas are given in Table Table 6.2. In this table the number of mapped features for each year as well as the affected area in m² and km² is given. The recalculated values are derived by multiplying the original values with the respective reassessment factor.

	1946 – 1949	1946 reassessed	1974 - 77	1974 reassessed	1999	2005
Erosion feature count	2.311	1.612,33	3.521	2.619,89	456	1965
Min feature area – m ²	41,58		31,19		0,94	3
Max feature area – m ²	18.487,31		36.665,58		15.076,58	24.098,78
Mean feature area – m ²	1.022,21		1.489,37		530,35	246,13
Erosion area – m ²	2.362.330,92	1.098.032,39	5.244.076,54	2.250.889,21	241.841,1	483.640,53
Erosion area – km ²	2,36	1,1	5,24	2,25	0,24	0,48
% of study area	1,07	0,5	2,37	1,02	0,11	0,22
R_N		0,69767		0,74408		
R_A		0,46481		0,42923		

Table 6.2: The mapped debris slides in the Southern Ruahines. The study area comprises 220,88 km². Individual numbers of single failures are outlined and their total inflicted area is presented in absolute values as well as a percentage of the total domain. Further information for the calculation of the reassessment factors R_N and R_A which are used to adjust the mapping values by Marden (1984) are found in chapter 4.2.3.

As already mentioned in the chapter referring to data properties, parts of the aerial picture set mainly recorded in 2005 were collected in 2008. This concerns the 2005 landslide data in a way, that 60 out of 1965 landslide features were mapped on the basis of 2008 material, comprising for 3,05 % of all features. Regarding to the relevant area, debris slides in the dimension of 43.335,04 m² involving 8,96 % of all mapped features are based on 2008 imagery interpretation.

In order to get a clearer picture of the trend of the total landslide inflicted area in the Southern Ruahines the relative values are shown in a diagram in Figure 6.13. The landslide affected area in the Southern Ruahines has its maximum in 1974 covering 1,02%

of the whole study area and drops to the lowest value in 1999, comprising only 0,11 % of that area. From this year to 2005 a slight rise can be seen, bringing the erosion value up to 0,22 %.

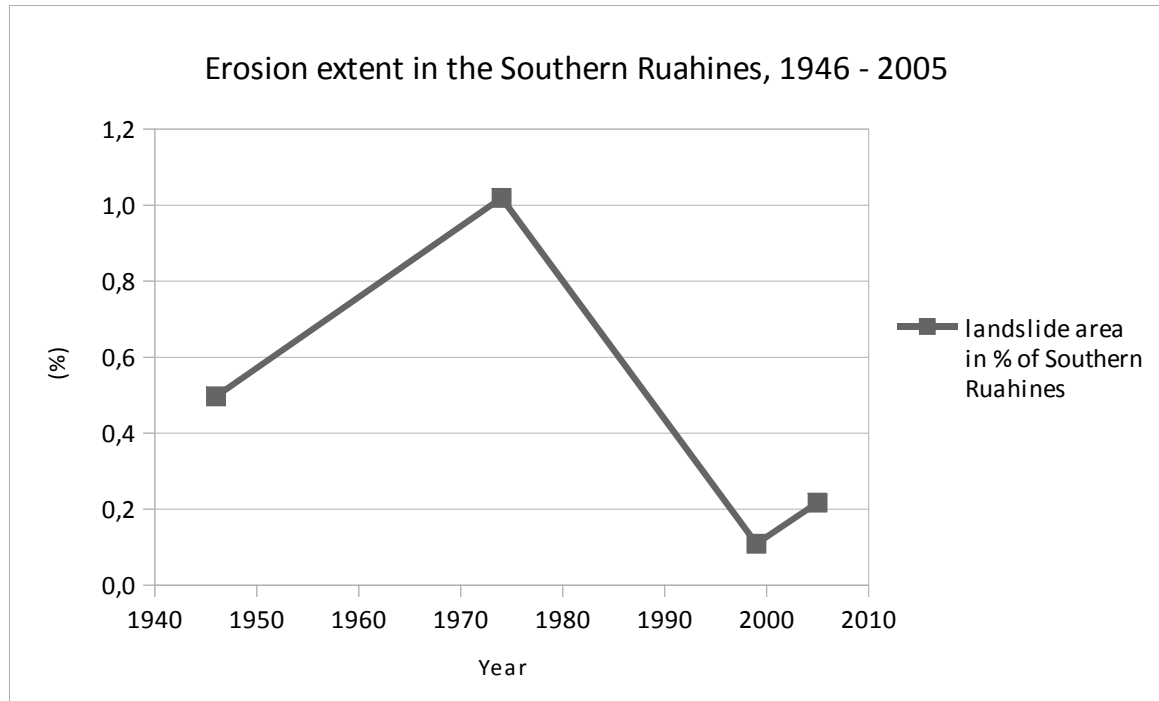


Figure 6.13 In the diagram, the temporal variability of the erosion extent in the Southern Ruahines is shown. The exact data for the figure can be seen in Table Table 6.2. Note the different dates of data generation.

As already mentioned during the presentation of the erosion maps for the Southern Ruahines, pasture as well as woody vegetation, mainly forest covers the study area. Here in Table Table 6.3 the accurate values for the years 1999 and 2005, where vegetation information could be derived from the aerial pictures are presented. The results are split in three categories showing the number of debris slides and their area on pasture, forested terrain and in total. To give an idea of the feature characteristics, their minimum, maximum and average size are given.

	1999			2005		
	pasture	forest	all	pasture	forest	all
Erosion feature count	114	342	456	704	1.261	1.965
Min feature area – m ²	0,94	4,41	0,94	5,51	3	3
Max feature area – m ²	847,77	15.076,58	15.076,58	9.461,12	24.097,78	24.098,78
Mean feature area – m ²	136,71	661,57	530,35	175,65	285,47	246,13
Erosion area – m ²	15.584,61	226.256,49	241.841,1	123.657,14	359.983,42	483.640,53
Erosion area – km ²	0,02	0,23	0,24	0,12	0,36	0,48
% of study area	0,01	0,10	0,11	0,06	0,16	0,22

Table 6.3: Landslides predominantly appearing on pasture or woody vegetation in the Southern Ruahines.

After presenting individual results for Tamaki West as well as for the Southern Ruahines, in the last illustration of this subchapter the relation between both is shown in Figure 6.20. Within this chart it is visible that all derived values for the whole study area lie below the characteristics of the smaller catchment. Still, the trend is the same. Both curves ascend and descend at the same periods. The difference is, that at all four dates available for both objects of investigation the graph is always steeper in the Tamaki West catchment than in the Southern Ruahines.

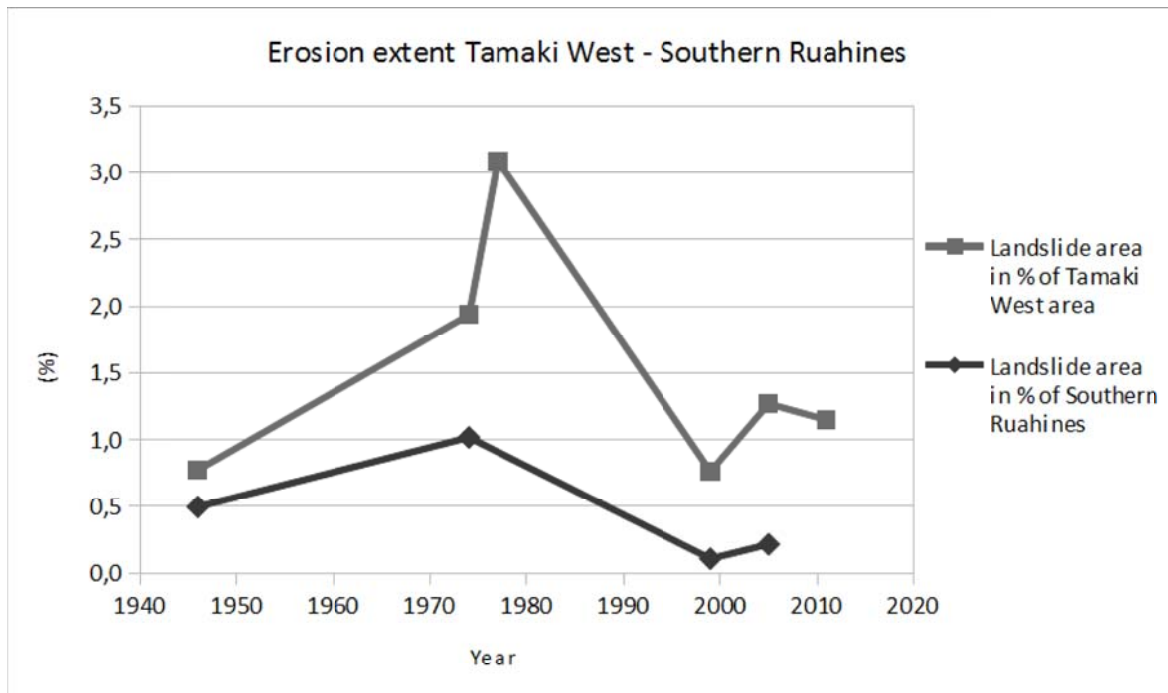


Figure 6.14: Landslide area of Tamaki West catchment and Southern Ruahines. The values are given in a relativ number related to the total region they are results are derived from.

6.1.3 Landslide-slope distribution

In this chapter the relation between inclination of valley slopes and the occurrence of landslides is presented. On one hand the slope values for all landslides in the Southern Ruahines based upon a slope raster derived from the 15 m DEM are shown. The values for Dry creek and Car Park creek rely on a more accurate two m DEM and are thus presented separately.

To show the distribution of the landslides within the respective slope, the individual values were converted to 10°-classes. All identified landslide pixels lie within the six classes shown in Figure 6.15. For a better comparison between the landslide grids which cover different areas, the slope classes are depicted in percent. The slope distribution of the study area is added for comparison reasons and is also shown in Table Table 3.1 and the slope map in Figure 3.7. It should be emphasized that the curves of showing the landslide slope classes have a very similar graph. The exception is 1999, which shows a

different pattern. All landslide slope classes show higher values than the slope of the study area in the three steeper classes. In all analysed years, the maximum pixels affected by landslides are situated on slopes inclined 30 to 40 degrees.

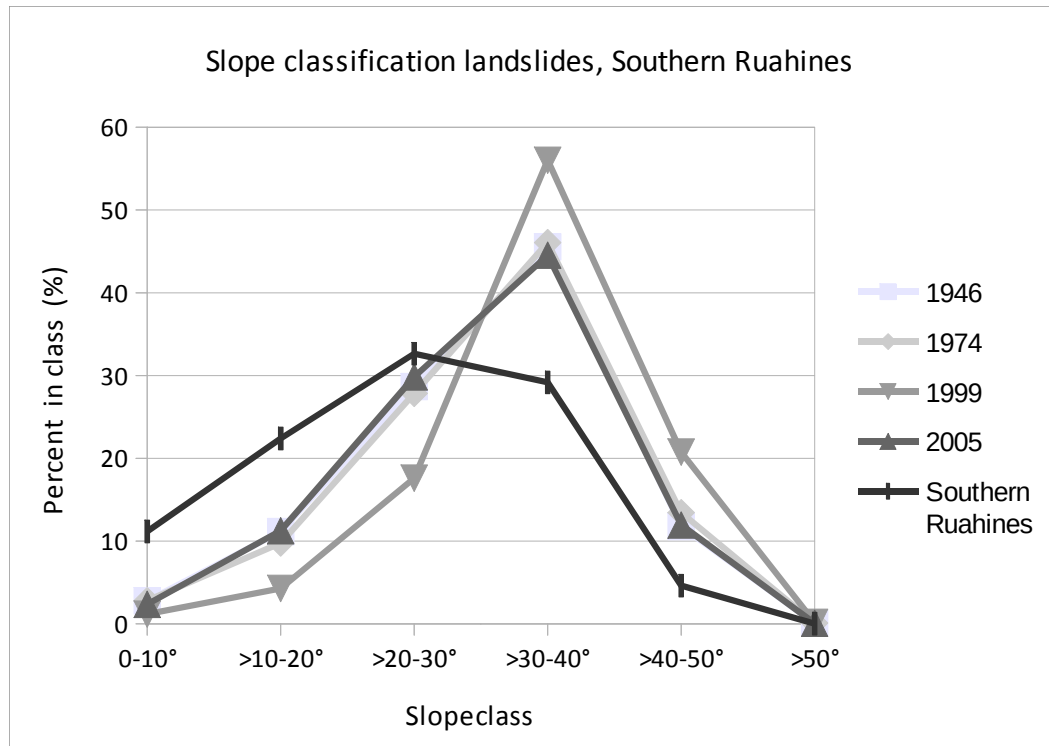


Figure 6.15: Slope classes for landslides in the Southern Ruahines in percent of the respective category. The values of the study area were added for comparison.

The mean values of all four analysed dates are shown in Table Table 6.4, together with the results for the more accurate two m DEM. Generally, the mean slope values derived from the two m DEM are higher in all categories compared to the 15 m DEM values. Throughout all mapped years, the slope at landslide affected areas is higher than the average for the respective analysis region. In both regions the highest values are recorded for 1999. For comparison reasons, the slope for Tamaki West catchments is added here. With a mean slope of 29,88° it is exactly located between the two other mean slope values.

	Mean slope (°)						whole area
	1946	1974	1977	1999	2005	2011	
Dry and Car Park creek	41,26	41,82	41,84	43,25	40,61	40,83	34,18
Southern Ruahines	30,24	30,78	-	34,19	30,14	-	24,33

Table 6.4: The mean slope values for the respective categories. Within the years, they represent the values for the landslide covered areas and the two values for the whole area represent the slope inclination in the respective region independent of mapped erosion features.

Besides the mean slope values, also more detailed results derived from the accurate two m DEM available for Dry creek and the adjacent Car Park creek are presented. For a better comparison of the different time slices, the results are grouped in 10° classes and shown in Figure 6.16. The most recent slope values for 2011 are shown in pink and should be treated with particular attention, because they represent the most recent condition. This is reasoned by the DEM data base, which is derived from the high resolution 2011 aerial picture. So the DEM accounts for all geomorphological changes which occurred after any of the other aerial images used for landslide mapping were recorded. This can result in inaccuracies which presumably increase with time. Besides this, all other values trend quite homogeneously. For comparison reasons the slope values for the 2011 landslides calculated on the base of the 15m DEM slope is added in the chart.

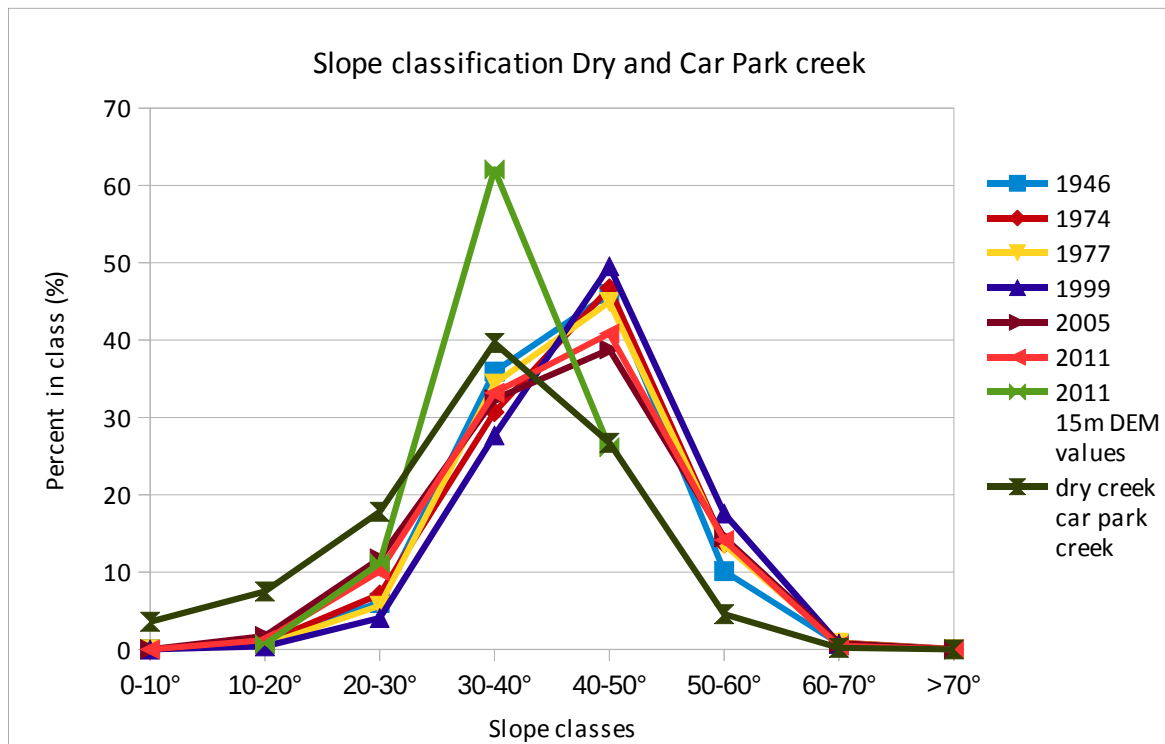


Figure 6.16: Slope values of landslide covered areas grouped in 10° classes derived from the two m DEM. Values for 2011 derived by the 15 m DEM were added for comparison.

6.1.4 Discussion

After presenting the results for the spatial and temporal variations of shallow landslides, these results are interpreted and discussed in this subchapter. The base for all results presented above is the accurate mapping of the debris slides from the aerial picture sets. It can be concluded that possible systematic errors through the mapping are low, because the mapping was carried out manually. As elaborated by several authors like Soeters and Van Westen (1996), Paine and Kiser (2003) or Schowengerdt (2007), expert knowledge is a very good way to produce accurate results. Based on that knowledge, it can be resumed that the produced data base for the presented results can be considered as solid. Based on that awareness, the results can be interpreted on their information value.

Besides the landslide extent in the Southern Ruahines, the more detailed analysis of the Tamaki West catchment is present. The later usage of the latter mapping to reassess the erosion maps by Marden (1984) arise the question if Tamaki West and the Southern Ruahines react in a similar erosion pattern at same years.

Therefore also the differences in the landslide patterns within single years has to be accounted for. Considerable differences appear in the minimum, maximum and mean debris slide area as shown in Table Table 6.2. In combination with the number of occurred features and the total landslide area, this can convey an idea how the single debris slides are characterised at higher or lower activity periods. The biggest minimum landslide area for the Southern Ruahines can be observed in the mapping carried out by Marden (1984) for 1946 with a value of 41,58 m². The smallest in 1999 which comprises 0,94 m². As the first value is derived from the original map, not only the existence and amount of smaller features could have influence on the value, but also the different mapping technique, as Marden (1984) used a mirror stereoscope for manual mapping whereas in 1999 the landslides were digitised in ArcGIS. Considering the maximum feature size, it is again Marden's map for the 1970's which has the highest value with 36.665,58 m². More obvious values are delivered by the mean feature size, where the smallest value is found in 2005 with 246,13m² which is about twice as big in 1999 and more than 4 times bigger in both of Marden's maps. This indicates that compared to the methods used in this work, generally smaller feature were not mapped and there is a slight overestimate of the landslide areas in Marden's maps. This is further underpinned by the fact that if the mean landslide area is reassessed in the same way the area was reassessed, the values are still about 3 times as high as the one from 2005. Compared to that, the mean feature size for the Tamaki West catchment in 1946, 1977, 1999 and 2005 range from 972,77m² to 1971,53m², so the highest value is not even twice as big as the lowest.

The difference between areas covered by woody vegetation and pasture are shown in Table Table 6.3. Here, also differences between the two landcover types can be identified. In both cases, 1999 and 2005 the biggest debris slide is found under woody vegetation

and is approximately 18 times in the former and 2,5 times bigger in the latter year. Both times mean landslide area values are bigger under forested areas, even though the difference to pasture is only minor. An interesting fact is that in 2005 about 704 (35,83% of total) and in 1999, 114 (25% of total) debris slides were recorded on pasture even though only 20,05% of the study area is covered by grassland and slope inclination on pasture is significantly lower than in the study area. This indicates, that slope failure is easier triggered on pasture than on forest and emphasises the importance of woody vegetation cover for hillslope stability explained in chapter 2, Landslides.

The comparison of the landslide affected area is best understood by looking at the two diagrams in Figure 6.8 and Figure 6.13 showing the relative area which is covered by landslide scars in the respective years. Here, a clear activity period can be identified in the 1940's and 1970's whereas the more recent dates after 1999 show a declined activity. No clear trend can be seen because all values are alternately rising and falling with the exception of the debris slides mapped in 1977 for the Tamaki West catchments which rise again after the results from 1974. An indication of the magnitude of change can be derived from the steepness of the curve connecting two dates. The steeper the curve is, the faster change occurred.

To further comprehend the relation between Tamaki West and the Southern Ruahines, the chart given in Figure 6.17 shows the relation of landslide affected area between these two regions. Through the interpretation of that curve, it becomes clear, that all values in the Tamaki West area always exceed the ones for the Southern Ruahines, and that also the response to changes is stronger in the small catchment. Partly, this can be attributed to the generally steeper environment in this particular catchment.

This leads to the second hypothesis, where it was stated:

The landslide extent of fresh landslides for the whole Southern Ruahines can be derived from the landslide cover in the Tamaki West catchment.

Generally it can be said that there seems to be a good correlation between the trend in the Tamaki West catchment and the Southern Ruahines. Still this conclusion has to be used carefully, because the continuous higher values in the small catchment seem to

overestimate possible deductions. So, a general statement as given in the Hypothesis has to be taken with care, although it could be considered as a possible result. If the erosion rises in Tamaki West, the landslide affected area also climbs in the Southern Ruahines and vice versa.

This correlation is crucial to evaluate the results derived from the mapped translational landslides by Marden (1984) which were adopted for this work. Here, some limitations at which detail results are directly comparable were already mentioned. The Tamaki West catchment has a size of 11,3 km² which covers about 5 % of the Southern Ruahines. Still, there are some crucial differences. The average slope in the smaller area is about 5,5° steeper and it is almost entirely (99,86 %) covered by forest and shrubs. Besides topographic disparities, the different mapping method used by two independent scientists, more detailed explained in chapter 4.2.3 has to be taken into account. In addition the landslide coverage in the Tamaki West is higher in all years than in the Southern Ruahines. Combining these findings, it can be assumed that the reassessment values R_N and R_A used to recalculate the results from Marden (1984) are qualified to obtain data which is better comparable to the mapping carried out in this work. It has to be concluded, that these factors already downsizing Marden's (1984) recorded areas, probably still are too high, and the reassessment factors would have to be even smaller.

Concerning the slope at which the landslides occurred, the biggest difference for the results are attributable to the data base, where the inclination values for the Southern Ruahines were derived from a 15 m and the values for Dry creek and Car Park creek from a two m DEM. The advantage of the coarse data set is, that through the generalisation it can be used for all acquired dates because almost all topographic changes in the meantime are neglectable. Within the more accurate DEM which was derived from 2011 data, this is more sophisticated. Because of its accuracy also small changes through channel incision or mass movements are displayed in the grid. So the values for earlier years derived from that data have to be treated with care as they give only an indication of the conditions at the respective time.

In the Southern Ruahines the dominant slope class where landslides are found spans among 30° and 40° shown in Figure 6.15 and in Dry and Car Park creek the majority of all values lies between 40° and 50° shown in Figure 6.16. In the study area between 44,54 % in 2005 and 56,02 % in 1999 reside within the former category whereas in the Dry and Car Park creek the latter category accounts for 38,78 % (2005) to 49,55 % (1999) of the total landslide area. To be able to compare the accuracy, an example of the landslide slope derived from the 15 m DEM for Dry and Car Park creek is given. The landslides mapped in 2011 for this small area additionally were analysed using the coarser slope grid. In the diagram shown in Figure 6.16 it can be seen that values range only from the class comprising more than 10° to the class of 40°-50° slope, and the majority of the landslide area (62,05 %) lies within the 30°-40° class. Within that classification results the significant differences to the finer two m DEM values are apparent and the behaviour act more similar to the rest of the 15 m DEM derived slope values.

Generally, the landslides trend to occupy higher slope classes compared to their mapping regions. Within both diagrams it is noticeable that the values for 1999 are the highest in the dominant slope class. For the small investigated area the difference between all curves generally is bigger and thus this fact is not very striking. On the contrary, within the Southern Ruahines all other three values in that class vary between 44,54 % and 46,06 % comprising a difference of 1,52 % whereas the value of 56,02 % in 1999 is almost 10 % higher than its preceding value. Besides this aberration the other tree curves run quite homogeneously. This suggests that the distribution of the slope values for 1999 follow a different pattern or some inconsistencies lie within the mapped data or its assigned slope values. Possible reasons for the different behaviour can result from the significantly coarser image properties of the aerial pictures resulting in altered mapped landslide extent. Another possible reason is, that different slope values result from the fact, that the 1999 sample is the smallest (0,11 % area coverage in the Southern Ruahines compared to values from 0,22 % to 1,02 %).

6.2 Landslide volume estimation

Landslides do not only occur and directly inflict the surface through the slope disturbance but also transport material downslope. As already mentioned in chapter 2, Landslides, eroded material can be deposited in temporal storages like hillslopes or get removed by several processes. The amount of material dispatched is also of interest. By knowing the volume eroded by shallow landslides and its connection to the channel-system, one important sediment source influencing the rivers within and outside the ranges can be assessed. In this chapter the results for the calculated volumes are presented. This is based on the individual connectivity analysis for each feature which was carried out parallel to the landslide mapping.

To obtain the volume results, several steps following the mapping procedure are necessary. These initial outcomes which are necessary to calculate the landslide cubature are presented first, followed by the desired volume values. First, the DEMs compiled from field surveyed elevation data are illustrated. Secondly, the calculated volumes for all four investigated landslides are given. Thirdly, the potential volumes for the study area are documented. And finally, the values for the coupled landslides are presented.

6.2.1 Compiled DEM's

The basis for the volume calculation is the field data obtained using a differential GPS system and a robotic total station. Derived from this data, DEMs were calculated using Surfer 9 software which form the basis for the volume calculations. For details concerning the compilation procedure please be referred to chapter 4.1.2 in the methods. The general data characteristics for the calculation of the DEMs are available in chapter 5.2. The actually used data is presented in Table Table 6.5, where the specific properties for all four surveyed landslides are given.

Between 215 and 1262 surveyed points including easting, northing and elevation values were used to compile the elevation grids. The basis for these digital elevation models

comprises of a minimum of 0,43 points/m² on one hand and 1,04 points/m² for the most densely covered landslide on the other hand. The investigated debris slides are located between 404 m.s.l. and 905 m.s.l., whereas the longest feature extends over 159,4 m in altitude.

	Landslide 1	Landslide 2	Landslide 3	Landslide 4
Number of surveyed points	1272	968	602	216
Number of used points	1262	968	600	215
Surveyed area (m ²)	2943,4	1875,37	1284,05	206,75
Points/m ²	0,43	0,52	0,47	1,04
m ² /point	2,33	1,94	2,14	0,96
Min. elevation (m.s.l.)	772,309	745,911	499,309	403,936
Max. elevation (m.s.l.)	846,374	905,314	535,924	421,056

Table 6.5: Data properties of the field survey for the investigated landslides. Landslide numbers are respective to the field site map shown in Figure 3.12.

To get an impression of the shape of an assembled DEM, a surface map compiled in Surfer is illustrated in Figure 6.17, documenting the current surface conditions in November 2011 of landslide number one situated in Dry creek. This illustration has a simulated light source, similar to an ArcGIS hillshade which gives the impression of 3D vision. The boundary of the landslide is cognizable through the change from ragged to smooth terrain underlined by an edge on the left and rear right side of the model as well as through the end of the image. The fingered scar edge at the top of the slope model is visible as well. All numbers displayed in the figure are in meters, including the colour scale. For comparison, the same landslide is shown from bird's eye view in Figure 4.3, including the survey data points used to compile this surface model.

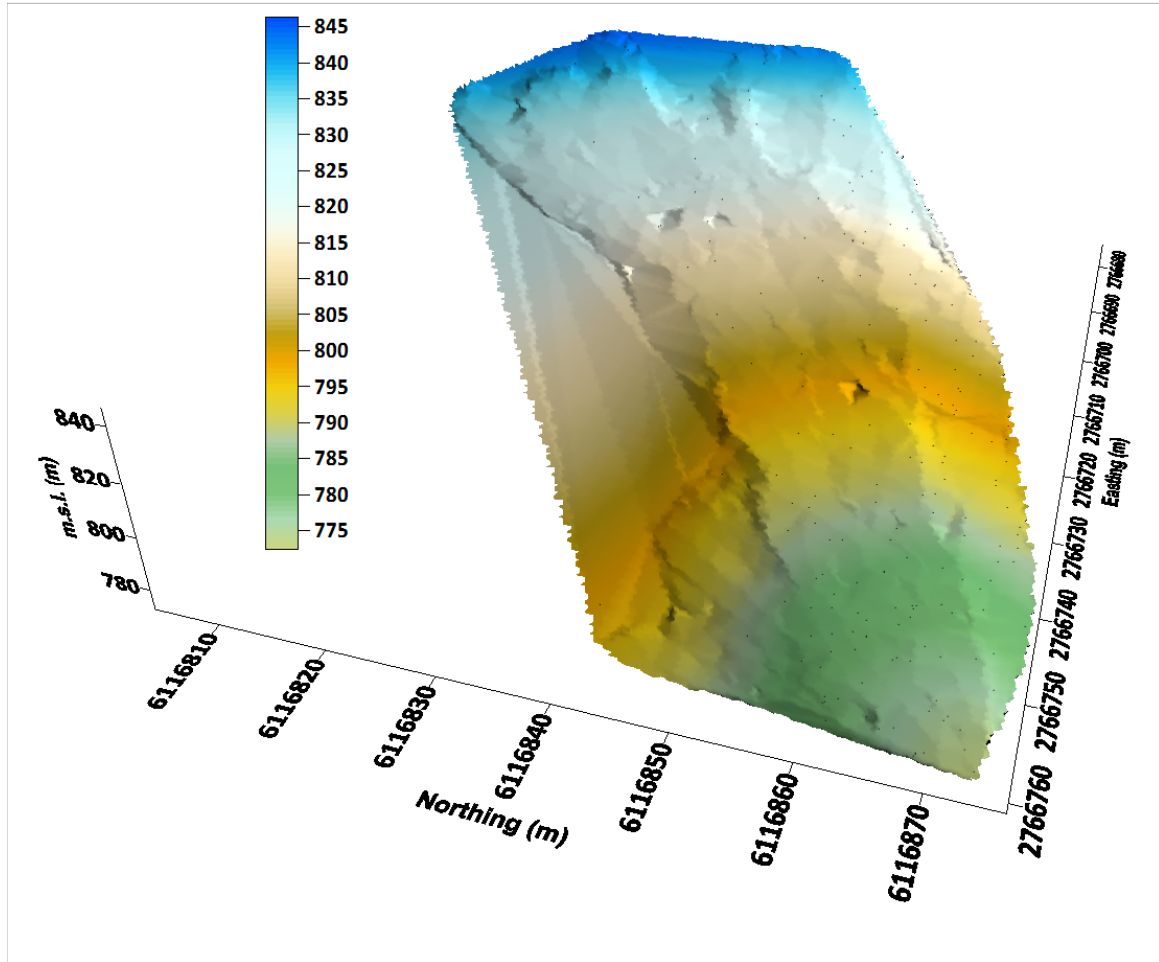


Figure 6.17: Surfer 3D model of landslide number one, Dry creek, 2011, geographic coordinate system: New Zealand Map grid. The unit of the color scale is meter. The simulated light source is positioned in 315°N and 45° above horizon.

6.2.2 Volume for surveyed landslides

Using the DEMs derived by the four accurately surveyed landslides the missing landslide volume for these features were calculated. The calculation was carried out using Surfer and the results are shown in Table Table 6.6. The deepest landslide is number one with a volume of 2,13 m³ for every m² of landslide-affected area. Here also the landslide volume of 8090 m³ is the largest. In contrast landslide number two is the most shallow one with an average volume of 0.45 m³/m². Because of this low value, it does only comprise for the

third biggest material amount even though it is the second biggest feature. Compiled from these four landslides an average volume of 1,247 m³/m² results. As the average volume is indicated in m³/m² this value equals landslide depth. If a feature is one meter deep, the volume of a landslide covering one m² is exactly one m³ and thus both values are convertible.

	Area (fill) m ²	Area (cut) m ²	Combined Area m ²	Volume m ³	m³/m²
Landslide 1	3585,88	219,68	3805,56	8090,04	2,13
Landslide 2	2600,21	373,39	2973,60	1341,46	0,45
Landslide 3	1248,71	112,84	1361,55	2284,01	1,68
Landslide 4	198,28	26,18	224,46	164,87	0,73

Table 6.6: Volume calculation for the 4 surveyed landslides. The Area (fill) value is the area where material was added in the calculation and Area (cut) where material needed to be subtracted.

To get a clearer idea about the appearance and physical properties of the analysed debris slides, the most deeply eroded and the most shallow landslide are shown on two photos in Figure 6.18 and Figure 6.19 on the next page. Within these, also the total absence of vegetation on the landslide scar is visible. Besides the absent plant cover also a difference in the scar surface is visible. Whereas in landslide number two the bare consolidated regolith is visible this is only the case on the steeper edges of landslide number one. The middle part of this debris slide is covered by coarse scree which either remained after the initial failure or more possibly is redeposited material from the steep edges.



Figure 6.18: Landslide 2 situated in dry creek, seen from the opposite valley flank. It ranges from left upper corner to right lower corner.



Figure 6.19: Landslide 1 in Dry creek, seen from the bottom of the feature.

6.2.3 Deduced volume for the research area

With the volume values calculated for four landslides, characteristic for debris slides found throughout the study area, the potential volume for all features in the area was calculated. For these results it was assumed that all four landslide types investigated are equally distributed throughout the study area and thus cover the same share of the landslide inflicted area. More accurate alternatives for this simplification are mentioned in the discussion as well as in the perspectives.

The results for the Southern Ruahines are presented in Table Table 6.7 and are calculated using the average volume derived from all four surveyed debris slides. As the resulting amount of landslide material is connected linearly to the area, the fluctuations between the investigated years is similar to the already presented erosion extent in chapter 6.1 and is thus not explained separately.

	1946	1974	1999	2005
Erosion area (m ²)	1.098.032,39	2.250.889,21	241.841,1	483.640,53
Volume (m ³)	1.369.523,12	2.807.426,12	300.967,46	603.221,63
Average volume:	1,247 m ² /m ³			

Table 6.7: Volume values for the Southern Ruahines and all analysed years.

6.2.4 Hillslope-channel coupling

Within this chapter the benefit of the previously presented investigations becomes apparent. Using the compiled DEMs to calculate landslide volumes, allows to account for the material distributed to the channel system by debris slides. The important component is the interpretation of the mapped features regarding their connectivity which is the crucial conjunction between mapped area and the calculations resulting in obtaining actual landslide dimensions.

It has to be stated that the presented material values are only potential values which are disposable as fluvial sediment, because the landslide debris is not necessarily transported into or within rivers. Merely the physical connection is present, and thus fluvial or other processes like very wet debris flows can be initiated mobilizing and transporting the available material.

Within Tamaki West the connectivity was determined for all years and the resulting figures are shown in Table Table 6.8. Besides the absolute extent of landslide area connected to the channel system, also their share on the total inflicted area is outlined in percent. This ratio varies significantly, as 38,33 % up to 77,91 % of all debris slides can be coupled to the river system. The highest value of connected area occurs in 1977 where 258.209,76 m² of landslide affected area has a physical connection to a river or a streambed. Besides the connected area, also the potential disposable material for the connected landslides is calculated. Compared to the relative number of connected features, the affected area by channel coupled landslides is always bigger. The minimum difference between those two is 19,44 % in 1977 and the maximum is 41,46% difference in 1974.

If the feature size of connected and unconnected debris slides is compared, the minimum connected feature area in 2011 is 12,7 times bigger than the unconnected one. In 2005 this coefficient is only 1,14 and for this reason the smallest

	1946	1974	1977	1999	2005	2011
Erosion feature count	90	157	176	50	110	102
Erosion area – m ²	87.549,36	218.797,72	348.990,91	86.275,43	143.509,36	129.864,72
% of Tamaki West catch.	0,77	1,94	3,09	0,76	1,27	1,15
Connectivity feature count	10	48	96	25	41	16
% of all features	11,11	30,57	54,55	50,00	37,27	15,69
Min feature size - m ²	108,21	29,77	85,6	174,67	23,39	145,89
Max feature size – m ²	17.947,22	18.420,21	16.267,59	15.076,58	24.097,78	17.161,06
Mean feature size – m ²	3.355,54	3.283,34	2.689,68	2.542	2.726,96	4.736,71
Connectivity area – m ²	33.555,43	157.600,1	258.209,76	63.550,06	111.805,338	72.030,05
% of erosion area	38,33	72,03	73,99	73,66	77,91	55,47
% of Tamaki West catch.	0,30	1,39	2,29	0,56	0,99	0,64
Vol. connected landslides - m ³	41.852,08	196.567,04	322.052,65	79.262,94	139.449,43	89.839,63

Table 6.8: Tamaki West hillslope-channel-coupling results for all years.

The relation between the totally eroded area and the connected landslide area is illustrated in Figure 6.20. All used numbers are presented in Table Table 6.8 in the three lines stating "% of Tamaki West catch." (two times), and "% of erosion area".

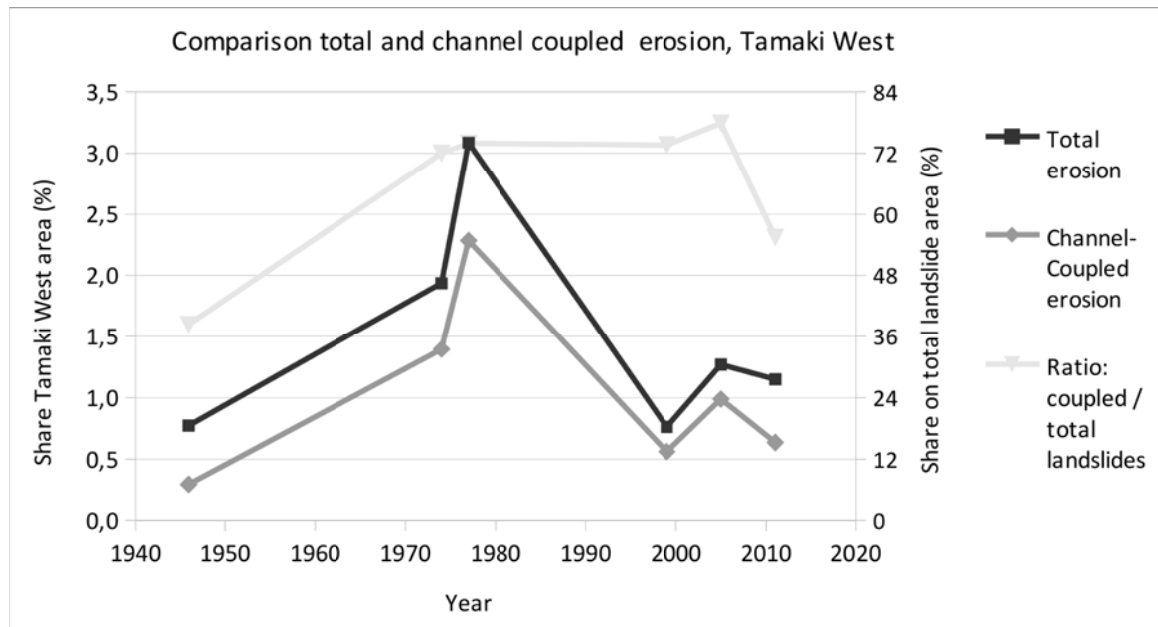


Figure 6.20: Comparison of landslide inflicted area and channel coupled landslide area in Tamaki West. The share of landslide area connected to the river system in relation to all debris slide affected area is given in percent in the light grey line (triangles).

For two dates it was also possible to derive the connectivity patterns for the Southern Ruahines. In 1999 and 2005 the hillslope-channel-coupling areas were identified and are outlined in Table Error: Reference source not found. Compared to the relative number of connected features the affected area by channel coupled landslides is greater. The biggest difference between the degree of landslide features which are connected and the percentage of channel coupled erosion area is 41,48 % in 1999.

Both landslides with the maximum feature size in 1999 and 2005 are connected.

	1999	2005
Erosion feature count	456	1965
Erosion area – m ²	241.841,1	483.640,53
% of Southern Ruahines	0,11	0,22
Connectivity feature c.	97	321
% of all features	21,27	16,34
Min feature size – m ²	9,13	7,95
Max feature size – m ²	15076,58	24097,78
mean feature size – m ²	1564,63	787,94
Connectivity area – m ²	151.769,53	252.929,63
% of erosion area	62,76	52,30
% of Southern Ruahines	0,07	0,11
Vol. connected landslides – m ³	189.294,85	315.466,99

Table 6.9: Southern Ruahines hillslope-channel-coupling results for selected years.

As all landslides are already shown in the maps in the previous subchapter, an illustration of the connectivity patterns for all years is not added here. To give an example of the visual decision criteria used and the pattern of the hillslope-channel-coupled areas in one year, the classification of all landslides in 2005 is shown in Figure 6.21. In this map it is recognizable that the connected landslides are mainly clustered around the valley heads, but also sparsely scattered over the river basin. Logically, the unconnected debris slides are mostly more distant from the gravel river beds.

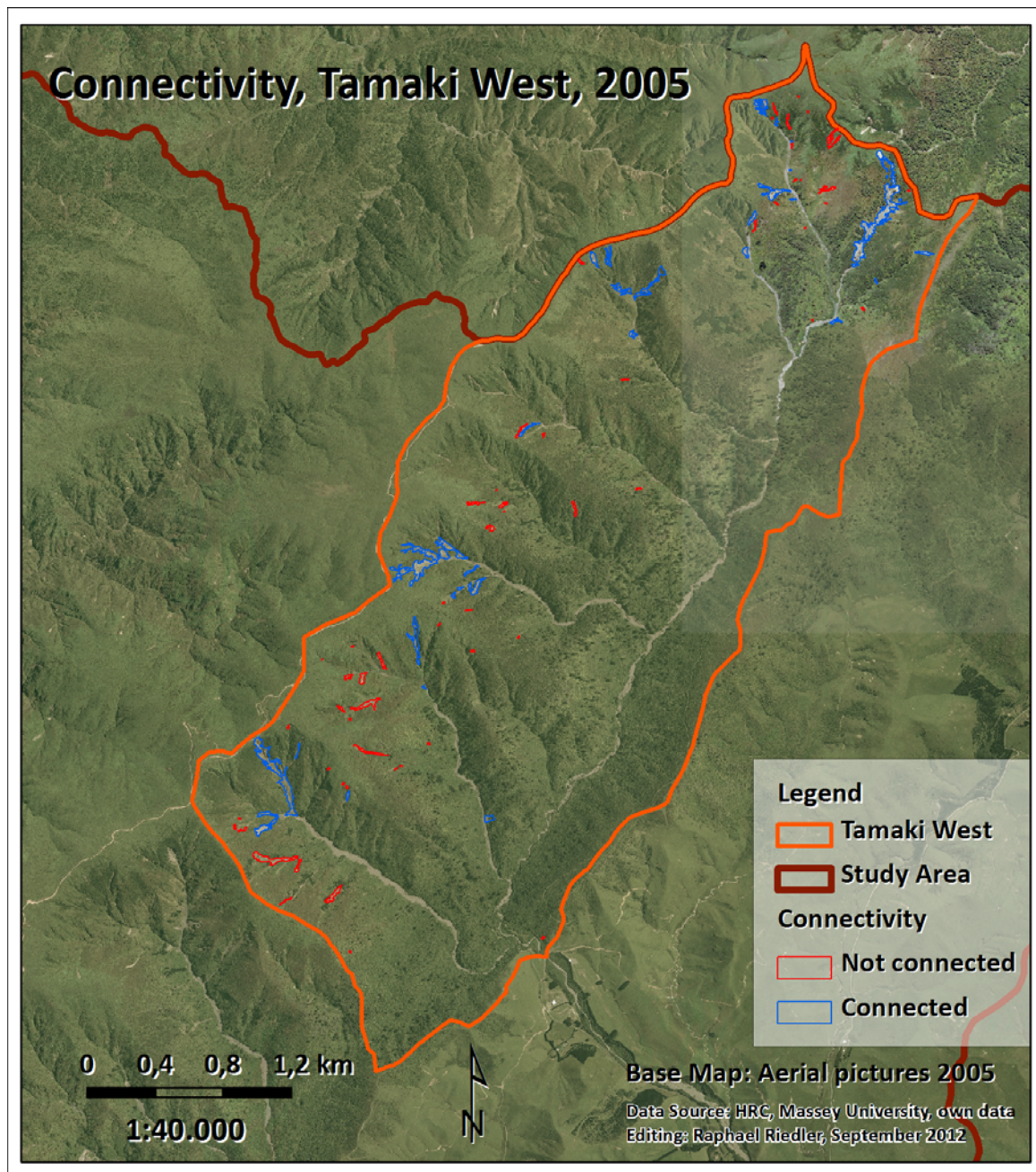


Figure 6.21: Hillslope-channel coupling in the Tamaki West catchment, 2005.

6.2.5 Discussion

Close landslide monitoring in the Southern Ruahines has several advantages and should be continued. By analysing the occurrence patterns of debris slides, crucial information

about their actual behaviour is gained, and within that also knowledge about sediment which is currently provided by shallow landslides. Of course, there are several sources of material present, but mass movements account for an important part of them in such steep environment. Within these, shallow translational slides occur frequently and consequently form a continuous source of supply. Indeed deep seated landslides also play a role, but are not treated in this work (Mosley and Blakely 1977, Mosley 1977, Marden 1984, Heerdegen and Shepherd 1992).

Because of the importance of the topic, several authors worked on landslide depth, resulting volumes in general and in the Southern Ruahine in particular. In the work of Cruden and Varnes (1996) a good summary of possible ways to calculate landslide volumes is presented. Other authors included specific numbers of landslide depths for the Ruahine Range in their work. As a simplification, and due to the fact that shallow translational landslides are investigated, the landslide depth is put on one level with the volume in m^3/m^2 .

In his report of 1977, Mosley stated that shallow soil slides in the Southern Ruahines (comparable to the debris slide type of this work) have an average depth of 0,5 – one meters. A greater value is supposed by Stephens (1981) who claims that the average depth spans between two and three meters. In coordination with Mosley, Marden (1984) also assumes 0,5 – one m profoundness. On a broader base, Dymond (2006) suggest an average landslide depth of one m. These values are in good coordination with the here acquired result of $1,247 \text{ m}^3/\text{m}^2$ and thus support the presented findings.

Certainly not each mapped landslide failed for the first time at certain locations. Looking at the maps in chapter 6.1, this gets obvious, especially at the maps for Tamaki West, which provide better comparability. When a landslide occurs for the first time, it can be assumed that more material gets eroded than at the second or any subsequent time. This is mainly caused by the degree of weathering and soil formation which takes time (Crozier et. al 1992). So, it can be assumed that the material amount degraded by a landslide which occurs on the spot of a formerly active feature, is smaller than the initial

amount. As this effect is not considered in the volume calculation carried out in this work, the results have to be interpreted regarding this aspect.

Another uncertainty is present since the detailed surface surveillance for four landslides were carried out in 2011 and thus represent the conditions in that year. The surveillance results are highly compatible for calculations carried out using the 2011 aerial pictures, because the data is from the same year. To be able to interpret the volumes derived for other dates, it needs to be stated, that the four investigated landslides are chosen in a way, that they are characteristic for debris slides throughout the entire study area. Here other studies can help to clarify that issue.

One of the first references to distinct landsliding in the Ruahines can be found as early as 1878 by Colenso, where also a detailed description of one mass movement is included. Still, if the analysed debris slides are compared with the description of shallow translational slides depicted in more recent literature, good analyses can be found starting in 1973. Mainly in the first three chapters of this work it was already referred to the observed features by other authors behaving alike and forming similar shapes as the currently observed debris slides. Thus, it can be stated, that landslides which occurred since the 1970's have a similar character than recently observed features (James 1973, Stephen 1975, Mosley 1977, Schumm 1977, Hubbard 1978, Hubbard and Neall 1980, Grant 1983, Marden 1984, Schwendel and Fuller 2011).

Underpinned by that finding, it can be stated that the derived average landslide depth is also valid for earlier calculations. Starting from the 1970's this can be assured by the detailed available literature.

An alternative option to improve the accuracy of the volume calculations for the mapped landslides would be to divide the investigated debris slides in several subtypes. Various possibilities were considered, and the most suitable option would be to form two subclasses. One containing landslides which generally erode deeper comprising of broader, more compact landslides like landslide number one and three. The second class would contain more shallow features developing longer, thinner erosion forms as well as very small features represented by landslide number two and four. Because of a lack of

resources, this was only tried by way of example for the 1999 mapping and thus results are not presented. This approach could carry interesting potential for further analysis concerning volume re-evaluation.

Referring to the hillslope-channel-coupling, it is apparent that compared to the relative number of connected features the affected area is outstanding. Besides this the minimum feature size is always larger than at uncoupled debris slides. In seven out of eight years in Tamaki West as well as in the Southern Ruahines the biggest landslide feature is connected. Resulting from this preconditions, also the mean feature size is bigger at hillslope-channel-coupled landslides. The conclusion which can be drawn from this finding is that channel-coupled debris slides are generally bigger.

For the area comparison of all mapped debris slides with the hillslope-channel-coupled area, a good overview is available in the diagram shown in Figure 6.20. In this figure, the share of the connected landslide area is compared with the total area. Contrasting to the clear relation of the single features number and their relation to the affected area, no clear trend can be identified. This aspect was investigated with special care, because it refers to the first hypothesis which states:

Stronger landslide activity in the research area results in a higher percentage of hillslope-channel connectivity.

Due to the ambiguous results concerning the area coverage compared to the total landslide area, this hypothesis has to be rejected. Especially in 1999 and 2005 the share of connected landslide area on the total area is eminently high with 73,66 % and 77,91 % respectively. Compared to the higher absolute values in 1974 and 1977 these numbers are considerably high. The 2005 proportion is the highest value observed even though the total debris slide coverage in this year is only the third biggest and is less than half of the 1977 total area.

7 Conclusion

In conclusion a strong temporal variability between the observed dates is visible, even though no clear trend can be identified. This could implement, that the analysed time window is too short to see a long term progression, and that further investigations are necessary. Referring to the geomorphic cycle of Schumm (1975) it is possible that the observed changes are within a phase which does not show an immanent trend so that the long term regime of the landslide patterns is not yet visible. This is also underpinned by Grant's (1983) finding which are also shown in Figure 1.1 where he identifies erosion and tranquil periods since the 13th century in the Southern Ruahines. In this light the temporal changes in the erosion patterns can also indicate a change from an erosion period to a tranquil interval. This would be underpinned by the rising values starting in 1946 until the maximum observed landslide area in 1977. Since that date the erosion values drop to a very low level and oscillate at that niveau until 2011.

Anyhow it can be pointed out that aerial picture interpretation is a very vivid tool to asses the landslide extent and their connectivity to the river system. Thus the generated data for landslide extent between 1946 and 2011 provides crucial information which can serve as an accurate data base for further investigations on the erosion pattern in the Southern Ruahines. Besides the knowledge of the potential hillslope-channel-coupling rate in a steep environment like the Southern Ruahines can be used for other regions.

The connection of the aerial picture interpretation and the closely investigated landslide volumes to derive the amount of eroded material makes it possible to assess landslide volumes at remote places and over longer time periods. In conjunction with determining the connectivity for debris slides by visual attributes, this leads to the possibility to obtain material values which are disposable for fluvial transport in areas which are not directly accessible. Consequently one component responsible for material input from mountain ranges to the adjacent lowland and river streams can be assessed. Obviously the subsequent step has to be to include temporal buffers within the system to see which part of the material actually gets transported by rivers after slope failures.

Several aspects still remain in question and require further analysis. Most important the future development of the landslide areas and their contribution to erosion in the Southern Ruahines.

8 Perspectives

During this work detailed results for landslide coverage and their potential volume were presented. In the research and data evaluation some further aspects of interest showed up. Based on the work carried out, there are multiple possibilities to refine the results and gather new insights presented in this chapter.

One of the main things which should be investigated if this work is continued, is to subdivide the landslide classification in this work. This could be done according to the landslide depth to be able to derive more precise material values for the connected features. The easiest classification would involve two types, one consisting of long, thin as well as very small features, which are both shallow and a second type which is broader, shorter and deeper. The advantage is, that this classification can be applied relatively easy during the aerial picture interpretation, because there are only few classification criteria. First the accurate surface surveillance of further landslides in the area would improve the bandwidth for volume calculations and secondly different classification schemes could be found according to the new findings. Reinvestigating the four already analysed features should also be considered during this second field phase to obtain data about reactivation or refilling patterns.

If it could be arranged that an airborne laserscanning survey is carried out, it would be interesting to compare the compiled DEMs from the field data with the laserscan data. Further more this would be an excellent base to reassess the present mapping and to use it to investigate deep seated slips in the Southern Ruahines.

A method which was used to gather information about the subsurface conditions on landslide scars was georadar (GPR). The results were not included because no clear statement could be made on them. One reason was that no reference profile on known

material with equal properties like the one in the study area was analysed. So it could be part of future analysis to produce such a profile and to properly evaluate the seven obtained GPR Profiles. If obvious changes occurred at the two investigated landslides, the possibility exists to gather more profiles at the same location. This would be possible because all profiles routes were tracked simultaneously to the GPR measurements by differential GPS.

The landslide reactivation pattern was introduced in the work, but not treated in detail. As the reactivation influences the amount of eroded material, this pattern is crucial to obtain accurate volume values. Thus finding a way to assess the amount of reactivated and fresh landslides should be carried out. The fact that all debris slides were mapped in ArcGIS and therefore are present in vector format as shapefiles opens some good opportunities.

A big complex are the causes for landslides. Surely the underlying factors like geology, vegetation and precipitation distribution were explained in this work. Still the triggering factors were not discussed. Referring to them and analysing especially the precipitation values which are recorded at several rainfall stations within and around the ranges could produce some interesting results.

Last but not least taking a closer look at the mitigation measures which were taken by several different agencies and political stakeholders is desirable. Within these precautions, revegetation efforts were already elucidated in this work, but the direct consequences and efficiency still should be further analysed. In Tamaki West also gravel mesh was found during the field work, holding back landslide scree and thus intending to stabilize slopes. Besides there are engineering structures like weirs or concrete barriers in the floodplains adjacent to the rivers. To assess their efficiency and to see which are the most useful would be an interesting challenge.

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All data providers mentioned in Table Table 5.1 on page 58.

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ERDAS IMAGINE

Surfer

Photoshop

Microsoft Office

Freehand

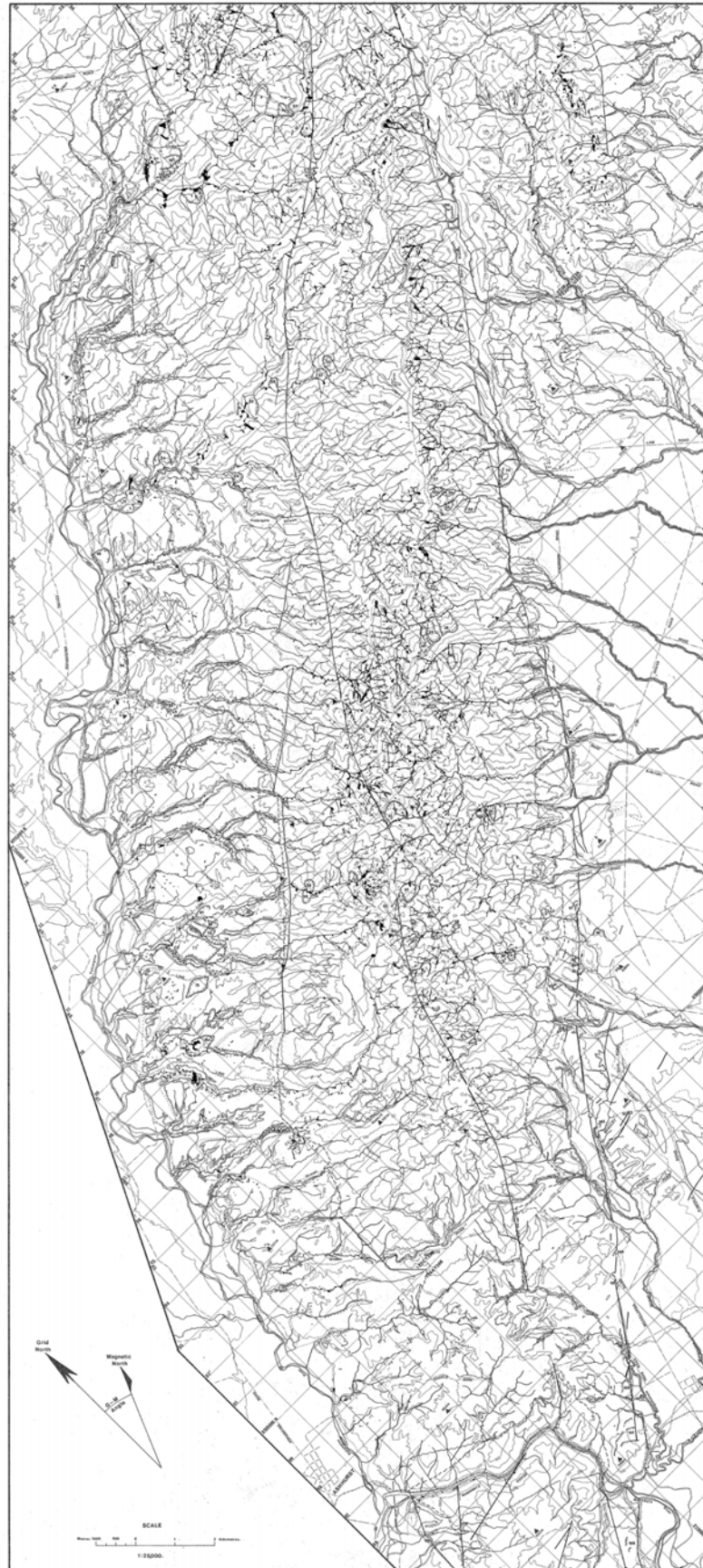
Apple Applications

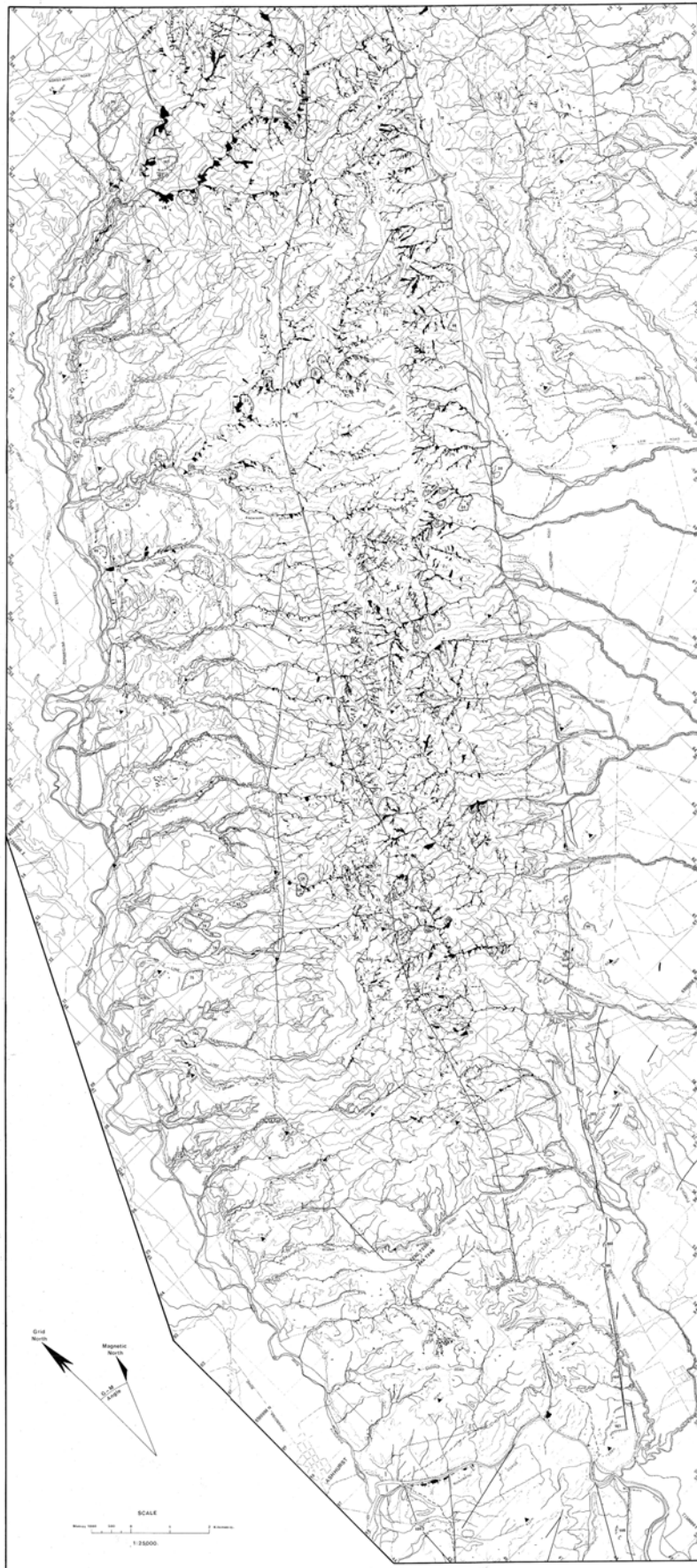
SPSS Statistics

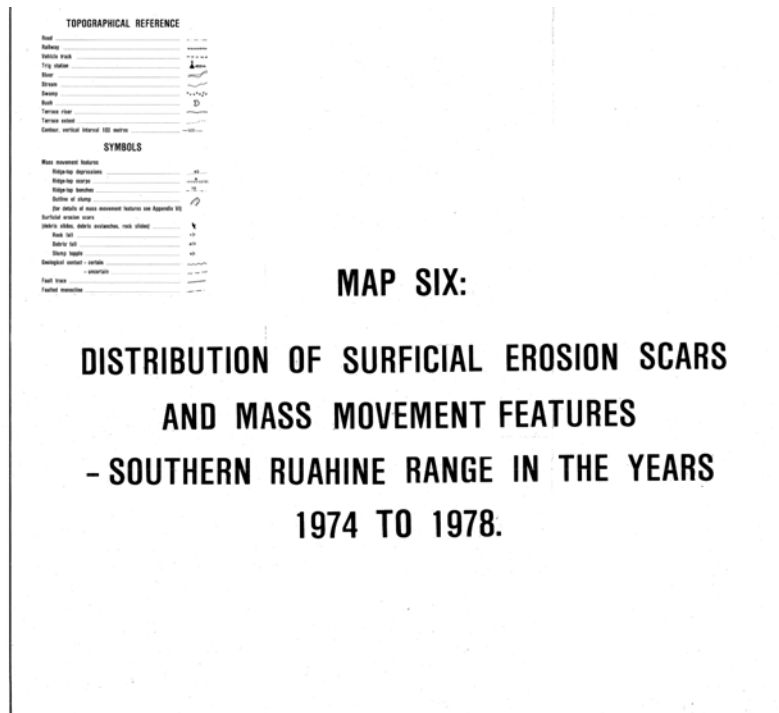
Leisure Time Activities

Rock climbing, mountain hiking, www.talkin.at, fire acrobatics, Latin dancing

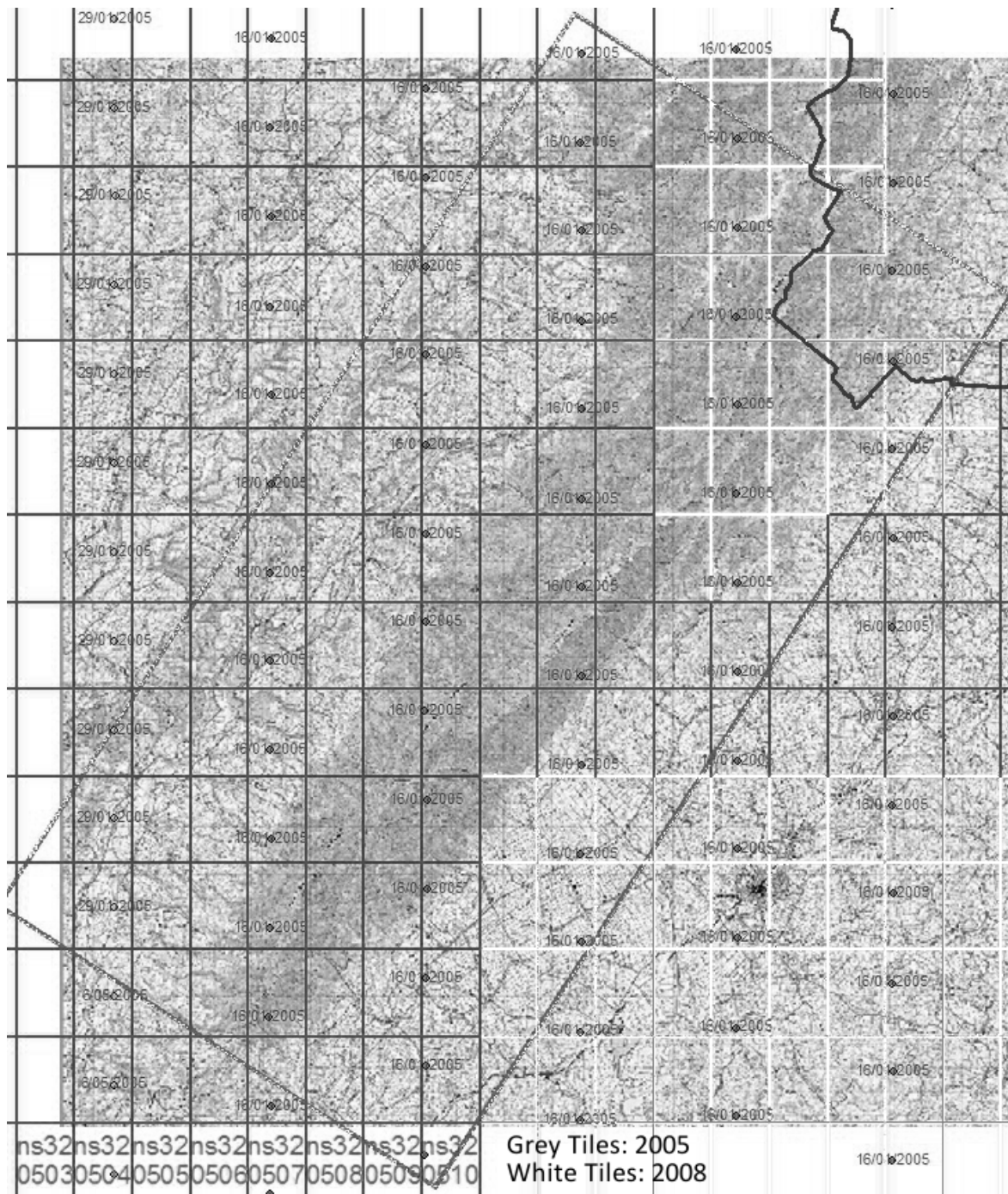
Appendix







Appendix II: Mapped landslides by Marden (1984) for the 1970's,



Appendix III: Flight Plan aerial pictures 2005/2008