Ministry for Primary Industries
Manatū Ahu Matua

Best options for land use following radiata harvest in the Gisborne District under climate change: Spatial analysis of erosion susceptibility in plantation forests, East Coast Region

SLMACC 405415

MPI Technical Paper No: 2018/47

Prepared for Janine Alfeld, Sector Partnerships and Programmes Branch by Raphael Spiekermann, Mike Marden;
Manaaki Whenua – Landcare Research

ISBN No: 978-1-77665-953-1 (online)
ISSN No: 2253-3923 (online)

June 2018

New Zealand Government

Disclaimer

While every effort has been made to ensure the information in this publication is accurate, the Ministry for Primary Industries does not accept any responsibility or liability for error of fact, omission, interpretation or opinion that may be present, nor for the consequences of any decisions based on this information.

Requests for further copies should be directed to:

Publications Logistics Officer
Ministry for Primary Industries
PO Box 2526
WELLINGTON 6140

Email: brand@mpi.govt.nz
Telephone: 0800 00 83 33
Facsimile: 04-894 0300

This publication is also available on the Ministry for Primary Industries website at:
http://www.mpi.govt.nz/news-and-resources/publications/

Reviewed by:	Approved for release by:
Dr Hugh Smith Senior Scientist – Geomorphologist Manaaki Whenua – Landcare Research	Chris Phillips Portfolio Leader – Managing Land & Water Manaaki Whenua – Landcare Research
MWLR Contract Report:	LC3202

Contents

Page

Executive Summary

Introduction

Some of the areas initially planted in exotic pines as an erosion mitigation strategy have experienced an increase in erosion when storm events happen to coincide with the period of harvesting. Such events can result in an increase in the delivery of sediment and associated woody debris to streams, resulting in significant downstream consequences.

Objectives

- Undertake process-based erosion susceptibility assessments for the current exotic forest estate within the East Coast region and – for four forested study sites – demonstrate the utility of the susceptibility maps to inform decisions concerning land use suitability.
- Identify the factors that predispose forested areas to repeat episodes of predominantly storm-initiated erosion.
- For areas identified as ‘moderate’ to ‘very high’ landslide susceptibility, assess the likely connectivity between landslide erosion and waterways with the potential for resulting in adverse consequences.
- Compare results with the 1:50,000 scale erosion susceptibility classification (ESC) for the National Environmental Standard for Plantation Forestry (NES-PF).

Methods

An erosion susceptibility assessment of the current forest estate in the East Coast region was carried out to identify areas considered to be marginal for repeat cycles of short-rotation exotic forestry. To characterise the inherent susceptibility of different land parcels to erosion, and to identify the dominant erosion processes involved, separate erosion susceptibility assessments were completed for landslide, gully, and earthflow erosion using expert knowledge and spatial datasets. These assessments were undertaken independent of the current land cover to allow an improved evaluation of erosion susceptibility inherent in the landscape. Four case study sites representative of the range of lithologic and topographic landscapes found within the East Coast region were selected to demonstrate the utility of the susceptibility maps to inform decisions concerning land use suitability. The potential connectivity between landslide erosion and waterways is also assessed to determine the likelihood of landslide-generated sediment entering waterways, and potentially resulting in adverse downstream consequences.

Results

Landslide erosion

- For the East coast region, 19% of hill country areas are classified as ‘moderately’ to ‘very highly’ susceptible to shallow landsliding. Catchments with the highest proportion of hill country within these susceptibility classes include the Waipaoa (32%) and Uawa catchments (39%), and the Waingaromia (32%) and Mangatu (30%) subcatchments.
- Irrespective of vegetation cover, the propensity for shallow landsliding to occur during a rainfall storm event increases greatly on slopes >16° in Tertiary terrain, and on slopes

> 28° on Cretaceous terrain, with a disproportionately high probability of landslides occurring on slopes with aspects facing north to north-east.

- Land currently covered in exotic forests in Tertiary terrain (1,210 km^2) is more susceptible to landsliding than the equivalent in Cretaceous terrain (1700 km^2). 35.9% of exotic forests in Tertiary terrain are classed as ‘moderate’ to ‘very high’ compared with 26.8 % in Cretaceous terrain.
- Within exotic forests, slope-channel connectivity, i.e. slopes with the potential for landslides to deliver sediment and other material such as woody debris into gullies and waterways, is slightly higher in Tertiary terrain, where 29.2% (353 km^2) of the highly susceptible land (‘moderate’ to ‘very high’) is connected to waterways compared to 21.9% (372 km^2) in Cretaceous terrain.
- Of the (sub-) catchments most relevant to the current production of exotic forests, the Uawa catchment and Waingaromia subcatchment are the most susceptible to landslide erosion.

Gully erosion

- Gully erosion affects 19% of the East Coast region, and is most extensive within the Waiapu (45.3%), Uawa (37.2%) and Mangatu (29.9%) catchments.
- The proportion of exotic forest with ‘moderate’ to ‘very high’ susceptibility to gully erosion is higher for forested hill country planted within the Cretaceous terrain (47%) than for forested areas planted within the Tertiary terrain (35%).
- There is good correlation between lithology and gully frequency and development. The greatest numbers of current and former gullies develop in areas where mudstone or fine siltstone, crushed argillite, and greywacke are the predominant lithology. The probability of gullies developing is greatest in areas where crushed argillite, mudstone (bentonitic) and sheared mixed lithologies are present.

Earthflow erosion

- Earthflow erosion is extensive throughout the East Coast region, but only 9% of the region is classified as ‘moderate’ to ‘very high’ earthflow susceptibility. The catchments most effected by earthflow activity (‘moderate’ to ‘very high’ susceptibility levels) include the Mangatu (23.5%) and Waingaromia (19.0%) subcatchments, and the Waiapu (15.1 %) catchment.
- For forested hill country, a higher proportion of the forest estate within the Cretaceous terrain (18%) is classified as ‘moderate’ to ‘very high’ earthflow susceptibility than Tertiary terrain (10%).
- The propensity for earthflow erosion is greatest where bentonitic mudstone is the dominant underlying rock type. Other highly favourable lithologies for earthflow erosion include ‘mudstone or fine siltstone – jointed’ and ‘crushed argillite’.

Comparison with ESC for the NES-PF

- To demonstrate the utility of the susceptibility maps to inform decisions concerning land use suitability, we compared the resulting erosion susceptibility maps with the 1:50,000 scale ESC for the NES-PF in the four case study sites.
- According to the ESC, the four selected case study sites are all considered to be highly susceptible to erosion, with the entire area (>98%) of all sites assigned to ‘moderate’ to ‘very high’ susceptibility classes.

- However, the results show that the susceptibility to different erosion processes within the units used by the ESC is widely variable. For example, the more detailed analysis of landslide susceptibility shows that just 50.4% of the forest is susceptible to 'moderate' to 'very high' levels of landslide susceptibility. Additionally, gully erosion, within Makomako Forest was classed as 'moderate' to 'very high' across 75% of the forest.

Conclusions

- The assessment of landslide connectivity is an important consideration, particularly within forest estates where landsliding is the main mechanism by which debris, logs and slash are delivered into gullies and waterways, particularly during the post-harvest 'period of vulnerability'. Within the exotic forests in the East Cape region, the degree of connectivity is greater in Tertiary (29.2%) terrain than Cretaceous (21.9%).
- The landslide susceptibility map provides a greater degree of detail compared to the ESC for the NES-PF, highlighting that within any given area or forest estate, the susceptibility to landslide initiation is highly variable.
- When evaluating land use options based on erosion susceptibility, the results show that it is important to consider different erosion processes (landslide, earthflow and gully erosion) as these are spatially variable within any given landscape or forest area – as is the landscape response to storm events, and resultant types of erosion processes.
- Providing susceptibility maps at a more detailed scale (e.g. 15-m pixel scale) can potentially be problematic in terms of land managers understanding how best to utilize the detailed information provided. The challenge therefore is to find a level of detail of erosion susceptibility that proves useful in the decision making processes towards improving forest management practices in steepland terrain.
- We propose that generalization techniques be used to define areas of susceptibility with a minimum spatial extent suited to forestry management (e.g. 2 ha), and rules be defined to allow a certain proportion of tolerable erosion susceptibility (e.g. 15%) per unit. In this way, a fine-scaled susceptibility map can be re-scaled.
- Best practice is to assemble data at the finest scale that is feasible and allow rescaling to create management units of varying susceptibility classes to guide land use decision making, while ensuring that the value of the detail is not lost in the process.

Recommendations

- Given that landsliding is the main mechanism by which debris, logs and slash are delivered into gullies and waterways, we recommend that a detailed assessment of erosion risk be extended to include all existing exotic forests. The risk assessment should include an evaluation of likely downstream impacts. The information provided would greatly help decisions regarding the future of forestry on these sites, and in deciding potential post-harvest land use options that may be more suited to providing long term sustainability and as a pathway to establishing a permanent forest cover.
- Since the risk of downstream impact is dependent on the spatial distribution of recently harvested forests, we recommend creating annual risk maps using knowledge of the intended timing of harvest.
- Furthermore, in light of the Government's 'Billion Trees' project, it is recommended that a detailed assessment of erosion susceptibility of areas identified as potential sites for future planting be undertaken to assess the long-term sustainability of each of the proposed planting/land use options.

1 Introduction

As a consequence of Cyclone Bola (March 1988), the East Coast region of New Zealand acquired an international reputation for its severe erosion, high sediment yields, and sedimentation rates. Multiple natural preconditioning factors contributed to the overall erodibility of the land in this region including lithology, the morphology with its steep slopes, and climatic drivers. This inherent susceptibility to erosion was exacerbated by rapid land use change beginning with widespread deforestation of the indigenous forest during the late 19th and early 20th centuries for conversion to pastoral farming. The resultant increase in erosion was highlighted during Cyclone Bola, and it became apparent that measures were needed to mitigate the worsening erosion on pastoral hill country. Since the cost of controlling erosion frequently exceeded the value of pastoral production, for the past ~60 years exotic reforestation – primarily using *Pinus radiata*, the species most preferred for treating shallow (e.g. storm-initiated landslides), deep-seated (e.g. earthflows and slumps) forms of mass movement, and gully erosion – was deemed the most economical way of reducing both the on-site and off-site impacts of erosion.

Some of the areas initially planted in exotic pines as an erosion mitigation strategy have experienced an increase in erosion when storm events happen to coincide with the period of harvesting, and, as has been the case in the past, such events are likely to result in increased delivery of sediment and associated woody debris (slash) to streams, resulting in significant downstream consequences. A recent case of this occurred on Queen's Birthday weekend in 2018 where there was extensive damage, both within the forest estate and downstream of forests located inland of Tolaga Bay. The impact of such events has gained greater attention in the public arena in recent times,[1] and the associated stories have helped increase awareness of the challenges related to forestry production in highly erodible terrain.

Despite the uncertainty around the magnitude of future climate forecasts over the next ~30-year period, particularly for rainfall, the climate for this region is predicted to be drier but likely to include more frequent extratropical cyclones with associated higher intensity rainfall (Ministry for the Environment 2004; Savage 2006; Gomez et al. 2009). It is therefore important that an erosion susceptibility assessment of the current forest estate, or part thereof, be undertaken to identify areas considered to be marginal for repeat cycles of short-rotation exotic forestry. In these areas, a change in land use to indigenous shrubland as a pathway to a permanent forest cover may be the best long-term option for mitigating the impact of damage likely to occur during future storm events.

In this report, we use expert knowledge and spatial data on the extent and types of erosion initiated during previous storms as the basis for assessing the erosion susceptibility for the current exotic forest estate in the East Coast region and – in more detail – for four currently forested study sites in the likely event that they will be subjected to episodic storms at some stage during the rotation cycle of *P. radiata* (~27–30 years). Furthermore, by selecting study sites within two lithologically and structurally contrasting terrains, we identify geologic and topographic factors that influence the development rate and type of erosion process that ultimately determines the degree of susceptibility (low to very high) of different areas within and between study sites (see Fig. 1). Additionally, using GIS modelling techniques, the

[1] For example, an article by Rebecca Macfie in the 12 May 2018 issue of the New Zealand Listener: "NZ needs to plant more trees to combat climate change – but what kind and where?"

potential connectivity between landslide erosion and waterways is assessed to determine the likelihood of process-based sediment entering waterways, and potentially resulting in adverse downstream consequences.

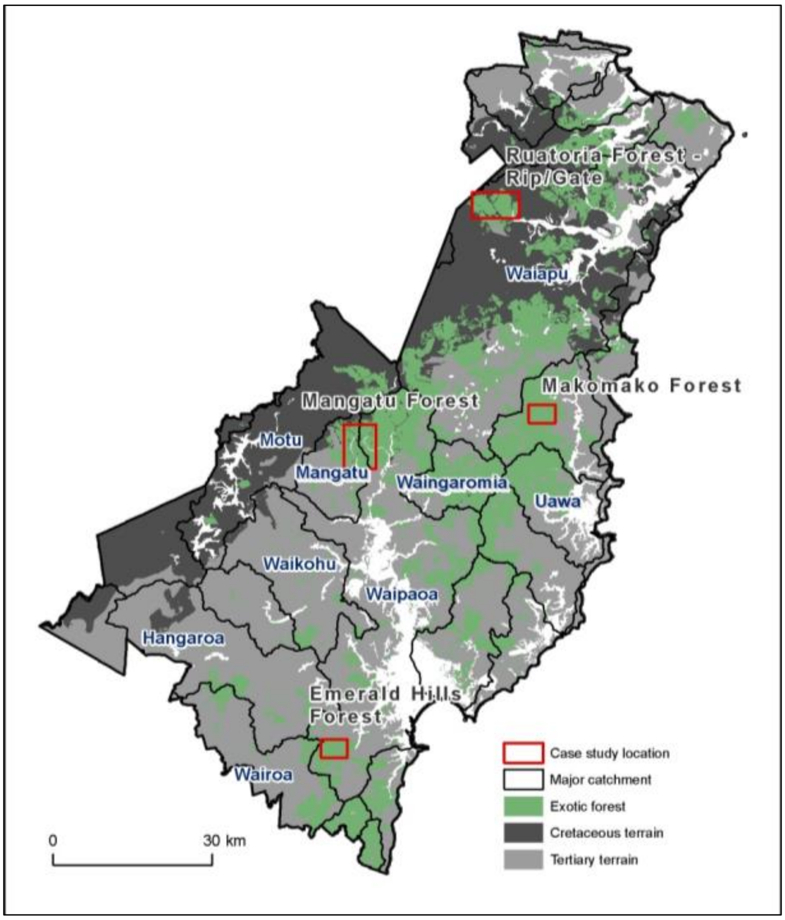


Figure 1. Location map showing the location of case study areas relative to geological terrain, in the East Coast segion.

2 Objectives

- Undertake process-based erosion susceptibility assessments for the current exotic forest estate within the East Coast region and – for four forested study sites – demonstrate the utility of the susceptibility maps to inform decisions concerning land use suitability.
- Identify the factors that predispose forested areas to repeat episodes of predominantly storm-initiated erosion.
- For areas identified as ‘moderate’ to ‘very high’ landslide susceptibility, assess the likely connectivity between landslide erosion and waterways with the potential for resulting in adverse consequences.
- Compare results with the 1:50,000 scale ESC for the NES-PF.

3 Methods

In order to characterise the inherent susceptibility of different land parcels to erosion, and to identify the dominant erosion processes involved, separate erosion susceptibility assessments – independent of the current land cover – were undertaken for selected sites representative of the range of lithologic and topographic landscapes found within the East Coast region. The rationale for doing so is that land cover is subject to change as the land use changes, whereas other predisposing factors are more-or-less constant (e.g. slopes, lithology, etc.). Since this project attempts to evaluate the 'risks' associated with land use change, it is important to understand the inherent erosion susceptibility of the land during the transition from one land use to another, the period when slopes are at their most vulnerable to erosion-triggering storms.

It is critical to distinguish between susceptibility, hazard, and risk in order to consider the strengths and limitations of each assessment. It is not uncommon to find these terms used interchangeably. The following definitions are given with reference to landslide erosion, but the definitions are equally valid for other forms of erosion. Lee and Jones (2004) define landslide susceptibility as 'the potential for landsliding to occur, while landslide hazard is the potential for landsliding to cause adverse consequences from a human perspective'. Guzzetti et al. (1999) proposed a more precise definition of landslide hazard as 'the probability of occurrence within a specified period and within a given area of a potentially damaging landslide of a given magnitude'.

It is thus apparent that susceptibility provides spatial information as to the relative likelihood of occurrence, and therefore answers the question as to the *where?* Hazard assessments attempt to derive information on the location (*where?*), frequency (*when?*) and magnitude (*what extent?*) of the process assessed. Risk assessments look to quantify the adverse consequences (damage) of the hazard, which results through the interaction of a hazard with vulnerable and exposed elements at risk.

We use a probabilistic approach to characterise land according to its likelihood to erode further — in which 'the past is the key to the future' (Varnes 1984; Soeters & van Westen 1996; Aleotti & Chowdhury 1999). Irrespective of the erosion type (process), there are several assumptions commonly related to probabilistic erosion susceptibility assessments, including:

- The surveyor is able to identify and map existing and old erosion features in order to prepare a reliable and reasonably complete inventory map;
- Similar erosion features will occur in future under the same circumstances and because of the same factors that produced them in the past;
- The location of new erosion features will be predominantly determined by the distribution of existing and past features;

In this report, we provide a separate susceptibility assessment for each of the three dominant erosion processes associated with this region: shallow landslides, earthflows and gullies. The landslide susceptibility assessment is at a finer scale (approximately 1:25,000) than is currently available (e.g. the Erosion Susceptibility Classification (ESC) for the National Environmental Standard for Plantation Forestry at 1:50,000), though the susceptibility assessments for gully and earthflow erosion are at 1:50,000, which is a scale both appropriate and adequate for these processes.

3.1 Case study sites

To evaluate the inherent erosion susceptibility of forested areas originally planted to control erosion, case study sites were selected as representing the range of erosion processes typically associated with forested areas located within each of two geological terrains. A predominant influence on erosion susceptibility is the contrasting lithological composition and structural integrity of the bedrock comprising these terrains; hereafter referred to by their geological age (Mazengarb & Speden 2000).

Four study sites were selected: two within each of the broad geological terrains. The location of the four case study sites is shown in Figure 1, with more detail for each site displayed in the Appendix.

Mangatu and Ruatoria Forests were selected as case study sites representative of the types and scale of erosion typically associated with forested areas located within the Cretaceous terrain. These were the earliest of the plantation forests to be established in the East Coast region and thus provide an opportunity to more closely examine and contrast the erosion susceptibility of these older forest estates to storm events over a longer time frame. Mangatu Forest is located in the headwaters of the Waipaoa River catchment, inland of Gisborne City. Ruatoria Forest is located in the headwaters of the Tapuaeroa River, a tributary of the Waiapu River, inland of Ruatoria township (Fig. 1). Both forests were established as Protection/Conservation forests targeted at stabilising the most actively eroding parts of these catchments. Both forests have been progressively harvested since 1990, and subsequently re-established in *Pinus radiata*.

The Emerald Hills and Makomako case study sites were selected as representative of the types and scale of erosion typically associated with forested areas located within the Tertiary terrain (Fig. 1). These forests were planted in the early to late 1980s in response to damaging storm events including Cyclones Bernie (1982) and Bola (1988). Makomako Forest is located inland of Tokomaru Bay; Emerald Hills Forest is to the south and west of Gisborne City (Fig. 1). Both forests were planted predominantly in *Pinus radiata*. Makomako Forest has been harvested and replanted, while the harvesting of Emerald Hills forest is about to commence.

Additionally, each study site is sufficiently extensive to include a wide range of topographic landforms so as to demonstrate differences in erosion susceptibility relative to slope aspect and slope angle. The erosion susceptibility assessments are then compared with the erosion susceptibility classification that was incorporated in the National Environmental Standard for Plantation Forestry (NES-PF).

For each site, the area of forest selected for analysis was based on the Land Cover Data Base (2012) – (classes ‘Exotic forest’ and ‘Forest – Harvested’). The area of exotic forest within each study site and geological terrain is listed in Table 1.

Table 1. Extent of exotic forest within each of the study sites, and geological terrain

	Area (ha)	*Area exotic forest (ha)*
Emerald Hills	1,722	1,634
Makomako	1,795	1,633
Mangatu	5,033	4,289
Ruatoria	4,313	2,963
Terrain type		
Cretaceous	239,800	170,400
Tertiary	509,700	121,100

3.2 Definitions of erosion types

Landslide, gully and earthflow erosion are defined by the LUC survey handbook (3rd edn) as follows:

3.2.1 Shallow landslides

We use the term ‘landslide’ here to characterise shallow soil slips.

> Soil slips are shallow, rapid slides and flows involving soil and regolith. Movement rates are typically 0.5–5 m/s, or fast walking to running pace. They comprise a scar (source area), and a debris tail. The failure surface is planar and parallel to the ground surface and <1 m deep. The slip plane or shear surface is often above relatively impermeable material. Movement is initially by sliding or a combination of sliding and flowing, but where the failed mass becomes saturated with water, it forms a chaotic mix of debris which can flow down slope for a considerable distance (10s to 100s of metres, or >10 times the scar length). The scar surface is slow to revegetate (often 10+ years), and the rate is influenced by such factors as hardness, weathering rate, fertility, water holding capacity and rainfall/drought conditions. The debris tails revegetate more quickly (usually several years). Typical shallow soil slips in pastoral hill country are <1 m deep and have a volume of between 150 and 500m^3. They are triggered by a variety of natural agents, most commonly intense and/or prolonged rainfall, earthquakes, and undercutting of slopes by stream or wave action. Soil slips are also induced by human activities, especially slope modifications for roads, tracks and buildings.
>
> Slope, aspect and vegetation are important determinants of soil slip occurrence. They rarely occur on slopes <8°, with the majority occurring on slopes >20°. Dependent upon rock type and rainfall intensity, mean slope angles are between 28–35°. Many storm damage assessments (Eyles 1971; James 1973; Crozier et al. 1980a; Salter et al. 1983; Phillips 1988; Hancox & Wright 2005a, 2005b) show an aspect preference for soil slipping that may be influenced by storm direction, or by previous erosion event. Land use change, especially removal of woody vegetation, increases susceptibility to soil slipping. Dependent on terrain type, densities under pasture are between 3 and 10 times that under either indigenous or exotic forest (Hicks 1991; Hicks et al. 1993; Marden & Rowan 1993; De Rose 1996; Page & Trustrum 1997; Hancox & Wright 2005b). (pp. 139–140)

3.2.2 Gully erosion

The definition of gully erosion is given as:

> Gullies are formed by the removal of soil, regolith or rock by fluvial incision. They are large, permanent features, >60 cm deep and >30 cm wide. Initially they form through the channelised flow of water and involve headward and sideward migration of the channel. Gullies may be linear or amphitheatre in shape, depending on rock type, and usually only carry water during rainstorms. In some instances gullies are formed by a complex process of mass movements, sheet erosion and debris flows in response to oversteepening of gully side walls by channel incision. They may also form through the deepening and coalescing of rills, small usually numerous features <60 cm deep and <30 cm wide, that usually form on bare surfaces during rainstorms. (p. 141)

In recent years, and as an acknowledgement that a high proportion of sediment is derived from mass movement failure of the slopes bordering gullies, many of the larger amphitheatre-shaped gullies are referred to as 'fluvio gully-mass movement complexes' (Betts et al. 2003).

3.2.3 Earthflow erosion

The definition of earthflow erosion is described as follows:

> Earthflow erosion is the slow movement of soil and associated regolith, usually along basal and marginal shear planes, with internal deformation of the moving mass. Movement rates vary from <0.5 m/yr to > 25 m/yr. The original vegetated surface, although often still present, is hummocky and may contain numerous tension cracks. The disrupted nature and high water content of the material impede both surface and subsurface drainage and often result in the development of ponds. Earthflows may be shallow (< 1–2 m) to deep-seated (>1–2 m to tens of metres, and typically 3–5 m). Deep-seated earthflows typically occur on slopes between 10 and 20° and can cover large areas of a hill slope (hundreds of square metres), while shallow earthflows are more common on slopes >20°, and are smaller in area.
>
> Rates and depth of movement are influenced by rock type (usually mudstones and argillites), degree of shearing and crushing, and proportion of associated plastic clays, slope, vegetation cover, and rainfall, which in turn strongly influence pore water pressures. Movement rates within earthflows usually vary, and are often most active where the toes are undercut by streams or roads, or where gullies have developed. Earthflows may show seasonal variation in activity and may reactivate following years of stability. They often commence or increase activity late in winter in response to periods of saturated soil-water conditions. (pp. 140–141)

3.3 Inventories used to assess susceptibility

3.3.1 Landslide inventories

A number of different landslide inventories have been used in the assessment of landslide susceptibility in the East Coast region. In the absence of all but one sufficiently detailed landslide inventory derived from a study in the East Coast region itself, spatial landslide data collected from terrains elsewhere in the North Island are used, but are nonetheless representative of similar topography to that comprising the two broad lithologic/tectonic terrains present in the East Coast region. (Fig. 1)

Tertiary terrain

Landslide characterisation for this terrain is based on the mapped distribution of 3,164 landslide scars digitised from aerial photography flown at five dates between 1944 and 2011, and covering three study sites located in the Manawatu, Pohangina, and Pahiatua catchments (see Betts et al. (2017) for details of this inventory). Here, the lithologies comprise weakly to moderately indurated sandstone and mudstone considered to be comparable in composition and stratigraphic age to the Tertiary-aged formations found within the East Coast region. Only one landslide inventory exists from within the East Coast region itself and consists of field-based measurements of landslides initiated during Cyclone Bola on Arai Matawai and Emerald Hills stations located approximately 20 km southwest of Gisborne City (Veld & Graaf 1990). Here, the dimensions (depth and width) of 576 features were mapped along 12 transects representative of six different Land Use Capability Units (LUC units; New Zealand Land Resource Inventory 1976).

Cretaceous terrain

Much of the Cretaceous terrain within the East Coast region is characterised by the deeper-seated forms of mass movement (e.g. earthflows and rotational slumps) associated with long, but less-steep slopes than is typical of the landslide-prone Tertiary terrain. Hence, apart from isolated occurrences of shallow landsliding associated with limited areas of exposed indurated sandstones resembling ‘greywacke’, and largely confined to the extreme western margin of this region (i.e. Raukumara Range), they are a minor form of hillslope instability within this terrain.

The characterisation of shallow landslides susceptibility in Cretaceous terrain assumes that the hard rock ‘greywacke’ is an adequate representative of this broader geological terrain. Cretaceous terrain within the East Coast region is therefore based on a mapped inventory derived from five dates of aerial photography covering the Eastern Ruahine ranges (Tamaki subcatchment) flown between 1946 and 2011.

3.3.2 Gully inventories

Two digitised gully inventories for the East Coast region form the basis of the gully susceptibility assessment. Gullies were mapped for two time periods for which region-wide aerial photographic coverage was available. The earlier coverage was based on aerial photography flown primarily in 1957 (1:15,000) and captured the extent of gully development following clearance of the indigenous forest (1880s to 1920s) up until the commencement of exotic reforestation in 1960. Gullies were also mapped based on aerial photography flown in 1997 (1:26,000) and this database captures the extent of gully development approximately 40 years after reforestation began, distinguishing between gullies in reforested areas from those in non-reforested areas. Analysis and discussion of the effectiveness of exotic reforestation as an erosion control strategy for ameliorating gully erosion and the significance of gully-derived sediment to the suspended sediment yield of the three main East Coast river systems, both past and in the future, has previously been published in Marden et al. (2008, 2011, 2012, 2018) and Herzig et al. (2011).

3.3.3 Earthflow inventory

There are very few NZ studies that have mapped individual earthflows over an extensive area. Marden et al. (2014) is the only attempt to capture changes in the activity of individual earthflows in the East Coast region and over a period of time that includes pre- and post-reforestation. Earthflows within the 14 km^2 Mangatu Forest were mapped for four time periods for which aerial photographic coverage was available. The earliest coverage was based on aerial photography flown in the late 1930s to mid-1940s (1:10,800) and captured the extent of earthflows considered to have been 'active' since the clear-felling of the indigenous forest (1880s to 1920s). A later coverage flown in 1960 (1:44,000) was used to capture the extent of earthflows present up until the commencement of exotic reforestation in 1960. Earthflows were also mapped based on aerial photography flown in 1970 (1:24,000) and this database captures the extent of earthflow development approximately 10 years after reforestation began. The final mapped coverage of earthflows was from photography (1:25,000) flown after a major cyclonic storm (Cyclone Bola in 1988) coinciding with the completion of reforestation in this forest. Analysis and discussion of the effectiveness of exotic reforestation as an erosion control strategy for ameliorating earthflows (Zhang et al. 1993; Marden 2004), the significance of earthflows as a sediment generation process, and their relative contribution to the suspended sediment yield of the Waipaoa River has previously been published in Marden et al. (2014). However, because the earthflow inventory by Marden et al. (2014) covers only a small area in the Cretaceous terrain, and given the lack of spatial data to characterise the pre-disposing factors of earthflow erosion, the susceptibility assessment for earthflows draws on the NZLRI (2nd edition), which includes the present erosion severity of earthflow erosion as mapped in 1990.

3.4 Landslide susceptibility assessment

Many different methods exist to produce landslide susceptibility maps. These are generally grouped into qualitative and quantitative methods (Aleotti & Chowdhury 1999); qualitative methods relying heavily on expert knowledge to weight conditioning factors, quantitative applying either deterministic or statistical methods (Sciarra et al. 2017). To guide the appropriate selection of conditioning factors, we used a combination of expert knowledge and empirical evidence to select three causal factors. These conditioning factors were subsequently assessed using statistical methods to characterize landslide susceptibility within the East Coast region. These include i) lithology, ii) slope, and iii) aspect, with rainfall being the cause of landslide failure. The conceptual framework used for the landslide susceptibility assessment is illustrated in Figure 2. The landslide scar-slope relationships according to different geological terrains and aspect are described in further detail below.

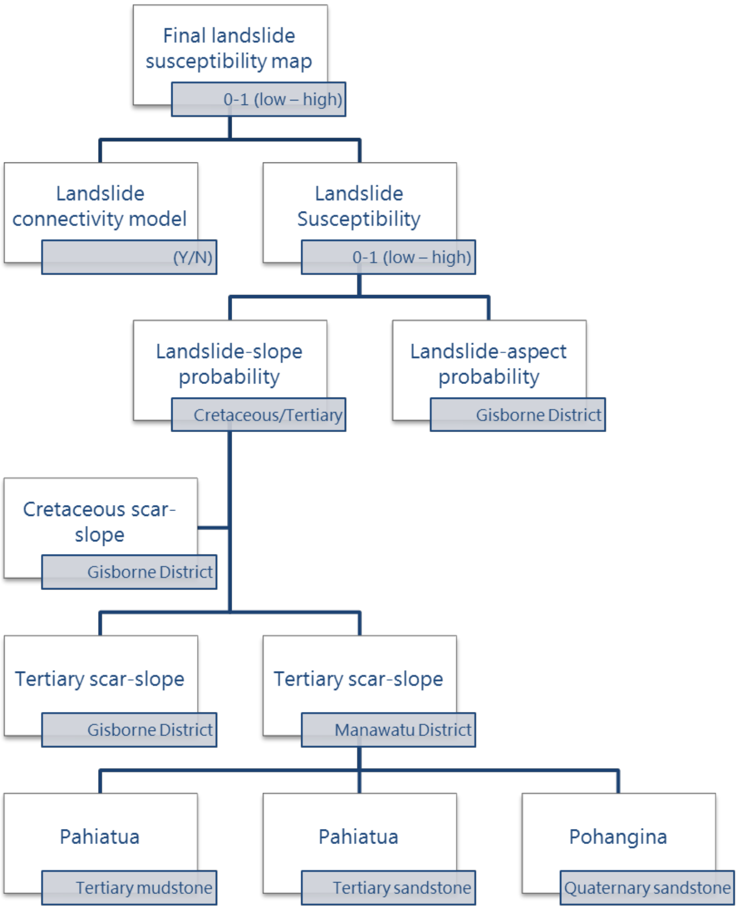


Figure 2. Conceptual framework to determine landslide susceptibility in the East Coast region.

3.4.1 Slope

Slope angle is one of the primary determinants of landslide susceptibility due to the effect of gravity on the movement of material on a slope. To establish relationships between landslides and slope angle we followed the empirical modelling approach developed for landslides at the three study sites located in the Manawatu, Pohangina, and Pahiatua catchments (Betts et al. 2017; Hölbling et al. 2018). Landslide-slope relationships at these sites were established at 2-m resolution using DEMs derived from orthophotography as well as the national 15-m DEM derived from contour data. The difference in the degree of precision between the 2-m and 15-m DEMs can be seen in Figure 3, demonstrating that the 15-m DEM is unable to represent the actual slope distribution of the study area; in this example, the landscape is smoother and less steep in the 15-m DEM compared with the LiDAR DEM. Therefore, it is important to use the same DEM to derive slope-scar relationships as is subsequently used in the assessment of landslide susceptibility. Due to the absence of LiDAR in the East Coast region, we used the slope-scar relationships derived from the 15-m DEM. Slope rasters calculated in ArcGIS 10.2 were used to calculate the slope angle of landslide scars within the Pohangina, Pahiatua, and Ruahine study sites (Fig. 2), whereas slope measurements derived from the Emerald Hills study site was measured in the field, and will therefore differ to measurements of slope using a 15-m DEM. The landslide scar-slope relationships developed for the Pohangina, Pahiatua, Ruahine, and Emerald Hills study sites were calculated as a probability by relating the proportion of scars per 1° slope angle class to the total area within each respective slope class (m^2 scars ha^{-1}) in the study area.

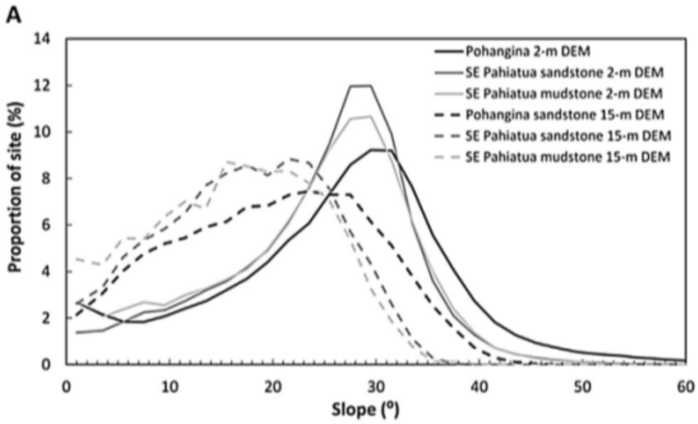


Figure 3. Example showing different slope distributions from 15 m DEM (derived from contour lines) and from 2 m digital surface model (derived from photogrammetry. Source: Betts et al. (2017).

To derive a single scar-slope relationship for the Tertiary terrain in the East Coast region, the databases used to generate each of the scar-slope curves for Pohangina, Pahiatua, and Ruahine were averaged. This averaged relationship was then merged with the local data by taking the average of Emerald Hills and the Manawatu data, and the mean probability of landslide occurrence per slope class was recalculated (see Fig. 4). This approach was aimed at giving more weight to the locally derived landslide slope-scar data. A moving average was used to smooth the curve to better account for the gaps in certain slope bands and then normalized using a linear min-max function to produce the landslide probability curve for Tertiary terrain as depicted in figure 4. A scar-slope relationship for Cretaceous terrain was derived using the single landslide inventory from the Eastern Ruahine Ranges.

3.4.2 Aspect

Inspection of aerial photography following Cyclone Bola showed that landslides were triggered disproportionately according to slope aspect. Veld and Graaf (1990) also found a significant relationship between sites of landsliding and aspect in the Emerald Hills study area. This data was used to calculate the probability of landsliding according to aspect (Figs 5 and 6).

3.5 Gully susceptibility assessment

Marden et al. (2012) assessed the change in frequency and gully size between 1957 and 1997 and found that reforestation was a cost-effective and efficient means of stabilising many of the smaller (<10 ha) gullies within a rotation length of *Pinus radiata* (~27 years) but that gullies already >10 ha in size at the time of planting continued to enlarge and were deemed to be beyond remediation. Indeed, a comparison of the gully statistics as at 1957 and again in 1997 show that the establishment of 135,000 ha of exotic forest has resulted in a reduction in overall gully numbers but that the composite gully area of untreated, together with those gullies that have been treated but as yet have not fully stabilised, has increased (Marden et al. 2018).The current state of gully erosion some 20 years after the 1997 mapping exercise and during which time another 20,000 ha of additional forest has been planted, is unknown. However, in terms of characterising the extent to which the Tertiary and Cretaceous terrains are susceptible to gully erosion, knowledge of the historic distribution and extent of gullying under different land use scenarios is an important detail. The aim here is to identify all areas with the potential to develop gully erosion, thus areas within which formerly active gullies existed but have since been stabilised through reforestation have been included in the assessment of gully susceptibility. It is unusual to have a comprehensive inventory of gullies for a region, and this is an obvious advantage when a characterisation of susceptibility is needed.

Thus, the two datasets of gullies mapped in 1957 and 1997 were merged to create the maximum extent of actively eroding gullies and used to characterise individual 2nd edition (1990) Land Resource Inventory (NZLRI) units in terms of their susceptibility to gullying. NZLRI mapping follows a ‘homogeneous unit area’ approach to record five physical factors (rock type, soil, slope, present type and severity of erosion, and vegetation) simultaneously to a level of detail appropriate for presentation at a scale of 1:50,000. LRI units generally characterise individual, homogeneous land units (average unit size in Gisborne is 110 ha). In contrast to landslide susceptibility, for which representation at 15-m pixel scale is more appropriate, gully systems can occupy much larger areas, so that a characterisation of land units as to their susceptibility has greater utility and practicality.

Using simple GIS analysis, the gully layer was intersected with the LRI layer to identify the frequency and magnitude of gullying within each LRI unit. In some instances, a unit had multiple small linear gullies within them, whereas in other units amphitheatre-shaped gully systems occupied a greater proportion of an LRI unit. It is therefore important to represent both the size and number of gullies per land unit since the *area* affected is a representation of both current/past gully incidence and magnitude, whereas the *frequency* reflects the potential of future gully erosion.

A matrix was used to create gully susceptibility classes (1–5), which ranks susceptibility based both on the number of gullies within each LRI unit and the proportion (% of area) of each unit affected by gullying (Table 2). There was not full agreement between the gullies mapped (1957 and 1997) and the 2nd edition NZLRI units that were assigned a ‘present gully erosion severity’ ranking. For example, neither the 1957 nor the 1997 gully data bases recorded the presence of gullies within 126 of the 2,097 units designated in the NZLRI as having ‘present gully erosion’. On the assumption that these 126 LRI units were assigned a severity ranking based on evidence of gully erosion present in the 1970s[2], the LRI gully severity was adopted.

Table 2. Definition of gully susceptibility classes

Number of gullies per unit	*Proportion (% area) of unit affected by gullying*		
	0-5	6-10	>10
1	Low	Moderate	High
2-3	Moderate	High	Very high
>4	High	Very high	Very high

* Susceptibility class ‘Very low’ defined as NZLRI units with gully erosion recorded but not identified in gully inventories (1957, 1997)

[2] The 1990 LRI 2nd edition did not involve new mapping or very much field verification, but rather was an exercise in amalgamating preexisting LRI units and editing boundary lines between units. The 126 LRI units identified as having gullies present was based on mapping done in the 1970s and is legitimate. However it is most likely that these former gullies have now been reforested and thus hidden by the forest.

3.6 Earthflow susceptibility assessment

As stated above, the susceptibility assessment for earthflows draws directly on the NZLRI (2nd edn), which includes an estimate of the present erosion severity of earthflow erosion as mapped in 1990. During the original mapping exercise, multiple earthflows were amalgamated into large polygons with similar topographic characteristics at a scale of 1 mile to the inch (1:63,360). We assume that the earthflows mapped in the NZLRI can be used to characterise the susceptibility of the LRI units to earthflow erosion. Though the degree of activity is influenced by the presence /absence of a mature woody vegetation cover (e.g. exotic forest, indigenous shrubland and forest), or may change in response to climatic influences (e.g. storms), the susceptibility to earthflow erosion remains present in the landscape. The classification of earthflow activity under the heading ‘present erosion severity’ in the LRI (coded as 0–4, i.e. negligible to very severe) is recoded to describe the susceptibility to earthflow erosion using the classes ‘none’ to ‘very high’.

3.7 Connectivity

Significant downstream implications can arise when landslides deliver sediment and other material such as woody debris (slash) into gullies and waterways. The final step in this exercise was therefore to use a landslide connectivity model developed by Dymond et al. (2006) to assess whether or not a landslide triggered within a given 15-m pixel would deliver sediment to a waterway. A DEM is used to predict the likely flow path of material generated by a landslide within a pixel, its flow direction and potential intervening accumulation zones to decide whether sediment and/or slash could potentially enter a stream network. If the flow path encounters any significant flat land (e.g. an alluvial terrace), that is, consecutive pixels below four degrees of slope, then the original susceptible pixel is tagged as ‘non-connected’, because sediment will deposit on the flat land before it reaches a stream. Otherwise, the pixel is tagged as ‘connected’. The connectivity was only considered for the ‘moderate’ to ‘very high’ landslide susceptibility classes as these are the most likely to be targeted for new erosion control plantings. If already afforested but identified as ‘at risk’ to future landslide occurrence and with a high probability of sediment and woody debris delivery to streams, these areas may be considered for retirement from forestry and either converted to mānuka plantings or allowed to passively revert.

The connectivity of earthflows (as a proportion of channel bank length) has previously been shown to be low. For example, over decadal time frames Marden et al. (2014) demonstrated that although earthflows were extensive in the landscape, during their peak period of activity only 5% of the study area displayed signs of earthflow activity connected to a major stream channel – a result not dissimilar to that found in similar topography in the northern California coast ranges (Mackey & Roering 2011). In contrast, gullies by definition have a connectivity of 1, and although a small percentage of sediment may remain as temporary storage within ephemeral gullies, all the sediment delivered to a gully system is eventually remobilised and delivered into the stream network.

4 Results and discussion

The results of the erosion susceptibility analyses are presented first for the three erosion processes separately – first at a regional and catchment scale for context, before focusing on areas with exotic forest cover (LCDB 2012) and the four selected case study sites in a fourth chapter. The final section compares the erosion susceptibility classification devised for the NES-PF with the results obtained in this study, discusses the implications of these findings for managing existing and new forests established on highly erodible hill country into the future.

4.1 Landslide susceptibility

4.1.1 Landslide susceptibility and geological terrain

The relationship between landslide susceptibility and slope (derived from 15 m DEM) for the two dominant geological terrains, Tertiary and Cretaceous, is shown in figure 3. Shallow landslides are most likely to be initiated during a storm event when rainfall is between 125-200 mm (Reid & Page 2002) and/or if rainfall intensities exceed 25 mm h^{-1} (Caine 1980). In areas of Tertiary terrain, the incidence of landsliding increases markedly on slopes>16°, a finding not dissimilar to landslides generated on Tertiary-aged lithologies in northern Hawke's Bay where no landslides occurred on slopes <18° (Harmsworth et al. 1987). Here, the underlying lithologies are well-indurated and over time fluvial incision has produced deeply incised valleys flanked by steep and long linear slopes mantled by volcanic ash and regolith. When saturated, these surface coverbed materials are predisposed to shallow and rapid failure as soil slips and debris avalanches. Soil slips typically have a small scar ≤ 1 m deep exposing a slip surface with debris being redeposited as a narrow debris tail downslope of the scar. A debris avalanche is a similar type of failure but tends to be larger, the scar is deeper (2–5 m), and hence the depositional debris tail tends to occupy a significant length of the slope (Eyles 1985). They often gain enough momentum to mobilise sediment and forest slash into the nearest watercourse.

In contrast, within the Cretaceous terrain the occurrence of shallow landslides is predominantly restricted to the steep flanks of the Raukumara Range which comprises indurated sandstone-dominated 'greywacke-like' formations where slope steepness approximates that associated with similar Cretaceous-aged lithologies found in the Ruahine Ranges (Fig. 4). However, elsewhere within the East Coast region, Cretaceous-aged lithologies have been subjected to tectonic shearing thereby weakening its internal structure. This in turn has resulted in slopes failing as deep-seated rotational slumps and earthflows thereby lowering slope angles to between 25 and 30°. The resultant topography is a complex system of low-angle swales and hollows connected by short, steeper (> 28°) convex and/or concave slopes. Thus, in this terrain, shallow landslides occur predominantly on short, convex, and concave slopes rather than on longer planar slopes, and/or where there are remnant blocks of more resistant lithologies, generally sandstones (e.g. Mounts Hikurangi, Aorangi, Taitai and Honekawa). Within both terrains, a significant proportion of landslides will also be associated with steep banks located adjacent to incised stream channels where slope will likely be in excess of 28°.

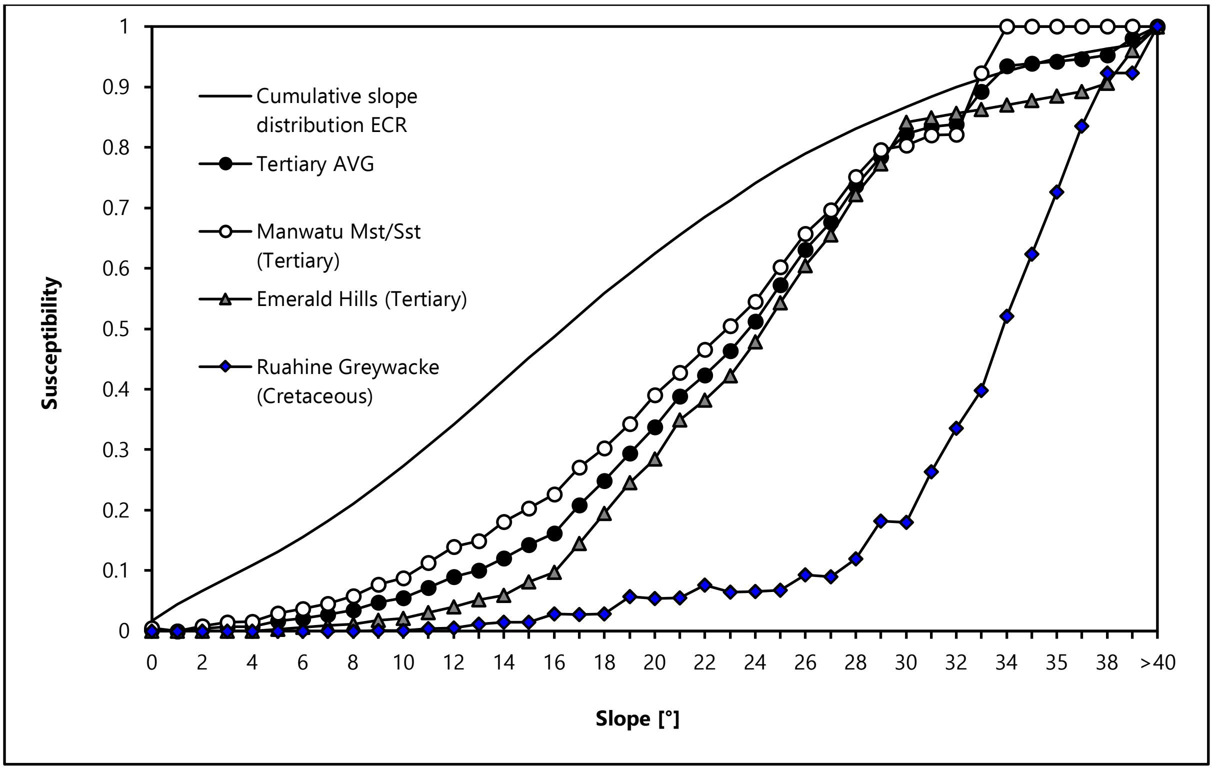


Figure 4. Relationships between landslide susceptibility and slope angle used to characterise the Tertiary and Cretaceous terrains in the East Coast region. The relationships are based on existing landslide inventories in similar terrain in the Manawatu and the Emerald Hills study site located within the Tertiary terrain southwest of Gisborne. The cumulative slope distribution for the extent of Cretaceous and Tertiary terrain in the East Coast Region is also shown.

4.1.2 Influence of slope aspect

Slope aspect is frequently used as a predisposing factor of landslide susceptibility (e.g. Lee 2005; Yalcin & Bulut 2007; van Westen et al. 2008; Galli et al. 2008). It has been suggested that topoclimate, i.e. contrasting microclimate between slopes of different aspect, can produce asymmetric valley morphology through control of slope weathering, erosional, and depositional processes (Burnett et al. 2008). The direction of incoming weather events (Cyclone Bola came from the north and created a strong easterly flow over the North Island), may also create a ‘shadow effect’, impacting some slopes more than others.

Slope aspect, relative to the direction that major landslide-initiating storm events most frequently approach the East Coast region, is also an important factor contributing to landslide susceptibility. For example, Figure 5 shows the extent of landslides initiated during Cyclone Bola in two different parts of the Emerald Hills study site. Here, there was a distinct relationship between landslide occurrence and aspect with a disproportionate number of landslides occurring on slopes with aspects facing north to north-east. Figure 6 shows the proportion of landslides within each of eight slope aspects where a value of 1 would be expected if the occurrence of landsliding was proportional to the land area within that slope aspect. Thus, in this instance, the landslide density on north facing slopes was 50% higher than average.

Previous studies in the Thames–Te Aroha area (Salter et al. 1983) and the Wairarapa (Crozier et al. 1980b) have also confirmed that irrespective of vegetation cover north and east facing slopes are more predisposed to shallow landsliding. They concluded that this is because these slopes are generally more weathered due to increased solar radiation, are also generally subjected to increased wetting and drying cycles, and are weathered to a greater depth. The wetting and drying cycles initiate cracking allowing water to penetrate down to an impervious layer (e.g. a compact layer of volcanic ash or the bedrock contact) where high water pressures build-up to the point where the overlying coverbeds become saturated and fail.

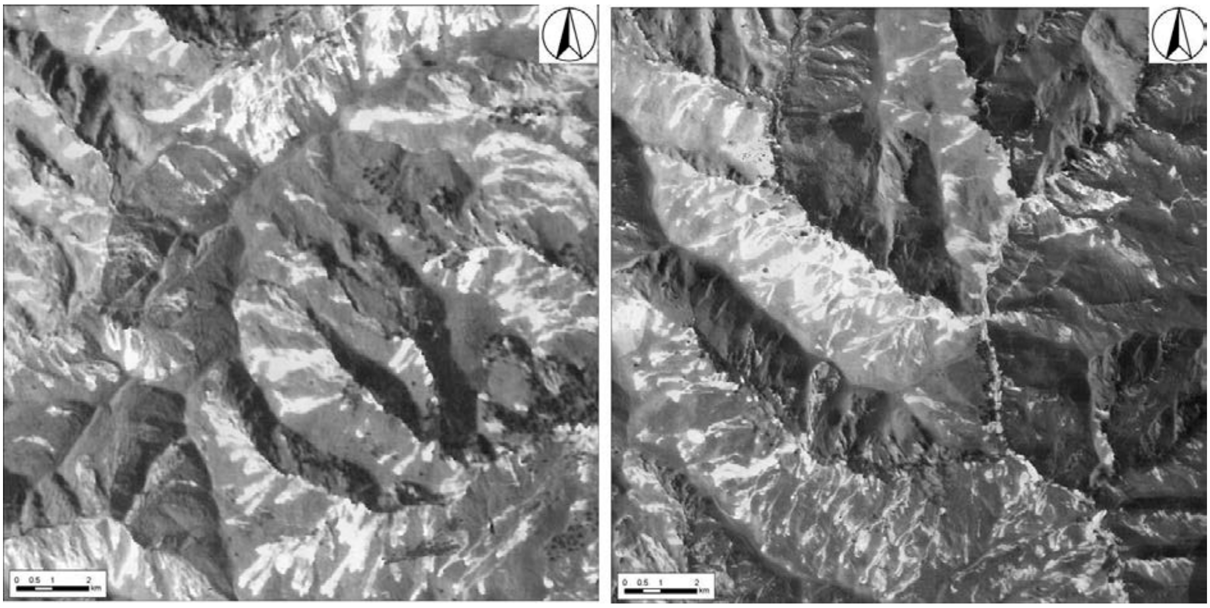


Figure 5. Aerial photography (1988) within the Emerald Hills study site showing the disproportionate occurrence of landsliding on slopes with a north to northeast aspect.

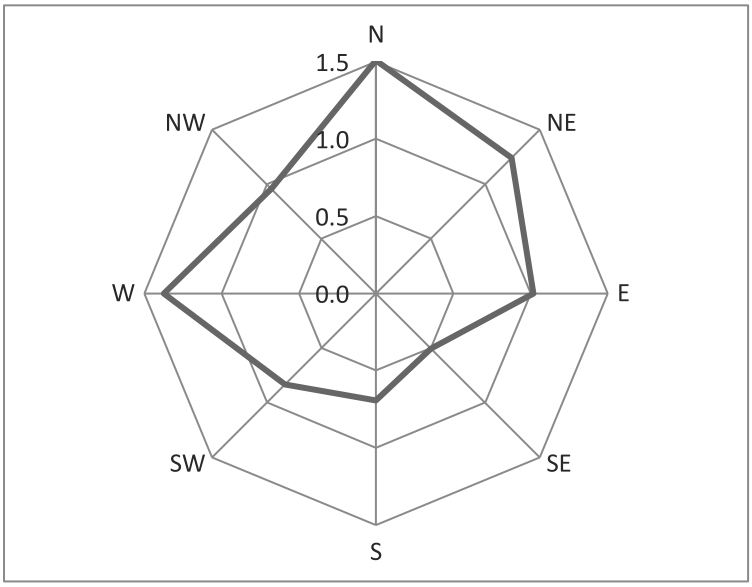


Figure 6. Landslide scar – aspect density. A value of 1 would be expected if the occurrence of landsliding was proportional to the land area of the slope aspect.

4.1.3 Region-wide analysis of landslide susceptibility and connectivity

For the East Coast region as a whole, 73.2% (5457 km^2) of the Tertiary and Cretaceous terrains are classed as ‘very low’ to ‘low’ susceptibility. 21.1% (1576 km^2) of the remaining 26.8% of ‘moderate’ to ‘very high’ susceptible land is potentially connected to waterways. This is the area where landslides are likely to occur during significant rainfall storm events and deliver sediment and other material into nearby waterways.

Of the two terrain types, the Tertiary terrain underlies the largest proportion of the East Coast region. Landslide susceptibility is considered to be ‘very low’ to ‘low’ on 67.4% of hill country areas, and ‘moderate’ to ‘very high’ on the remaining 32.6% of hill country, of which approximately 1650 km^2 (22%) of hill country slopes are directly connected to waterways (Fig. 7). The topography is deeply incised by a dense drainage network with steep sided, long, and near-linear valley slopes stretching from ridge lines to stream channels. Thus, irrespective of vegetation cover, the connectivity to waterways in Tertiary terrain is high. 1,250 km^2 (24.7%) of hill country slopes identified as ‘moderately’ to ‘very highly’ susceptibility have potential for either natural hillslope failures (landslides) or anthropogenic disturbances to result in sediment, and any associated woody debris, entering a water course.

In comparison, within the Cretaceous terrain, where slopes are generally less steep, the susceptibility to landsliding is considered to be ‘very low’ to ‘low’ on 85.5% of hill country areas, and ‘moderate’ to ‘very high’ on just 14.5% (348 km^2) of remaining hill country areas, of which 327 km^2 (13.7%) of hill country slopes have been deemed as directly connected to waterways (Fig. 7), and therefore have the potential to contribute sediment to a water course.

Landslide susceptibility of hill country areas within each of the two geologic terrains was assessed and compared to the susceptibility of exotic forests within the same two terrains. Figure 7 shows that exotic forests have higher levels of landslide susceptibility compared to the respective terrains as a whole. A larger proportion of the current forest estate is found on Cretaceous terrain (1,700 km^2) than Tertiary terrain (1,200 km^2) according to LCDB (2012). However, land occupied by exotic forests in Tertiary terrain has a much higher proportion of land susceptible to landsliding (35.9 % in classes ‘moderate to very high’) than the exotic forests in Cretaceous terrain (26.8%). This high proportion of highly susceptible land highlights how forests were planted in steep terrain specifically as an erosion mitigation measure.

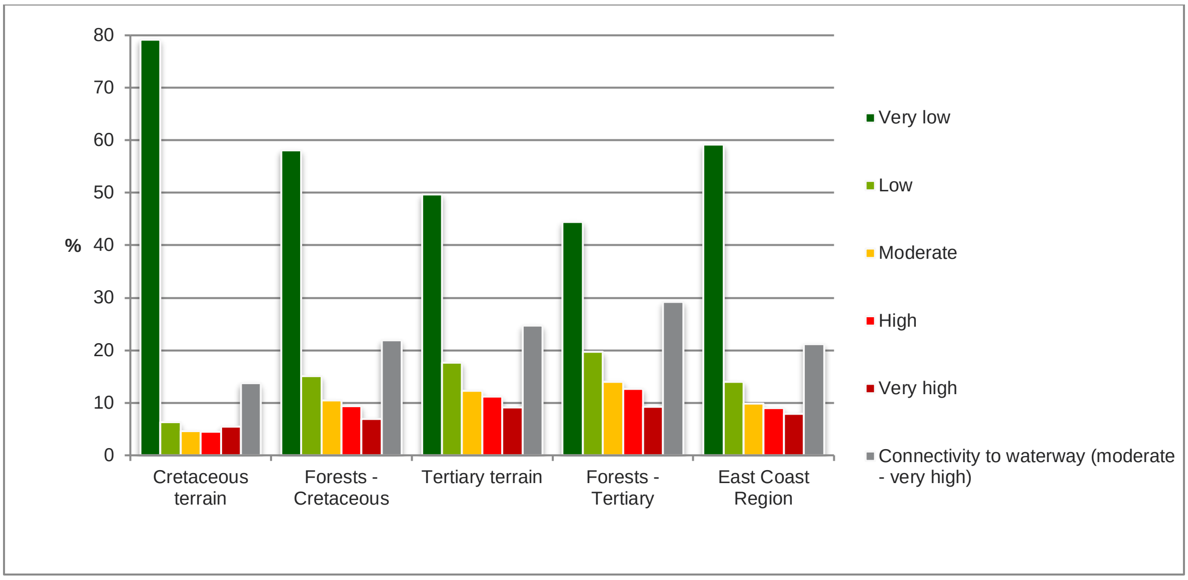


Figure 7. Landslide susceptibility, as apercentage of forested areas, the total area comprising the Tertiary and Cretaceous terrains, and for the East Coast region. The percentage of hill country with moderate to very high landslide susceptibility and with the potential for landslides to connect to waterways is also shown.

4.1.4 Catchment based assessment of landslide susceptibility and connectivity

The results of an assessment of landslide susceptibility of hill country areas in the Waipaoa, Waiapu and Uawa catchments, and the East Coast region are shown in Figure 8. (Note, due to its large size, the Waipaoa has been split into two further major subcatchments: the Mangatu and Waingaromia, see Figure 1). The Waiapu catchment (1,693 km^2) is the second-largest in the Gisborne district, and 89.9% of the catchment (1523 km^2) lies within the Tertiary (60.1%) and Cretaceous (29.9%) terrains. Within this catchment, 14.7% of hill country is classified as having a 'moderate' to 'very high' susceptibility to landslide initiation, of which 200 km^2 (13.1%) has a 'high' to 'very high' potential to connect with and contribute sediment to waterways. Within forestry estates, such areas of connectivity are associated with increased risk post-harvest, where rainfall storm events can trigger landslides that deliver large quantities of sediment and slash into waterways.

Of the catchments presented in figure 8, the Uawa catchment and Waingaromia subcatchment have the largest proportion of hill country classified as 'moderate' to 'very high' landslide susceptibility (38.7% and 32.1% of respective catchment areas), of which 52.4 km^2 (26.6% of the area) and 42.4 km^2 (24.6%) are potentially connected to waterways (Fig. 8). These are significant areas, a proportion of which will be within existing forest estates (see section 4.4), where storm events are more likely to trigger landslides capable of delivering large quantities of sediment and slash into waterways, particularly during the post-harvest period.

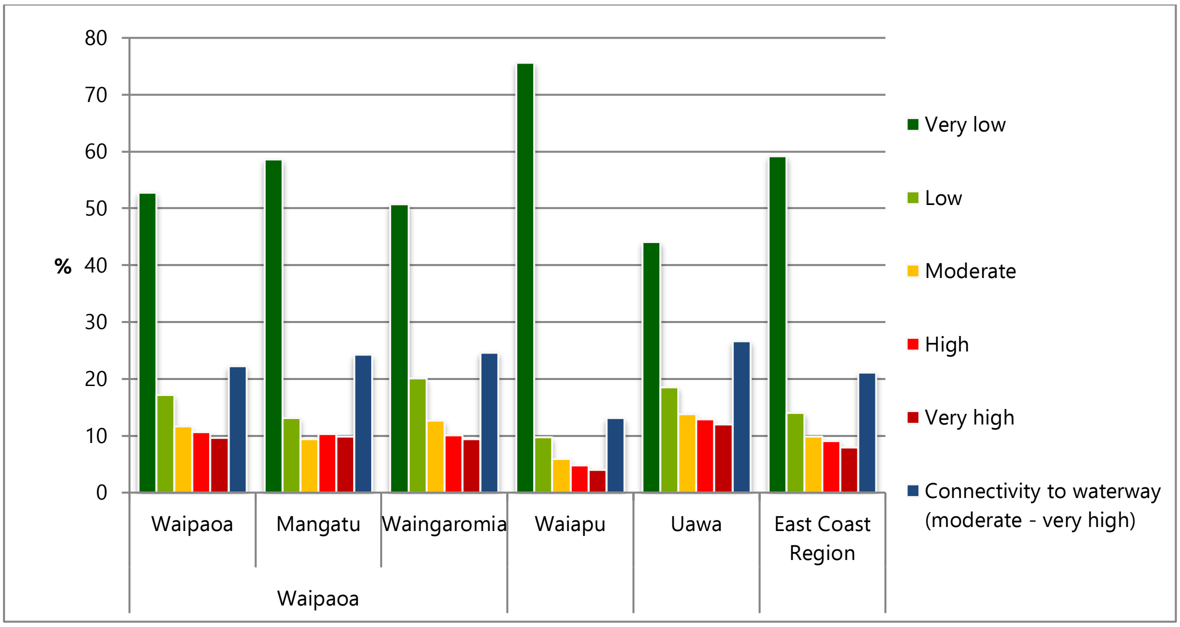


Figure 8. Percentage of catchment hill country within each of 5 landslide susceptibility classes. The percentage of hill country with 'moderate' to 'very high' landslide susceptibility, and with the potential for landslides to connect to waterways is also shown.

4.2 Gully susceptibility

4.2.1 Gully susceptibility in the East Coast region

In 1957, there were 3360 actively eroding gullies with a combined area of 5,600 ha present within the East Coast region. By 1997, the number of gullies had decreased to 2,150 with a total area of 7,710 ha. Of the LRI units represented in the East Coast region (7,619), 2,380 units (31%) encompassing an area of 359 km^2 are or have been affected by gully erosion. Figure 9 shows the percentage of catchments, and the region as a whole, classified by gully susceptibility class.

From Figure 9, 81% of the region is either not affected or has a 'very low' to 'low' susceptibility to gully erosion, and 19% is classified as having a 'moderate' to 'very high' gully erosion susceptibility. By catchment, the Waingaromia catchment is the most susceptible of the catchments in the East Coast region to gully erosion with 60% of its area classified as susceptible to 'moderate' to 'very high' gully erosion. Other catchments with a significant proportion of their catchment prone to high levels of gully susceptibility include the Waiapu (45.3%), Uawa (37.2%) and Mangatu (29.9%). Given that gullies are by definition part of, and therefore directly connected to, the stream network, no representation of connectivity is shown in Figure 9.

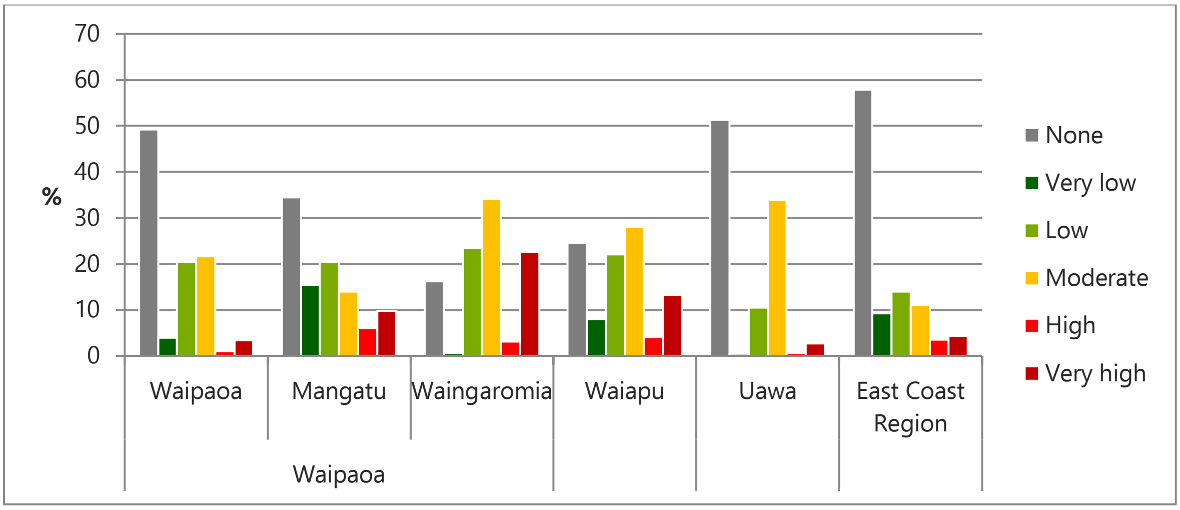


Figure 9. Percentage of catchment area within each gully susceptibily class for the Waipaoa, Mangatu, Waingaromia, Waiapu, Uawa catchments, and East Coast region.

4.2.2 Lithology as a determinant of gully erosion

The analysis of gully susceptibility does not investigate the relationship to driving factors such as lithology or morphology. As gullies form as a result of fluvial incision into bedrock – their occurrence is dictated by the type/composition of the underlying lithology. The NZLRI includes a description of the principal underlying lithology. Table 3 lists the dominant lithologies where the sum of susceptibility classes 'moderate' to 'very high' exceeds 10% of the area occupied by that rock type. Most of the gullies mapped in 1957 and 1997 are found in mudstone or fine siltstone, crushed argillite, and greywacke rock types. Though the total number is greatest for the rock type 'mudstone or fine siltstone – jointed', the probability of gullying in crushed argillite, mudstone (bentonitic) and sheared mixed lithologies is greater (~95% of the area occupied by these LRI units have experienced some form of gully erosion). Other controlling factors related to bedrock structure and tectonic influences (e.g. faulting) (Parkner et al. 2006, 2007) and land cover (Marden et al. 2008, 2011, 2012, 2014, 2018) have previously been investigated to help explain the initiation, growth and distribution of gullying in the East Coast region.

Table 3. Dominant lithologies (base-rock) considered susceptible to gully erosion, by susceptibility class, in the East Coast region. The final two columns list the area (km^2) and percent of the region underlain by each rock type. Rock types are listed if the sum of gully susceptibility classes ‘moderate’ to ‘very high’ exceeds 10% of the total area occupied by the rock type

	Gully susceptibility class					*Area of class (km^2)*	*Area (%) in ECR*
Rock type	None	Low	Moderate	High	Very high		
Argillite	45.6%	22.4%	15.3%	0.9%	2.5%	557.1	6.7%
Argillite — crushed	4.8%	26.7%	31.3%	6.0%	21.9%	649.3	7.8%
Conglomerate & breccia	71.1%	0.0%	28.9%	0.0%	0.0%	0.6	0.0%
Gravels	50.2%	9.7%	33.0%	0.1%	0.3%	192.4	2.3%
Greywacke	55.6%	13.5%	13.7%	2.4%	5.7%	1213.7	14.5%
Lavas, ignimbrite & other ‘hard’ volcanic rocks	75.9%	7.5%	10.0%	0.0%	0.0%	124.9	1.5%
Mudstone — bentonitic	3.4%	24.9%	33.7%	6.1%	31.2%	41.1	0.5%
Mudstone or fine siltstone — jointed	23.7%	24.4%	32.4%	2.9%	9.6%	1868.4	22.3%
Mudstone or fine siltstone — banded	44.5%	19.0%	25.3%	2.2%	3.3%	905.5	10.8%
Mudstone or fine siltstone — massive	58.1%	20.7%	16.1%	0.3%	1.1%	352.0	4.2%
Sheared mixed lithologies	4.4%	26.3%	36.3%	7.3%	9.7%	85.3	1.0%

4.3 Earthflow susceptibility

4.3.1 Earthflow susceptibility in the East Coast Region

Within the East Coast region, 22.5% of the hill country is to some degree classified as being susceptible to earthflow erosion, with just 8.8% classed as ‘moderate’ to ‘very high’ susceptibility. Figure 10 compares the distribution of the earthflow susceptibility classes across catchments and the wider region, and shows that 91% of the East Coast region has either ‘none’ or ‘very low’ susceptibility to earthflow erosion. By catchment, areas with ‘moderate’ to ‘very high’ earthflow susceptibility are highest in the Mangatu catchment (23.5%), and affects 19.0% of the Waingaromia and 15.1% of the Waiapu catchments (Fig. 10).

Other smaller catchments with significant areas with ‘moderate to very high’ levels of earthflow susceptibility are the Waiomoku (21.4%) and Pakarae catchments (12.6%), both northeast of Gisborne (not shown in Figure 10). Similarly, the coastal strip between the Waiapu River in the north southwards to Tolaga Bay is shown to have a very high proportion of the area (24.4%) classed as having ‘moderate’ to ‘very highly”’ susceptibility to earthflow erosion. Here, the presence of crushed argillite, bentonitic mudstone or fine siltstone, and sheared mixed lithologies are particularly susceptible to this type of mass failure.

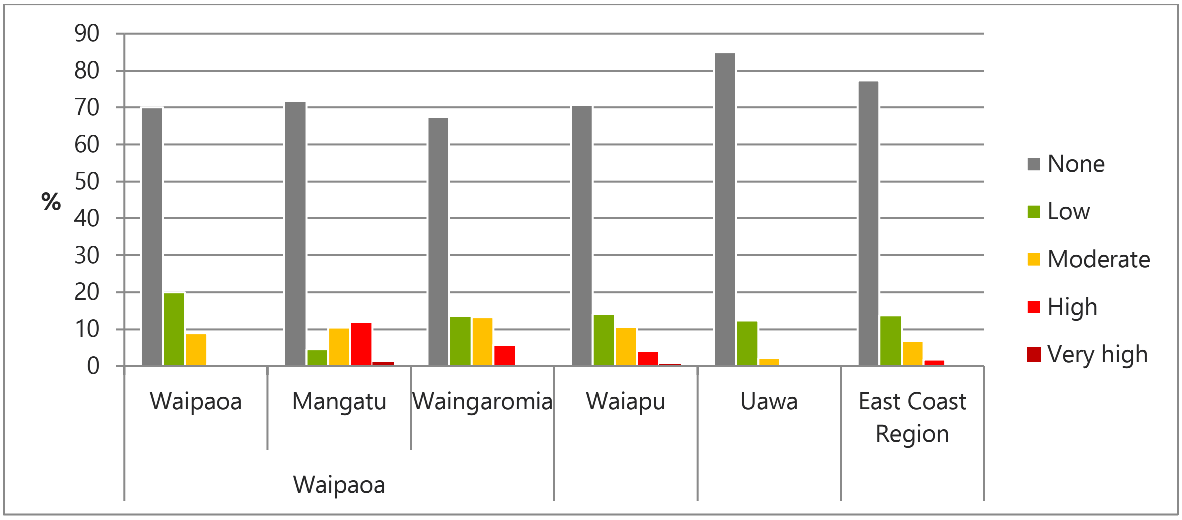


Figure 10. Percentage of catchment area within each earthflow susceptibily class for the Waipaoa, Mangatu, Waingaromia, Waiapu, Uawa catchments, and East Coast region.

4.3.2 Lithology as a determinant of earthflows

Since earthflows are generally no more than a few meters deep moving along basal and marginal shear planes, they are very much influenced by rock type, the degree of shearing and crushing, as well as the influence of gravity on moderately inclined slopes. Table 4 lists the most dominant surface lithologies of LRI units that are susceptible to earthflow erosion. Of these, bentonitic mudstone rocks are the most susceptible to earthflow erosion, but comprise an area of just 41 km^2 (0.5% of the region). Their susceptibility is likely due to the presence of swelling plastic clays including montmorillonite (Pearce et al. 1981).

Of the rest of the region, 50% and 67% underlain by ‘mudstone or fine siltstone – jointed’ and ‘crushed argillite’ are classified as ‘low’ to ‘very high’ susceptibility to earthflow erosion. Though the area is very large for these rock types, the proportion is not as high as mudstone (bentonitic). This is a likely indicator that other controlling factors such as the morphology (e.g. slope) have greater influence on reducing the susceptibility, despite the lithology favouring earthflow erosion. A multivariate analysis would be useful to determine the relative importance of such controlling factors.

Table 4. Dominant lithologies (base-rock) considered susceptible to earthflow erosion in the East Coast region. The final two columns list the area (km^2) and percent of the region underlain by each rock types. Rock types are listed if susceptibility levels exceed 'low' susceptibility

Rock type class	*Earthflow susceptibility classes* None	Low	Moderate	High	Very high	*Area of class (km^2)*	*Area (%) in ECR*
Argillite	84.6%	13.8%	1.3%	0.3%	0.0%	557	6.7%
Argillite — crushed	32.9%	25.0%	30.1%	11.4%	0.5%	649	7.8%
Greywacke	92.8%	5.2%	2.0%	0.0%	0.0%	1214	14.5%
Mudstone — bentonitic	0.0%	7.1%	43.0%	39.2%	10.7%	41	0.5%
Mudstone or fine siltstone — jointed	50.1%	34.3%	14.7%	0.9%	0.0%	1868	22.3%
Mudstone or fine siltstone — banded	87.0%	11.9%	1.2%	0.0%	0.0%	906	10.8%
Sheared mixed lithologies	1.8%	6.7%	32.1%	48.6%	10.8%	85	1.0%
Unconsolidated to moderately consolidated clays, silts, sands, tephra & breccias	47.8%	37.7%	14.5%	0.0%	0.0%	108	1.3%

4.4 Case studies

The landslide susceptibility of exotic forest comprising each of the four study areas and the two geological terrains is shown in Figure 11. By terrain, exotic forests within the Tertiary terrain (1,211 km^2) are more susceptible to landsliding with 36% of the area classified as 'moderately' to 'very highly' susceptible to landsliding, compared with 26.8% of the forest estate (1,704 km^2) located in the Cretaceous terrain (Fig. 11). A comparison of landslide susceptibility of forested areas within the two Tertiary case study sites (Emerald Hills, Makomako) with that in the two study sites located within the Cretaceous terrain (Mangatu, Ruatoria) shows susceptibility to the occurrence of landsliding is significantly less within the two Cretaceous study sites. Across 89% of the exotic forest within the Mangatu and Ruatoria sites, landslide susceptibility is 'very low'.

In contrast, the susceptibility of forested hill country within the two study sites located in the Tertiary terrain to landsliding is significantly greater. For example, 50.4% of the Makomako Forest is classed as 'moderately to very highly' susceptible to landsliding, almost all of which (47.6%) is potentially connected to waterways. Similarly, forested areas within Emerald Hills Forest are also very susceptible to landsliding, more so in the steeper and more dissected terrain located in the western part of this forest. Overall, 32.5% of the Emerald Hills Forest is classed as 'moderately' to 'very highly' susceptible to landslide erosion, of which 26.1% of is potentially connected to waterways.

In Appendices 1 (Emerald Hills Forest) & 2 (Makomako Forest), insets A show the extent of storm-related landslide damage initiated during Cyclone Bola (1988), and insets C are the resultant landslide susceptibility maps. It is interesting to note that even though both the Tertiary study sites are overall very susceptible to landsliding, the susceptibility to landsliding for large areas of these forested study sites (47% of Emerald Hills Forest, 30% of Makomako Forest), is low.

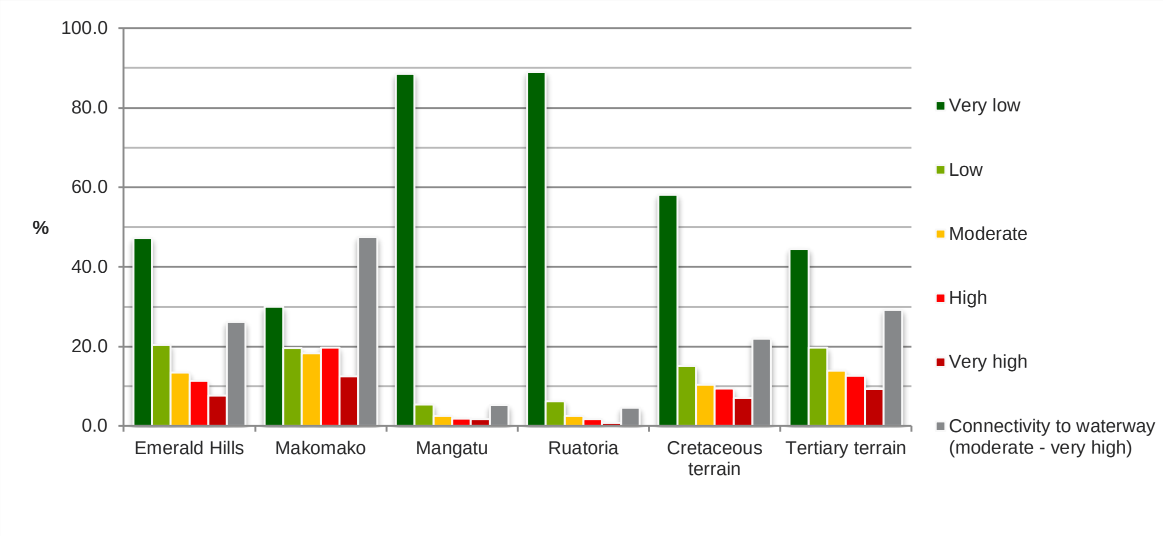


Figure 11. Landslide susceptibility, as a percentage of forested area, for each of four study sites, and the Cretaceous and Tertiary terrains. The percentage of forested areas with moderate to very high landslide susceptibility, and with the potential for landslides to connect to waterways, is also shown.

Figures 12 and 13 show the susceptibility of gully and earthflow erosion, respectively, in each of the four case studies, and for hill country planted in exotic forests within the Tertiary and Cretaceous terrains (see Fig. 1). To better evaluate the susceptibility of the relatively small study sites to gully and earthflow erosion, additional areas of exotic forest located within 1500 m of the study sites and within the same terrain (see Appendix 1) were included in the analyses (see Table 1).

In terms of gully erosion susceptibility, 47% of forested areas within the Cretaceous terrain are 'moderately' to 'very highly' susceptible to gully erosion, compared with 35% within the same classes in Tertiary terrain (Fig. 12). The case study sites provide a contrasting view of gully susceptibility across different terrains. For example, Emerald Hills Forest has low levels of susceptibility to gully erosion (see case study map in Appendix 1, inset D). Makomako Forest, though also located within the Tertiary terrain (mainly mudstone with some sandstone), has a high level of gully susceptibility comparable with that associated with forests planted in the Cretaceous terrain, such as Mangatu Forest.

Factors conducive to the development of high levels of gully susceptibility within Makomako Forest, and in most other forested areas with the Tertiary terrain, include (i) a landscape comprising a dense network of connecting ephemeral and permanent streams formed by fluvial incision, (ii) channels that are deeply incised and have steep valley slopes, (iii) the presence of lithologies with low resistance to fluvial incision, and (iv) structural controls such as bedding and fault zones that influence the type of gully (linear versus amphitheatre-shaped gully-mass movement complexes), and either constrain or facilitate gully development. The majority of gullies within the Tertiary terrain are constrained by structural controls and are therefore generally of small size, and linear in shape. Conversely, in areas of Cretaceous terrain, the lack of structural controls and predominance of lithologies with low resistance to fluvial incision and mass movement failure, many gullies develop into large amphitheatre-shaped gully-mass movement complexes. The Mangatu Forest site features two of the largest amphitheatre-shaped gully mass movement complexes in the East Coast region, namely the

Mangatu and Tarndale gullies (Appendix 4). These and other gullies have formed within areas of crushed argillite (Whangai Shale) (Mazengarb & Speden 2000) affected by acid sulphate weathering (Pearce et al. 1981).

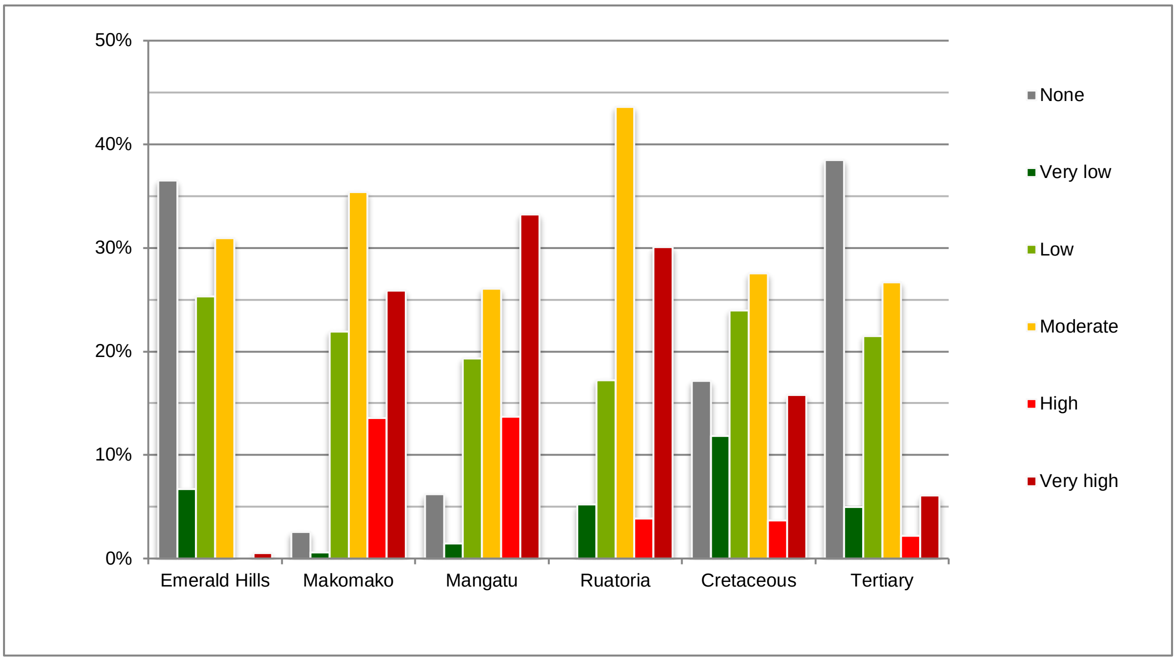


Figure 12. Gully susceptibility, as a percentage of forested area, for each of four study sites, and the Cretaceous and Tertiary terrains.

In terms of areal extent, earthflow erosion is not as important as gully and landslide erosion. By terrain, forested areas classified as ‘moderate’ to ‘very high’ earthflow susceptibility are more extensive within the Cretaceous terrain (18%) than in the Tertiary terrain (10%) (Fig. 13). Similarly, the proportion of forested areas within the two study sites located in the Cretaceous terrain classified as ‘moderate’ to ‘very high’ earthflow susceptibility, is more extensive than in the two study sites located within the Tertiary terrain. Mangatu Forest has the greatest proportion (44%) of forest area classified as ‘moderate’ to ‘very high’ earthflow susceptibility (Appendix 4).

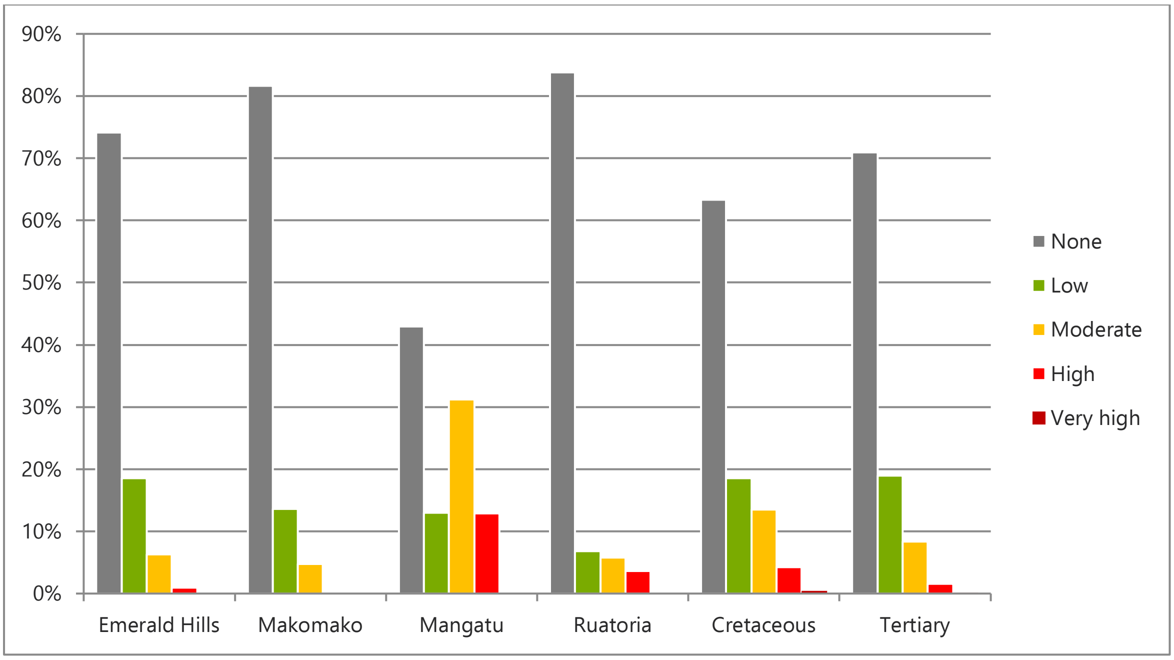


Figure 13. Earthflow susceptibility, as a percentage of forested area, for each of four study sites, and the Cretaceous and Tertiary terrains.

4.5 Comparison with the Erosion Susceptibility Classification for the NES-PF

The Erosion Susceptibility Classification (ESC; MPI 2017) was produced for the NES-PF[3] and is designed to guide councils with the implementation of regulations according to the erosion risk of different landscapes over the eight forestry activities that are regulated under the NES-PF. The ESC can be viewed as a coarse-scaled assessment of erosion susceptibility based on the NZLRI. It assigns a susceptibility class based on the severity of the dominant erosion process of each unit. Figure 14 shows the distribution of the ESC classes by area for the four case study sites and the extent of exotic forest in the Cretaceous and Tertiary terrains. The results exclude areas of 'water', 'shingle' or 'other' classes. Appendix 7 shows the ESC of the four case study sites at 1:50,000 scale (NES-PF) and Appendices 1–6 show the results of an erosion susceptibility of the same 4 study sites at a scale of approximately 1:25,000 scale. The four case study sites are considered to be highly susceptible to erosion, with the entire area (>98%) of all sites assigned to 'moderate' to 'very high' susceptibility classes. According to the NES-PF, afforestation is a 'restricted discretionary activity' in 'red zones', and resource consent is required prior to planting these areas if > 2 ha; If already under forestry production, replanting within 'red zones' is a 'controlled' activity. Additionally, harvesting is a restricted discretionary activity in any 'red zone' of Land Use Capability Class 8e.

As an example, the NES-PF for Makomako Forest has 90% of its area classified as 'very highly' susceptible to erosion. Appendix 2, inset A, shows the extent of storm-initiated damage, predominantly landsliding and gully erosion, within Makomako Forest and in the unforested area to the west of the Waiau River, during Cyclone Bola (1988). At this time, the area to the west of the Waiau River lacked a protective forest cover and it is evident that the

[3] Resource Management (National Environmental Standards for Plantation Forestry) Regulations 2017.

‘storm-effect’ was particularly damaging. In contrast, the more detailed analysis of landslide susceptibility shows that just 50.4% of the forest is susceptible to ‘moderate’ to ‘very high’ levels of landslide susceptibility (Fig. 14 and Appendix 2). East of the Waiau River, the level of landslide susceptibility is not as great; indeed, 30% of the site is not susceptible to landsliding. Additionally, gully erosion, within Makomako Forest was classed as ‘moderate’ to ‘very high’ across 75% of the forest; 39% is considered to be ‘highly’ to ‘very highly’ susceptible to gully erosion. Only 5% of Makomako Forest is considered to be ‘moderately’ to ‘very highly’ susceptible to earthflow erosion.

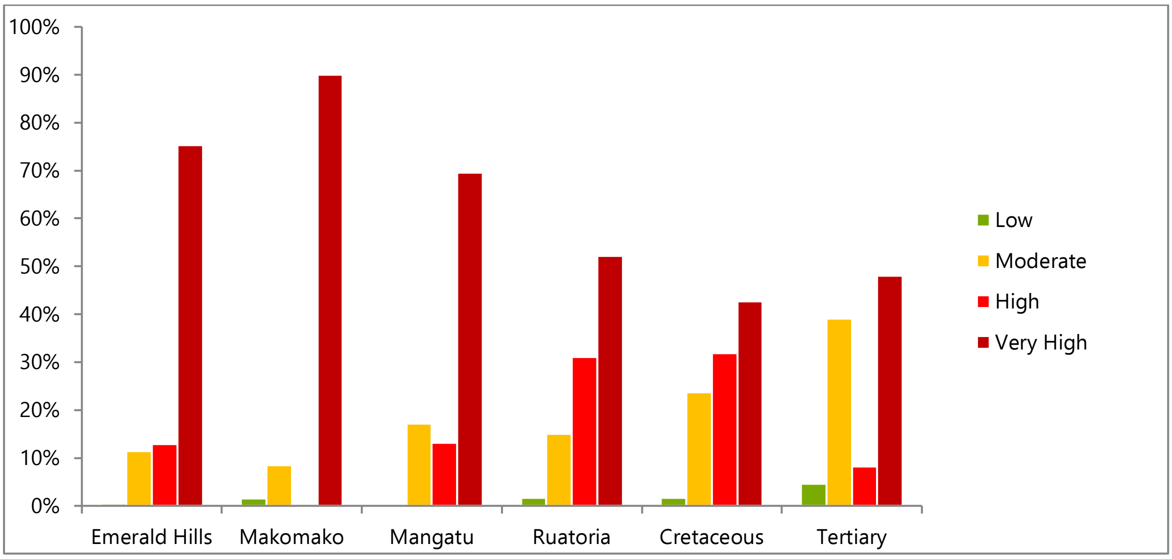


Figure 14: Erosion susceptibility of LRI units in four study sites and the two broad geological terrains based on the ESC NES-PF 2018.

5 Conclusions

The results of this study have shown that the propensity for shallow landsliding to occur during a rainfall storm event increases greatly on slopes >16° in Tertiary terrain, and on slopes > 28° on Cretaceous terrain, with a disproportionately high probability on slopes with aspects facing north to north-east. Land currently planted in exotic forest and located within the Tertiary terrain is therefore more susceptible to landsliding than are forested areas established within the Cretaceous terrain. Landslide susceptibility analyses show that 35.9% of the exotic forest estate within the Tertiary terrain has a ‘moderate’ to ‘very high’ propensity for landsliding compared with 26.8 % of the forest estate located within the Cretaceous terrain. The degree of connectivity, i.e. the potential for landslides to deliver sediment and woody debris into gullies and waterways, is greater in Tertiary (29.2%) terrain than Cretaceous (21.9%). Of the (sub-) catchments most relevant to the current production of exotic forests, the Uawa catchment and Waingaromia subcatchment are the most susceptible to landslide initiation.

Gully erosion occurs throughout the region but only 19% of hill country areas are affected by ‘moderate’ to ‘very high’ levels of gully activity, and this is largely confined to the Waingaromia subcatchment (60%), the Waiapu catchment (45%), and the Mangatu subcatchment (30%). Overall, gully susceptibility is significantly higher within the Cretaceous terrain than in the Tertiary terrain. Of the forested areas located within the

Cretaceous terrain, 47% of hill country areas are ‘moderately’ to ‘very highly’ susceptible to gully erosion, and for forested areas within the Tertiary terrain the affected area is 35% of the forest estate. The greatest numbers of current and former gullies are associated with mudstone or fine siltstone, crushed argillite, and greywacke rock types. The probability of gullies initiating and developing is greatest in areas underlain by crushed argillite, bentonitic mudstone, and sheared mixed lithologies.

As much as 91% of the region is not affected by or is susceptible to low levels of earthflow activity, while only 9% of hill country areas are susceptible to high levels of earthflow erosion (classes “moderate” to “very high”) most of which occurs in the Mangatu catchment (23.5%), the Waiapu catchment (15.1 %) and the Waingaromia subcatchment (19.0%). A greater proportion of exotic forest with “moderate” to “very high” susceptibility to earthflow erosion is found within areas of Cretaceous terrain (18 %) than in areas of Tertiary terrain (10%). The propensity for earthflow erosion is greatest where bentonitic mudstone is the dominant underlying rock type while high levels of earthflow susceptibility are also associated with “mudstone or fine siltstone – jointed” and “crushed argillite”. Across the region, 50% of the area underlain by bedrock dominated by mudstone or fine siltstone were classed as “low” to “very high”; for areas underlain by crushed argillite the percentage area was higher at 67%.

It was beyond the scope of this project to include a multivariate analysis of controlling factors governing different erosion processes. However, multi- or bivariate statistical approaches such as random forest modelling based on existing earthflow and gully inventories (e.g. the Mangatu study area in Marden et al. 2014) could deliver further insights into predisposing factors that determine the incidence of these erosion processes. Nonetheless, the findings of this project have demonstrated that significant relationships exist between earthflow and gully erosion and lithology.

A comparison of the ESC developed for the NES-PF at 1:50,000 scale and the revised classification at 1:25 000 scale presented here, shows that the latter classification provides a more detailed erosion process-based assessment of areas deemed to have a high erosion susceptibility. When evaluating land use options based on erosion susceptibility, it is clearly important to consider that the susceptibility of different erosion processes (landslide, earthflow and gully erosion) is spatially variable within any given landscape or forest area – as is the landscape response to storm events, and resultant types of erosion processes. As has been demonstrated, for any given parcel of land, there are likely to be large areas that are sustainable for farming and/or forestry, and other areas that are not, and for which there may be more suitable land use options. Providing susceptibility maps at a more detailed scale (e.g. 15-m pixel scale) can be problematic in terms of land managers understanding how best to utilize the detailed information provided to better inform management practices. From a land management perspective, the question then becomes one of what scale best suits different land use options including pastoral farming, forestry, assisted reversion (planting native species including mānuka plantations for honey production), and/or passive reversion. Creating useable information from fine-scaled spatial data is a reasonably straight-forward exercise. Generalization techniques can be used to define areas of susceptibility with a minimum aerial extent (e.g. 2 ha), and rules can be defined to allow a certain proportion of tolerable erosion susceptibility (e.g. 15%). In this way, a fine-scaled susceptibility map can be re-scaled to create management units of varying susceptibility classes. Best practice is to assemble data at the finest scale that is feasible and allow rescaling to coarser resolutions to meet the demands of land managers and ensuring that the value of the detail is not lost in the process.

6 Recommendations

Given that landsliding is the main mechanism by which debris, logs and slash are delivered into gullies and waterways, particularly during the post-harvest ‘period of vulnerability’, we recommend that a detailed assessment of erosion *risk* be extended to include all existing exotic forests. Such an analysis should include the identification of parts of forested estates that are connected to waterways, and where there is a high ‘risk’ of slope failure, the probability that sediment and woody debris will be transported into a stream channel. A risk assessment should also include an evaluation of likely downstream impacts. The information provided will greatly help decisions regarding the future of forestry on these sites, and in deciding potential post-harvest land use options that may be more suited to providing long term sustainability and as a pathway to establishing a permanent forest cover. Moreover, since the risk of downstream impact is dependent on the spatial distribution of recently harvested forests, annual risk maps could be generated using knowledge of the intended timing of harvest.

Furthermore, in light of the Government’s ‘Billion Trees’ project, it is recommended that a detailed assessment of erosion susceptibility of areas identified as potential sites for future planting be undertaken to assess the long-term sustainability of each of the proposed planting/land use options. Such an assessment needs to be carried out before planting to ensure the adoption of optimal long-term land uses.

A validation of the landslide and earthflow susceptibility maps was not possible due to the scarcity of landslide inventories within the East Coast region, and mapping landslides was beyond the scope of this project. Further research should thus focus on generating landslide inventories that are related to specific storm events in the region to verify the transferability of regional slope-scar relationships (Fig. 4) and allow a validation to be undertaken. Such inventories are invaluable for probabilistic landslide susceptibility, hazard and/or risk assessments that rely heavily on the past distribution of landslide scars to enable a refined representation across different terrains. For this study, we were largely reliant on landslide datasets from similar geological terrains in the Manawatu. Availability of a LiDAR DEM would provide greater precision in terms of terrain characterisation (e.g. morphometrics). Unfortunately, existing coverage in the East Coast region is still very limited. Further work should also evaluate the roll of additional controlling factors such as topographic curvature and drainage density. The main objective of this study was to characterise the susceptibility inherent in the landscape independent of the current exotic forest land cover. The existing land cover is a function of the current land use, which is liable to change depending on a number of socio-economic and environmental factors. We recommend that further research should include an analysis of how different land uses impact on erosion susceptibility.

7 Acknowledgements

We thank MPI for providing the post-Cyclone Bola orthorectified historic aerial photography. Thanks to Dr John Dymond for the use of the landslide connectivity model. Special thanks also to Dr Hugh Smith for reviewing the report, and Anne Austin for editing.

8 References

Aleotti P, Chowdhury R 1999. Landslide hazard assessment: summary review and new perspectives. Bulletin of Engineering Geology and the Environment 58:21–44.

Betts HD, Trustrum NA, De Rose RC 2003. Geomorphic changes in a complex gully system measured from sequential digital elevation models, and implications for management. Earth Surface Processes and Landforms 28: 1043–1058.

Betts H, Basher L, Dymond J, Herzig A, Marden M, Phillips C 2017. Development of a landslide component for a sediment budget model. Environmental Modelling and Software 92: 28–39. https://doi.org/10.1016/j.envsoft.2017.02.003

Burnett BN, Meyer GA, McFadden LD 2008. Aspect-related microclimatic influences on slope forms and processes northeastern Arizona. Journal of Geophysical Research Earth Surface 113: 1–18. https://doi.org/10.1029/2007JF000789

Caine N 1980. Rainfall intensity-duration control of shallow landslide and debris flows. Geografiska Annaler 62A(1–2): 23–29.

Crozier MJ, Eyles RJ 1980a. Assessing the probability of rapid mass movement. Third Australia-New Zealand Conference on Geomechanics, Vol. 2. Wellington, New Zealand Institute of Engineers Proceedings of Technical Groups. Pp. 247–253.

Crozier MJ, Eyles RJ, Marx SL, McConchie JA, Owen RC 1980b. Distribution of landslides in the Wairarapa hill country. New Zealand Journal of Geology and Geophysics 23: 575–586.

De Rose RC 1996. Relationship between slope morphology, regolith depth, and the incidence of shallow landslides in eastern Taranaki hill country. Zeitschrift für Geomorphologie Supplementband 105: 49–60.

De Rose RC, Gomez B, Marden M, Trustrum NA 1998. Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models. Earth Surface Processes and Landforms 23: 1045–1053.

Dymond JR, Ausseil AG, Shepherd JD, Buettner L 2006. Validation of a region-wide model of landslide susceptibility in the Manawatu–Wanganui region of New Zealand. Geomorphology 74: 70–79.

Eyles GO 1985. The New Zealand land resource inventory erosion classification. (Water and Soil Miscellaneous Publication 85). Wellington, New Zealand, National Water and Soil Conservation Authority.

Eyles RJ 1971. Mass movement in Tangoio Conservation Reserve, northern Hawke’s Bay. Earth Science Journal 5: 79–91.

Galli M, Ardizzone F, Cardinali M, Guzzetti F, Reichenbach P 2008. Comparing landslide inventory maps. Geomorphology 94: 268–289.

Gomez B, Cui Y, Kettner AJ, Peacock DH, Syvitsky JPM 2009. Simulating changes to the sediment transport regime of the Waipaoa River, New Zealand, driven by climate change in the twenty-first century. Global and Planetary Change 67: 153–166.

Guzzetti F, Carrara A, Cardinali M, Reichenbach P 1999. Landslide hazard evaluation: an aid to a sustainable development. Geomorphology 31: 181–216.

Hancox GT, Wright K 2005. Landslides caused by the February 2004 rainstorms and floods in southern North Island. Institute of Geological and Nuclear Sciences Science Report 2005/10.

Hancox CT, Wright K 2005. Analysis of landslides caused by the 15–17 February 2004 rainstorm in the Wanganui-Manawatu hill country, Southern North Island, New Zealand. Institute of Geological & Nuclear Sciences Science Report 2005/11.

Harmsworth GR, Hope GD, Page MJ, Manson PA 1987. An assessment of storm damage at Otoi in northern Hawke's Bay. Soil Conservation Centre Aokautere Publication No. 10. Wellington, New Zealand, National Water and Soil Conservation Authority.

Herzig A, Dymond J, Marden M 2011. A gully-complex model for assessing gully stabilisation strategies, Geomorphology 133: 23–33 (doi: dx.doi.org/10.1016/j.geomorph.2011.06.012).

Hicks DL 1991. Erosion under pasture, pine plantations, scrub and indigenous forest: a comparison from Cyclone Bola. New Zealand Forestry 36(3): 21–22.

Hicks DL, Fletcher JR, Eyles GO, McPhail CR, Watson M 1993. Erosion of hill country in the Manawatu–Wanganui region 1992: Impacts and options for sustainable land use. Landcare Research Contract Report LC9394/51.

Hölbling D, Spiekermann R, Betts H, Phillips C 2018. Landslide hotspot mapping and susceptibility assessment in Pahiatua, New Zealand. Geophysical Research Abstracts. Vol. 20, EGU2018-421,

James IL 1973. Mass movement in the Upper Pohangina Catchment, Ruahine Range. New Zealand Journal of Hydrology 12: 92–102.

Lee,EM, Jones DKC 2004. Landslide risk assessment. London, Thomas Telford. 454 p.

Lee S 2005. Application of logistic regression model and its validation for landslide susceptibility mapping using GIS and remote sensing data. International Journal of Remote Sensing 26(7): 1477–1491.

Leithold EL, Blair NE, Childress LB, Brulet BR, Marden M, Orpin AR, Kuehl SA, Alexander CR 2013. Signals of watershed change preserved in organin carbon buried on the continental margin seaward of the Waipaoa River, New Zealand. Marine Geology 346: 355–365.

Lynn IH, Manderson AK, Page MJ, Harmsworth GR, Eyles GO, Douglas GB, Mackay AD, Newsome PJF 2009. Land Use Capability Survey Handbook – a New Zealand handbook for the classification of land. 3rd edn. Hamilton, AgResearch/ Lincoln, Landcare Research/ Lower Hutt, GNS Science.

Mackey BM, Roering JJ 2011. Sediment yield, spatial characteristics, and the long term evolution of active earthflows determined from airborne LiDAR and historic aerial photographs, Eel River, California. Geological Society of America Bulletin 123: 1560–1576.

Marden M, Rowan D 1993. Protective value of vegetation on tertiary terrain before and during Cyclone Bola, East Coast, North Island, New Zealand. New Zealand Journal of Forestry Science 23: 255–263.

Marden M, Betts H, Arnold G, Hambling H 2008. Gully erosion and sediment load: Waipaoa, Waiapu and Uawa rivers, eastern North Island, New Zealand, Proceedings Sediment dynamics in changing environments, Christchurch, New Zealand, IAHS 325, pp. 339–350.

Marden M, Herzig A, Arnold G 2011. Gully degradation, stabilisation and effectiveness of reforestation in reducing gully-derived sediment, East Coast region, North Island, New Zealand, Journal of Hydrology (NZ) 50(1): 19–36.

Marden M, Arnold G, Seymour A, Hambling R 2012. History and distribution of steepland gullies in response to land use change, East Coast Region, North Island, New Zealand, Geomorphology 153-154: 81–90 (doi: dx.doi.org/10.1016/j.geomorph.2012.02.011).

Marden M, Herzig A, Basher L 2014. Erosion process contribution to sediment yield before and after the establishment of exotic forest: Waipaoa catchment, New Zealand. Geomorphology 226: 162–174. https://doi.org/10.1016/j.geomorph.2014.08.007

Marden M, Fuller IC, Herzig A, Betts DH 2018. Badass gullies: fluvio-mass-movement gully complexes in New Zealand's East Coast region, and potential for remediation. Geomorphology (in press).

Mazengarb C, Speden IG 2000. Geology of the Raukumara area. Institute of Geological and Nuclear Sciences 1:250 000 geological map 6. Lower Hutt, Institute of Geological and Nuclear Sciences. 1 sheet + 60 p.

Ministry for the Environment 2004. Climate change effects and impacts assessment: a guidance manual for local government in New Zealand. Wellington, Ministry for the Environment New Zealand Climate Change Office. 147 p. http://www.mfe.govt.nz / publications / climate / effects-impacts-may04 / index.html.

Ministry for Primary Industries 2017. Plantation forestry erosion susceptibility classification. risk assessment for the national environmental standards for plantation forestry. MPI Technical – Paper No: 2017/47. https://www.mpi.govt.nz/dmsdocument/19340-plantation-forestry-erosion-susceptibility-classification-risk-assessment-for-the-national-environmental-standards-for-plantation-forestry

National Water and Soil Conservation Organisation 1976. New Zealand Land Resource Inventory Worksheets. Wellington, New Zealand Government Printer.

Owens PN, Batalla RJ, Collins AJ, Gomez B, Hicks DM, Horowitz AJ, Kondolf GM, Marden M, Page MJ, Peacock DH, Petticrew EL, Salomons W, Trustrum NA 2005. Fine-grained sediment in river systems: environmental significance and management issues. River Research and Applications 21: 693–717.

Page MJ, Trustrum NA 1997. A Late Holocene lake sediment record of the erosion response to land use change in a steepland catchment, New Zealand. Zeitschrift für Geomorphologie 41: 369–392.

Parkner T, Page MJ, Marutani T, Trustrum NA 2006. Development and controlling factors of gullies and gully complexes, East Coast, New Zealand. Earth Surface Processes and Landforms 31: 187–199.

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

Pearce AJ, Black RD, Nelson CS 1981. Lithologic and weathering influences on slope form and process, eastern Raukumara Range, New Zealand. Erosion and Sediment Transport in Pacific-rim Steeplands: International Association Hydrological Sciences Publication 132, Proceedings of Christchurch Symposium, Christchurch, 1981. Pp. 95–122.

Peltzer DA, Payton IJ 2006. Analysis of carbon monitoring system data for indigenous forests and shrub lands collected in 2002/03. Landcare Research Contract Report LC0506/099. 55 p.

Phillips CJ 1988. Rheological investigations of debris flow materials. Ph.D. thesis, Lincoln College, New Zealand.

Reid LM, Page MJ 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. Geomorphology 49: 71–88.

Salter RT, Crippen TF, Noble KE 1983. Storm damage assessment of the Thames-Te Aroha area following the storm of April 1981. Publication l. Palmerston North, New Zealand: Soil Conservation Centre.

Sciarra M, Coco L, Urbano T 2017. Assessment and validation of GIS-based landslide susceptibility maps: a case study from Feltrino stream basin (Central Italy). Bulletin of Engineering Geology and the Environment 76: 437–456. https://doi.org/10.1007/s10064-016-0954-7

Savage L 2006. An overview of climate change and possible consequences for Gisborne District. Internal report prepared for Gisborne Civil Defence and Emergency Management Group. Gisborne, Gisborne District Council. 70 p.

Soeters R, Van Westen CJ 1996. Slope stability: recognition, analysis and zonation. In: Turner AK, Shuster RL eds Landslides: investigation and mitigation. Transportation Research Board Special Report 247, pp. 129–177.

van Westen CJ, Castellanos E, Kuriakose SL 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. Engineering Geology 102: 112–131.

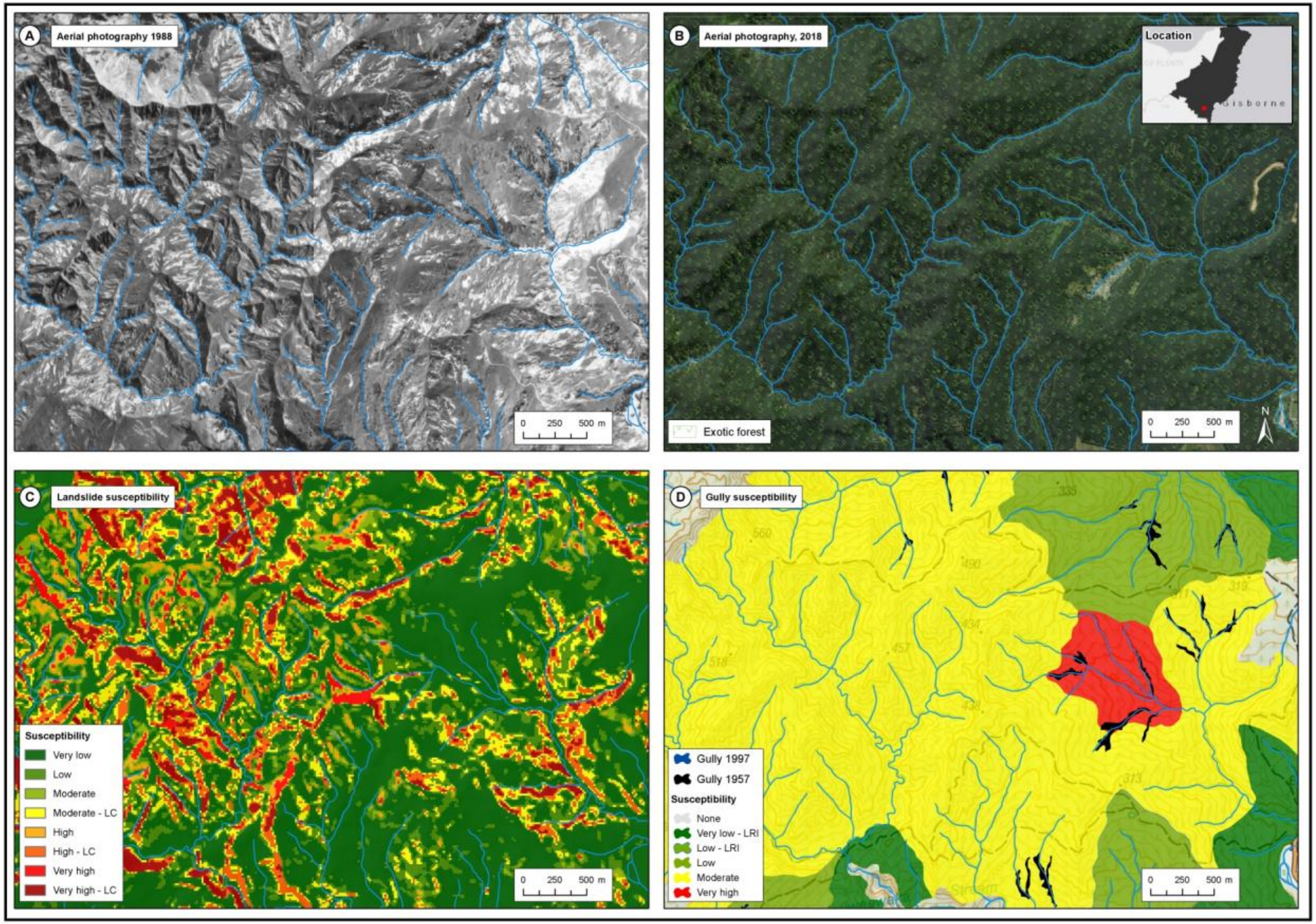
Varnes JD 1984. IAEG commission on landslides and other mass movements, landslide hazard zonation: a review of principles and practice. Paris, UNESCO Press. 63 p.

Veld GJ, de Graaf F 1990. Erosion damage as a result of Cyclone Bola: an assessment on Arai Matawai and Emerald Hills properties East Coast Region, North Island, New Zealand. Gisborne, Forest Research Institute, Ministry of Forestry. 41 p & Appendices.

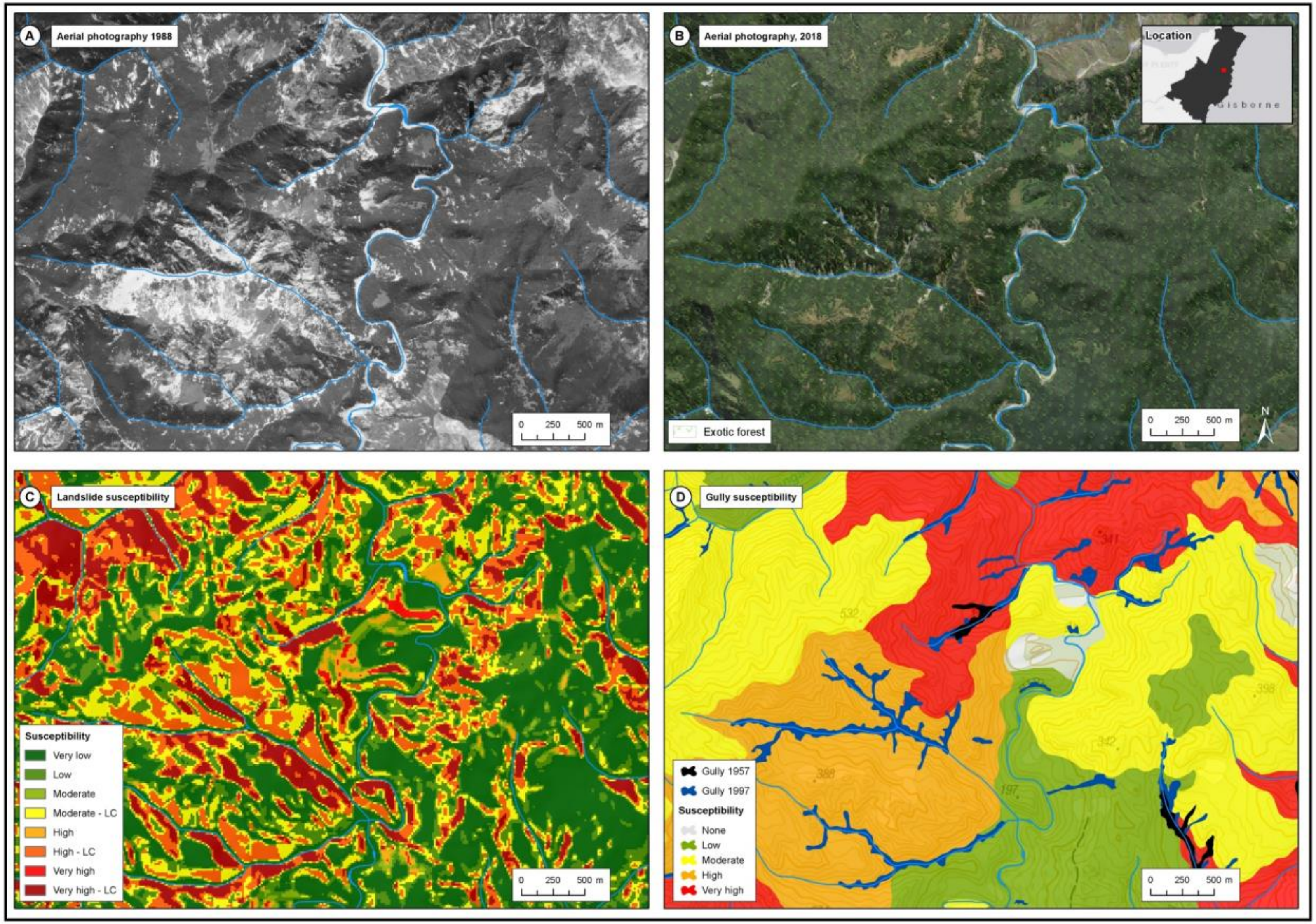
Yalcin A, Bulut F 2007. Landslide susceptibility mapping using GIS and digital photogrammetric techniques: a case study from Ardesen (NE Turkey). Natural Hazards 41: 201–226.

Zhang X, Phillips C, Marden M 1993. A comparison of earthflow movement mechanisms on forested and grassed slopes, Raukumara Peninsula, North Island, New Zealand. Geomorphology 6: 175–187.

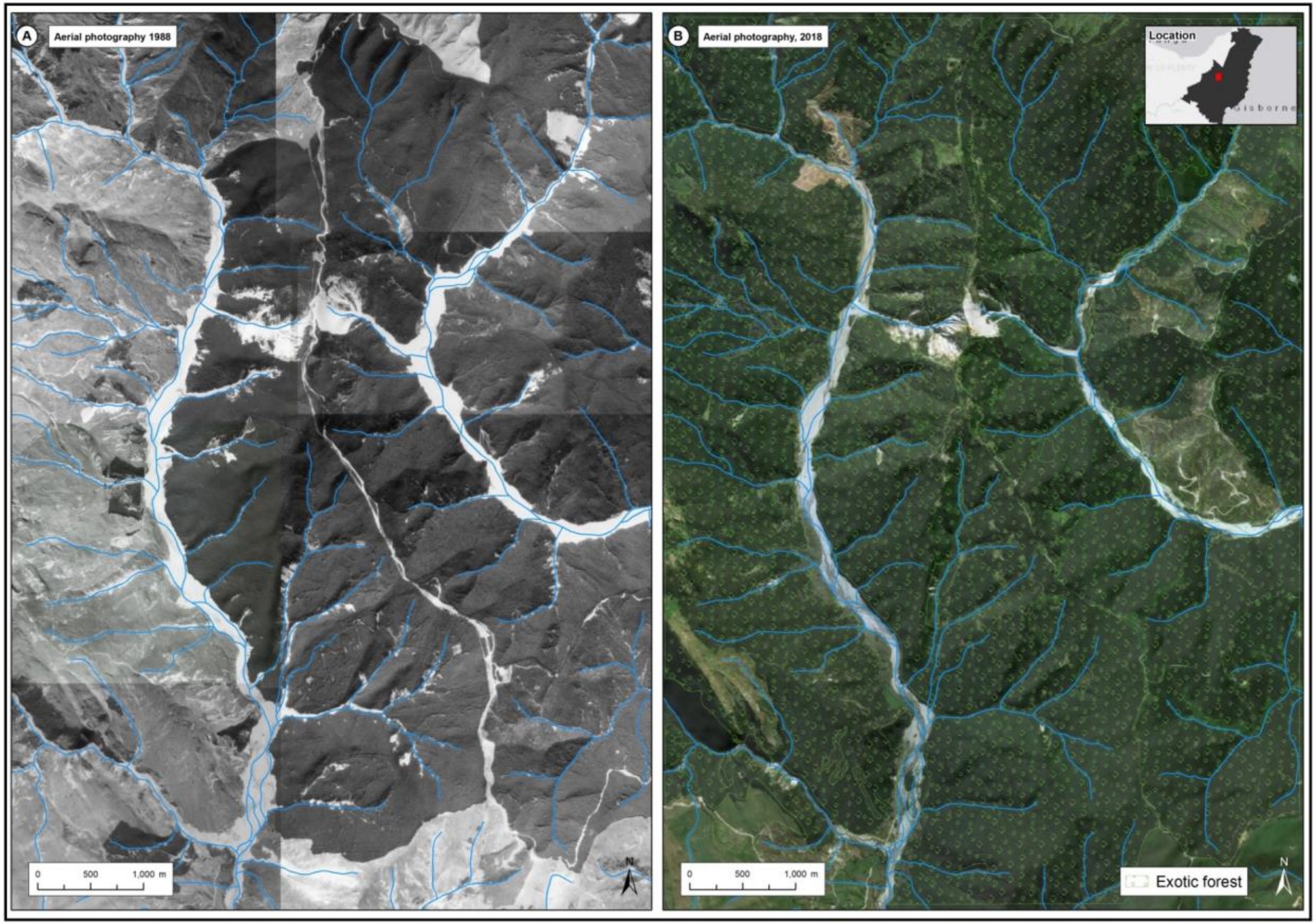
Appendix 1 – Erosion susceptibility in the Emerald Hills case study site



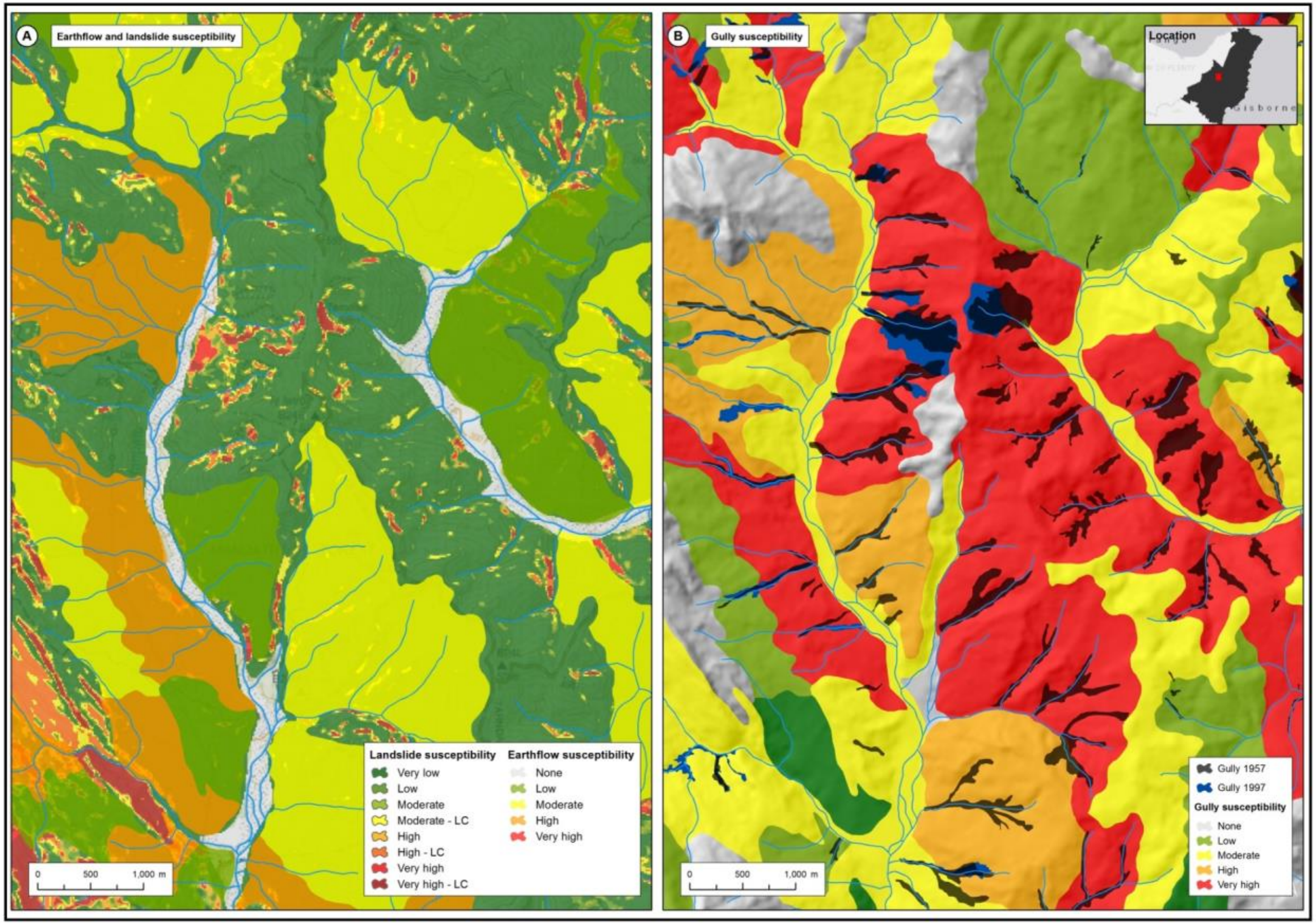
Appendix 2 – Erosion susceptibility in the Makomako case study site



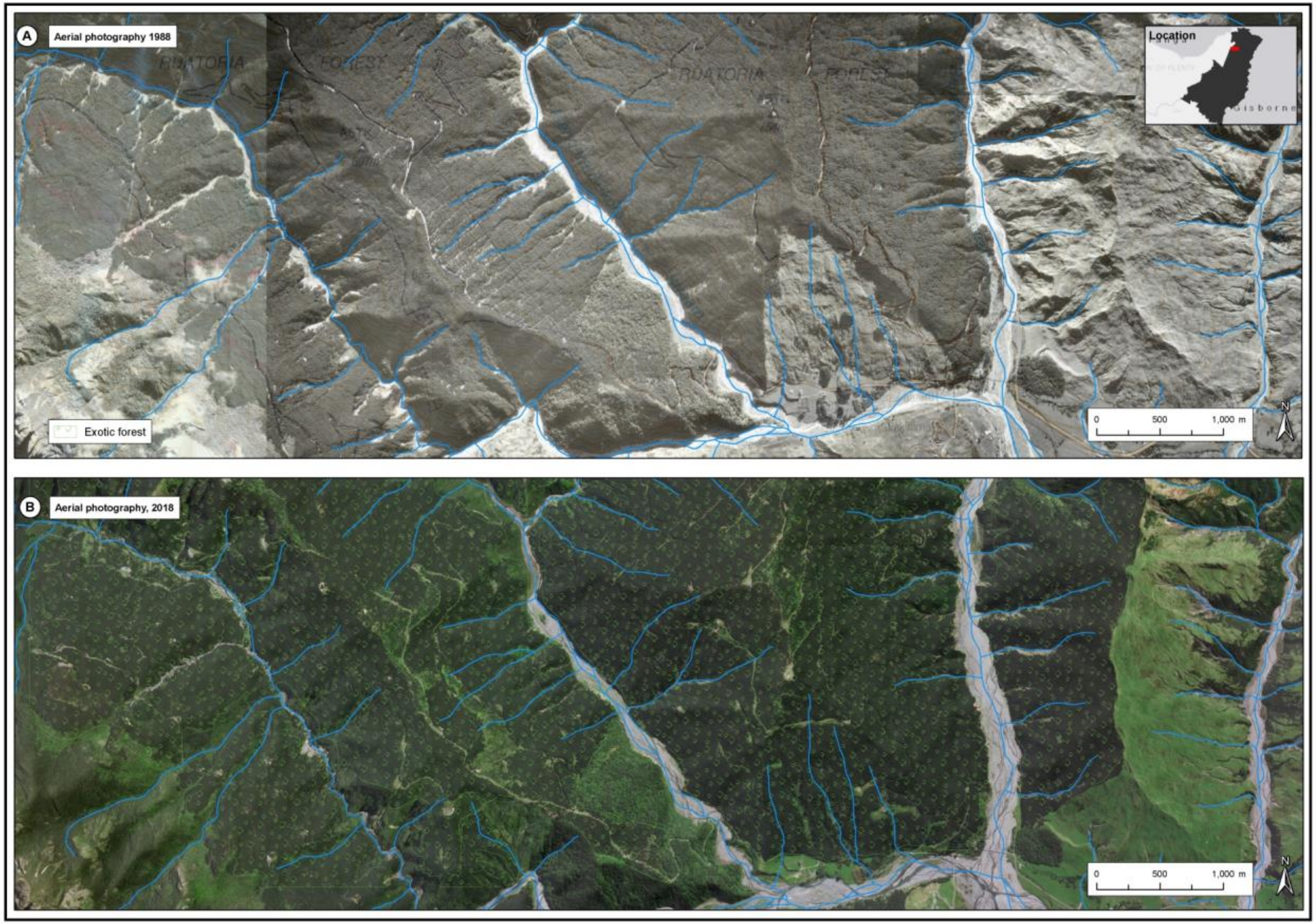
Appendix 3 – Aerial photography of the Mangatu Forest case study site in 1988 and 2018



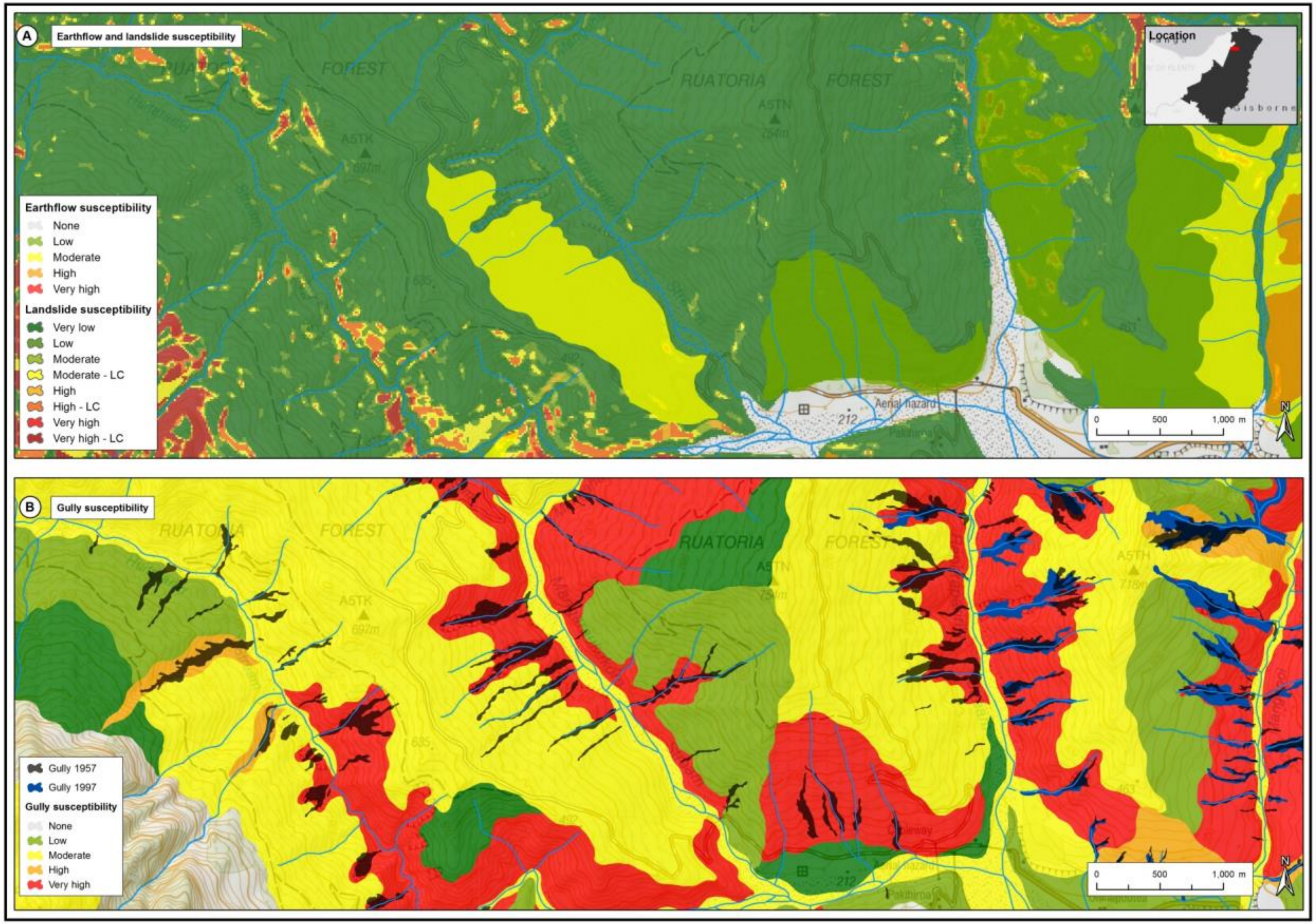
Appendix 4 – Erosion susceptibility in the Mangatu Forest case study site



Appendix 5 – Aerial photography of Ruatoria Forest case study 1988 and 2018



Appendix 6 – Erosion susceptibility in Ruatoria Forest case study site



Appendix 7 – Erosion susceptibility classification for the NES-PF (2018) in the four case study sites