Analysis of landslide events in the Wakaroa and Makiri Forests, and adjacent areas

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July 2019

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Introduction

On the 3rd and 4th and again on the 11th and 12th of June 2018, two severe storm hit the Gisborne Region. For the second storm, the highest rainfalls occurred in the northern catchments of the Waiapu and Wharekahika catchments. Significant flooding also occurred in the Waipaoa Catchment adjacent to the Wakaroa Forest (Cave 2018b).

Subsequent to the storms, GNS were commissioned to undertake an analysis of landsliding within the Uawa Catchment arising from the 3rd and 4th of June storm. To facilitate this, high resolution post-event satellite imagery at 0.75m resolution was tasked. This image was acquired on the 25th of August 2018 and compared with pre-event satellite imagery dated 25th August 2017 as well as aerial imagery acquired by Gisborne District council over the summer of 2017-2018.

Ultimately the satellite acquisition imaged a far greater area than that required for the Uawa project. The final imagery thus covered the eastern edge of the Poverty Bay Flats through to the headwaters of the Waiapu. This has been released on Google Earth, albeit at a lower resolution, but still a higher resolution than normal.

This imagery has therefore been used to assess the impact of landslide resulting from the Queens Birthday storms for the forests at the head of the Waimata catchment which experienced significant landslide activity with major debris flows from the forest resulting in the blocking of the Waimata valley road at Uttings Bridge (culvert) on Waimata Valley Road.

This report forms two parts. Firstly it provides a spatial analysis of the number and distribution of landslides within the study area, and secondly an analysis of the types of failures and the mechanisms driving the failures.

Part One Spatial Analysis

Methodology

Google Earth allows for satellite imagery of different dates to be overlain thus allowing change over time to be measured. A 172.5 km^2 [17,250 ha] area encompassing the top of the Waimata catchment and the eastern Waipaoa catchment was used as the area for analysis (**Figure One**). This area included the Wakaroa and Makiri forests as well as adjacent farmland.

The area within the area for analysis was scanned repeatedly with the 25th August 2018 imagery analysed to identify areas of new slipping. Each slip was then checked against the summer of 2017-2018 aerial photograph and slips present in 2017 excluded from the analysis. The slips were digitised in Google Earth and then exported as a .kml file for importing into a GIS. Once in a GIS the slips could be converted to shape files and the area of each slip calculated. This allowed for any slips that occurred prior to the June 2018 storms to be excluded from the analysis.

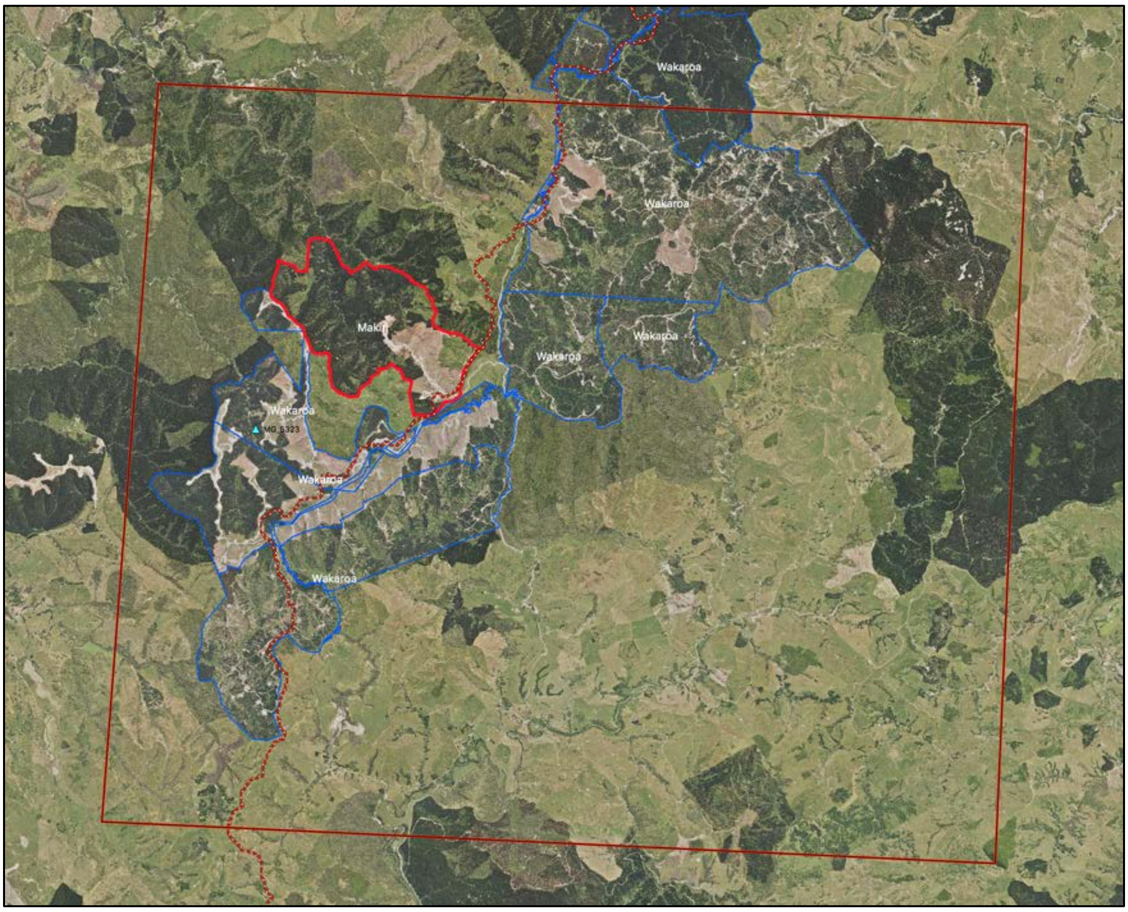

Figure One. *Wakaroa-Makiri landslide analysis study area showing the Makiri Forest (red) and Wakaroa Forest (blue).*

Land use classes

The area was then classed by landuse, namely;

1. Farmland (areas predominantly covered with pasture)[**Figure Two**],
2. Closed canopy forest (Mature and sub mature pine forest with a dense canopy, indigenous forest, or densely planted riparian margins) [**Figure Three**],
3. Open canopy forest (young to sub mature pine trees with the ground clearly visible between stems, open stands of indigenous trees or spaced willows and poplars in riparian margins or gullies) [**Figure Four**],
4. Replanted with stems visible in the imagery [**Figure Five**], and
5. Recently harvested forest areas (zero to 5 year harvested areas with either bare land or with small saplings individually undiscernible in the imagery [**Figure Six**].

It is noted that while it is easy to determine the areas categorised as farmland, closed canopy and open canopy forest, the boundary between recent harvest and replanted with stems visible will be a bit blurred. This is not considered to materially alter the findings of this study.

Figure Two. *Open pasture on Duncan Road with Makiri Forest on the left.*

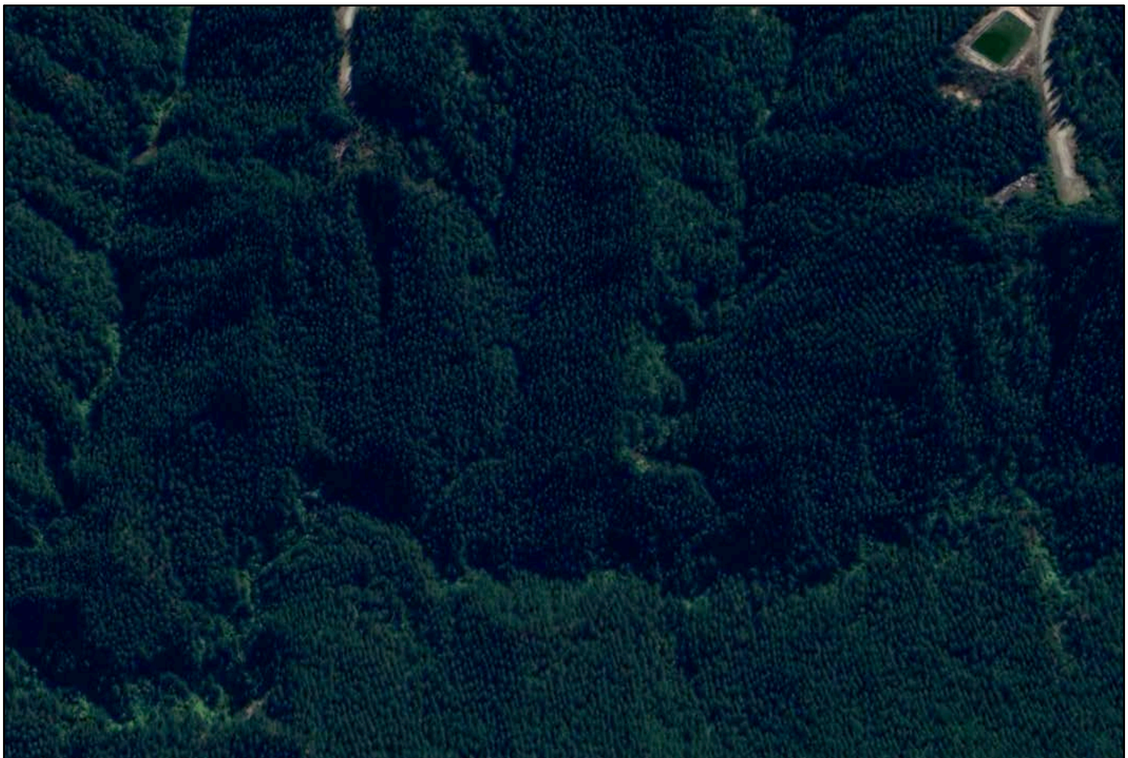

Figure Three. *Closed canopy pine forest east of Waimata Valley Road.*

Figure Four. *Open canopy pine forest Wakaroa Forest.*

Figure Five. *Visible pine saplings Wakaroa Forest.*

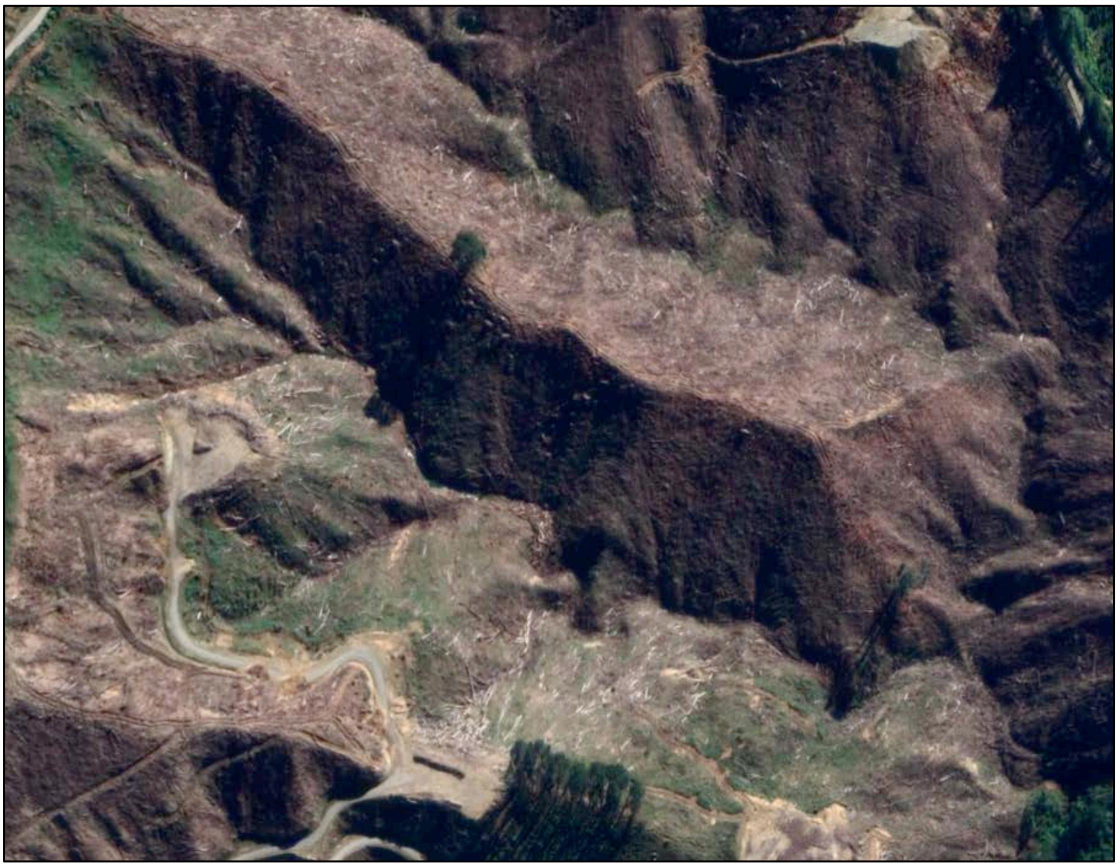

Figure Six. *Recently harvested forest, Wakaroa Forest.*

Photographs taken either on the ground or from a helicopter were used to calibrate the analysis. This allowed for the key landuses within the study area to be accurately analysed and mapped.

The Analysis

Nearly half of the study area is in farmland pasture (7,836 ha~46%), with closed canopy exotic and indigenous forest the second largest land use (7,452ha ~43%). Around 746 ha has been recently harvested (4%), while open canopy forest comprises 838ha (5%), while replanted forest with stems visible in the satellite imagery comprises 376 ha (2%) (see **Table One** below and **Figures Seven and Eight**).

Land use	ha
Closed Canopy	7452.4
Farmland	7836
Recent Harvest	746
Replanted (stems Visible)	376.3
Open Canopy	838

Table One *Landuse within the study area (17,250ha)*

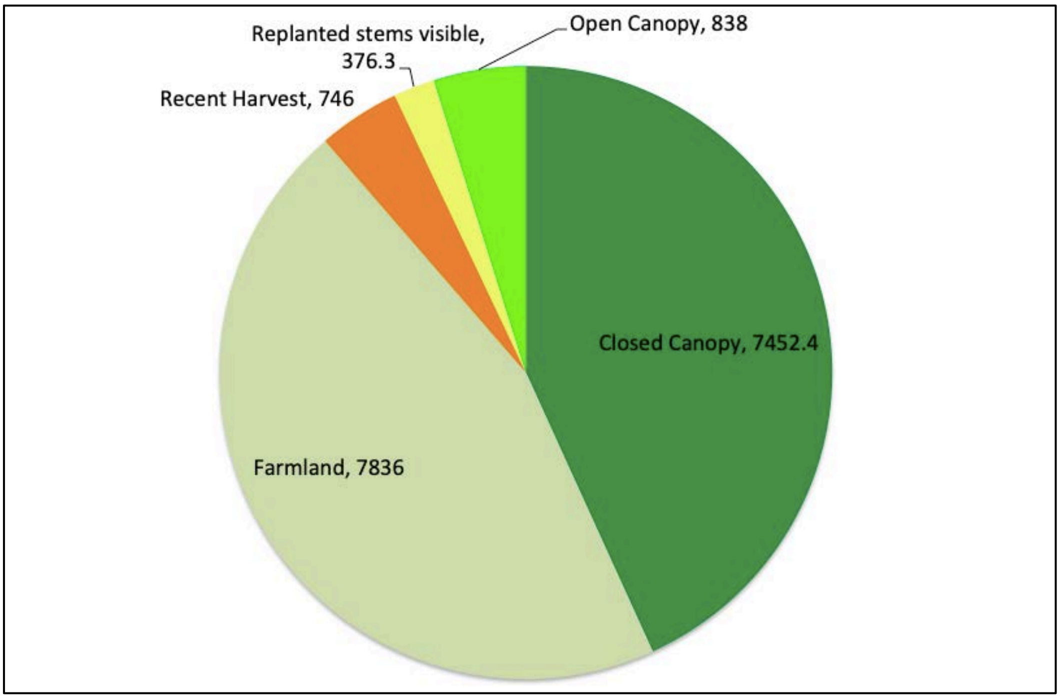

Figure. Seven. *Landuse within the study area (17,250ha)*

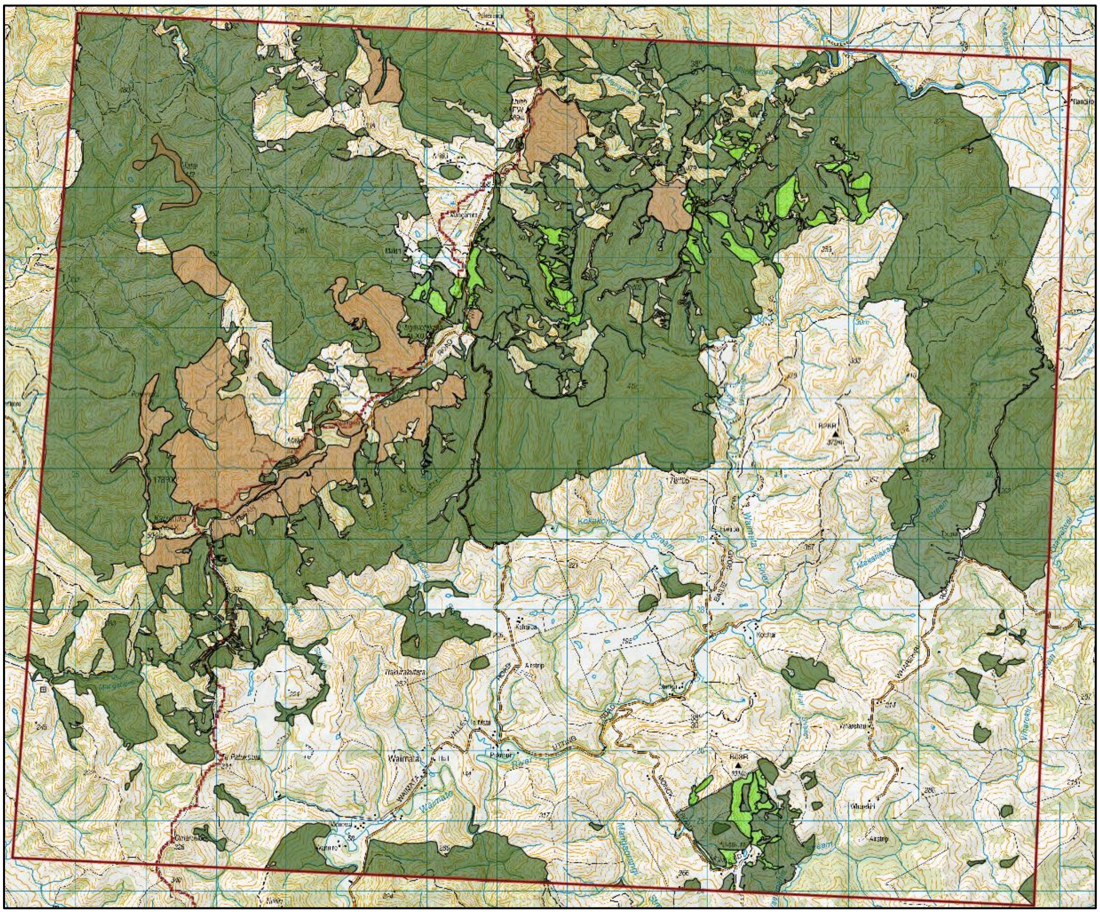

Figure Eight. *Map showing the various land uses within the study area.*

The number and area of landslides

Once these land use categories were determined, it was then possible to calculate the overall number and the area of slips occurring within each land use class. As shown in **Table Two** and **Figure Nine** below, the largest area of landsliding occurred in closed canopy forest at 13.8 ha. This was initially unexpected but re-examination of the data confirmed the result. The second highest area of landsliding occurred in areas of recent harvest at 12.5 ha which was more aligned with the helicopter and field inspections carried out prior to initiating this study. Notably, farmland, open canopy forest and replanted forest with stems visible in the satellite imagery had significantly lower areas affected by landsliding since the 2017-2018 summer aerial imagery (**Table Two**).

Land use	Area	Ha
Closed canopy forest	7452.4	13.8
Recently Harvested	746	12.5
Farmland	7836	1.7
Open canopy	838	1.7
Replant stems visible	376.3	1.2

Table Two. *Area of landsliding by landuse.*

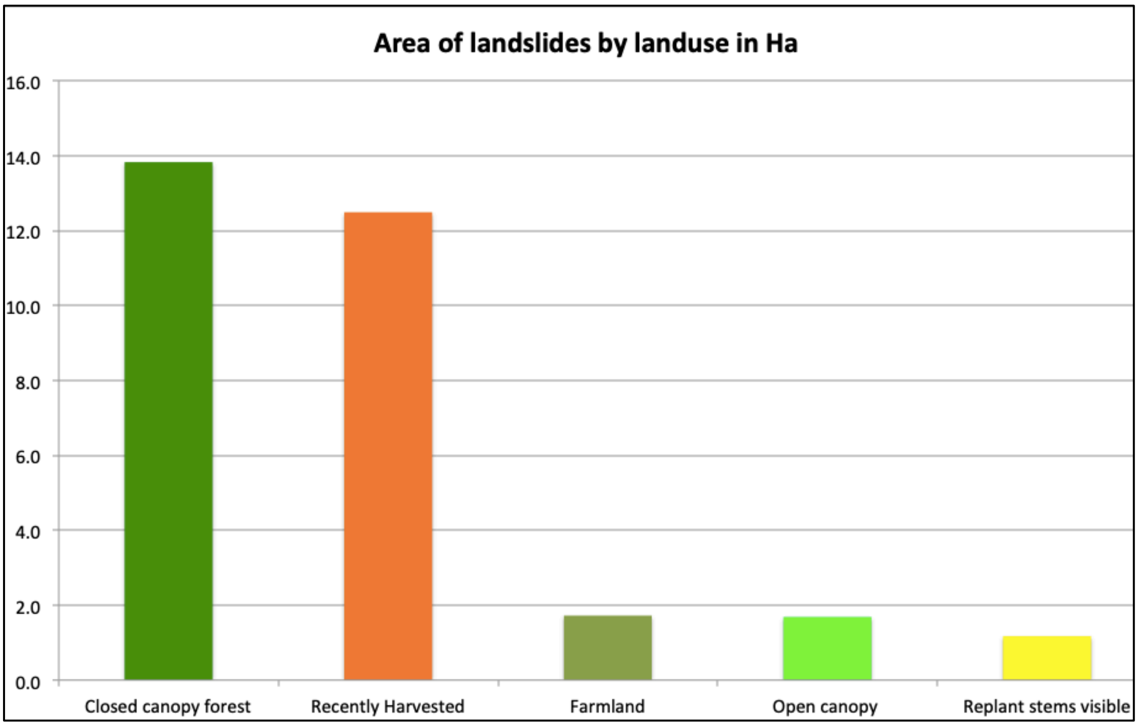

Figure Nine. *Area affected by landsliding by landuse.*

A similar story is revealed when the number of landslides by land class is analysed. As before the largest number of slips occurs in recently harvested areas (264) and closed canopy forest (131 slips) while farmland (76), open canopy (33) and replanted with stems available (25 slips) are an order of magnitude less (**Table Three** and **Figure Ten**).

Land use	No of slips
Closed canopy forest	131
Recently Harvested	264
Farmland	76
Open canopy pine	33
Replant stems visible	25

Table Three. *Number of landslides by land use.*

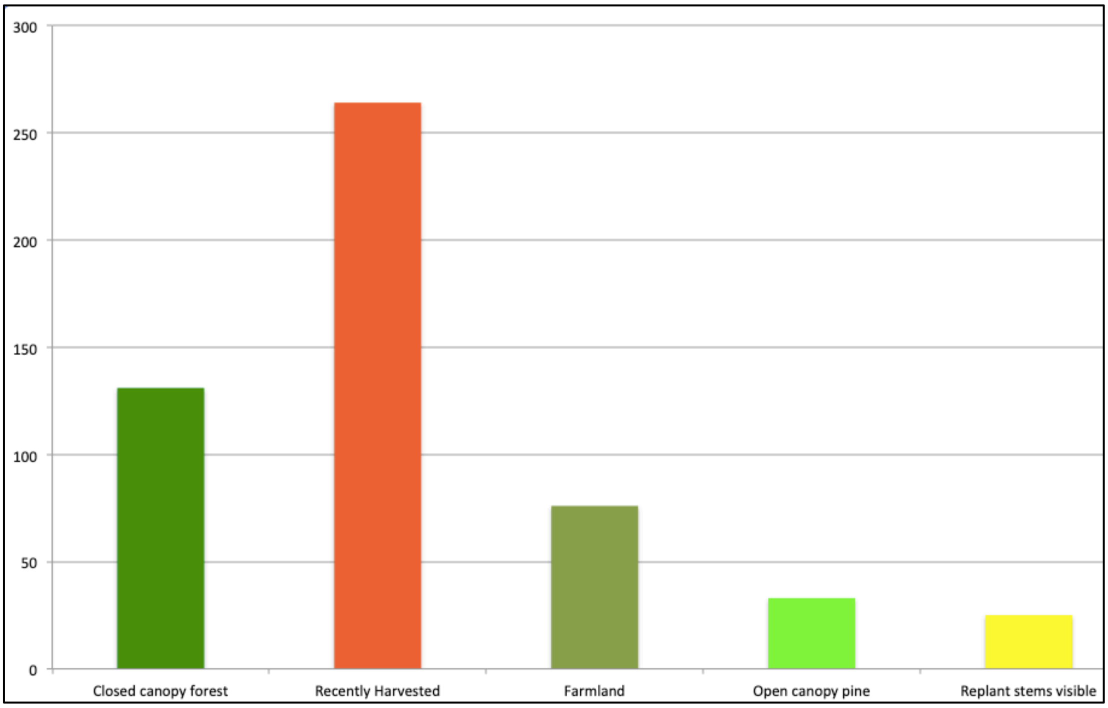

Figure Ten. *Number of landslides by land use.*

Overall, it is clear that the largest number and area of landslides occurred in closed canopy forest and recently harvested forest. The area affected by landsliding in these two land use classes is similar at 13.8 ha for closed canopy and 12.5ha for recently harvested areas. It may seem counter intuitive that the greatest area occurred in closed canopy forest but closed canopy forest as a land use occupies around 10 times the area of recent harvested. Proportionally, therefore the area of landslides in recent harvested land is around 9 times that of closed canopy forest.

Similarly, the number and area of landslides in the remaining three land use classes are an order of magnitude less than for closed canopy and recently harvested forest. The number of landslides occurring in farmland is nearly twice that of open canopy and replanted forest with stems visible but by area farmland and open canopy were the same. The total area of farmland is, however, over 9 times the area of open canopy forest thus with only 1.7ha of 7836ha of farmland affected by landslides, it is evident that farmland experienced only minor landslide effects compared with the other land use classes (see **Figure Eleven**).

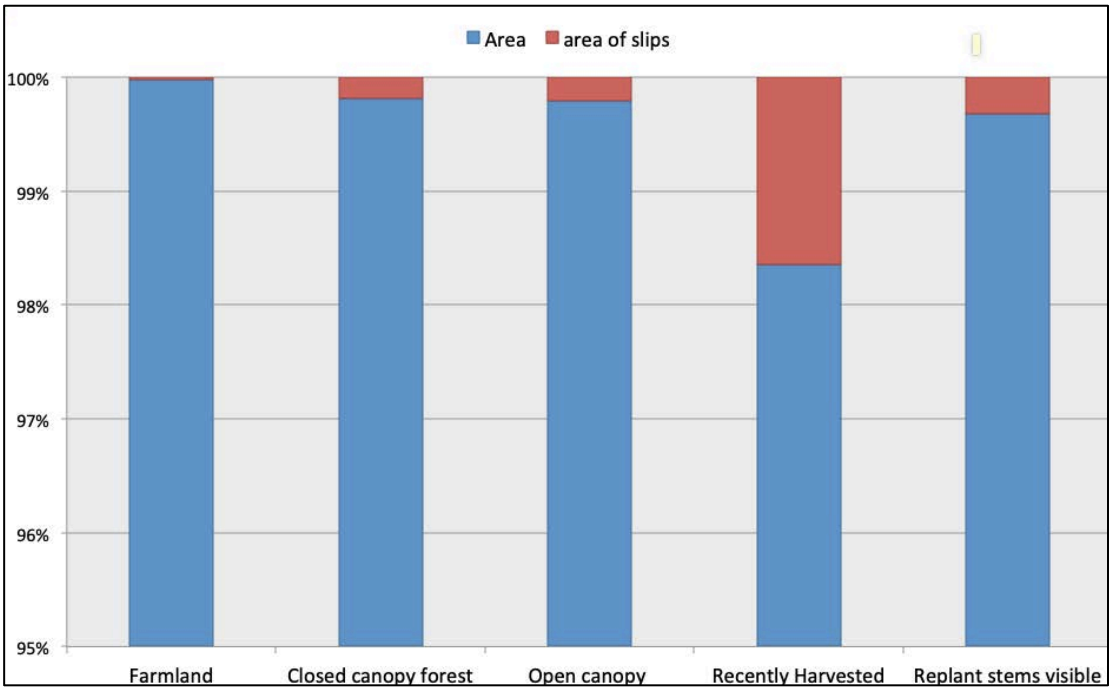

Figure Eleven. *Area of landslides by area of land use that graphically shows the significance of landslide activity in recently harvested forest compared with other land classes (Note, only that the y axis starts at 95%).*

The spatial distribution of landslides

The majority of the landslides occurred at the crest of the Waimata catchment with the majority occurring on the Waimata side of a the crest and somewhat less on the western side in the upper Waipaoa Catchment (**Figure Twelve**). The relationship between landslide distribution and the 24 hour rainfall for the 11th to 12th June is shown in **Figure Thirteen** which shows that the more landslides occurred in the 50mm rainfall band than occurred in the 100mm rainfall band (see Cave 2018b).

The relationship between the landslide distribution and geology is shown in **Figure Fourteen** below. This indicates that the majority of landslides were underlain by undifferentiated fossiliferous north-west dipping mudstones and sandstones of early Pliocene Age. Additionally, the majority occur along the Arakihi fault, although this is not known to be an active feature.

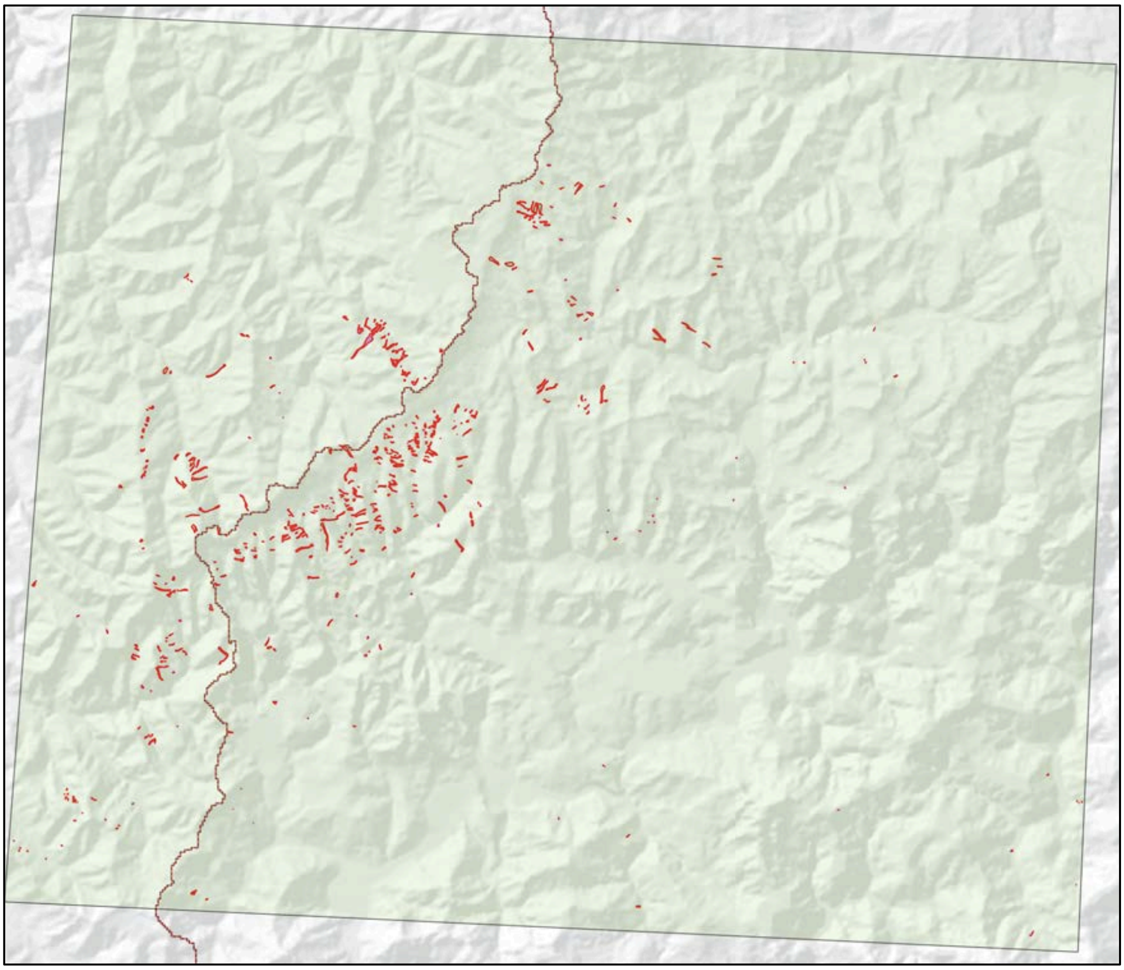

Figure Twelve. *Spatial distribution of landslides within the study area. The boundary between the Waimata (east) and Waipaoa catchment (west). See Appendix One.*

The land use classification (LUC) is underpinned by geology, particularly rock type, but also takes into account soil, slope angle, erosion type and severity, and vegetation cover (Lynn et al, 2009). With respect to forestry the National Environmental Standard for Plantation Forestry has used LUC to aggregate land into 4 zones based on an erosion susceptibility;

a) Very High (Red Zone),

b) High (Orange Zone),

c) Moderate (Yellow Zone), and

d) Low (Green Zone).

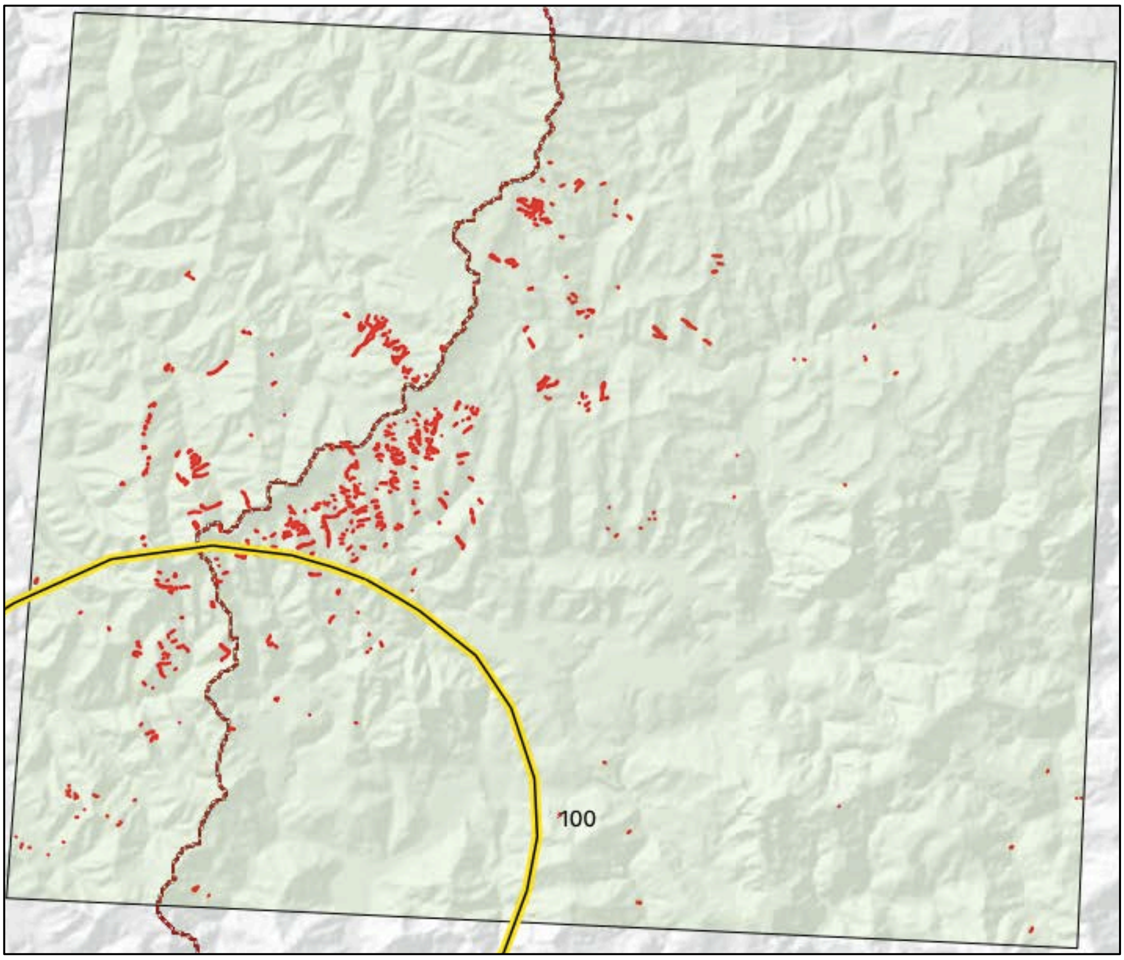

Figure Thirteen. *The study area showing landslide distribution relative to the 100mm isoheyt.*

These 4 classes are shown in **Figure Fifteen** below. Not surprisingly, a large number of landslides occurred on red zone land which has a very high erosion susceptibility, but more significantly, a larger number have occurred on yellow zone land which has moderate erosion susceptibility or where streams had their heads on yellow zoned land.

Comparing landslide distribution with topography suggests that a greater proportion of slope failures occurred on north-east to east facing slopes rather than on south or west facing slopes. For the Makiri Forest the majority of landslides originate at the boundary of the yellow and red zones and occur on north-east slopes. For the Wakaroa Forest around 75% of landslides are on north-east to east facing slopes (**Figures Sixteen** and **Seventeen**).

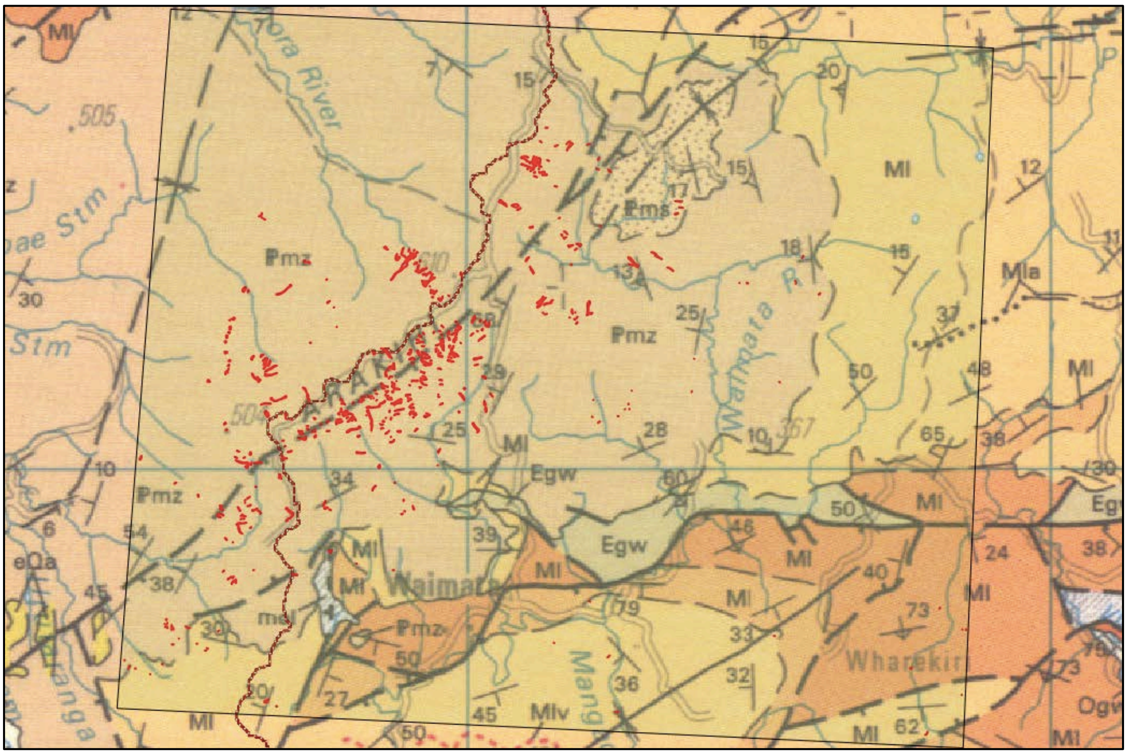

Figure Fourteen. *Distribution of landslides and underlying geology.*

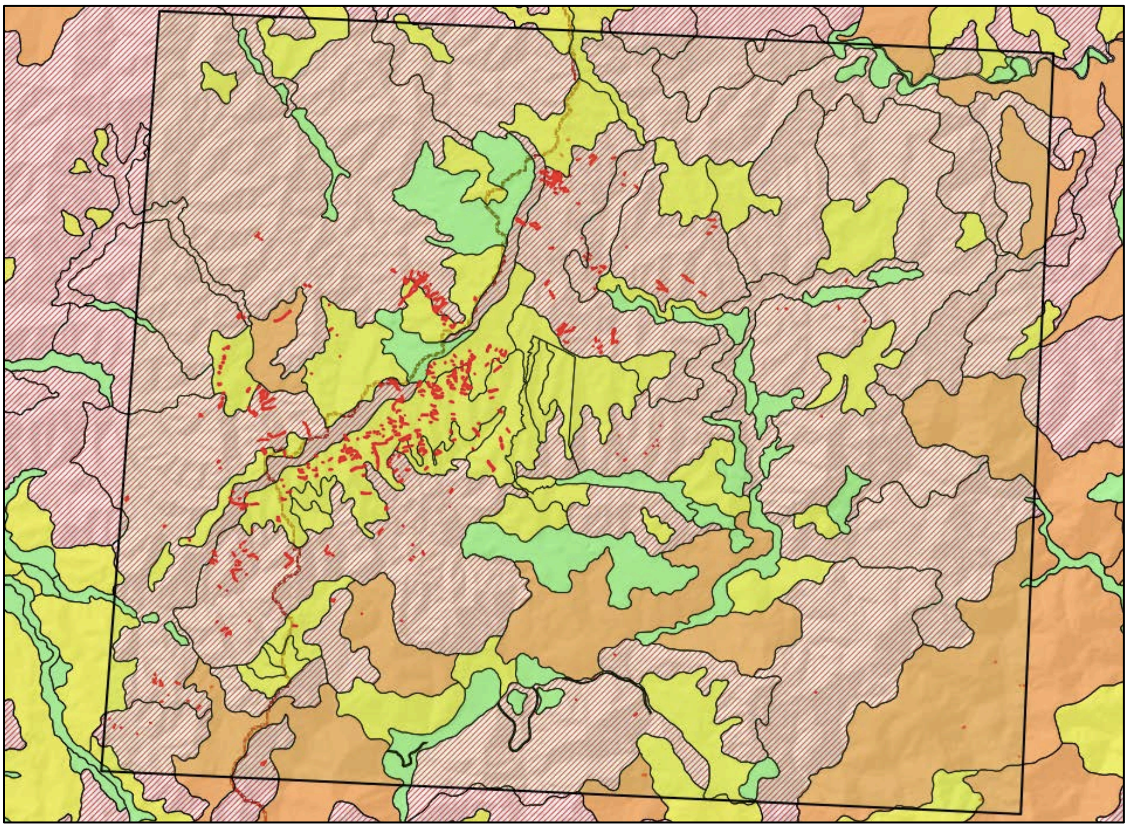

Figure Fifteen. *Distribution of landslides according to NES-PF red (very high erosion susceptibility), orange, yellow and green (Low erosion susceptibility) zones.*

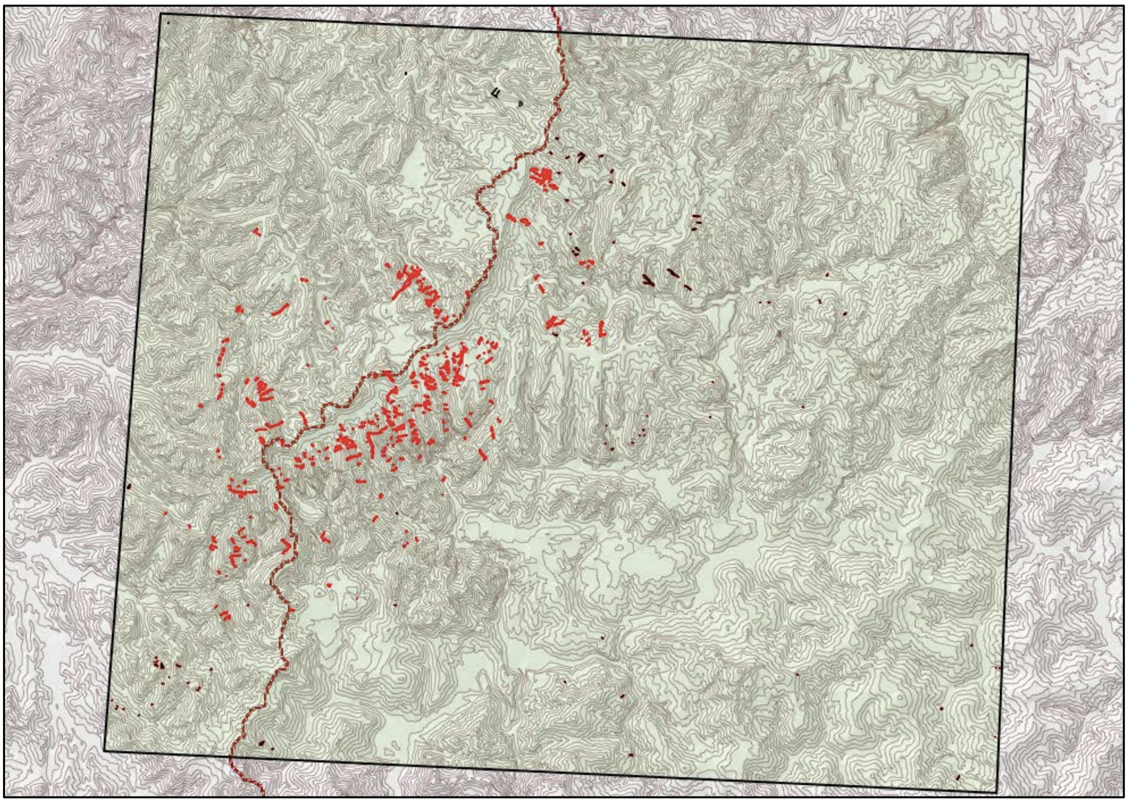

Figure Sixteen. *Landslide distribution compared with topography.*

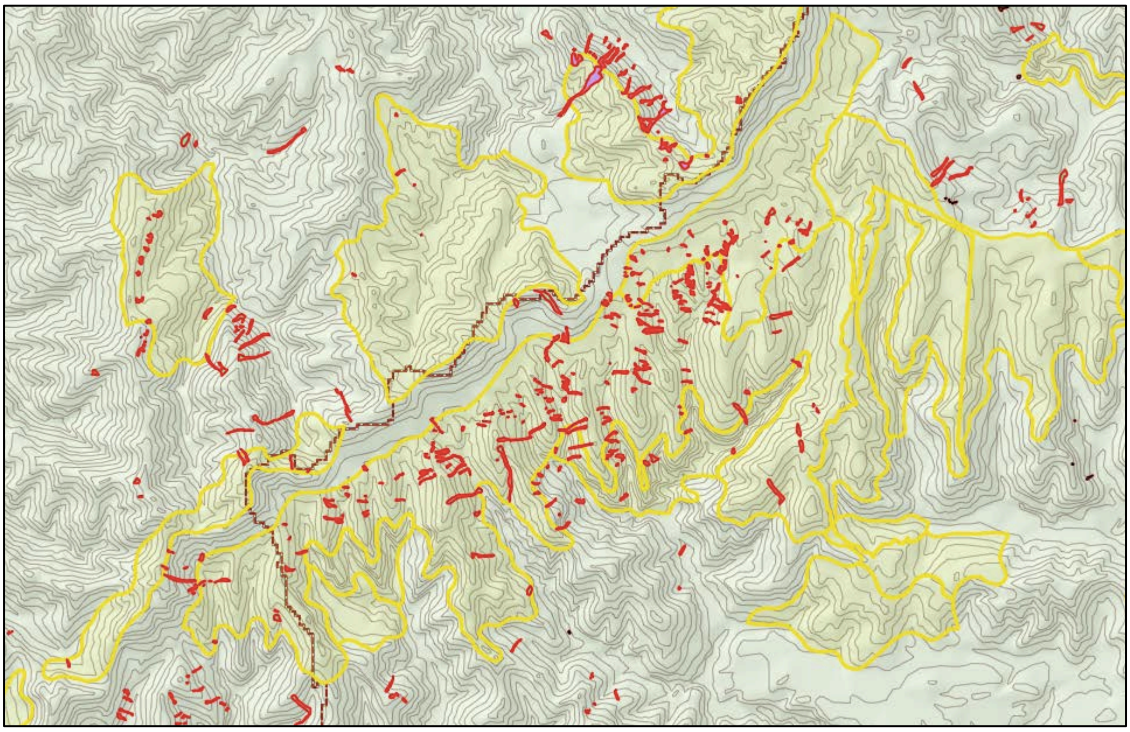

Figure Seventeen. *Detail of the area of greatest Landslide density compared with topography within the yellow zone. For the Makiri Forest the majority of landslides originate at the boundary of the yellow and red zones and occur on north-east slopes. For the Wakaroa Forest around 75% of landslides are on north-east to east facing slopes.*

Part Two Landslide Types and Mechanisms

Types of landslides

There are a number of classification systems for landslides but the most commonly used classification is the United States Geological Survey (USGS) (**Figure Eighteen, Table Four**). These are idealised end points and many landslides may combine elements from each type; for example, the toe of a rotational or translational slide may resemble or generate an earthflow.

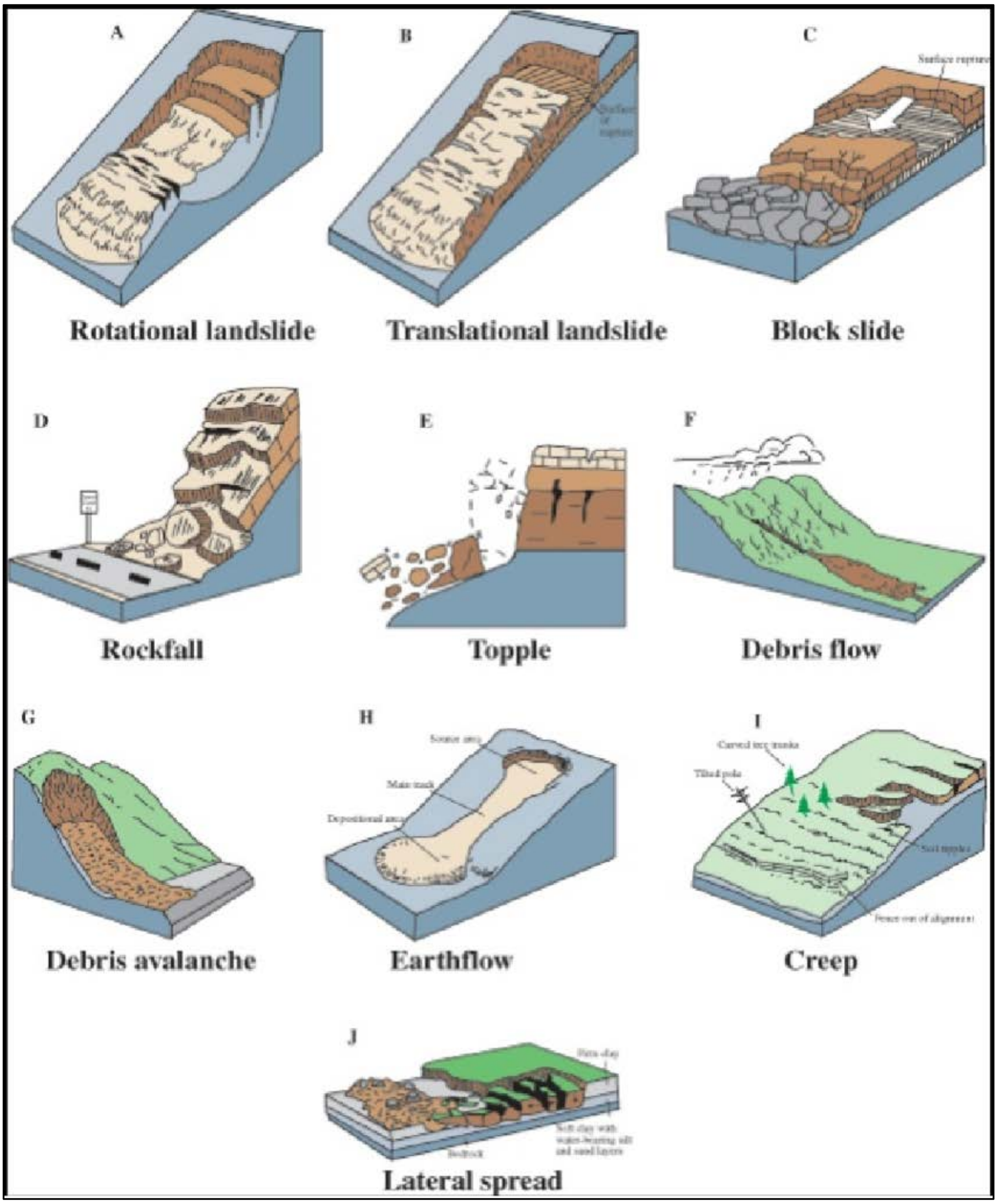

Figure Eighteen. *Types of landslides based on the mechanism of movement and the substrate involved (rock vs. soil).*

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow (deep creep)	Debris flow (soil creep)	Earth flow
COMPLEX		Combination of two or more principal types of movement		

Table Four. *Relationship between the types of movement within landslides and the types of materials involved (Varnes 1978).*

In the context of this study, the site investigations associated with the spatial analysis indicates that three main types of failure occurred; translational debris and earth slides (**Figure Nineteen**), debris flows (**Figure Twenty**), and debris falls and avalanches (**Figure Twenty One**).

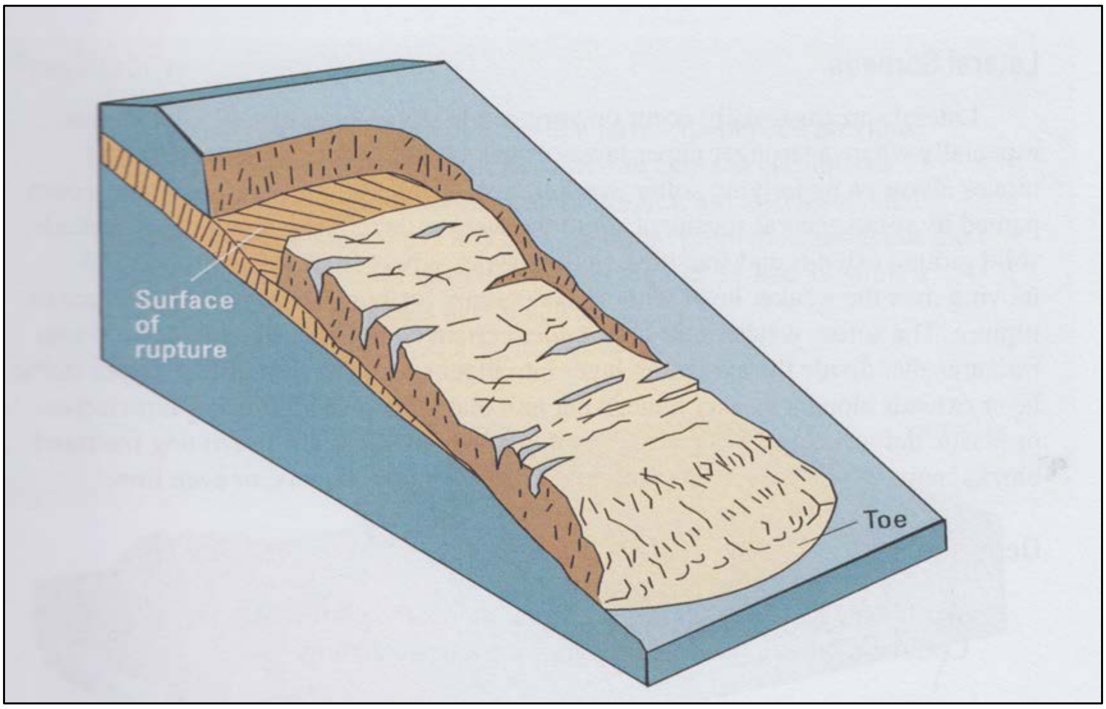

Figure Nineteen. *Translational debris/earth slide. These are landslides that move along a planar surface with little or no rotational movement or backward tilting. Such landslides can move over significant distances if the rupture surface is sufficiently steep. Such landslides commonly fail along geological discontinuities such as faults, joints, bedding planes or dip surfaces, or along the contact between rock and soil.*

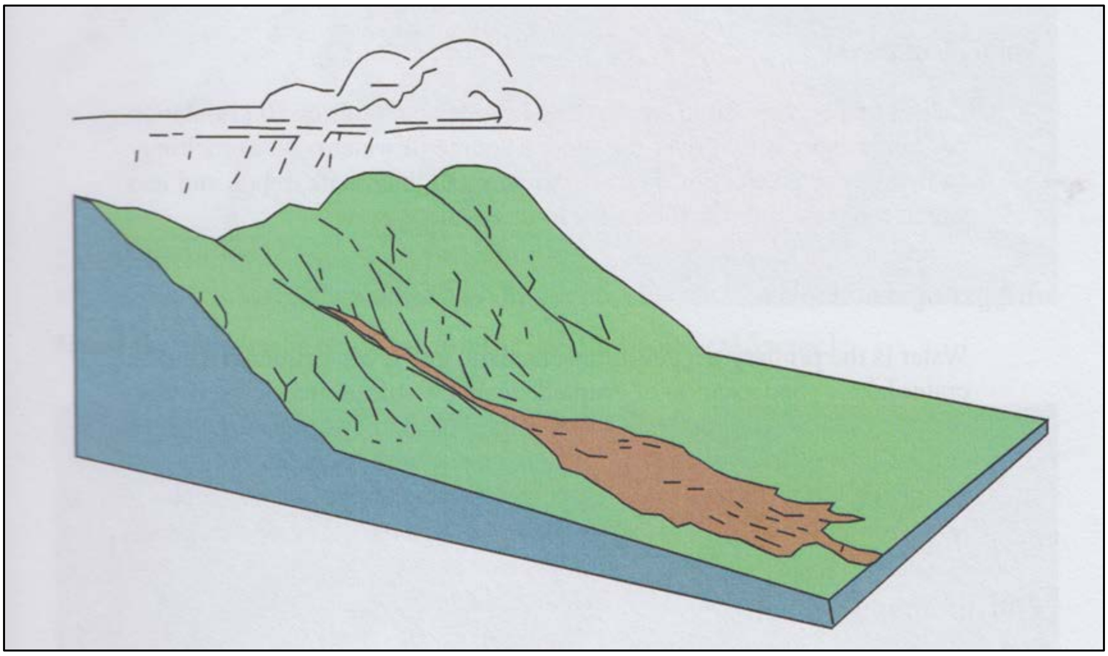

Figure Twenty. *Debris Flow. These are landslides that are characterised by rapid mass movement in which loose soil, rock and sometimes organic material combine with water to form a slurry that flows downhill. Occasionally, as a translational landslide gains velocity and the internal mass loses cohesion or gains water, it may evolve into a debris flow.*

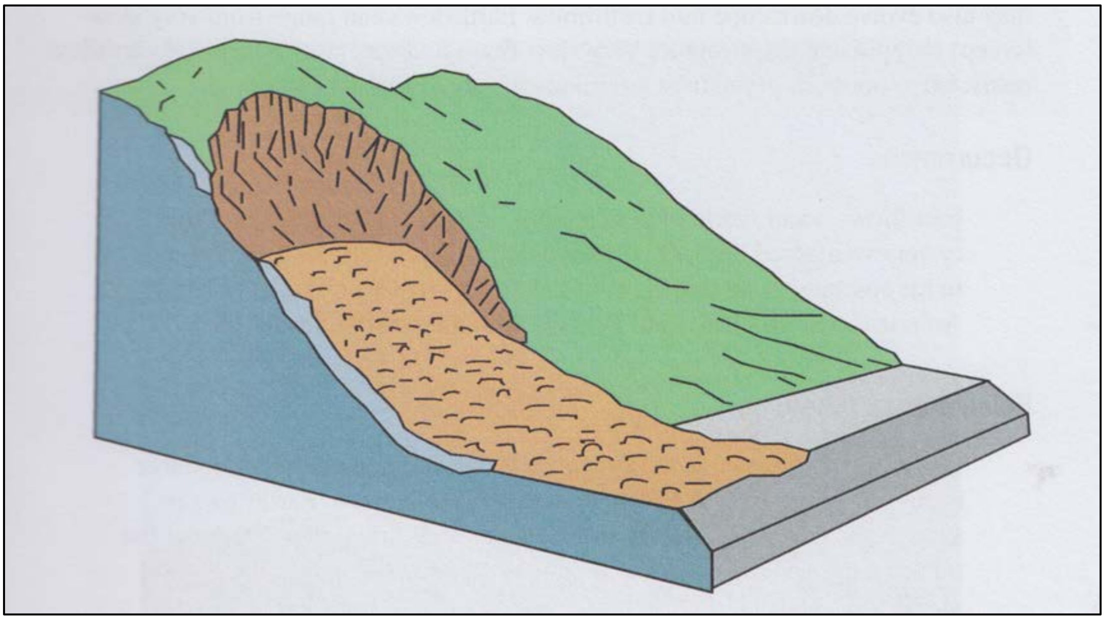

Figure Twenty One. *Debris falls or avalanches. These are typically large scale landslides that move rapidly and behave similarly to debris flows but can carry large sized material.*

Landslides are typically, but not always, caused by water saturation of slope materials. Saturation can result from heavy rainfall, ground-water level changes and surface-water level changes along riverbanks. Flooding can cause landslides by undercutting the toe of slopes and overland flow of water on slopes may result in the failure of slopes above streams. The particular cause of any one landslide may be indeterminable and it is the repetition of the type of failure that is the best guide to the cause of landslide events during a storm event.

The problem with mid slope failures

A particular type of landslide referred to as a mid slope failures have been cited frequently in discussions with respect to the events of June 2018 and other storm events affecting forested land. Despite the frequent reference to the term, the significance of mid slope failures is uncertain. A discussion about debris flows in the August 2015 edition of Timber Talk published by the Eastland Wood Council appears to typify what is understood by the term mid slope failure;

"Unless created directly from a failure in road or skid site infrastructure (which was not the case in the recent events south of Gisborne), most debris flows are not initiated from lots of slash left in streams. The initiation is almost always a small slope failure somewhere between two thirds to near the top of a hill slope." And

"Recent storm events have not caused any failures of engineering structures such as roads or skid sites. Debris flows have come from small slips on the hillside usually only a few meters wide. Their location is quite unpredictable."

There is, however, little scientific research to confirm the basic tenor of the statements above; that initiation is almost always a small failure somewhere between two thirds to near the top of a hill slope, and that their location is quite unpredictable.

A search of the international literature found few references to mid slope failures. It is not, for example, referenced in the benchmark publication (Turner and Schuster 1996). Guthrie and Evans (2004), noted with respect to a landslide event in Loughborough Inlet that;

"Spatially, the landslides initiate on slopes between about 30° and 45° (typically midslope) and, in coastal British Columbia at least, tend to continue downslope to the valley floor".

Aipassa (1991) discussed a series of landslides in Japan and noted;

"*As it was expected, proximity to stream channels proved to be an important variable. They were associated with both more frequent and larger slope surface failure. Sixty-one per cent of the slope surface failure occurred contiguous to stream channels,* ***twenty three per cent were found in midslope****, and only sixteen per cent were in the upper slope. It was suggested that the stream channel accelerates the growth of slope surface failure by undercutting the foot of the slope. The slope sites adjacent or contact to the stream channel might be also subject to higher pore pressures and seepage forces.*

Aipassa concluded that;

"*The sloping sites adjacent or contacting with the stream channels, however, were the sites most prone to sliding. Stream channels might accelerate the growth of surface slide by undercutting the foot of the slope."*

Mid slope failures are cited in a small number of New Zealand papers. Korup (2006) referencing large scale land sliding in the Southern Alps noted;

"About 70% of the large landslides appear to be either presently inactive or extremely

slow moving. API (Air Photo Interpretation) shows well-developed multiple tension cracks, lateral scarps along plunging ridge lines, differential slope deformation, and bulging mid- to toe-slopes indicating partly detached rock masses."

Phillips *et. al.* (1996) discussed forestry related landsliding in the Marlborough Sounds and noted;

"Excluding road-related failures, eight landslides occurred in the cutover during the November storm, mostly in the areas which had been logged first. All occurred below 200 m elevation on steep (often over 30°), upper or mid-slope gully depressions, in stony, silty-clay loam". And;

"The cutover did not appear to be visibly damaged by the rain storm other than in those few mid-slope localities where land-slides occurred." Finally Phillips et al (1996) noted; "Most of the landslides were not related to logging-road construction, but were initiated in upper-slope or mid-slope gully depressions generally on slopes over 30°."

Ballie and Evanson (2014) described an extreme weather event in eastern Bay of Plenty that occurred in 2011 and citing an unpublished Hancock Forest Management report noted that;

"*The event caused widespread flooding, damage to roads and other infrastructure and extensive mid-slope failure and gully erosion."*

Douglas et. al. (2011) describes the same storm and figures a typical mid slope failure in the Whakatane catchment (see **Figure Twenty Two** below) noting;

"The natural loss of the soil from the slopes as a result of erosion has affected many aquatic ecosystems through deposition into once pristine ecological areas. It must be noted however that this mid slope failure has been attributed to extremely heavy rainfall and similar soil loss was more serious in adjoining pastoral areas with similar soil types and slopes where extreme rainfall events had occurred."

Photo 1 in Douglas *ET. al.* (2011) is useful in that it is the only instance in the technical literature that graphically shows what has been considered mid slope failure. Many of the landslides shown below, however, do not demonstrate an obvious mid slope origin with many originating at landings or other infrastructure to the ridgeline while others are more likely to be the result of toe failure.

Accordingly, a search of the many photographs taken during the Queens Birthday storm investigation to locate examples which better fit the description of a landslide triggered mid slope. A number of examples, particularly from farmland were found and a typical example is shown in **Figure Twenty Three**. Key features of mid slope failures are a lack of association with ridgeline infrastructure or toe undercutting by streams.

Photo 1: Typical mid slope failure in the lower Whakatane catchment which has light volcanic soils known as Kaharoa ash over lapilli.

Figure Twenty Two. *Reproduction of Photo 1 from Douglas et al (2011) showing what is described as mid slope failure but also showing significant toe and ridgeline failures associated with infrastructure.*

Figure Twenty Three. *Example of mid slope landslides on farmland, Te Arai Valley, July 2018. Mid slopes can be identified by the lack of connection to either streams at the toe or infrastructure on ridgelines (Photo GNS).*

Characteristic features of landslides in the Upper Waimata

Closed Canopy landslides Wakaroa Forest

The type of landslide activity arising from the June 2018 storms in closed canopy forest is shown in the satellite imagery below (**Figure Twenty Four**) and detailed in the following figures.

Figure Twenty Four*. Typical closed canopy landslide activity visible in the August 2018 satellite imagery and not present in the 2017-18 aerial imagery, northern Wakaroa Forest. The landslides are typified by being full ridgetop to valley floor and generally originate from roadways for forestry landings.*

The landslides at the western end of **Figure Twenty Four** are shown in **Figure Twenty Five** below. This shows three landslides originating at a forestry roadway while another occurs at the end of an old skid site. One further landslide may perhaps be classed as a mid slope failure as the headwall is not connected with the roadway above. The toe of this landslide is at river level downstream of the other landslides, however, and a toe failure is more likely.

Landslides at the eastern end of **Figure Twenty Four** are shown in **Figure Twenty Six** below. There are a number of small slips occurring on the middle of slopes below a ridgeline disconnected with any infrastructure. The most significant landslide, however, is clearly associated with the collapse of a skid site

Figure Twenty Five. *Landslides in closed canopy forest associated with forestry roads.*

Figure Twenty Six*. Minor midslope failures below a ridgeline (left) and a significant landslide resulting from the collapse of a forestry landing.*

A largely closed canopy debris flow failure has been examined in some detail at Site 3 (GDC reference) on Woolshed Road (**Figure Twenty Seven**). This landslide is described in some detail in Cave (2018c) which noted the role of poor drainage design and loading of the landing edge as causes of the failure.

Figure Twenty Seven. *Composite image (drone video screenshots) of the western side of Site Two debris flow from the headscarp to the toe of the slope in a deeply incised gorge in a tributary of Mangahouku Stream.*

Recent harvest landslides Wakaroa and Makiri Forests

The landslide activity arising from the June 2018 storms in recently harvested forest were typically debris flows originating from skid sites, forestry roadways or as a result of toe failure. This area was extensively assessed on the ground as well as by drone and helicopter(**Figure Twenty Eight**). This figure shows a series of landing collapses in Makiri Forest and **Figure Twenty Nine** shows the on-ground down-slope view of the eastern side of the failure at Landing 8 shown in the top of **Figure Twenty Eight**.

Figure Twenty Eight. *Satellite imagery August 2018 showing the post-storm event landslide activity with failures occurring at roadways and landings. The landing collapse at top (Landing 8) is shown in **Figure Twenty Nine** below.*

Figure Twenty Nine. *Photo of the landing collapse shown at the top of **Figure Twenty Seven**. The landing collapse has generated a debris flow with an obvious levee on the righthand side.*

A series of satellite images have been used to further assess the slope failures at Landing 8 in Makiri Forest. The site was being actively used in August 2017 and Figure Thirty shows the shape of the landing and the activity underway at 17th August 2017.

A further satellite image of Landing 8 is available for the 17th of May 2017 shortly before the Queens Birthday storms. By this stage operations at the site had been completed but notably the obvious right angle bend noted in **Figure Thirty** is absent. Also notable is the presence of significant harvest residues and some a failure of the edge of the landing on the north eastern side of the landing (**Figure Thirty One**).

Satellite imagery is also available from shortly after the Queens Birthday storms (13th July 2018) showing the changes that occurred at Landing 8 since May 2018 (**Figure Thirty Two**). This shows a pronounced tension crack at the northern end of the south western side of the landing and a more extensive failure of the landing on the north eastern side (see also Figure **Twenty Nine**) but any changes to the south western edge are otherwise subtle at the scale shown in the imagery.

Figure Thirty. *View of Landing 8 in Makiri Forest dated 17th August 2017. A key feature of this image is the right angle bend on the south western edge of the landing (arrowed) along with the confined state of the landing with logs stacked along both the south western and north eastern edge of the landing.*

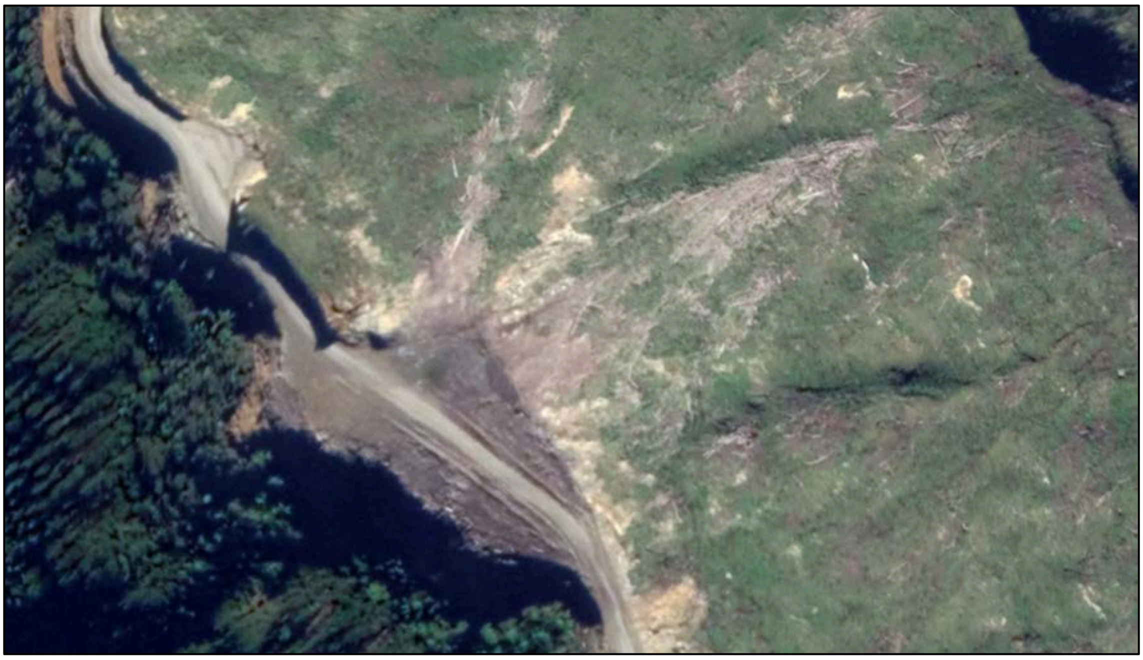

Figure Thirty One. *View of landing 8 Makiri Forest dated 17th May 2018 showing the change in edge shape on the southern western side, and the harvest waste and landing collapse on the north eastern side.*

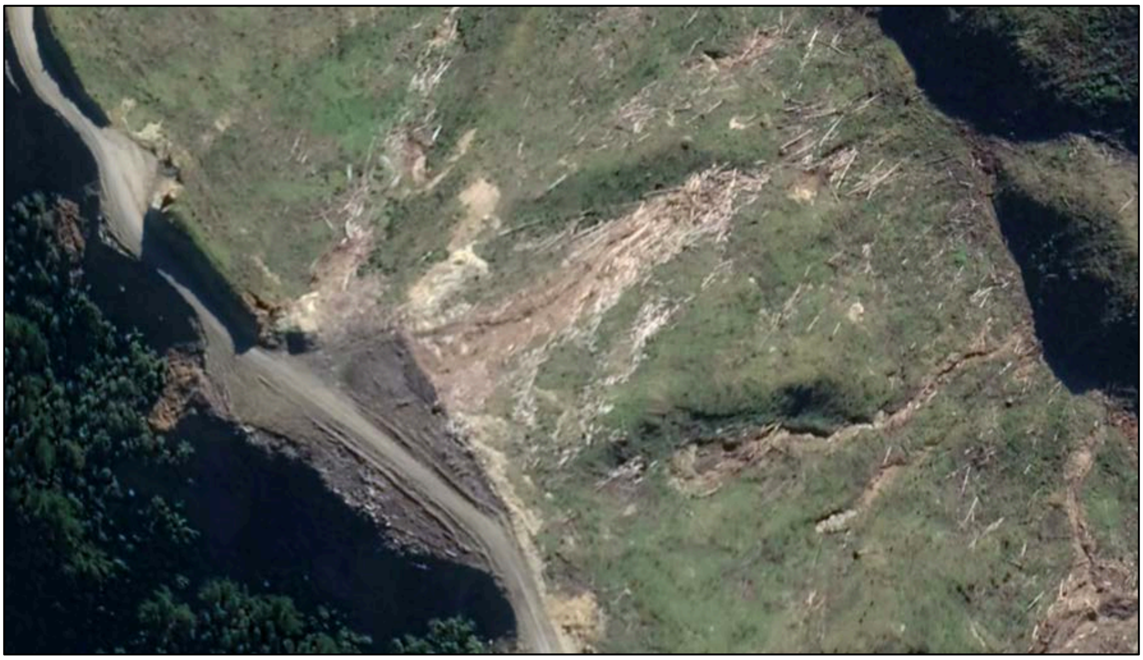

Figure Thirty Two. *View of landing 8 Makiri Forest dated 13th June 2018 showing only subtle changes in edge shape on the southern western side, and the more extensive harvest waste and landing collapse on the north eastern side.*

To further assess the level of change particularly the south western edge of Landing 8, the satellite imagery cited above was analysed in greater detail. As the satellites have slightly different paths and acquisition altitudes it is necessary to use readily identifiable features present in each image for calibration.

The edge of the landing was digitised for each satellite image and then overlain in the GIS and adjusted so that the features in common in each image merged. This then allowed for the changes in the position of the landing edge to be measured.

The change between 17th August 2017 and the 17th May 2018 is shown in **Figure Thirty Three A** and shows that the edge of the landing had been extended out by around 10 metres at some stage between August 2017 and May 2018. Since the underlying aerial image with the roading is dated at 12th December 2017 and shows harvest residues sitting on the slope inside the May 2018 edge, it indicates that the landing was extended out over the harvest residues over that time. Construction of an extension of the landing out over harvest waste is significant as this would have minimal long term stability.

The change between the 17th of May 2018 and the 13th of July 2018 is shown in **Figure Thirty Three B**. This shows that the edge of the landing has retreated by an average 4.9 metres between May and July 2018.

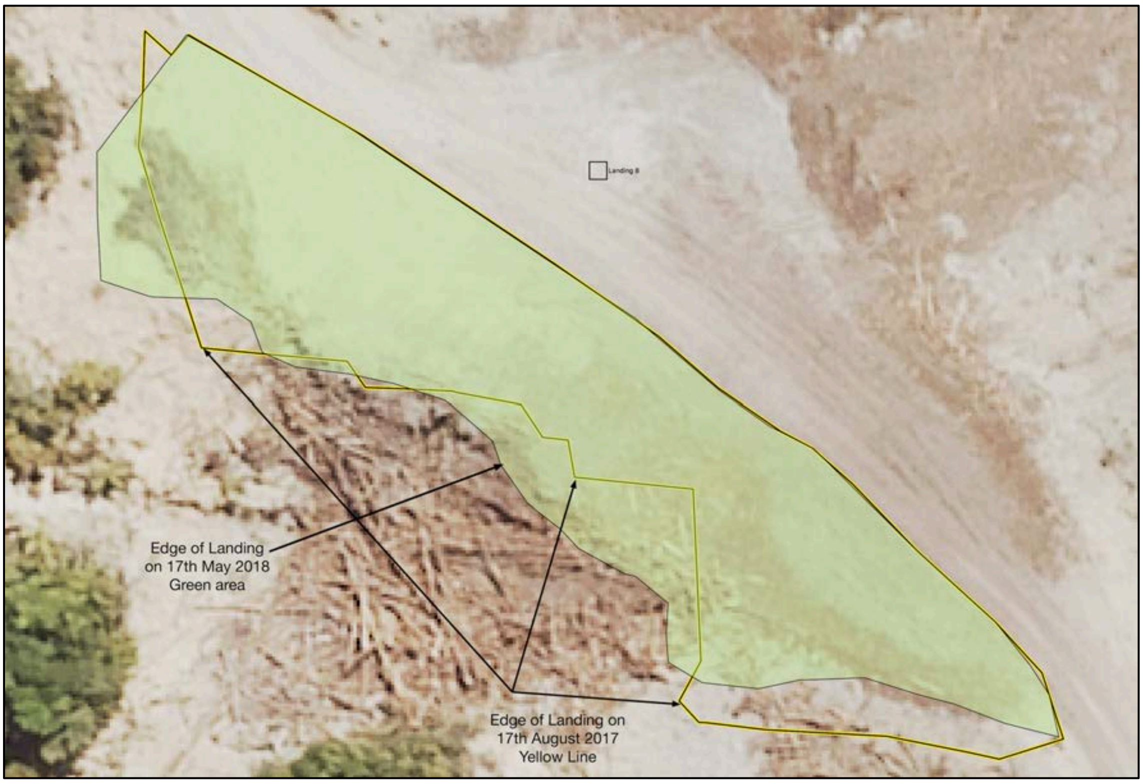

***Figure Thirty Three A**. The digitised edge of Landing 8 dated 17th of August 2017 (yellow) compared with the landing edge on the 17th of May 2018 showing where the landing has been extended out over harvest waste (green).*

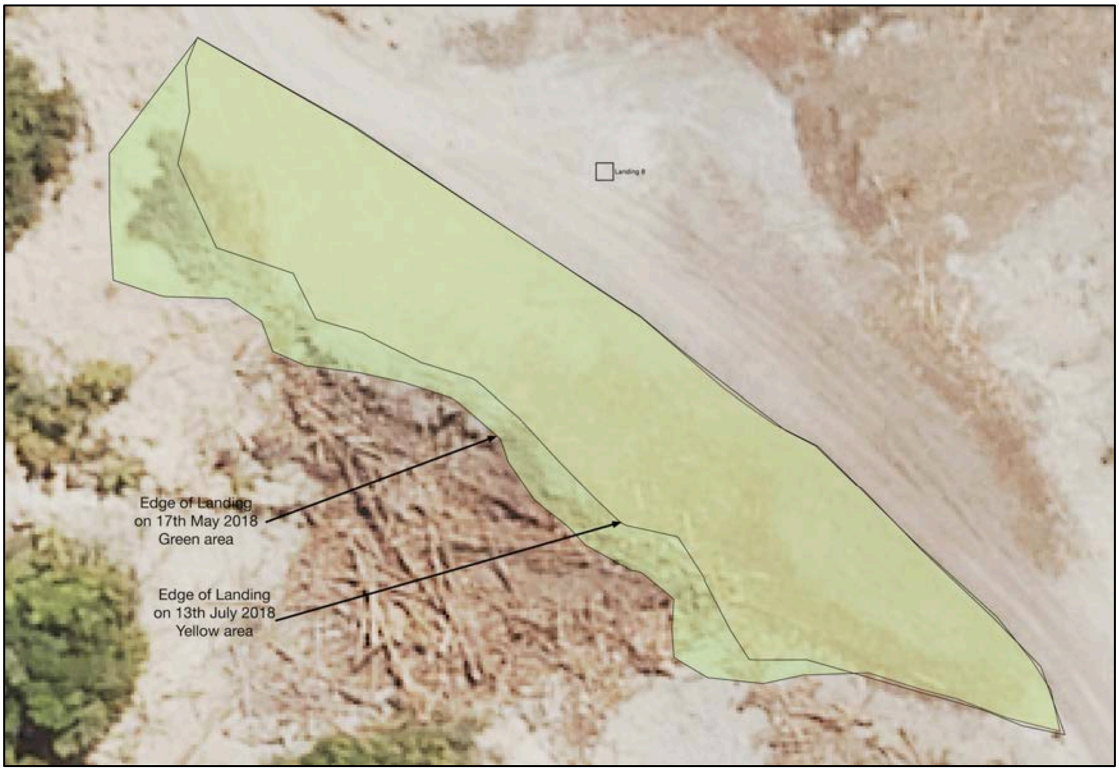

***Figure Thirty Three B**. The digitised edge of Landing 8 dated 17th of May 2018 (green) compared with the landing edge on the 313th of July 2018 (pale yellow) showing that the landing has retreated by an average of 5 metres.*

The Wakaroa forest has also been intensively studied on the ground and from the air by drone and helicopter since the June 2018 events and are described in detail in Cave (2018c). **Figure Thirty Four** below shows Site 3 on Woolshed Road (GDC site numbering).

***Figure Thirty Four.** Landslide activity at site 3 Woolshed road, Wakaroa Forest showing a translational landslide (left hand side) in full canopy forest resulting from a birdsnest collapse while the right hand side shows a debris flow that resulted from water being directed from the landing across sidecast material.*

On the right hand side of **Figure Thirty Four** is a translational landslide occurring in full canopy forest and caused by the collapse of the slash birdsnest that had been stowed on the edge of the landing. On the right hand side of **Figure Thirty Four** is a significant debris flow that resulted from drainage channels on the landing directing water onto sidecast material. This debris flow is also shown in **Figure Thirty Five**.

The area in the vicinity of site 11 in Wakaroa Forest is described in detail in Cave (2018c) and is shown in the middle ground of **Figure Thirty Six**. This landing had a large translational landslide resulting from the collapse of a birdsnest stowed on the eastern edge of the landing. This failure then formed a debris flow at its lower end where the initial collapse impacted onto a natural bench.

A feature of this landing was the installation of a longitudinal channel cut through the landing to direct water from the road leading to the landing across the landing. This had the effect of concentrating water on the landing adjacent to a perched birds nest of slash that then failed. **Figure Thirty Six** also shows the nature of the extensive landsliding adjacent to site 11. These are typified by being connected with infrastructure on the ridgelines or with the base of gullies or streams. **Figure Thirty Seven** shows the extensive nature of the scouring within the streambed below Site 11.

Figure Thirty Five. *View of debris flow at site 3, Woolshed Road, Wakaroa Forest*

Figure Thirty Six. *View of Site 11 Wakaroa Forest (Cave 2018c). Evident on this landing is a large grove cut longitudinally from the to to bottom of the landing. This resulted in significant water being concentrated at the birdsnest located on the eastern side of the landing. Note the extensive full slope length landsliding connected to roadways and toe failures. It is most likely that the collapse of the landing and the roadways at middle left exacerbated the effect of high stream flow in the creek downstream resulting in a significant number of toe failures.*

Figure Thirty Seven*. Extensive scouring and toe failures in the creek bed below site 11.*

The impact that poor drainage controls can have on slope stability is well demonstrated in **Figure Thirty Seven** below. This shows an debris flow landslide on Bush Road immediately east of site 11 in Wakaroa Forest.

Figure Thirty Eight. *Landslide resulting from water from a culvert and short sock being discharged onto a steep slope*

Open Canopy landslides Wakaroa Forest

Typical landsliding in open canopy forest is shown in **Figure Thirty Eight** below. These are full slope length debris flows connected to forestry roadways at the top of the slope and the creek bed at the base. The lack of extensive scouring of the creek bed compared with **Figure Thirty Six** suggests that the primary cause of these landslides was water being directed onto vulnerable slopes from inadequate roadway water controls. The on-ground inspections outlined in Cave (2018c) highlighted the lack of adequate water controls on roadways in this forest exacerbated by poor maintenance.

The occurrence of such landslides in open canopy forest is of some significance with respect to how the vulnerability of forested lands to storm-induced slope failures. A five-year post harvest window of vulnerability is commonly cited in the literature with the assumption that the ground cover afforded by growing trees significantly improves the resilience of the slopes to withstand the impacts of overland flow of water. This may be the case where there is no forestry infrastructure above the slope but as was seen in the closed canopy forest, infrastructure such as roadways and landings can result in an increased vulnerability where drainage controls are inadequate or poorly designed and post-harvest landing management leads to excess weight loading of the landing edges.

Figure Thirty Nine. *Full length debris flow landslides in open canopy forest at Wakaroa.*

Landsliding on adjacent farmland

The scale and type of landslides on farmland is typified by **Figures Forty** and **Forty One** below which shows several small earthslide landslides on the slope.

Landslides on farmland were generally smaller than landslides in closed canopy or recently harvested forest land. They were typified by being either originating from midslope locations and no connecting to valley floors or alternatively they originated from farm tracks. Almost all landslides occurring on farmland occurred on red zoned land and were either earth-slides or small debris flows.

There appeared to be a low correlation with rainfall with almost no landslides occurring in the area of highest rainfall. Complicating the analysis of landslides on farmland is the issue of active mud diapirs. The Waimata area has experienced uplift and fracturing in these zones since the September 2016 Te Araroa Earthquake (**Figure Forty Two**) and it is possible that some landslides in the mud diapiric area have been triggered by diapiric uplift.

Figure Forty. *August 25th 2018 Satellite imagery of farmland immediately south of Wakaroa Forest showing typical landslide activity arising from the June storms.*

Figure Forty One. *Typical small-scale earthslide type landslides occurring on farmland immediately south of the Wakaroa Forest. Those in the middle ground appear to have occurred where gullies or swales on the slope above have concentrated overland water flow.*

Figure Forty Two. *Recent landslides within the diapiric zone upper Waimata Valley immediately south of Wakaroa Forest.*

Conclusions

1. Closed canopy forest was the second largest landuse within the study area at 7452 ha (43%) and had the highest area of landsliding at 13.8 ha.
2. The distribution of the closed canopy landslides are poorly correlated with either erosion susceptibility or the area of most intense rainfall. There is, however a good correlation with slope with slopes facing north east or east.
3. A large proportion of the closed canopy landslides were full ridgeline to valley floor translational landslides or debris flows and there was a strong correlation with ridgeline infrastructure, particularly forestry roadways or landings and those failures visited on the ground frequently had poor water controls and failure was strongly associated with harvest residue birds nests stored on the edges of landings.
4. Pastoral farmland (pasture) was the largest landuse in the study area at 7836 ha but had only 1.7 ha of area affected by landslides.
5. The majority of landslides that occurred on farmland were within the erosion susceptibility red zone, and the majority of landslides were not associated with infrastructure or toe failure but occurred as isolated small-scale earthslides occurring on slopes. Some landslides were, however, associated with farm tracks.

6. Recently harvested forest land comprised 746 ha of the study area and had 12.5 ha affected by landslides. While the area affected by landslides is 1 ha less than that for closed canopy forest, the area of recent harvest is only 10% of the area in closed canopy forest. Thus recently harvested forest had proportionally far more land affected by landslides than any other land class.
7. Overall, landslide numbers and area cannot be directly correlated with erosion susceptibility except for those landslides occurring in farmland. Equally the correlation with rainfall is poor with significantly less landslides occurring in the area of highest rainfall. There is a correlation with north and north east facing slopes.
8. The strongest correlations are with proximity to infrastructure, and the main failure mechanisms were debris flow and translational landslides.
9. Satellite images taken between 2017 and July 2018 are valuable and demonstrate that significant change to the edges of landings can be identified as occurring during the June 2018 storms.
10. Except for on farmland where relatively small landslides disconnected with ridgelines and creekbeds, a large number of landslides were generated by failure of forestry landings, particularly as a result of the collapse of birdsnests stored at the edge of landings. The other common correlation is with forestry roadways with poor water controls.
11. Toe failures were also common and there is a possible association of toe failures with locations downstream from landslides originating from landings and roadways. This suggests that the debris flows generated by landings and roadways may have generated floods of debris and sediment charged water that undercut the toe of slopes.

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Appendix One

Figures One, Eight, and Twelve to Seventeen reproduced at a larger size