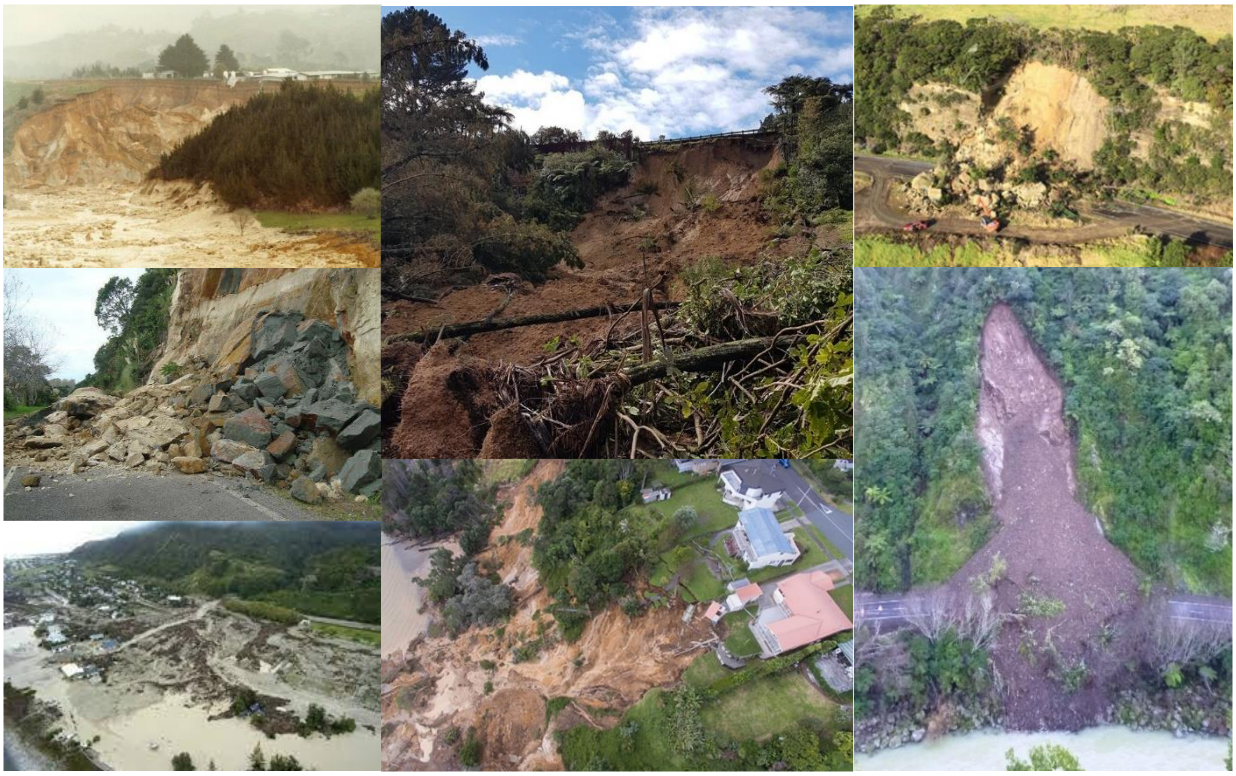
Project Number: 2-9Z696.00

Bay of Plenty Regional Landslide Susceptibility Study

27 February 2024



Technical Report

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Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Bay of Plenty Regional Council ('**Client**') in relation to the assessment and mapping of landslide susceptibility across the Bay of Plenty Region ('**Purpose**') and in accordance with the Short Form Agreement CON000358 (2021 0225). The findings in this Report are based on and are subject to the assumptions specified in the Report and the Contract. WSP accepts no liability whatsoever for any reliance on or use of this Report, in whole or in part, for any use or purpose other than the Purpose or any use or reliance on the Report by any third party.

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This study represents a regional-scale, high level assessment of the susceptibility to landslide hazards across the Bay of Plenty region. This assessment has been completed through a review of desktop information, mapping and photography that was available at this time. It is not intended to precisely describe landslide hazards or risk at an individual property level. Actual risk for an individual property should be determined through appropriate investigations, analyses and reporting completed by a suitably qualified and experienced geo-professional.

Cover image references

Top left. https://view.taurangaheritagecollection.co.nz/objects/24780/print-photographic-ruahihi-power-station
Middle left: https://www.sunlive.co.nz/news/71305-unstable-rock-fall-closes-road.html Accessed 12/08/2022
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Executive Summary

The Bay of Plenty region includes significant areas of steep hilly terrain underlain by a variety of materials that are prone to landsliding. Bay of Plenty Regional Council (BOPRC) has developed a natural hazard programme to deliver the outcomes expected under the natural hazards provisions of the Regional Policy Statement. This includes research to identify and map areas susceptible to natural hazards across the region. This study has been prepared as part of this programme and provides a regional scale assessment of landslide susceptibility consistent with the Regional Policy Statement. The methodology of the study is generally based on the “basic” level assessment described in the Australian Geomechanics Society Guideline for Landslide Susceptibility, Hazard and Risk Zoning (AGS, 2007a).

The study area consists of the Bay of Plenty regional boundary, excluding the Tauranga City district and five other areas where landslide susceptibility studies have previously been carried out or are currently being undertaken. It also includes the part of the Rotorua Lakes District that lies within the Waikato region.

Several data sets were compiled into a singular landslide inventory over the region. Additional landslides were mapped on recent aerial photographs within 12 identified urban areas.

The geology, geomorphology and characteristic mechanisms of landsliding across the study area are described, based on the results of a literature review of available information. Factors that influence slope stability are identified from the results of the literature review, including correlation to an inventory of previous landslides. Assessment of the landslide susceptibility is based on weighting of the influencing factors and combining these in Geographical Information System (GIS) platform using available geospatial datasets.

Four categories of landslide susceptibility are described, from Very Low to High, and these are mapped across the region in GIS showing the spatial distribution and extent of the different susceptibility categories. The maps do not present potential areas of regression and runout of landslide debris, which have not been assessed at this stage. The region was mapped at a 1:50,000 scale, except for urban areas identified by BOPRC, which were mapped at 1:25,000. The maps should be used at appropriate scales suggested, and where made available to the public through the Council natural hazards GIS viewer, the scale should be restricted to 1:25,000 for the 12 identified Urban Areas, and 1:50,000 for the remainder of the region.

Recommendations for follow on actions and future enhancements are provided and include assessment of regression and runout areas which could also be impacted by the failure of steep slopes. It is also proposed that the maps be used in future land use planning, urban growth strategies and plan change proposals and could also be useful for the Council’s infrastructure departments to understand the resilience of the services provided and for planning for civil defence emergency response. Other lifeline authorities would also benefit from the maps to understand the resilience of their infrastructure networks.

Glossary

Term / Acronym	Definition / Meaning
AEP	Annual Exceedance Probability
BOPRC	Bay of Plenty Regional Council
DEM	Digital Elevation Model
Deposition Zone	The area within a landslide where the failure materials accumulate at the base of the slope or where there is a change to a gentler slope
EQC	Earthquake Commission
Failure zone	The area within a landslide where the ground detaches and slides outwards towards the free face
GIS	Geographic Information System, a mapping system to manage and analyse spatial data
GNS	Institute of Geological and Nuclear Sciences
Hazard	AGS (2007a) definition: A condition with the potential for causing an undesirable consequence. The description of landslide hazard should include the location, volume (or area), classification and velocity of the potential landslides and any resultant detached material and the probability of their occurrence within a given period of time.
Hazard Susceptibility Area (HSA)	BOPRC Regional Policy Statement definition: The spatial extent of a potential hazard event identified by susceptibility mapping. In this study, HSA's include land classified as moderate susceptibility and above
Landslide	AGS (2007a) definition: The movement of a mass of rock, debris, or earth (soil) down a slope
Landslide Inventory	AGS (2007a) definition: An inventory of the location, classification, volume, activity and date of occurrence of individual landslides in an area
Landslide Susceptibility	AGS (2007a) definition: A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area
Landslide Terrain	An area of land with similar geological and geomorphological characteristics
LiDAR	Light Detection and Ranging, a remote sensing method that uses lasers to measure the earth's surface
LIM	Land Information Memorandum
Urban Areas	Urban areas (covering existing and potential growth areas) requested by BOPRC to be mapped at 1:25,000 scale.
Regression Zone	The area behind the head scarp of a landslide where the over-steepened scarp face continues to erode and regress over time.
RPS	Bay of Plenty Regional Policy Statement
Runout Zone	The area of a landslide below the slope where the landslide debris and any saturated earth flows run out away from the deposition zone
Terrane	A large scale geological formation, comprised of a crust fragment formed on a tectonic plate and accreted or "sutured" to crust lying on another plate
TVZ	Taupō Volcanic Zone
WSP	WSP New Zealand Limited
Zoning	AGS (2007a) definition: The division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk.

1 Introduction

Bay of Plenty Regional Council (BOPRC) is aiming to improve the understanding and mapping of landslide hazards across the region, as part of a wider initiative to better define risks from natural hazards to assist in land use planning processes. The Bay of Plenty Regional Policy Statement (RPS) Policy NH 7A requires identification and mapping of natural hazards including earthquake induced landslide and rockfall, and extreme rainfall induced landslip and debris flow/flood.

The primary objective of this study is to define areas susceptible to landsliding. This has been undertaken in accordance with internationally recognised guidance produced by the Australian Geomechanics Society (2007a): 'Guideline for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning'.

This report outlines the methodology developed for characterising and mapping areas susceptible to landsliding across the Bay of Plenty region and presents the results and limitations of the study.

1.1 Commission

The Council has commissioned WSP to provide a desktop assessment of landslide hazard susceptibility for both earthquake-induced and extreme rainfall-induced scenarios across the Bay of Plenty Region, excluding some areas. This work was completed under Contract No. CON000358 (2021 0225) between BOPRC and WSP.

1.2 Scope and purpose

The scope of the study was to provide a desktop assessment of landslide susceptibility for both seismic induced and rainfall induced scenarios.

The principal outputs of the study are:

- Classification of land in the study area that is susceptible to landslides, and presentation of the results of this assessment in GIS maps at 1:25,000 within Urban Areas which were provided by BOPRC, and 1:50,000 scales outside of the Urban Areas. These include:

Maketū	Te Puna
Kawerau	Ngongotahā
Waihi Beach	Eastern Rotorua
Te Puke	Central Rotorua
Awakeri	Western Rotorua
Ōmokoroa	Minden

- Preparation of a technical report describing the approach taken and results of the assessment.

We understand that the results of the assessment are intended to be used to identify areas of land susceptible to landslide hazards in accordance with Policy NH 7A of the Regional Policy Statement (RPS). Hazard and risk assessment was not required in the scope of the study. The methodology of the study generally follows the AGS 2007a Guidelines for Landslide Susceptibility, Hazard and Risk Zoning for Land Use Planning. It is expected the information from the maps will be used by BOPRC as well as city and district councils within the Bay of Plenty region to inform land use planning. in line with Table 6 of AGS 2007a. The maps would also be useful as a screening tool for land developers, disaster management, and developing major infrastructure such as highways and railways.

1.3 Study area

The study area is shown in Figure 1 below. The study area includes the Bay of Plenty region and the part of the Rotorua Lakes District that lies within the Waikato region; this was included in this study to provide coverage of the entire district for Rotorua Lakes DC. The following areas within the Bay of Plenty region were excluded from this study, as they had been mapped in previous studies:

- Tauranga City Council boundary
- Ōhope escarpment
- Matatā escarpment
- Whakatāne escarpment

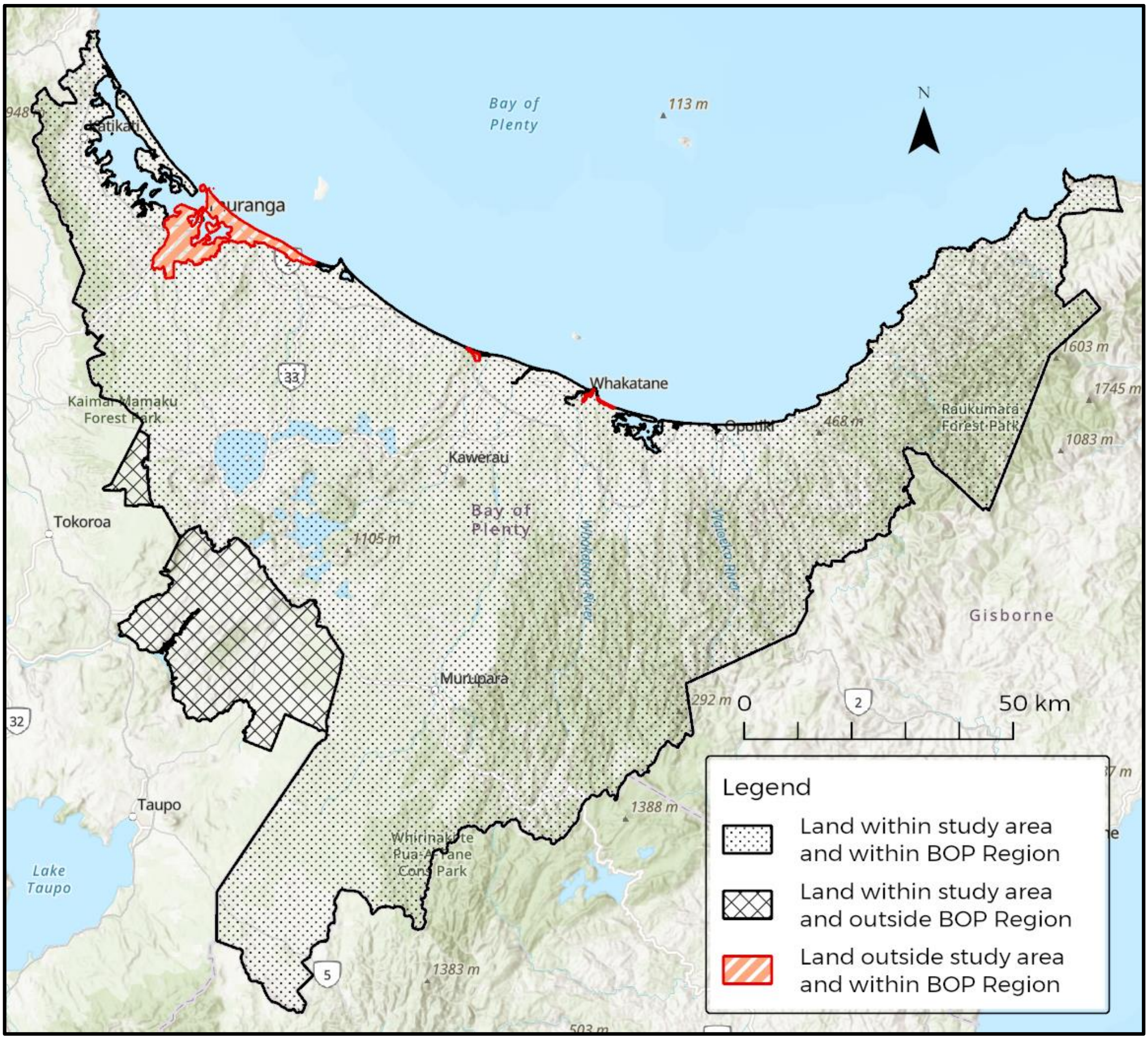


Figure 1 Study area map

2 Study methodology

2.1 Outline

The objective of the study was to identify areas susceptible to landsliding during rainfall and earthquake events to inform future studies and planning, based on the available datasets. To identify these areas, we have identified factors that influence slope instability in the region in rainfall and earthquake events and combined these to develop maps of landslide susceptibility.

The methodology has been developed in accordance with the Australian Geomechanics Society (AGS, 2007a) guidelines for landslide susceptibility zoning. Key terms and definitions defined by AGS (2007a) are shown in Table 1.

Table 1 Key landslide susceptibility mapping terminology from AGS (2007a).

Term	Definition
Landslide	The movement of a mass of rock, debris, or earth soil down a slope.
Landslide inventory	An inventory of the location, classification volume, activity, date of occurrence and other characteristics of landslides in an area.
Landslide susceptibility	A quantitative or qualitative assessment of the classification, volume (or area) and spatial distribution of landslides which exist or potentially may occur in an area
Landslide susceptibility zoning	The division of land into homogeneous areas or domains and their ranking according to degrees of actual or potential landslide susceptibility, hazard or risk.

This section of the report outlines the methodology adopted for this study. Where necessary, we have adapted AGS Guidelines to align with the study objectives. Any adaptations made reflect the quality of the data, expert understanding of local landslide processes, and BOPRC's specifications. A similar approach has recently been used to map landslide susceptibility in Tauranga City (WSP, 2022). Further details of the method are included in each section of the report text.

2.2 Desktop appraisal

A desktop review of available data, reports and research papers was undertaken in order to:

- Understand the geological and geomorphic characteristics of the region.
- Understand where landslides have previously occurred in the study area.
- Create a list of factors reported to affect slope stability in the region.
- Create a list of typical landslide failure mechanisms in the region and similar environments.
- Collect information on the different triggers of landsliding, particularly with respect to factors relevant for rainfall-induced and earthquake-induced landsliding.

2.2.1 Data sources

- Reports on landslides and slope stability within the region, including collation of WSP landslide reports from our database.
- Documented storm events that have caused significant landsliding (e.g. 1979, 2004, 2005 and 2017 storms), supplemented by WSP's experience in responding to numerous storm events in Tauranga and throughout New Zealand.
- International literature on landslides, with particular focus on earthquake-induced landsliding in volcanic regions in Japan.
- The Western Bay of Plenty Road resilience study previously undertaken by WSP, which included reconnaissance following storm events in 2005 and 2006.
- SH2 Waioeka Gorge resilience studies in 2001 and 2020-2021 (Opus, 2001; WSP, 2021a)

- Wellington Earthquake induced slope hazard study (Brabhaharan et al, 1994), which assessed and used factors contributing to earthquake induced landslide hazard to map the hazards.
- Hutt City Landslide susceptibility mapping (WSP, 2021b) which mapped landslide hazards by integrating contributing factors using a geospatial platform.
- Lists of significant landsliding events in the region were collected, including specific storms and earthquakes, based on existing literature, local knowledge, media reports, and past severe weather records from NIWA.
- Landslide studies carried out by WSP and others in the region and throughout New Zealand.

2.3 Landslide inventory preparation

AGS (2007a) states that the preparation of a landslide inventory is essential for any assessment of landslide susceptibility. The landslide inventory should be prepared by collating existing records of past landslides and completing additional mapping if necessary.

Records of past landslides in the region were identified and captured onto a GIS platform. Additional mapping was undertaken to delineate areas of landsliding in the urban areas to broaden the spatial coverage of the landslide inventory.

2.4 Factors influencing landslide susceptibility

Research in the desktop study focused on identifying the key factors that influence landslide susceptibility in the region. The relevance of each predisposing factor for rainfall and earthquake triggers was also evaluated. These factors represent particular characteristics of the region (such as slope angle or geological unit) that are proxies for the physical processes that contribute to landsliding.

GIS layers for each factor were mapped from published datasets and collated in the GIS database. The data layers were processed to obtain a consistent grid cell size of 4m by 4m for each susceptibility factor, allowing each factor to be combined on a cell-by-cell basis.

2.5 Landslide susceptibility assessment

AGS (2007a) define three levels of assessment ('Basic', 'Intermediate' and 'Sophisticated') based on the quality and availability of input data and the required usage and scale. The approach adopted for this study is designed to match the 'Basic' level of assessment, given the regional scale and based on the available datasets.

The susceptibility assessment was developed to identify the sources (i.e., the failure zones) of landslides, and does not include areas that may be subject to further regression of the landslide scarps or areas that may be inundated by landslide debris. The assessment consisted of the following steps:

1. Assess correlation between landslide occurrence and susceptibility factors

The correlation between the mapped landslides and each of the influencing factors was analysed to assess the relative importance of each factor for landslide occurrence (the 'factor value'). Larger weightings were applied to factors displaying a greater correlation to the mapped landslides.

2. Apply factor weightings

Relative weightings (the 'factor value') were determined for each factor class, with higher class values applied to factors with a greater influence on landslide susceptibility (such as the steepest slope angles). The weightings were determined from the analysis of the landslide inventory as well as a heuristic approach involving judgement-based assignment of factor weightings, based on a review of past studies, local experience and an analytic hierarchy review of each pair of factors (Goepel, 2013).

3. Combine weighted factors

The relative importance (factor weighting, W_i) and value of each factor (F_i) were combined using a raster calculation function to calculate the weighted value for each factor within each grid cell in the GIS dataset. The weighted values for all factors were then summed in each grid cell to determine the slope failure susceptibility score, as shown in the equation below.

$$Landslide\ susceptibility\ score\ = \sum(F_i \times W_i)$$

2.6 Calibration

The susceptibility classes were calibrated using the landslide inventory, past reports, local knowledge and terrain data. Rainfall-induced susceptibility was validated using the existing inventory including previous landslide observations in recorded storm events. Earthquake-induced susceptibility was validated by comparing to landslides recorded in earthquake events in the Bay of Plenty as well as the 2016 Kaikōura earthquake (for the axial greywacke ranges in eastern BOP) and the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan (for volcanic materials in western BOP).

2.7 Landslide susceptibility classes

The rainfall-induced and earthquake-induced landslide susceptibility scores were separated into four classes to represent Very Low, Low, Moderate, and High landslide susceptibility, using the susceptibility descriptors recommended in AGS (2007a). These susceptibility classes were then presented in maps.

2.8 Reporting

This technical report was prepared to present the methodology, results and limitations of the landslide susceptibility assessment for the Bay of Plenty. The associated GIS data has been provided to BOPRC for use on their online maps and for future studies.

3 Setting

This section briefly describes the broad geological, climatic, and seismic setting of the Bay of Plenty Region.

3.1 Geology and geomorphology

The Bay of Plenty region is a geologically young landscape that has been shaped by faulting and volcanism associated with the oblique subduction of the Pacific Plate below the Indo-Australian Plate. Figure 2 shows the influence of the plate boundary zone on the geology and geomorphology of the North Island. The BOP Region lies within the Coromandel Volcanic Zone (CVZ), Taupō Volcanic Zone (TVZ) and North Island Axial Ranges. The axial ranges contain steep and high bedrock hills, and the TVZ and CVZ contain incised volcanic plateaus and volcanic landforms. Pleistocene and Holocene sedimentary deposits infill valleys inland, and sedimentary basins towards the coast (Leonard et al., 2010; Mazengarb and Speden, 2000).

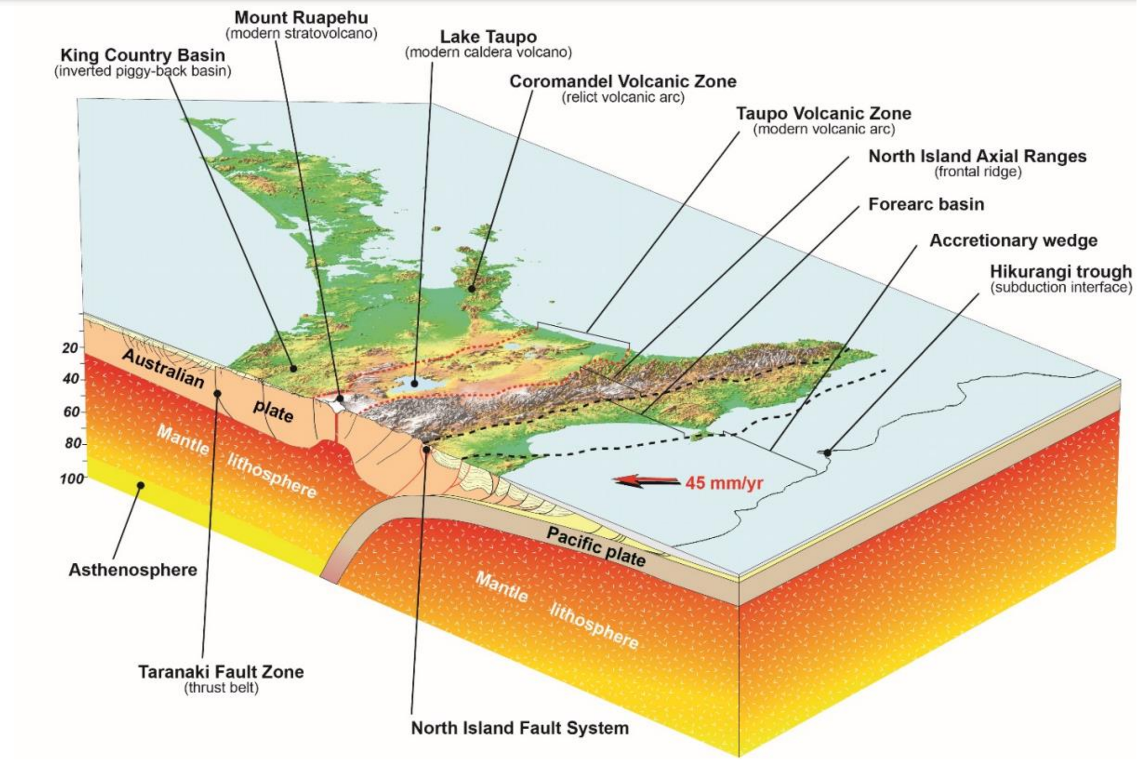


Figure 2 The subduction zone below the North Island (from Crampton et al., 2018).

The types of landslides that occur in these different terrains are strongly linked to both the geomorphic environment and the underlying geology. Therefore, we have characterised the geology and geomorphology of the region into a series of landslide terrains for the purposes of classifying the landslide susceptibility. The landslide terrain units were derived using terrain data, geological mapping, and available information on geomorphic features and landslide types across the region. The integrated geological and geomorphic terrains are summarised in Table 2 and their distribution across the region is shown in Figure 3. The geomorphic features and typical landslide types are described in the following sections.

Table 2 Generalised geotechnical and geological properties of each landslide terrain

Landslide terrain		Generalised geotechnical/geological characteristics
Axial ranges	Allochthon	Highly indurated, highly fractured, chaotic structure, weak – moderately strong intact strength but low mass strength, moderately weathered.
	Mélange	Highly indurated, very highly fractured/sheared, chaotic structure, prone to weathering, weak – strong intact strength but low mass strength
	Greywacke	Highly indurated, moderately fractured, moderately weathered, moderately – very strong intact strength, moderate mass strength
	Mudstone	Very weak – moderately strong intact strength, moderately to highly weathered, often deep weathering profile, high erodibility, prone to stream erosion, deep residual soil profile, can weather to expansive soils
Volcanic terrains	Welded ignimbrite sheet	Highly indurated, highly cemented, vertical, widely spaced joints, slightly weathered, moderately – very strong
	Partially welded ignimbrite sheet	Varies between welded/non-welded properties as described above and below
	Non-welded ignimbrite sheet	Comprise mostly pumiceous material, slightly - moderately weathered, high friction angles, slightly – moderately cemented
	Non-welded weathered ignimbrite	Stiff – hard consistency, deep weathering profiles, clay rich, may have sensitive soils, highly variable strata
	Volcanic ranges	Strong – very strong intact strength, closely - widely spaced, tight joints, can be moderately weathered
	Rhyolitic volcanism	Strong – very strong intact strength, highly indurated, tight joints
Recent sedimentary terrains	Low lying hills	Normally consolidated, often horizontally bedded, marine /terrestrial sand silt and clays or weakly indurated, weak rock. Often interbedded with soft - stiff tephra horizons which may be sensitive,
	Lake deposits	Normally consolidated, lacustrine clays, sand, and silts, often diatomaceous, stiff to very stiff, can be sensitive
	Lowlands, gully/stream/river edges	Unconsolidated alluvial and colluvial and silts, clays and gravel, low cohesion and friction angles, soft – very stiff, higher water content
	Coastal margins	Unconsolidated, loose sand/ gravel deposits, high erodibility, low friction angles
	Loose tephra	Unconsolidated, poorly sorted, sands, silts and breccia, slightly weathered, highly susceptible to piping, high erodibility
	Active landslides	Larger scale, slow moving or dormant landslides. Land contained within these features is more deformed, susceptible to weathering, and may be more susceptible to further sliding of the wider landslide feature

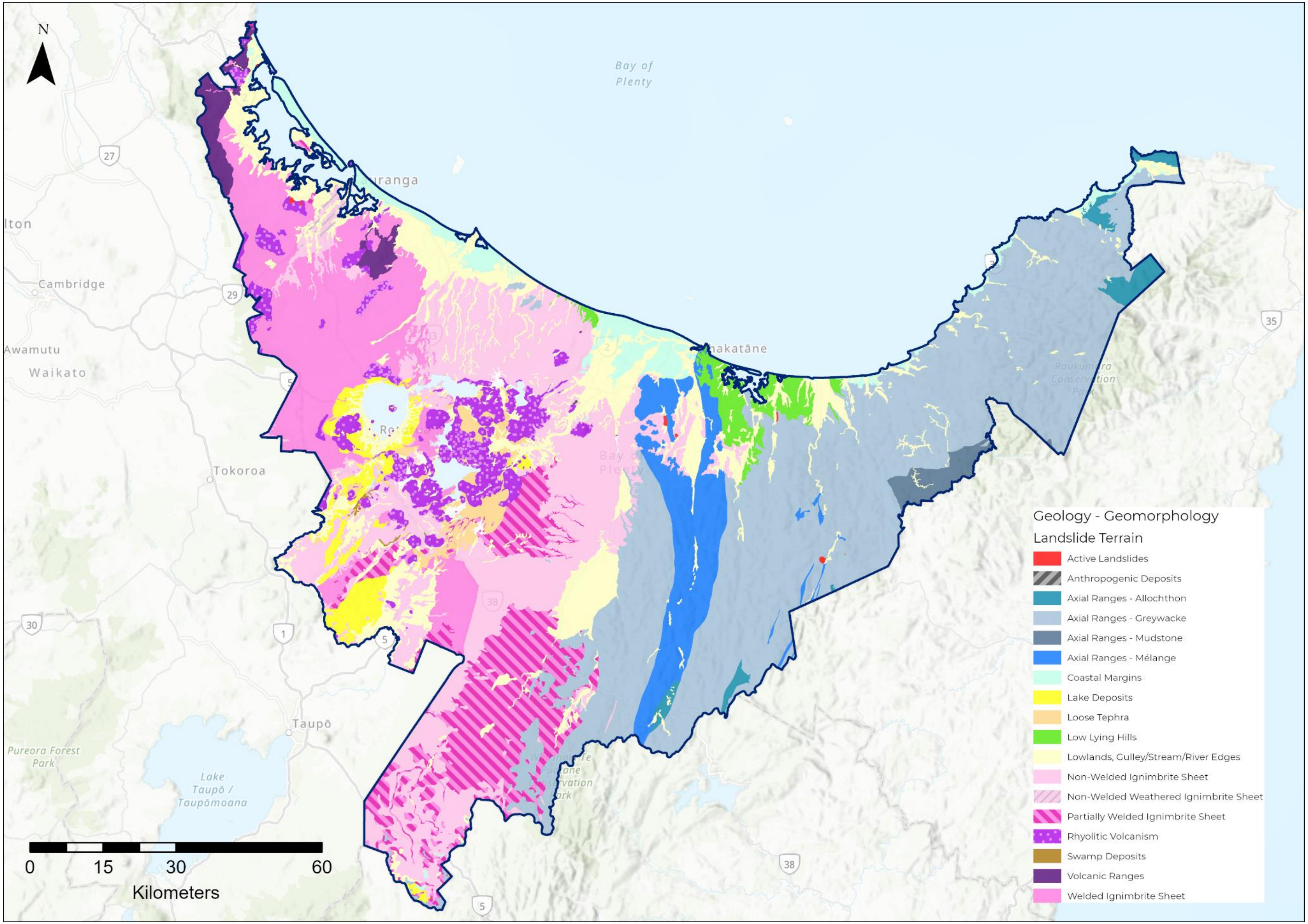


Figure 3 Geology and geomorphology characterisation of the study area

3.1.1 Axial ranges

The axial ranges comprise an area of elevated hills and ranges that dominates the interior of the eastern parts of the map. The axial ranges largely comprise uplifted terranes of highly fractured, interbedded volcaniclastic marine mudstone and sandstone. These rocks were originally deposited in deep marine environments. The terranes then underwent three orogeneses during Zealandia's formation, the latest of which (~Miocene - present) formed the present-day axial ranges (Jiao et al., 2015). The high degree of compression during orogenesis has resulted in a rock character that is highly indurated, and highly fractured (Mazengarb and Speden, 2000). During the formation of the present-day plate boundary, these rocks have been further compressed and sheared by the northern expression of the North Island Fault System (NIFS). Original internal bedding structures have been highly deformed so that bedding planes and joints are unpredictable in terms of their persistence and lateral continuity. During the Early Miocene, thrust sheets of allochthonous material, known as the East Coast Allochthon, were emplaced near the tip of the Raukūmara Peninsula. The East Coast Allochthon is comprised of variable lithologies, that have been highly sheared and deformed during emplacement.

The axial ranges were categorized into three separate geological-geomorphic terranes; (1) the ranges that are underlain by indurated greywacke, (2) the ranges underlain by mudstone, and (3) the ranges underlain by the East Coast Allochthon. The geology and geomorphology of the axial ranges for each of the landslide terrains are described below.

Greywacke

Most of the axial ranges are comprised of a range of volcaniclastic Torlesse marine sediments, including those of the Waioeka, Pahau, and Rakaia Terranes (Mazengarb & Speden, 2000). Lithologies range from indurated, alternating thinly to thickly bedded mudstone–sandstone sequences, to massive sandstone and minor massive mudstone. Lithological units are not continuous laterally and vertically, and highly deformed broken formation is common.

Typical geomorphological elements that are observed include sharp ridge lines, steep slopes and deeply incised valleys. Large talus material may exist towards the base of the slopes. Riverbeds become wide near the coast. Most of the ranges lie between 500 m and 1000 m elevation, reaching a maximum of 1000 m to 1500 m near the axis of the ranges along the Raukūmara Range, and up to 500 m towards the coast.

Rocks are extremely strong to strong when unweathered. The rock becomes more prone to weathering and failure along contacts between sandstone and argillite, and where there are many contacts/ fractures in the rock mass. Rocks are much more prone to failure where strata dip towards the free face,

(A) Deeply incised Waioeka Gorge, with active and recent instability on the steep natural hillslopes and road cuts

(B) Sandys Slip, on SH2 in Waioeka Gorge particularly over-steepened slopes such as road cuttings or alluvial channels.

The western portion of the axial ranges has been sheared by the North Island Fault Belt. In this region, valleys and ridges align in an NNE - SSW direction. Drainage patterns in this region include rectangular (controlled by linear faulting) and dendritic (controlled by valley erosion).

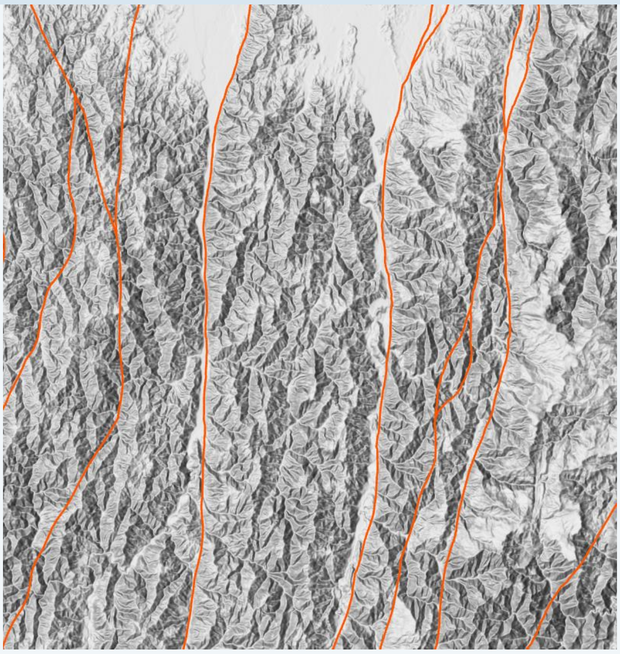
The eastern portion of the ranges is less affected by active faulting, with valleys and ridges crests following structural lineaments reflecting inactive E-W trending faults (between Motu and Raukōkore River mouths), and the NE-SW orientation of the subduction zone.

Mudstone

A portion of the axial ranges are underlain by mudstone. While it is indurated and reasonably hard, it is more susceptible to erosion. Because of this, ridges are more rounded, valleys are wider, and slopes are generally longer and less steep. Because it is more prone to weathering, a thicker residual soil crust is often present. This may be susceptible to rill erosion and sheet erosion. Typical landslides that occur in the mudstone ranges include earth flows, earth creep, debris flows, earth slumps and translational earth failures. Slopes in the greywacke and mudstone terrains are often undercut and oversteepened by stream erosion at their bases.

Mélange

Mélange rocks form a band through the Axial Ranges along the Whakatāne River valley. Mélange is classically defined as broken formation. In this instance the Mélange has been highly sheared within the northern expression of the North Island Shear Belt. The Mélange Axial Ranges consist of deformed rock with pockets and discontinuous layers of mudstone and argillite, and rare pockets of chert, basalt, limestone and marble (Leonard et al 2010). While rocks within this terrain have a high intact strength, the high degree of surface fracturing, joints and susceptibility to weathering results in low rock mass strength.



(C) Hillshade map showing alignment of major river valleys in the Axial Ranges with active faults of North Island Fault System

(D) Whakatāne Mélange, showing packets of strata (A and B) within a highly sheared matrix (C), from T+T (2013a).

(E) Lower Whakatāne River valley in mélange materials

Intact blocks can be present, within a highly deformed matrix (Tonkin and Taylor, 2013a).

Mélange rocks are typically prone to discrete small to medium sized rock falls and topples, caused by wedge or planar failures. Large scale failures of the rock mass are rarer (WSP, 2019).

Allochthon

Localised areas of Allochthon are exposed in the far northeastern boundary of the Bay of Plenty region, near the East Cape. These materials consist of sandstones, mudstones, limestones and basalt.

The Matakaoa volcanics are hard to very hard and are generally resistant to landsliding. The rest of the Allochthon is generally comprised of crushed marine sediments, and is more prone to landsliding, including slumping, and translational sliding (Mazengarb and Speden, 2000).

3.1.2 Volcanic terrains

Many of the landform features of the Bay of Plenty region (and, naturally, the underlying materials) are volcanic in origin. In the Tauranga area and northwards, older, highly weathered volcanic landforms that were active prior to the formation of the TVZ (~>2 Ma) are present. This includes volcanism that was related to the CVZ, and several intermediary volcanics local to the Tauranga region (for example, Pāpāmoa Ignimbrite).

Since formation of the TVZ, which has been active from approximately 2 Ma years ago to the present day, explosive, rhyolitic caldera related eruptions have resulted in the formation of extensive ignimbrite plateaus, which have been subsequently incised into steep-sided gorges by alluvial weathering and erosion. Effusive volcanic activity has formed more localised lava domes and stratovolcanoes, as well as lakes within collapsed calderas. The volcanic terrains are subdivided into five categories for classifying their landslide susceptibility. Geological, geomorphological and geotechnical properties of each are outlined below.

Welded Ignimbrite

Welded ignimbrite is comprised of welded pumice, lithics and entrained materials such as burnt logs. These materials were deposited as pyroclastic flows that mantled and infilled the pre-existing topography, forming extensive plateaus. The plateaus have subsequently been incised by stream erosion, forming steep-sided V-shaped valleys with narrow valley floors. The slopes on the valley margins commonly include prominent vertical exposed rock bluffs.


(A) Incised ignimbrite plateau

The degree of welding within ignimbrites can vary. A higher degree of welding results in a stronger, densely welded matrix, and presence of columnar joints. For welded ignimbrites, the spacing and persistence of joints is the dominant control of failure of the material. Joints are inconsistent throughout the unit, but can include widely spaced vertical joints, with some horizontal joints. Welded Ignimbrites can include isolated pockets or columns of rock that may be exposed within the landscape as the surrounding less welded ignimbrites are eroded away.

Partially Welded Ignimbrite

Variations in the temperature, gas concentration and material type of the pyroclastic flow, as well as the pre-existing topography, impact the variability of the ignimbrites that are deposited, which can manifest primarily in the degree of welding. Partially welded ignimbrites underlie similar incised plateaus as the welded ignimbrites. These materials have similar material characteristics to welded ignimbrites however are more variable in terms of the strength and density of the matrix and the presence of columnar joints.

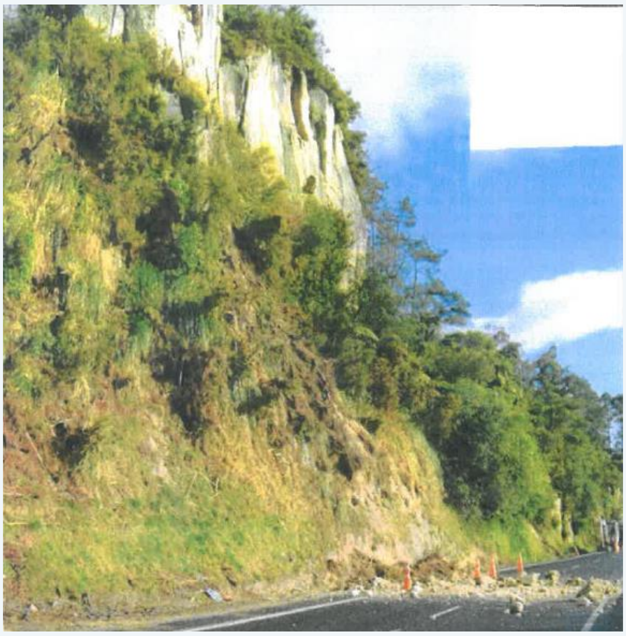
Partially welded ignimbrites are susceptible to piping erosion, which leads to gully formation. Geomorphic features include wide gullies and valleys that have a topography that is less incised and more mantled. Partially Welded Ignimbrites have high friction angles (~40°), therefore steep slopes exist along valley margins.

Non-Welded Ignimbrite

Non-Welded Ignimbrites are dominated by non-welded pumice. Non-Welded Ignimbrites are more permeable and as they are unwelded, are lower strength than the welded deposits. This makes them more prone to the effects of erosion and weathering. Successive cycles of wetting and drying within Non-Welded Ignimbrites has led to the formation of clay minerals. Geomorphic features can included rounded ridges, “horseshoe” shaped slope crests, and wide valley floors. Non-Welded Ignimbrites are susceptible to piping erosion leading to the formation of tunnel gullies.

(B) Welded ignimbrite of the Whakamaru Group, forming very steep bluffs

(C) Erosion-resistant rock on the tops of welded ignimbrite plateaus



(D) Rock fall from Ruahihi Bluff in ignimbrite materials

Non-Welded, weathered ignimbrite

Older units, such as the Chimp Ignimbrite and Pāpāmoa Ignimbrite in the Tauranga area, are often weathered, low-permeability clays, including halloysite rich sensitive clays. These ignimbrites often form peninsula's as a result of the ignimbrite being eroded over time. The slopes on the peninsula's can be steep, with horseshoe shaped scarps. We have categorized this ignimbrite differently as the clay minerals present, such as halloysite, increase the susceptibility to landsliding.

Rhyolitic Volcanism

The Rhyolitic Volcanism landslide terrain consists of rhyolite lava domes and associated volcanic landforms within the Taupō Volcanic Zone. Geomorphic characteristics include steep sided lava domes, valleys, caldera rims and gently sloping central depressions (caldera) such as those in the Rotorua District. Rhyolite lavas may be weathered to form halloysite-rich clays.

Volcanic Ranges

Rocks within the Volcanic Ranges terrain relate to older volcanism from the Coromandel Tauranga Volcanic Zone.

There are several of these ranges within the north and northwestern areas of the study area, such as the Kaimai Ranges. These consist of moderately to highly weathered andesite often with a thick soil cover. The underlying materials include high intact rock strengths but often have close fracturing and highly weathered joints. These volcanic rocks also have a deep weathering profile with development of halloysite and allophane clay minerals. The geomorphology within this terrain includes deeply incised V-shaped valleys, bluffs, block-faulted terrain, and flat-topped plateaus.


(E) Rhyolite domes and lakes near Rotorua


(F) Kaimai Ranges

3.1.3 Recent sedimentary terrains

The eastern part of the region, along the coastline, consists of young geological formations and landforms. The geomorphology is dominated by the effects of tectonic uplift, coastal erosion, sea level changes, and volcanism. These terrains are subdivided into four groups:

Low-Lying Hills

Low lying hills are underlain by a sequence of late Quaternary sandstone, mudstone and tephra deposits. These are typically unconsolidated and are consequently highly erodible. Geomorphic characteristics within this terrain include low lying hills and ranges with rounded ridges. Fans extending from the margins of these hills onto the adjacent alluvial or coastal plains is evidence of active erosion within the hill terrain as well as the long runout of flow-type failures common in these materials (e.g. the 2005 Matatā debris flows).

Loose Tephra

Loose tephra covers much of the study area, mantling the pre-existing topography. The tephra is dominated by Quaternary-aged pumiceous sands and gravels with massive bedding. Unweathered pumiceous soils typically have high friction angles but hillslopes underlain by these materials are prone to shallow landslides, erosion and piping failures due to low consolidation of the tephra.

Alluvial Terrains

Landforms within this group consist of low-lying alluvial terraces, gully or valley margins, and flat to gently sloping land surrounding the Rotorua lakes. The materials underlying this terrain are often poorly sorted and highly variable laterally and with depth, consisting of mixtures of gravels, sands, silts, clays and peat lenses. These deposits are generally unconsolidated and consequently prone to erosion and failure in rainfall events. Unconsolidated sands and silts at the margins of rivers and lakes are also prone to liquefaction-induced failure in earthquakes.

Coastal Margins

The Coastal Margins consist of dune or windblown deposits forming elevated coastal terraces along the coast. These are underlain by older alluvial, marine and volcanic deposits.

(A) Shallow rainfall-triggered landsliding on low-lying hill slopes near Ōhope

(B) Loose tephra (pumice and ash deposits) exposed in road cutting

(C) Low lying alluvial terrains along the Whakatāne River

Coastal Margins also include eroded coastal backdunes forming unstable terraces.

Lake Deposits

Lake deposits consist of normally consolidated, horizontally bedded, lacustrine clays, sand, and silts. These include tephra beds and diatomaceous deposits, which can be sensitive. Lake deposits are most often present in low lying, flat areas, however they form some slopes in the Rotorua region, where older deposits have been incised by alluvial processes.

Active landslides

These features are mapped on the GNS Q Maps as large-scale landslide features that are either dormant or occurred during the Pleistocene/ Holocene and are now considered inactive. The material within these landslides has been displaced and likely deformed, leaving it more susceptible to weathering and erosion.

(D) Windblown dune deposits exposed in coastal slopes at Mount Maunganui

(E) A Google Earth Image of an active landslide in Minden, NZ

3.2 Climate

The climate of the Bay of Plenty region is strongly influenced by the geomorphology, most notably the axial ranges in the east and the elevated volcanic hills and ranges to the south and west. These areas of high ground shelter the region from south and southwest airstreams and create an orographic effect with rainfall concentrated on the ranges and plateaus in north and northeast flows. This affects the distribution of rainfall across the region, from ~1,200 mm median annual rainfall along the coastal lowlands and on the ignimbrite plateau south of Murupara to >2,200mm annual rainfall in the Urewera ranges and the volcanic plateaus around Rotorua. Figure 4 shows the median annual total rainfall of the BOP Region (Chappell, 2013).

Seasonally, ~30% of annual rainfall occurs from June to August, and ~22% of rain falls in summer (Chappell, 2013). Heavy rainfalls can occur from the passage of low-pressure systems from the northwest, forming north and northeast airstreams. The region has experienced numerous extreme weather events, such as intense rainfall, thunderstorm and ex-tropical cyclone events. These events cause significant damage and disruption.

Some notable recent events include:

- July 2004 – A stationary front caused heavy rain to the eastern Bay of Plenty. There was extensive flooding and landslides throughout the area, with landsliding exacerbated by a swarm of earthquakes at the same time. A stopbank on the Rangitāiki River burst and forced the evacuation of large areas of farmland on the opposite bank to the town of Edgecumbe.
- May 2005 – The presence of convergence zones within airstreams produced significant levels of high rainfall in the Tauranga and Matatā areas. Rainfall near Matatā was estimated to have between a 200-year to 500-year recurrence interval, but could be more frequent. Landslides, flooding and debris flows caused significant damage.

- April 2017 – Ex-tropical cyclones Debbie and Cook brought heavy rain, flooding and landslides to many parts of Bay of Plenty. Many remote communities around the region were isolated due to flooding and landslides. A stop bank on the Rangitāiki River burst and forced the evacuation of the town of Edgecumbe.

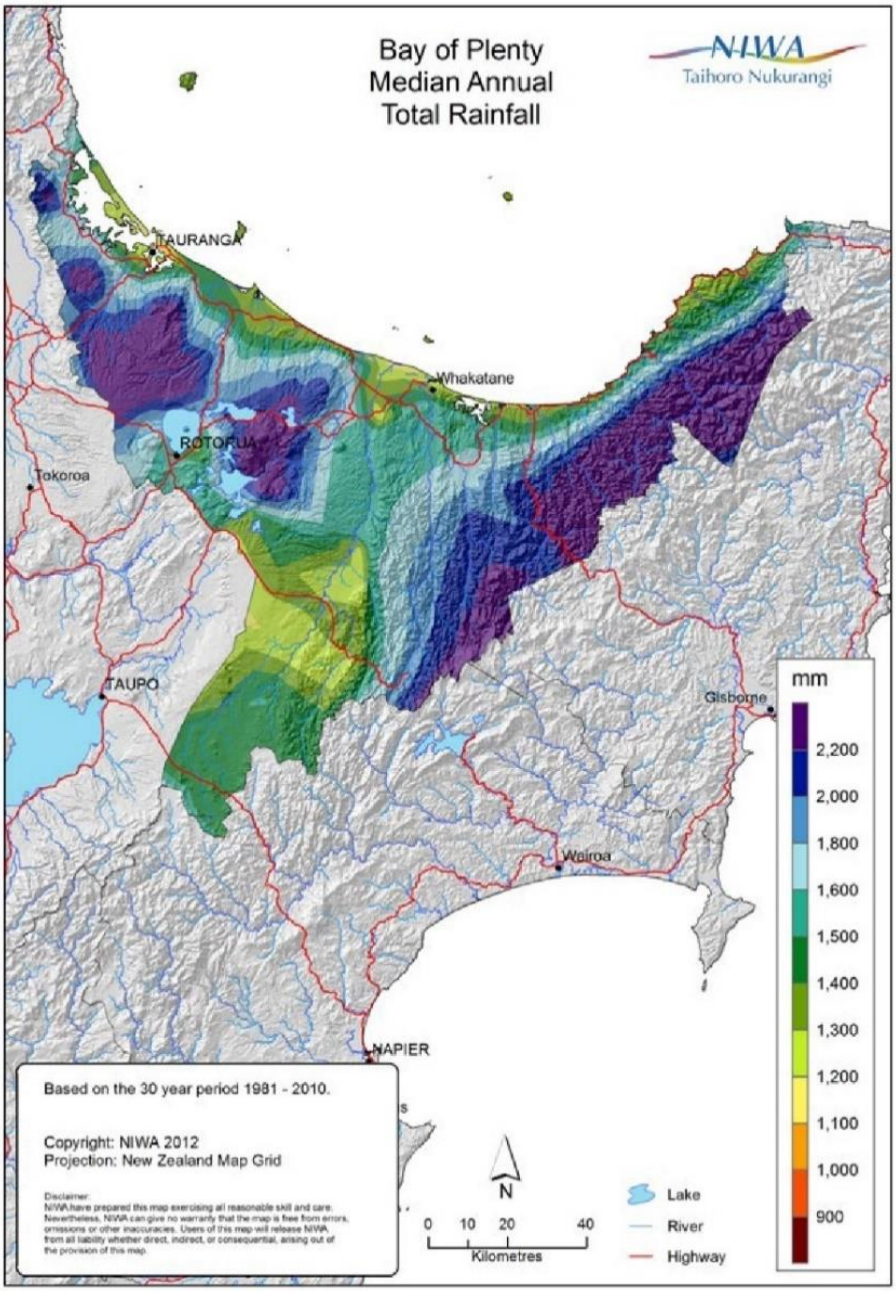


Figure 4 Annual rainfall depths for the Bay of Plenty (Chappell, 2013)

3.3 Seismicity

The eastern and southern Bay of Plenty region are seismically active, with frequent historical earthquake activity (Leonard et al., 2010). Numerous active faults have been mapped across the region in two principal zones: major strike slip faults in the eastern ranges, associated with the North Island Fault System, and closely spaced normal faults in the Taupō Volcanic Zone (Figure 5).

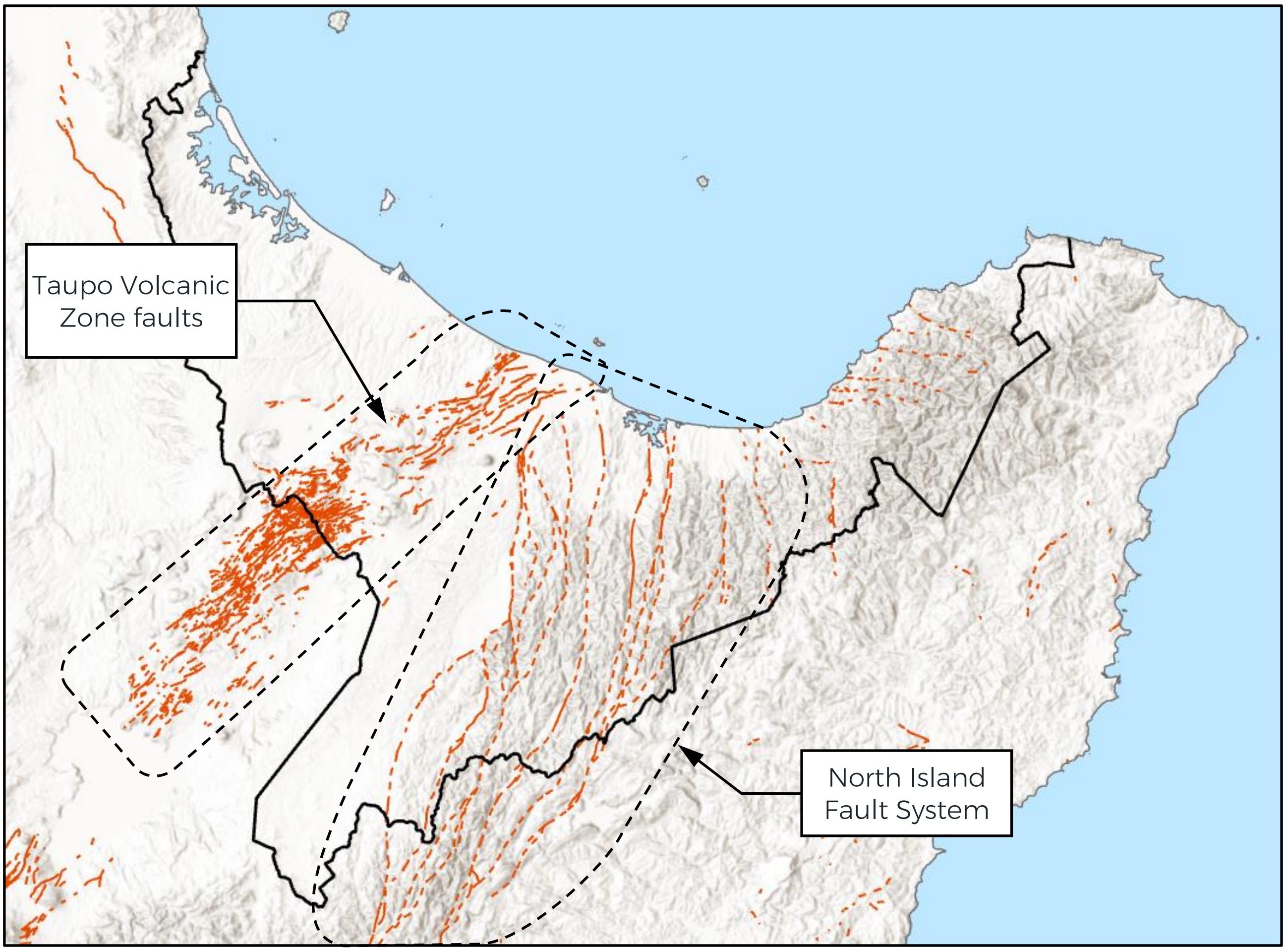


Figure 5 Active faults in the Bay of Plenty region (GNS Active Faults Database)

4 Landsliding in Bay of Plenty

The commonly accepted definition of a landslide is “the movement of a mass of rock, debris or earth (soil) down a slope”. This definition is used in AGS (2007a) guidance and in New Zealand guidelines for land use planning in relation to landslide hazards (Saunders & Glassey, 2007).

Terms such as “landslip”, “slippage” and “falling debris” are used to refer to landslide-type features in New Zealand regulations and codes like the Building Act 2004, the Resource Management Act 1991 and the EQC Act 1993. In this study, “landslide” is used as the dominant terminology.

4.1 Previous studies

Investigations of past landslides within the region are summarised below.

- **Houghton and Hegan (1980)** studied landslides in the Tauranga area, providing an overview of the geology of the Tauranga area, factors influencing instability and commentary on potential causes of landslides there. As part of this study, reconnaissance mapping of historic landslides and review of vertical aerial photography was carried out, identifying 250 relic landslides across the city as well as investigating landslides triggered by a 1-in-100-year storm event which occurred in March 1979 in Tauranga.
- **Jane and Green (1983)** characterised landslides at over 150 sites in the Kaimai Ranges, recording the failure type, geology, soil type, and vegetation at each site. They found that shallow debris flows and avalanches were the most common landslide type. They observed landslides scarps to originate on slopes as shallow as 15°, however most originated between slopes of approximately 20° and 30° degrees. They noted that most landslides originated near slope crests, at gully heads, and sometimes near mid slope. Within lowland areas, they found most landslides to be attributed to undercutting by stream banks. landslides that were observed away from stream banks were on slopes of greater than 40°.
- **Hancox et al. (1997)** compiled data on landslides triggered by the 1987 Edgecumbe earthquake. Landslides were concentrated within the MM IX isoseismal, which was generally closely confined to the area around the fault rupture. Other areas of shallow landsliding were reported on the coastal hills between Ōhope and Whakatāne and near Matatā, within the MM VII and VIII isoseismals. The predominant landslide mechanisms were generally rock falls and shallow rockslides in ignimbrites and semi-translational soil slides in pumice and tephra soils.
- **Bell et al. (2001)** investigated more than 2000 slip features and 400 slope debris features around Tauranga. This study characterised typical failure mechanisms and runout zones observed across the city. A frequency distribution of head scarp attributes is provided, indicating the average angle of scarp features is quite low at about 15°, with many of the slip scarps occurring at angles less than 20°. A frequency distribution was also performed for the slope debris runout zone, indicating mean debris runout angles of about 15°, corresponding to approximately a 3.75H:1V slope. The paper also mentioned that debris runout can be of the order of 4H:1V or more and indicated that the greater runout distances are attributed to lower density of the ash soils that are more sensitive to high groundwater pressures during periods of intense rainfall.
- **Rae (2003)** characterised the geology and geomorphology of the Maketū area and observed that rock fall and debris flow failures are common in the hilly terrain in the vicinity of Matatā, with translational sliding more common to the west.
- Opus (now WSP) undertook a resilience study of the Western Bay of Plenty road network in 2006 **(Opus, 2006)**. Slope instability was identified as one of the primary hazards for the road network. As part of the study, geotechnical inspections of road damage were

undertaken in response to rainfall-induced landslides caused by storms in May 2005 and July 2004. Opus also studied earthquake hazards for lifelines in the Western Bay of Plenty **(Opus, 2002)**. This study focused on active fault, ground shaking, and liquefaction hazards. Landslide hazards were reviewed but not investigated in detail at the time, due to the quality of terrain data available at that time.

- **Dellow (2010)** defined landslide susceptibility in the Rotorua district based on a landslide inventory, terrain data (DEM), and a series of 'landslide terrains' that grouped areas of similar geology and geomorphology, similar to the approach taken to classify landslide terrains in this study.
- **Tonkin and Taylor (T+T, 2013a)** mapped landslides as part of landslide risk assessments for the Whakatāne and Ōhope escarpments, and **T+T (2013b)** mapped landslide and debris flow hazards for Matatā. The principal landslide types observed in these areas were rotational (to semi-rotational) slides, rock falls, debris avalanches, and debris flows.
- **Opus (2015)** and **T+T (2018)** mapped slope instability and erosion hazards along the coastal cliffs in Tauranga Harbour and identified the effects of geology, groundwater including stormwater control as well as the wave effects from the sea.
- Landslides in sensitive ash soils on the coastal cliffs of the Ōmokoroa Peninsula have been investigated in detail by **Mills (2016)** and **Kluger et al. (2017, 2019)**. These studies concluded that pore pressure accumulation during static (e.g. rainfall) and cyclic (e.g. earthquake) loading results in progressive shear band development, leading to contractive failure and liquidation of the material. This results in rapid failure, and earth flows with long runout distances. The degree of sensitivity was observed to be related to the morphology of halloysite.
- Landslides in the basement terranes in the eastern Bay of Plenty along road corridors have been described by **O'Loughlin et al. (2015)** and **Martins et al. (2021)**, who observed that translational rockslides and disaggregated rock and debris avalanches are common in the bedrock in the eastern axial ranges.
- **Opus (2001)** and **WSP (2021a)** identified landslide hazards along the State Highway 2 Waioeka Gorge as part of a resilience study and enhancement of resilience of the highway. This study identified the failure mechanisms in rock influenced by defects leading to rock falls, rockslides and disaggregated rock or debris avalanches, including large landslides such as the Sandy's landslide. This helps characterise the landslide mechanisms in the axial ranges.
- **WSP (2022)** has carried out a comprehensive assessment of landslide hazards in the Tauranga District including parts of the Bay of Plenty along water supply routes into Tauranga. This identified the critical factors influencing landsliding in Tauranga.

The Local Authorities within the region hold information on landslides within their districts, particularly along the road corridors. These datasets typically record the date of landslide occurrence but do not often have detailed information on the location of the landslides. GNS Science maintains a New Zealand Landslide Database (NZLD-https://data.gns.cri.nz/landslides/), which holds data on landslides from across the country. The landslides within the NZLD are sourced from geological maps within the region as well as from reconnaissance mapping undertaken by GNS following storm and earthquake events.

4.2 Where landslides occur

Guidance from AGS (2007a) provides examples of topographical, geological and development situations where landsliding is potentially an issue. Some of these examples that are relevant for the Bay of Plenty are given in Table 3 below.

Table 3 Topographical, geological and development settings where landslides may occur

Settings where landslides are a potential issue	Examples
Where there is a history of landslides	Widespread shallow landslides on steep natural slopes
	Debris flows and earth slides from previously failed slopes
	Landslides in cuts, fills and retaining walls associated with urban development
	Deep-seated sliding on natural slopes
	Rock falls from steep slopes and cliffs
	Large currently inactive landslides subject to undercutting at the toe or reactivation by development
Where there is no history of landslides, but the topography dictates that landslides may occur	Natural slopes steeper than 35° (landslide travel is likely to be rapid)
	Natural slopes between 20° and 35° (rapid landslide travel is possible)
	Cliffs (coastal and inland)
	Steep, high road or rail cuttings
	Steep slopes degraded by recent forest logging and/or construction of roads
	Large currently inactive landslides subject to rising groundwater regimes
Where there is no history of landslides, but geological and geomorphologic conditions mean that landsliding is possible	Slopes in highly sensitive weak clays
	Slopes in weathered or fractured bedrock
	Steep natural slopes in regions affected by large earthquakes
	River banks in soil subject to floods and/or active erosion
	Slopes in loose saturated soil which are susceptible to liquefaction
	Where there is active undercutting of slopes by rivers or the sea
Where there are constructed features which, should they fail, may travel rapidly	Large retaining walls
	Side cast fills on steep slopes
	Loose silty sandy fills

Anthropogenic modification of slopes, through activities including farming, forestry, infrastructure or urban development, can have a negative effect on slope stability. An overview of these various anthropogenic factors is provided by McColl (2015). Brabhaharan et al. (1994) mapped slope modification within the Wellington region during their study of earthquake-induced landslide hazards, and highlighted the importance of three anthropogenic factors in determining the susceptibility of modified slopes to landsliding:

1 Filling of gullies with poorly compacted materials;
2 Excavation, cutting and over-steepening of slopes when building infrastructure; and
3 Poor stormwater or wastewater drainage allowing uncontrolled flow onto slopes.

Anthropogenic modification could also have a positive effect on slope stability when well-engineered, for example where cuts and fills are formed to gentler slopes or through the construction of engineering and drainage measures.

4.3 Landslide hazard zones

This section describes each of the different hazard zones within landslides, including the regression, failure, deposition, and runout zone, which each present different hazards. The characteristics of the landslide hazard zones and the consequences on the levels of hazard are discussed below. Figure 6 depicts the location of the respective hazard zones on a slope.

The susceptibility maps presented in this study capture failure hazard zones only. Assessing runout, regression, and deposition landslide hazard zones is out of the scope of this study as it requires more detailed assessment. However, each zone is described below for context.

In general, landslides consist of:

1) **A failure zone**, where the ground detaches and slides outwards towards the free face. The depth of the failure surface and the extent of the hillslope that is affected by failure will depend on the geological conditions, the failure mechanism, and the intensity of the triggering event. Shallow-seated translational and flow-type failures will occur on the steepest parts of the hillslopes that lie forward of the slope crest within this zone. Deeper-seated landslides can affect a larger proportion of the hillslope, as well as areas of shallower slope angles (e.g. Hegan and Wesley, 2005; Moon et al., 2017). Severe damage could be expected for structures and services located within or across the failure zone, as failure and translation of the slope causes ground surface rupture and large displacements of many metres.

2) **A deposition zone,** where the failure materials accumulate at the base of the slope or where there is a change to a gentler slope. The zone of land at the toe of the slope is prone to inundation by landslide debris. This can cause extensive damage to structures located in close proximity to the slopes, or where the geo-environmental conditions on the slope lead to large volume failures impacting structures sited further away. A prominent example of the potential impacts of landsliding on structures in this zone is the landslide on Vale St in Tauranga in the 2005 storm where a house at the base of the slope was pushed off its foundations (Hegan and Wesley, 2005). Buried infrastructure located within this zone is not likely to be significantly impacted, other than potential blockage or obstruction of manholes and other services at the ground surface.

3) **A runout zone,** below the slope where the landslide debris and any saturated earth flows run out away from the landslide affected slope. Transport of the failed materials can inundate the built and natural environments. An example is the runout affecting transport corridors as well as the Matatā debris flow which engulfed a settlement.

4) **A regression zone,** behind the head scarp where the over-steepened scarp face continues to erode and regress over time. Landslides are often characterised by steeply sloping back scarps at the head of the failure zone, which are typically steeper than the long-term stable angles of the slope-forming materials. Consequently, following a landslide there is a period of regression as the scarp locally erodes back to a more stable angle. This regression can encroach into flat land behind the crest of landslides.

   The regression zone generally poses a lower degree of ground damage hazard than the failure zone, however this zone can extend beyond the crest of the landslide onto flat land. The damage effects can vary from creep deformation or minor slumping to ground surface rupture and further evacuative failure of the slope.

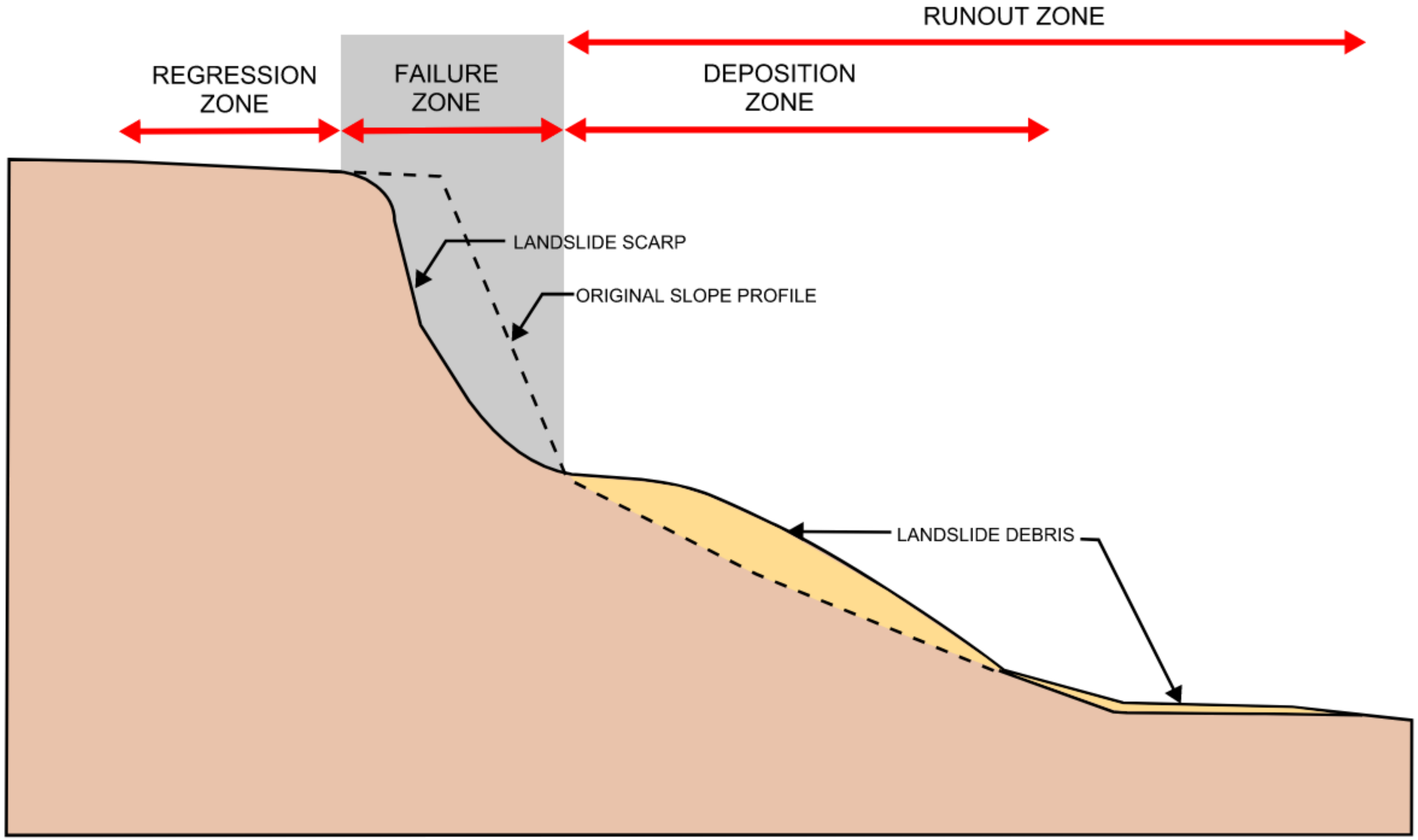


Figure 6 Schematic illustration of landslide hazard zones.
This study assesses the susceptibility of the failure zone only (grey shaded region on the slope)

4.4 Typical landslide mechanisms

The typical mechanisms by which slopes fail in the Bay of Plenty vary according to the lithology of the materials and their degree of weathering or alteration. Localised geological conditions and terrain as well as the trigger events (e.g. earthquake or storm) generally determine which of these failure mechanisms occurs, while slope modification can also increase the likelihood of some failure mechanisms. Some landslides may exhibit characteristics of two or more failure mechanisms. Diagrams of typical landslide types (adapted from Cruden and Varnes, 1996) are depicted in Figure 7 below.

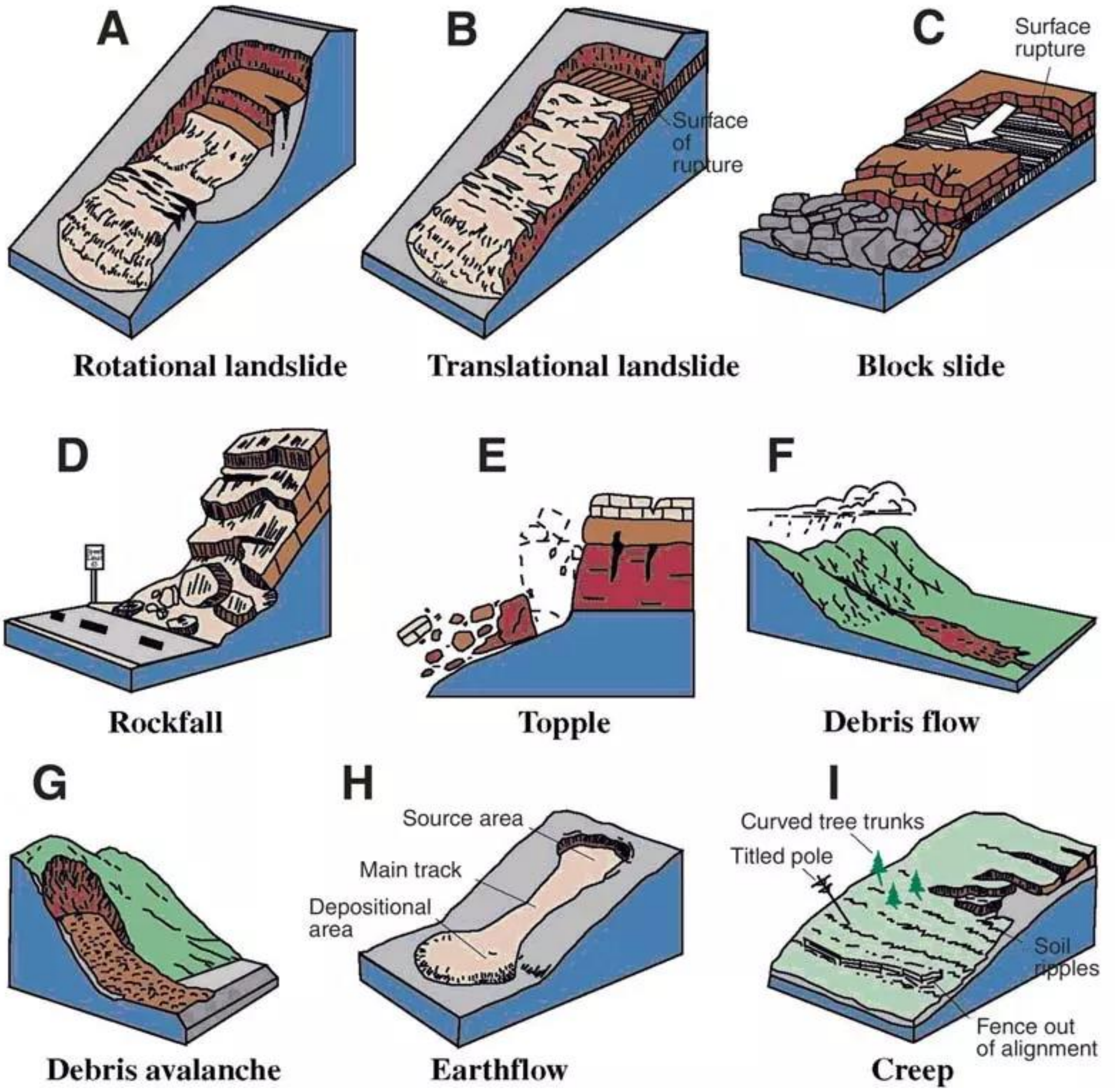


Figure 7 Diagrams of typical landslides, modified from Cruden and Varnes (1996).

4.4.1 Axial ranges

In the basement terranes underlying the axial ranges in the eastern part of the region, rock falls, rockslides and disaggregated rock or debris avalanches commonly occur on the steep slopes in these materials. Modification of the slopes increases their susceptibility to these failures, particularly steep cuttings along road corridors. The stability of these bedrock materials is highly dependent on the presence of defects (joints, crushed and sheared zones, and clay gouge zones). If defects are closely spaced, persistent through the rock mass, and dipping out of the slope, then failure susceptibility tends to be higher.

The mudstone lithologies in the eastern ranges often weather to clay and are susceptible to rotational slides and earth flows. Shallow soil slides are common in the surficial regolith materials overlying the bedrock materials, particularly if a slope is bare or lightly vegetated. These shallow failures can extend into debris flows if sufficient water is present to fluidise the slip debris, during large storms for example. The runout distances of debris flows can be significant, particularly if they become confined within a stream channel.

4.4.2 Volcanic terrains

In the volcanic terrains in the central and western parts of the region, the hillslopes display a range of characteristic failure mechanisms. Welded ignimbrites are prone to rock block topples and falls, with the failure surface controlled by the position and orientation of defects (such as cooling joints) within the rock mass, and weathering of the rock mass around these defects.

In the non-welded ignimbrites two types of landslide failure mechanisms are common:

1) shallow sliding failures in unweathered pumice-rich ignimbrites, and;

2) deep seated rotational slides and sensitive flow slides in highly weathered clay-rich ignimbrites.

The position of the failure surface in the ignimbrite deposits may be controlled by the transition from the unwelded ignimbrite to the underlying base rock.

Shallow debris avalanches and debris flows are the most common landslide type in the rhyolitic terrain and volcanic ranges in the north and northwestern part of the region.

4.4.3 Recent sediments

Recent sediments include those that are of Pleistocene age or younger. In the Bay of Plenty region, these sedimentary deposits include alluvial, lacustrine, ash airfall, coastal deposits, and soft Pleistocene marine rocks. In general, these materials are unconsolidated and loose, resulting in high susceptibility to landsliding.

Coastal terrace and beach deposits are common along the coastal margin of the East Cape. Failures in these materials can include sand/gravel debris slides and rotational earth slumps. Piping erosion may contribute to failure in these materials.

Ash airfall deposits that are mapped include thick tephra deposits from the TVZ. These materials comprise pumice and unweathered ash. These materials generally have high internal friction angles and are prone to shallow seated debris slides on steep slopes, particularly where the natural slopes are oversteepened by cutting for roads or other development, and stream/river erosion. These deposits are also highly susceptible to piping erosion, which can lead to formation of sinkholes and subsequently formation of gullies.

Near Matatā, loose alluvial deposits overlying ignimbrite are susceptible to saturated debris flows and slides. Landslides frequently occur in heavy rainfall where loose, unconsolidated soil material is exposed on steep slopes overlying less permeable or more competent rock. The landslide trigger is usually excess pore pressure, which causes a loss in soils strength. Where landslides occur in steep valleys, they may coalesce to generate debris flows, with the saturated material rapidly surging down the valley, eroding and entraining material along the way. These are likely to be exacerbated by increased precipitation events associated with climate change.

Pleistocene marine sediments are present as low-lying hills in the Whakatāne Graben, and mantling existing topography from Whakatāne southwards.

In the Tauranga region, volcanic tephra deposits have been reworked by fluvial processes to form a series of coastal terraces. Weathering of these deposits has resulted in growth of clay minerals such as halloysite, which lead the development of sensitive soil behaviour (Kluger et al., 2017). During static or cyclic loading (e.g. during heavy rainfall or seismic events), the soils fail along the bedding plane of the sensitive layer in a catastrophic manner, resulting in sensitive clay flow slides.

Much of the study area is overlain by ash airfall deposits from TVZ eruptions. On the most part, these units are not mapped, as they are highly variable in their horizontal and vertical continuity. Many landslides across the region are caused by loose ash airfall sliding off less permeable units. As these units are not consistently mapped, these materials cannot be analysed separately in this study.

4.5 Rainfall triggers

Rainfall is the most significant trigger of landslides in New Zealand, with about 90% of landslide failures linked to a period of intense precipitation (NIWA et al., 2012). Rainfall can cause changes to groundwater conditions within a slope, such as increasing pore water pressures, inducing water flow within a slope, softening and weakening of soil and rock defects, and saturating slope materials (increasing the slope mass), all of which can negatively affect slope stability (McColl, 2015). Surface runoff from rainfall can also cause erosion of slopes. Prolonged and/or intense rainfall therefore increases the susceptibility of slopes to landslides.

4.5.1 Rainfall triggers in BOP

Rainfall events have triggered widespread landsliding in the region, with the most relevant examples being a series of storms during 1979, 1998-2000, 2004, 2005, 2008, 2013, 2017, and 2023. Topographical, geological and hydrological factors have been shown to play an important role in the location, type and extent of landsliding induced by rainfall.

The relationship between rainfall thresholds and landslide triggering has not been studied in detail in the BOP Region, although several studies have estimated triggering thresholds for certain events in local areas. Hegan and Wesley (2005) reported that shallow slides and flows, as well as deeper-seated rotational failures, occurred during the May 2005 storm. They also indicated that infiltration of stormwater into slopes was a significant factor contributing to landslide occurrence. The rain gauge at Tauranga Airport received 346.8mm in 48 hours, with 217mm rain falling within 24 hours. Prior to these events, Tauranga received 207mm of rain (NIWA, 2018). The debris flow that occurred at Matatā in 2005 followed an exceptionally high rainfall intensity of 94.5mm over 1 hour, peaking at 30.5mm over a 15 minute interval (McSaveney et al., 2005). Tonkin and Taylor (2013a) concluded that landsliding in the Whakatāne and Ōhope Escarpment areas is associated with rainfall of greater than 120mm per day.

4.5.2 Influence of climate change

The future influence of climate change on rainfall-induced landslide occurrence is complex. It is generally accepted, however, that total rainfall will increase in western New Zealand, and storm frequency and intensity will increase throughout the country, which are expected to lead to increased landslide occurrence (MfE, 2008). Storms producing rainfall are projected to be more frequent and more intense in the Bay of Plenty due to climate change during the 21st century (Pearce et al., 2019). “Winter rainfall is projected to increase by 10-15% for some coastal areas around Maketū and the far eastern end of the region, with increases of 6-10% around the Rotorua Lakes and hill country south of Whakatāne.” (Pearce et al., 2019). This is expected to lead to increased instances of rainfall-induced landsliding, although at a local scale the effects of climate change could be obscured by changes to the landscape from human activity such as urbanisation and land cover change (Crozier, 2010). The effects of urbanisation could also be exacerbated by climate change.

European studies have indicated that climate change is leading to increased frequency and severity of extreme weather events with high rainfall, and this correlates with observance of the frequency of extreme weather events in New Zealand. Frequent extreme events have occurred in New Zealand over the past 5 years, and these have led to numerous landslides that have affected lifeline infrastructure and property. These include events in Canterbury, Northland and Napier in 2020, in Marlborough, East Cape and the West Coast in 2021, in Wellington, Gisborne, Nelson/Tasman and Marlborough in 2022, and the recent January 2023 events in Northland, Auckland, Coromandel and Bay of Plenty.

These events highlight the importance of understanding the landslide hazards in New Zealand including the Bay of Plenty Region, so that appropriate responses can be planned and implemented.

4.6 Earthquake triggers

Strong ground shaking during earthquakes can cause landslides by inducing elevated shear stresses and increased pore water pressures, which make a slope more susceptible to failure (McColl, 2015). Earthquake ground motions can be amplified in areas of high topographic relief. This effect was investigated by Kaiser et al. (2014) for the Port Hills area during the Canterbury earthquake sequence of 2010 – 2011, with significant topographic amplification often observed at ridge-top locations and confirmed during research into the performance and design of high cut slopes (Brabhaharan et al., 2017).

Hancox et al. (2002) reviewed historical records of earthquake-induced landsliding in New Zealand, to investigate the minimum earthquake magnitude and ground shaking intensity required to trigger landsliding. They observed that significant landsliding is generally triggered where the ground shaking exceeds modified Mercalli (MM) intensities of VII (very strong) to VIII (severe), corresponding to peak ground accelerations of 0.2 g to 0.35 g. This level of ground shaking would be expected in the BOP region in events with a probability of exceedance of 10% in 50 years (Stirling et al., 2012). The most recent update to the NSHM (published in 2022) indicates this level of shaking would have a return period of ~100 years in the eastern part of the region to ~800 years in the western areas (GNS, 2023).

In some cases, seismic shaking can weaken slopes without causing immediate failure. There is then a greater probability of failure during a subsequent earthquake or storm events. This effect was observed following the 2016 Kaikōura earthquake (Mason and Brabhaharan, 2021) as well as in overseas events (e.g. Lin et al., 2006).

4.6.1 Earthquake triggering in BOP

The type and extent of landslides triggered by earthquakes is strongly influenced by the geology, slope angle and slope height. The BOP region is underlain by basement bedrock in the eastern mountains and volcanic materials in the western hills. Extensive landslide inventories are available for the 2016 Kaikōura, 1968 Inangahua and 1929 Murchison earthquakes, which affected areas with similar geological and topographic characteristics to the eastern BOP ranges. Conversely, few landslide-triggering earthquakes have occurred in volcanic materials in NZ in recent times, so records of earthquake-triggered failures in these materials are rare. The most recent/relevant are the 1987 Edgecumbe and 2003 Rotoehu earthquakes in the region. Hancox et al. (2004) noted that landsliding occurred over a 250 km^2 area of the Rangitāiki Plains during the Edgecumbe earthquake in 1987. Landsliding was concentrated within MM9 and MM10 isoseismals mapped, close to Edgecumbe Township, however some moderate landsliding occurred in the MM7 zones, including small scale rock and soil falls along the Ōhope Escarpment. Overseas earthquakes (particularly the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan) have landslide inventories in volcanic materials, and therefore these have also been used for assessing the susceptibility factors for the volcanic materials in BOP.

5 Landslide inventory

A landslide inventory was compiled as part of this study for use in assessing the importance of landslide-influencing factors on landslide occurrence, and for calibrating the final landslide susceptibility maps. The inventory was compiled from a series of existing data sources and additional mapping undertaken by WSP during this study. An overview of the landslide inventory data and associated limitations is provided below.

Table 4 summarises the existing landslide datasets that were accessed during the desktop appraisal. Table 5 summarises the number of additional landslides mapped in Urban Areas.

5.1 Existing data sources

Several sources of data are available to identify past landslide locations in the region. Available spatial landslide data were compiled in a GIS platform, which allowed comparison of landslide locations with the mapped landslide-influencing factors. The types of data available range from maps of many landslide features to written descriptions of individual landslides (usually in site-specific geotechnical reports). The entire landslide inventory comprised a combination of historical records, which included point, line, and polygon data, as well as additional polygons mapped within the Urban Areas. An example of what points, lines and polygons refer to in GIS is depicted in Figure 8 below.

Figure 8 Examples of how landslides are depicted in GIS
(A) Point within the landslide body; (B) Line around the head scarp of the landslide; (C) Polygons delineating the failure zone (red solid line) and the debris runout zone (orange dashed line)

Table 4 Source, data and number of landslides in the landslide inventory

Data source	Data type (point, line, polygon)	No. of landslides			
		Rainfall induced	Earthquake induced	Unknown trigger	Total
GNS NZ Landslide Database	Point	108	139	182	429
GNS QMAP	Polygon (area of evacuation)	-	-	1	1
BOPRC and District Councils	Points, lines and polygons	2018	-	-	2018
EQC landslip claims	Point (property addresses only)	499	-	-	499

5.2 Additional inventory mapping

During the compilation of the landslide inventory, gaps were identified in the coverage of available landslide data in the urban areas within the region. Additional inventory mapping was therefore undertaken by WSP to build a more complete inventory of landslides in these areas. Landslides were identified using aerial imagery from 1930 to 2019, and these were mapped as polygons in GIS to provide an indication of the extent of landslides. Where possible, landslides were divided into source and runout areas and the date of occurrence was recorded as far as practicable. This constitutes 'basic' level landslide inventory mapping as described by AGS (2007a).

Table 5 Landslide inventory mapping for urban areas

Urban Area	Landslide points from historic records	No. additional landslide polygons mapped
Maketū	5	7
Kawerau	1	11
Waihi Beach	11	16
Te Puke	4	0
Awakeri	0	6
Ōmokoroa	5	19
Minden	5	14
Te Puna	0	1
Ngongotahā	1	5
Eastern Rotorua	1	3
Central Rotorua	6	0
Western Rotorua	9	7

5.3 Inventory compilation

The landslide inventory compiled in this study includes the following datasets:

- GNS NZ Landslide Database (primarily point data).
- GNS QMAP (landslide units and boundaries, including some scarps).
- BOPRC and District Council-held slip data.
- EQC landslip claims (addresses only).
- Relic slip scarps in the Tauranga City area (Bell et al., 2001).
- Past investigations and landslide inventory mapping completed by WSP.
- Available records from the Edgecumbe and Rotoehu earthquakes.

The entire landslide inventory comprised a combination of historical records, which included point, line, and polygon data, as well as additional polygons mapped within the Urban Areas. All have been captured onto a GIS platform to be used in the assessment.

The locational accuracy of landslides in the inventory is variable. This is particularly true for the available point data, such as EQC landslip claims, with some point locations reflecting only the property addresses rather than the actual landslide position. The distribution of landslides in the inventory collated from the desk study is shown in Figure 9 below.

The combined landslide inventory provides the basis for characterising the relationships between landslide occurrence and causative factors, and for calibrating the susceptibility maps. Figure 9 shows that the recorded landslides are concentrated in particular areas, such as the Tauranga and Whakatāne urban areas, and along road corridors.

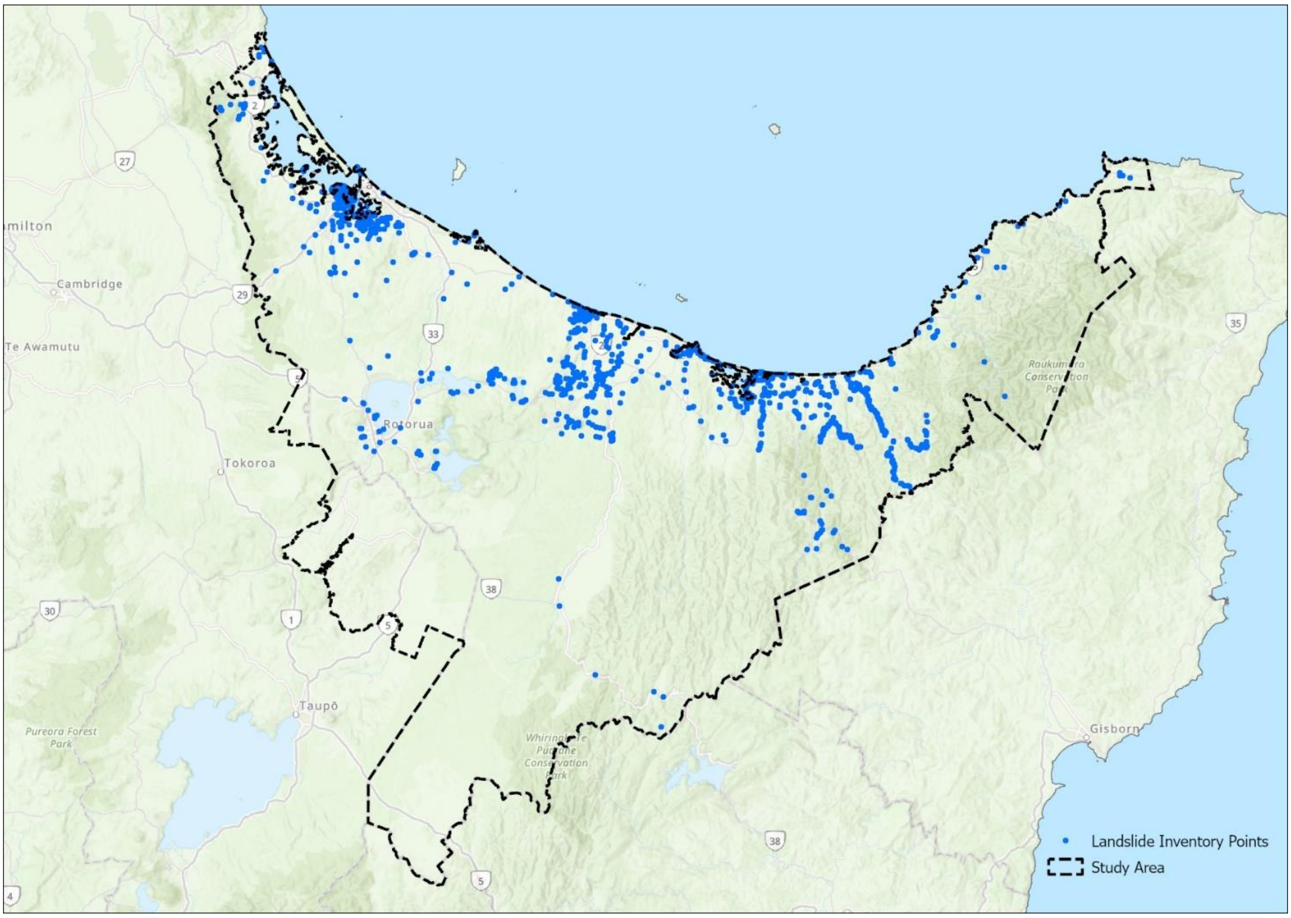


Figure 9 *Inventory of landslide locations in the study area collected from the desktop study*

5.4 Limitations

Limitations associated with the landslide inventory compiled for use in the susceptibility assessment are discussed below.

5.4.1 Locational inaccuracies

Locational accuracy of the landslide data in the inventory is variable and sometimes poor. For the scarp line data and landslides mapped by WSP from historic imagery, locational accuracy is dependent on the quality of aerial imagery used to identify the features. For example, cloud cover in the aerial imagery increased the difficulty of identifying landslides. As discussed above, the locational accuracy of the point and address-based landslide data is often poor.

5.4.2 Differing data types

Landslides are mapped as different data types (lines and polygons). This means there is inconsistency in the format of the landslide inventory. It is also difficult to use scarp line data for correlation with landslide-influencing factors, as the landslide extent downslope can be unclear.

5.4.3 Bias towards particular triggering events

The susceptibility map is intended to be independent from specific storm or earthquake events, however the available inventory data is often dominated by features triggered by a particular event (e.g. the 18 May 2005 storm in Tauranga and the 1987 Edgecumbe earthquake). As there are relatively few of these landslide-triggering events in the inventory, this will limit the potential for a robust statistical calibration of the final landslide susceptibility map.

5.4.4 Lack of earthquake-induced landslide records

The available landslide datasets include 139 earthquake-triggered landslide features, most of which occurred during the 1987 Edgecumbe. These were concentrated in a localised area of hilly terrain to the west of Edgecumbe. As this is only a small proportion of the overall region, landslide data from other earthquake events in New Zealand and overseas were reviewed in order to verify and calibrate the earthquake-induced landslide susceptibility. Similarly, the NZLD included features from the Edgecumbe earthquake on the flat river terraces between Kawerau and the coast but without any attribute data to identify what sort of ground damage feature they represent. As these are located on flat, low lying land close to rivers and streams, these are presumed to be liquefaction-related deformation features (such as sand boils or lateral spreading) and have been excluded from the landslide inventory.

6 Landslide susceptibility assessment

6.1 Overview

The susceptibility assessment carried out for this study focused on the failure zone as described in Section 4.3. Assessment of landslide runout or head scarp regression is not included and this would be necessary as part of a landslide hazard or risk assessment.

Landslide susceptibility was evaluated by identifying geological and geomorphic factors that represent predisposing factors of the landscape or are proxies for the physical processes that contribute to landsliding. Each factor and its constituent classes were weighted according to their relative importance in contributing to landslide occurrence. Landslide susceptibility to rainfall and earthquakes was assessed independently, where the most important factors were chosen for each. This is described further in the following sections.

The weighted values for each of the predisposing factors were calculated by multiplying the factor value and class value using a raster calculation function in GIS. The susceptibility rating was then calculated for each grid cell in the GIS dataset by summing the weighted values for all factors.

$$\text{Landslide susceptibility rating} = \sum(F_i \times W_i)$$

Where F_i = Factor value and W_i = factor weighting. Finally, the landslide susceptibility ratings were then classified into four categories to represent Very Low, Low, Moderate, and High landslide susceptibility.

6.2 Weighting of factors

The susceptibility of a slope to instability is dependent on a combination of factors, which can be divided into controlling factors and triggering factors (Kritikos and Davies, 2015). Controlling factors are inherent geological and geomorphological conditions (such as slope angle or lithology) or variable conditions (such as weathering or the removal of vegetation) that predispose a slope to failure and can change over time (Crozier and Glade, 2005; McColl, 2015).

This study has focused on identifying the key geological and geomorphic factors that influence landslide susceptibility. These factors are quantified characteristics (such as slope angle or geological unit) that represent proxies for the physical processes that contribute to the occurrence of landslides and are particularly relevant for the region. Quantitative and qualitative (heuristic) approaches to determining the relative importance of each susceptibility factor were investigated.

Quantitative methods involve assessing the statistical relationship between landslide occurrence and the influencing factors. The quality of the resulting susceptibility model is therefore strongly dependent on the quality of the data. Quantitative approaches using the frequency ratio method were investigated, but the extent and level of detail within the available landslide inventory was insufficient across the region to represent all the geological and geomorphic terrains equally. A heuristic approach was therefore adopted, using assignment of factor weightings based on a review of past studies, local experience, and statistical assessment of the landslide inventory in combination with an analytic hierarchy review of pairs of factors (Goepel, 2013).

Weightings for each influencing factor were assigned based on the assessed relative importance of each factor (the ‘factor weighting’ in Table 7 and Table 8). The weightings were determined from the analysis of the landslide inventory as well as a heuristic approach involving judgement-based assignment of factor weightings, based on a review of past studies, local experience and an analytic hierarchy review of each pair of factors (Goepel, 2013).

Larger weightings were applied to factors judged to have a greater influence on landsliding and that display a greater correlation to the mapped landslides. For example, slope angle was assigned a higher value than land cover. Different weightings were also used for the rainfall-induced and earthquake-induced landslide susceptibility cases, where appropriate, to reflect the relative importance of these factors in landslides being triggered by these events.

For the rainfall-induced landslide susceptibility case, the importance ranking of selected factors is as follows (from most important to less important):

1) Slope angle
2) Geological and geomorphic unit
3) Local slope relief
4) Land cover
5) Distance to road
6) Distance to stream
7) Slope profile curvature

For the earthquake-induced landslide susceptibility case, the importance ranking of selected factors is as follows (from most important to less important):

1) Slope angle
2) Geological and geomorphic unit
3) Local slope relief
4) Distance to road
5) Slope profile curvature
6) Distance to active fault

The factors were subdivided into different classes, with each class assigned a numeric value (the 'factor value' in Table 7 and Table 8). Higher values were assigned to the classes associated with greater landslide susceptibility. For example, steeper slopes were given a larger value than shallower slopes, with the relative values representing the influence on slope instability.

The correlation between the mapped landslides and each of the influencing factors was analysed to assess the relative importance of each factor for landslide occurrence (the 'factor value'). Larger weightings were applied to factors displaying a greater correlation to the mapped landslides.

The factors and weighting were kept relatively consistent with the Tauranga landslide hazard study, recognising the differences in the data available between Tauranga and the wider BOP region as well as the wider geology and terrain in BOP relative to Tauranga. This was important to gain reasonable consistency between the recent Tauranga study and this BOP study.

The factors and their weightings are given in Table 7 and Table 8 below, with comments on the basis for each factor and its influence on landslide susceptibility.

6.3 Factor maps

GIS layers for each factor were mapped from published datasets and collated in the GIS database. The data layers were processed to obtain a consistent grid cell size for each susceptibility factor, allowing each factor to be combined on a cell-by-cell basis. These maps can be viewed in Appendix A. A summary of the data used and original resolution is presented in Table 6.

Table 6 Data sources and the original resolution of each data source

Factor map	Data source	Original resolution
Slope angle	Derived from Digital Elevation Model (DEM) – Bay of Plenty Northwest 1 m 2020-2021 Bay of Plenty 1 m 2018-2019 Bay of Plenty Tauranga and Coast 1 m 2015 NZ 8 m 2012	 1 m 1 m 1 m 8 m
Geological and geomorphic unit	GNS 1:250,000 geological maps	1:250,000
Local slope relief	Derived from Digital Elevation Model (DEM) – Bay of Plenty Northwest 1 m 2020-2021 Bay of Plenty 1 m 2018-2019 Bay of Plenty Tauranga and Coast 1 m 2015 NZ 8 m 2012	 1 m 1 m 1 m 8 m
Land cover	Land Cover Data Base V5	1:50,000
Distance to road	LINZ – NZ Road Centrelines	1:150,000
Distance to stream/waterway	LINZ – NZ River Centrelines LINZ – NZ Lake Polygons LINZ – NZ River Polygons	1:150,000
Slope profile curvature	Derived from Digital Elevation Model (DEM) – Bay of Plenty Northwest 1 m 2020-2021 Bay of Plenty 1 m 2018-2019 Bay of Plenty Tauranga and Coast 1 m 2015 NZ 8 m 2012	 1 m 1 m 1 m 8 m
Distance to active fault	GNS 1:250,000 geological maps	1:250,000

6.4 Model calibration and refinement

Various checks were undertaken to validate the landslide susceptibility map. The susceptibility ratings were calibrated using the landslide inventory, past reports, local knowledge and terrain data, with adjustments made to factor weightings and class values as required. A different amount and quality of data was available for calibrating the rainfall-induced and earthquake-induced landslide susceptibility scores.

The rainfall-induced landslide susceptibility ratings were calibrated by overlaying rainfall-induced landslides from the landslide inventory with the susceptibility ratings, to determine whether the modelled susceptibilities correctly reflect past landslide locations. The earthquake-induced landslide susceptibility ratings were compared to available landslide information for the 2004 Rotoehu, 1987 Edgecumbe, and 2016 Kaikōura earthquakes in New Zealand, and the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan. Sensitivity analysis of the factor weightings was undertaken to test the output susceptibility rating against different combinations of slope angle, geology and relief.

The landslide susceptibility model was refined to remove artefacts or features where the modelled susceptibility map was judged to overestimate the true susceptibility. Slope features that were known to be engineered slopes such as stopbanks and dams were removed from the susceptibility rating using available GIS mapping of those features, as the performance of these are expected to be considered by the relevant authorities. Some temporary features in the digital elevation model such as spoil or aggregate stockpiles were identified using aerial photographs and hillshade maps; given the region-wide scale of this study it is impractical to manually identify and remove all of these features, and we recommend that this is done for Urban Areas in conjunction with site inspection/ground-truthing. Several map errors were noted in the geology-geomorphology factor maps. These were manually corrected on the factor maps prior to processing.

Table 7 Rainfall-induced landslide susceptibility factors

Group	Factor	Factor weighting	Factor Class	Factor value	Influence on landslide susceptibility
Slope	Slope angle	6	α ≤ 15°	0	The steeper slope angles generally correspond to higher susceptibility to landsliding.
			15° < α ≤ 20°	2	
			20° < α ≤ 25°	5	
			25° < α ≤ 35°	7	
			35° < α ≤ 45°	8	
			45° < α ≤ 55°	9	
			α > 55°	10	
	Local slope relief	3	r ≤ 5 m	0	Higher steep slopes are generally more susceptible to failure. Slope height also influences the size and runout of landslides. This factor represents the local height and angle of the slope surrounding each grid cell in the elevation dataset (i.e. the broader steepness rather than just the slope angle of each cell). It is calculated by comparing the difference in elevation between the cells within a given radius of the selected cell.
			5 < r ≤ 10 m	6	
			10 < r ≤ 20 m	8	
			20 < r ≤ 50 m	10	
			50 < r ≤ 100 m	12	
			r > 100 m	15	
	Slope profile curvature	1	Convex (c ≤ -0.1)	0	The curvature (convex, flat, or concave) of a slope influences the flow of water across it, with concentration of flow in areas of concave slope curvature. This can also represent weaker materials or presence of weaker deposits. These can in turn influence the susceptibility to landsliding.
			Linear (-0.1 < c ≤ 0.1)	2	
			Concave (c > 0.1)	4	
Geology	Grouped geology-geomorphology	6	Axial ranges – Allochthon	6	The lithologies of slope materials have different shear strength, rock mass strength, moisture sensitivity and permeability characteristics, which influence the vulnerability of the slope to erosion and weathering. Weaker, unconsolidated materials are generally more susceptible to instability than strong consolidated soil or rock. Geomorphic units are defined to group areas of similar geology and terrain. Units with weaker geological materials and soils, and shallower groundwater are generally more susceptible to landslides. The active landslides are from GNS QMaps and appear to be large scale landslides that appear to have not moved in the Holocene. These were checked and there no specific evidence of recent instability. Therefore they have been assigned a modest Factor Value of 6.
			Axial ranges – Mélange	6	
			Axial ranges – Greywacke	4	
			Axial ranges - Mudstone	6	
			Welded ignimbrite sheet	3	
			Partially welded ignimbrite sheet	3	
			Non-welded ignimbrite sheet	3	
			Non-welded weathered ignimbrite	5	
			Volcanic ranges	2	
			Rhyolitic volcanism	2	

Group	Factor	Factor weighting	Factor Class	Factor value	Influence on landslide susceptibility
			Low lying hills	5	
			Lake deposits	5	
			Lowlands, gully/stream/river edges	8	
			Coastal margins	8	
			Loose tephra	8	
			Active landslides	6	
			Anthropogenic deposits	6	
Hydrology	Distance to stream	1	d ≤ 5 m	4	Slopes located close to streams are likely to have shallower groundwater levels and may be undercut and oversteepened (destabilised) by scour erosion at the toe of the slope.
			5 m < d ≤ 10 m	2	
			10 m < d ≤ 20 m	1	
			d > 20 m	0	
Land cover	Land cover	2	Landslide	10	The type of land cover can affect the susceptibility of a slope to instability by influencing the rates of surface water runoff, infiltration, and erosion. Increased vegetation cover is generally considered to improve slope stability due to the additional strength the root systems contribute to shallow slope stability.
			Bare	8	
			Grassland	5	
			Scrub/shrubland	4	
			Artificial areas	4	
			Forest	2	
			Water bodies	0	
Slope modification	Distance to road	2	d ≤ 25 m	5	Slope modification can increase the susceptibility of slopes to landsliding (e.g. cut and fill earthworks). This factor is used to capture potential slope modification (cutting, filling and vegetation removal) along the road corridors and urban development.
			25 m < d ≤ 50 m	3	
			50 m < d ≤ 75 m	0	
			d > 75 m	0	

Table 8 Earthquake-induced landslide susceptibility factors

Group	Factor	Factor weighting	Class	Factor value	Influence on landslide susceptibility
Slope	Slope angle: Soil and weak rock materials	8	$\alpha \leq 15^\circ$	0	The steeper slope angles generally correspond to higher susceptibility to landsliding. For earthquakes, soil and weak rock materials are susceptible to ground shaking at shallower angles than bedrock materials, hence the value of the slope angles within the various classes have been separated according to the geology classification.
			$15^\circ < \alpha \leq 20^\circ$	2	
			$20^\circ < \alpha \leq 30^\circ$	6	
			$30^\circ < \alpha \leq 35^\circ$	8	
			$\alpha > 35^\circ$	10	
	Slope angle: Bedrock materials	8	$\alpha \leq 20^\circ$	0	
			$20^\circ < \alpha \leq 30^\circ$	2	
			$30^\circ < \alpha \leq 40^\circ$	6	
			$40^\circ < \alpha \leq 50^\circ$	8	
			$\alpha > 50^\circ$	10	
	Local slope relief	6	$r \leq 5$ m	0	Higher steep slopes are generally more susceptible to failure, particularly in earthquakes since ground shaking can be amplified by steep slopes of greater height. Slope height also influences the size and runout of landslides. This factor represents the local height and angle of the slope surrounding each grid cell in the elevation dataset (i.e. the broader steepness of the slope rather than just the slope angle of each cell). It is calculated by comparing the difference in elevation between the cells within a given radius of the grid cell.
			$5 < r \leq 10$ m	6	
			$10 < r \leq 20$ m	8	
			$20 < r \leq 50$ m	10	
			$50 < r \leq 100$ m	12	
			$r > 100$ m	15	
	Slope profile curvature	1	Convex ($c \leq -0.1$)	4	The curvature of a slope influences the amplification of ground shaking near sharp convex changes in slope, which in turn can increase the susceptibility to landsliding.
			Linear ($-0.1 < c \leq 0.1$)	2	
			Concave ($c > 0.1$)	0	
Geology	Grouped geology / geomorphology	6	Axial ranges – Allochthon	6	The lithologies of slope materials have different shear strength, rock mass strength, brittleness and permeability characteristics, which influence the vulnerability of the slope to earthquake-induced deformation and failure. Weaker, unconsolidated materials are generally more susceptible to instability than strong consolidated soil and rock. Geomorphic units are defined to group areas of similar geology and terrain. Units with steeper slopes, weaker geological materials and soils, and shallower groundwater are generally more susceptible to landslides.
			Axial ranges – Mélange	5	
			Axial ranges – Greywacke	4	
			Axial ranges - Mudstone	5	
			Welded ignimbrite sheet	6	
			Partially welded ignimbrite sheet	6	
			Non-welded ignimbrite sheet	3	
			Non-welded weathered ignimbrite	5	

Group	Factor	Factor weighting	Class	Factor value	Influence on landslide susceptibility
			Volcanic ranges	4	
			Rhyolitic volcanism	2	
			Low lying hills	5	
			Lake deposits	5	
			Lowlands, gully/stream/river edges	8	
			Coastal margins	8	
			Loose tephra	8	
			Active landslides	6	
			Anthropogenic deposits	6	
Faults	Distance to active fault	1	d ≤ 50 m	8	An increased intensity of landsliding close to active faults has been observed in previous earthquakes (e.g. 2016 Kaikōura earthquake), due to the effects of strong ground motion, near fault effects, reduced rock mass strength and topography in close proximity to the faults.
			50 m < d ≤ 500 m	8	
			500 m < d ≤ 1000 m	4	
			d > 1000 m	0	
Slope modification	Distance to road	2	d ≤ 25 m	5	Slope modification can increase the susceptibility of slopes to landsliding (cut and fill earthworks). This factor is used to capture potential slope modification (cutting, filling and vegetation removal) along the road corridors and urban development. Slope modification is weighted higher than distance to fault, as it is well established that is reduces slope stability, whereas the relationship to landsliding and distance to fault is less well established.
			25 m < d ≤ 50 m	3	
			50 m < d ≤ 75 m	0	
			d > 75 m	0	

6.5 Landslide susceptibility classification

The landslide susceptibility scores were divided into four classes to define zones of Very Low, Low, Moderate and High landslide susceptibility. The class boundaries are listed in Table 9 for rainfall-induced landsliding and in Table 10 for earthquake-induced landslides. The classes were defined following the recommendations in AGS (2007a), based on comparison of the susceptibility scores to the landslide inventory and the geology and geomorphology of the study area. The total land area within each of the susceptibility class has been compared to the area of landslides within the landslide inventory, to calibrate the susceptibility assessment (Table 9). The table shows that the majority of the landslides in the inventory lie within the high to moderate susceptibility classes. A small proportion of landslides fall within the low susceptibility class; high magnitude events such as the 2005 storm would result in significantly elevated landslide potential, such that land of low susceptibility may still experience landsliding. For earthquake-induced landslides, the available inventory is too sparse to make statistical correlations to the susceptibility classes. It is likely that the proportion of the entire study area for rainfall triggered landslides is in reality greater than the percentages in Table 9, as the inventory was based on limited information.

Table 9 Rainfall-triggered landslide susceptibility classes

Susceptibility class	Susceptibility rating	Study area		Landslide inventory		
		Area in class (km^2)	Proportion of study area	Area of landslides in class (m^2)	Proportion of total area of landslides	Proportion of total study area
Very low	< 40	5,182	38.0%	3,248	0.6%	0.00006%
Low	41 – 65	879	6.4%	50,416	8.6%	0.006%
Moderate	66 – 100	3,349	24.6%	259,360	44.4%	0.008%
High	> 101	4,212	31%	271,360	46.4%	0.006%

Table 10 Earthquake-triggered landslide susceptibility classes

Susceptibility class	Susceptibility rating	Study area	
		Area in class (km^2)	Proportion of study area
Very low	< 40	5,160	37.9%
Low	41 – 70	634	4.7%
Moderate	71 – 130	2,860	21.0%
High	> 131	4,945	36.4%

6.6 Characteristics of susceptibility classes

6.6.1 *High susceptibility*

Zones of high susceptibility consist primarily of steep to very steep hillslopes, areas where there is active or known past slope instability, and moderate to steep slopes underlain by weak or soft sediments or sensitive ash soils. Typical slope morphologies associated with this zone include the steep hillslopes in the axial ranges, coastal bluffs, steep gully slopes associated with incised ignimbrite terraces, and modified land such as cut slopes.

6.6.2 *Moderate susceptibility*

Zones of moderate susceptibility consist of moderately steep to steep slopes, such as rounded or undulating hills and land on the margins of gullies or at the base of hillslopes. Areas of flatter land that are near steep slopes such as the edges of terraces or the peaks of hills and ranges, as well as areas of shallower slopes underlain by weaker materials, also fall within this zone.

The potential for landslides in these areas will depend on site-specific conditions such as the thickness and strength of surficial soils, the underlying geological formations, and the prevailing drainage and groundwater conditions, as well as the intensity and duration of the triggering event. Given the region-wide nature of this study, analysis of site-specific conditions and stability are not captured in the susceptibility mapping.

6.6.3 Low susceptibility

Zones of low susceptibility consist of shallow slopes at the margins of hillslopes and gullies, as well as areas with low to moderate slopes in more competent geological materials.

Given the region-wide appraisal undertaken in this study, land classed as having a low landslide susceptibility cannot be confirmed to have no potential for land instability. Site-specific conditions that locally increase landslide susceptibility may not have been captured at the scale of mapping appropriate in this regional study.

6.6.4 Very low susceptibility

Zones of very low susceptibility are comprised of flat areas of the alluvial and ignimbrite terraces (away from the terrace edges and gullies), valley floors, and coastal flats. In these areas slope instability would generally be unlikely, but given the scale of the regional study, there could be localised areas of instability. In addition, these areas could be subject to runout of debris or debris flows from adjacent slopes or gullies.

6.7 Landslide susceptibility maps

6.7.1 Scale

Maps of the landslide susceptibility classes have been compiled for the study area. The landslide susceptibility maps are shown in Figure 10 and Figure 11, and are provided in Appendix B at the following scales:

- Urban Areas: 1:25,000
- Rural areas: 1:50,000

The landslide susceptibility zones have also been provided as GIS layers for BOPRC's GIS team, for inclusion on the regional online hazard maps.

The AGS (2007a) guidelines suggest that scales between 1:100,000 and a maximum of 1:25,000 are appropriate for susceptibility zoning mapping completed across regional areas (defined as 1,000 km^2 to 10,000 km^2; the study area is approximately 14,000 km^2). The maps should be used based on these guidelines, we recommend that, zones based on this landslide susceptibility study are not displayed at scales larger (i.e. in more detail) than 1:25,000.

6.7.2 Disclaimer

A disclaimer should be included on the maps to inform readers that they are for information only and are not intended for assessments of individual properties. This could be as follows:

> The maps indicate the susceptibility of slopes to failure, and do not include areas where regression or runout might occur. The maps do not replace site specific investigations and assessment required for Building or Resource Consent and shall not be solely relied upon for interpreting landslide susceptibility. The maps should be viewed at 1:25,000 in Urban Areas, and 1:50,000 in areas outside of Urban Areas.

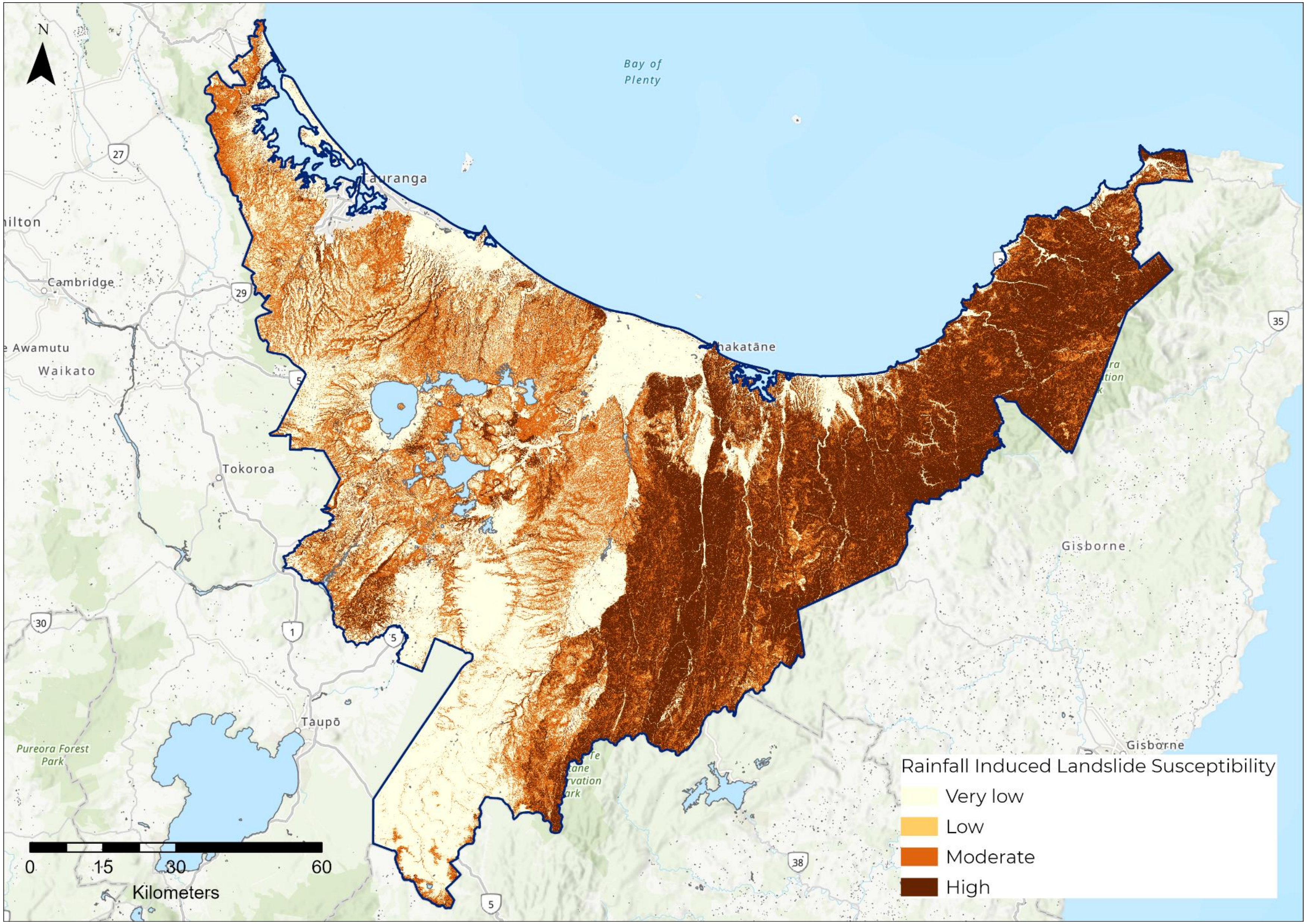


Figure 10 Rainfall-triggered landslide susceptibility map

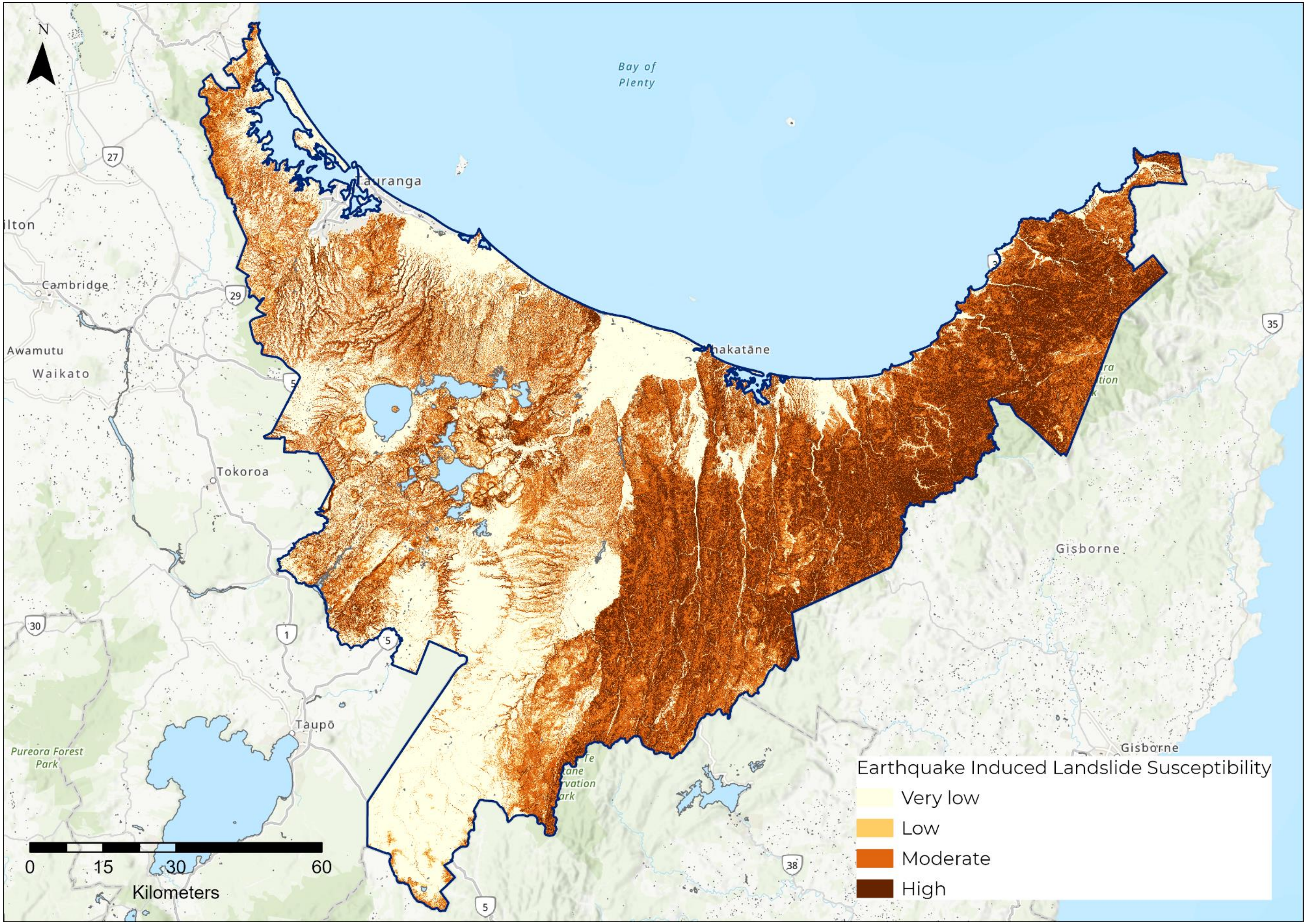


Figure 11 Earthquake-triggered landslide susceptibility map

6.8 Limitations and uncertainties

The following sections describe the limitations and sources of uncertainty in the susceptibility assessment associated with the regional-scale desktop-based approach, as well as the level of detail of the available input information.

6.8.1 Scale of assessment

The landslide susceptibility mapping completed in this study represents a desk-based, region-wide assessment that was carried out from examination of remotely sensed data including LiDAR and aerial imagery, along with regional-scale datasets. No access was gained to properties, and site-specific stability assessments have not been undertaken. Property owners and developers should seek independent advice on land stability at their particular property when considering development or the existing level of slope instability hazard.

6.8.2 Resolution of input layers

The study utilised a variety of geospatial data, including LiDAR-derived DEM data, and digitised polygon, point and line features. As these data have been collected and/or digitised at different resolutions, artefacts in the landslide susceptibility classes can potentially be created where individual input layers do not align correctly. For example, the geologic-geomorphic boundaries were mapped at a small scale (1:250,000), and consequently some of the boundaries do not align with the higher resolution LiDAR-derived slope layers, resulting in inaccuracies in the assessment where the data is not reliable.

6.8.3 Differentiation of landslide type and runout

The desk study highlighted the key failure mechanisms in the various geological formations across the region, and we note that different mechanisms have different failure and runout characteristics. As there is limited or no identification of the failure mechanisms available in the landslide inventory, it is not currently possible to differentiate the failure types in the susceptibility maps presented in this study. Similarly, the susceptibility considers only the vulnerability of the hillslope surface to failure, and does not take into account the potential for regression into flatter land above over time following the initial failure, or the areas below that may be affected where the landslide debris deposited or runs out onto flatter land.

6.8.1 Landslide inventory location bias

The landslide inventory used in this study comprises collated historical records of landslides, and some additional mapped landslides in the Urban Areas. These records are not exhaustive over the region; many of the mapped landslides are located in urban centres, along road corridors, or where dwellings are located. This results in a location bias; it is likely that many landslides have occurred in less well populated areas.

6.8.2 Human bias

Because the extent and level of detail within the available landslide inventory was insufficient across the region to represent all the landslide terrains equally, a heuristic approach was adopted using assignment of factor weightings based on a review of past studies, local experience, and statistical assessment of the landslide inventory in combination with an analytic hierarchy review of pairs of factors (Goepel, 2013). Because the heuristic method involves judgement-based decisions, there may be bias introduced during factor selection and weighting.

6.8.3 Modification of slopes

Slope modification is not captured beyond that which is captured in the LiDAR and aerial imagery. The capture of slope modification is therefore limited by the scale, quality and age of these datasets, and the scale of the assessment. Any modifications post-dating the acquisition of the LiDAR and aerial imagery will not be captured in the susceptibility maps. Actual susceptibilities may therefore differ from those presented in this study and are subject to change with time.

Confirmation of susceptibilities within individual properties would require more detailed, site-specific information on the subsurface conditions and the efficacy of any existing measures to mitigate instability hazards, which is beyond the scope of this study.

6.8.4 Engineered slopes

There are many engineered and treated slopes in the region, including cuttings, fills, and retaining structures built during residential and commercial development and as part of road and rail networks. The available terrain and property information used for mapping the landslide susceptibility zones does not differentiate engineered slopes from unsupported natural slopes (dams and BOPRC-owned stopbanks have been removed from the assessment) and the regional scale of the study makes it impractical to assess whether individual slopes have been engineered and the standards to which the slope has been designed. Consequently, the susceptibility mapping includes engineered slopes and may therefore overestimate or underestimate the true failure susceptibility of those slopes. It should be noted that engineered slopes may not have been designed for large earthquakes or major storms and the effects of climate change.

6.8.5 Data currency

The maps of landslide susceptibility presented in this study should not be regarded as static. The use of updated and/or higher quality datasets and particularly improved mapping of past and existing landslide can allow the susceptibility zones to be refined. We recommend that the landslide susceptibility mapping be updated using new data periodically, or when there is significant step change in data available or need.

7 Applications for the study

7.1 Bay of Plenty Regional Policy Statement Application

The Bay of Plenty Regional Policy Statement (RPS) contains provision for the management of natural hazards within the region and aims to create more resilient communities through improved identification and management of natural hazard risks. The objectives of the natural hazards policy are implemented through a natural hazard risk management process. The landslide susceptibility assessment and mapping completed for this study forms part of the hazard identification part of this process.

The RPS defines 'hazard susceptibility areas' (HSA) as the spatial extent of a potential hazard event identified by susceptibility mapping. The purpose of the HSA is to identify areas that are susceptible to landslides, where a risk assessment is then required under the RPS. The results of this assessment can be used to identify areas of land susceptible to landslide hazards in accordance with Policy NH 7A of the RPS.

7.2 Intended use for the maps

This study was undertaken at a regional scale and is limited to indicating landslide failure zones only; regression zones and runout zones are not included. The maps are for high-level land-use planning purposes and should not be used for site specific analysis of landslide susceptibility. This is because:

(a) The resolution of the data that the maps are based upon is not appropriate for site specific use;
(b) The maps do not incorporate the regression or runout/inundation zones that form a part of landslide hazard.

For the purpose of implementing the RPS, the HSA for landslides can be defined as land classified as moderate susceptibility and above. Site specific analysis should be completed in addition to what is indicated on the susceptibility maps (including consideration of landslide runout and regression) when planning new developments, and/or when applying for Resource or Building Consents.

7.3 Risk reduction measures

In order to manage the risk of landsliding to property, life, buildings, and lifeline infrastructure in the BOP region, different controls on activities and development can be implemented. The landslide susceptibility maps presented in this study can be used to inform these controls. The implementation of specific risk reduction measures should be based on discussions between geotechnical engineers and planners, to ensure that controls are appropriate.

7.3.1 Land use planning

Plan rules and policies, and consenting requirements under the RMA can be used to ensure development proposals do not create future landslide risks or additional costs to communities, and lead to resilience risks to roads and utilities serving these areas (Mason et al., 2015). It would be prudent for the Council to use the landslide susceptibility maps as a screening tool to inform land use planning, urban growth strategies and plan change proposals to manage landslide risk.

Where land is considered susceptible to landslides, the requirement for a geotechnical assessment by a suitably qualified and experienced geotechnical engineer can be implemented as a control by Council. Prospective developers should provide a report summarising such an assessment prior to applying for consent to develop in these areas. We recommend that the Council ensures that this assessment is done by an appropriately experienced Chartered Professional Engineer with geotechnical practice area or Professional Engineering Geologist registered with Engineering New Zealand.

A geotechnical assessment of slope stability should be completed following established guidelines, such as 'Practice Note Guidelines for Landslide Risk Mitigation 2007' (Australian Geomechanics Society, 2007). The report should demonstrate that the risk of proposed activities is not greater than a low risk to property and life, under these guidelines.

7.3.2 Resilience of lifeline and infrastructure systems

The landslide susceptibility maps would also be useful to assess the resilience of Council and other government or privately owned lifeline networks and infrastructure such as transport, water supply, wastewater, power, communications etc., and should be used to inform these assessments. They would also be useful for planning the development of new infrastructure, and for maintenance management.

7.3.3 Emergency management

Landslides cause significant disruption and damage in earthquake and storm events. The hazard maps will be a valuable information resource for lifeline utility providers and the Civil Defence Emergency Management Group to conduct emergency response planning, as it allows analysis of susceptible areas in the event of heavy rainfall or earthquake.

8 Conclusions

Areas of land within the Bay of Plenty region that are susceptible to rainfall- and earthquake-induced landsliding have been assessed and mapped in accordance with internationally recognised guidance and local experience. Landslide susceptibility has been assessed on a region-wide scale, considering factors such as geology, slope angle and relief, and the susceptibility zones have been calibrated using the available landslide inventory data. The methodology used in producing the susceptibility maps is generally in accordance with a “Basic to Intermediate” level assessment as described in AGS 2007a. The outputs of the susceptibility assessment have been mapped in GIS to provide a regional map identifying areas of land that are susceptible to landslide hazards, consistent with Policy NH 7A of the Regional Policy Statement.

The susceptibility maps highlight that moderately steep to very steep slopes in weak soil and rock, sensitive volcanic soils or highly deformed bedrock are the most vulnerable to landsliding. Areas of high susceptibility occur in the axial ranges and on steep bluffs and incised gullies in the volcanic terrains. Records of past landsliding also show these to be areas most prone to landsliding.

Site-specific conditions, analysis of landslide likelihood, and consideration of post-failure effects such as landslide runout or head scarp regression are not captured in the susceptibility mapping. Flat, low-lying areas at the base of hillslopes will be in low susceptibility zones but may still be prone to damage from inundation by landslide debris or debris flows. Therefore, the specific hazards and risks posed by landslides at any given location would need to be further assessed with consideration of the landslide potential (of which susceptibility is a key factor) as well as the consequential effects of landslide runout and headscarp regression.

The severity and frequency of landslides can be expected to increase with climate change and associated more frequent high rainfall events.

The landslide susceptibility maps provide valuable hazard information to inform land use planning, urban growth strategies and plan change proposals, to ensure that development is discouraged in areas of high susceptibility, and instead directed to areas of lower susceptibility. The maps also provide information to understand and plan for the impacts on the resilience of infrastructure networks, and planning of emergency response and recovery after earthquake and severe storm events.

9 Recommendations

Based on the landslide susceptibility assessment, we make the following recommendations for consideration:

1. The landslide susceptibility maps are presented on the regional natural hazards spatial viewer as an overlay, to identify natural hazard susceptibility zones. A disclaimer should be added to the maps, such as:

   The maps indicate the susceptibility of slopes to failure, and do not include areas where regression or runout might occur. The maps do not replace site specific investigations and assessment required for Building or Resource Consent and shall not be solely relied upon for interpreting landslide susceptibility. The maps should be viewed at 1:25,000 in Urban Areas, and 1:50,000 in areas outside of the Urban Areas.

2. More detailed assessment be carried out in Priority Areas. This should include hazard mapping, considering landslide runout and regression to refine the assessment of high landslide susceptibility slopes in prioritised areas, such as the Urban Areas, other urban areas within the Bay of Plenty region, critical infrastructure facilities/corridors, or sites identified for future land use intensification. Further assessment could include refining susceptibility zones and considering landslide runout and regression.

3. The mapped landslide susceptibility zones are reviewed and updated periodically using newly acquired LiDAR terrain, geology, geomorphology data or when there is a step change in data available or need.

4. Require a geotechnical assessment and report by a suitably qualified and experienced Chartered Professional Engineer with geotechnical practice area or Professional Engineering Geologist registered with Engineering New Zealand, where development is proposed in land susceptible to landslides. The geotechnical assessment should follow established guidelines, such as the ‘Practice Note Guidelines for Landslide Risk Mitigation 2007’ (Australian Geomechanics Society, 2007), and demonstrate that the risk of proposed activities is not greater than a low risk to property and life, before a consent is granted.

5. The landslide inventory is continued to be developed, by capturing past as well as future landslides, so that these are widely known and can be used to for quantitative landslide hazard and risk assessments. WSP recommends applying a consistent approach to capturing and recording landslide data. A new National Landslide Database has recently been created by GNS, EQC and Auckland Council. The website (https://landslides.nz/) includes opportunities for both consultants, and the public, to record information on landslides in a consistent manner. WSP recommends this as a viable option, subject to the websites data sharing availabilities, which are unknown at this time.

6. Landslide and rainfall information be collected to improve understanding of landslide hazards and the impacts of climate change on increased landslide occurrence and severity. Rainfall gauges with continuous hourly recording may be installed in areas where BOPRC would like to map landslide hazard at a future date. A greater concentration of rainfall gauges will improve the accuracy of any future landslide hazard map. Geo-professionals should be consulted prior to installing any additional rain fall gauges for this purpose.

10 Limitations of the assessment

This study represents a region-wide appraisal of slope failure susceptibility to assist the Council in managing the risks associated with landslide hazards.

This appraisal is based on regional-scale datasets along with elevation data and aerial imagery, and this should be appreciated in any use of the maps. Some site observations have been undertaken to validate mapping classification, but the maps should be used for region-wide considerations.

The datasets used are appropriate for a regional study but not at the scale of individual properties. Assessments at individual property level have not been carried out, and no intrusive investigations have been completed to determine site-specific conditions. The actual slope failure susceptibility at a particular property may therefore differ from that shown in the maps from this study and would require more detailed site-specific investigation to confirm.

Given the region-wide nature of this study, the areas classed as Very Low or Low slope failure susceptibility cannot be taken to have no land instability. Property owners and developers should seek independent advice on land stability at their particular property, prior to development.

Regression and runout have not been considered during this mapping exercise.

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Appendix A Factor maps

Slope angle

Geological and geomorphic unit

Local slope relief

Land cover

Distance to road

Distance to stream/waterway

Slope profile curvature

Distance to active fault

Appendix B Landslide susceptibility maps

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