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Project Number: 2-9B441.00

Tauranga Landslide Susceptibility Study

Technical Report

22 September 2023

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150 YEARS IN AOTEAROA

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Document Details:

Report No: GER 2023/92
Date: 22 September 2023
Reference: 2-9B441.00
Status: Final

Prepared by

[redacted] s 7(2)(a) - Privacy

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Approved for release by

[redacted] s 7(2)(a) - Privacy

Document History and Status

Revision	Date	Author	Reviewed by	Approved by	Status
0	25 May 22	[redacted]	[redacted]	[redacted]	Draft for peer review
1	16 Aug 22	[redacted]	[redacted]	[redacted]	Revised draft
2	06 Oct 22	[redacted] s 7(2)(a) - Privacy	[redacted]	[redacted]	Final
3	31 Jul 23	[redacted]	[redacted]	[redacted]	Final
4	22 Sept 23	[redacted]	[redacted]	[redacted]	Final

Revision Details

Revision	Details
0	Draft report for external peer review
1	Revised draft report for external peer review
2	Final report following external peer review
3	Extension of maps to complete TCC district and incorporation of observations following significant landslide-triggering rain events
4	Split report into two reports – landslide susceptibility (this report) and slope hazard (IDC) zones

Disclaimers and Limitations

This report ('**Report**') has been prepared by WSP exclusively for Tauranga City Council ('**Client**') in relation to the Tauranga Landslide Study ('**Purpose**') and in accordance with the Short Form Agreement TC103_19 and subsequent variations, amended by mutual agreement. The findings in this Report are based on and are subject to the assumptions specified in the Report. 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.

In preparing the Report, WSP has relied upon topographical data, geological maps, asset data, and other information ('**Client Data'**) provided by or on behalf of the Client. Except as otherwise stated in the Report, WSP has not verified the accuracy or completeness of the Client Data. Conclusions and recommendations in this Report are based on the Client Data, and those conclusions are contingent upon the accuracy and completeness of the Client Data. WSP will not be liable in relation to incorrect conclusions or findings in the Report should any Client Data be incorrect or have been concealed, withheld, misrepresented or otherwise not fully disclosed to WSP.

This study represents a regional-scale assessment of the potential for landslide hazards to occur across the Tauranga City area. This assessment has been completed through a review of desktop information, mapping and photography. It is not intended to precisely describe landslide risk on an individual property level. Actual risk for an individual property should be determined through appropriate investigations, analyses and reporting completed by a Tauranga City Council (TCC) Geo-Professional.

Summary

Tauranga City includes significant areas of steep terrain that are underlain by materials that can be prone to slope failure. Tauranga City Council (TCC) is aiming to improve the understanding and mapping of landslide hazards across the district, as part of a wider initiative to research, quantify and map a variety of major natural hazards affecting the city. This study has been prepared as part of this programme and provides a city-wide assessment of landslide susceptibility.

The scope of the study was evolved in discussion with TCC, and included development of an inventory of landslides in Tauranga, an assessment of landslide susceptibility and mapping this across the city. The study area consists of the Tauranga City boundary, excluding Mauao.

The geology, geomorphology and characteristic mechanisms of landsliding across the study area are described, based on our long-standing experience in the area and the results of a literature review of available information. Factors that influence slope stability were identified and developed from our prior landslide hazard studies in New Zealand and from the results of the literature review, including consideration of the inventory of previous landslides.

Landslide susceptibility is assessed for rainfall-induced landslides and earthquake-induced landslides which have different trigger mechanisms, and the susceptibility varied somewhat depending on these triggers. For the rainfall trigger case, we have applied our experience of the Tauranga district and utilised an inventory of landslides in Tauranga and elsewhere in New Zealand. For the earthquake trigger case, we have considered the limited available information about landsliding in New Zealand volcanic terrains, and supplemented this with observations from reconnaissance following earthquakes in Japan and reports in the literature.

Assessment of the landslide susceptibility is based on weighting of the influencing factors and combining these in a Geographical Information System (GIS) platform using available geospatial datasets. Four categories of slope failure susceptibility are described, from Very Low to High, and these are mapped across the study area in GIS showing the spatial distribution and extent of the different susceptibility categories. Separate maps have been prepared for rainfall- and earthquake-induced landslide susceptibility. The maps should be used at appropriate scales suggested, and where made available to the public through TCC's online GIS mapping platform (Mapi), the scale at which it can be viewed should be restricted.

Recommendations for follow-on actions and future enhancements are provided, including when new terrain data, geology – geomorphology data and landslide inventory data becomes available. It is also proposed that the maps be used in future land use planning, urban growth strategies and plan change proposals, and for TCC's infrastructure departments and made available for other government and private infrastructure owners to understand the resilience of the services provided. The maps would be valuable for use in managing the risk to future development through district plan rules, resource consent applications and for development control. The maps would also be valuable for planning for civil defence emergency response.

Glossary

Term / Acronym	Definition / Meaning
AGS	Australian Geomechanics Society
Aurecon	Aurecon New Zealand Limited
BOP	Bay of Plenty
BOPRC	Bay of Plenty Regional Council
BOPLASS	Bay of Plenty Local Authority Shared Services, a company owned by nine councils in the Bay of Plenty / Gisborne regions to promote shared services between local authorities, including mapping and imagery data.
DEM	Digital Elevation Model
EQC	Earthquake Commission
GIS	Geographic Information System, a mapping system to manage and analyse spatial data.
GNS	Institute of Geological and Nuclear Sciences
IDC	Infrastructure Development Code
LiDAR	Light Detection and Ranging, a remote sensing method that uses lasers to measure the earth's surface.
LIM	Land Information Memorandum
Mapi	Tauranga City Council's publicly accessible online GIS mapping platform, accessed at: https://mapi.tauranga.govt.nz/Html5/index.html?viewer=Mapi.
TCC	Tauranga City Council, 'Council'
TCC Category 1 Geo-Professional	A Chartered Professional Engineer or Professional Engineering Geologist who is acknowledged by TCC as possessing the appropriate qualifications, skills and relevant experience in Tauranga City to provide advice on all geotechnical issues found within the TCC area.
TCC Category 2 Geo-Professional	A Chartered Professional Engineer or Professional Engineering Geologist who is acknowledged by TCC as possessing the appropriate qualifications, skills and relevant experience in Tauranga City to provide advice on a limited number of less complex geotechnical issues found in the TCC area.
Tonkin & Taylor, T+T	Tonkin and Taylor Limited
TVZ	Taupō Volcanic Zone
RPS	Regional Policy Statement
WBOPDC	Western Bay of Plenty District Council
WSP	WSP New Zealand Limited

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1 Introduction

Tauranga is a rapidly expanding regional centre with a growing urban area and planned investment in new growth areas, with a need to construct new infrastructure or upgrade existing infrastructure for improved resilience. The city has a unique geographical and geological setting that makes it prone to landsliding, particularly in response to rainfall and earthquake events.

Tauranga City Council (TCC) is aiming to improve the understanding and mapping of landslide hazards across the district, as part of a wider initiative to research, quantify and map a variety of major natural hazards affecting Tauranga to support initiatives to enhance the resilience of infrastructure and the built environment.

TCC have previously invested in landslide hazard mapping supported by academic and professional studies, but this work has primarily focused on specific events or specific localities within Tauranga. None of the previous studies addressed earthquake-induced landslide susceptibility. The study detailed in this report represents a city-wide assessment of landslide susceptibility that is aligned to the current best practice and regulatory framework, and accounts for observations of landslides in heavy rainfall events in the district and in similar volcanic terrain in Japan that post-date many of the previous studies.

1.1 Commission

WSP New Zealand Ltd (WSP) has been engaged by TCC to undertake a city-wide landslide study to improve the understanding of landslide hazards in the Tauranga district. This study consists of a desktop assessment of landslide hazard susceptibility for earthquake-induced and extreme rainfall-induced landslides across the Tauranga area.

This study has been commissioned as part of a wider TCC initiative to research, quantify and map a variety of major natural hazards affecting Tauranga, including landslide hazards. The other hazards being considered are sea level rise, storm surge, coastal erosion, tsunami, earthquake shaking, liquefaction, volcanic ashfall, and flooding.

The landslide hazard zones used by TCC for development control were also updated and the results included in a separate report (WSP, 2023).

1.2 Scope

The scope for this study includes the following items:

(a) Develop a landslide inventory from existing information and through additional mapping.

(b) Undertake an assessment of landslide susceptibility and produce maps indicating areas that have potential for landsliding.

(c) Provide maps of slope hazard zones that update the existing maps using more recent, higher-resolution terrain data and using engineering geology – geotechnical review (the methodology and results are provided in a separate report (WSP, 2023)).

The assessment of landslide susceptibility is undertaken in accordance with internationally recognised guidance from the Australian Geomechanics Society (AGS, 2007a): 'Guideline for Landslide Susceptibility, Hazards and Risk Zoning for Land Use Planning.'

Two landslide susceptibility maps have been prepared, with susceptibility to rainfall-induced landsliding and earthquake-induced landsliding being assessed separately.

The likelihood of landsliding in different earthquake or storm trigger events has not been considered in this study. It would be appropriate to consider this on a site-specific basis, as required. The likelihood for earthquake triggers will depend on the new National Seismic Hazard Model under development, and storm triggers will vary with the evolving climate change effects.

1.3 Study area

The study area for assessment is shown in Figure 1. Further detail on the study area for assessment is provided in Section 3.1.

The study area includes the Tauranga City district boundary, with the exception of Mauao which was excluded from the study.

Two additional areas to the south of the Tauranga district boundary were included in the study, consisting of water pipeline routes to provide information that was required at the time for assessment of risk/resilience of water assets. However, a regional landslide susceptibility study for Bay of Plenty Regional Council (BoPRC) has since been completed which incorporates these areas. These additional areas are therefore not discussed in this report.

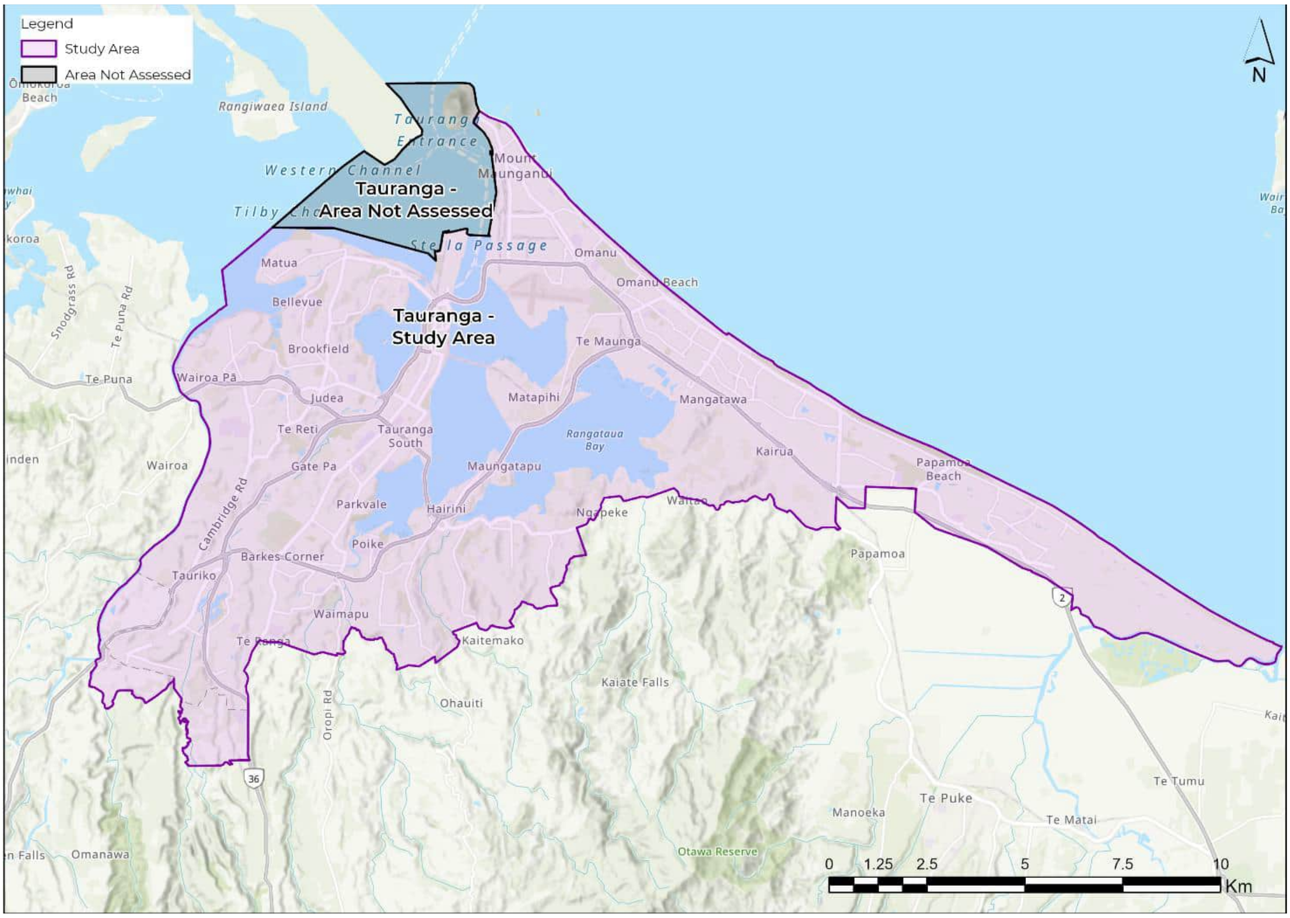

Figure 1: Study area for assessment and excluded area.

1.4 Report purpose

This technical report outlines the methodology developed for building a landslide inventory and characterising and mapping areas susceptible to landsliding across Tauranga. The report then presents the results and limitations of this assessment, including output maps.

2 Study Methodology

2.1 Outline

The objective of this study was to identify areas susceptible to landsliding triggered by rainfall and earthquakes. To identify these areas, we have identified factors that influence slope stability in Tauranga in rainfall and earthquake events and combined these to develop maps of landslide susceptibility. This section of the report details the steps taken in our approach to developing a landslide inventory and identifying areas susceptible to landsliding in Tauranga.

This approach has been developed in accordance with AGS (2007a) guidelines for landslide susceptibility zoning. Key landslide mapping terms defined by AGS (2007a) are shown in Table 1.

This approach has previously been used for mapping earthquake-induced landslide hazards in the Wellington Region (Brabhaharan, et al., 1994) and for mapping landslide susceptibility in Hutt City (WSP, 2021). An ongoing study by WSP to map landslide susceptibility for the wider Bay of Plenty also utilises this approach.

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. Susceptibility may also include a description of the velocity and intensity of the existing or potential landsliding.
Landslide susceptibility zoning	The classification, volume (or area) and spatial distribution of existing and potential landslides in the study area. It may also include a description of the travel distance, velocity and intensity of the existing or potential landsliding. Landslide susceptibility zoning usually involves developing an inventory of landslides which have occurred in the past together with an assessment of the areas with a potential to experience landsliding in the future, but with no assessment of the frequency (annual probability) of the occurrence of landslides.

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

2.3 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 Tauranga were collated and captured onto a GIS platform. Additional mapping was undertaken to delineate areas of landsliding, most of which were attributed to the major storm of 18 May 2005. Landslides were visually identified using historic aerial images, with polygons representing the source and runout zones captured onto a GIS platform with the other records of past landslides.

2.4 Factors influencing landslide susceptibility

Research in the desktop study focused on identifying the key factors that influence landslide susceptibility in Tauranga. 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 or ground conditions 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 4 m by 4 m for each susceptibility factor, allowing each factor to be combined on a cell-by-cell basis. Terrain layers were initially created from a 1 m by 1 m digital elevation model (DEM) that was derived from LiDAR data captured for BOPLASS in 2021. An extract of the DEM is shown in Figure 2, with shading and colouring to highlight the terrain and elevation (blue = lower elevation, yellow = higher elevation).

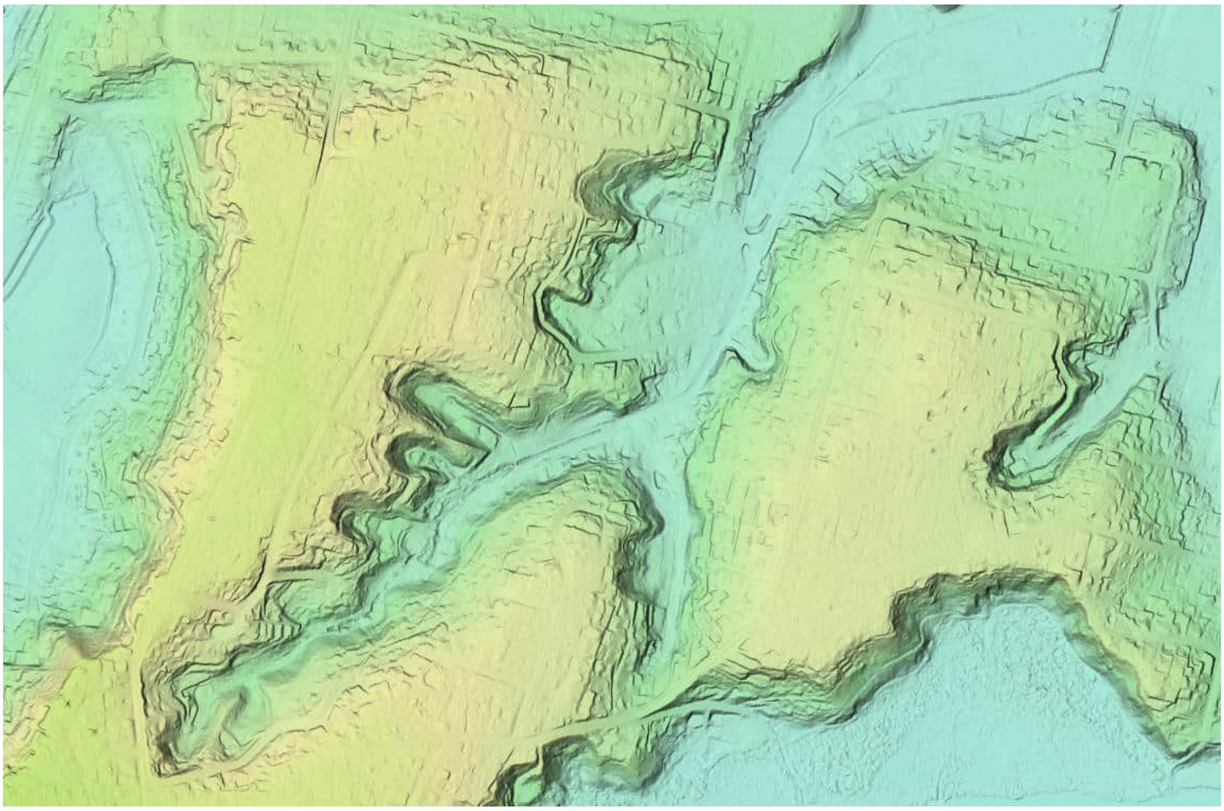

Figure 2: Extract of the 1 m by 1 m DEM (with shaded relief), derived from 2021 LiDAR data.

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 scores were calibrated using the landslide inventory, past reports, local knowledge and terrain data, with adjustments made to factor weightings and class values as required.

Rainfall-induced landslide susceptibility scores were validated using the existing inventory including previous landslide observations in recorded storm events.

Earthquake-induced landslide susceptibility scores were validated by comparing to available information for earthquake-induced landsliding events in New Zealand (e.g., the 2004 Rotoehu, 1987 Edgecumbe, 2016 Kaikōura earthquakes) and overseas (e.g., the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan).

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. 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 Tauranga. Susceptibility map outputs are attached in Appendix A. The associated GIS data has been provided to TCC for use on their online maps and for future studies.

3 Setting

3.1 Study area

The study area for this assessment was defined by TCC and covers the Tauranga City Council area.

Figure 3 shows the location and elevation of the study area and various suburbs around the city. The slopes of Mauao are excluded from the assessment.

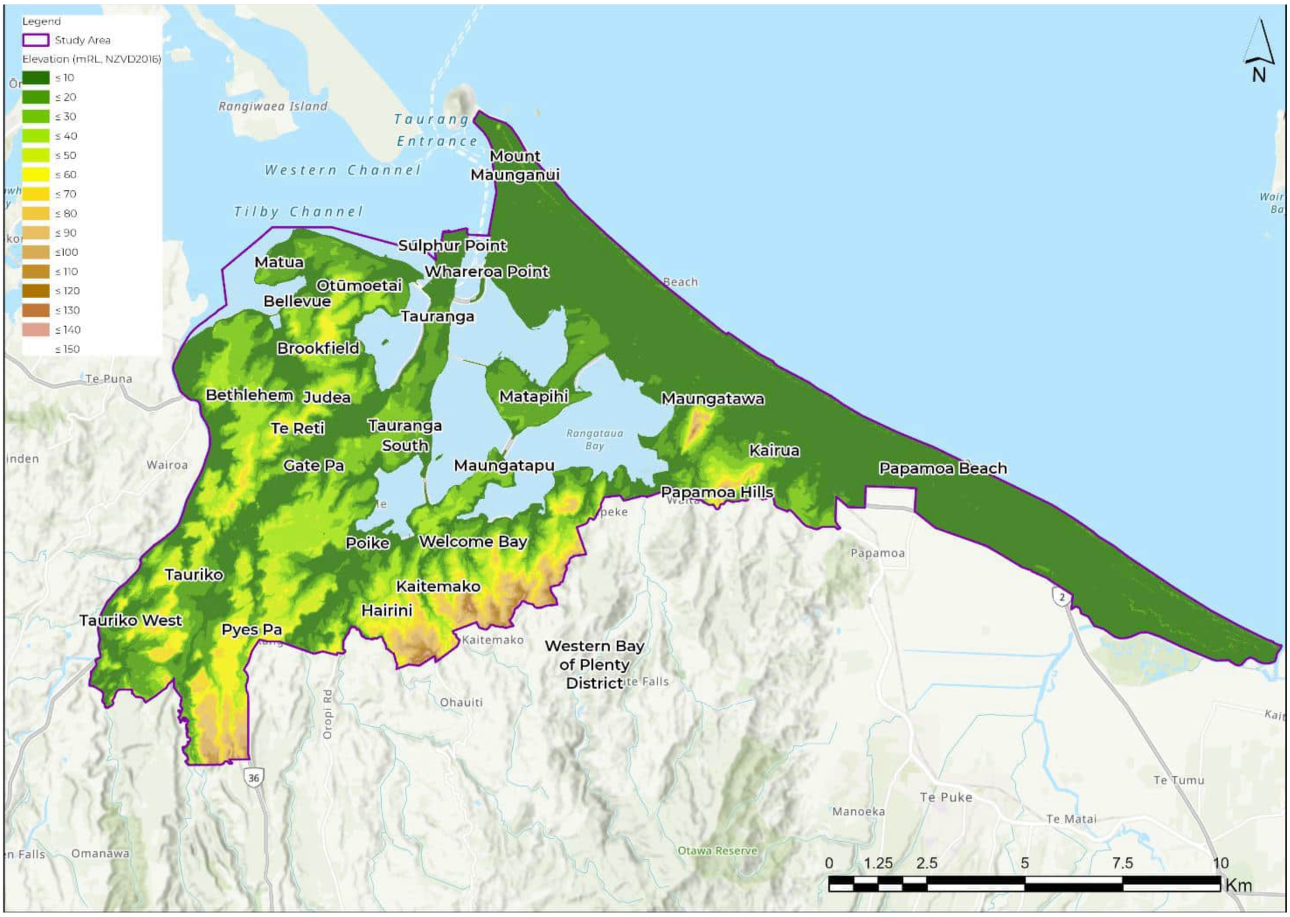

Figure 3: Study area for assessment, showing ground elevation.

3.2 Geology

The boundaries of Tauranga City are generally located within the physiographic extents of the Tauranga basin surrounding the Tauranga Harbour, on a series of NNE-trending terraced peninsulas and coastal features with steeply incised gullies in places. The Tauranga basin is an actively subsiding basin which has been partially infilled by a sequence of terrestrial and estuarine volcaniclastics, ignimbrites and air fall deposits.

The geology of the Tauranga region has been mapped at 1:50,000 scale by (Briggs, et al., 1996), and at 1:250,000 scale by Leonard et al. (2010) and previously Healy et al. (1964). Figure 4 shows the generalised stratigraphy presented by Briggs et al. (1996). A map of the geological units in Tauranga is included in Appendix B.

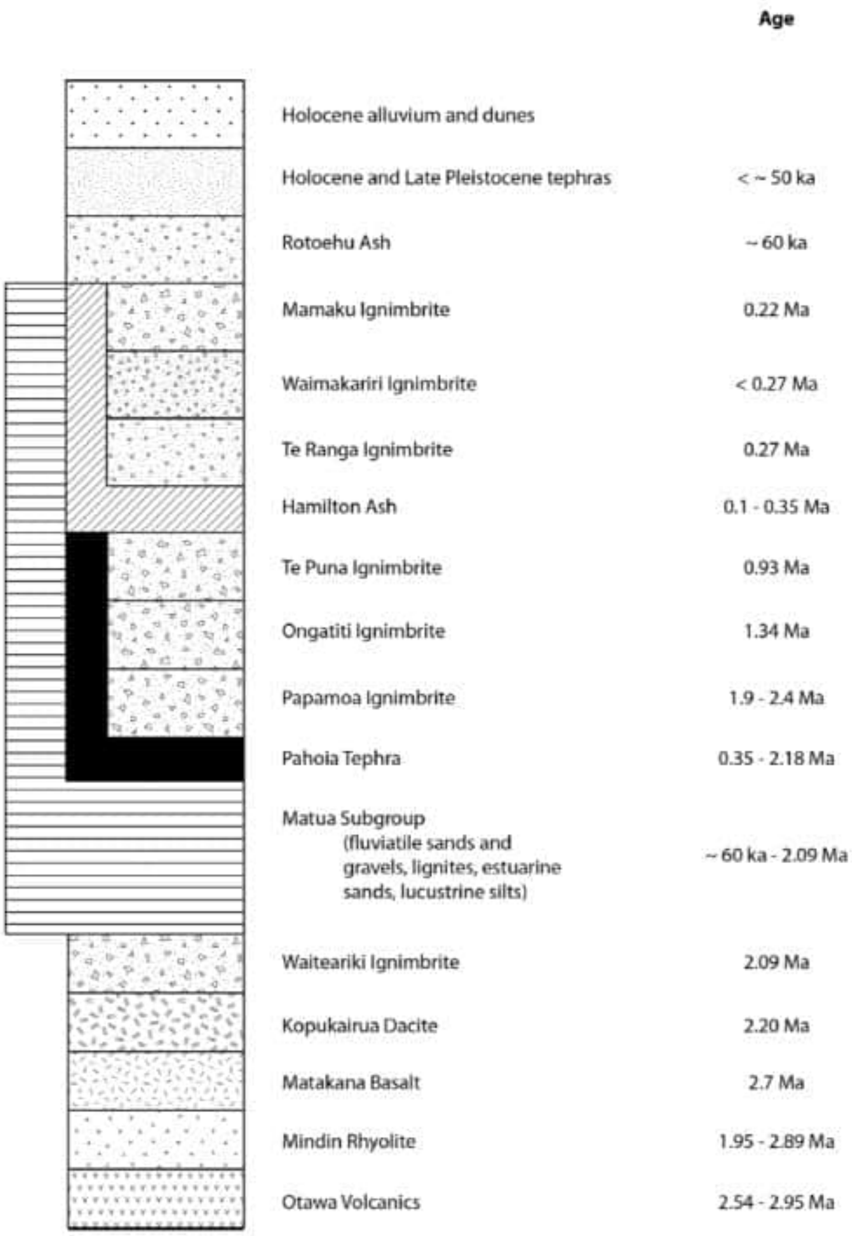

Figure 4: Stratigraphy of the Tauranga region compiled from Briggs et al. (1996).

The Waiteariki Ignimbrite generally forms the local basement within the Tauranga basin. This deposit has been found to be over 200 m thick in places, and gently dips eastward beneath the basin. Within the study area, present-day outcrops of the underlying volcanic deposits only occur in small areas within the Pāpāmoa Hills.

The Waiteariki Ignimbrite was covered by a series of basin-infilling terrestrial and estuarine sediments generated through the reworking of the underlying volcanic units. A sequence of ignimbrites sourced from the Taupo and Coromandel Volcanic Centres were also deposited on top of the Waiteariki Ignimbrite basement. These younger ignimbrites were subsequently incised and eroded, with present-day exposures mapped in elevated areas such as the upper terraces found in the hills in the southern and eastern parts of the city (e.g., Welcome Bay and Pyes Pa).

Reworked ignimbrite materials were deposited in the Tauranga basin, forming part of the Matua Subgroup deposits. This unit is highly variable and is intercalated with ash fall deposits of the Pahoia Tephras. The Matua Subgroup and associated Pahoia Tephras are often significantly weathered and contain sensitive clay materials that make these deposits vulnerable to landslides.

Matua Subgroup and Pahoia Tephra deposits are generally mapped in the lower elevation terraces of Tauranga and have been observed to a depth of up to 150 m in drillholes.

A series of Taupō Volcanic Zone tephras (the Hamilton, Rotoehu and Younger Ashes), unmapped by Briggs et al. (1996), mantle the underlying geological units with a thickness that is highly variable but can be up to 10 m in places.

The Matua Subgroup and Pahoia Tephra deposits are typically the most relevant geological units for landsliding in Tauranga, along with the overlying sequence of ash fall layers. Additionally, some of the younger ignimbrite deposits (notably the Te Ranga Ignimbrite) are non-welded and can therefore be quite weak and prone to landsliding, especially when weathered. These units relevant to landsliding in Tauranga are described in Table 2.

Table 2: Key geological units relevant to landsliding in Tauranga.

Geological Unit	Description
Younger Ash	Pale brown, Holocene and Late Pleistocene tephra deposits from the Taupō Volcanic Zone (TVZ) that post-date the Rotoehu Ash. These deposits form the uppermost soil layer.
Rotoehu Ash	White-grey, pumice-rich rhyolitic tephra deposit, with a fine to coarse sandy texture. This deposit is vulnerable to erosion by groundwater, which can create subsurface cavities (tomos). This unit directly overlays the Hamilton Ash.
Hamilton Ash	Orange-brown, strongly weathered clay-rich formation derived from a sequence of rhyolitic ash fall units. The sequence can be up to 6 m thick and contains several paleosols (old topsoil layers). The upper paleosol, known locally as the 'Chocolate Layer', has a distinctive dark brown colour.
Pahoia Tephras	Clay-rich, rhyolitic ash deposits comprising all tephras pre-dating the Hamilton Ash and post-dating the Waiteariki Ignimbrite. These deposits are intercalated with Matua Subgroup deposits and are often reworked.
Matua Subgroup	Highly variable terrestrial and estuarine sedimentary deposits derived from reworked volcanic materials, intercalated with Pahoia Tephra deposits. Matua Subgroup units form the backbone of Tauranga's terraced peninsulas such as Maungatapu, Matapihi, Matua and Otūmoetai, and Te Papa (the CBD).
Te Ranga Ignimbrite	Light grey, sandy, pumiceous ignimbrite that is unconsolidated and non-welded, thought to originate from a local Tauranga volcanic source. This unit is reported to be prone to gully erosion by Briggs et al. (1996).

3.2.1 Sensitive soils in Tauranga

Sensitive clays occur within deposits of volcanic origin in Tauranga. These materials play a particularly important role in the occurrence of landslides in Tauranga. A significant amount of research has been conducted into the influence of sensitive soils on slope stability in Tauranga and the surrounding areas, particularly by researchers at the University of Waikato.

Halloysite clay has been identified as the key mineral involved in the development of sensitivity in Tauranga's volcanic soils (Moon, et al., 2017). Halloysite forms in silica-rich environments that are slow-draining. In Tauranga, these conditions commonly exist within weathered rhyolitic tephra deposits, especially those that are underlain by less permeable layers, allowing a high groundwater table to be sustained.

Research at Ōmokoroa has shown that the Pahoia Tephras exhibit particularly favourable conditions for the development of halloysite. These materials are predominantly of silica-rich rhyolitic composition and have a high natural water content attributed to a high porosity and low permeability. Additional silica is leached into the Pahoia Tephras through the highly permeable overlying tephras, such as the Hamilton Ash. As a result, Pahoia Tephra samples often exhibit a high proportion of halloysite and a high sensitivity (Kluger, et al., 2017).

3.3 Geomorphology

The geomorphology of the Tauranga area is characterised by a series of terraced surfaces at different elevations, formed by volcanic deposition (e.g., ash fall or pyroclastic flow deposits) and fluvial aggradation.

Subsequent erosion and stream incision dissected the terrace surfaces and resulted in moderately steep to steeply sloping terrace edges. Many of these steep terrace edges form the cliffs around the NNE trending peninsulas that sit in the Tauranga Harbour. The combination of steep terrace edges and sensitive volcanic soils is widely reported to produce areas that are vulnerable to landsliding (Houghton & Hegan, 1980; Oliver, 1997; Bell, et al., 2001; Hegan & Wesley, 2005; Mills, 2016; Moon, et al., 2017).

A map of geomorphic terrains in the Tauranga region was created for the 2020 Tauranga Liquefaction Study. The creation of this map involved collating and interpreting available terrain data, geological mapping, soil mapping, aerial photographs, geotechnical investigation data and a groundwater model. Geomorphic terrains in the eastern part of the city were mapped by Tonkin & Taylor (2020), and the western half of the city was mapped by Aurecon (2020). Mapping was completed at a scale of approximately 1:25,000. A small area in the south-western corner of the study area for the Tauranga Landslide Study was not included in the geomorphic terrain mapping previously completed by Aurecon. For this study, WSP extended the mapping to cover the full study area. A map of the geomorphic units in Tauranga is included in Appendix B.

Table 3 describes each of the geomorphic terrains defined for Tauranga. The mapped geomorphic terrains include upper terraces dominated by ignimbrite deposits with a thin cover of Matua Subgroup alluvial deposits and a thick (>5 m) sequence of mantling ashes sourced from the TVZ (Figure 5). Lower alluvial terraces (Figure 6) typically comprise thick deposits of Matua Subgroup with an overlying ash cover that has a maximum thickness of 5 m to 6 m (Aurecon, 2020). Additional geomorphic terrains are defined to represent alluvial channels, flood plains and coastal margins.

It is noted that there are some inaccuracies in the boundaries between geological and geomorphic units, attributed to inaccuracies in the base data and used for mapping these datasets, and the small scale at which they were mapped. As a result, some of the boundaries do not align with the higher resolution LiDAR-derived slope layers, resulting in accuracies in the assessment where the data is not reliable.

Table 3: Geomorphic terrains in Tauranga, after Aurecon (2020) and Tonkin & Taylor (2020).

Terrain Name	Landform description	Typical geology (upper 10 m)	Expected groundwater depth	Examples in Tauranga
Upper (Ignimbrite) Terrace	Steep-sided upper terraces (up to 60+ m RL) which are generally flat to gently sloping to the northeast. The terraces are inferred to include a thick layer of mantling ash covering ignimbrite deposits.	Ash overlying thin Matua Subgroup alluvium and ignimbrite. Ash cover is >5 m thick.	Typically less than 20 m	Pyes Pa, Welcome Bay hills
Volcanic Hills and Ranges	Low ranges and hills, typically higher in elevation than the Upper (Ignimbrite) Terraces. May also be determined by surficial exposures of rock or capped locally with thin layer of tephra and residual soils.	Variable volcanic deposits including rhyolite, welded ignimbrite, andesite, and dacite are dominant. Ash and alluvial cover deposits are thin or absent. In the study area, this terrain typically coincides with mapped deposits of Minden Rhyolite.	Typically less than 30 m	Mangatawa, hills behind Kairua
Lower (Alluvial) Terrace	Generally steep-sided terraces and sea cliffs (up to 30 mRL). The terraces typically comprising Pleistocene-age or older alluvium, with various interbedded ash and tephra deposits.	Ash covering Matua Subgroup alluvium. The Ash cover is variable and is typically a thickness of maximum 5 m to 6 m at the top of the terrace ridges and thins around the terrace perimeter.	Typically less than 5 m	Maungatapu, Matapihi, Matua, Te Papa Peninsula (CBD)
Alluvial Channels	Active fluvial systems eroding older volcanic terraces forming steep-sided, typically narrow, north-south channels or small gullies. Characterised by colluvial / alluvial deposition typically at the base of gullies or within the upper reaches of stream valleys. Also includes the deposits of side slope processes and fans. May be capped by surficial terrestrial or low energy fluvial sediments, and organic deposits.	Thin deposits of Holocene to recent alluvium, colluvium or peat cover overlying predominantly Matua Subgroup silts / sands with in-situ and reworked tephra. In upper reaches, overlying shallow ignimbrite. The geology is inferred to be significantly influenced by underlying geological units.	Likely to be shallow (less than 5 m)	Kaitemako and Waiorohi Streams, various streams in the Welcome Bay hills
Alluvial Flood Plain	Alluvial Flood Plain and stream valley floors, characterised by low-lying flat topography, and typically dominated by active alluvial processes.	Undifferentiated Holocene-aged alluvium comprising gravel, sand, silt, mud and clay with localised peat; includes modern river beds. Occasionally interbedded with estuarine deposits and peats.	Shallow (less than 1 m)	Wairoa Valley, Kopurererua Valley
Harbour Margin	Low-lying areas surrounding the present-day shoreline of the Tauranga Harbour inferred to be dominated by estuarine type processes, rather than by alluvial or deltaic processes.	Variable combination of Holocene estuarine silts and clays, beach sand or loosely poorly consolidated littoral / fluvial sands.	Shallow (less than 2 m)	Otūmoetai and Matua foreshore

Terrain Name	Landform description	Typical geology (upper 10 m)	Expected groundwater depth	Examples in Tauranga
Land Reclamation	Variable landforms associated with coastal reclamation, infilled gullies, and landfills.	Uncontrolled and engineered fill reworked natural soils or construction waste > 3m. Could also include loose fill end-tipped into the water.	Variable, but typically less than 5 m	Sulphur Point (Port of Tauranga)

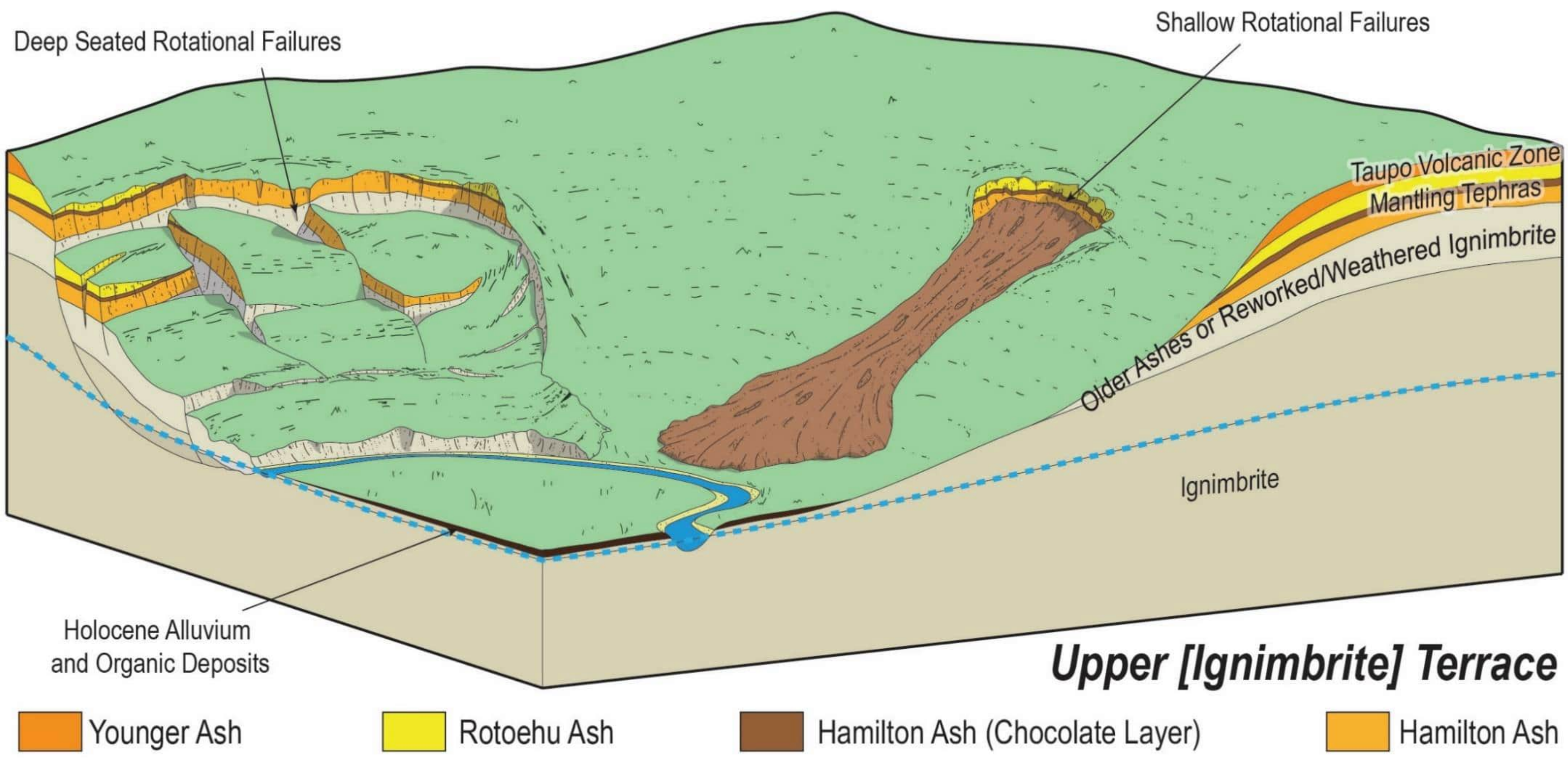

Figure 5: Typical Upper (Ignimbrite) Terrace geomorphic terrain in Tauranga, including typical landslide types observed. Graphic supplied by Aurecon (2022).

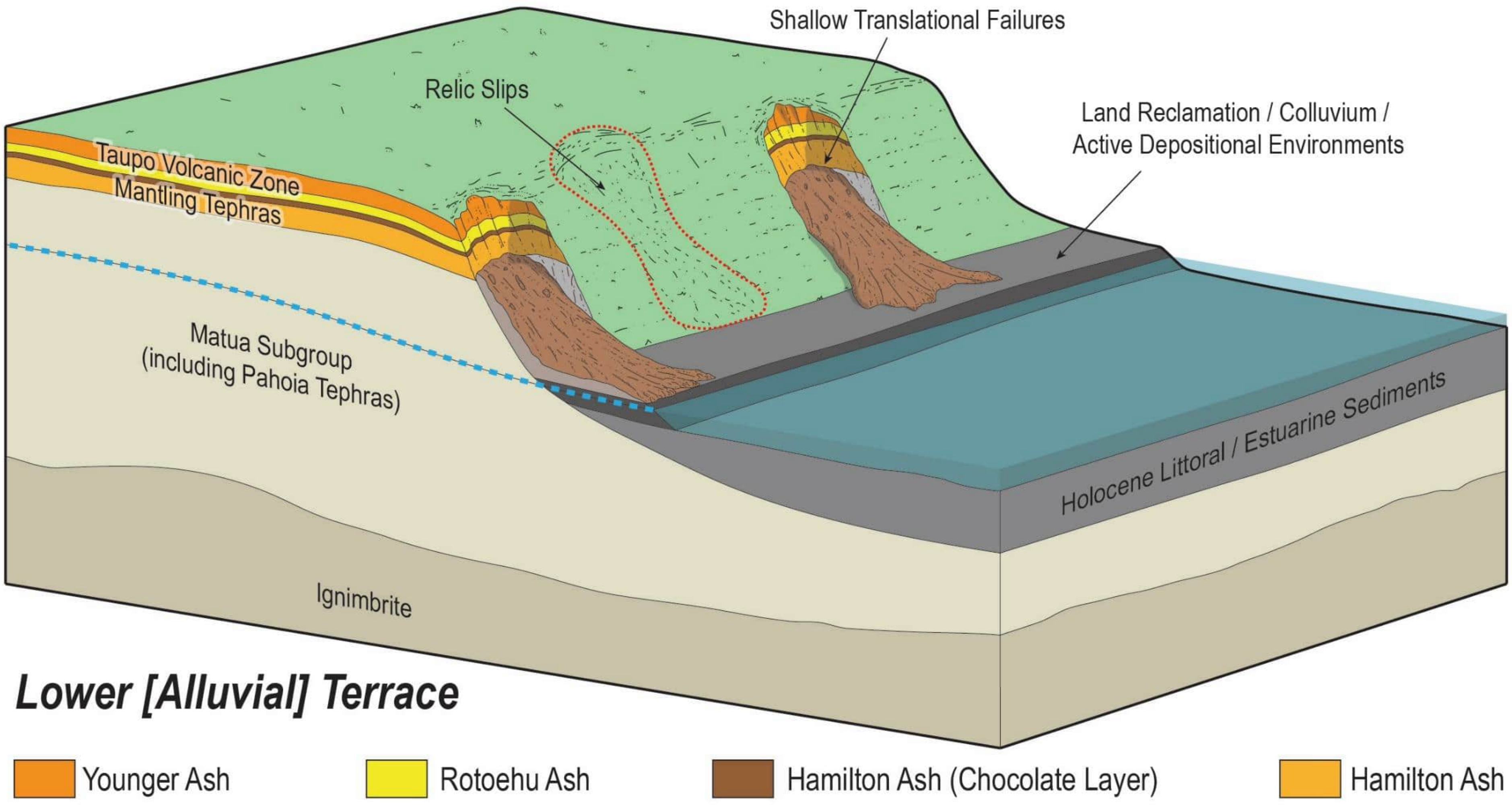

Figure 6: Typical Lower (Alluvial) Terrace geomorphic terrain for a coastal setting in Tauranga, including typical landslide types observed. Graphic supplied by Aurecon (2022).

3.4 Hydrology

Numerous streams flow northwards in incised gullies towards Tauranga Harbour, primarily fed by catchments in the hills to the south of the city. These incised gullies are grouped together in the geomorphic mapping of Tauranga as 'Alluvial Channels'.

The Wairoa River forms part of the western boundary of the TCC area. This river is the largest freshwater tributary to Tauranga Harbour. Parts of the Wairoa River flood plain are located within the TCC boundaries, on the western side of Bethlehem and Tauriko.

Slopes around watercourses are exposed to scour erosion and are also expected to have elevated groundwater levels. These slopes are therefore considered to be more prone to instability compared with an equivalent slope located outside the influence of a watercourse.

LINZ 1:50,000 streams and rivers are used in this assessment to identify the location of watercourses. Distance from these watercourses is used as a metric in the landslide susceptibility assessment, with a lower distance to watercourse associated with greater susceptibility. A map showing distance to watercourses in Tauranga is included in Appendix B.

3.5 Overland flow path

During periods of heavy rainfall, surface flows of water can be created between areas of higher and lower elevation. These overland flow paths form more easily in developed areas where rainwater cannot immediately soak into the ground due to the presence of hard surfaces.

It was highlighted in previous studies that the flow of surface water along overland flow paths increased the likelihood of landsliding in some areas during the 18 May 2005 storm (Hegan & Wesley, 2005; Richards, 2005). The amount of water injected into natural ground can be increased where overland flow paths converge, leading to saturation and elevated pore water pressures. Scour erosion by surface water flows can also destabilise slopes.

When overland flow paths are obstructed, this can affect surface water flow and potentially create issues (such as increased scour or ground infiltration) for adjacent areas.

Overland flow paths were modelled by TCC from a 2D flood model that was derived using high-resolution LiDAR data. Flow paths were classified based on the size of the upstream catchment. 'Major' flow paths have a contributing catchment of 2 ha (20,000 m^2) or more, while 'Minor' flow paths have a contributing catchment of less than 2 ha.

A GIS layer of overland flow paths was provided by TCC for use in this study. This data is presented in Figure 7, and is also available on TCC's online GIS mapping platform (Mapi). Distance from these flow paths is used as a metric in the landslide susceptibility assessment, with a lower distance to flow path associated with greater susceptibility. A map showing distance to overland flow paths is included in Appendix B.

As seen in Figure 7, the overland flow path modelling completed in Tauranga excludes a small section in the southwestern corner of the study area. These exclusions are due to changes to the TCC boundary in the years since the overland flow path modelling was completed. Additionally, no overland flow paths are modelled in the Tauriko West growth area.

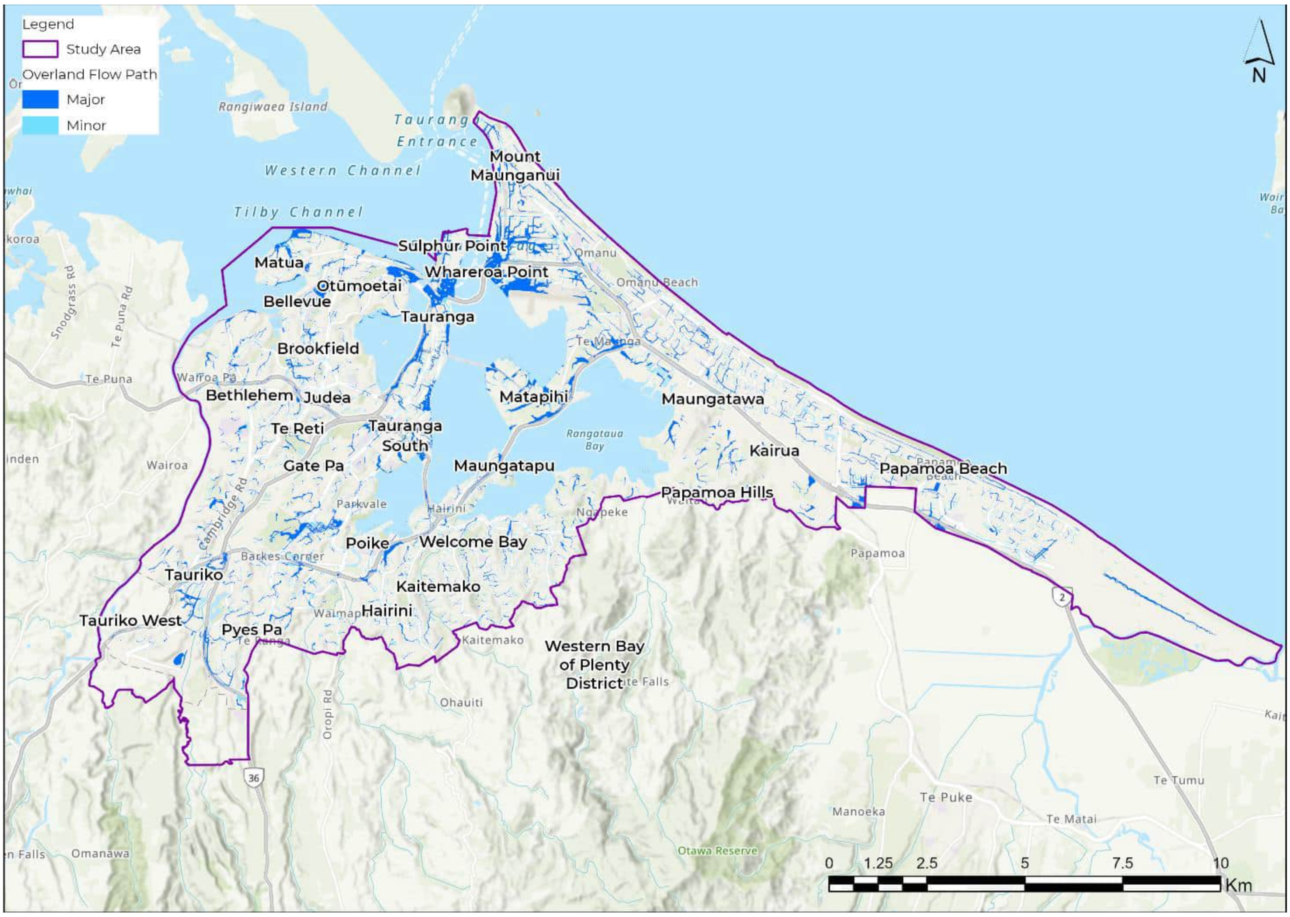

Figure 7: Overland flow paths in the study area. Data provided by TCC.

3.6 Groundwater

Shallow groundwater depths are generally expected to be found in low-lying parts of Tauranga, especially those areas close to the harbour. Groundwater levels are also expected to be elevated in slopes adjacent to rivers.

Elevated terraces on Tauranga's peninsulas are generally expected to have greater depths to groundwater. However, the geology and geomorphology of these terraces affects the groundwater depth. The upper ash cover on many of these terraces is often highly permeable, allowing water infiltration at the surface. Impermeable layers, such as paleosols, exist deeper in the sequences of older tephras and ignimbrites. This combination of permeable surficial layers and impermeable layers at depth can promote perched and elevated groundwater levels in some terrace areas.

Tonkin & Taylor (2019) have developed a groundwater model for TCC (Figure 8). This model was based on data collected from dozens of groundwater monitoring instruments located around the city. These instruments are located in areas close to the harbour coastline and in places with ground elevation less than about 10 mRL.

The Tonkin & Taylor (2019) groundwater model confirms that many parts of Tauranga have shallow depths to groundwater, particularly the low-lying areas close to the harbour and rivers, which are typically underlain by thick sediment sequences that retain groundwater. Elevated terraces, mostly mapped as Lower (Alluvial) and Upper (Ignimbrite) Terrace geomorphic terrains, have groundwater depths of more than 10 m in most places.

The piezometers monitoring points used to collect input data for the model were located primarily in the low-lying flat areas, and therefore the groundwater levels in the elevated areas subject to slope instability are subject to much larger uncertainty. The groundwater model also does not cover the full extent of the area for assessment in this study, with areas in the southern part of the city excluded (Figure 8). These areas are typically higher in elevation and are mostly underlain by Upper (Ignimbrite) Terrace geomorphic terrains where groundwater is known to be at significant depth.

Given the uncertainties and lack of full coverage associated with the available groundwater model, this model was not included as a factor in the landslide susceptibility assessment. Instead, typical groundwater conditions were characterised for the mapped geomorphic terrains, and the effects of shallow groundwater levels were implicitly considered in determining the weightings for each terrain.

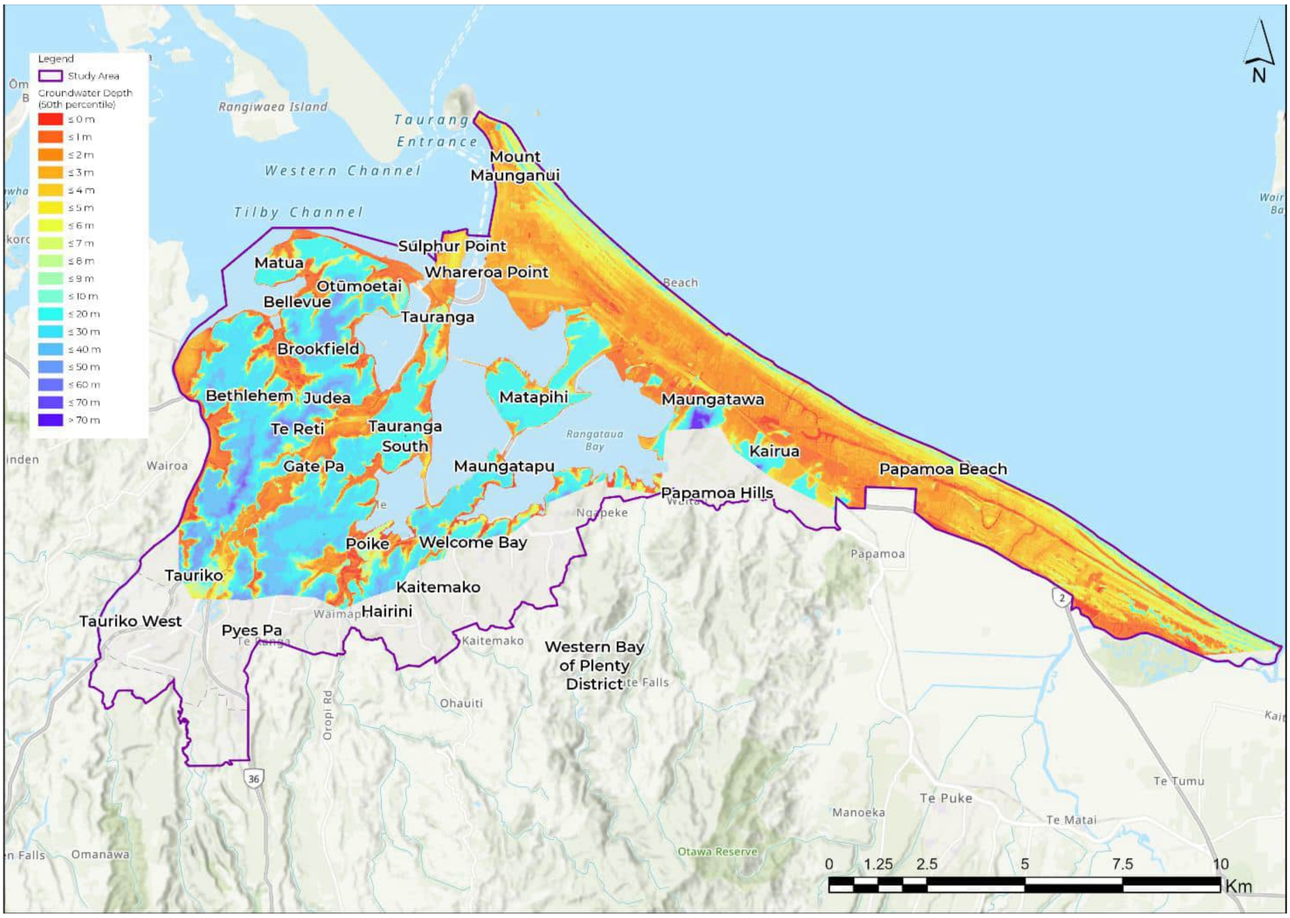

Figure 8: Model of groundwater depth (50th percentile, NZVD2016) produced by Tonkin & Taylor (2019).

3.7 Rainfall

Tauranga receives an average annual rainfall total of approximately 1400 mm (NIWA, 2019). During the southern hemisphere cyclone season (November to April), the region can be exposed to extra-tropical cyclones that bring intense and/or prolonged rainfall. These storms begin as cyclones in the low-latitudinal tropics, and can move south towards New Zealand, transitioning into extra-tropical systems over the cooler oceans.

Intense and/or prolonged rainfall increases the potential for slope failures. Stormwater infiltration into natural ground can cause changes to the groundwater conditions of a slope, such as increasing pore water pressures, inducing water flow within a slope, and saturating slope materials (McColl, 2015). All of these changes can negatively affect slope stability. Surface water runoff along overland flow paths can cause scour erosion that may destabilise slopes.

There are several instances of widespread rainfall-induced landsliding being triggered in Tauranga. Examples include a series of storms in 1979, the 18 May 2005 storm and extra-tropical cyclones Debbie and Cook in April 2017.

Storms producing wet spells (periods starting with a daily rainfall total over 25 mm and ending when daily rainfall drops below 1 mm) are projected to be more frequent and more intense in the Bay of Plenty due to climate change during the 21st century (NIWA, 2019). This is expected to lead to increased instances of rainfall-induced landsliding.

3.8 Seismicity

Compared to many parts of New Zealand, Tauranga is an area of historically low earthquake activity. There are few records of significant seismicity in the historic period, with the most notable event being the 1932 Bay of Plenty earthquake, which had a magnitude of approximately M_S 6.0. In Tauranga, this earthquake caused a ground shaking intensity of MM 5 on the Modified Mercalli (MM) scale of 1 to 12 (Downes, 1995). This earthquake is unlikely to have triggered landsliding in Tauranga.

The New Zealand Active Faults Database from GNS (https://data.gns.cri.nz/af/) indicates that there are no mapped active faults in Tauranga. However, the Christchurch earthquake in 2011 demonstrated that damaging earthquakes can occur on previously unmapped faults hidden beneath layers of sediment.

A probabilistic seismic hazard assessment (PSHA) for Tauranga, completed by Bradley (2019), demonstrated that the seismic hazard in Tauranga is predominantly affected by distributed seismicity (representing earthquakes on unmapped faults) and nearby faults, including offshore faults associated with the extensional Havre Trough and Taupō Rift fault zones. Persaud et al. (2016) also reported that the Kerepehi Fault, running through the Hauraki Plains with a closest distance of about 35 km to Tauranga, could produce ground shaking intensities of MM 6 to MM 7 in Tauranga.

The Hikurangi subduction zone, capable of producing major megathrust earthquakes, is located off the east coast of the North Island. At a distance of over 200 km from Tauranga, the Hikurangi subduction zone does not make an appreciable contribution to seismic hazard in Tauranga.

Ground shaking intensity during an earthquake is affected by near-surface ground conditions. Vs30 values, which reflect the stiffness and composition of materials in the upper 30 m below ground, are often used to represent the ground conditions at a site.

Lower Vs30 values are associated with areas underlain by thick sequences of sediments overlying a deep basement. These conditions exist in Tauranga at the harbour margins, flood plains, and the lower elevation alluvial terraces underlain by thick Matua Subgroup and Pahoia Tephra deposits. Higher Vs30 values in Tauranga are associated with the more competent ignimbrites found in the higher elevation terraces and hills to the south and east of the city (such as Welcome Bay and the Pāpāmoa Hills).

Strong earthquake shaking can trigger landslides by inducing elevated shear stresses and increased pore water pressures, which make a slope more susceptible to failure (McColl, 2015).

Given that there are no records of strong earthquake shaking in Tauranga, there are also no records of associated earthquake-induced landslides. However, there are abundant relic landslide scars identifiable in the Tauranga's terrain, some of which may relate to prehistoric landslides triggered by ground shaking during earthquakes.

4 Previous Studies

During the desktop appraisal, a review of many previous investigations into landslides in Tauranga and similar environments was completed. The purpose of this review was to identify landslide trigger mechanisms on a regional scale, for both rainfall and earthquake triggers, and to refine the methodology implemented for the landslide susceptibility assessment.

4.1 Landslides in Tauranga

Landslide research in Tauranga has primarily focused on rainfall-induced landslides and has often been completed in relation to preceding landslide events, notably in 1979 and 2005. However, researchers from University of Waikato have investigated cyclic shear behaviour of weathered tephras, which can inform the behaviour of these soils in earthquakes (Mills, 2016; Kluger, et al., 2019).

Houghton and Hegan (1980) and Bird (1981) investigated geological factors influencing the occurrence of landslides in March and August 1979, in Maungatapu and Ōmokoroa respectively. Houghton and Hegan (1980) also identified about 250 relic landslides from aerial photographs. Shallow landslides were reported to occur where topsoil layers became saturated and slipped over less permeable underlying layers. Deep-seated landslides were reported to occur due to the disturbance of sensitive materials at depth, probably initiated by excess pore water pressures.

Further landslides occurred in Maungatapu during storms in May and December 1995. Oliver (1997) completed a geotechnical investigation of these landslides and identified both shallow colluvium/topsoil failures and deeper-seated block failures, including some where wave erosion of the slope toe was a contributing factor.

Landslides triggered by the 18 May 2005 storm was investigated by Hegan and Wesley (2005) and by Richards (2005). Landslides were triggered during extreme rainfall (maximum 347 mm 24-hour rainfall total), with heavy rain having also fallen two weeks prior, on 03 May. The events also caused landslides along road corridors in the region causing much disruption to the road network (Opus, 2006). The size of the 18 May storm event corresponded to a return period of approximately 100 years. Hegan and Wesley (2005) noted that groundwater infiltration at soakholes and discharge from overland surface water flow paths onto slopes had contributed to landslide initiation in many cases.

Bell et al. (2001) reviewed aerial images dating from 1943 to 1997 to identify >2,000 relic landslide features across Tauranga. An extract of the map of landslide features they produced is presented in Figure 9. These landslide features have also been added to TCC's online mapping platform (Mapi). Many of the landslide features were not considered to be active and were instead thought to have formed under different physical and climatic conditions to those currently observed in Tauranga. Alternatively, some of these landslide scars may have been associated with historical earthquake events. Based on analysis of the mapped landslide features, Bell et al. (2001) suggested that TCC manage landslide hazards by defining:

- A failure zone, within a line projected upslope from the toe of the slope at 2H:1V (~26.5°).
- A regression zone, within a line projected upslope from the toe of the slope at 3H:1V (~18.5°).
- A runout zone, within a line projected downslope from the crest of the slope at 4H:1V (~14°).

As discussed further in Section 8.2, some landslides (typically fluidised debris flows and mud flows) have been observed to inundate land beyond the 4H:1V zone.

Additional information about slope stability in Tauranga was included in assessments of coastal erosion hazard areas completed by Opus (2015) and Tonkin & Taylor (2018). Consolidated cliffs and banks were one of three coastal morphologies considered in the study. Stable angles for coastal cliffs in Tauranga were based on previously published ranges. High cliffs (such as those in Matua, Matapihi, and Maungatapu) were reported to be the areas of highest coastal erosion hazard.

Researchers from the University of Waikato are regularly conducting studies of slope stability in Tauranga, particularly with regard to the role of sensitive clay minerals. Many of these studies have focused on the Bramley Drive landslide in Ōmokoroa (e.g., Moon, et al., 2017), but other locations within Tauranga City have also been studied, such as Matua (Mills, 2016). Kluger et al. (2020) determined rainfall thresholds for triggering failure in the weathered tephras commonly seen in Tauranga, reporting that a rainfall duration of 25 hours was critical for the occurrence of landslides, when rainfall intensities were moderate (4 mm/hr).

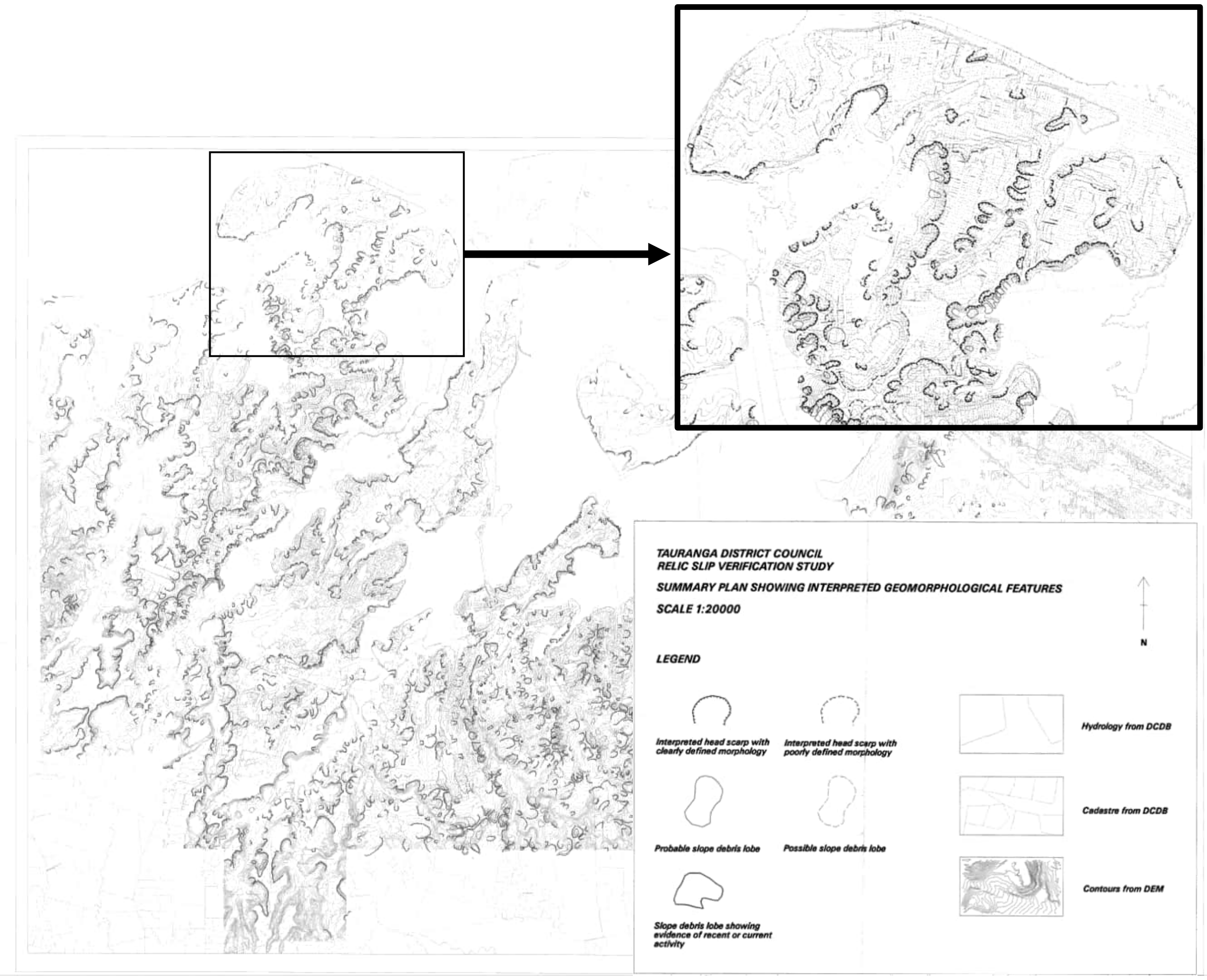

Figure 9: Landslide scarp and debris features mapped in Tauranga by Bell et al. (2001).

4.2 Earthquake-induced landslides

There are no historic records of strong earthquake shaking in Tauranga. To assess the potential for earthquake-induced landslides in Tauranga, it is instead necessary to look at comparable events elsewhere in New Zealand and overseas.

4.2.1 New Zealand

There are limited records of earthquake-induced landslides in volcanic terrains in New Zealand. The 2004 Rotoehu earthquake swarm was reported to have triggered over 100 landslides in the Rotorua lakes area (Hancox, et al., 2004). The most significant landslides occurred due to a M_L 5.4 earthquake on 18 July 2004, which followed three days of heavy rainfall (200 to 300 mm).

Landslides were also triggered during the 1987 Edgecumbe earthquake (M_W 6.5), although this earthquake occurred in summer after a dry spell, which is thought to have contributed to the fact that fewer landslides were triggered compared to the Rotoehu earthquake (Hancox, et al., 2004).

Elsewhere in New Zealand, landslide inventories have been compiled for large magnitude earthquakes such as the 1855 Wairarapa, 1942 Masterton, and 1948 Marlborough earthquakes (Hancox, et al., 1994), 1929 Murchison and 1968 Inangahua earthquakes (Hancox, et al., 2014; Hancox, et al., 2016), and the 2016 Kaikōura earthquake (Massey, et al., 2020).

It is important to note that the geological conditions in Tauranga are different to those in which landslides occurred during the Wairarapa, Masterton, Marlborough, Murchison, Inangahua, and Kaikōura earthquakes. Tauranga is underlain by volcanic soils that can exhibit significant sensitivity due to the presence of halloysite clay (Moon, 2016). As a result, these soils are vulnerable to rapid failure, including during ground shaking that may occur in earthquakes.

4.2.2 Overseas

Recent overseas earthquakes provide the best-studied examples of earthquake-induced landslides in volcanic soils similar to those found in Tauranga.

In Japan, the 2018 M_W 6.6 Hokkaido Eastern Iburi earthquake (Kameda, et al., 2019), the 2016 M_W 7.0 Kumamoto earthquake (Chiaro, et al., 2016), and the 2011 M_W 9.1 Tōhoku earthquake (Chigira, et al., 2013) all triggered landslides in volcanic soils where sensitive clay materials were identified. An earthquake reconnaissance team from New Zealand visited the Kumamoto area after the 2016 earthquakes and observed numerous landslides in volcanic terrain including those that had been triggered by the loss of strength in sensitive volcanic sol layers (Chiaro, et al., 2016). A volcanic deposit rich in halloysite was reported to be the key deposit involved in most landslides that occurred during the 2018 Hokkaido earthquake (Li, et al., 2020).

In Indonesia, the 2009 M_W 7.6 Padang earthquake triggered nearly 1,000 landslides that killed at least 600 people (Nakano, et al., 2013). Many landslides had long runout distances. A halloysite-rich deposit, formed by mixing between a pumice layer and an underlying paleosol, was identified as the primary sliding layer in the landslides generated during the earthquake.

Tauranga is expected to have lower ground shaking intensities than those generated during the Japanese earthquake examples given above. In the 2018 M_W 6.6 Hokkaido earthquake, landslides were primarily identified in areas of 0.4 g to 0.7 g peak ground accelerations (PGAs) and MM 7 to MM 8 shaking intensity (Zhang, et al., 2019). In comparison, MM 6 to MM 7 may occur during an earthquake along the Kerepihi Fault System (Persaud, et al., 2016), while 1,000-year return period PGAs may reach 0.2 g to 0.25 g (Bradley, 2019).

The severity and extent of landslides in Tauranga may therefore not match that seen in the Hokkaido earthquake and other Japanese earthquakes, but these examples are useful for identifying the relationships between landslide-influencing factors and the occurrence of landslides during earthquakes. For example, Kasai and Yamada (2019) reported that slopes of 20° to 30° had the highest probability density for landslides in the Hokkaido earthquake. These investigations were used as a reference when defining the relative importance of landslide-influencing factors for the earthquake-induced landslide susceptibility assessment.

4.3 Resilience studies

Opus (now WSP) undertook a resilience study of the Western Bay of Plenty road network in 2006 (Opus, 2006). This study excluded the Tauranga district but included areas of similar terrain and geology, such as Ōmokoroa. 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, 2002a), including the Tauranga district. 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.

4.4 Other landslide hazards studies

Many landslide susceptibility and hazard mapping studies undertaken by other researchers were reviewed while the methodology for the Tauranga landslide study was developed. Previous regional landslide mapping studies undertaken by WSP were also reviewed.

The first systematic landslide hazard assessment in New Zealand was an earthquake-induced landslide hazard study for the Wellington region (Brabhaharan, et al., 1994). In this study, records of historical landslides caused by earthquakes in the region were compiled, and an approach to identify and combine factors that contribute to landslide susceptibility was developed. Factor weightings were calibrated by considering typical slope characteristics and the observation of past landslides. A susceptibility map was derived, mapped in GIS, and presented, and a table provided landslide magnitudes and hazard that be expected in different earthquake trigger events.

Landslide hazards were mapped as part of the Queenstown-Lakes District Hazards Register and Risk Management study (Opus, 2002b) and this mapped existing landslides and categorised them based on their level of activity.

Dellow (2010) defined landslide susceptibility in 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 geomorphic terrains used in this study for Tauranga.

England (2011) produced a landslide susceptibility map for the West Coast region. This map was produced by combining weighted factors, similar to this study for Tauranga, with factor weights calculated by defining a ranking based on a pairwise comparison of factors.

A slope hazard study for parts of the Whanganui District was carried out by considering slope angle maps, mapping of past rainfall-induced landslides and existing scarps, to provide a two-level hazard map to supplement planning mechanisms formed for the District Plan for the control of development in areas prone to land instability (Mason, et al., 2015).

Kritikos and Davies (2015) used multiple statistical approaches to develop a susceptibility map for shallow, rainfall-induced landslides in the western Southern Alps (between Haast and Hokitika). They reported that a weighted combination of slope angle, lithology, slope aspect, proximity to fault, soil induration (hardness) and proximity to drainage network (e.g., streams) provided the best representation of landslide susceptibility.

A landslide susceptibility study was carried out for the Hutt City district, for the Hutt City Council District Plan Review (WSP, 2021). This study was carried out using a GIS platform, compiling factor maps and then spatially combining them to develop landslide susceptibility maps considering both rainfall and earthquake-induced landslides. A number of landslide inventories were brought together and used to calibrate the landslide susceptibility assessment. This framework formed the basis for this Tauranga landslide study.

5 Landsliding in Tauranga

5.1 Overview

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.

5.2 Where do landslides occur?

AGS (2007a) provides examples of topographical, geological and development settings where landslides may occur. Table 4 presents the examples that are most relevant to Tauranga.

Table 4: Topographical, geological and development settings where landslides may occur

Settings where landslides are a potential issue	Examples	Where in Tauranga?
Where there is a history of landslides	Widespread shallow landslides on steep natural slopes	Welcome Bay, Pāpāmoa Hills
	Debris flows and earth slides from previously failed slopes	Welcome Bay, Pāpāmoa Hills
	Landslides in cuts, fills and retaining walls associated with urban development	Developed areas on steep slopes
	Deep-seated sliding on natural slopes	Maungatapu, Matapihi
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)	Otūmoetai, Matua
	Natural slopes between 20° and 35° (rapid landslide travel is possible)	Welcome Bay, Pāpāmoa Hills
	Cliffs (coastal and inland)	Maungatapu, Matapihi, Matua
	Steep, high road or rail cuttings	Welcome Bay
Where there is no history of landslides, but geological and geomorphologic conditions mean that landsliding is possible	Slopes in highly sensitive weak clays	Slopes city-wide
	Slopes in weathered volcanic rocks	Slopes city-wide
	Steep natural slopes in regions affected by large earthquakes	Slopes city-wide
	Where there is active undercutting of slopes by rivers or the sea	Maungatapu, Matapihi, Matua, CBD
Where there are constructed features which, should they fail, may travel rapidly	Large retaining walls	Developed areas on steep slopes
	Side cast fills on steep slopes	Roads traversing slopes

Tauranga has experienced many instances of shallow and deep-seated landsliding across the city. There are many areas of steep hillslopes, often located near coastal cliffs and/or rivers, and commonly underlain by weathered volcanic soils and rocks. Significant urban development in hillslope areas has seen the modification of slopes using cuts, fills and retaining walls. The geographical and tectonic setting of the city also exposes Tauranga to intense rainfall in storms and ground shaking in earthquakes.

5.3 Types of landslides observed in Tauranga

Tauranga is vulnerable to various types of landslides, but most historic landslides on natural slopes can be grouped by failure mechanism into a small number of categories. Table 5 provides an overview of the most common and important types of landsliding that occur in Tauranga. The landslide classification presented by Hungr et al. (2014) is used when naming failure mechanisms.

Landslides in Tauranga tend to involve rapid movement as opposed to slow creep. This is particularly true for landslides initiated during heavy rainfall, as the presence of stormwater runoff and elevated groundwater levels typically fluidise debris and produce rapid flows with long runout distances.

There is generally limited warning of landslides in Tauranga, and signs of incipient instability, such as tension cracking, ground subsidence, or the formation of subsurface cavities (tomos), can be difficult to identify.

Continued regression at the site of past slope failure is a common feature of many landslides, particularly if exposed ground is subjected to scour by subsequent stormwater runoff or scarps are not stabilised. Regression of an existing landslide feature has been well documented at Bramley Drive in Ōmokoroa and, although less well documented, landslides in Tauranga also undergo regression.

The role of sensitive soils

Sensitive clays, particularly halloysite clay, play a particularly important role in landsliding in Tauranga. Halloysite is a prominent weathering product in silica-rich tephra deposits, such as the Pahoia Tephras.

Sensitive soils experience a significant strength decrease when disturbed, causing soils to rapidly transform into weak, liquefied materials. Elevated pore water pressures are often the cause of this disturbance. In Tauranga, pore water pressure increases can be induced by water infiltration through the permeable ash cover during intense or prolonged rainfall. Ground shaking during earthquakes can also increase pore water pressures and trigger failure in sensitive soils (Mills, 2016).

If failure of a sensitive layer occurs at depth, this layer can act as a basal shear surface on which the overlying layers become rafted and slide downslope. This kind of failure mechanism has been observed at the well-studied Bramley Drive landslide in Ōmokoroa (Moon, et al., 2017).

Table 5: Types of landslides that are common in Tauranga

Type of landslide	Description	Example(s) in Tauranga	Image
Shallow translational slide-flows	Failure in shallow volcanic ash layers, with relatively planar failure surface. Relatively small amount of material. Often due to water infiltration into (and possible saturation of) permeable layers overlying a less permeable layer (e.g., a paleosol). Long runout distances, particularly if lots of water is present. Hamilton Ash deposits at the surface often exhibit tension cracking, allowing water ingress, and contain several lower permeability paleosols. This failure mechanism is therefore more likely within this unit.	Various locations where there is a shallow ash cover. Past examples: - Pāpāmoa Hills - Welcome Bay - Coastal cliff areas in Maungatapu and Matua (and in nearby Ōmokoroa)	 *Ōmokoroa (Moon et al. (2017), University of Waikato)*
Shallow rotational slide-flows	Failure in shallow volcanic ash layers, with rounded failure surface. Relatively small amount of material. Often due to erosion by surface and groundwater, which can create cavities that can trigger rotational failure. Flows are generated when water mixes with debris. The pumice-rich Rotoehu Ash is prone to erosion by surface and groundwater, meaning this failure mechanism is more likely within this unit.	Various locations where there is a shallow ash cover. Past examples: - Pāpāmoa Hills - Welcome Bay	 *Pāpāmoa Hills (Emma Kapua (2017), Facebook)*
Deeper-seated rotational slides	Failure in deeper, sensitive volcanic soils (e.g., Matua Subgroup and Pahoia Tephra deposits). Relatively large amount of material. Collapse often caused by disturbance or elevated pore water pressures. Multiple regressive failures possible over time (e.g., Bramley Drive, Ōmokoroa). Often occur where the groundwater table is shallow. Loss of support (e.g., due to erosion of coastal cliffs) can make these failures more likely.	Areas mapped in the Lower Terrace geomorphic unit featuring the Matua Subgroup / Pahoia Tephras. Past examples: - Coastal cliff areas in Maungatapu and Matua (and in nearby Ōmokoroa)	 *Ōmokoroa (WBOPDC website, 2017)*

6 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.

6.1 Existing data sources

Several sources of data are available to identify past landslide locations in Tauranga. The types of data available range from maps of many landslide features to written descriptions of individual landslides (usually in site-specific geotechnical reports).

Where available, spatial landslide data were compiled in a GIS platform. This allowed comparison of landslide locations with maps of landslide-influencing factors.

Table 6 summarises the existing landslide datasets that were accessed during the desktop appraisal.

Table 6: Available landslide datasets for the Tauranga area.

Dataset	Source	No. landslides in study area	Landslide date range	Data type
Relic landslide features	Bell et al. (2001)	1361 scarps, 726 debris features	Up to 1997	Lines showing scarp and debris features
NZ Landslide Database	GNS	18	2005 to 2011	Point locations
EQC landslide claims	EQC	210	2000 to 2021	Addresses only
Landslides from 1979 storms	TCC	75	1979	Addresses only
Landslides from May 2005 storm	TCC	67	2005	Point locations
Past inspections by WSP	WSP in-house database	17	1977[1] to 2007	Points, addresses, and road distances

[1] One landslide not dated but believed to have been present since at least 1977.

6.1.1 *Relic landslides features*

Relic landslide features mapped by Bell et al. (2001) included scarp lines and debris features, separated into different types including:

- Poorly defined head scarps with no associated debris
- Poorly defined head scarps with associated debris

- Clearly defined head scarps with no associated debris
- Clearly defined head scarps with associated debris
- Features with evidence of recent or current movement

Figure 9 shows an extract of the relic landslide features mapped by Bell et al. (2001). Note that some of features are outside the area assessed in this study. The data are included in TCC's online GIS mapping platform (Mapi).

Each feature was assigned attributes such as slope angles (for the scarp and runout debris), scarp height, width, and elevation, and geological unit. The presence of seepage was recorded where identified.

Bell et al. (2001) noted that many of the landslide features were not considered to be active because they were thought to have developed under different physical and climatic conditions to those observed in Tauranga at present. These features are not explicitly differentiated from more recent landslides in the map.

6.1.2 New Zealand landslide database

The GNS New Zealand Landslide Database (NZLD, https://data.gns.cri.nz/landslides/index.html) comprises a mix of point, line, and polygon data showing landslide locations across the country. Locations are identified from a variety of sources, including aerial imagery, reconnaissance studies, and media reports.

Only 18 landslide points are available in Tauranga. Upon inspection of these points, we identified some mis-locations. One notable example is a landslide on Vale Street during the 18 May 2005 storm, which was mapped in the NZLD in a location over 1 km away from the actual landslide site, in an area mapped by Leonard et al. (2010) as a different geological unit (Figure 10).

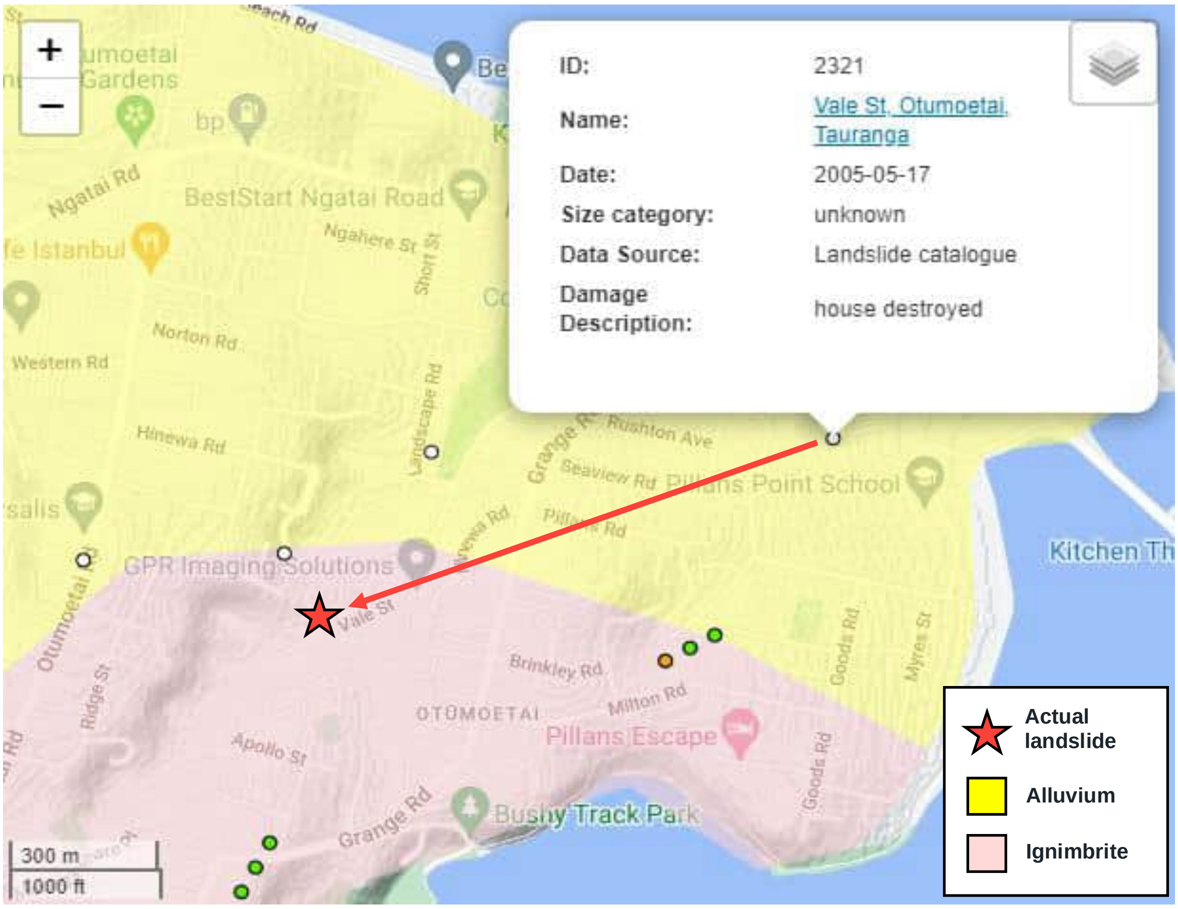

Figure 10: Mis-location of an 18 May 2005 landslide on Vale Street, in the GNS New Zealand Landslide Database (with GNS geological mapping underlay).

6.1.3 EQC landslide claims

Addresses where insurance claims had been lodged in relation to landsliding were provided by EQC. Of these claims, 210 entries were located within the study area in Tauranga. The locational accuracy of these landslides is poor because only the property address is available, as opposed to the actual landslide location. An example of this is shown in Figure 11. In addition, EQC landslide claims can relate to failure of retaining walls and other man-made structures, for which the correlation of landslide occurrence to landslide-influencing factors is likely to be different when compared to unsupported slopes.

Figure 11: EQC data point (yellow pin) for an April 2017 landslide in Maungatapu. EQC data has only address information, so points are not located at the true landslide location.

6.1.4 TCC-held landslide data, 1979 and 2005 storms

Point data were provided by TCC for landslides relating to storms in 1979 and May 2005. Like the EQC data, the 1979 landslide data comprise property addresses only, so location accuracy is poor. The May 2005 landslide point data are generally located closer to the true landslide locations, but locational errors of up to 50 m were still apparent in some cases.

6.1.5 Past inspections by WSP

A number of past geotechnical reports completed by WSP were reviewed, and 17 landslides were identified within the study area. A further 12 landslides were located on low-volume roads in the Pāpāmoa Hills, outside the study area.

Most landslide locations are described in the text of the reports using reference points such as road route positions or associated property addresses.

Several of the landslides reported on by WSP are also included in other datasets, such as an underslip on Welcome Bay Road near Rocky Cutting Road that was initiated during the 18 May 2005 storm.

6.2 Additional inventory mapping

During a review of available historic imagery, WSP identified numerous landslides that were not captured in the existing landslide inventory. Additional inventory mapping was therefore undertaken by WSP to build a more complete inventory of landslides. Landslides were mapped as polygons to provide an indication of the extent of landslides. Where possible, landslides were divided into source and runout areas.

The majority of additional landslides mapped were triggered during the 18 May 2005 storm. These landslides were mapped using Google Earth imagery captured before and after the storm event (in March 2003 and May 2005). 256 landslide features were mapped, with debris runout areas being mapped for 69 of these. An additional 8 features believed to be associated with retaining wall failures were mapped.

A small number of landslides triggered at other times were identified from historic imagery available on Google Earth and Retrolens and added to the inventory. 21 landslides were identified as having occurred after May 2005, and 6 landslides were identified as having occurred before May 2005. An additional 4 landslides were not dated.

6.3 Inventory compilation

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

- Relic landslide features from Bell et al. (2001)
- NZ landslide database from GNS
- Residential landslip insurance claims from EQC
- Landslide data relating to storms in 1979 and May 2005 from TCC
- Landslides identified in past investigation by WSP
- Landslide polygons mapped by WSP as part of this study (mostly comprising landslides triggered in the 18 May 2005 storm)

A map of the compiled landslide data is included in Appendix C.

When undertaking calibration and verification of the final landslide susceptibility maps in this study, the Bell et al. (2001) landslide features and the landslides mapped by WSP were used as the primary reference data from the landslide inventory. This is because, as noted in Section 6.1, several of the existing landslide data sources comprise point locations, with some datasets providing only the address of a property within which landslides had occurred.

Point landslide data can be problematic for use in correlating landslide occurrence with landslide-influencing factors. The extent of the landslides is unclear from point data and locational accuracy can be poor. For example, landslides on cut slopes around transport corridors may be represented by a point located on the adjacent road surface.

6.4 Limitations

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

6.4.1 Indistinct past landslide features

Some slopes in Tauranga, particularly at steep terrace edges and coastal cliffs, are the product of retrogressive landsliding over long time periods. These features may no longer be active, as noted by Bell et al. (2001), but some may still be included in the available database of relic landslide features. There are other slopes formed through long-term retrogressive landsliding which are not displayed as relic landslide features in the Bell et al. (2001) inventory. Distinct scarps and debris deposits may not be visible on these slopes, but there may still be potential for landsliding in these areas.

6.4.2 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.

6.4.3 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 highly dependent on the quality of aerial imagery used to identify the features. For example, partial cloud cover was present in places in the imagery captured after the 18 May 2005 storm, which increased the difficulty of identifying landslides. As discussed in Section 6.1, the locational accuracy of the point and address-based landslide data is often poor.

6.4.4 Dependence on the May 2005 storm

The landslide polygons mapped by WSP are predominantly triggered by a single event (the 18 May 2005 storm), which somewhat limits the potential for a robust statistical calibration of the final landslide susceptibility map. Each storm or earthquake is different, but the susceptibility map is intended to be independent from specific storm or earthquake events.

6.4.5 Lack of earthquake-induced landslide records

No earthquake-induced landslide data are available for Tauranga. Instead, landslide data from comparable events in New Zealand and overseas had to be reviewed in order to verify and calibrate the earthquake-induced landslide susceptibility.

7 Landslide Susceptibility Assessment

7.1 Overview

The susceptibility assessment carried out for this study focused on the landslide failure zone. Assessment of runout susceptibility was not included, and this would be necessary as part of a hazard or risk assessment. Landslide susceptibility was evaluated by identifying and combining geological and geomorphic factors that have been spatially mapped and that represent predisposing factors of the landscape or are proxies for the physical processes that contribute to landslides. The rainfall-induced and earthquake-induced landslide susceptibility cases were assessed independently.

Each factor and its constituent classes were weighted according to their relative importance in contributing to landslide occurrence. The weightings are described in the following section. 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 score was then calculated for each grid cell in the GIS dataset by summing the weighted values for all factors, as shown in the equation below.

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

The landslide susceptibility scores were then classified into four categories to represent Very Low, Low, Moderate and High landslide susceptibility. The scoring breaks used to define these classes are shown in Appendix D.

7.2 Weighting of factors

Factors that influence the potential for landsliding in Tauranga were identified during the desktop appraisal, based on WSP's knowledge of the study area and a review of previous investigations into landsliding in Tauranga and similar environments (as summarised in Section 4). These factors are characteristics that represent proxies for the physical processes that contribute to the occurrence of landslides and are particularly relevant to Tauranga.

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. A quantitative approach using the frequency ratio method was 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 factor were assigned based on the assessed relative importance of the factor. 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 slope profile curvature.

Different weightings were used for the rainfall and earthquake trigger cases, where appropriate, to reflect the relative importance of these factors in landslides being triggered by each event type.

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

1. Slope angle
2. Geomorphic unit
3. Local slope relief
4. Geological unit
5. Distance to overland flow path
6. Distance to stream
7. Slope profile curvature

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

1. Slope angle
2. Local slope relief
3. Geomorphic unit
4. Geological unit
5. Slope profile curvature

Maps of the selected factors are presented in Appendix B. Other factors that were investigated but not included in the assessment are discussed further in Section 7.7.

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

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

7.3 Model calibration and refinement

Various checks were undertaken to validate the landslide susceptibility map. The susceptibility scores 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 scores were calibrated by overlaying rainfall-induced landslides from the landslide inventory with the susceptibility scores, to determine whether the modelled susceptibilities correctly reflect past landslide locations. Sensitivity analysis of the factor weightings was undertaken to test the output susceptibility score against different combinations of slope angle, geology and relief.

Since no earthquake-induced landslides are included in the existing landslide inventory for Tauranga, the earthquake-induced landslide susceptibility scores were compared to available information for earthquake-induced landsliding events in New Zealand (e.g., the 2004 Rotoehu, 1987 Edgecumbe, 2016 Kaikōura earthquakes) and overseas (e.g., the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan). In particular, the 2016 Kumamoto and 2018 Hokkaido earthquakes in Japan were used to calibrate the susceptibility scores since these earthquakes were associated with landsliding in volcanic materials, which are also the predominant geology in Tauranga.

Table 7: Selected landslide susceptibility factors for rainfall trigger case.

Susceptibility factor	Factor weighting	Factor class	Factor value	Influence on landslide susceptibility
Slope angle (α)	6	α ≤ 15° 15° < α ≤ 20° 20° < α ≤ 25° 25° < α ≤ 35° 35° < α ≤ 45° 45° < α ≤ 55° α > 55°	0 2 5 7 8 9 10	Steeper slope angles are considered to correspond to greater susceptibility to landslides. The shear force acting on a slope due to gravity is greater when the slope is steeper, meaning that the shear strength of the material on the slope (that acts to resist downslope movement) is more likely to be overcome in a trigger event.
Local slope relief (r)	3	r ≤ 3 m 3 m < r ≤ 5 m 5 m < r ≤ 10 m 10 m < r ≤ 20 m r > 20 m	0 2 6 8 10	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.
Geomorphic unit	4	Lower (alluvial) terrace Upper (ignimbrite) terrace Volcanic hills and ranges Alluvial channels Harbour margin Alluvial flood plain Fixed foredunes Land reclamation	6 4 2 8 6 6 6 4	Geomorphic units are defined to group areas of similar geology and terrain. Units with weaker geological materials and soils, and shallower groundwater are more susceptible to landslides. Lower (Alluvial) Terrace geomorphic terrains are particularly susceptible as there are often steep slopes at the terrace edges and incised gullies, and these terrains typically have thick deposits of Matua Subgroup and the sensitive Pahoia Tephras. The Lower (Alluvial) Terrace terrain is also often reported to have relatively high groundwater table due to the presence of permeable ashes near the surface and impermeable horizons at depth (both at the basement ignimbrite and within the Matua Subgroup / Pahoia Tephra deposits).
Geological unit	2	Pahoia Tephra; Matua Subgroup Te Ranga Ignimbrite Minden Rhyolite Waimakariri Ignimbrite Mamaku Ignimbrite Ongaiti Ignimbrite Papamoa Ignimbrite	10 8 6 4 2 2 2	The lithologies of slope materials have different shear strength and permeability characteristics, which influence the vulnerability of the slope to erosion and weathering. Weaker, unconsolidated materials (such as Quaternary age alluvial and estuarine sediments) are more susceptible to instability than strong consolidated rocks. Deposits of Matua Subgroup and Pahoia Tephra are particularly susceptible due to the sensitivity of halloysite clays known to be

Susceptibility factor	Factor weighting	Factor class	Factor value	Influence on landslide susceptibility
		Waiteariki Ignimbrite Pleistocene alluvium Holocene alluvium Holocene peat Holocene fixed foredunes Reclaimed land	2 10 8 8 6 4	present in the Pahoia Tephras. Ignimbrites are more susceptible to landslides when non-welded, and less susceptible when highly welded.
Distance to stream (d_{st})	1	$d_{st} \leq 5$ m 5 m < $d_{st} \leq 10$ m $d_{st} > 10$ m	6 4 0	Slopes located closer to streams are more susceptible to landslides given that there is a higher likelihood of undercutting and destabilisation due to scour erosion at the toe of the slope. Groundwater conditions are also likely to be elevated in slopes around a stream, meaning the likelihood of slope materials being saturated and having elevated pore water pressures is greater, which in turn increases the susceptibility of these slopes to failure.
Distance to overland flow path (d_{fp})	1	Within flow path $d_{fp} \leq 5$ m 5 m < $d_{fp} \leq 10$ m $d_{fp} > 10$ m	10 6 2 0	Increased surface water flow increases the susceptibility of a slope to saturation and elevated pore water pressures, which in turn increases the susceptibility of the slope to failure. Scour from water flow along the slope can also erode material and destabilise the slope. Weaker, unconsolidated materials are typically more vulnerable to this scour erosion. Overland flows of water were reported to have increased the occurrence of landslides in the 18 May 2005 storm. Major overland flow paths (with a larger contributing catchment) are more likely to increase landslide susceptibility compared to minor overland flow paths.
Slope profile curvature (c)	1	Convex ($c \leq -0.1$) Linear ($-0.1 < c \leq 0.1$) Concave ($c > 0.1$)	0 2 4	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.

Table 8: Selected landslide susceptibility factors for earthquake trigger case.

Susceptibility factor	Factor weighting	Factor class		Factor value	Influence on landslide susceptibility
		Upper (Ignimbrite) Terrace	Non-ignimbrite terrains		
Slope angle (α)	8	α ≤ 20° 20° < α ≤ 30° 30° < α ≤ 40° 40° < α ≤ 50° α > 50°	α ≤ 15° 15° < α ≤ 20° 20° < α ≤ 30° 30° < α ≤ 35° α > 35°	0 2 6 8 10	Steeper slope angles are considered to correspond to greater susceptibility to landslides. The shear force acting on a slope due to gravity is greater when the slope is steeper, meaning that the shear strength of the material on the slope (that acts to resist downslope movement) is more likely to be overcome in a trigger event.
Local slope relief (r)	6	r ≤ 3 m 3 m < r ≤ 5 m 5 m < r ≤ 10 m 10 m < r ≤ 20 m r > 20 m		0 2 6 8 10	Steeper and higher slopes are more susceptible to failure, particularly in earthquakes since ground shaking can be amplified by steep slopes of greater height. Slope height also influences the maximum potential size and runout of landslides. This factor represents the local height and angle of the slope surrounding each DEM grid cell (i.e., the larger scale slope steepness). It is calculated by comparing the difference in elevation between the cells within a given radius of the sample grid cell.
Geomorphic unit	4	Lower (alluvial) terrace Upper (ignimbrite) terrace Volcanic hills and ranges Alluvial channels Harbour margin Alluvial flood plain Fixed foredunes Land reclamation		6 4 2 8 6 6 6 4	Geomorphic units are defined to group areas of similar geology and terrain. Units with weaker geological materials and soils, and shallower groundwater are more susceptible to landslides. Lower (Alluvial) Terrace geomorphic terrains are particularly susceptible as there are often steep slopes at the terrace edges and incised gullies, and these terrains typically have thick deposits of Matua Subgroup and the sensitive Pahoia Tephras. The Lower (Alluvial) Terrace terrain is also often reported to have relatively high groundwater table due to the presence of permeable ashes near the surface and impermeable horizons at depth (both at the basement ignimbrite and within the Matua Subgroup / Pahoia Tephra deposits).
Geological unit	2	Pahoia Tephra; Matua Subgroup Te Ranga Ignimbrite Minden Rhyolite Waimakariri Ignimbrite Mamaku Ignimbrite Ongaiti Ignimbrite Papamoa Ignimbrite		10 8 6 4 2 2 2	The lithologies of slope materials have different shear strength and permeability characteristics, which influence the vulnerability of the slope to erosion and weathering. Weaker, unconsolidated materials (such as Quaternary age alluvial and estuarine sediments) are more susceptible to instability than strong consolidated rocks. Deposits of Matua Subgroup and Pahoia Tephra are particularly susceptible due to the sensitivity of halloysite clays known to be

Susceptibility factor	Factor weighting	Factor class	Factor value	Influence on landslide susceptibility
		Waiteariki Ignimbrite Pleistocene alluvium Holocene alluvium Holocene peat Holocene fixed foredunes Reclaimed land	2 10 8 8 6 4	present in the Pahoia Tephras. Ignimbrites are more susceptible to landslides when non-welded, and less susceptible when highly welded.
Slope profile curvature (c)	1	Convex ($c \leq -0.1$) Linear ($-0.1 < c \leq 0.1$) Concave ($c > 0.1$)	4 2 0	The curvature can influence the amplification of ground shaking near sharp changes in slope. Convex curvature represents a proxy for ridges and terrace edges and is therefore considered to correspond to greater susceptibility to landslides in earthquakes.

7.4 Landslide susceptibility classes

The landslide susceptibility scores were divided into four classes to define zones of Very Low, Low, Moderate, and High landslide susceptibility. The scoring breaks used to define these classes are shown in Appendix D. 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 classes 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 and moderate susceptibility classes. A small proportion of landslides fall within the low susceptibility class; these were triggered by the 1979 or 2005 storms. High magnitude events such as those storms would result in significantly elevated landslide potential (see Section 7.5), and therefore landslides may occur in areas of low susceptibility.

Table 9: Comparison of landslide inventory to landslide susceptibility classes.

Susceptibility class	Study area		Landslide inventory		
	Area in class (m^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	65.9 M	65%	358	0.4%	0.00%
Low	14.3 M	14%	7,043	8.4%	0.05%
Moderate	10.6 M	11%	15,644	18.5%	0.15%
High	10.0 M	10%	61,447	72.7%	0.61%

The characteristics of slopes within the susceptibility classes are discussed below.

7.4.1 High susceptibility

Zones of high susceptibility consist primarily of very steep land, areas where there is known past slope instability, and moderate to steep slopes underlain by sensitive ash soils such as the Pahoia Tephras. Typical slope morphologies associated with this zone include coastal bluffs (such as those around Maungatapu and Matapihi), steep slopes associated with steeply incised gullies and hills (such as those in Otūmoetai and around Kaitemako Stream), and modified land such as cut slopes.

7.4.2 Moderate susceptibility

Zones of moderate susceptibility consist of moderately steep to steep slopes, including the rounded undulating slopes often found between the Upper (Ignimbrite) and Lower (Alluvial) Terrace geomorphic terrains, the fringes of large gullies and slopes within smaller gullies (such as those in Welcome Bay and Kaitemako), and residential cut and fill slopes. Areas of shallower slopes underlain by weaker materials also fall within this zone.

The potential for slope failures in these areas is often highly dependent 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 city-wide nature of this study, analysis of site-specific conditions and stability are not captured in the susceptibility mapping.

7.4.3 Low and Very Low susceptibility

Zones of low and very low susceptibility comprise the shallowest slopes and flat areas of the Tauranga City area. This includes flat areas on the elevated terrace surfaces away from the terrace edges and gullies (such as the central portion of Matapihi, Maungatapu, and Tauranga CBD), valley floors (such as the Wairoa River valley) and coastal flats (such as the Matua and Otūmoetai foreshore). Zones of low susceptibility include areas with low to moderate slopes in more competent geological materials (such as gentle slopes underlain by Waiteariki Ignimbrite in Welcome Bay and Kaitemako).

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

7.5 Landslide potential

The maps produced in this study reflect which areas of land are susceptible to landslides based on the local terrain, geological and hydrological conditions. The *potential* for landslides, and the area affected, is a function of the slopes' susceptibility to failure and the intensity and duration of triggering events such as storms and earthquakes. Events comprising more intense and longer rainfall or ground shaking are likely to lead to more significant landslides, when compared with less intense and shorter duration events.

The assessment of rainfall-induced landslide potential is complicated by the following factors:

a) Landslides are highly dependent on antecedent conditions. The rainfall and hence saturation of ground or groundwater levels due to precipitation in the days, weeks and months preceding the event has a major effect on the occurrence of landslides.

b) Climate change is having a significant effect on the recurrence interval of precipitation in events, with evidence from past events being a poor indicator of future recurrence intervals. Research by Myhre et al. (2019) in Europe clearly shows that there is a significant increase in the intensity and frequency of extreme rainfall events and can be attributed to climate change.

The lack of data on past earthquake-induced landslides in Tauranga means that a reliable assessment of earthquake-induced landslide potential is very difficult. Therefore, the susceptibility to earthquake-induced landslides is presented in this study. The potential for earthquake-induced landslides in specific earthquake events should be considered on a site-specific basis.

7.6 Output

This study represents a district-wide appraisal of areas susceptible to rainfall-induced and earthquake-induced landslides in Tauranga. International guidelines published by AGS (2007a) suggest that an appropriate scale range for susceptibility zoning is between 1:25,000 and a maximum of 1:5,000 for mapping completed across local areas, which are defined as 10 km^2 to 1000 km^2. The study area for this assessment in Tauranga is approximately 100 km^2. Maps of rainfall-induced and earthquake-induced landslide susceptibility are presented at 1:15,000 scale in Appendix A.

Based on the AGS guidelines, we recommend that zones based on this landslide susceptibility study are displayed at scales of 1:5,000 or greater. A disclaimer should be included that the maps should not be displayed or considered at a larger scale, potentially as overlay text on the map. In addition, the limitations of this landslide susceptibility maps should accompany any release of this information to the public, developers and other stakeholders.

7.7 Limitations

7.7.1 Scale of assessment

The landslide susceptibility mapping completed in this study represents a desk-based, city-wide assessment that was carried out from examination of remotely sensed data including LiDAR and aerial imagery, along with regional-scale datasets. No site inspections were carried out nor was access 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.

7.7.2 Differentiation of landslide type and runout

The desk study of previous landslides in Tauranga highlighted the key failure mechanisms to be shallow slides and flows, and deeper-seated rotational and translational slides. These mechanisms have different failure and runout characteristics. However, the susceptibility mapping does not differentiate between these failure types. 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 upslope, or the debris deposition and runout below the slope (i.e., the runout impacts) that may be associated with slope failures.

7.7.3 Data currency

The maps of slope failure 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 slope failures can allow the susceptibility zones to be refined. We recommend that the slope failure susceptibility mapping be updated using new data as it becomes available.

7.7.4 Unmapped ash sequence

The available regional geological mapping from Briggs et al. (1996) does not include any map data for the upper ash sequences (the Hamilton, Rotoehu and Younger Ashes) that are present in Tauranga. These deposits mantle the underlying geological units with a thickness that is highly variable across the city but can be up to 10 m in places.

Previous field observations and studies have highlighted the importance of the upper ash cover for landslide susceptibility in Tauranga, but it has not been possible to explicitly consider these materials in the susceptibility assessment due to the absence of regional mapping. However, typical thicknesses of the ash cover were considered by Aurecon (2020) and Tonkin & Taylor (2020) when they defined the geomorphic terrains that are used in this landslide susceptibility assessment.

7.7.5 Other factors not considered

Other landslide-influencing factors were investigated but not included in the assessment of landslide susceptibility. These factors are discussed below.

Slope modification

Anthropogenic slope modification, such as retaining walls, cuts, fills, and in-ground soakage activities, can influence landslide occurrence, as observed during the 18 May 2005 storm (Hegan & Wesley, 2005). Slope modification often exacerbates existing slope stability issues and makes a landslide more likely during a subsequent storm or earthquake, but it is also possible for slope modification to trigger landslides in the absence of rainfall or an earthquake. Slope modification could also enhance stability, for example if it involves drainage, soil reinforcement, anchoring, retention, or other similar modification.

The influence of anthropogenic slope modification has not been explicitly considered in this study, beyond those modified slopes which are captured in the terrain data and aerial imagery. The capture of such features is therefore limited by the quality and age of these datasets, with any modifications post-dating these datasets not captured.

Manual mapping of the location and extent of slope modification would be difficult on a district-wide scale. Even if slope modification were accurately mapped, information relating to the design of retaining walls, cuts, fills, and soak holes, which would be important for assessing the potential for failure, is typically not available.

Given that some anthropogenic slope modification features are not captured in the susceptibility maps, actual landslide susceptibilities may differ from those presented in this study. 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.

Groundwater

Groundwater is important in influencing slope instability in Tauranga. However, available groundwater models for Tauranga in the hill terrain and upper terrace areas are based on sparse data and are therefore unlikely to accurately represent the perched water tables and high water pressures in stratified deposits underlying the terraces for use as an independent factor in the susceptibility assessment.

In this assessment, typical groundwater conditions were characterised for the mapped geomorphic terrains, and the effects of shallow groundwater levels were implicitly considered in determining the weightings for each terrain.

Groundwater is not explicitly represented in the susceptibility assessment but has been considered through the use of the geomorphology, overland flow path and proximity to stream factors.

Coastal erosion

Active erosion of slopes at the coastal margin is common in Tauranga and has been highlighted as an important control on landslide occurrence (Houghton & Hegan, 1980; Bird, 1981; Tonkin & Taylor, 1981; Oliver, 1997). The hazard posed by coastal erosion has been assessed and mapped in separate studies by Opus (2015) and Tonkin & Taylor (2018).

Given that coastal hazards have been assessed in separate, specific studies, susceptibility to coastal erosion was not included as a variable in this landslide susceptibility assessment.

Land cover

The type of land cover can affect the susceptibility of a slope to instability by influencing surface water runoff, infiltration, and erosion. Increased vegetation cover is generally considered to improve slope stability due to the binding effect of plant roots, but Oliver (1997) highlighted the destabilising effect of large, shallow-rooted trees like Pōhutukawa at shallow landslide locations in Maungatapu, where trees applied a significant destabilising load to soils on the slope.

Land cover data is available from Manaaki Whenua / Landcare Research at 1:50,000, which does not capture significant variability within the Tauranga area. Given the variable influence of vegetation on slope stability, and the potential for significant changes in vegetation cover to occur within the Tauranga district, land cover was not included in this city-wide landslide susceptibility assessment.

8 Landslide Consequences

Landslides can cause loss of land, loss of support to land and structures upslope, ground subsidence, and inundation of land and structures located downslope. The socio-economic costs from landslides can be significant, in terms of the injuries and fatalities that may occur, and the economic cost associated with damage to land and infrastructure. Several pieces of critical infrastructure in Tauranga, such as Tauranga Hospital, are located close to steep slopes and may be affected by landslides in the short or long term, with severe societal and economic impacts.

In Appendix L of the BOP Regional Policy Statement (RPS), consequences of natural hazards are defined in terms of:

a) The percentage of buildings of social/cultural significance that would have functionality compromised.

b) The percentage of affected buildings that would have functionality compromised.

c) The percentage of critical buildings that would have functionality compromised.

d) The percentage of the population serviced by a lifeline utility affected by disruption of the lifeline utility and the length of time the service is likely to be compromised.

e) The number of human deaths.

f) The number of injuries to people.

The consequences of landslides can vary in severity, extent, and timeframe, depending on whether the elements at risk (e.g., structures, services, or people) are located in the landslide failure, runout, or regression zone (as discussed below).

8.1 Slope failure zone

The slope failure zone is where landslides initiate, generally on moderately steep to steep slopes. In this zone, large displacements and translation of the ground surface occur.

The failure zone for deep seated landslides has been defined by previous studies in Tauranga as the area of land within a line projected at 2H:1V from the toe of the slope. For this type of landslide, the slope failure zone will also include flat land that lies behind the crests of the existing slopes. In past storm events, deep-seated flow-slides were observed to initiate in the upper part of the slope and extend back beyond the crest of the slope (Hegan & Wesley, 2005; Moon, et al., 2017).

Shallow-seated translational failures will generally affect only the steepest parts of the hillslopes that lie forward of the slope crest.

Severe damage could be expected for structures, services, or people located within or across the failure zone, as failure and translation of the slope may cause ground surface rupture and large displacements of many metres.

8.2 Landslide runout zone

8.2.1 Debris inundation

Land downslope of the failure zone is prone to inundation by landslide debris. Structures, services, or people in the inundation zone can suffer extensive damage or injury, particularly those located closest to the slope. A prominent example of the potential impacts of landslides on structures in the inundation zone is the landslide on Vale St in Otūmoetai in the 18 May 2005 storm, where a house at the base of the slope was pushed off its foundations (Hegan & Wesley, 2005).

Buried infrastructure located within the inundation zone is not likely to be significantly impacted, other than potential blockage or obstruction of manholes and other services at the surface.

Runout of the landslide debris has been observed from past events to be within a 4H:1V line projected from the head scarp (Bell, et al., 2001; Hegan & Wesley, 2005). An example of the 4H:1V runout zone is shown in Figure 12 below.

We note that the majority of the landslide debris volume is likely to be deposited within a zone steeper than the 4H:1V line. Figure 12 shows an example of a landslide in Matapihi where the main body of the debris lobe falls within a line projected at 2.5H:1V from the head scarp.

When assessing the impact of landslide inundation for specific structures, it would be beneficial to subdivide the 4H:1V inundation zone into an inner sub-zone of major debris accumulation (adjacent to the slope, where structures would experience the most damage) and an outer sub-zone where lower damage is expected. To do this though, more quantitative information on the relationship between failure volumes and runout distance is required. Limited information may be obtained from the landslide inventory, but information from landslide deposits measured at the time of the failure (for example, from EQC landslip damage inspections) would be necessary to subdivide the runout zone appropriately.

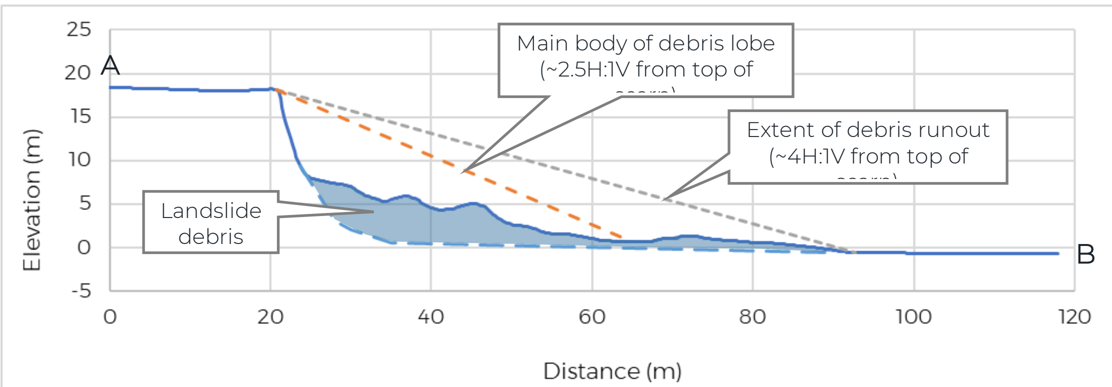

Figure 12: Map and cross section of a failure of coastal cliffs adjacent to State Highway 29A at Matapihi, showing the extent of debris runout within a line projected 4H:1V from the head scarp.

8.2.2 Debris / mud flow inundation

Saturated debris and earth flows are mixtures of soil and water and can have long runout distances over flat land. The likelihood of these flows developing, and the extent of their runout, depends on the upslope catchment area and the amount of groundwater and surface water runoff available to mix with the landslide debris and develop the fluidised flow materials.

Where the path of a debris or mud flow is laterally constrained, such as in gullies or other channels, runout distances can be particularly long. In some cases, the runout distance has been observed to extend beyond the 4H:1V zone included in the TCC IDC (as shown in Figure 13).

The impacts of debris flows are generally less significant than for the near-slope zone of debris deposition, but significant destruction can be caused in some cases. The debris flow that occurred in Matatā during the 18 May 2005 storm is a prime example of this.

Measures such as deflection bunds or drainage channels could be constructed to mitigate the impact of debris and mud flows on structures, services, and people.

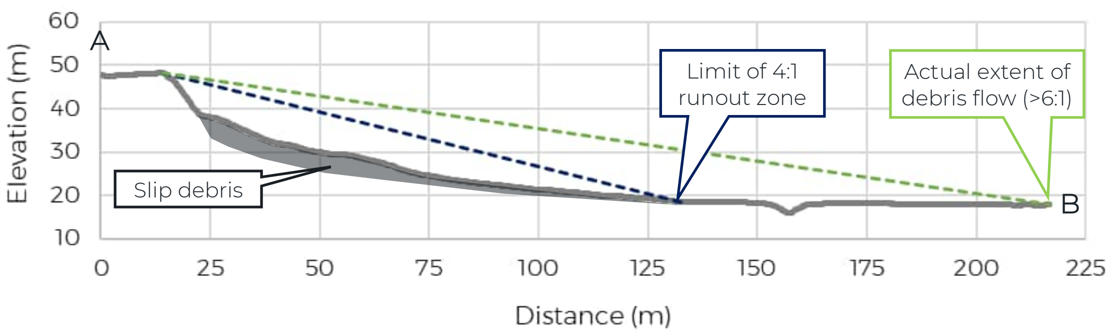

Figure 13: Map and cross section of a failure in the 2005 storm on Welcome Bay Road, showing the debris runout extending to a 4H:1V line projected from the head scarp, with a debris flow extending well beyond this line (approximately 6.5H:1V from the head scarp).

8.2.3 Observations of landslide runout in 2022 and 2023 storms

Following a series of landslides triggered by prolonged or intense rainfall in mid-2022 and early 2023, a selected number of landslides were reviewed by WSP to record the landslide runout at each site and compare these with the 4H:1V slope runout zone. The observations made during this study show that the runout of landslide debris was generally encompassed by the 4H:1V zone, although saturated debris and earth flows extended further than the 4H:1V zone, as noted above. This review of landslide observations highlighted the combination of geological and geomorphic factors, such as sensitive soils, confined groundwater, relict landslides and the larger-scale slope geomorphology, that are important considerations in identifying the height and extent of potential failure and runout zones.

8.3 Landslide regression zone

Many landslides in Tauranga are relatively small and shallow, but there is potential for regression to occur over time. Landslides can develop into larger features, affecting a wider area with potentially more severe consequences, if not identified and remediated.

Deeper seated flow-slides can extend tens of metres back into the slope behind the crest during the initial failure (Moon, et al., 2017). These failures are characterised by steep back scarps, due to the presence of sub-vertical tension cracks (Bell, et al., 2001). Steep back scarps are typically steeper than the long-term stable angles for the materials present, and consequently there is a period of regression as the scarp locally erodes back to a more stable angle. As a result, flat land behind the crest of recent landslides may be prone to future landslides. The regression zone has been defined by previous studies as the area of land within a line projected at 3H:1V from the toe of the slope (Bell, et al., 2001).

Structures, services, or people located in the regression zone are exposed to a lower degree of ground damage hazard in the short-term compared with those within the failure zone. However, in the long term, regression can affect an area many tens of metres behind the crest of the slope. The damage effects from eventual slope failure of land in the regression zone would vary from limited ground deformation and slumping to major displacement and evacuative failure. If landslides are not identified and remediated, land in the regression zone may become more vulnerable to slope failure over time. However, remediation of landslides is often very expensive and, depending on the structure, service, or population located upslope, may be considered uneconomical. In some cases, the complexity or ongoing activity of the landslide means that effective remediation is not physically viable.

8.4 Landslides in the 18 May 2005 storm

The 18 May 2005 storm provides a good example of the potential consequences of landslides in Tauranga. A civil defence emergency was declared, and the Ministry of Civil Defence & Emergency Management (MCDEM) later reported that around 400 people were evacuated from homes across the city, with 471 properties damaged and 14 ultimately condemned (MCDEM, 2005). Figure 14 shows a landslide in Otūmoetai, where several properties were later demolished due to the initial failure and potential for future regression (at the top of the slope), and due to debris inundation (at the bottom of the slope).

Properties in the debris inundation zone generally suffered the most significant damage in landslides that occurred during the 18 May 2005 storm. Many other subdivisions around the city are constructed below sloping ground, in many cases on flat land (such as in Pyes Pa). Based on the observations from the 18 May 2005 storm, it is important that debris inundation is considered as a hazard, and that appropriately designed catchment structures are built where needed. The potential location, extent, and impacts of debris inundation can vary depending on water availability and land use and should be assessed on a case-by-case basis.

Figure 14: Landslide above Landscape Rd in Otūmoetai on 18 May 2005 (photo from BOPRC: https://www.boprc.govt.nz/living-in-the-bay/emergencies/our-natural-hazards).

8.5 Resilience

Considering landslide consequences in terms of functionality and disruption (as Appendix L of the BOP RPS does) is a good approach that encourages resilience-based design of the built environment.

Greater resilience means the normal level of service can be restored quickly after an event. Resilience-based design is therefore particularly important for lifeline infrastructure such as roads and utilities, where provision of service is critical to societal and economic function (Brabhaharan, 2006; 2021).

8.6 Risk reduction

Appropriate measures to reduce risk from landslides vary depending on, for example, the type of landslide anticipated, the scale (e.g., property-specific, or wider scale), and the available funding.

Appendix M of the BOP RPS provides a non-exclusive list of options for reducing the risk of natural hazards (including landslides). Options that are particularly relevant for landslide hazards include:

- Ensuring new subdivision and development avoids specific landslide hazard locations.
- Replacing or modifying existing developments over time to reduce potential consequences.
- Allowing only low intensity activities in specific locations.
- Applying setbacks and undeveloped buffer land within areas of new subdivision and development.
- Use of relocatable or recoverable structures.
- Considering property-specific works (e.g., debris nets and slope stability works) as part of development proposals.

Other options are available, and the most appropriate measure should be determined on a case-by-case basis.

9 Landslide Hazard Management

9.1 BOP Regional Policy Statement

The Bay of Plenty Regional Policy Statement (RPS) provides a framework for sustainably managing the Bay of Plenty region's natural and physical resources (BOPRC, 2016). The RPS highlights significant issues which relate to land which must be considered by city councils when developing district plans. It also sets out what needs to be achieved and how it will be achieved through policies and methods.

Policy NH 3B of the RPS outlines the long-term strategic direction and the outcomes for the way natural hazard risk is managed throughout the Bay of Plenty region. Appendix L of the RPS provides a methodology to evaluate potential likelihood and consequences of the hazards to assign appropriate hazard risk levels (low/medium/high).

9.2 TCC Infrastructure Development Code

The TCC Infrastructure Development Code (IDC) outlines requirements relating to landslide hazards in Tauranga. The current criteria are based on landslide zones recommended by Bell et al. (2001) and Hegan and Wesley (2005). Properties located within these zones have a notice added to their TCC LIM reports, to inform landowners of the potential landslide hazards affecting their property.

9.2.1 IDC Requirements

The IDC includes criteria relating to the level of accreditation that a 'Geo-Professional' must obtain in order to carry out certain landslide risk assessments and mitigation in Tauranga. The requirements of the current IDC are summarised below. Note that the IDC currently uses the term "slip", which is considered to be equivalent to the term "landslide" used in this report.

1. Category 1 Geo-Professionals are required to undertake assessments when the following conditions apply:

   - Where structures are proposed to be located within the 2H:1V upslope zone or the 4H:1V downslope zone. (Both sets of zones are defined on TCC's GIS platform, Mapi).
   - Where structures are proposed to be located within the 2H:1V and 3H:1V upslope zones but where combined with various other factors i.e., relic slip geomorphic features.
   - Where sites include possible/probable slope movement feature with:
     - *Clearly or poorly defined head scarp*
     - *Indications of recent or current activity*
     - *Hummocky debris*
   - Lateral spread issues.
   - Seepage issues from slope at any height.
   - Where a soakage method for stormwater disposal is proposed within the areas defined as "Specific Design" and within 150 m of a relic slip geomorphic feature or from the outer extent of the displayed 2H:1V zone and not within a soak hole decommissioning zone.
   - To certify fill where placed on any ground defined above (i.e., where original slope is greater than 2H:1V or where evidence of instability is present); or elsewhere where fill thickness exceeds 3 m.

- Assessment and design of boulder or rock-faced slopes.

2. Category 1 or 2 Geo-Professionals can undertake assessments when the following conditions apply:
   - Where site exhibits no evidence of relic slip geomorphic features within or in close proximity to the proposed development.
   - Where proposed structures are to be located outside of the 2H:1V upslope and 4H:1V downslope zones.
   - Areas not covered by Categories 1 or 3.
   - Where a soakage method for stormwater disposal is proposed within the areas defined as “Specific Design” but is outside of the distance of 150 m from a relic slip geomorphic feature or from the outer extent of the displayed 2H:1V zone and not within a soak hole decommissioning zone.
   - To certify fill where placed on ground sloping between 18° and 26°.
   - Where building on flat sites or sites sloping less than 14° (4H:1V).
   - Where building adjacent to steeper slopes, beyond the 3H:1V upslope zone.
   - Soakage reports where the surrounding ground stability does not need to be proven.

9.2.2 2003 IDC Landslide Zones

The upslope failure (2H:1V) zone, upslope regression (3H:1V) zone and downslope runout (4H:1V) zone included in the current Infrastructure Development Code (IDC) are based on recommendations made by Bell et al. (2001) and Hegan and Wesley (2005). The configuration of these zones is illustrated in Figure 15.

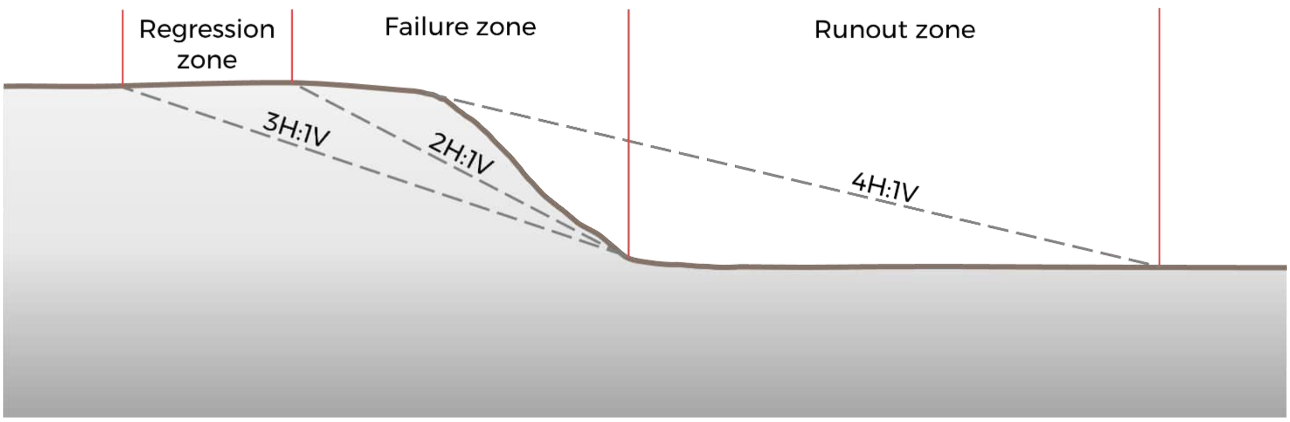

Figure 15: 2003 TCC slope hazard zones

In 2003, TCC commissioned Explorer Graphics Ltd to produce digital maps of the 2H:1V, 3H:1V and 4H:1V zones, using a 3 m resolution DEM in a GIS platform. The output maps from Explorer Graphics Ltd are used in the application of the IDC requirements, and the zones are presented to the public in TCC’s online GIS mapping platform (Mapi).

An update of the IDC slope hazard zones has also been undertaken and discussed in a separate report (WSP, 2023).

9.3 Building Act 2004

Section 71 of the Building Act 2004 states that a building consent authority (such as TCC) cannot grant building consents for buildings intended to be constructed on land subject to one or more natural hazards. Natural hazards in the Building Act include "slippage", "falling debris", and "subsidence". These hazards are relevant to land within the 2H:1V, 3H:1V, and 4H:1V landslide zones in the IDC.

A building consent may only be granted on the basis that adequate provision is made to protect the land, building work, or other properties from the natural hazard(s). This means that slopes considered prone to instability must be engineered to IDC requirements (e.g., by retaining, anchoring, re-profiling, or stabilising the slope). Certain building methods, such as the use of piled foundations, may not be appropriate because they do not address land instability.

10 Conclusions

Areas of land within the Tauranga City district that are susceptible to rainfall- and earthquake-induced landslides have been assessed and mapped in accordance with internationally recognised guidance. These maps are presented in Appendix A. Landslide susceptibility has been assessed on a district-wide scale, considering factors such as geology, slope angle and relief. Maps of the selected factors are presented in Appendix B. The landslide inventory compiled to inform the susceptibility assessment is presented in Appendix C.

The susceptibility maps highlight that moderately steep to steep slopes underlain by sensitive volcanic soils are vulnerable to landslides, with the highest susceptibility areas on the steep bluffs and terrace slopes such as in Otūmoetai, Matua, Maungatapu and Matapihi. Records of past landslides also show these to be areas most prone to landslides.

In the rolling hill and gully terrain in the south-eastern part of Tauranga (Welcome Bay and Kaitemako), landslide susceptibilities are more variable but are generally lower than at the terrace slopes nearer to the harbour, as slope angles in these rolling hills tend to be shallower.

Factors that contribute to localised intensification of landslide susceptibility within the moderate and high susceptibility zones include areas of pre-existing (relic) instability, sharp changes in slope profile, and the presence of overland flow paths down the slopes.

The flat areas above and below the terrace edges are much less susceptible to slope failure, other than where flat land above the slopes is near the terrace edge.

Site-specific conditions, analysis of slope failure likelihood, and consideration of post-failure effects (i.e., landslide runout) are not captured in the susceptibility mapping. Flat, low-lying areas at the base of hillslopes will be in low or very low susceptibility zones but may still be prone to damage from inundation by landslide debris or debris flows. Therefore, the hazards posed by landslides at any given location would need to be assessed with consideration of the landslide potential (of which susceptibility is a key factor) as well as the consequential effects of landslide runout. The 4H:1V IDC zone could be used to identify areas of land prone to landslide inundation to complement the susceptibility map, albeit with limitations on the identification of longer-runout failure types such as debris flows or mud flows, as noted above.

The landslide susceptibility zones have been calibrated with the landslide inventory. The 2005 storm inventory shows that most landslides were triggered within the high and moderate susceptibility classes. A small proportion of the landslides triggered by that event lie within the low susceptibility class, which reflects the high intensity of that storm and the consequent potential for landslides even on slopes of low susceptibility in high magnitude events.

11 Recommendations

Based on the results of the study, we make the following recommendations for consideration:

Application of the outputs of the study

1. The landslide susceptibility maps are used by TCC for resource consenting processes.
2. The landslide susceptibility maps are used at a scale no greater than 1:5,000. A disclaimer should be included that the maps should not be displayed or considered at a larger scale, potentially as overlay text on the map.
3. The landslide susceptibility maps are used to inform land use planning, urban growth strategies and plan change proposals, to ensure that development is discouraged in areas of high hazard, and instead directed to areas of lower hazard.
4. The landslide susceptibility maps are reviewed periodically as new elevation and geotechnical data for the city is collected, and updated in areas where there is new information.
5. The landslide susceptibility assessment is used as the basis for assessment of the resilience of TCC and other government or privately owned lifeline systems and infrastructure such as transport, water supply, wastewater, power, communications etc. The maps would also be useful for planning the development of new infrastructure, and for maintenance management.
6. The landslide susceptibility maps are used for emergency response planning by lifeline utility owners and TCC's civil defence and emergency management groups to plan their response.

Opportunities for further enhancement

7. The susceptibility mapping is extended to incorporate the associated hazard effects of landslide regression and runout.
8. The landslide inventory, including the landslides mapped by WSP as part of this study, is added to the TCC GIS so it can be used in future studies. The landslide inventory would become a live database that is continually updated with new mapping of the location and impacts of landslides – including failure and runout areas, rainfall records, and the antecedent conditions.
9. Ongoing data collection and geotechnical investigations are implemented, to improve understanding of the distribution, impacts and controlling factors of landsliding across Tauranga. Such measures could include:
    - A programme of landslide data collection for TCC maintenance staff to capture systematic and regular records of failures as they occur. The data captured could include information on the location, type and size of failure, using data capture tools (e.g., Survey123, Mobile Road, Pocket RAMM).
    - Periodic investigation of individual landslides, to advance the understanding of the ground and groundwater conditions at the time of failure and following failure (using instrumental monitoring). This should include assessment and documentation of relationships between the failure mechanism, landslide volume, and runout characteristics. Collection of instrumental data would allow for better correlation with rainfall and seismic data, to improve the understanding of slope behaviour in relation to these triggers.
    - A programme of groundwater monitoring and soil permeability testing in areas susceptible to landslides, to enhance the understanding of the groundwater regime in the ash soils close to slopes. This could be extended to investigate the effects of surface

water infiltration on slope instability, to assess the risks associated with stormwater soakage and overland flow in critical areas.

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