REPORT

Tararua District Council Liquefaction Vulnerability Study

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Tararua District Council
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LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes' published by the Ministry for the Environment and the Ministry of Business, Innovation and Employment in 2017. https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land/	
Client	Tararua District Council (TDC)
Assessment undertaken by	Tonkin & Taylor Ltd, PO Box 9544, Hamilton 3240
Extent of the study area	The Study Area aligns with the Tararua District boundary.
Intended RMA planning and consenting purposes	To provide TDC with a district-wide liquefaction vulnerability assessment to help inform land use, subdivision and building consent applications which are undertaken in accordance with the Horizons Regional Council Regional Policy Statement (RPS). The vulnerability assessment outputs will be utilised by stake holders to inform the risk assessment requirements for liquefaction prone land.
Other intended purposes	Not applicable
Level of detail	Level A (basic desktop assessment).
Notes regarding base information	The available base information provides enough information for a Level A (desktop assessment) level of detail across the Study Area. The main factor controlling this level of detail is the spatial extent of the available geotechnical investigations across the Study Area.
Other notes	This assessment has been made at a broad scale across the entire district and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations). A key consideration of the liquefaction vulnerability categorisation undertaken in accordance with the MBIE/MfE Guidelines (2017) is the degree of uncertainty in the assessment. Discussion about the key uncertainties in this study is provided in Sections 3.3 and 3.4 of this report.

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1 Introduction

1.1 Overview

Tonkin & Taylor Ltd (T+T) was engaged by the Tararua District Council (TDC) in July 2020 to undertake a liquefaction vulnerability assessment.

This study has been undertaken in accordance with the Ministry of Business Innovation and Employment (MBIE) & Ministry for the Environment (MfE) guidance document: *Planning and engineering guidance for potentially liquefaction prone land*, referred to as the MBIE/MfE Guidance (2017) (MBIE/MfE, 2017). This study provides a risk-based assessment of liquefaction vulnerability across the district.

The extent of the study area covered by the liquefaction risk identification and analysis is the whole Tararua District, and is shown in Figure 1.1 below.

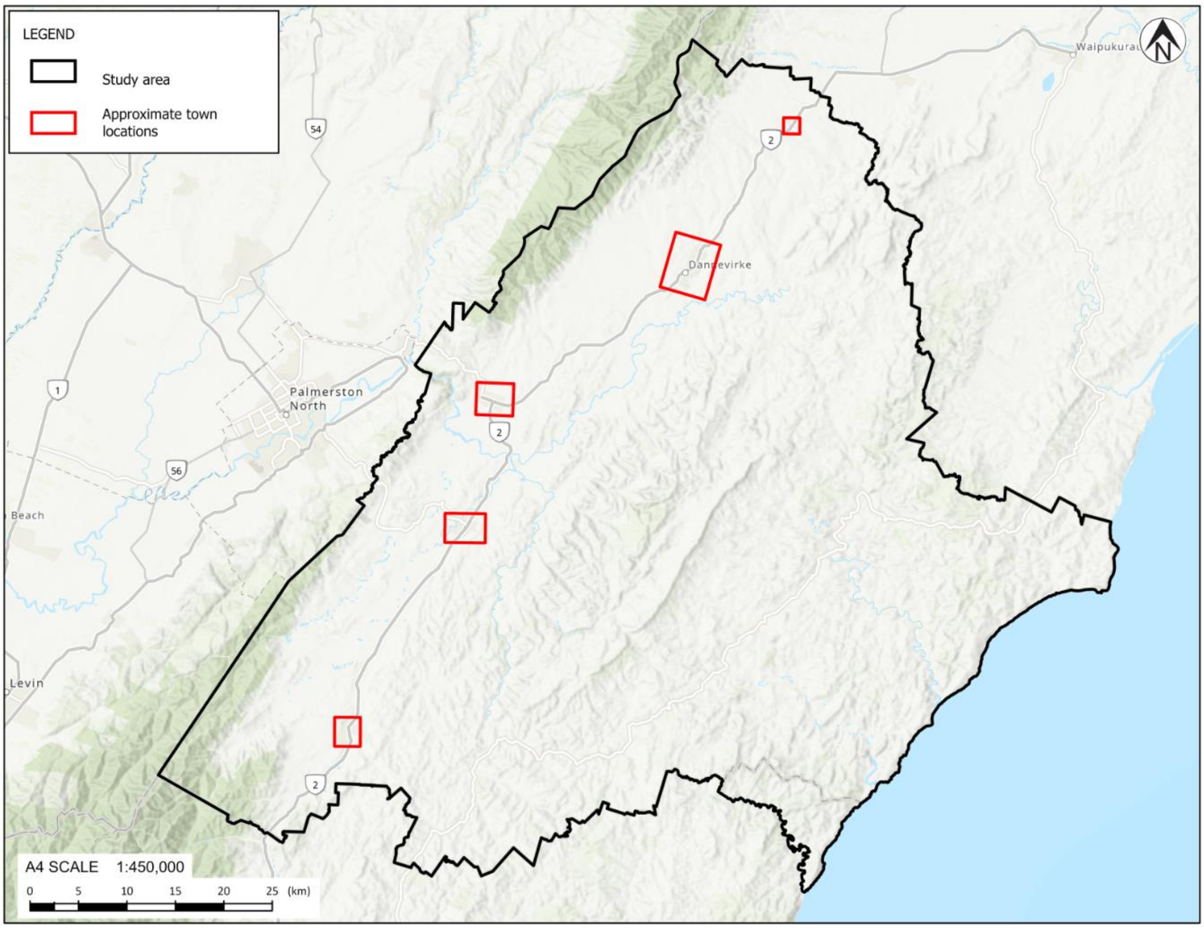


Figure 1.1: Map showing the location and extent of the TDC liquefaction vulnerability study area.

The Tararua District covers approximately 4,360 km^2. It is bounded by the open coast along the east of the district. The district is bounded to the west and northwest by the Tararua and Ruahine Ranges. The remaining area is primarily composed of hill country, although there are also substantial areas of flat land following wide river valleys. Land in the district is currently used for a range of different purposes including residential, commercial, industrial, agricultural, recreation and rural uses.

The purpose of this report is to summarise the general approach adopted for the assessment of liquefaction risk in the district by T+T and the subsequent results. This report includes:

- The context in which this study has been undertaken and the intended purposes for its use, and a summary of previously collated information about the liquefaction hazard across the study area (Section 2).
- Risk identification including summary of previously collated information about the geological, groundwater, and seismic conditions for the study area (Section 3.2).
- Analysis of the uncertainty associated with the collected information (Section 3.3)
- The evaluation of groundwater levels and earthquake scenarios to be assessed, and the delineation of the study area into zones of similar expected ground performance (Sections 4.1, 4.2, and 4.3).
- The determination of the expected degree of liquefaction-induced ground damage for the chosen groundwater levels and earthquake scenarios (Section 4.4).
- The assessment of liquefaction vulnerability as determined from the performance criteria provided in the MBIE/MfE Guidance (2017) (Section 4.4).
- Discussion about the results of this study and a summary of the key conclusions (Section 5).

The liquefaction vulnerability assessment and the layout of this report follows the risk management process recommended in ISO 31000:2009, as shown in Figure 1.2.

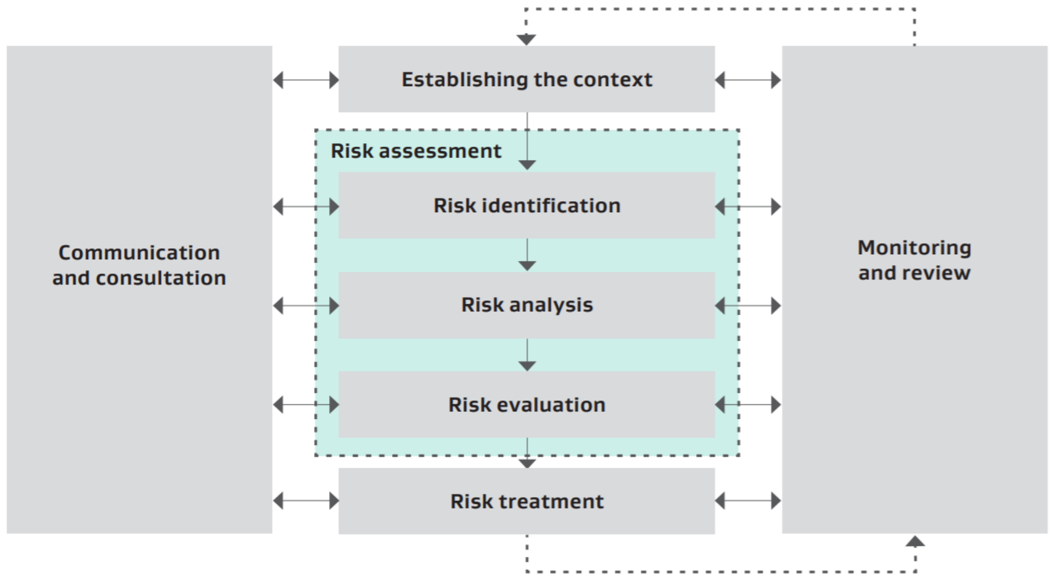


Figure 1.2: Risk management process defined in ISO 31000:2009, which has been used to guide the liquefaction vulnerability assessment and the layout of this report - from MBIE/MfE Guidance (2017). Note, this figure has been slightly modified in the ISO 31000:2018 standard, however the general concepts remain unchanged.

1.2 MBIE/MfE Guidance

The MBIE/MfE Guidance (2017) presents a risk-based approach to the management of liquefaction-related risk in land use planning and development decision-making. The guidance was developed in response to the Canterbury Earthquake Sequence 2010-2011 as a result of recommendations made by the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes.[1]

[1] The MBIE/MfE Guidance (2017) does not provide technical guidance on liquefaction analysis or earthquake engineering. Detailed information about this topic can be found in the NZGS/MBIE Earthquake Geotechnical Engineering Practice series (NZGS/MBIE, 2016; NZGS/MBIE, 2017).

The focus of the MBIE/MfE Guidance (2017) is to assess the potential for liquefaction-induced ground damage to inform Resource Management Act (RMA) and Building Act planning and consenting processes. However, there are a number of ways in which liquefaction information may be used which are outside of the planning and consenting process and the following is a non-exhaustive list that is provided in Section 1.2 of the guidance document:

- Long term strategic land use and planning.
- Developing planning processes to manage risks and the effects of natural hazard events.
- Design of land development, building and infrastructure works.
- Informing earthquake-prone building assessments.
- Improving infrastructure and lifelines resilience.
- Civil defence and emergency management planning.
- Catastrophe loss modelling for insurance, disaster risk reduction and recovery planning.

While there may be specific additional information required to inform the uses above that are outside of the planning and consenting process, many of the concepts presented in the MBIE/MfE Guidance (2017) are likely to be relevant and provide useful information to support these uses.

The MBIE/MfE Guidance (2017) includes the overview of the recommended process for categorising the potential for liquefaction-induced ground damage shown in Figure 1.3. That figure shows the key steps in this categorisation process, namely establish the *Context, Risk Identification, Risk Analysis, and Monitoring and Review* broken down into high level tasks. Comparison of Figure 1.3 with Figure 1.2 also demonstrates how the process maps to the risk management process defined in ISO 31000:2018.

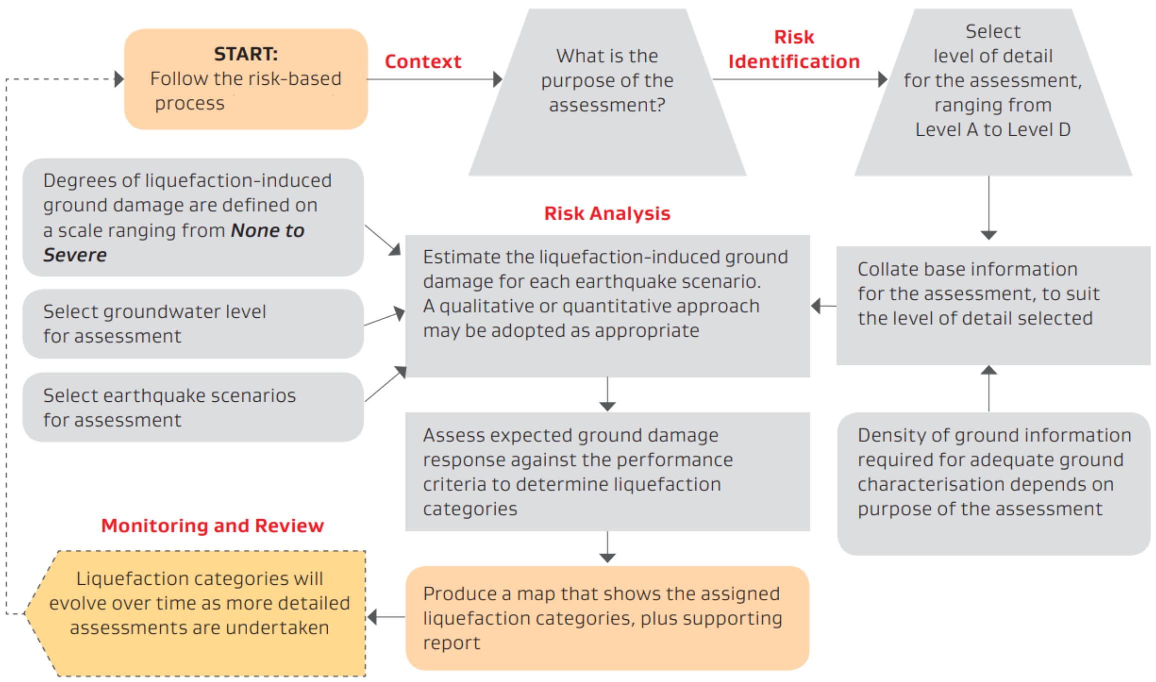
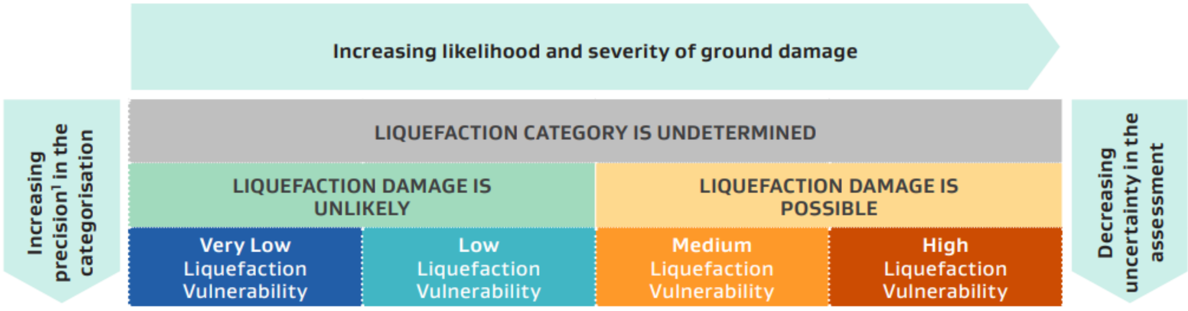


Figure 1.3: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage - from MBIE/MfE Guidance (2017).

The MBIE/MfE Guidance (2017) provides a performance-based framework for categorising the liquefaction vulnerability of land to inform planning and consenting processes. That framework is based on the severity of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Figure 1.4 shows the recommended liquefaction vulnerability categories for use in that performance-based framework. The categorisation of the liquefaction vulnerability of the land within the Tararua District into one of these seven categories is one of the key deliverables of this study. It is important to note that, regional scale studies such as this one typically result in categorisation of the land into one of the top three vulnerability categories of "Liquefaction Category is Undetermined" or "Liquefaction Damage is Unlikely" or "Liquefaction Damage is Possible".



Note:

1 In this context the 'precision' of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

Figure 1.4: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes - from MBIE/MfE Guidance (2017).

As shown in Figure 1.4, the liquefaction vulnerability categories established in the MBIE/MfE Guidance (2017) are a function of both the precision in the categorisation and the degree of uncertainty in the assessment. To provide guidance on how to manage these aspects, recommendations are provided in the MBIE/MfE Guidance (2017) for the minimum level of detail required in the liquefaction assessment for specific applications. Figure 1.5 shows the categories used to define the levels of detail for liquefaction vulnerability studies.

LEVEL OF DETAIL
Level A – Basic Desktop Assessment
Level B – Calibrated Desktop Assessment
Level C – Detailed Area-Wide Assessment
Level D – Site-Specific Assessment

Figure 1.5: Categories used to define the levels of detail for liquefaction vulnerability studies - from MBIE/MfE Guidance (2017).

Regional scale studies such as this one are typically undertaken to a Level A or Level B level of detail. Level C and Level D studies are typically associated with site specific development to support subdivision and building consent applications.

The key feature defining each level of detail is the degree of "residual uncertainty" in the assessment, such that the residual uncertainty is reduced as the level of detail in the liquefaction assessment increases. It is likely that substantial residual uncertainty will remain in some locations, so this should be acknowledged, recorded and clearly conveyed. Further information about the level of detail hierarchy and residual uncertainty is provided in Section 3.1. Section 3.3 provides discussion about the key sources of uncertainty associated with this assessment.

2 Context

2.1 Background to this study

Tararua District Council (TDC) has funded this project to identify areas of land within the district that have potential for liquefaction induced ground damage. The district spans across a variety of landscapes that have varying vulnerability to liquefaction related hazards. Identifying areas of the district that are prone to liquefaction induced damage will be beneficial for providing safe communities within the district and allow planning to take place to identify areas for future district growth. This assessment will significantly improve the understanding of liquefaction vulnerability in the district and will produce a liquefaction hazard map that can be utilised by different stakeholders. The outputs of the study will have two specific uses, the first being related to recent changes to the Building Act and the second being Resource Management Act applications.

On 28 November 2019, the Building Code was amended to relate to ground prone to liquefaction and/or lateral spreading. The changes were:

- Limiting the application of the B1 Acceptable Solution B1/AS1 so that it may not be used on ground prone to liquefaction or lateral spreading.
- Limiting the application of B1/AS1 Foundation Design buildings to those that are on 'good ground' that is not prone to liquefaction or lateral spreading.

The outputs of the vulnerability study will provide information to users that can directly relate to these two Building Code amendments.

The current solutions to 'good ground' in B1/AS1 will continue to comply until 28 November 2021. The intent of this transition period appears to be to allow councils and territorial authorities to complete liquefaction vulnerability mapping in accordance with the MBIE/MfE Guidance (2017) by 28 November 2021.

The changes are being made in response to recommendations from the Royal Commission of Inquiry into the Canterbury Earthquakes and T+T understand that MBIE's objectives for implementing changes are to:

- Reduce the likelihood of extensive and catastrophic failures of foundations of structures where known liquefaction and lateral spread hazards exist across the country.
- Where ground is prone to liquefaction, ensure new buildings (and especially homes) are designed and built with the right level of resilience to manage the liquefaction-related risk appropriately and affordably.
- Provide clarity to territorial authorities (TAs), building consent authorities (BCAs) and engineers when designing for liquefaction-prone ground.

TDC has commissioned T+T to undertake this study in response to these changes to the Building Code as well as to provide input into resource consent processing and resilience of Council infrastructure and assets. The main deliverable from this study is to provide a liquefaction vulnerability map layer in accordance with the MBIE/MfE Guidance (2017) for the district's GIS system.

2.2 Liquefaction hazard

2.2.1 Liquefaction susceptibility

Liquefaction is a natural process where earthquake shaking increases water pressure in the ground in some types of soil, resulting in temporary loss of soil strength.

The following three key elements are all required for liquefaction to occur in susceptible soils:

1 Fine grained, loose non-plastic soil (typically sands and silts, or in some cases gravel if they have a low permeability or are confined by less permeable layers) (Bray, J. et al, 2014)
2 Saturated soil (i.e. below the groundwater table) (Bray & Sancio, 2006), (Boulanger & Idriss, 2006)
3 Sufficient ground shaking (a combination of the duration and intensity of shaking).
4 Young, typically Holocene-aged (≤12,000 years old) deposits.

These elements are shown in Figure 2.1 and Figure 2.2 summarises the process of liquefaction with a schematic representation.

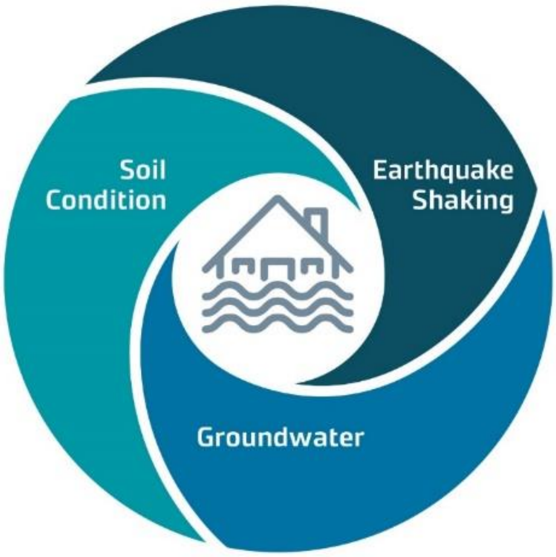


Figure 2.1: Three key elements required for liquefaction to occur.

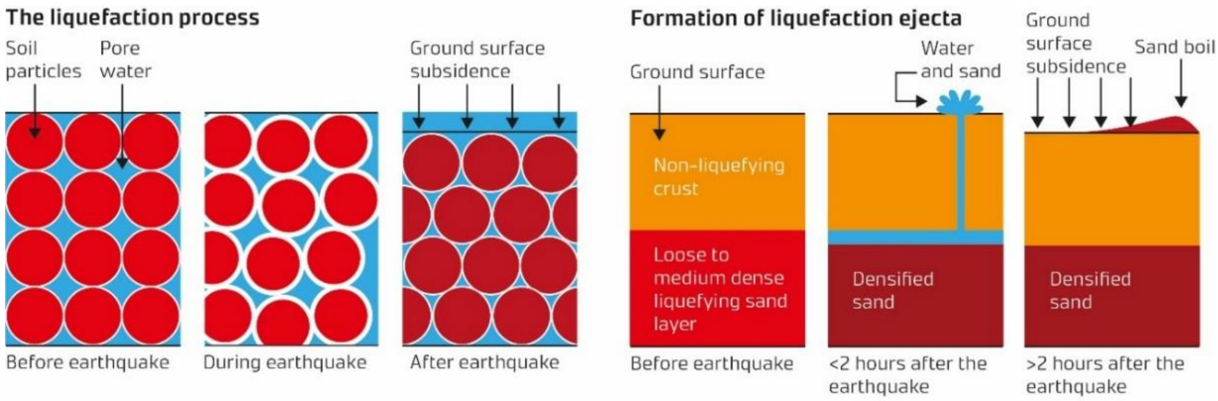


Figure 2.2: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta - reproduced from MBIE/MfE Guidance (2017).

2.2.2 Liquefaction vulnerability indicators

"Vulnerability" of the land relates to the consequence of liquefaction and/or lateral spreading at the ground surface. It is dependent on the depth to groundwater (i.e. crust thickness), the thickness of liquefiable soils, the level of earthquake shaking, the ground surface topography and the proximity to nearby free faces. The closer the liquefiable soils are to the ground surface, the more vulnerable the land is to damage due to liquefaction (all else being equal). Also, the nearer to a river edge or other free face the more likely that land is vulnerable to damage due to lateral spreading.

2.2.3 Liquefaction consequences

Liquefaction can give rise to significant land and building damage through, for example, the ejection of sediment to the ground surface, differential settlement of the ground due to volume loss in liquefied soil and lateral movement of the ground (known as lateral spreading). These effects are schematically presented in Figure 2.3 and summarised in Table 2.1.

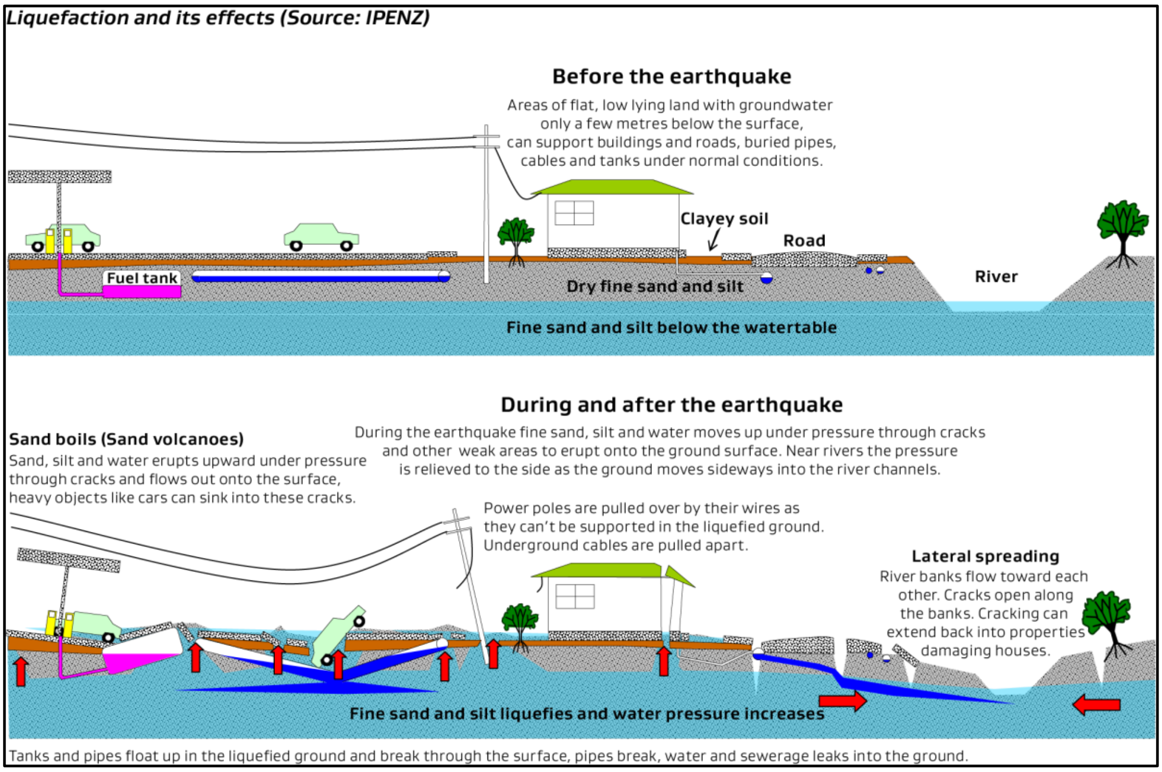


Figure 2.3: Visual schematic of the consequences of liquefaction - reproduced from the MBIE/MfE Guidance (2017).

Table 2.1: Overview of potential consequences of liquefaction (reproduced from MBIE/MfE (2017))

Land	• Sand boils, where pressurised liquefied material is ejected to the surface (ejecta). • Ground settlement and undulation, due to consolidation and ejection of liquefied soil. • Ground cracking from lateral spreading, where the ground moves downslope towards an unsupported face (e.g. a river channel or terrace edge).
Environment	• Discharge of sediment into waterways, impacting water quality and habitat. • Fine airborne dust from dried ejecta, impacting air quality. • Potential contamination issues from ejected soil. • Potential alteration of groundwater flow paths and formation of new springs.
Buildings	• Distortion of the structure due to differential settlement of the underlying ground, impacting the amenity and weather tightness of the building. • Loss of foundation-bearing capacity, resulting in settlement of the structure. • Stretch of the foundation due to lateral spreading, pulling the structure apart. • Damage to piles due to lateral ground movements, and settlement of piles due to down drag from ground settlement. • Damage to service connections due to ground and building deformations.
Infrastructure	• Damage to road, rail, and port infrastructure (settlement, cracking, sinkholes, ejecta). • Damage to underground services due to ground deformations (e.g. 'three waters', power, and gas networks). • Ongoing issues with sediment blocking pipes and chambers. • Uplift of buoyant buried structures (e.g. pipes, pump stations, manholes and tanks). • Damage to port facilities. • Sedimentation and 'squeezing' of waterway channels, reducing drainage capacity. • Deformation of embankments and bridge abutments (causing damage to bridge foundations and superstructure). • Settlement and cracking of flood stopbanks, resulting in leakage and loss of freeboard. • Disruption of stormwater drainage and increased flooding due to ground settlement.
Economic	• Lost productivity due to damage to commercial facilities, and disruption to the utilities, transport networks, and other businesses that are relied upon. • Absence of staff who are displaced due to damage to their homes or are unable to travel due to transport disruption. • Cost of repairing damage.
Social	• Community disruption and displacement – initially due to damage to buildings and infrastructure, then the complex and lengthy process of repairing and rebuilding. • Potential ongoing health issues (e.g. respiratory and psychological health issues).

These consequences can have severe impacts that range from land damage through to social disruption as seen in the 2010-2011 Canterbury Earthquake Sequence.

The risk identification and analysis undertaken for this study considered how the severity of these consequences at any particular location can vary depending on a range of factors, such as:

- **Soil condition –** Liquefaction typically occurs in loose non-plastic soils i.e. silts and sands and, in some cases, loose gravels. Liquefaction does not typically occur in soils with higher plasticity such as clay and does not occur in rock or dense gravel.
- **Depth to groundwater –** Soil can only liquefy if it is below the groundwater table, so deeper groundwater can mean there is a thicker surface “crust” of non-liquefied soil at the ground surface that helps to reduce the consequences from liquefaction below.
- **Strength of earthquake shaking –** Stronger shaking can mean that greater thickness of the soil profile liquefies, resulting in more severe consequences.
- **Layering of the soil profile –** The way in which a soil was deposited (e.g. by a river, an estuary, or the sea) can influence how the soil profile is layered. If there are thick continuous layers of liquefied soil, then this can have more severe consequences than if there are thinner isolated layers of liquefied soil interbedded between layers of non-liquefied soil.
- **Proximity to free faces or sloping ground –** For lateral spreading to occur liquefiable soils must be within close proximity to a free face (such as a river channel or a road cut) or sloping ground. Typically, a location that is closer to these topographic features will sustain more severe consequences than a location that is further away.

2.3 Intended purpose and scope of works

The information produced from this liquefaction vulnerability assessment will be used for natural hazards planning using a risk-based approach. T+T understands that TDC intends to use the findings of this assessment to identify areas susceptible to liquefaction in accordance with the Horizons Regional Council Regional Policy Statement (RPS). It is also likely that the information will be utilised to inform land use planning and consenting requirements under the RMA and Building Act. Note that a more detailed assessment of liquefaction vulnerability may be required depending on the particular activity under consideration.

The key outputs for this liquefaction vulnerability study are as follows:

- Categorisation of the land in accordance with the MBIE/MfE Guidance (2017) into the liquefaction vulnerability categories shown in Figure 1.4 (provided in a digital format).
- Assessment and production of an associated map of the level of detail supported by the currently available base information (provided in a digital format).
- Preparation of a report to accompany the liquefaction hazard risk identification and analysis.

2.4 Previous information about liquefaction in the Tararua District

From a review of publicly available information, we were unable to find many previous regional studies of liquefaction in the Tararua District. A key reference is a GNS Science (GNS) report from 2016, that assessed hazard information for Horizons Regional Council (Dellow, 2016).

TDC provided T+T with selected geotechnical reports that were available and contained geotechnical and seismic discussions. These reports, as well as some from the T+T project database, are outlined in Table 2.2 and summarised in the following paragraphs.

Table 2.2: Project locations and associated technical reports provided by TDC

Project location	Report title	Authors	Published date
Pahiatua	Geotechnical Report – Lot 40 & Lot 41 DP 748	Opus International Consultants	March 2013
Dannevirke Camping Ground	Dannevirke Camping Ground Subdivision – Slope Stability and Hazard Analysis	Wai Waste Environmental Consultants Ltd.	October 2014
Fairless Subdivision	Fairless – Subdivision of Part Section 15 BLK V and Lot 1 DP16162	Wai Waste Environmental Consultants Ltd	August 2018
Putara Road, Eketahuna	Geotechnical and Site Assessment Report - LOT 1 DP455553 - Putara Road, Eketahuna	Cameron Fauvel Projects	March 2020
Bowen Street, Woodville	11 Lot Subdivision – 7 Bowen Street, Woodville	Resonant	June 2020
Pahiatua Transfer Station	Geotechnical Investigation for Proposed Pahiatua Transfer Station Site	Tonkin + Taylor*	May 2010
Mangatainoka	Tui Brewer Tower, Mangatainoka. Geotechnical and Ground Contamination Assessment	Tonkin + Taylor*	March 2015

* Report was retrieved from T+T's archive (i.e. not supplied by WDC)

The following is a summary of each project location and information contained in the associated reports that is relevant to this liquefaction vulnerability study:

- **Pahiatua –** The report was compiled to describe the site, location, regional geology, ground conditions and provide an assessment of ground condition suitability and fill stability, as well as recommendations for a residential development project for two land titles (Opus International Consultants Ltd, 2013).

  The report describes seven test pits, each dug to 4 m depth. None of these test pits are currently available on the NZGD. The report broadly describes the geology as being poorly to moderately sorted gravel with minor sand and silt, underlying a terrace surface with overlying loess and tephra. The ground investigations indicate a surface layer of clayey silt, which is underlain by round to sub-rounded gravels.

  Although no specific reference to liquefaction is made, a seismic hazard assessment was made in relation to a fill slope on-site. The Peak Ground Acceleration (PGA) at the location was calculated to be 0.36 based on NZS 1170.5, with a seismic reduction coefficient of 0.65 being used.

- **Dannevirke Camping Ground –** The report was compiled to provide an engineering analysis for the stability hazard associated with a slope nearby a proposed subdivision lot within the Dannevirke camping ground. The hazard analysis involved both a desktop study and on-site investigations (Wai Waste Environmental Consultants Ltd, 2014).

  Based on the site investigations involved with this report, a full geotechnical description of the subsoils has been provided: "Sandy, fine to coarse GRAVEL with a trace of clay; light reddish brown, homogenous. Medium dense to densely packed; moist; well graded homogenous subangular to subrounded particles less than 50 mm in size."

  The ground investigations described in the report include four Scala penetrometer tests. These were conducted at random locations around the site. Subsoil investigations on the site included two hand-bored holes which achieved a maximum depth of 0.9 m. These hand-bored holes were supplemented with an extensive site walkover and examination of any exposed slope profiles to determine soil geologies.

Extensive description of potential failure mechanisms at the site are detailed in the report. The report states that the area around Dannevirke is predicted to have a 150-year return period for a magnitude 8.0 and a 1000-year return period for a magnitude 9.0 earthquake based on an active fault approximately 5 km from the site (Wai Waste Environmental Consultants Ltd, 2014). No specific mention of liquefaction was made.

- **Fairless Subdivision** – The report was compiled as part of the investigation of the stability for the proposed lot and to identify the potential for on-site wastewater disposal (Wai Waste Environmental Consultants Ltd, 2018).

  The report states that the site has a moderate earthquake risk, with a 150-year return period earthquake likely having a magnitude of 8. It also states that the area has a low susceptibility for liquefaction, based the Pahiatua Fault being approximately 7 km from the site (Wai Waste Environmental Consultants Ltd, 2018).

  No site-specific assessments of seismic hazards or liquefaction vulnerability are presented in the report.

  No ground investigations were included in this investigation.

- **Putara Road, Eketahuna –** The report was compiled to complete a site-specific investigation for the purpose of assessing the ground conditions, building platform stability, foundation recommendations, and assessment of wastewater and stormwater disposal options for a subdivision development (CF Projects Ltd, 2020).

  Site investigations of the area involved four Scala penetrometer tests and two hand-augered boreholes with shear vane testing. The hand auger tests terminated at 1.8 m and 1.0 m below ground level. The predominant subsoils were clayey silts with undisturbed shear strengths of up to approximately 210 kPa. The geology was determined to be on the boundary between an area of alluvial deposits and the sedimentary Esk Head Belt.

  No specific mentions of liquefaction or seismic loading were made.

- **Bowen Street, Woodville** – The investigations associated with this report were for the purpose of determining whether the ground at the site was suitable for future development of residential dwellings on each lot of an 11-lot subdivision (Resonant Consulting Limited, 2020).

  No reference was made to the wide-scale geological conditions of the area.

  Site investigations involved in this report consisted of 11 Scala penetrometer tests, 4 hand-auger tests and shear vane tests at each auger location. Hand augers identified topsoil then soft silty clays. In two hand augers, they have identified “rocks” between 0.6 and 0.9 mbgl, it is likely that they are referring to gravel/cobble soils in this location.

  No assessment of seismic hazard or liquefaction vulnerability is presented in the report.

- **Pahiatua Transfer Station** – The report was compiled to investigate a possible site for a new transfer station (Tonkin & Taylor, 2010).

  The site is located at the base of a hill, sloping to the north and flat to the south. The northern part of the site is described as “Castlecliffian gravels, sands and silts, either in marine sequences or dissected high terraces”. The southern part of the site is described as “Woodville Alluvium – fluviatile deposits laid down by Manawatu River System”.

  Site investigations comprised nine test pits. To the north, the material was described as 3 to 4 m of clayey silt with discontinuous layers of rounded gravels above a pumiceous sand layer, beneath which were silts. To the south, the materials were described as rounded gravels and cobbles beneath 1 m of alluvial silts. Groundwater was not mentioned in the report other than a reference to water level in a nearby drain which was around 0.5 m below adjacent ground level.

A seismic assessment defined the site as Class C shallow soils. It stated that the site has a low liquefaction vulnerability due to the cohesive nature of Castlecliffian formation, and dense nature of the Woodville Alluvium gravels.

- **Tui Brewery Tower – Mangatainoka** – This report was compiled to outline the results of a geotechnical and ground contamination investigation related to earthquake strengthening works and provides proposed foundations to support building consent (Tonkin & Taylor, 2015).

  The geology underlying the site is described as Early Pliocene deposits comprising massive calcareous mudstones with minor alternating siltstone and sandstone. These rocks are overlain by Holocene alluvium consisting of gravel, sand and silts.

  Two boreholes were drilled to 23 and 24 m depth. Holocene alluvium comprising sandy silts and silty sands above sandy gravels was encountered to 4 m depth. Shallow marine mudstones were encountered to 11 m which were underlain by interbedded siltstone and sandstone to the base of the holes. Groundwater measured in the BH2 standpipe was 2.0 m below ground level.

  The report has classified the site as a Class D – deep soil site (Tonkin & Taylor, 2015). The liquefaction vulnerability of the site is considered to be low based on dense granular soils over rock encountered in the boreholes.

3 Risk Identification

The following sections outline the risk identification that has been carried out for the liquefaction hazard assessment for the study area.

The first task is the determination of the level of detail required for the intended purposes (refer to Section 3.1.2). This requires consideration of the key features associated with each level of detail as established by the MBIE/MfE Guidance (2017) and consideration of the TDC's intended purposes for undertaking the liquefaction hazard assessment.

The second task is a review of the base information currently available for this liquefaction hazard assessment (refer to Section 3.2). The base information that has been reviewed for the Tararua District includes the following:

- Ground surface levels (refer to Section 3.2.1)
- Geology and geomorphology (refer to Section 3.2.2)
- Geotechnical investigations (refer to Section 3.2.3)
- Groundwater (refer to Section 3.2.4)
- Seismic hazard (refer to Section 3.2.5)
- Historical observations of liquefaction (refer to Section 3.2.6).

The third task is the assessment of the uncertainty associated with the base information and the assessment undertaken (refer to Section 3.3). This uncertainty assessment feeds into the fourth task which is the determination of the level of detail supported by the base information (refer to Section 3.4).

3.1 Level of detail

3.1.1 Level of detail hierarchy

The MBIE/MfE Guidance (2017) provides recommendations for four different levels of detail ranging from the least detailed (Level A) to the most detailed (Level D). Figure 3.1 shows the key features associated with each level of detail.

LEVEL OF DETAIL	KEY FEATURES
Level A **Basic desktop assessment**	Considers only the most basic information about geology, groundwater and seismic hazard to assess the potential for liquefaction to occur. This can typically be completed as a simple 'desktop study', based on existing information (eg geological and topographic maps) and local knowledge. **Residual uncertainty:** The primary focus is identifying land where there is a ***High*** degree of certainty that ***Liquefaction Damage is Unlikely*** (so it can be 'taken off the table' without further assessment). For other areas, substantial uncertainty will likely remain regarding the level of risk.
Level B **Calibrated desktop assessment**	Includes high-level 'calibration' of geological/geomorphic maps. Qualitative (or possibly quantitative) assessment of a small number of subsurface investigations provides a better understanding of liquefaction susceptibility and triggering for the mapped deposits and underlying ground profile. For example, the calibration might indicate the ground performance within a broad area is likely to fall within a particular range. It may be possible to extrapolate the calibration results to other nearby areas of similar geology and geomorphology, however care should be taken not to over-extrapolate (particularly in highly variable ground such as alluvial deposits), and the associated uncertainties (and potential consequences) should be clearly communicated. Targeted collection of new information may be very useful in areas where existing information is sparse and reducing the uncertainty could have a significant impact on objectives and decision-making. **Residual uncertainty:** Because of the limited amount of subsurface ground information, significant uncertainty is likely to remain regarding the level of liquefaction-related risk, how it varies across each mapped area, and the delineation of boundaries between different areas.
Level C **Detailed area-wide assessment**	Includes quantitative assessment based on a moderate density of subsurface investigations, with other information (eg geomorphology and groundwater) also assessed in finer detail. May require significant investment in additional ground investigations and more complex engineering analysis. **Residual uncertainty:** The information analysed is sufficient to determine with a moderate degree of confidence the typical range of liquefaction-related risk within an area and delineation of boundaries between areas, but is insufficient to confidently determine the risk more precisely at a specific location.
Level D **Site-specific assessment**	Draws on a high density of subsurface investigations (eg on or very close to the site being assessed), and takes into account the specific details of the proposed site development (eg location, size and foundation type of building). **Residual uncertainty:** The information and analysis is sufficient to determine with a ***High*** degree of confidence the level of liquefaction-related risk at a specific location. However, the scientific understanding of liquefaction and seismic hazard is imperfect, so there remains a risk that actual land performance could differ from expectations even with a high level of site-specific detail in the assessment.

Increasing level of detail and decreasing degree of uncertainty

Figure 3.1: Levels of detail for liquefaction assessment studies and the defining key features (reproduced from MBIE/MfE Guidance (2017)).

As highlighted in Figure 3.1 the key feature of the level of detail assessment is the degree of residual uncertainty in the assessment. This refers to the uncertainty which remains after the available information has been analysed. The concept of residual uncertainty is important because it informs the suitability of the information for the intended purpose.

There are two key parts to the determination of the level of detail as follows:

1 **Determination of the level of detail required for the intended purpose.** This step involves consultation with the key stakeholders and a review of the different applications to which this information will be applied (refer to Section 3.1.2 of this report); and

2 **Determination of the level of detail supported by the currently available base information.** This step involves collation and review of the base information available for the assessment (refer to Section 3.2 of this report) including consideration of the uncertainty associated with that information (refer to Section 3.3 of this report).

3.1.2 Level of detail for intended purposes

The MBIE/MfE Guidance (2017) provides recommendations about the minimum level of detail likely to be appropriate for a liquefaction assessment, depending on the intended purpose, likelihood/severity of ground damage and the development intensity. Refer to Section 3.5 of the MBIE/MfE Guidance (2017) for further detail.

The target level of detail in the assessment (in accordance with MBIE/MfE Guidelines (2017)) that is required for TDC's intended purposes was developed in a workshop held on 21 September 2020. This establishment of the target level of detail included consideration of the following:

- The range of intended purposes for the liquefaction assessment
- The target level of detail required for those intended purposes
- The availability and spatial density/extent of data required for assessment at the selected level of detail
- Whether a better overall outcome could be achieved by adopting a higher target level of detail than the minimum requirements.

As shown in Figure 3.2 and Figure A1 in Appendix A, a Level A (Desktop Assessment) level of detail was targeted for the for the Study Area. TDC have confirmed that this level is sufficient for their intended initial screening purposes but have also indicated that some areas may require further assessment in future to reduce uncertainty.

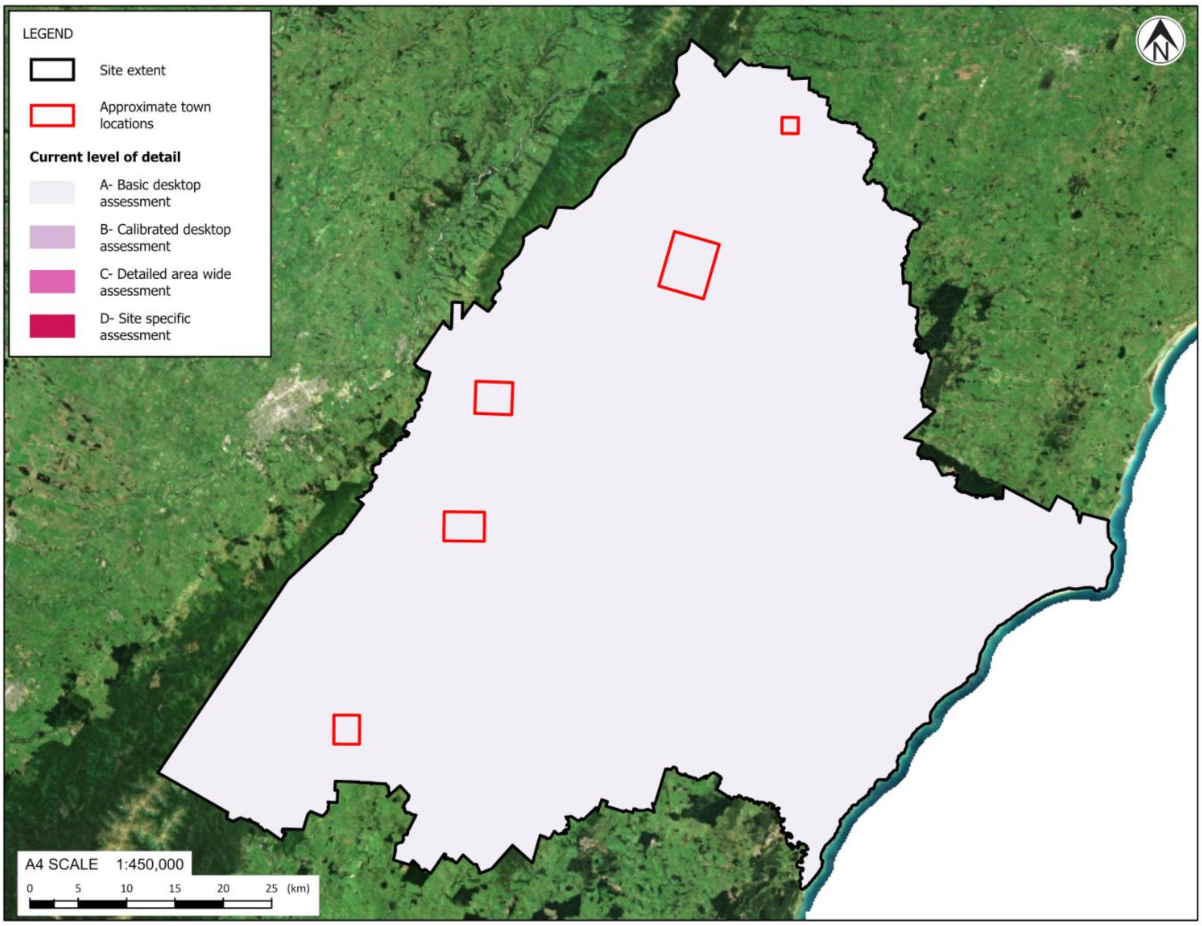


Figure 3.2: Target level of detail for the assessment across the Study Area

3.2 Base information currently available

This section of the report outlines the available base information that was used for the vulnerability assessment within the Study Area. This section of the report collates and documents the types of base information and how the information was used for the eventual risk assessment.

3.2.1 Ground surface levels

The ground surface level of the district is characterised by a high-resolution Light Detection and Ranging (LiDAR) derived Digital Elevation Model (DEM). Table 3.1 provides information about the LiDAR data acquisition provided by TDC that was used for this liquefaction assessment.

Table 3.1: Recent LiDAR data acquisitions for the Tararua District

Year of acquisition	Acquisition by	DEM resolution (m)	Coverage of study area
2015	TDC	1 m	Entire
Unknown	TDC	1 m	Woodville
2016	TDC	1 m	Dannevirke and Eketahuna

The ground surface elevation within the district varies from approximately 0 m to 1463 m RL (NZVD 2016)[2] across the area although the majority of the study area is between 0 and 400 m RL. Elevated features in the area above 400 m RL include the hills and mountain ranges. The low-lying portions of the study area include alluvial and costal deposits.

Figure 3.3 and Figure A2 in Appendix A show the ground surface elevation over the district as represented by the DEM developed from the 2015 LiDAR survey that covers the whole district.

We note that this dataset appears not to have been processed. Both buildings in towns and areas of forest and trees have not been removed (see Figure 3.4) and therefore the elevation shown in Figure 3.3 and Figure A2 in Appendix A is not a true ground surface. For the scale of this assessment, the data still provides us with enough information to understand the elevations across the area, to approximate the geomorphological unit boundaries. This uncertainty is further discussed in Section 3.3.1.

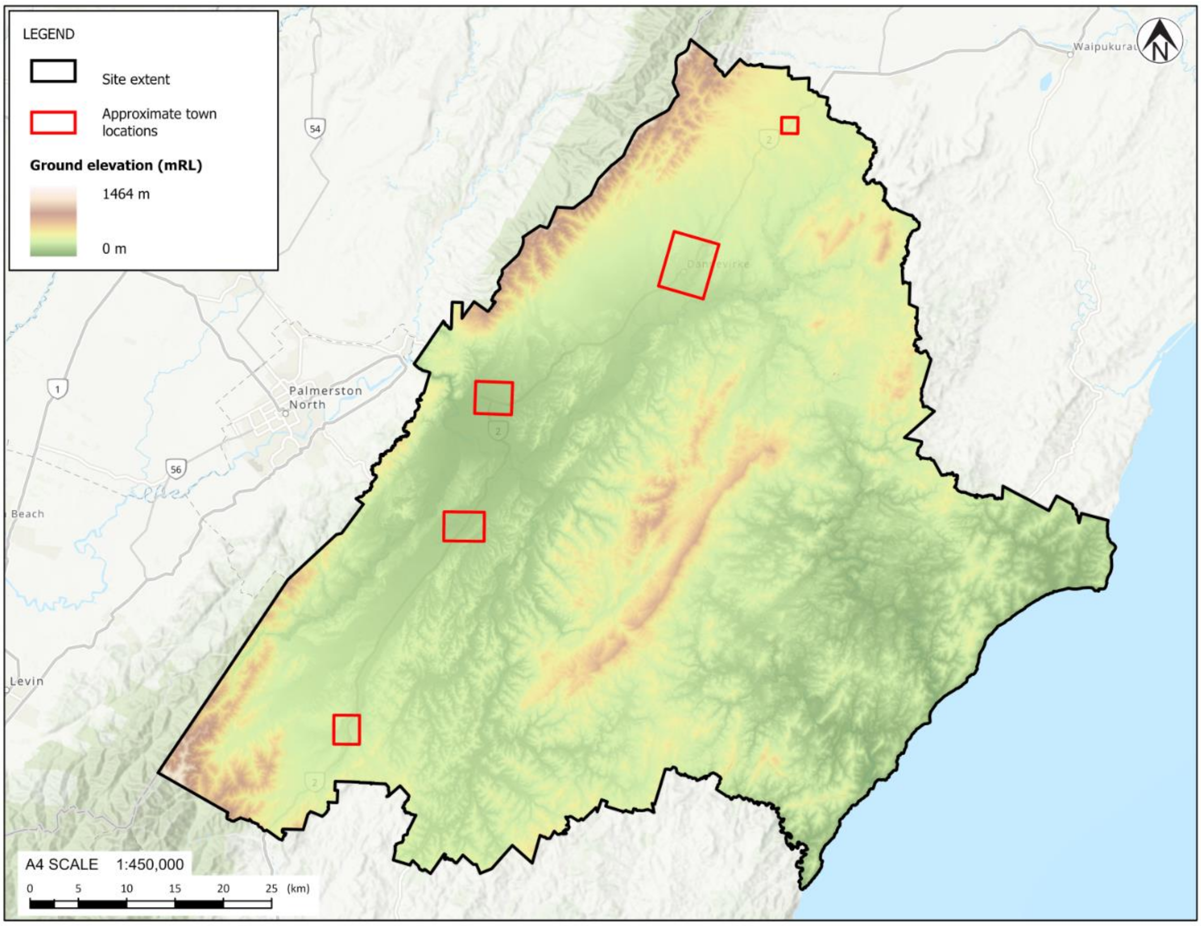


Figure 3.3: Ground surface elevation over Tararua District as represented by the 2015 LiDAR Survey.

[2] All elevations are provided to New Zealand Vertical Datum 2016 unless otherwise stated.

Figure 3.4: Examples of areas where buildings and trees have not been removed from the elevation data and therefore have distorted the contours created for this assessment at 1:5,000 scale. Left: buildings in Pahiatua; Right: trees and vegetation along streams and in farmland to the north-west of Dannevirke.

3.2.2 Geology and geomorphology

Geology

The geology of the Tararua District is well represented by many published geological maps. As summarised in Table 3.2 below, the maps collectively cover the entire project area. Additional maps and associated reporting that cover parts of the district were also reviewed.

Table 3.2: Utilised geological maps that cover the Tararua District area

Title	Authors	Published date	Scale	Comments
Geology of the Hawkes Bay area (QMAP)	GNS Science	2011	1:250,000	Georeferenced
Geology of the Wairarapa area (QMAP)	GNS Science	2002	1:250,000	Georeferenced
Geological Map of New Zealand - Dannevirke - Sheet 11	NZGS	1975	1:250,000	Georeferenced
Geological Map of New Zealand - Wellington - Sheet 12	NZGS	1967	1:250,000	Georeferenced
Geological Map of New Zealand - Eketahuna - Sheet N153	NZGS	1974	1:63,360	Georeferenced
The Geology of the Dannevirke Subdivision – Bulletin ns46	NZGS	1953	-	-

The QMAP series published by GNS will be the main sources of geological data for the liquefaction vulnerability study. It should be noted that the QMAP series of geological maps are a compilation of many different geological maps published by various authors/institutes.

The Tararua District is located within the Horizons Region on the continental Australian Plate, approximately 65 to 200 km west of the Hikurangi Trough. The Hikurangi Trough is the surface manifestation of the Hikurangi Subduction Zone, where the Pacific tectonic plate subducts beneath the Australian tectonic plate (Figure 3.5). Many faults have been mapped in this area related to the tectonic activity related to the subduction zone processes (Figure 3.6). It is noted that GNS are currently engaged by Horizons Regional Council to undertake fault mapping within the region, including the Tararua District. Because this current regional liquefaction vulnerability study is a high-level assessment which focusses primarily on whether or not liquefaction-susceptible soils are present, the results are not expected to be sensitive to the exact location of mapped faults. However, the findings of this GNS study, once available, should be taken into consideration in future more detailed liquefaction assessments in the district.

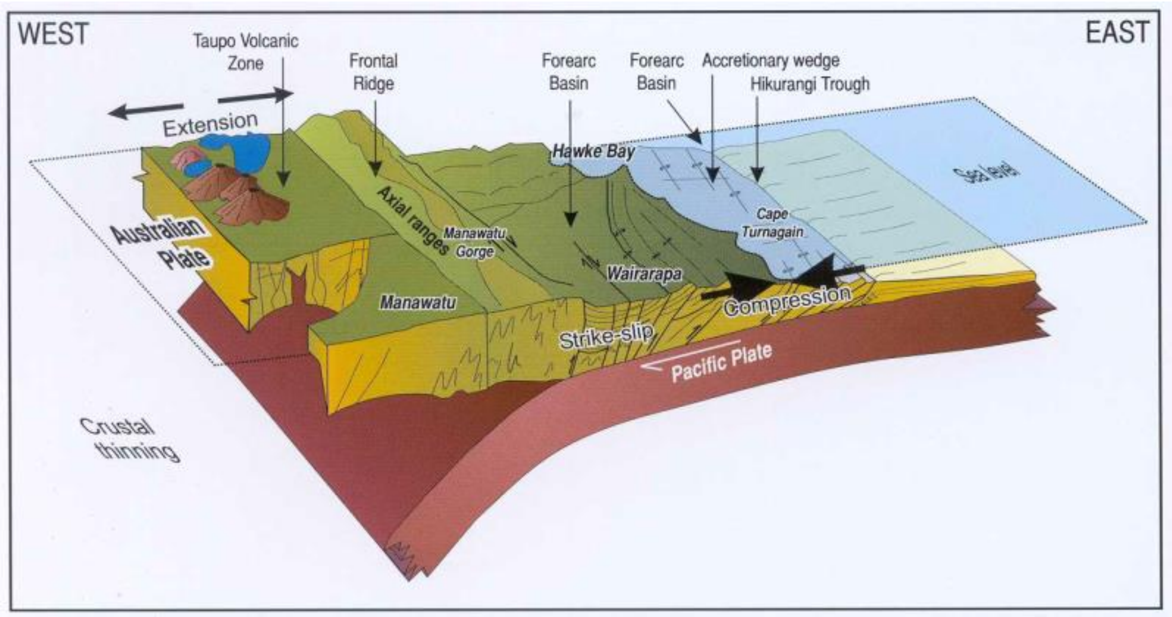


Figure 3.5: Schematic of the tectonic setting for the Wairarapa map area (Lee & Begg, 2002)

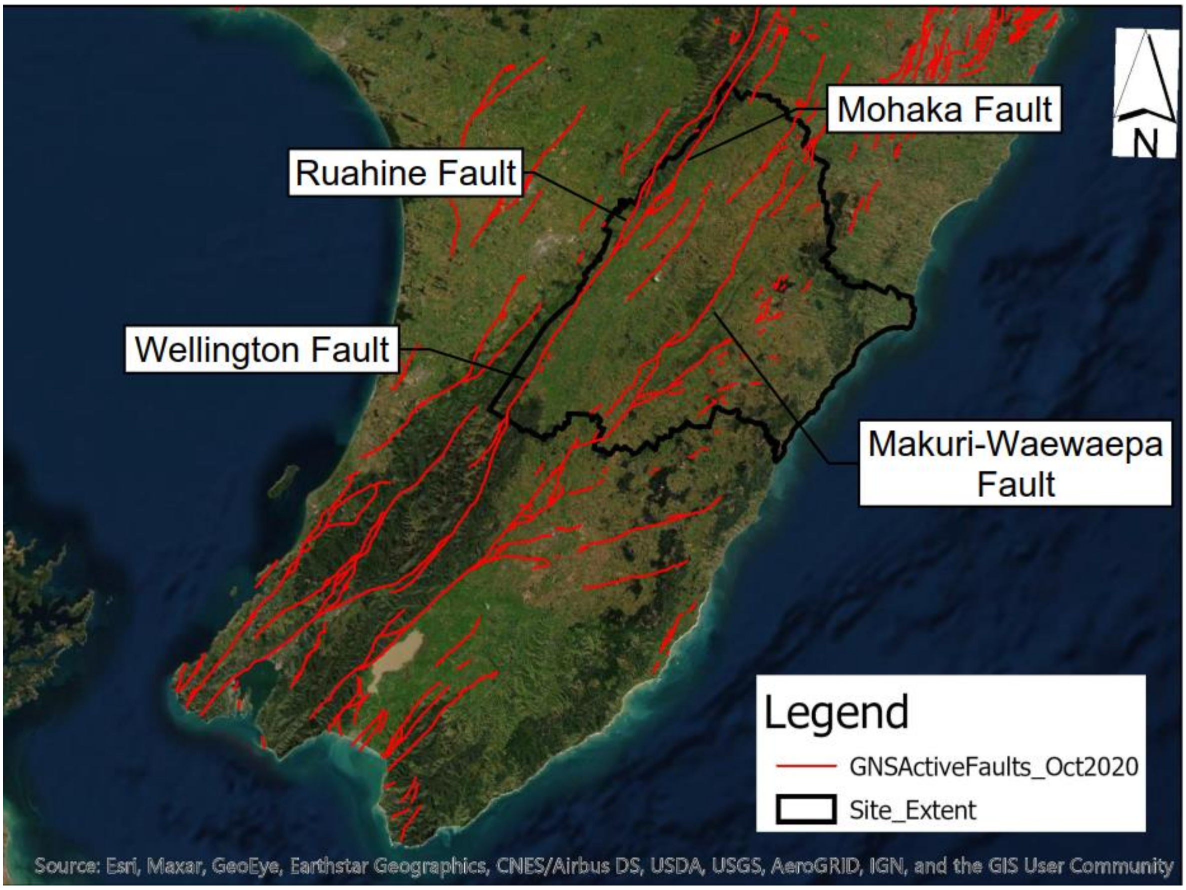


Figure 3.6: Overview of Active Faults passing through the district (GNS Science, 2020).

The geological history of the area has been summarised below into four main periods:

1. Cretaceous to Paleogene: The basement rocks in the district are predominantly deep-water marine sedimentary rocks, deposited in forearc-trench environments related to subduction of the Pacific Plate beneath the Australian Plate (Lee, Bland, Townsend, & Kamp, 2011). During the Cretaceous period, tectonic uplift occurred which raised the environment from deep-water to continental shelf depths. From the Cretaceous period to the Paleogene, the area was more stable but slowly subsided to deep water depths.
2. Miocene to Pliocene: During the Miocene, episodic uplift and subsidence in different basins caused localised deposition of limestone and sandstone. While this was ongoing, sediments were collecting in shallow basins along the margins of the emerging axial ranges in the Dannevirke area. In the early Pliocene, uplift raised the Cretaceous to Paleogene rock as the coastal hills and axial ranges (Tararua and Ruahine Ranges, Eastern Uplands, Waewaepa and Puketoi Ranges, see Figure 3.7). This formed a seaway, the Ruataniwha Strait, that extended through to Hawke’s Bay (likely through Pahiatua Basin and Ruataniwha Plains areas). Uplift of the Strait in the Pliocene resulted in the formation of shallow marine platforms which closed the seaway.
3. Early-Mid Quaternary: In the early to mid-Pleistocene, rapid uplift of the Tararua and Ruahine Ranges resulted in large volumes of greywacke gravels depositing in the Ruataniwha Plains and Pahiatua Basin. Ongoing uplift and folding during this time raised these deposits, forming alluvial terraces.
4. Late Quaternary: During the late Pleistocene and Holocene the area has remained fairly stable, and alluvial sediments have deposited in the Ruataniwha Plains and Pahiatua Basin. These deposits are typically in river channels, alluvial fans, and flood plains. Deposits of this age are also found in some smaller valleys in the hills.

Due to the ages and likely characteristics of the Cretaceous to the Pliocene rocks in the area, these are not deemed to be susceptible to liquefaction based on the criteria outlined in Section 2.2. The more recent Quaternary sediments are the focus of this assessment as the soil condition and landforms that they generate indicate that they may be susceptible to liquefaction.

The early-mid Pleistocene terraces are predominantly gravels sourced from erosion of the axial ranges and could be less susceptible to liquefaction due to their dense nature. These deposits have also experienced uplift meaning that they are likely to have experienced some degree of consolidation.

In contrast, the late Pleistocene-Holocene alluvial deposits are typically more sandy in nature, forming lower lying areas and are likely to be more prone to liquefaction than the elevated gravel terraces.

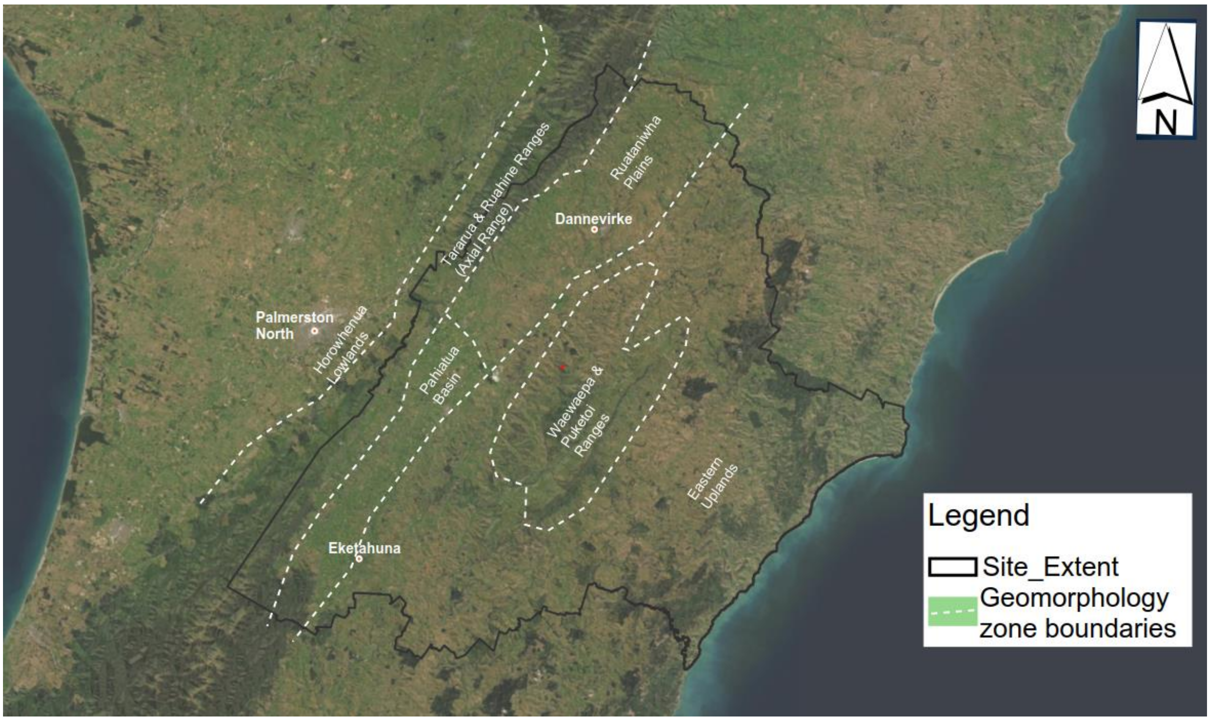


Figure 3.7: Geomorphology zones interpreted from GNS Geological Maps (Lee & Begg, 2002) (Lee, Bland, Townsend, & Kamp, 2011)

Geomorphology

An existing geomorphic map specific to the study area was not found during this assessment, therefore T+T utilised the geological base information and LiDAR to undertake geomorphic mapping. Part of this included review of high level geomorphology maps provided in the GNS Science geological map texts (which have been adapted into Figure 3.7). The following is a summary of the methodology applied and outcome of this task for the Tararua District.

Geomorphic terrains have been defined and mapped to help identify areas of liquefaction susceptible soils. Terrains expected to comprise silt, sand and gravelly sediments (e.g. river channels and flood plains) are more likely to be susceptible to liquefaction when compared to the various types of hill country landforms within the district. The geomorphic terrain mapping methodology is summarised in Table 3.3.

Table 3.3: Geomorphic terrain mapping methodology

Data sources:	Geological maps – see this section Current and historical aerial imagery Ground surface levels – see section 3.2.1 Topographical screening tool and associated geomorphons – see this section below
Terrain definition:	Geomorphic terrain categories have been defined based on their general susceptibility to liquefaction following guidance outlined in MBIE (2017) and research by Youd and Perkins (Youd & Perkins, 1978)). Areas expected to be more susceptible to liquefaction have been divided into more detailed terrain units (i.e. alluvial channels and plains) compared with less susceptible hill and range areas.
Terrain mapping:	Terrain mapping has been undertaken as a desktop assessment largely based on the ground surface levels and associated geomorphons (described below) and the QMAP geological units. Surface elevation data was used to derive information of landform features, such as areas of low lying and elevated land, flat land or gently sloping to steeply sloping land. These areas of land often control sedimentary depositional processes that relate to liquefaction susceptibility of soils. The QMAP geological units have also been rationalised into the geomorphic terrain categories and incorporated into the landform feature interpretation listed above. The resulting geomorphic terrains have been reviewed against aerial imagery and the geomorphons produced by the topographical screening tool. During this process, terrain extents can be modified or re-classified.
Mapping Scale	1:25,000[3]

A topographical screening tool was developed to quantitatively interpret ground surface levels across the Study Area. The purpose of this initial screening tool was to provide an automated means of identifying different topographical features from the DEM.

The method on which the screening tool is based was proposed by Stepiniski and Jasiewicz (2011) and considers single elevation points from a DEM dataset in relation to adjacent elevation points at a set distance. The adjacent elevation points are interpreted to be above, below or in-line with the initial elevation point and the algorithm can then categorise these patterns into broad landform classification, which are known as geomorphons.

For the purposes of this study, two key landform types were considered to get a general understanding of the land. These geomorphons were:

- Flat land – for example areas of alluvial channels and plains
- Sloping land – for example areas of hills and ranges.

The geomorphons generated from this algorithm are shown in Figure 3.8 and Figure A3 in Appendix A.

[3] In practice, we have reviewed or drawn terrain boundaries within GIS at an onscreen scale between 1:25,000 to 1:15,000.

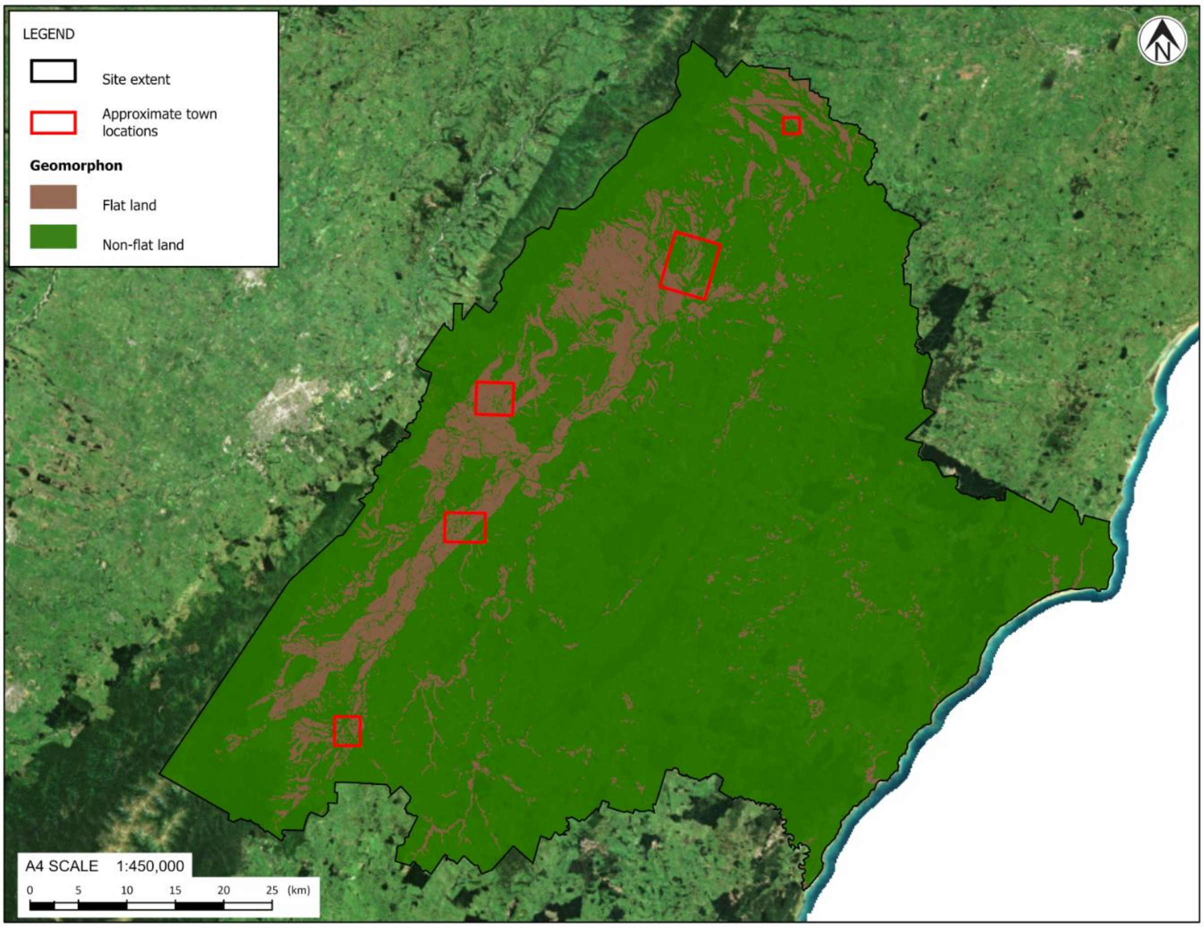


Figure 3.8: Geomorphons produced by the screening tool across the Study Area.

Following the initial topographic screening tool, the geomorphic mapping process identified five different geomorphic terrains across the study area. The classifications of these geomorphic terrains are described briefly below. More detailed descriptions of the geomorphological terrains are provided in Table A1, Appendix A. The geomorphic map of the Study Area is shown in Figure 3.9 and Figure A4 in Appendix A.

- **Alluvial Channels and Plains:** These areas comprise approximately 785.2 km^2 of the study area (17.9%) and represent areas that are typically the product of alluvial depositional processes and active fluvial systems. Alluvial channels have narrow valley floors relative to the alluvial flood plains which are wider. Alluvial fans are also included in this unit, which are areas of gently to steeply sloping topography at the bases of hills and gullies. This unit typically comprises Late Pleistocene and Holocene-aged deposits.
- **Elevated alluvial terraces:** These comprise approximately 154.5 km^2 of the study area (3.65%) and are elevated terraces above the current alluvial channels and plains. The terraces typically contain Pleistocene-aged or older alluvium and colluvium. This unit comprises early to mid-Pleistocene-aged deposits that are dominated by gravels.
- **Beaches:** These areas comprise approximately 2.0 km^2 of the study area (0.05%) and are associated with active landforms found along the eastern coastline and are predominantly associated with beach environments.
- **Landslide debris:** These comprise approximately 35.0 km^2 of the study area (0.8%) and are associated with areas of land with hummocky, gently to steeply sloping topography mapped

as landslides. These areas are based on mapping by others from a range of sources and are not expected to be a complete record of all landslides in the district.

- **Hills and Ranges** comprise approximately 3387.5 km^2 of the study area (77.6%) and are associated with elevated landforms characterised by highly dissected hills with many gullies, as well as hills that are more rolling in nature. This terrain was differentiated into three sub-terrains generally based on the geological origins of the predominant landforms.
  - **Tararua-Ruahine Ranges**: Extends from the south-west to north-east of the study area along the north-western boundary of the district. This sub-terrain is characterised by basement greywacke deposits of the Torlesse Supergroup.
  - **Waewaepa and Puketoi Ranges**: Found as isolated ranges in the centre of the district, within the Eastern Uplands. This sub-terrain is characterised by Cretaceous to Pliocene deposits of basement greywacke, mudstone and limestone.
  - **Eastern Uplands**: Covers the majority of the district and extends from the Pahiatua Basin to the coastline of the study area (Figure 3.7). This sub-terrain is characterised by Cretaceous and Cenozoic-aged deposits of sandstone, mudstone and limestone.

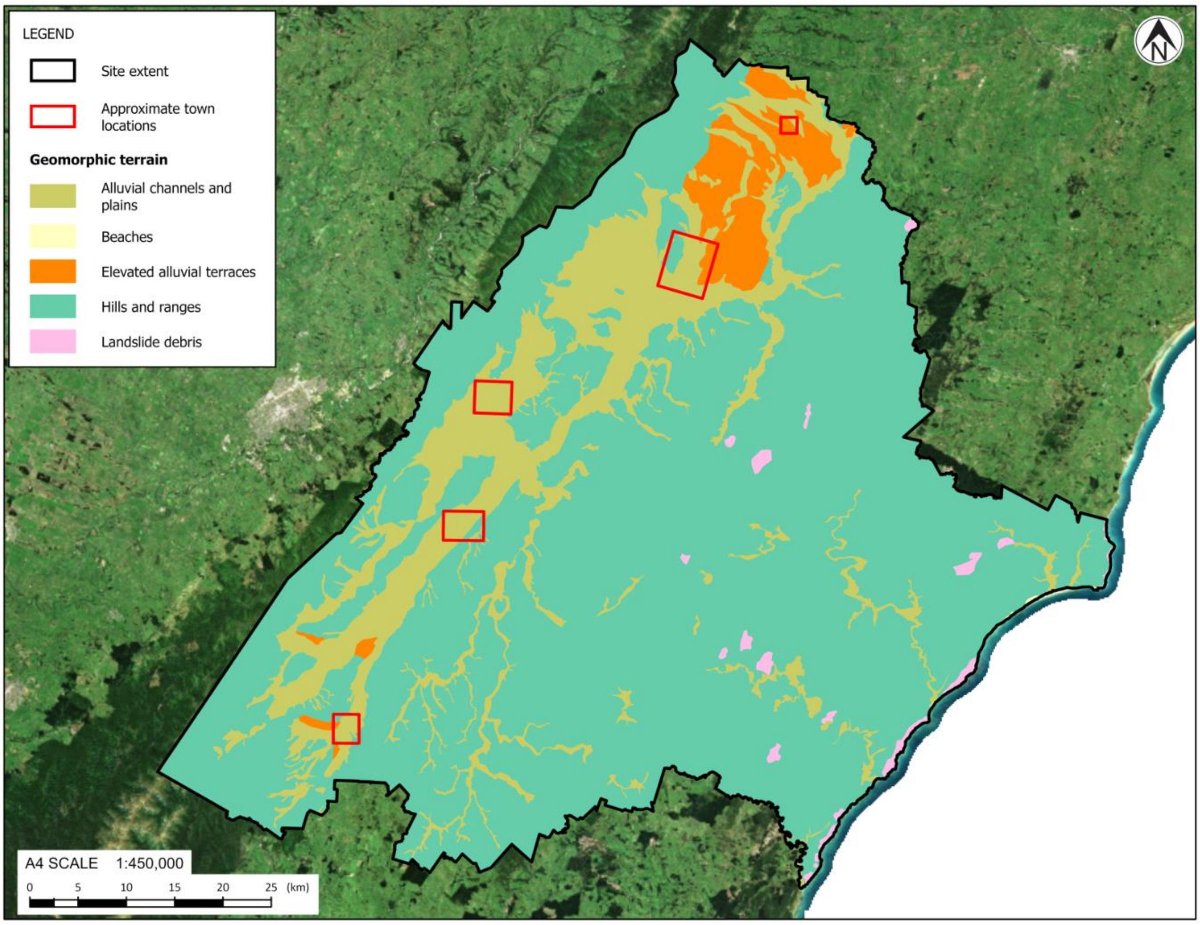


Figure 3.9: Geomorphic map of the Study Area

3.2.3 Geotechnical investigations

Existing geotechnical investigations from the publicly available New Zealand Geotechnical Database (NZGD) and from T+T's records have been considered for this study. Cone penetration tests (CPT) and boreholes are typically the most useful deep investigation methods for assessing liquefaction. For residential and light commercial development, the MBIE/MfE Guidance (2017) recommends that these be undertaken to a depth of at least 10-15 m below ground level or at least 20-25 m for heavier structures or critical facilities. In some circumstances test pits and hand augers can be utilised to help understand the shallow sub-surface profile but they are not considered to be an appropriate tool when more detailed analysis is required.

Three sources of information have been used to gather existing geotechnical investigations for the study area:

1. Publicly available New Zealand Geotechnical Database (NZGD)
2. T+T's geotechnical Database (TTGD)
3. Geotechnical reports provided by TDC

The number of investigations available by geomorphic terrain is shown in Table 3.4.

Table 3.4: Geotechnical investigation count by high level geomorphic terrain as at October 2020

Geomorphic terrain	Cone Penetration Tests (No.)	Borehole (No.)	Test pit (No.)	Hand auger (No.)	Window Sampler (No.)	Reports (No.)
Alluvial Channels and Plains	2	5	24	12		6
Elevated Alluvial Terrace				2		1
Beaches						
Landslide Debris			11			
Hills and Ranges		18	10		7	
Total	2	23	45	14		
Note: The CPT identified in this table terminated early so did not assess deeper soils. These CPT are therefore not useful to help determine liquefaction vulnerability categories.						

Figure 3.10 and Figure A5 in Appendix A show the location of the geotechnical investigations available on the NZGD as of October 2020. Note that this map does not show investigations from T+T's internal records because we do not have client permission to publish the locations of these investigations.

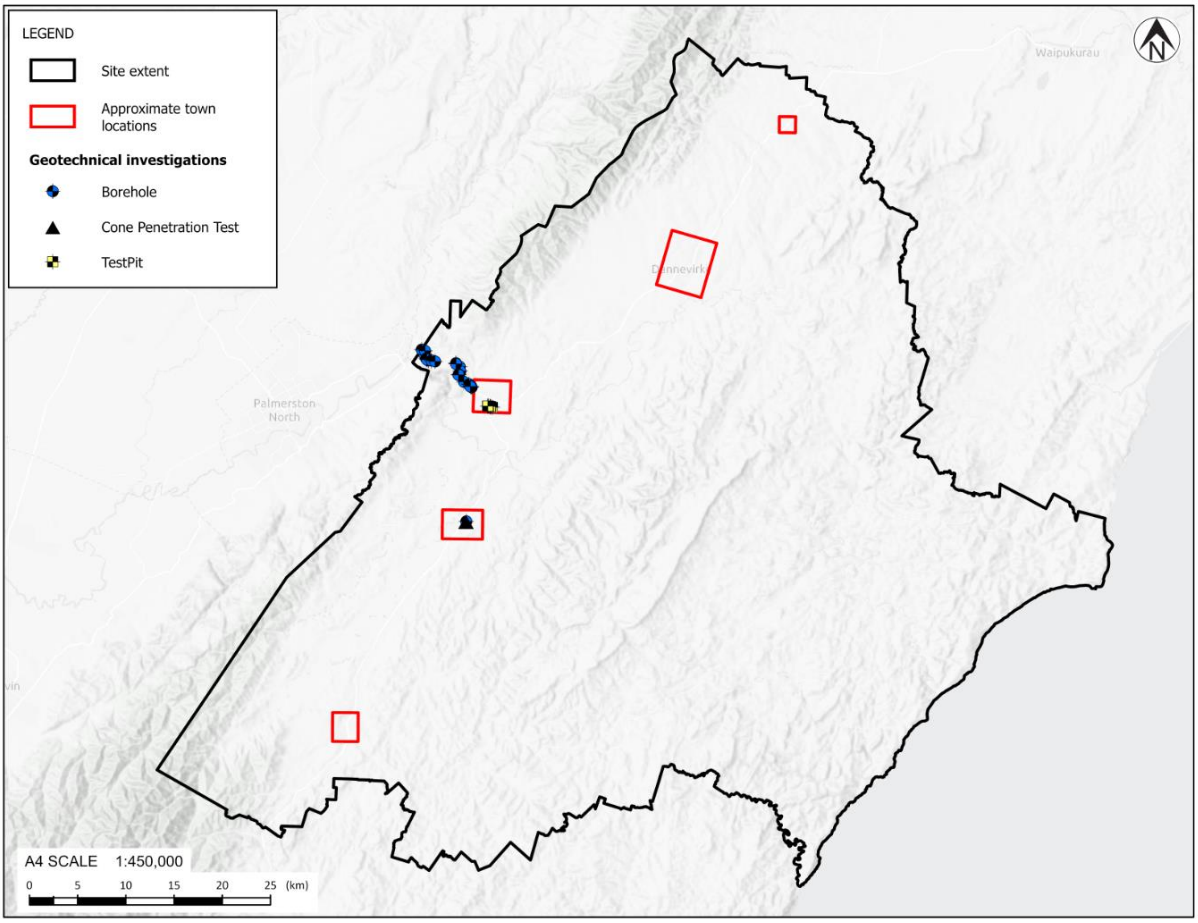


Figure 3.10: Geotechnical investigations available on the NZGD as of October 2020.

Compared to other parts of New Zealand there are relatively few geotechnical investigations available on databases within the Tararua District. As shown in Figure 3.10, the investigations on the NZGD that are available are predominantly located within town centres or along road developments. The spatial distribution of geotechnical investigation records on T+T's internal database also follows this pattern. The uncertainty associated with the spatial distribution is discussed further in Section 3.3.3.

3.2.4 Groundwater

Groundwater data

Within the Study Area, there are 1,286 bores recorded in the Horizons Regional Council GIS database. These have been installed for a variety of reasons (e.g. water supply, water monitoring etc.). T+T applied the following screening criteria to estimate how many of these bores are representative of shallow groundwater (water table) and therefore can be used to provide information about the groundwater surface elevation:

1 Bore depth less than or equal to 20 m (and not equal to 0 m) because bore depths of greater depth may encounter deeper confined aquifers and therefore not be representative of the shallow groundwater; and

2 Measured water level not equal to 0 m.

A total of 447 investigations met these screening criteria. In addition, there are thirteen long term monitoring wells that are part of Horizon's Manual Monthly Water Level Monitoring Programme which have measurements dating back to 1992.

In addition, based on the Geotechnical Investigation database, there are three geotechnical investigations within the Study Area which have recorded groundwater levels and the depth of the investigation is less than or equal to 20 m bgl.

The spatial distribution of the in-situ groundwater data is shown in Figure 3.11 and Figure A6 in Appendix A.

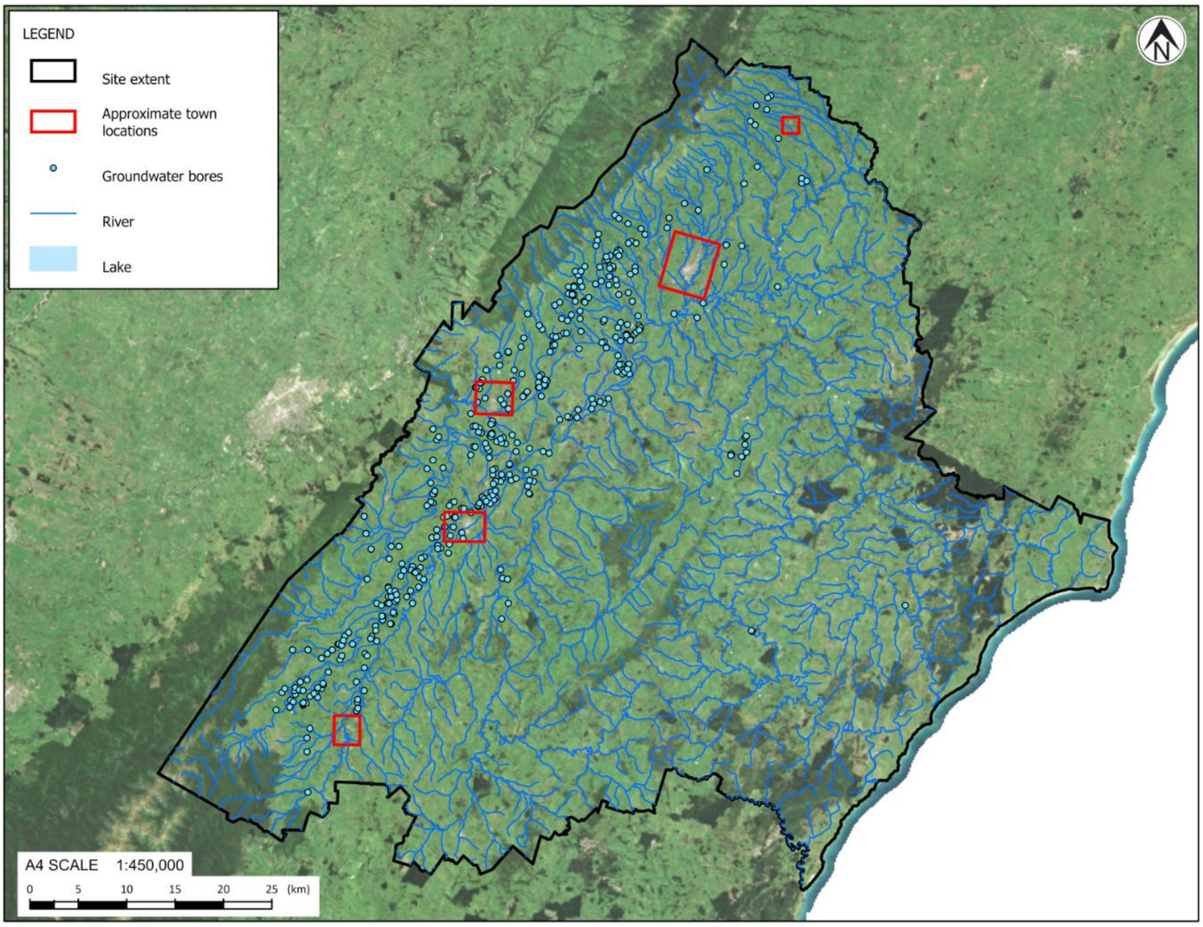


Figure 3.11: In-situ groundwater data and mapped locations of surface water bodies from the 1:250,000 scale topographic map.

Groundwater studies

The depth to groundwater for the Tararua District is represented sparsely in several regional studies which are primarily based on static groundwater levels readily available from well/bore locations from the Horizons Regional Council Open Data GIS.

Table 3.5: Available groundwater studies in the study area

Title	Authors	Published date	Coverage of study area
Hydrogeology of the Upper Manawatu and Mangatainoka catchments	Rawlinson, Z.J.; Begg, J.	June 2014	Partial - Upper Manawatu and Mangatainoka catchments
Report on Horizons Regional Council Groundwater Level Monitoring Network and Groundwater Quantity Management Issues	Callander, P.; Thomas, N.	May 2013	All monitoring wells within study area

The following is a summary of the studies listed in Table 3.5:

- *Hydrogeology of the Upper Manawatu and Mangatainoka catchments* (Rawlinson & Begg, 2014)was completed by GNS Science contracted by Horizons Regional Council. The study provided a three-layer subsurface hydrogeological conceptual model for the priority catchments within the Tararua Groundwater Management Zone (GWMZ), including the Upper Manawatu and Mangatainoka catchments. It had a primary focus on the Mangatainoka catchment. Through this work, a potentiometric surface was created using a combination of static water levels taken during drilling and mean water levels at long-term monitored sites. The 25 mbgl potentiometric contours provides a surface that is representative of regional-scale groundwater conditions. However, the surface has high uncertainty due to the temporal disparity of static water level measurements. Therefore the resultant use of the mean water levels at monitored sites as a more temporal-specific statistic would not be meaningful.
- *Report on Horizons Groundwater Level Monitoring Network and Groundwater Quantity Management Issues* (Callander & Thomas, 2013) summarised the seasonal and long-term trends based on the available groundwater network within Horizons Regional Council. Based on this assessment, the majority of the shallow bores (<20 m) in the Tararua District show low seasonal fluctuations (1-2 m) and neutral to slight rise in groundwater levels based on statistical trend analyses from observations from 2005.

Based on the MfE[4] climate change projections by region, the Horizons Region can expect seasonal increases of rainfall by 6-10% in the winter, which in turn could potentially increase seasonal recharge to groundwater. In addition, the amount of time the region spends in drought is forecasted to possibly double by 2090. The combined increase in winter rainfall, and periods of drought would likely affect the seasonal fluctuations observed in monitoring wells which may impact the range and increase the uncertainty in the modelled median depth to groundwater.

3.2.5 Seismic Hazard

Soils that are susceptible to liquefaction require a certain level of earthquake shaking (duration and intensity of ground shaking) to cause them to liquefy. A key source of uncertainty in liquefaction analyses is the intensity of shaking that will occur at a particular location in future earthquake events. The following is a summary of the available seismic hazard information for the Tararua District.

Regional tectonic setting

The Tararua District is known to be situated within a neotectonic terrain and as such experiences relatively high seismicity, with a significant number of active faults. The New Zealand Active Faults database (GNS Science, 2020), shows several active faults passing through the Tararua District (see Figure 3.6).

The most significant faults in the area shown on Figure 3.6 are right-lateral strike-slip faults which have significant vertical components of movement, and result from the convergence of the Australian and Pacific tectonic plates.

- The Wellington Fault is a significant, active strike-slip fault that bisects the Wellington region. The Wellington Fault follows a predominantly northeast/southwest (NE/SW) trend and approximately follows the eastern side of the Tararua Range (close to the western extent of the study area) before transitioning at its northernmost extent into the Mohaka and Ruahine Faults, approximately 5 km southwest of Woodville.

[4] 2018. Climate change projections for the Manawatu-Whanganui region. https://www.mfe.govt.nz/climate-change/likely-impacts-of-climate-change/how-could-climate-change-affect-my-region/manawatu. Accessed January 12 2021.

- The Mohaka and Ruahine faults also trend NE/SW and follow approximately parallel with Ruahine Range, along the north-western extent of the study area. They continue out of the study area, inland from Hawke's Bay on the same NE/SW trend.
- The Makuri-Waewaepa Fault (MWF) forms another significant, active strike-slip fault system that passes approximately through the centre of the study area on a NE/SE trend, approximately parallel with the Wellington, Ruahine, and Mohaka fault systems. The MWF transitions from the Wairarapa Fault system to the south. The fault has a right-lateral sense of slip and is oblique, experiencing significant vertical movement, with land being upthrown on the western side of the fault and downthrown on the eastern side. This vertical movement has resulted in the Waewaepa Range which follows the trace of the MWF.

Horizons Regional Council has engaged GNS to undertake fault mapping within the study area. The mapping exercise is unlikely to identify new major faults within the study area but are more likely to identify lesser faults and delineate fault avoidance zones. The potential effect of any newly-identified faults on the liquefaction vulnerability of a site will need to be assessed as part of more detailed site-specific assessments as required in future.

Table 3.6: Summary of notable historic earthquakes in the Tararua District

Date	Location	Earthquake Magnitude	Earthquake Depth (km)
9 August 1904	20 km south-west of Porangahau	7.0	16 km
12 February 1930	10 km south-west of Porangahau	6.2	33 km
5 March 1934	5 km east of Pongaroa	7.2	12 km
19 February 1990	20 km north-east of Pongaroa	6.2	34 km
13 May 1990	15 km south-west of Porangahau	6.4	30 km
20 January 2014	10 km east of Eketahuna	6.2	34 km
Search based on earthquakes in the district exceeding 6.0 Magnitude from https://quakesearch.geonet.org.nz/#			

The Z Factor parameter outlined in NZS1170.5 provides a high-level overview of seismic hazard across New Zealand. The regional variation is generally consistent with the updated Bridge Manual methods used in this assessment (NZTA, 2018). The Z Factor map for the North Island is provided for regional context below as Figure 3.12, and provides a visual overview of the anticipated seismic hazard of the Tararua District in the context of the North Island.

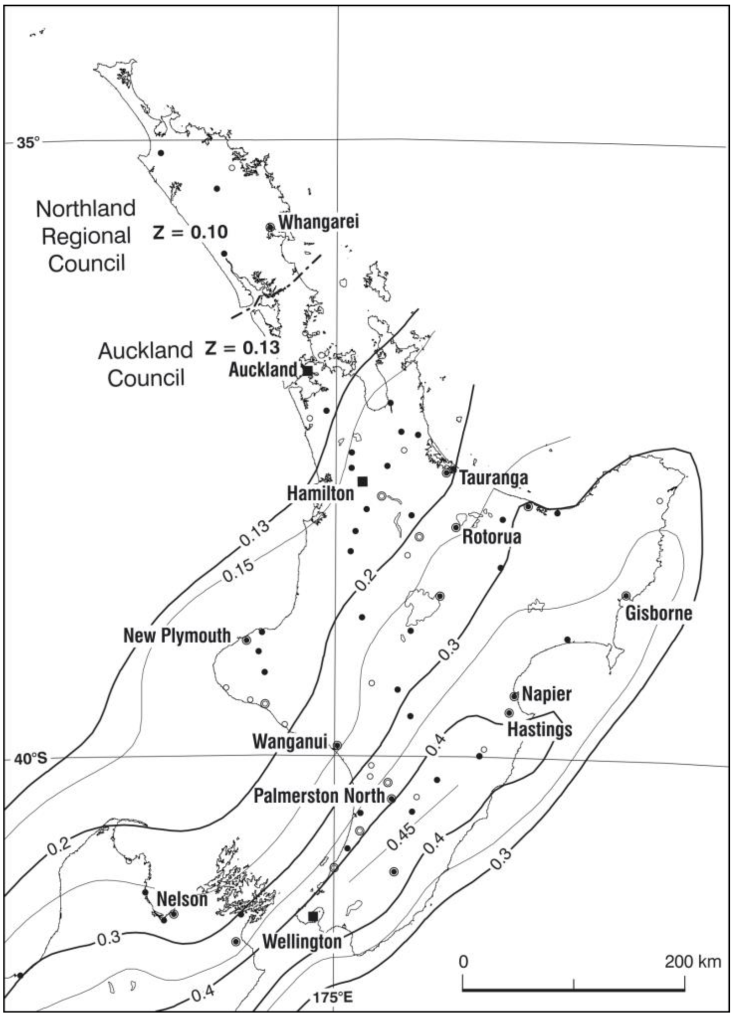


Figure 3.12: Z Hazard Factor map for the North Island. (Source: Standards New Zealand NZS 1170.5:2004).

High-level seismic ratings (MBIE, 2018) for New Zealand based on Z Factor values are provided below for context in Table 3.7.

Table 3.7: Categorisation of Seismic Hazard from Z Factor for New Zealand (MBIE Building Performance website)

Seismic Hazard Rating	Z Factor
Low Seismic Risk	< 0.15
Medium Seismic Risk	0.15 to 0.30
High Seismic Risk	≥ 0.30

In common New Zealand engineering practice, the procedure for calculating seismic hazard is adopted from the NZTA Bridge Manual (NZTA, 2018), which gives a representative earthquake magnitude ranging between 6.2 to 7.1 for the Tararua District and a range of peak ground acceleration (PGA) values depending on the design scenario and location. Derivation of seismic hazard parameters is discussed further in the following section.

Seismic hazard information available for this study

The main sources of seismic hazard information within the district are the NZTA Bridge Manual (NZTA, 2018) and the GNS Science Lifelines Risk and Responsibilities Report (Dellow, 2016).

- **NZTA Bridge Manual (2018)** – For routine engineering projects, the NZTA Bridge Manual is currently the commonly accepted method for determination of seismic hazard for liquefaction analysis in New Zealand in the absence of a site-specific assessment or regional study.
- **Lifelines Risk and Responsibilities Report (2016)** – GNS Science completed a hazards assessment which included the site subsoil class, and an assessment of the seismic hazard, using GNS Science's National Seismic Hazard Model. The subsoil class section of the GNS Science report shows the Tararua District as comprising Subsoil Class B (weak rock) for the hills and ranges with the plains and alluvial terraces comprising D (deep or soft soil) flanked by Class C (Shallow Soils) as shown in Figure 3.13. The determination of Subsoil Class in the GNS study is based on Perrin et al (2015) which uses values derived from site-specific measurements, established correlations with strength and density parameters from site investigations and extrapolation based on geological unit and topography. While these values are appropriate for a district or regional scale study, a site-specific assessment would need to consider which Subsoil Class is appropriate for use to determine seismic hazard at a given site.

  The report also depicts the different PGA's over the district for events at 1 in 500, 1 in 1000 and 1 in 2500-year annual exceedance probabilities. An example for the 1 in 500-year event is shown in Figure 3.14 For the Tararua District, the range in PGA is between 0.35 and 0.45 g.

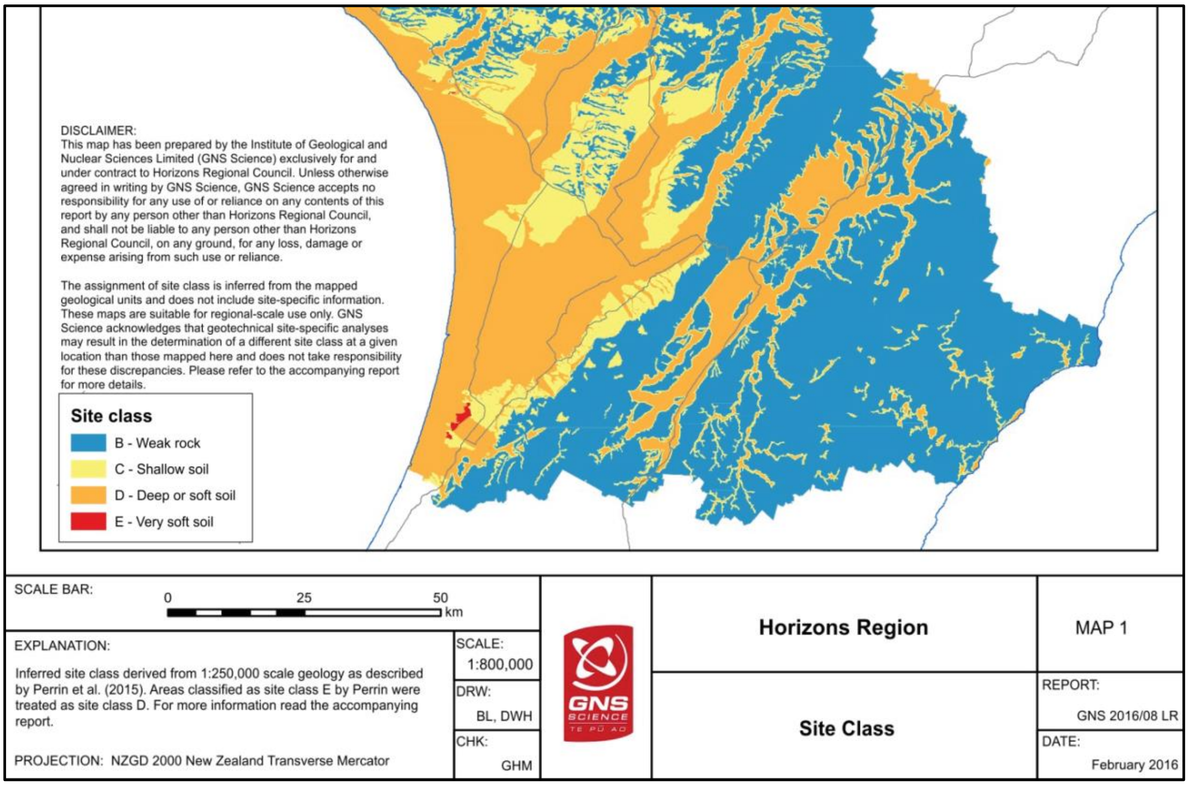


Figure 3.13: Site subsoil class at regional level scale as per (Dellow, 2016).

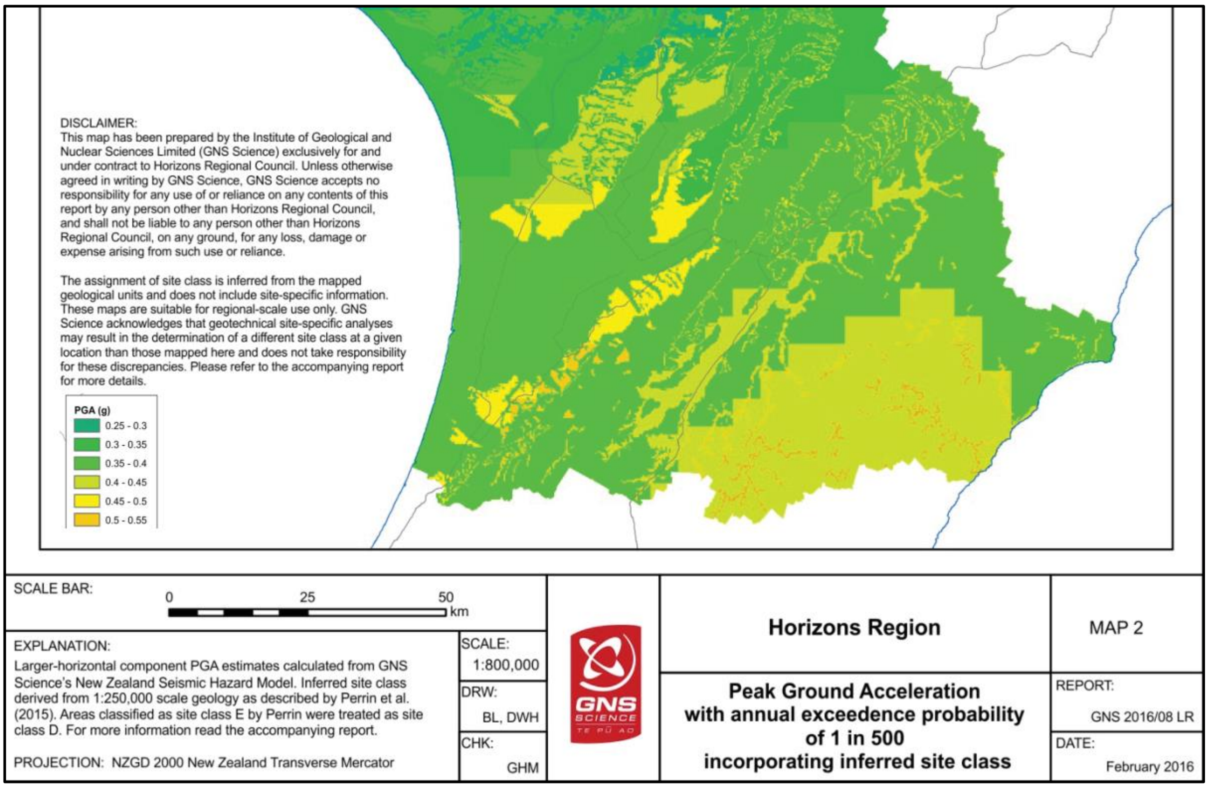


Figure 3.14: PGA output for a 1 in 500-year event over the Tararua District (Dellow, 2016)

Seismic hazard design parameters

For this assessment, New Zealand Standards 1170.0 and 1170.5 (New Zealand Standards, 2002) (New Zealand Standards, 2004) have been used in conjunction with the NZTA Bridge Manual (NZTA, 2018) to estimate representative values for the effective magnitude (M_{eff}) and a corresponding PGA for a variety of return periods. These parameters are summarised below in Table 3.8.

Table 3.8: Estimated seismic parameters for three towns within the Tararua District based on the NZTA Bridge Manual methodology (NZTA, 2018)

Dannevirke				
Design Case	**Magnitude (M_{eff})**	**Peak Ground Acceleration, PGA (g)**		
		Subsoil Class A & B	Subsoil Class C	Subsoil Class D & E
1 in 25 Years (SLS)	6.2	0.08	0.11	0.09
1 in 500 Years (ULS)	7.0	0.33	0.44	0.35
1 in 1000 Years	7.0	0.430	0.57	0.46
Woodville				
Design Case	**Magnitude (M_{eff})**	**Peak Ground Acceleration, PGA (g)**		
		Subsoil Class A & B	Subsoil Class C	Subsoil Class D & E
1 in 25 Years (SLS)	6.2	0.09	0.11	0.09
1 in 500 Years (ULS)	7.0	0.34	0.45	0.35
1 in 1000 Years	7.0	0.44	0.59	0.46
Pahiatua				
Design Case	**Magnitude (M_{eff})**	**Peak Ground Acceleration, PGA (g)**		
		Subsoil Class A & B	Subsoil Class C	Subsoil Class D & E
1 in 25 Years (SLS)	6.2	0.09	0.12	0.09
1 in 500 Years (ULS)	7.1	0.35	0.46	0.36
1 in 1000 Years	7.1	0.45	0.60	0.47

3.2.6 Historical observations of liquefaction

No reports of historical liquefaction have been found for the study area. Some reference was found for damaged chimneys in Dannevirke following the 1934 Pahiatua earthquake (included in Table 3.6) (Downes, 1999), but no discussion of liquefaction related to that event.

3.3 Uncertainty assessment

This section presents an assessment of the uncertainty associated with the base information currently available in the TDC area. The key output from this uncertainty assessment is determination of the level of detail supported by the currently available base information.

3.3.1 Ground surface levels

As described in Section 3.2.1 the available information to define the ground surface levels is high resolution LiDAR DEM. For this study, this data is used primarily in the development of the geomorphic map. It would also be a key data source in the development of any future depth to groundwater models and the identification of free-faces for lateral spreading assessment. The key uncertainties associated with the ground surface levels are discussed below.

Uncertainty due to the accuracy and limitations of LiDAR derived DEM

While the available LiDAR derived DEM is high resolution and considered fit for the purposes of the scale of this liquefaction assessment, the following accuracy limitations generally associated with this survey technique should also be acknowledged:

- Measurement error associated with the LiDAR point cloud collection method.
- Localised error due to interpolation in areas with low density of ground classified points.
- Spatial resolution of the DEM and the accuracy and appropriateness in representing the ground surface elevation such as presence of houses and trees in unprocessed parts of the data.

In most cases these limitations will have a relatively minor effect on the representation of the ground surface at this regional scale. However, there are some specific applications which result in significant uncertainty in the assessment. A key example of this is the inability of LiDAR to penetrate water bodies. This limits the usefulness of LiDAR data for mapping free faces in water features because when water bodies are present at the invert of free faces, the height of the free face may be under-estimated resulting in under prediction of the extent and severity of lateral spreading. Also, where the LiDAR used in this study still includes houses and trees, these areas that are not ground level and this could affect assessments of liquefaction vulnerability if this data is used at a more local scale. It is recommended that smaller, local scale assessments check the data used for their analysis of ground surface levels and process it as required.

Uncertainty due to temporal changes in ground surface elevation

To a greater or lesser extent, any ground surface will be undergoing change in elevation. These changes may be attributable to natural processes (e.g. tectonic movement and earthquake induced ground deformation) or anthropogenic (man-made) changes (e.g. land development activities).

It is not feasible to predict with any reasonable degree of accuracy the extent and degree of future changes in ground surface elevation. However, by reviewing historical aerial imagery it is possible to map areas of anthropogenic modification of the ground surface elevation such as quarries, dams and landfills. Although, mapping from historic aerial imagery may not capture all areas of anthropogenic change. The historic images may not cover the period when filling occurred, or the modification was simply not visible in the imagery.

3.3.2 Geology and geomorphology

As discussed in Section 3.2.2 the geology and geomorphology of the study area is presented in the form of maps. This mapped information is used in the liquefaction assessment to group areas of similar expected performance. The key uncertainties associated with the geology and geomorphology are discussed below.

Uncertainty due to the precision of mapping and the accuracy of boundaries between terrains

This can result in the incorrect categorisation of the land (if placed into the wrong geomorphology type) and hence incorrect estimation of ground performance. The specification of a scale of approximately 1:25,000 for the geomorphic mapping provides an indication of the degree of uncertainty and areas where there is more uncertainty associated with the location of the boundary have been identified.

This uncertainty has been allowed for by providing buffer zones of "Liquefaction Damage is Undetermined" in the liquefaction vulnerability classification map where an area classified as "Liquefaction Damage is Possible" is adjacent to an area classified as "Liquefaction Damage is Unlikely."

Uncertainty due to anthropogenic landform changes

Some anthropogenic landform changes, in particular those associated with large infrastructure or land development projects, can result in changes to the severity of liquefaction related land damage under seismic load. In some cases, these changes will result in an improvement of liquefaction performance (e.g. ground improvements such as dynamic compaction or stone columns) or in some instances there will be a degradation in liquefaction performance (e.g. reduction of the ground surface elevation resulting in a reduced depth to ground water).

The level of detail targeted by this assessment (i.e. Level A) means that incorporating the site-specific information that would be required to assess the effects of these landform changes is not included in the scope for this project. More detailed assessment that incorporates site specific information (i.e. Level C or D) would be required to differentiate different geomorphic terrains.

Uncertainty due to age of geological units

Based on the descriptions and ages of different geological units, we have separated out certain units as being less prone to liquefaction based on their age (early and middle Pleistocene separated from late Pleistocene). We have also assumed that the early to mid-Pleistocene sediments, are less vulnerable to liquefaction as they are predominantly gravel and have also experienced uplift during the Quaternary period, likely subject to more earthquakes, and therefore are likely to be more consolidated.

These uncertainties can be overcome by site specific assessment of land being developed, to confirm the materials and geological units present on site.

3.3.3 Geotechnical investigations

As discussed in Section 3.2.3, there is a range of geotechnical investigations available on the NZGD within the study area. These geotechnical investigations can be used to estimate the expected liquefaction related performance of the land. The key uncertainties associated with the geotechnical investigations are discussed below.

Uncertainty due to geotechnical investigation data quality

Each geotechnical investigation has inherent data quality issues. Some of these are readily identifiable, are logged as part of the investigation and can be allowed for in the analysis (e.g. CPT investigations terminating at a shallow depth). Others are not readily identifiable without being able to refer to the data source and must be considered as part of engineering judgement (e.g. incorrectly logged borehole data). The relatively few geotechnical investigations within the Study Area and the level of detail targeted (i.e. Level A) means that this source of uncertainty does not contribute significantly to the overall uncertainty in the assessment.

Uncertainty due to variability in ground conditions within geomorphic terrains

Within each geomorphic terrain there is a degree of natural variability in ground conditions that results in a degree of variability in expected liquefaction related performance. Some geomorphic terrains, such as the Hills and Ranges, are likely to have a low degree of variability and this would be reflected in a relatively uniform estimate of liquefaction related performance for a constant depth to groundwater. Other geomorphic terrains, such as the Alluvial Channels and Plains, are much more variable in the soil conditions encountered and this would be reflected in a relatively variable estimate of liquefaction related performance for a constant depth to groundwater.

This source of uncertainty is managed by considering the likely variability in soil conditions within each geomorphic unit as part of the liquefaction vulnerability categorisation process. The results of this are discussed in Section 4.4 .

Uncertainty due to geotechnical investigation spatial density

Section 3.4 of the MBIE/MfE Guidance (2017) provides guidance about the required spatial density of ground information. It emphasises that the key features which define the level of detail for a particular assessment are the nature of the assessment undertaken and the residual uncertainties, not simply the investigation density.

Specifically, it states that:

"The key requirement is that the investigations should be sufficient for adequate ground characterisation for the specific purpose of the assessment and ground conditions encountered."

With that noted it provides the indicative spatial density of deep ground investigations for adequate ground characterisation for liquefaction assessments shown in Figure 3.15.

LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT [1,2]	AVERAGE INVESTIGATION DENSITY	AVERAGE SPACING BETWEEN	MINIMUM TOTAL NUMBER OF INVESTIGATIONS
Level A[3] **Basic desktop assessment**	0.01 to 1 per km^2	1 to 10 km	–
Level B **Calibrated desktop assessment**	0.5 to 20 per km^2	220 to 1400 m	3 for each geological sub-unit
Level C **Detailed area-wide assessment**	0.1 to 4 per Ha	50 to 320 m	5 if area > 1 Ha 3 if area 0.25 – 1 Ha 2 if area < 0.25 Ha
Level D[4] **Site-specific assessment**	2 to 40 per Ha	15 to 70 m	2 within or very close to the building footprint

Notes:

1 Investigation densities listed in this table are cumulative – suitable data from investigations undertaken in previous stages of work should be incorporated in subsequent stages.

2 The key feature defining each level of detail is the degree of residual uncertainty in the assessment (refer Table 3.1), not necessarily the spatial density of ground investigations. In some circumstances a significantly higher or lower investigation density might be appropriate to provide the required degree of certainty for a particular target level of detail or purpose. For example, the lower end of the recommended minimum range might be appropriate where investigations show ground conditions to be reasonably consistent (eg some marine or lake deposits), while the upper end of the range may be more appropriate if ground conditions prove to be highly variable (eg many river deposits).

3 There are no minimum investigation density requirements for a ***Level A*** liquefaction assessment. However, the geological maps that are normally used for a ***Level A*** assessment have often been 'ground-truthed' at approximately the density shown. New ground investigations are unlikely to be required, provided that existing information such as geology, geomorphology and groundwater maps is suitable (relative to the scale and purpose of the assessment), and categories are assigned with appropriate consideration of the uncertainties.

4 For a ***Level D*** assessment, the key requirement is to confidently characterise the ground conditions at the specific location of the proposed building. Therefore the particular arrangement and proximity of investigations within and surrounding the building footprint will often be of greater importance than the minimum investigation density criteria.

Figure 3.15: Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes.

Compared to other parts of New Zealand there are relatively few geotechnical investigations within the study area on the NZGD and within T+T's records. For a Level A level of detail, this spatial density issue means it is not possible to reliably calibrate the soil conditions from the available geotechnical investigations.

While calibration with geotechnical investigations is not required for a Level A study, it does help reduce some of the uncertainty associated with inferences about ground conditions within a particular area. To manage this issue, we have carefully considered this source of uncertainty in the assignment of liquefaction vulnerability categories and areas with significant residual uncertainty about the nature of the soil conditions have been mapped as "Liquefaction Category is Undetermined".

3.3.4 Groundwater

As discussed in Section 3.2.4, there are several in-situ groundwater data records within the Tararua District, the majority of which are single measurements from boreholes that are sourced from the

Horizons Regional Council Open Data database. The key uncertainties associated with the available groundwater data are discussed below.

Uncertainty due to groundwater data spatial density

The available groundwater data records are predominantly widely spaced throughout the district leaving significant gaps between these records. This makes meaningful interpolation of the depth to groundwater between locations with groundwater records challenging. While not critical for the areas where a Level A level of detail is targeted, this uncertainty becomes increasingly important in areas where quantitative analysis is required to support a higher level of detail.

Uncertainty due to length of groundwater data records

The groundwater data that T+T has been able to source to date are only single measurements of groundwater at one point in time. As noted in Section 3.2.4, there are some wells that have a classified "Purpose" of Monitoring. At these locations it seems likely that a record of groundwater level monitoring over time exists. While not critical for the areas where a Level A level of detail is targeted, this information becomes increasingly important at higher levels of detail because it provides valuable information about the variability in ground in groundwater levels (e.g. due to seasonal influences).

Uncertainty due to the effects of climate change

Climate change introduces further uncertainty regarding the groundwater conditions that could exist at some time in the future when an earthquake occurs. The key effects of climate change on the future groundwater conditions may include:

- Changes in the intensity and distribution of rainfall influencing the recharge rate of the groundwater surface.
- Reduction in the depth to groundwater due to the effects of sea level rise.

The uncertainty associated with the available groundwater data does not contribute significantly to the uncertainty in this study in areas where a Level A level of detail is targeted. However, it does represent a significant source of uncertainty in areas where a Level B level of detail is targeted.

Validation and possible ground truthing of existing records would be a useful first step to reduce some of the uncertainty associated with the existing records. More detailed analysis would require installation of a network of piezometers to monitor groundwater level fluctuations over time. Development of groundwater models from this information would provide valuable information for such studies and other applications.

Such information would provide a significant reduction in uncertainty in the assessment and potentially enable more detailed classification of the liquefaction vulnerability in the area. In addition, monitoring in these areas could infer potential relationships between groundwater and sea level rise, and provide a foundation for future management of sea-level rise hazards from groundwater.

3.3.5 Seismic hazard

Seismic parameters have been derived for this assessment based on the NZTA Bridge Manual methodology (NZTA, 2018). However, Module 1 of the NZGS Earthquake Geotechnical Engineering Practice Guidelines (NZGS/MBIE, 2016) notes the following issues have been identified with this approach, indicating a significant degree of uncertainty:

1. Compatibility issues between the magnitude weighting factors embedded in the hazard evaluation and the magnitude scaling factors in the liquefaction evaluation procedures adopted in this guideline series

2 The use of an "effective earthquake magnitude"

3 The need to incorporate updates in the National Seismic Hazard Model.

These issues indicate there is a significant degree of uncertainty associated with the estimation of seismic hazard using this methodology. Furthermore, the seismic parameters are highly variable across the study area Table 3.8.

The base information review outlines discrepancies between NZTA Bridge Manual Methodology and the GNS Science Lifelines report (Dellow, 2016). The GNS report utilises the NSHM instead of the bridge manual. While there are existing PGA's for the district established by GNS Science, for this assessment we will use the Bridge Manual results. For any further site-specific work, or work on a Level C/D scale, it is likely these will utilise the Bridge Manual method.

The geological units that have been identified as being prone to liquefaction are typically found in basins where sediment has deposited over time. Basin effects are known to raise the PGA during an earthquake event due to rebounding of seismic waves off the basin walls. The depth of the basins in the area are unknown, and therefore the effect of the basin on PGA levels for this district is also unknown.

The primary focus of a Level A level of detail is to identify land where there is a high degree of certainty that "Liquefaction Damage is Unlikely" (so that it can be taken off the table without further assessment) (refer to Figure 3.1). This involves the use of qualitative methods that do not rely heavily on the precise seismic hazard parameters adopted. Furthermore, regardless of the method used, the 500-year level of earthquake shaking (i.e. PGA and magnitude pairing) across the Tararua District is well above the level of shaking required to trigger liquefaction in most soils. This is the primary consideration in this qualitative assessment of liquefaction vulnerability. Therefore, due to a Level A level of detail being targeted in this study, the uncertainty associated with the methods used to calculate seismic hazard parameters does not contribute significantly to the residual uncertainty in the current assessment.

3.3.6 Assess ground damage response against the performance criteria

The MBIE/MfE Guidance (2017) provides the performance criteria shown to determine the liquefaction vulnerability category for a particular area of land.

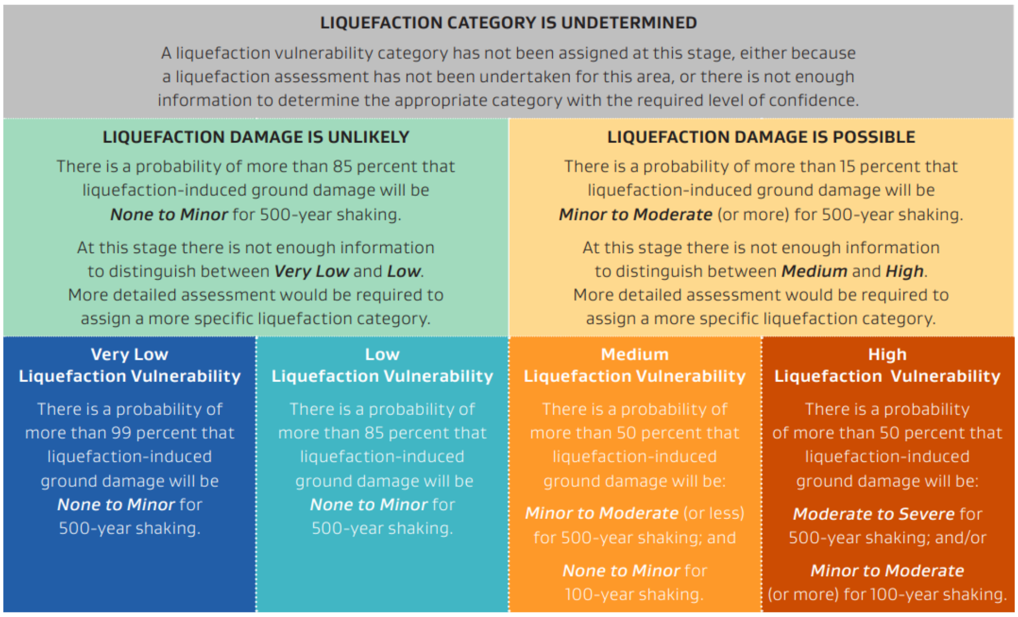


Figure 3.16: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017).

As discussed in Section 4.5.2 of the MBIE/MfE Guidance (2017), the performance criteria make reference to particular probabilities of a certain degree of damage occurring. These probabilities are intended to provide an indication of the level of confidence required to assign a particular category, rather than specific numerical thresholds to be calculated for each category. It is also important to recognise that these probabilities relate to the total effect of all uncertainties in the assessment, a characteristic that makes probabilistic calculation particularly challenging.

For this liquefaction vulnerability study, the level of confidence has been evaluated qualitatively with these indicative probabilities used as guidance. As with any qualitative assessment, it is necessary to apply a degree of judgement to determine the liquefaction vulnerability category for each area of land within the study area and there is inherent uncertainty associated with this subjective process.

For typical buildings and infrastructure, the consequences (or costs) of over-predicting the hazard are incurred upfront in the form of unnecessary capital expenditure on overly robust solutions. Conversely the costs of under-prediction are incurred at some time in the future when sufficiently strong earthquake shaking occurs and the buildings and infrastructure must be rebuilt or repaired. The potential consequences of this uncertainty in characterising the liquefaction vulnerability are discussed further in Appendix J of the MBIE/MfE Guidance (2017) and are reflected in the relativity between indicative probabilities specified for various categories in Figure 3.16.

For the current study, a key outcome of this balanced cost/benefit approach to uncertainty can be seen in areas where there is currently insufficient certainty to assign a category of "Liquefaction Damage is Unlikely" (i.e. an indicative confidence level of less than 85%). In many of these areas the nature of the expected ground conditions means that if more detailed site-specific assessment was undertaken in future then this would likely indicate a category of "Low Liquefaction Vulnerability".

Rather than assign the areas described above an interim category of "Liquefaction Damage is Possible" in the current study "just to be safe" (imposing upfront costs from over-prediction), these have been assigned "Liquefaction Category is Undetermined". This lack of a definitive category might appear to be unhelpful because it does not immediately tell people whether their land is vulnerable to liquefaction damage. Therefore, supporting information should be provided which draws on the technical work undertaken to date to provide clear direction on the process that people can follow to efficiently determine which liquefaction vulnerability category applies.

Section 4.4 discusses key aspects for future assessments in each geomorphic terrain. For example, in some geomorphic terrains, undertaking simple shallow hand auger boreholes and plasticity testing of soil samples would likely be sufficient to demonstrate "Low Liquefaction Vulnerability". This supporting information will be provided via the GIS metadata, which accompanies each sub area of similar expected performance.

3.4 Level of detail supported by the currently available base information

As shown in Figure 3.17 and Figure A7 in Appendix A, a Level A – basic desktop assessment was targeted across the Study Area and this is the level of detail that has been achieved in this study.

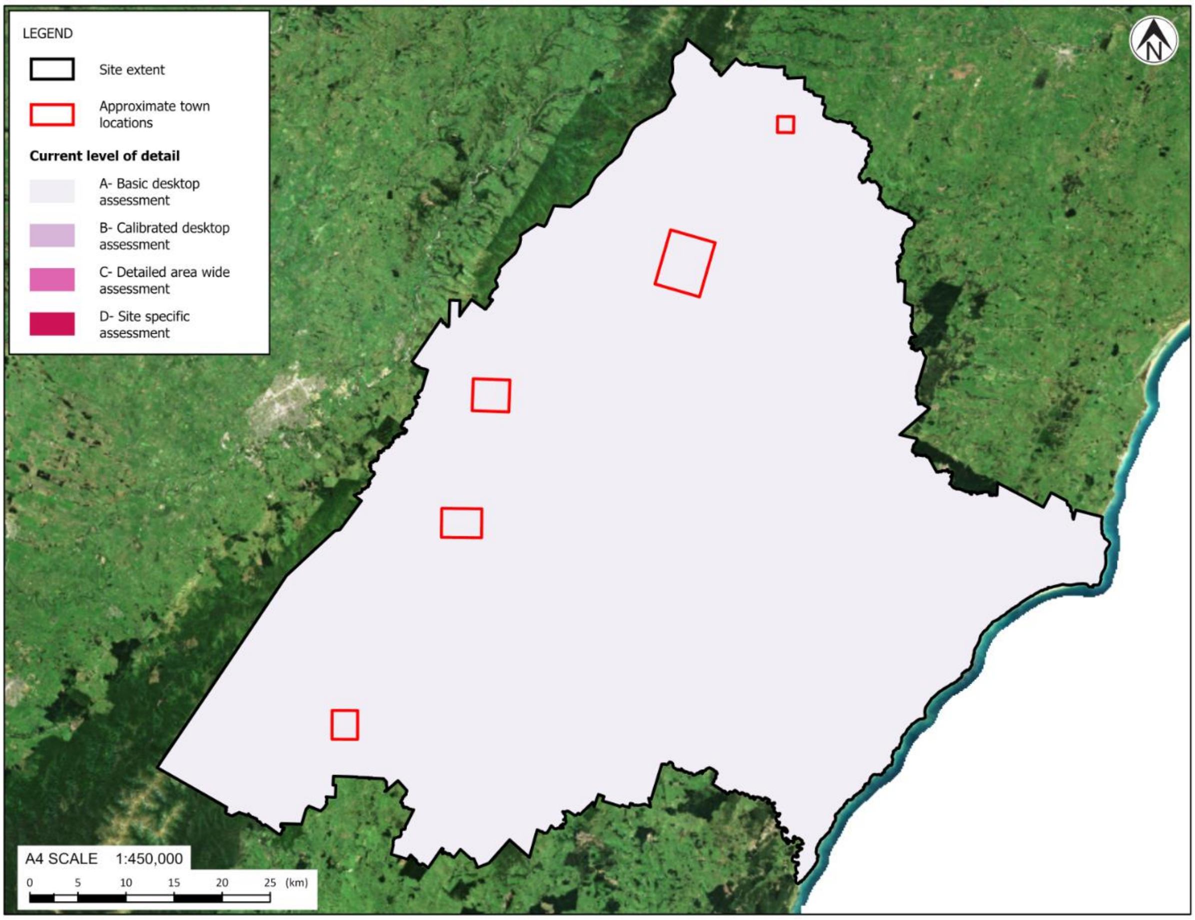


Figure 3.17: Level of detail supported by currently available base information (Level A throughout study area).

4 Risk analysis

The section of the outlines how the base information was analysed to determine the liquefaction vulnerability of the land within the Study Area. The key tasks in this step involve the following:

- Choosing groundwater levels to support the analysis
- Choosing earthquake scenarios to support the analysis
- Identifying sub-areas of similar expected performance
- Evaluating the expected degree of liquefaction-induced ground damage
- Assessing the liquefaction vulnerability category against the performance criteria

Each of these key tasks are discussed in further detail below.

4.1 Groundwater levels for analysis

As described in Section 3.2.4 and Section 3.3.4, within the Study Area there are relatively few in-situ groundwater data points available. Based on our summary of the monitoring groundwater bores (Section 3.2.4), seasonal water level trends indicate weak seasonal effects (0.2 - 1 m fluctuations) to limited effects (1 - 2 m fluctuations) and longer trends indicate neutral to slight rise in groundwater levels.

To accurately assess the approximate median depth to groundwater for each geomorphology, depth to groundwater was modelled over the district, taking into account spatial variability of elevation and distance to surface water features. As the groundwater surface is highly correlated to elevation and is locally influenced by surface water features, readily available mapped surface water features[5,6], 1m LiDAR[7], and static water levels[8,9] reported from bores were used to compute a spatially variable depth to groundwater for each geomorphology. Median statistics were subsequently derived for each geomorphology zone.

The depth-to-groundwater model is based on the methodology of Kriging with External Drift, which is a method which separates the modelling into two major steps. The first step is the determination of the “External Drift” model that is based on a statistical correlation between the variable of interest (groundwater level in mRL) and secondary variables, such as elevation and distance to surface water feature. The second step is the Kriging of the residuals from the first step.

Due to the extent of the model area, and the spatial distribution of the readily available data, the modelling approach has been undertaken using two levels of uncertainty. These levels are based on groundwater level data available within each unique geomorphology area. Based on the output from the model, assumed depth to groundwater has been calculated for each geomorphology zone (Table 4.1).

Due to the distribution of available data, the outputs form this model are considered high level, but a reasonable approximation for this scale of assessment.

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[5] Land Information New Zealand. NZ Coastlines (Topo, 1:50k). https://data.linz.govt.nz/layer/50258-nz-coastlines-topo-150k/

[6] NIWA. River Environment Classification (REC2) version 5. https://niwa.co.nz/freshwater-and-estuaries/management-tools/river-environment-classification-0

[7] Tararua District Council data

[8] Horizons Regional Council. OpenData GroundwaterBore. Accessed October 23, 2021. https://data-horizonsrc.opendata.arcgis.com/datasets/opendata-groundwaterbore-1

[9] NZ Geodatabase & TT Geodatabase

Table 4.1: Assumed depth to groundwater in each geomorphic terrain

Geomorphic terrain	Assumed median depth to groundwater (minimum - maximum)
Alluvial Channels and Plains	2.5 m (0.5 – 6.6 m)
Elevated Alluvial Terraces	3.3 m (0.5 – 5.2 m)
Landslide Debris	3.2 m (0.5 – 4.1 m)
Beaches	2.5 m (1.9 – 4.0 m)
Hills and Ranges	> 8 m

4.2 Earthquake scenarios for analysis

For the purposes of this liquefaction vulnerability study we have adopted the seismic hazard parameters shown in Table 4.2.

The 500-year return period is the recommended minimum earthquake scenario for Level A and B studies (as per MBIE/MfE Guidance, 2017). Regardless of the method used, the 500-year level of earthquake shaking (i.e. PGA and magnitude pairing) across the Tararua District is well above the level of shaking required to trigger liquefaction in most susceptible soils. This is the primary consideration in this qualitative assessment of liquefaction vulnerability (at a Level A level of detail). Therefore, for this assessment we have considered uniform shaking across the Study Area to inform the analysis.

To understand the variability in liquefaction vulnerability across the Study Area we have considered five earthquake shaking scenarios, with PGA of 0.1 g, 0.2 g 0.3 g, 0.4 g and 0.5 g (scenarios 1 to 5 respectively). The approximate equivalent return periods using the NZTA Bridge Manual Methodology (2018) for three of these scenarios (scenarios 1, 3 and 5) are shown in Table 4.2.

Table 4.2: Earthquake scenarios for analysis

Town	Earthquake Shaking Scenario (Average Return Period, years)					
	1 (PGA = 0.1 g)		3 (PGA = 0.3 g)		5 (PGA = 0.5 g)	
	Site Class A & B	Site Class D & E	Site Class A & B	Site Class D & E	Site Class A & B	Site Class D & E
Dannevirke	40	40	390	340	1600	1310
Woodville	40	40	370	340	1500	1310
Pahiatua	40	30	350	320	1400	1230

Note for future more detailed liquefaction vulnerability assessments (i.e. Level B or higher) that incorporate quantitative assessment methods, it would be important to consider the potential spatial variability in seismic hazard across the district, and evaluate the uncertainty associated with the information available in the location under consideration.

4.3 Sub areas of similar expected performance

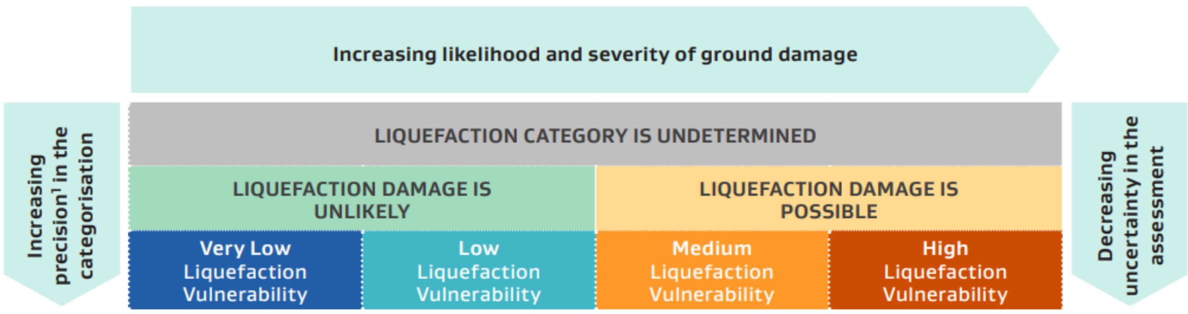
Sub areas of similar expected performance have been created by grouping areas of land according to the following characteristics:

- **Geomorphic screening** – as described in Section 3.2.2, the Study Area has been mapped according to the dominant geomorphic processes shaping each terrain. This is used as the primary basis for evaluating the likely soil conditions within each sub-area of similar expected performance. Where available, selected geotechnical investigations have been utilised to inform the potential variability in soil conditions within a given terrain.

- **Topographical screening** – The LiDAR derived DEM has been processed using GIS analytical tools to divide the Study Area into Slopes and Flat Land geomorphons. These subcategories have been used to qualitatively assess the typical groundwater depth ranges.
- **Lateral spread screening** – A high level screening of areas where lateral spreading is more likely to be possible has been undertaken by applying a 100 m buffer to the water bodies identified in the 1:250,000 scale topographic maps (sourced from the LINZ data service). Land within the buffer is mapped as “Liquefaction is Undetermined”. This has been applied to geomorphic terrains that are mapped as “Liquefaction is Unlikely” as all other geomorphic terrains are either “Possible” or “Undetermined” and therefore the buffer of land is not necessary to capture the uncertainty in those terrains.

4.4 Liquefaction vulnerability assessed against performance criteria

Using the available information, the liquefaction vulnerability of each sub-area has been assessed against the performance criteria. Each sub-area is then assigned one of the corresponding liquefaction vulnerability categories shown in Figure 4.1. The liquefaction vulnerability map of the Study Area is shown in Figure 4.2 and Figure A7 in Appendix A.



Note:

1 In this context the ‘precision’ of the categorisation means how explicitly the level of liquefaction vulnerability is described. The precision is different to the accuracy (ie trueness) of the categorisation.

Figure 4.1: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes - from MBIE/MfE Guidance (2017).

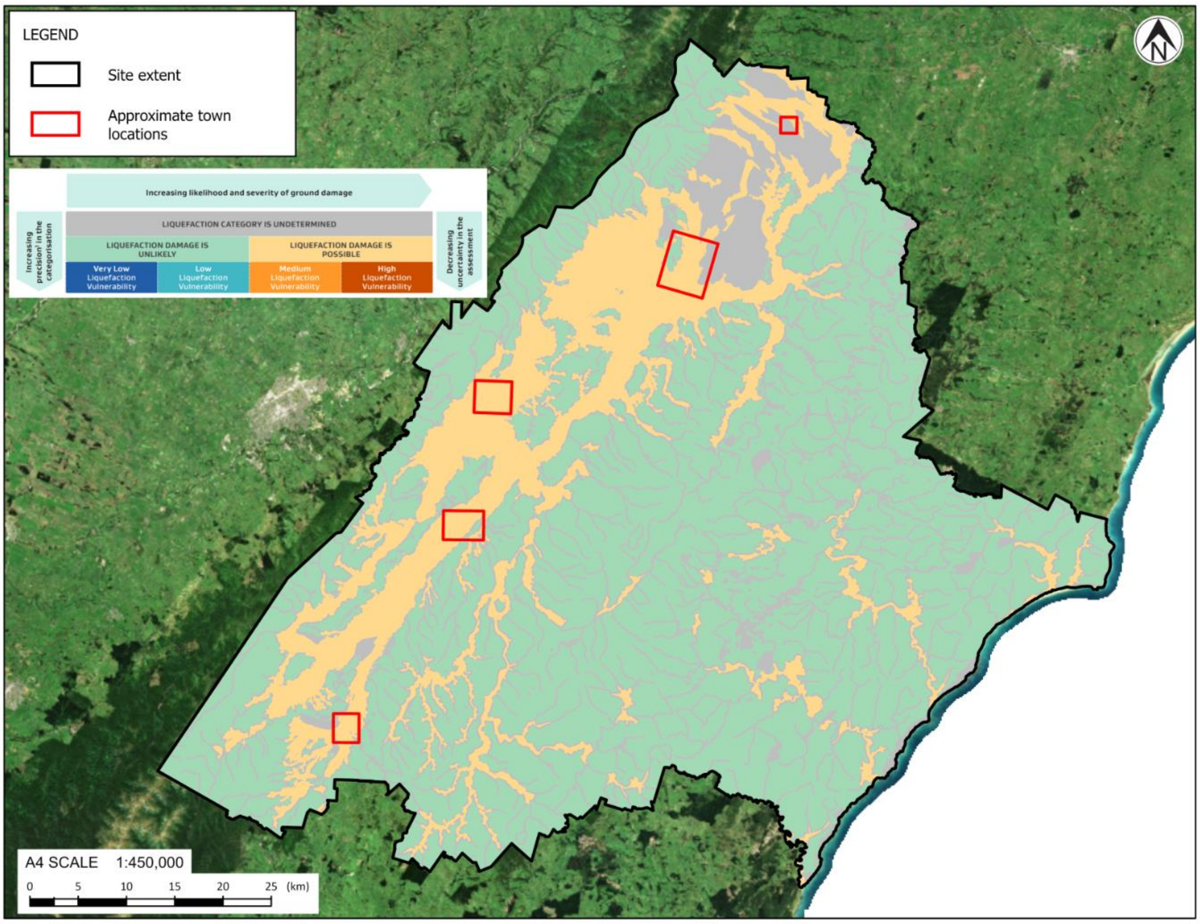


Figure 4.2: Liquefaction vulnerability classification assessed against performance criteria.

The following sections provide a summary of the assessment for each geomorphic terrain.

4.4.1 Hills and Ranges

This terrain comprises elevated landforms characterised by highly dissected hills with many gullies and valleys, as well as hills that are more rolling in nature, ultimately depending on the underlying geological units. The ground conditions vary from exposed rock at the ground surface to thick deposits of residual soils.

Based on the available information, it is likely that the Hills and Ranges predominantly comprise some cohesive (plastic) residual soils and rocks that are not considered to be susceptible to liquefaction. However, although this terrain comprises the majority of the Study Area, there are relatively few geotechnical investigations available to calibrate this assumption. Based on the target 1:25,000 scale of geomorphic mapping, some isolated pockets of alluvial deposits on the hills may not have been captured. To reduce some uncertainty around the potential presence of liquefaction susceptible soils in these areas, we used the topographic screening tool to identify areas of “flat land” within the sloping land. From these areas, we applied a 100 m wide buffer and classified the land within the buffer zone as “Liquefaction is Undetermined”.

In addition, as per Section 4.3, lateral spreading is more likely to be possible in areas close to free faces more than 2 m high (such as gullies and riverbanks) if liquefaction susceptible soils are present. To reduce some uncertainty in this case, we also applied the 100 m wide buffer around water bodies within this geomorphic terrain and classified them as “Liquefaction is Undetermined”.

The depth to groundwater is highly variable across this geomorphic terrain. However, as described in Section 3.2.4 and Section 3.3.4 in the elevated areas the depth to groundwater is likely to be over 8 m bgl. Based on the information considered in this liquefaction assessment, in the Hills and Ranges terrain, "…there is a probability of more than 85 percent that liquefaction-induced ground damage will be none to minor for 500-year shaking." Therefore, these areas (not including the above buffer zones) are classified as "Liquefaction Damage is Unlikely".

4.4.2 Landslide Debris

This terrain covers a small proportion of the Study Area and maps debris flows and landslide deposits that are associated with historic slope instability in the Hills and Ranges terrain. There is limited information about the soil and groundwater conditions associated with this terrain, with both of these factors likely being highly variable. As such, there is currently insufficient information to characterise the expected land performance. Therefore, in this terrain "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.6, the nature of the expected ground conditions means that if more detailed site-specific assessment was undertaken in the future, then this would likely indicate a category of "Low Liquefaction Vulnerability". For future assessments, it is likely that undertaking simple shallow hand auger boreholes and confirming soil properties and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

4.4.3 Elevated Alluvial Terraces

This terrain comprises elevated land positioned above the alluvial channels terrains and typically comprises Pleistocene-aged or older alluvium. These terraced areas were uplifted, folded and faulted during the Quaternary period, relating to the rising of the axial ranges. Based on geological information and local knowledge, this terrain comprises sediments deposited in both high energy and low energy environments, which likely have both plastic and non-plastic behaviours. However, the older age of these sediments means that they are less likely to contain liquefaction-susceptible soils than the alluvial channel terrain described below.

Due to the higher elevation of this terrain, the depth to groundwater is likely to be deeper (> 4 m). The main exception to this is the gullies associated with streams that intersect the alluvial terraces, where groundwater is likely to be shallower (< 4 m). Note that these gullies are small and difficult to differentiate based on the information available and therefore many of the smaller gully features have not been mapped at the target scale for the geomorphic mapping (1:25,000). This also introduces a significant source of uncertainty into the assessment.

In the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as terrace edges). However, as described above, there is currently significant uncertainty as to whether liquefaction-susceptible soils are present in the alluvial terraces.

Due to the uncertainty associated with whether liquefaction-susceptible soils are present and the depth to groundwater, there is currently insufficient information to characterise the expected land performance. Therefore, in this terrain "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.6, in many of these areas the nature of the expected ground conditions means that if more detailed site-specific assessment was undertaken in the future, then this would likely indicate a category of "Low Liquefaction Vulnerability". For future assessments, it is likely that undertaking simple shallow hand auger boreholes and confirming soil properties and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

4.4.4 Beaches

The beach terrain is likely to comprise thick (> 10 m) deposits of sands and silts (which are susceptible to liquefaction) and are unlikely to contain a significant proportion of cohesive (plastic) materials (which are not susceptible to liquefaction). This terrain is relatively easy to map from aerial photography and typically has consistent soil conditions.

Groundwater is also generally shallow (< 4 m) in this terrain because it is typically flat and close to the coastal margins. The proximity to coastal margins means that the depth to groundwater is likely to become shallower with sea-level rise. For these reasons, this terrain is identified as a landform that is commonly susceptible to liquefaction in Section 2.3 of the MBIE/MfE Guidance (2017).

In the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free-faces more than 2 m high in areas where free-faces are identified along the coastline.

Based on the information considered in this liquefaction assessment, *"…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*". Therefore, the mapped beach terrains have been classified as "Liquefaction Damage is Possible".

4.4.5 Alluvial Channel and Plains

Typically, soils found in this terrain are geologically young (Holocene-aged) and deposited in low to high energy environments forming a variety of soils, including loose and soft strata. The characteristics of the soils comprising these terrains are highly variable in nature and vary spatially across the landscape. Alluvial sediments typically range from granular gravels, sands and silts to fine grained soil deposits (clay and silt) with plastic-type behaviours. These soils typically contain materials that are susceptible to liquefaction.

The depth to groundwater is also likely to be shallow (< 4 m) within this terrain because it is generally associated with active and historic river and stream systems, as well as water bodies such as lakes. The MBIE/MfE Guidance (2017) typically associates these alluvial terrains as being susceptible to liquefaction. Some areas could have variable groundwater levels due to variation in ground elevation, where groundwater typically becomes deeper at higher elevations. More certainty on groundwater levels in this terrain could be achieved by understanding the local water courses in the area of a site specific assessment, and completing some groundwater investigations as outlined in Section 3.3.4.

Free faces are associated with this terrain in the form of riverbanks, stop banks, streams and drainage ditches, all of which are visible on aerial photography and LiDAR imagery. In the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible within 200 m of free faces more than 2 m high.

Based on the information considered in this liquefaction assessment, "*…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*." Therefore, the mapped alluvial plains and river flats terrain have been classified as "Liquefaction Damage is Possible".

5 Conclusions and recommended future work

T+T has completed a Level A – Basic Desktop Assessment to determine the liquefaction vulnerability of the Study Area outlined by TDC in accordance with the MBIE/MfE Guidelines (2017). The key conclusions and recommendations are:

- The land within the Study Area has been classified into one of three liquefaction vulnerability categories: “Liquefaction Category is Undetermined”, “Liquefaction Damage is Unlikely” or “Liquefaction Damage is Possible”. The currently available information does not support further classification of the land into the other more precise categories of “Very Low”, “Low”, “Medium” and “High”.

  This degree of liquefaction vulnerability categorisation precision is consistent with a regional scale study (such as this) undertaken to a Level A level of detail.
- The liquefaction outputs of this study provide a regional base layer which will be useful for Resource Management Act (RMA) applications within the Tararua District. In particular, the outputs of this study relate to the Horizons Regional Council Regional Policy Statement (RPS), which outlines areas within the region that are prone to natural hazards. In some areas where liquefaction damage has not been ruled out, it is likely that liquefaction vulnerability studies will need to be completed to a higher level of detail to satisfy RMA requirements.
- TDC can also use the outputs of the study to inform building consent applications. In some cases, where liquefaction has not been ruled out, it is likely that liquefaction vulnerability assessment will need to be completed to a higher level of detail to satisfy Building Code requirements.
- Regardless of the vulnerability classification given, any proposal for development within the Tararua District should be accompanied by a statement that either confirms or updates the vulnerability classification assigned in this report. Section 4.4 provides guidance on approaches for efficiently assessing liquefaction vulnerability for each geomorphic terrain.

To improve the resolution of the liquefaction vulnerability output to promote additional uses of the liquefaction vulnerability information, further information will need to be collected. The two main areas where additional base information is required to support higher level of detail studies include geotechnical investigations and groundwater information. Potential steps to address this information limitation are as follows:

- **Geotechnical investigations:** A key source of uncertainty in this liquefaction assessment is the relatively limited amount of geotechnical investigation data in the Study Area. This information is important for both the assessment of liquefaction vulnerability and for other future applications.

  To help facilitate the collection of more geotechnical investigation data, TDC may wish to undertake the following:
  - Identification of geotechnical investigations from historic projects and uploading of these investigations onto the NZGD.
  - Advocation of uploading supporting geotechnical investigations onto the NZGD as part of the process of evaluating resource and building consent applications. Local engineering and scientific practitioners may need to be educated about why this uploading process is important.
  - Engagement of suitably competent geo-professionals to undertake geotechnical investigations within given areas where more information about the ground conditions is required (e.g. areas where a Level B, C or D level of detail is targeted).

- **Groundwater information**: A key source of uncertainty in this liquefaction vulnerability assessment is the limited amount of groundwater information in the Study Area. While not critical for this Level A study, detailed information about shallow groundwater levels becomes increasingly important when targeting higher level of detail liquefaction vulnerability studies. It also provides a valuable data source for other purposes such as asset management.

  To help facilitate the collection of more detailed groundwater data, TDC could consider installing a network of piezometers to monitor groundwater level fluctuations over time. This data could also be used to develop depth to groundwater surface models.

The outputs of this study have been provided in a geospatial format which can be displayed and viewed on a GIS platform.

6 Applicability

This report has been prepared for the exclusive use of our client Tararua District Council, with respect to the particular brief given to us and it may not be relied upon in other contexts or for any other purpose, or by any person other than our client, without our prior written agreement.

Recommendations and opinions in this report are based on data from individual CPT and borehole locations. The nature and continuity of subsoil away from these locations are inferred and it must be appreciated that actual conditions could vary from the assumed model.

The susceptibility analyses carried out represent probabilistic analyses of empirical liquefaction databases under various earthquakes. Earthquakes are unique and impose different levels of shaking in different directions on different sites. The results of the liquefaction susceptibility analyses and the estimates of consequences presented within this document are based on regional seismic demand and published analysis methods, but it is important to understand that the actual performance may vary from that calculated.

This assessment has been made at a broad scale across the Tararua District and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations).

Tonkin & Taylor Ltd

Report prepared by:	Authorised for Tonkin & Taylor Ltd by:
....	....
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John Brzeski Engineering Geologist	Mike Jacka Geotechnical Engineer

4-Nov-21
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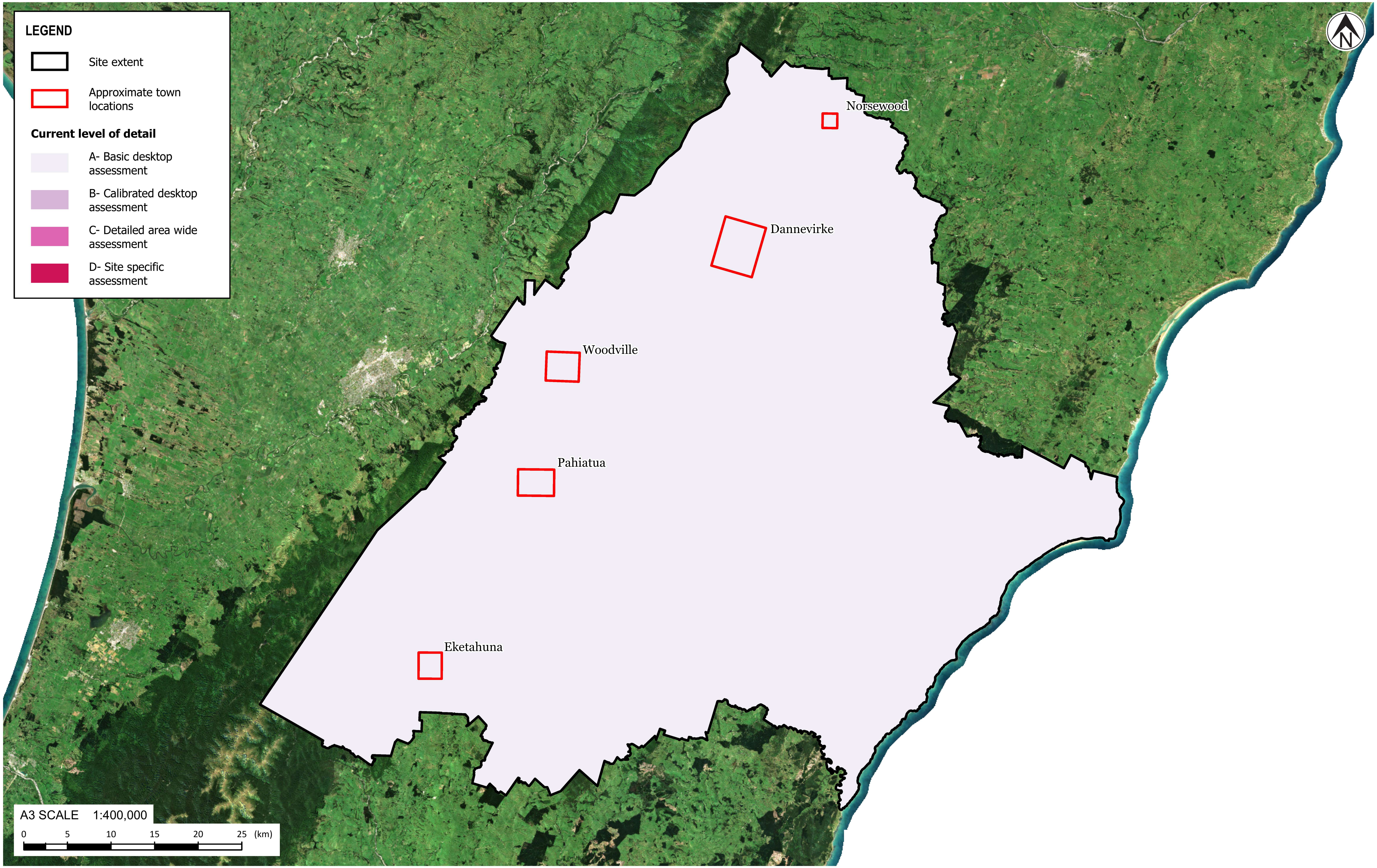
Appendix A: Figures



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2. Map indicates the level of detail in the liquefaction assessment that will be targeted. Refer to Table 3.3 of the MBIE guidelines (2017) for further information about the detail in the liquefaction assessment.

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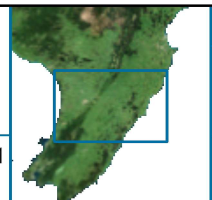

LOCATION PLAN

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CHECKED	JORB	JAN.21
APPROVED		DATE

CLIENT TARARUA DISTRICT COUNCIL

PROJECT LIQUEFACTION VULNERABILITY ASSESSMENT

TITLE TARGET LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT

SCALE (A3) 1:400,000 FIG No. FIGURE A1 REV 0

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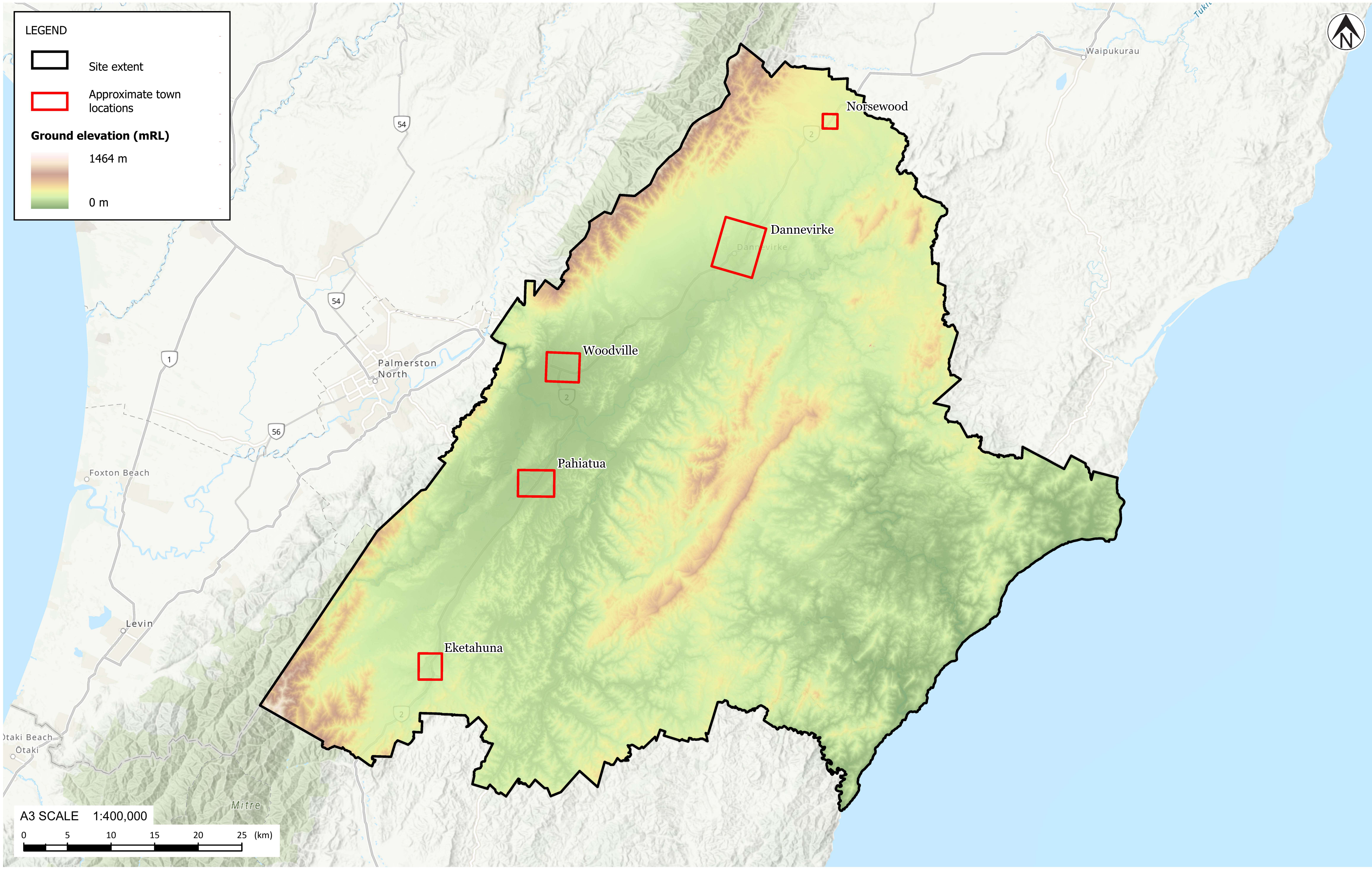

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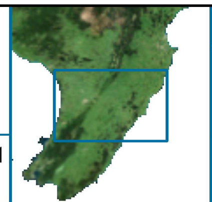

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CLIENT TARARUA DISTRICT COUNCIL

PROJECT LIQUEFACTION VULNERABILITY ASSESSMENT

TITLE GROUND SURFACE ELEVATION (2015 LIDAR SURVEY)

SCALE (A3) 1:400,000   FIG No. FIGURE A2   REV 0

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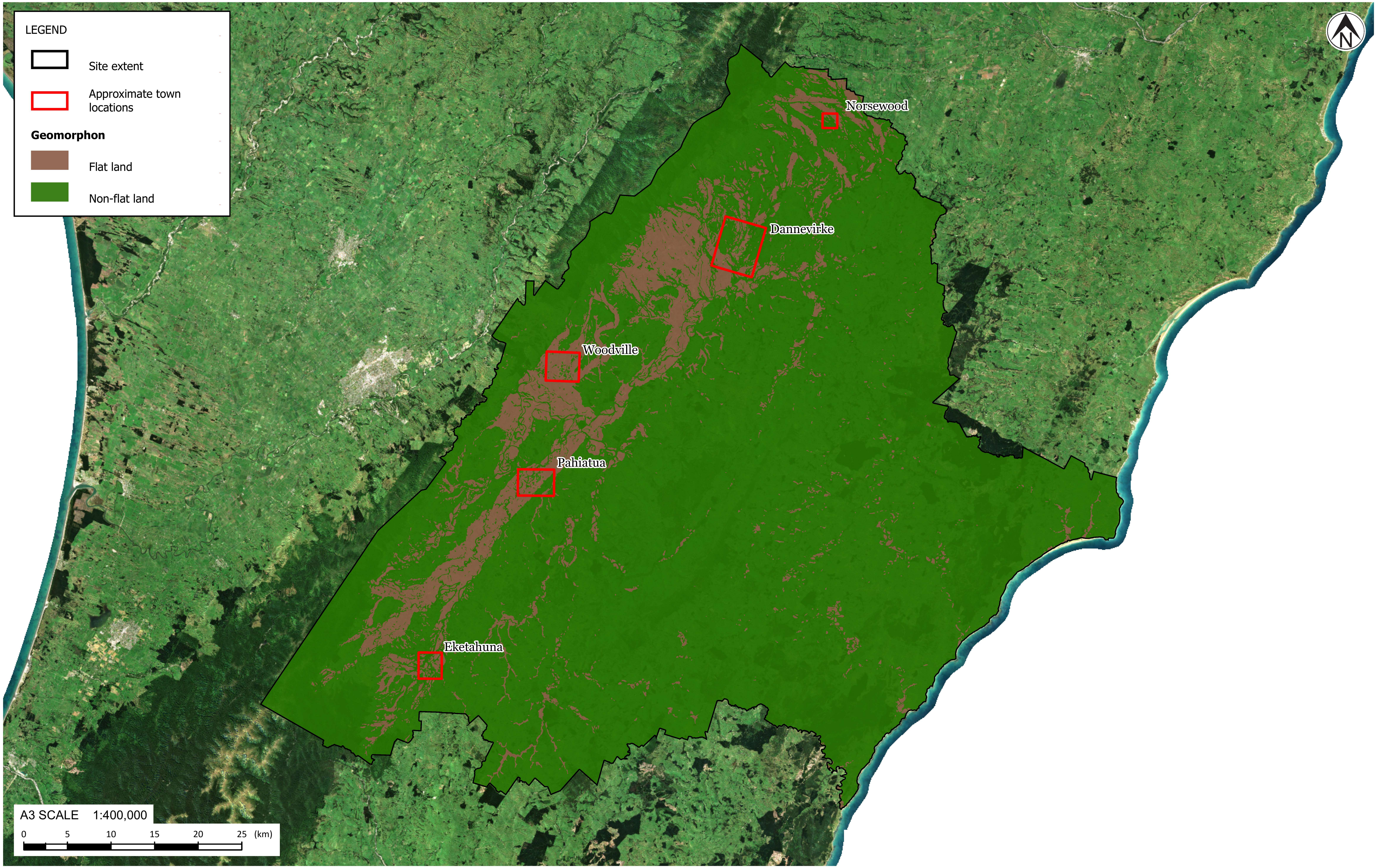

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PROJECT LIQUEFACTION VULNERABILITY ASSESSMENT

TITLE GEOMORPHONS PRODUCED BY TOPOGRAPHICAL SCREENING TOOL

SCALE (A3) 1:400,000 FIG No. FIGURE A3 REV 0

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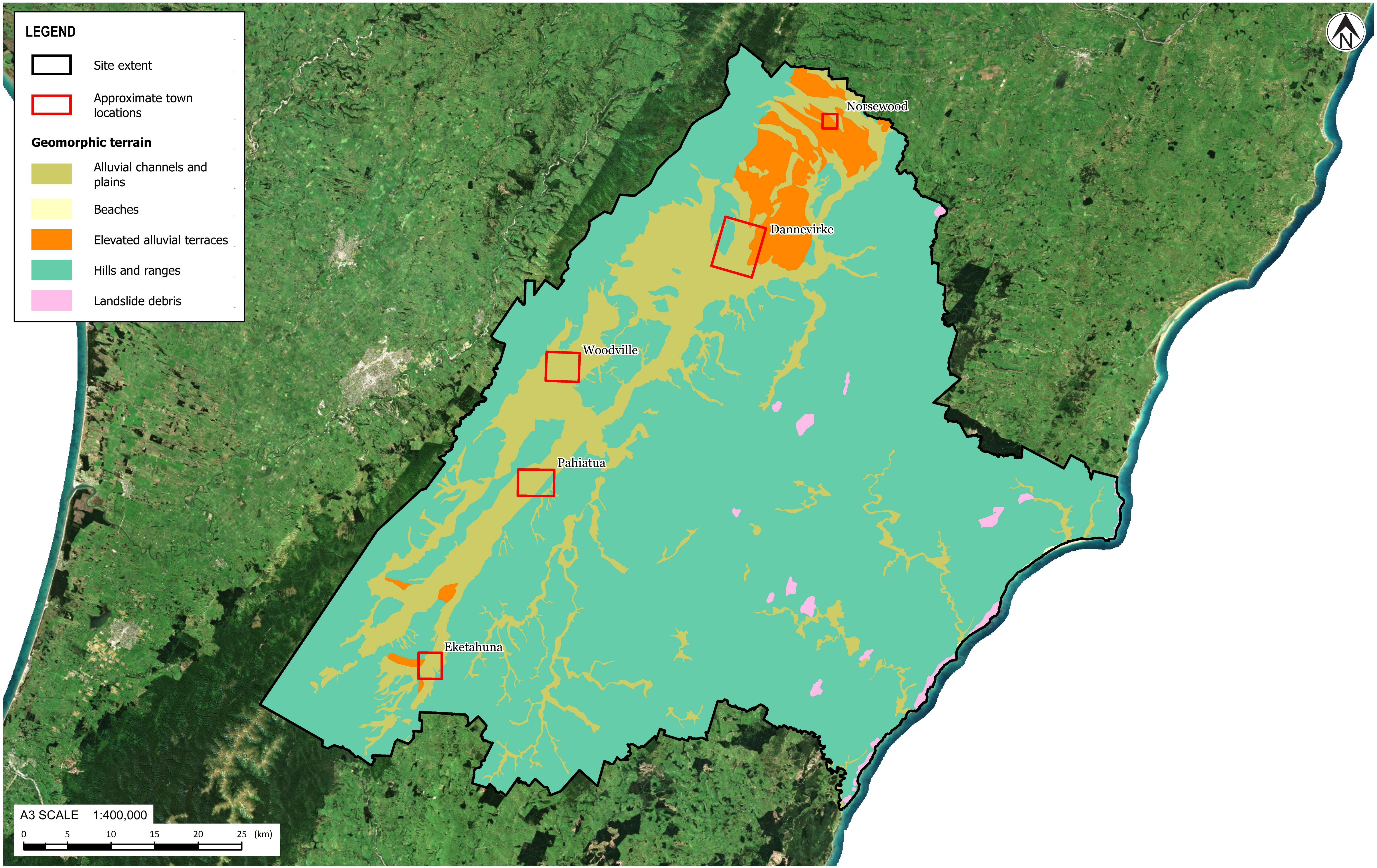

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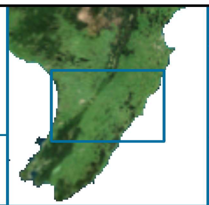

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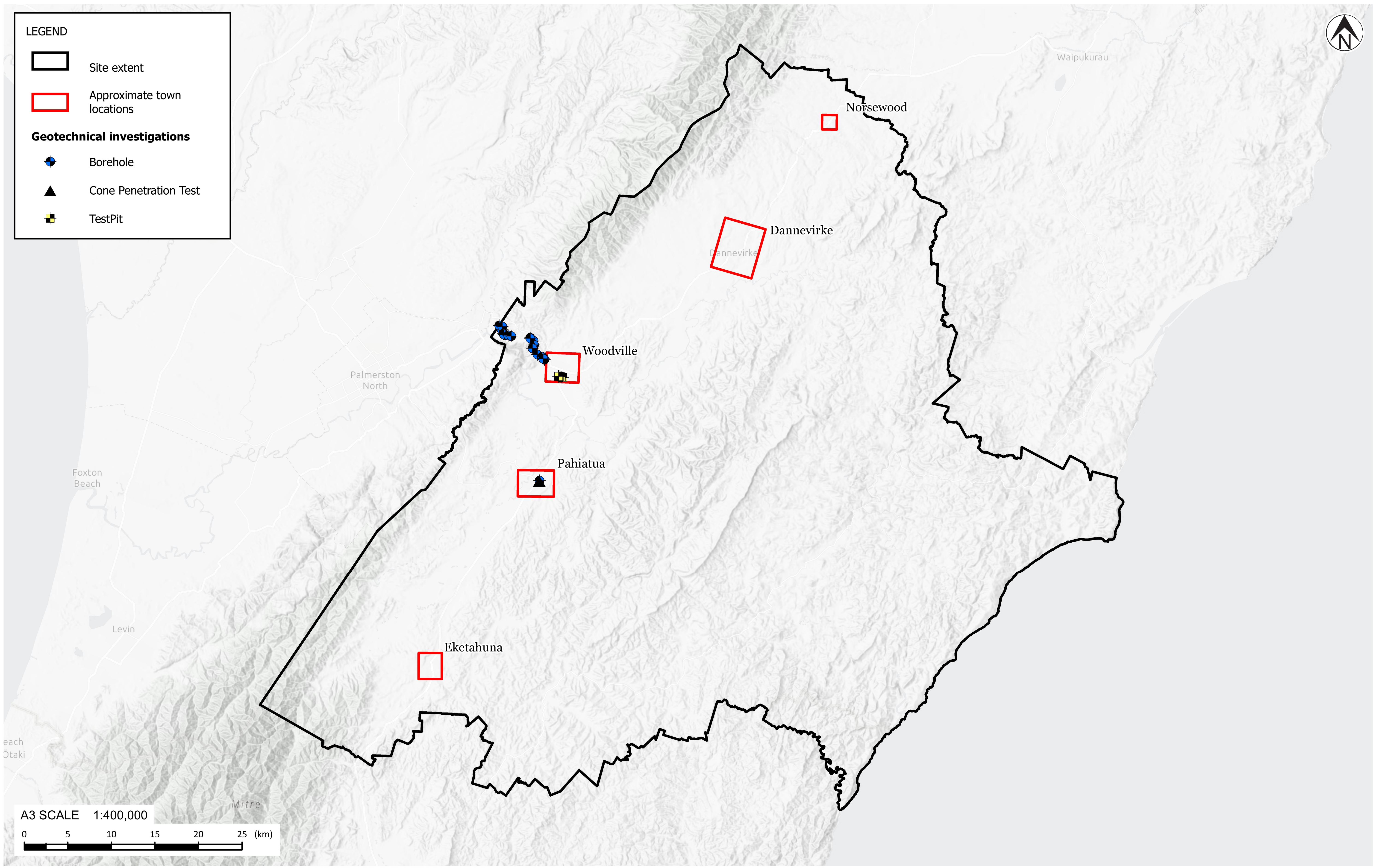
CLIENT **TARARUA DISTRICT COUNCIL**

PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**

TITLE GEOMORPHIC TERRAIN

SCALE (A3) 1:400,000 FIG No. FIGURE A4 REV 0



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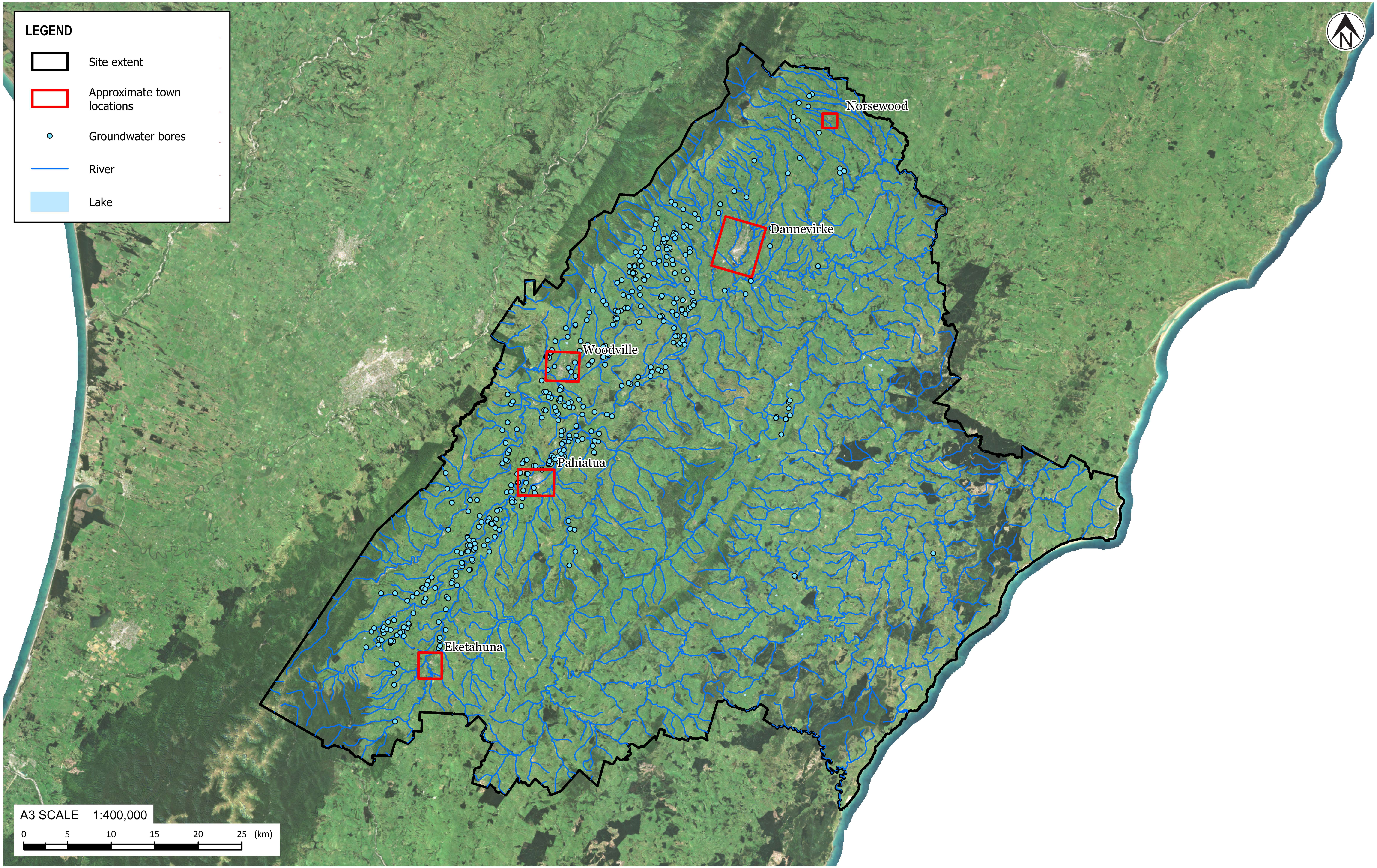
PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**

TITLE GEOTECHNICAL INVESTIGATIONS AVAILABLE ON NZGD WITHIN STUDY AREA

SCALE (A3) 1:400,000 FIG No. FIGURE A5 REV 0



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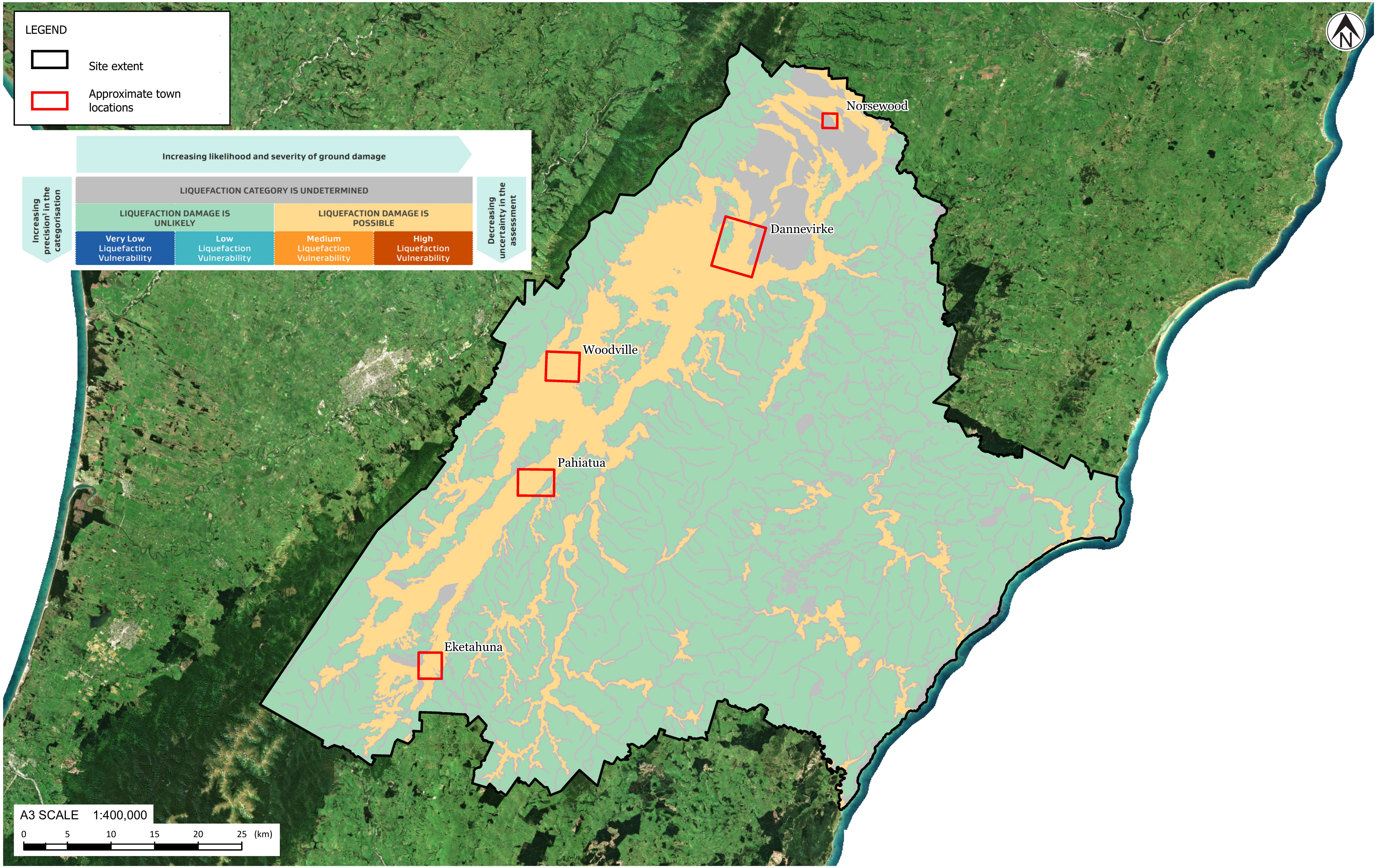
PROJECT LIQUEFACTION VULNERABILITY ASSESSMENT
TITLE SHALLOW GROUNDWATER MONITORING LOCATIONS
SCALE (A3) 1:400,000 FIG No. FIGURE A6 REV 0



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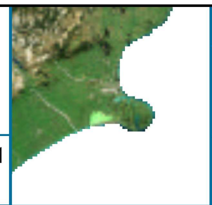

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PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**
TITLE LIQUEFACTION VULNERABILITY CATEGORIES

SCALE (A3) 1:400,000   FIG No. FIGURE A7   REV 0

Table A1: Geomorphic terrain descriptions

Geomorphic terrain	Terrain description	Geological age	Typical geology (top 10 m)	Anticipated GW conditions (range)	Liquefaction Vulnerability Classification
Alluvial Channels and Plains	The base of valleys and channels, typically where alluvium and potentially colluvium has accumulated. Alluvial channels have narrow valley floors relative to the wider alluvial terraces and can also be found in streams through the hills and ranges. Alluvial fans at the base of the Tararua-Ruahine Ranges have also been included here as these are gently sloping alluvial or colluvial landforms.	Holocene	Silts, sands and gravels	2.5 m (0.5 – 6.6m)	Possible
Beaches	Coastal landforms associated with beach processes, found along the eastern coastline.	Holocene	Sands and gravels	2.5 m (1.9 – 4.0m)	Possible
Elevated Alluvial Terraces	Elevated terraces above the current alluvial channels and floodplains. The upper terraces typically comprising Early to Middle Pleistocene-age alluvium and colluvium, derived from the Tararua-Ruahine Ranges, and is typically identified at the base of the Hills and Ranges.	Pleistocene	Sands and gravels	3.3 m (0.5 – 5.2m)	Undetermined
Landslide Debris	Land with hummocky, gently to steeply sloping topography mapped as landslides in the geological maps that can be observed at the 1:25,000 scale, typically found on hillsides or along the coastline.	Holocene	Silts, sands and gravels with boulders	3.2 m (0.5 – 4.1m)	Undetermined
Hills and Ranges	Elevated, undulating landforms characterised by dissected hills with many gullies, as well as some elevated valleys, with many areas showing evidence of being fault bound due to the tectonic history. This terrain represents the oldest terrain in the district and covers the majority of the area.	Older than Pliocene	Residual soil then rock	> 8 m	Unlikely

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