REPORT

Tonkin+Taylor

Liquefaction Vulnerability Study - Whangarei District

Prepared for

Whangarei District Council

Prepared by

Tonkin & Taylor Ltd

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IQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Planning and engineering guidance for potentially liquefaction-prone land' 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	Whangarei District Council (WDC)
Assessment undertaken by	Tonkin & Taylor Ltd, Tonkin + Taylor House, 105 Carlton Gore Road, Newmarket, Auckland 1023
Extent of the study area	The area of the WDC territorial boundary defined as the study area in Figure 1.1.
Intended RMA planning and consenting purposes	To provide WDC with a district-wide liquefaction vulnerability assessment to help inform spatial planning and assessment of land use, subdivision and building consents.
Other intended purposes	Not applicable
Level of detail	Level A (basic desktop assessment)
Notes regarding base information	The available base information is only sufficient to support a Level A level of detail across the district. To achieve a higher level of detail additional information will need to be collected.
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 Section 0 of this report.

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1 Introduction

1.1 Overview

Tonkin & Taylor Ltd (T+T) was engaged by Whangarei District Council (WDC) in April 2020 to undertake a liquefaction vulnerability assessment.

The work comprises risk identification and analysis of liquefaction hazard in accordance with the Ministry of Building, Innovation and Employment (MBIE) and the Ministry for the Environment (MfE) *Planning and engineering guidance for potentially liquefaction-prone land* (MBIE/MfE, 2017) to help inform various future activities (hereinafter referred to as the MBIE/MfE Guidance (2017)).

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

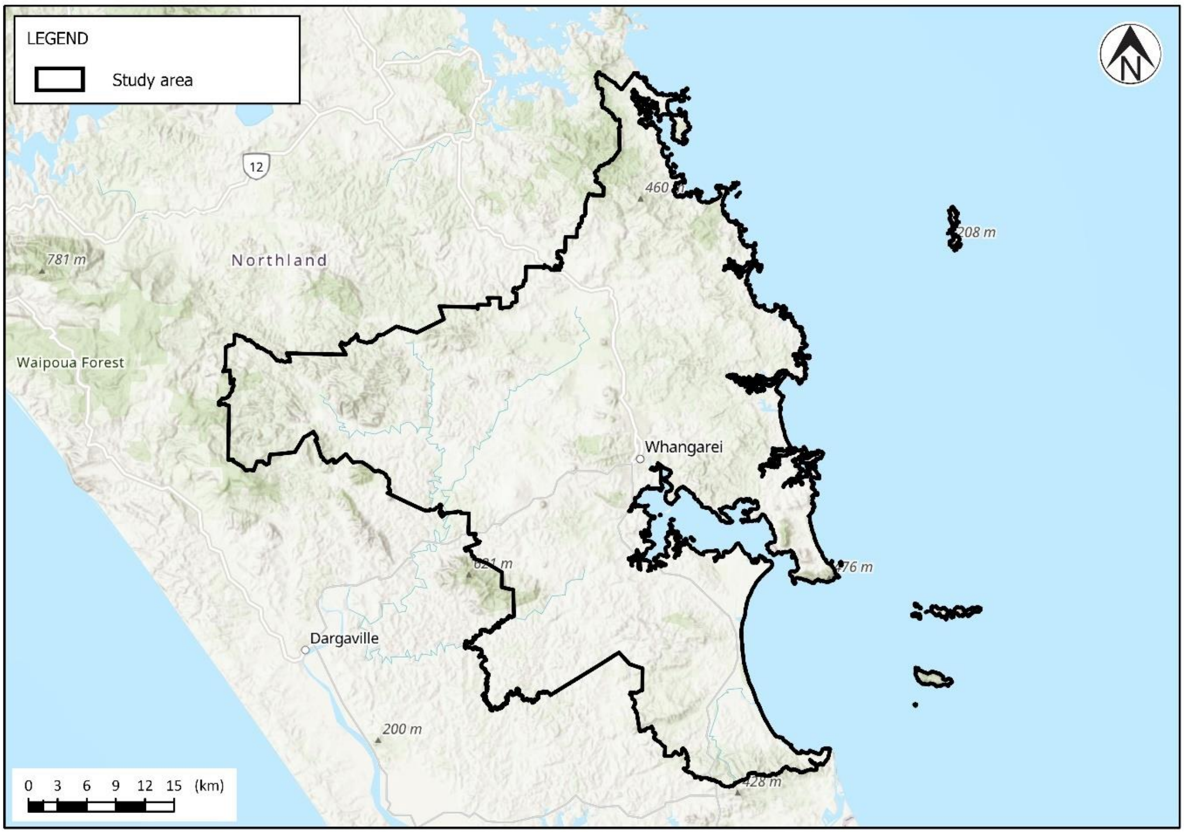


Figure 1.1: Map showing the location and extent of the WDC liquefaction vulnerability study area.

The Whangarei district covers approximately 2,712 km^2 of land. It is bounded by the open coast to the east of the district, and hill country to the north, south and west. The Whangarei Harbour is located in the centre of the district, connected to the coastline to the east. The 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 including analysis of the uncertainty associated with the collated information (Section 3)
- Risk analysis including the assessment of liquefaction vulnerability measured against the performance criteria in MBIE/MfE Guidance (2017) (Section 4)
- A summary of the key conclusions and recommendations (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.

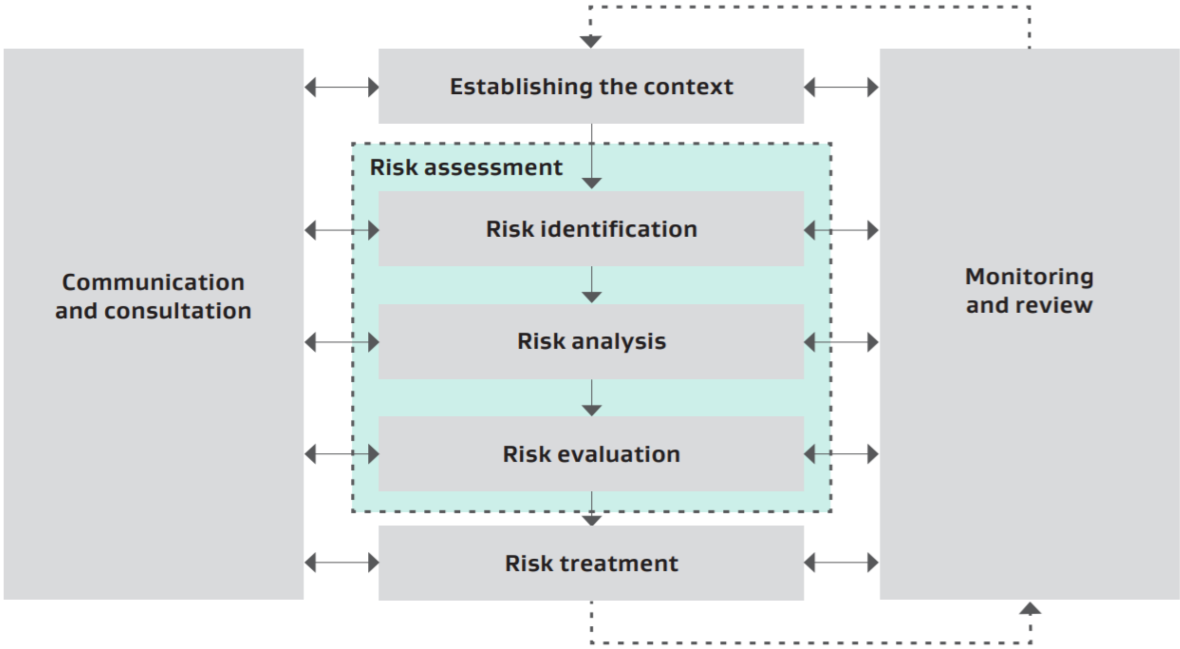


Figure 1.2: Risk management process defined in ISO 31000:2009, which has been used to guide the liquefaction vulnerability assessment and the layout of this report - from MBIE/MfE Guidance (2017).

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 and 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, 2017a – 2017f).

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 several 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:

- 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 and Risk Analysis, 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 31000:2009.

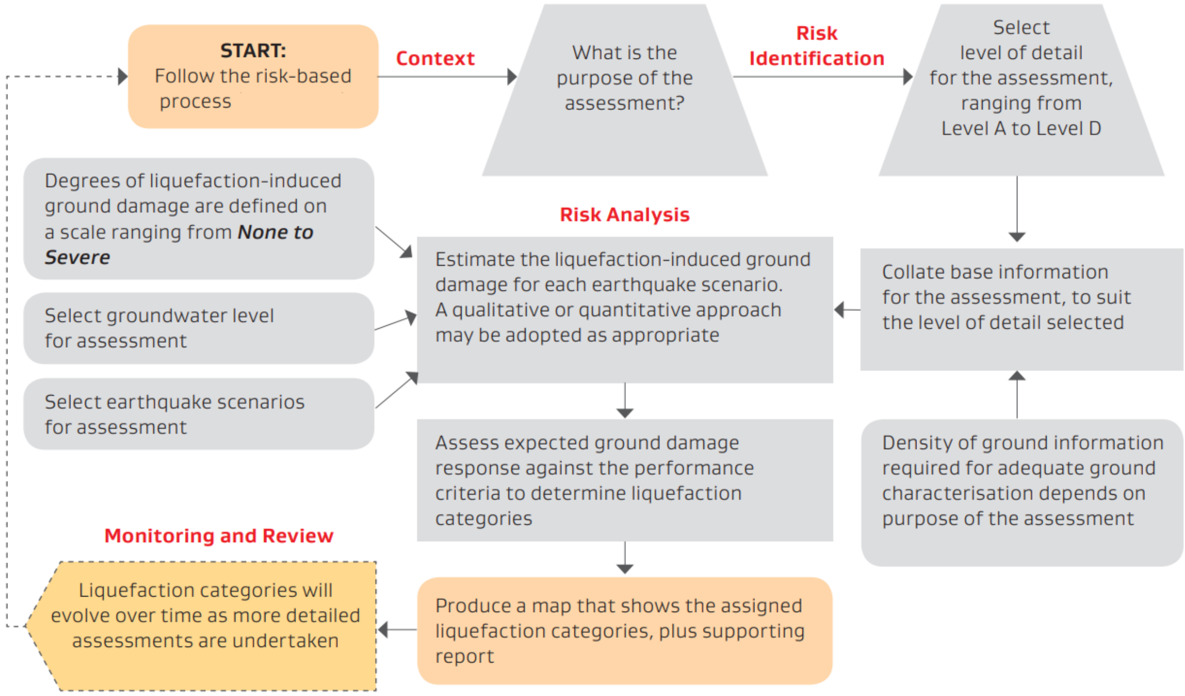


Figure 1.3: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage - from MBIE/MfE Guidance (2017).

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 study area into one of these seven categories is one of the key deliverables of this study. We 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".

It needs to be appreciated that within all liquefaction vulnerability categories there may be specific areas where liquefaction is not physically possible (e.g. because the ground profile comprises rock or clay all the way up to the surface). However, it is not practical to precisely map all these areas using the information available in a basic desktop assessment for the entire district, so these areas are grouped together with the surrounding land under the high-level vulnerability categories.

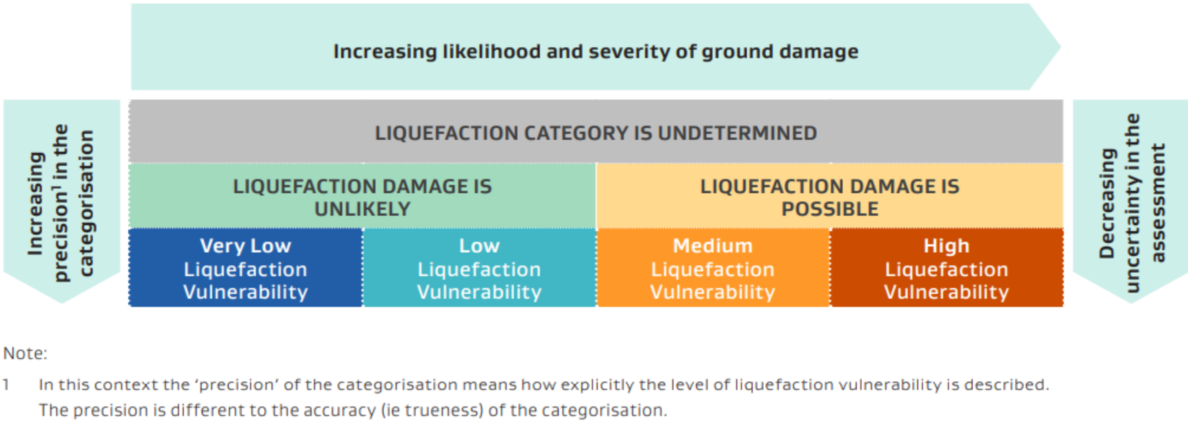


Figure 1.4: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform planning and consenting processes - from MBIE/MfE Guidance (2017).

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 3.1.1. Section 0 provides discussion about the key sources of uncertainty associated with this assessment.

2 Context

2.1 Background to this study

On 28 November 2019, the Building Code was amended to include the following changes:

- 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 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.

WDC has commissioned T+T to undertake this study in response to these changes to the Building Code. 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

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:

1. Loose non-plastic soil (typically sands and silts, or in some cases gravel)
2. Saturated soil (i.e. below the groundwater table)
3. Sufficient ground shaking (a combination of the duration and intensity of shaking).

These elements are shown in Figure 2.1.

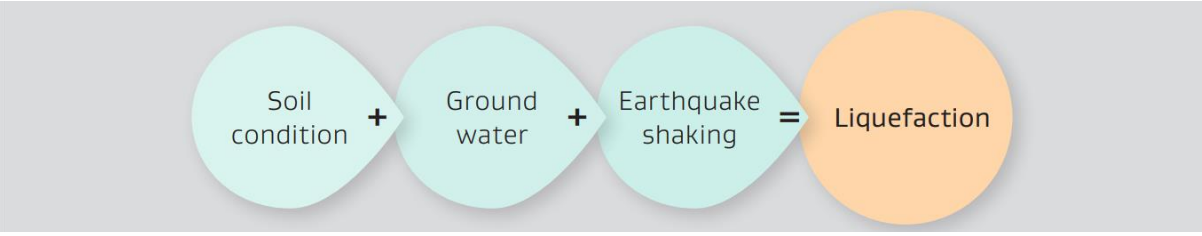


Figure 2.1: Three key elements required for liquefaction to occur - reproduced from MBIE/MfE Guidance (2017).

Figure 2.2 summarises the process of liquefaction with a schematic representation. For a more detailed explanation of the liquefaction process, refer to the MBIE/MfE Guidance (2017).

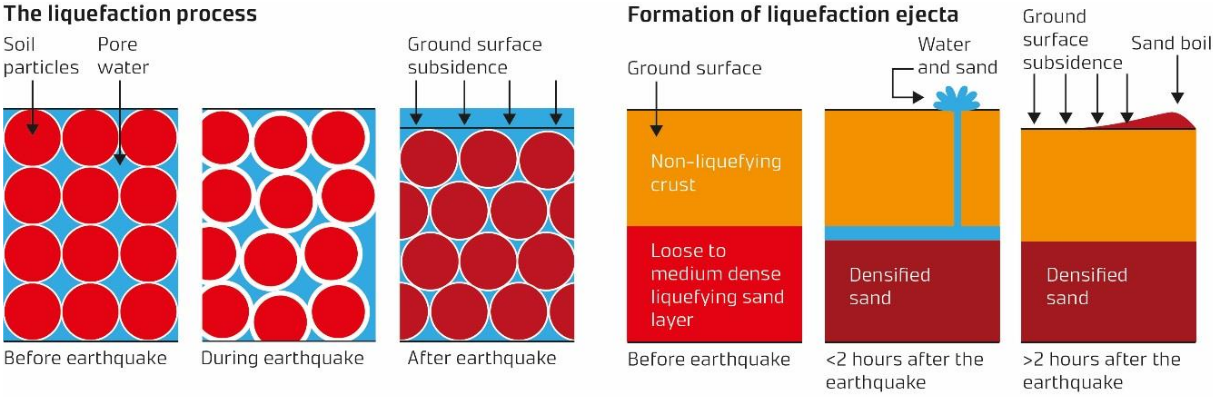


Figure 2.2: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta - reproduced from MBIE/MfE Guidance (2017).

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.

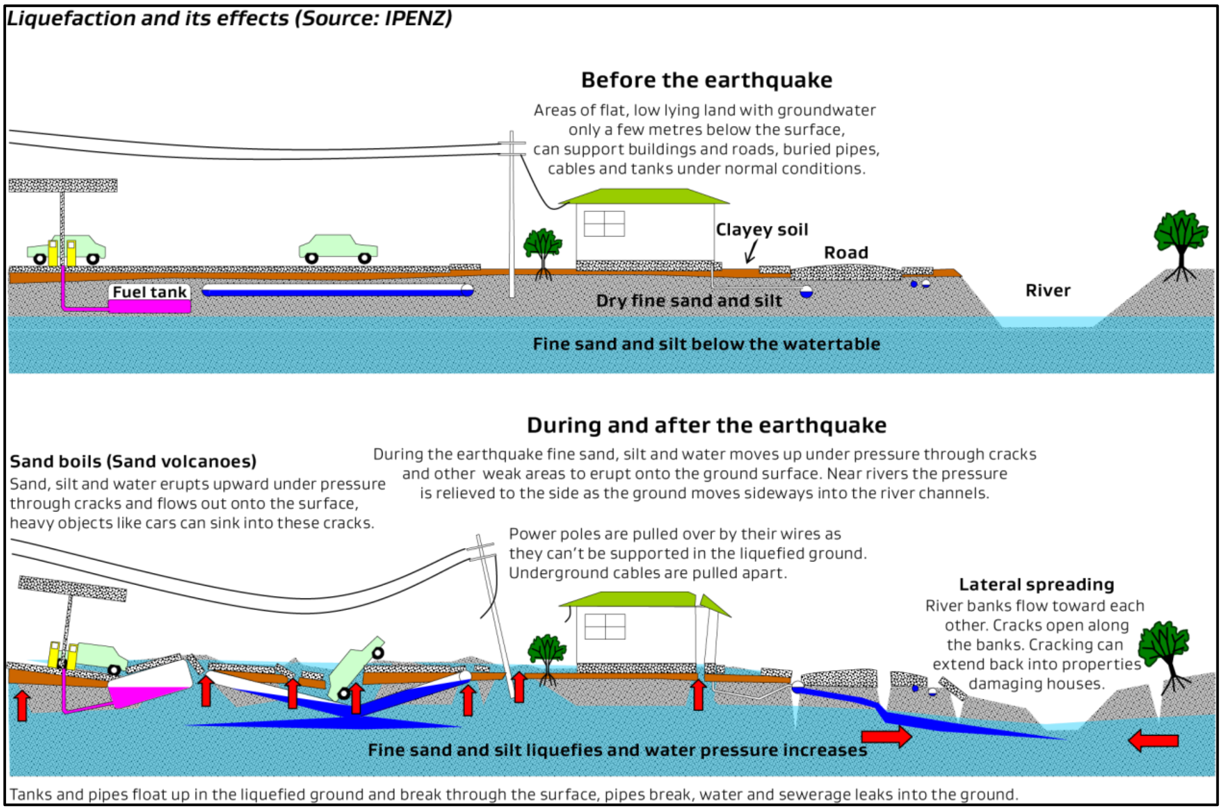


Figure 2.3: Visual schematic of the consequences of liquefaction - reproduced from the MBIE/MfE Guidance (2017).

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 downdrag 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 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

WDC's primary objective in commissioning this study was to ensure that buildings are located and built with appropriate consideration of the land conditions. WDC intend to use this information to inform policy, planning and consenting processes.

The specific scope of T+T's risk identification and analysis of the Whangarei district is described in detail in the WDC contract *PC139 Land Instability (Liquefaction Vulnerability Assessment Mapping)* dated 13 March 2020. The key outputs 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
- Assessment and production of an associated map of the level of detail supported by the currently available base information
- Preparation of a report to accompany the liquefaction hazard risk identification and analysis.

2.4 Previous information about liquefaction in Whangarei District

From a review of publicly available information, we were unable to find any previous regional studies of liquefaction in the Whangarei District. However, WDC provided T+T with a number of technical reports, three of which included specific project locations where liquefaction had been considered as part of the design and/or consenting process. The project locations and the associated technical reports are listed in Table 2.2.

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

Project location	Report title	Authors	Published date
Marsden Cove	Marsden Cove – Geotechnical and Hydrogeological Investigation Report	Earthtech Consulting Ltd.	August 2002
Dent Street Modifications	Dent Street Modifications: Design and Supervision – Geotechnical Investigation Data (Factual Report)	MWH New Zealand Ltd.	December 2002
Lower Hatea Bridge	Lower Hatea Bridge – Preliminary Geotechnical Investigation Factual and Interpretive Report	Tonkin + Taylor Ltd.	March 2007
	Lower Hatea Crossing – Preliminary Geotechnical Design Report	Opus International Consultants Ltd.	November 2009
	Lower Hatea River Crossing Whangarei – Geotechnical Factual Report	Opus International Consultants Ltd.	April 2010
	Lower Hatea Crossing – Supplementary Geotechnical Report	Opus International Consultants Ltd.	April 2010
	Lower Hatea Bridge Joint Project – Geotechnical Design Philosophy Report SP3	Peters and Cheung Ltd.	July 2011
	Lower Hatea Bridge Project Bridge Foundation Piles – Geotechnical Detailed Design Report	Peters and Cheung Ltd.	March 2012
Porowini Avenue Extension	Porowini Ave Extension – Geotechnical Investigation Factual and Interpretive Report*	Tonkin + Taylor Ltd.	March 2007
	Porowini Avenue Extension – Geotechnical Interpretive Report	Opus International Consultants Ltd.	February 2009
Hatea Pumping Station	Whangarei District Council Hatea Pumping Station – Emergency Storage	Opus International Consultants Ltd.	January 2010
Tarewa Park	Appendix D, Borehole No. 1, Tarewa Park**	Opus International Consultants Ltd.	January 2016
	General Soils Assessment – Tarewa Park Proposed Sewer Alignment	Wilton Joubert Consulting Engineers	April 2016

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

** The main report associated with this borehole was not included with this appendix item

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

- **Marsden Cove** – The report was compiled to support consenting, design and construction of a large 568-lot housing project that was completed on the low-lying flats adjacent to Marsden Bay. The development included construction of canals for a marina. The low-lying flats are described as comprising alluvium overlying Holocene age dune deposits.

  The report describes 5 boreholes, 26 cone penetration tests (CPT), and 9 test pits that have been evaluated in the geotechnical report. None of these investigations are currently available on the NZGD.

  For seismic design purposes, Peak Ground Accelerations (PGA) are estimated as 0.07 g for a 150-year return period event, and 0.14 g for a 450-year return period event. Based on quantitative analysis of the CPT available the author concludes that "…liquefaction is unlikely…" and as such no additional protection measures are recommended.
- **Dent Street Modifications** – The report was compiled to support design and construction of a road realignment. The report presents only factual information and does not provide a description of the geological context.

  The report describes 4 boreholes, 14 CPT, 4 test pits, and associated laboratory tests. None of these investigations or laboratory tests are currently available on the NZGD.

  No assessment of seismic hazard or liquefaction vulnerability is presented in the report.
- **Lower Hatea Bridge** – These reports were compiled to support design and construction of a new road bridge and the associated approaches. The site geology is described as comprising alluvial and estuarine silt and clay deposits overlying the Northland Allochthon mudstone/sandstone. Both embankments are founded on reclamation fills, the west embankment is founded on up to 3 m thick clay hardfills, the east embankment is founded on what is described as landfill refuse.

  Geotechnical investigations for the project were undertaken in 3 stages and at least 11 boreholes, 21 CPT, and 8 test pits were undertaken for the project. Only the investigations described in the T+T report (3 boreholes and 5 CPT) are currently available on the NZGD.

  For seismic design purposes, PGA are estimated as 0.19 g for a 1,000-year return period earthquake, and 0.26 g for a 2,500-year return period earthquake. Specific analysis of the liquefaction vulnerability at the site is not provided, however the Peters and Cheung Ltd. pile foundation report indicates that "…liquefaction induced ground settlements are not expected for the cohesive deposits…" around the bridge piles.
- **Porowini Avenue Extension –** These reports were compiled to support design and construction of a road bridge and associated approach embankments. The site geology is described as swamp and alluvial deposits overlying Northland Allochthon bedrock. Fill material also overlies the site in places.

  The reports describe 5 boreholes, 13 CPT, and 6 test pits that have been evaluated for the project. None of these investigations are currently available on the NZGD.

  For seismic design purposes, PGA are estimated as 0.09 g for a 100-year return period earthquake, and 0.17 g for a 2,500-year return period earthquake. The Opus report provides the following commentary about liquefaction potential at the site:

  "Inspection of boreholes, associated SPT values and CPT data indicate that sand type soils susceptible to liquefaction under strong seismic shaking are not present in the soil profile and therefore mitigation via design for this hazard is not considered appropriate for this site."
- **Hatea Pumping Station –** This report was compiled to support design and construction of an approximately 20,000 m^2 emergency storage tank. The site geology is described as most likely underlain by the Parahaki Rhyolites and Dacite from the Eocene Period.

The report describes 4 boreholes and two hand augers that have been evaluated for the project. It appears as if none of these investigations are currently available on the NZGD.[2]

Approximately one month after the site investigations were undertaken, the depth to groundwater at the site was measured at 1.55 m below ground level during a period of relatively dry weather. The soil conditions are summarised as predominantly clay materials with occasional lenses of sand from 3.6 to 4.5 m depth.

Seismic design parameters are not discussed in the report.

- **Tarewa Park** – The geotechnical report provided for Tarewa Park that was prepared by Wilton Joubert consulting engineers has been prepared to support design and construction of a proposed sewer alignment. The provided "Appendix D" that contains a single borehole log appears to have been prepared for the design and construction of a tank, but no further information is available. Presumably, these projects were at the same site but that is not clear from the available information.

  The available information describes 1 borehole, 2 hand augers and 3 mechanical augers that have been evaluated for the projects. None of these investigations are currently available on the NZGD.

  The soils are described as fill comprising silty clay and gravels in the top 1 to 2 m underlain by natural alluvial soils predominantly comprised of clay materials. Perched groundwater is noted as being encountered at the site.

  Seismic design parameters are not discussed in the report.

A key finding from this review of publicly available information is that the majority of the geotechnical investigation data presented in the reports supplied by WDC has not yet been uploaded onto the NZGD. This data is of considerable value to both WDC, its clients and local consultants. It is likely that there is more geotechnical investigation data from previous projects that could be uploaded to the NZGD.

[2] T+T was not able to determine the precise location of the project from the information available in the report. However, there are currently no geotechnical investigations available on the NZGD in close proximity to Whareora Road (the road shown on the borehole location plan).

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 WDC'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 Whangarei 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 0)

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 0 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 WDC's intended purposes was developed in a workshop held on 29 April 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.

Based on the workshop discussions it was agreed that a Level B level of detail is suitable for WDC's intended purposes in the following areas:

- Whangarei City Central Business District (CBD)
- North Port Commercial/Industrial Area
- One Tree Point/Marsden Cove Residential Area
- Marsden Point Commercial/Industrial Area
- Ruakaka Residential Area

For the rest of the district a Level A level of detail would be sufficient for WDC's intended purposes. Figure 3.2 and Figure A1 in Appendix A show the target level of detail in the liquefaction assessment for the study area. Section 3.4 examines the information that is available to assess whether or not it is sufficient to support this target level of detail across the district.

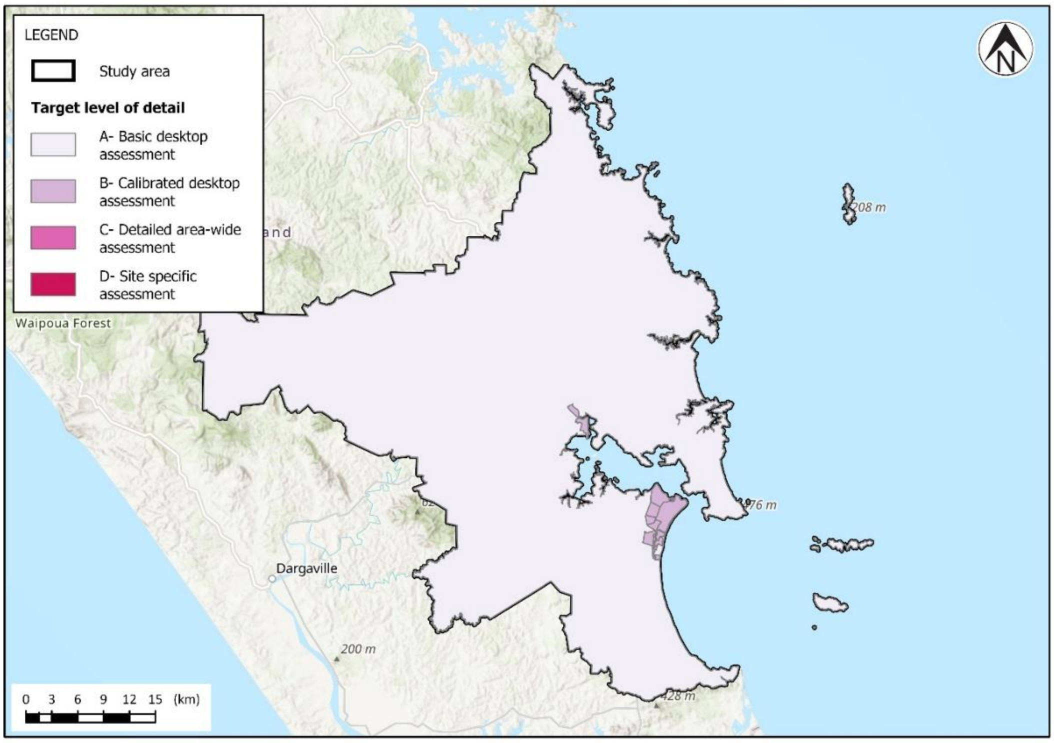


Figure 3.2: Target level of detail in the liquefaction assessment for the Whangarei District.
Also refer to Section 3.4 for achieved level of detail supported by the currently available base information.

3.2 Base information currently available

3.2.1 Ground surface levels

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

Table 3.1: Recent LiDAR data acquisitions for the Whangarei District

Commissioning agency	Year of acquisition	Acquisition by	DEM resolution (m)	Coverage of study area
Northland Regional Council	2019	Aerial surveys	1.0	Entire

The ground surface elevation within the district varies from approximately 0 to 690 m RL (NZVD 2016)[3] across the area although the majority of the study area is between 2 and 150 m RL. Elevated features in the area above 150 m RL include the top of the mountain ranges, predominantly ones topped with volcanic deposits including scoria cones and volcanic dome features. The low-lying portions of the study area include the open coast along the Eastern boundary, the harbour (also part of the Eastern boundary), and river and stream channels throughout the area.

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 2019 LiDAR Survey.

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

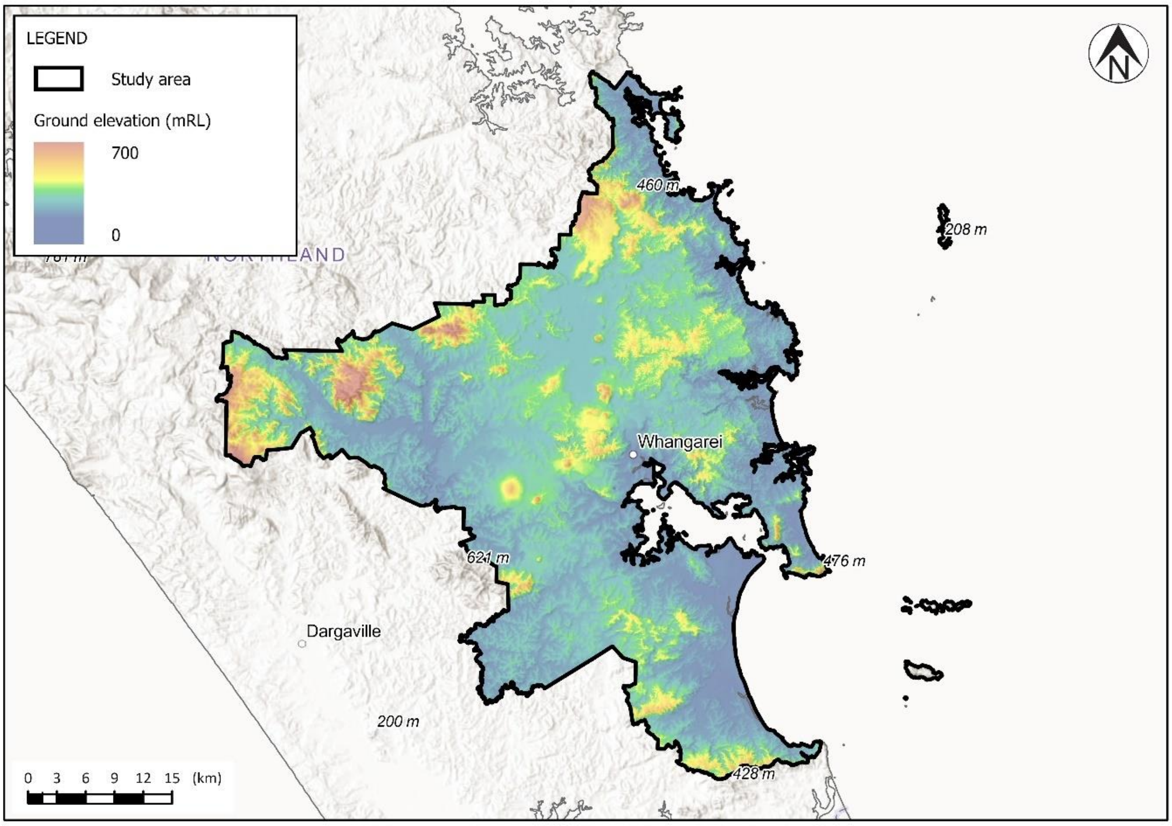


Figure 3.3: Ground surface elevation over Whangarei district as represented by the 2019 LiDAR Survey.

3.2.2 Geology and geomorphology

Geology

The geology of the Whangarei district is represented by two published geological maps. As summarised in Table 3.1 below, both maps were published by GNS Science.

Table 3.2: Published geological maps that cover the study area

Title	Authors	Published date	Scale
Geology of the Whangarei Area (QMAP)	Edbrooke and Brook (compilers)	2009	1:250,000
Geology of the Whangarei Urban Area	White and Perrin	2003	1:25,000

The GNS Science geological maps are accompanied by reports that detail the geological setting and geological deposits of the Whangarei area. The majority of these geological terrains were deposited from the Jurassic to Miocene periods. The majority of low-lying terrains are of middle to late Quaternary age.

The following is a summary of the geological terrains that compromise the study area:

- The oldest geological terrains in the study area comprise sedimentary deposits. These are represented by the following:
  - Waipapa Group greywacke which forms the basement rocks in the area

  - Te Kuiti Group sediments which represent a time where sea level rose over the area
  - Northland Allochthon complexes which were tectonically emplaced in the region as ground level was subsiding
  - Waitemata Group sediments that were deposited on top of the majority of these older geological units in the Whangarei basin.
- Following this, two periods of volcanism occurred throughout the region between 23.8 – 1.8 million years ago. These resulted in various geological formations that have been deposited within or on top of the earlier sedimentary units including lava flows and scoria cones.
- The most recent geological terrains are Quaternary in age, and represent alluvial, coastal and estuarine deposits. These are typically found along the coastline, inner harbour and streams and rivers which have cut into the sedimentary and volcanic deposits already in place.
- On top of these units are residual soils that have formed as a result of weathering processes. These tend to vary in depth, from a couple of metres to more than 10 metres depth.

A more detailed geological history of the area is provided in Table A1 in Appendix A.

Geomorphology

A geomorphic map of the study area was not available, therefore T+T utilised the base information to undertake geomorphic mapping. The following is a summary of the methodology applied and outcome of this task for the Whangarei district.

Geomorphic terrains have been defined and mapped to help identify areas of potential liquefaction vulnerability. Terrains expected to comprise silt, sand and gravelly sediments (e.g. sand dunes and flood plains etc.) are more likely to be vulnerable to liquefaction and have been sub-categorised in more detail compared to the various types of hill country and volcanic landforms within the region, which are less likely be vulnerable to liquefaction. The geomorphic terrain mapping methodology is summarised in Table 3.3.

Table 3.3: Geomorphic terrain mapping methodology

Data sources:	Geological maps – see description above Ground surface levels – see Section 3.2.1 Current and historical aerial imagery
Terrain definition:	Geomorphic terrain categories have been defined based on their general susceptibility to liquefaction following guidance outlined in the MBIE/MfE Guidance (2017) and research by Youd and Perkins (1978). Areas expected to be more vulnerable to liquefaction have been divided into more detailed terrain units (i.e. alluvial channels, alluvial floodplains etc.) compared with less susceptible hill and rocky areas.
Terrain mapping:	Terrain mapping has been undertaken as a desktop assessment largely based on the QMAP geological units. The QMAP geological units have been rationalised into the geomorphic terrain categories. The resulting geomorphic terrain boundaries have been reviewed against the ground surface information and aerial imagery using GIS and where required unit boundaries modified or terrains re-classified. In relevant coastal locations, historical aerial photography has been reviewed to help define areas of reclaimed land.
Mapping Scale	Approximately 1:25,000 – note we have reviewed or drawn terrain boundaries within GIS at an onscreen scale between 1:25,000 to 1:15,000.

Figure 3.4 shows the completed geomorphic map. A larger version of this map is included as Figure A3 in Appendix A.

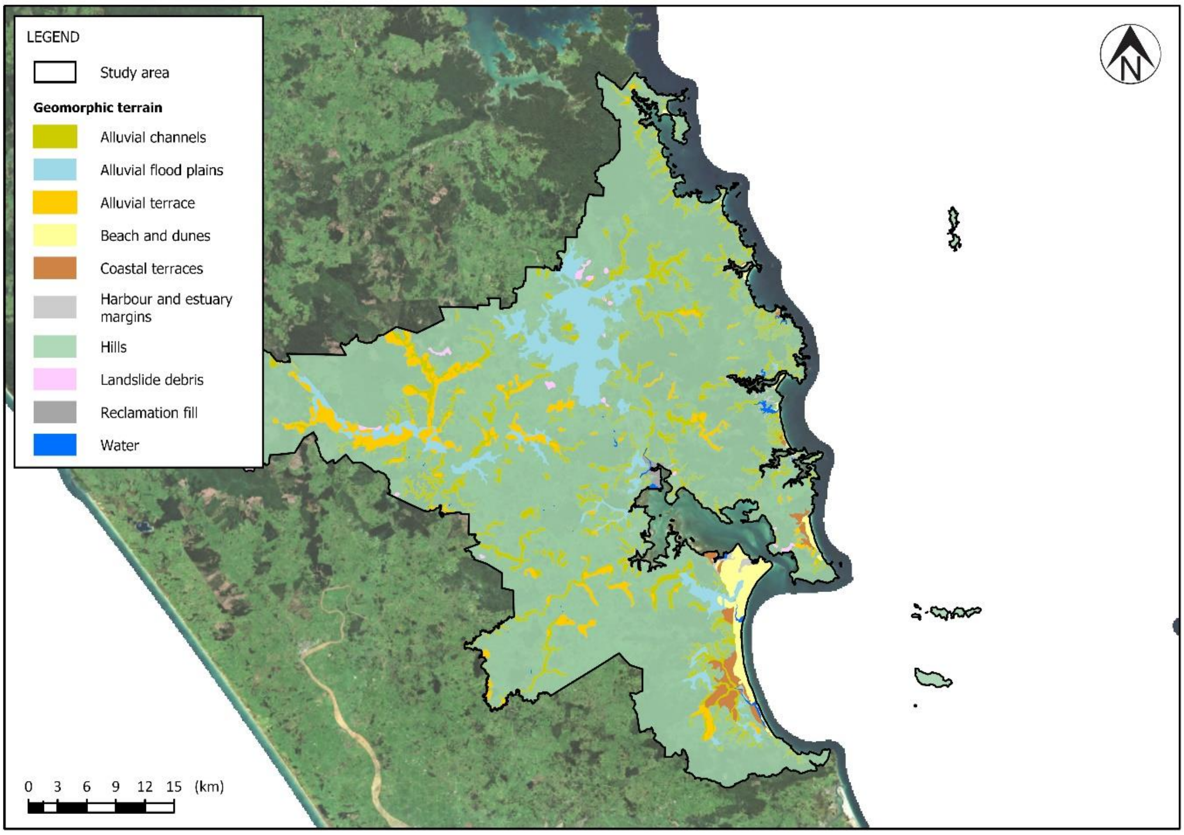


Figure 3.4: Geomorphic map of the Whangarei District.

The geomorphic mapping process identified several different geomorphic terrains across the study area. The classifications of these geomorphic terrains are described briefly below:

- **Reclamation fill** comprises approximately 4 km^2 of the area (0.1% of the study area) and includes variable landforms associated with coastal reclamation around harbour and estuary margins, based on previous mapping by others or historic aerial mapping.
- **Landslide debris** comprise approximately 18 km^2 of the area (0.5% of the study area) and these 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 area.
- **Alluvial** areas comprise approximately 490 km^2 of the area (13.7% of the study area) and are associated with alluvial channels, flood plains and alluvial terraces. These are typically the product of alluvial depositional processes and active fluvial systems eroding the older hillside deposits. This area has been further sub-classified as follows:
  - **Alluvial channels** comprise approximately 292 km^2 of the area (8.2% of the study area) and include the base of valleys and channels, where alluvium and colluvium typically accumulate. Alluvial channels have narrow valley floors relative to the alluvial flood plains which are wider.
  - **Alluvial flood plains** comprise approximately 132 km^2 of the area (3.7% of the study area) and include flat to gently sloping topography on plains and wide valley floors, typically dominated by alluvial processes. Wetlands and swamps are also included.

- **Alluvial terraces** comprise approximately 66 km^2 of the area (1.8% of the study area) elevated terraces above the current alluvial channels and floodplains. The terraces typically contain Pleistocene-age or older alluvium and colluvium.

- **Coastal** areas comprise approximately 52 km^2 of the area (1.5% of the study area) and are associated with low-lying beaches, sand dunes and estuarine environments that represent both the present-day and some relict shorelines. This area has been further sub-classified as follows:
  - **Beach and dunes** comprise approximately 38 km^2 of the area (1.1% of the study area) and are active and relict coastal landforms found along the eastern coastline and associated with beach and sand dune processes.
  - **Harbour and estuary margins** comprise approximately 8 km^2 of the area (0.2% of the study area) and are low-lying areas surrounding the present-day shoreline of the coastal margins and harbours, typically influenced by low energy estuarine and tidal processes.
  - **Coastal terraces** comprise approximately 6 km^2 of the area (0.2% of the study area) and comprise terraced land along the coastal margin approximately 3 m above the current sea level. They are differentiated from the alluvial terraces because they are or have been subjected to coastal processes.
- **Hills** comprise approximately 3,004 km^2 of the area (83.9% of the study area) and are associated with elevated landforms characterised by highly dissected hills with many gullies, as well as hills that are more rolling in nature, depending on the underlying geological units. Isolated cone or dome shaped landforms can represent hills of volcanic origin such as scoria cones.

More detailed descriptions of the geomorphological terrains are provided in Table A2, Appendix A.

While mapping geomorphic terrains, areas of anthropogenic modification (such as quarries, landfills and dams) have also been mapped using historic aerial imagery. These areas provide an additional reference layer for liquefaction vulnerability classification. We note it is likely that some areas of anthropogenic modification will not be captured with this high-level mapping process. The uncertainty associated with this is discussed further in Section 3.3.2.

3.2.3 Geotechnical investigations

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.

Existing geotechnical investigations from the publicly available New Zealand Geotechnical Database (NZGD) and from T+T's internal records within the study area include 86 CPT, 86 boreholes, 50 test pits and 54 hand augers. There are currently no records of laboratory tests in either of these databases however it is likely that such tests have been undertaken for specific projects but are not currently available on these databases. For example, laboratory test results are included in the factual report for the Dent Street Modifications project described in Section 2.4.

The number of CPT, boreholes, test pits and hand augers within each geomorphic terrain is shown in Table 3.4. The relatively large number of investigations in the reclamation fill and alluvial flood plains is primarily attributable to the typically complex nature of the ground conditions found in these terrains and because a lot of development happens in these areas. Note that a significant proportion of the geotechnical investigations within the alluvial flood plains have been undertaken on a single site at Whangarei Boys High School.

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

Geomorphic terrain	CPT (No.)	Borehole (No.)	Test pit (No.)	Hand auger (No.)
Reclamation fill	41	6	0	0
Landslide debris	0	0	0	0
Alluvial channels	9	8	4	4
Alluvial flood plains	63	17	20	20
Alluvial terraces	0	0	0	0
Beach and dunes	0	9	0	0
Harbour and estuary margins	0	7	0	0
Coastal terraces	0	0	0	0
Hills	10	37	26	30
Water	8	2	0	0
Total	**131**	**86**	**50**	**54**

Figure 3.5 and Figure A4 in Appendix A show the location of the geotechnical investigations available on the NZGD as of July 2020. Note that this map does not show investigations from T+T's internal records because we do not have permission to publish the locations of these investigations.

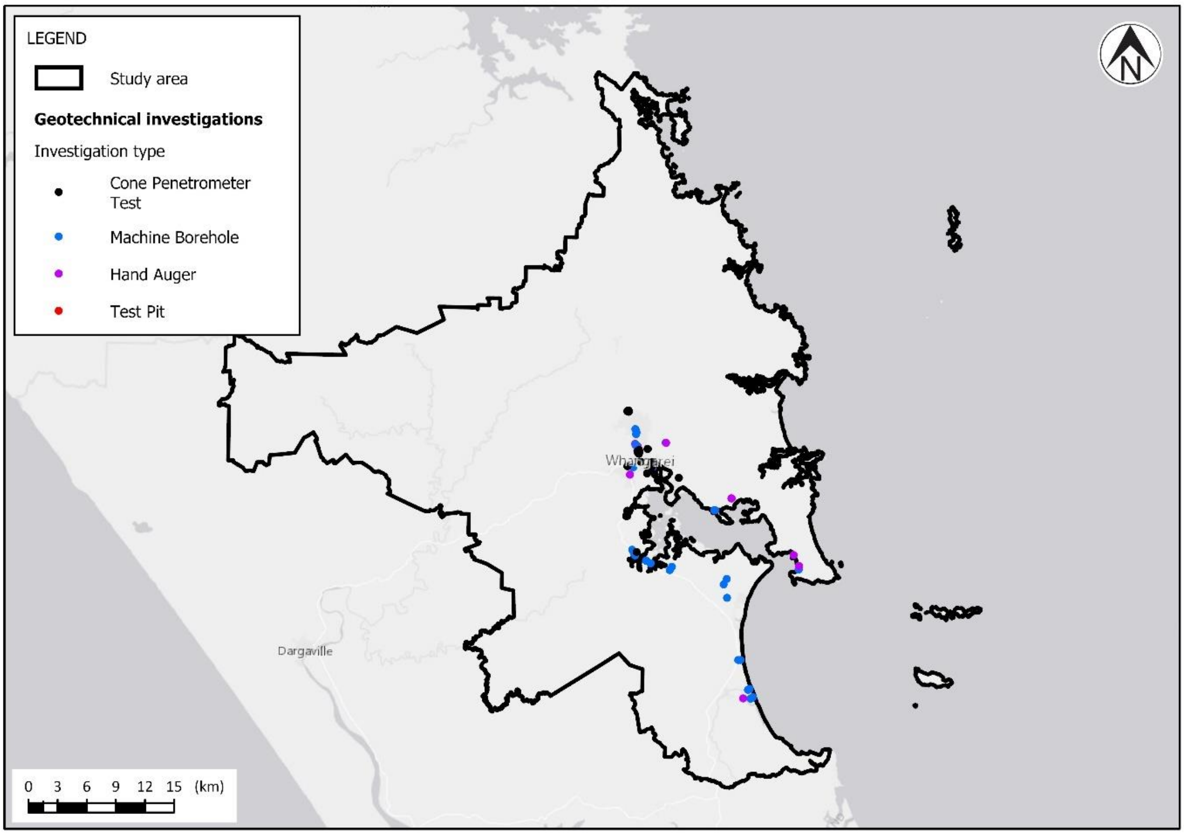


Figure 3.5: Geotechnical investigations available on the NZGD as of July 2020.

Compared to other parts of New Zealand there are relatively few geotechnical investigations available on databases within the Whangarei District. As shown in Figure 3.5, the investigations on the NZGD that are available are predominantly located within Whangarei City and within the area to the south along Bream Bay. 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 1,818 bores available on the Northland Regional Council (NRC) Open Data database (NRC, 2020) which 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 located within unconfined aquifers and therefore can be used to provide information about the groundwater surface elevation:

- Bore depth less than or equal to 20 m; and
- Measured water level not equal to 0 (assumed a null record).

Of the 449 bores that met these screening criteria, 70 of the wells have a classified "Purpose" of Monitoring. At these locations it is likely that a record of groundwater level monitoring over time exists. However, despite requesting the data from NRC, WDC and T+T have not been able to access any monitoring data. Records of groundwater levels over time are important because they help to estimate fluctuations in groundwater depth that may occur. The single measurements that are available may represent seasonally high or seasonally low records that may impact the validity of any liquefaction analysis undertaken.

In addition, there are 107 geotechnical investigations[4] within the study area which have recorded groundwater levels and the depth of the investigation is less than or equal to 20 m below ground level (bgl). Table 3.5 provides a count of the readily available in-situ groundwater investigations within the study area.

Table 3.5: Summary of in-situ groundwater data sources

In-situ groundwater investigation type	Count
Screened NRC Open Data database bores	449
Geotechnical investigation with groundwater measurement	107

In addition, shallow groundwater is often in hydraulic connection with springs, river networks, and other surface water bodies (i.e. lakes and ocean), which can be used to infer groundwater levels. The River Environment Classification dataset developed by NIWA for the Ministry for Environment contains valuable information such as stream gradient which can help infer groundwater trends. In addition, mapped rivers, coastlines boundaries, and lakes are readily available from LINZ through the National Topographic Office.

The spatial distribution of the in-situ groundwater data and the recorded locations of surface water bodies from the 1:250,000 scale topographic map is shown in Figure 3.6 and Figure A5 in Appendix A.

[4] Machine borehole, Cone Penetrometer Test, Hand Auger, Hand Auger Scala, Scala, and Test Pit.

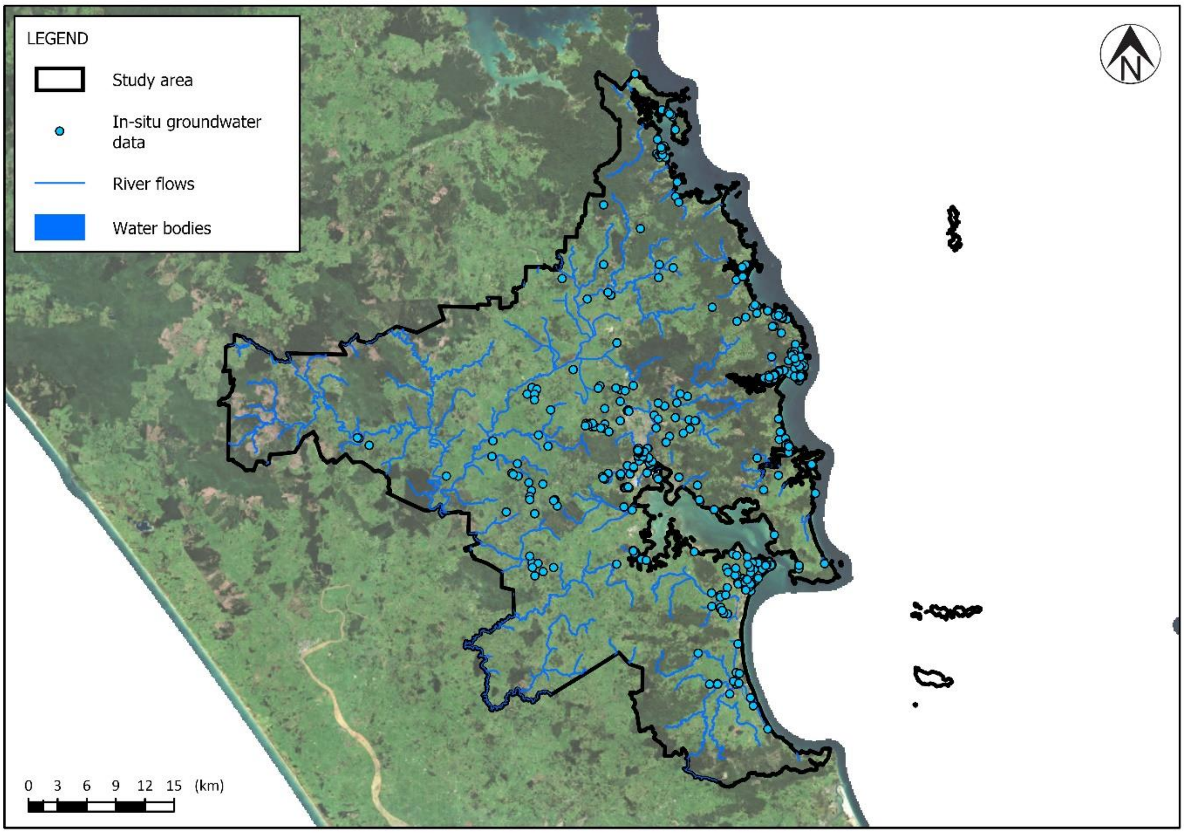


Figure 3.6: In-situ groundwater data and mapped locations of surface water bodies from the 1:250,000 scale topographic map.

Review of the in-situ groundwater data available indicates that the depth to groundwater is typically less than 4 m below ground level (bgl) in areas where records exist. However, we note that these records are single point measurements and do not capture seasonal variations in ground water level. Furthermore, as this data was collected by a range of different people for a range of different purposes, there is some uncertainty associated with the quality of the records. These records would need to be validated and possibly ground-truthed prior to being utilised in the development of groundwater models.

Groundwater studies

As shown in Table 3.6, several groundwater monitoring studies have been undertaken in relatively recent times. These studies have primarily been undertaken to assess the sustainability of the rate of abstraction from the aquifer under consideration. While they provide some useful background information for understanding groundwater regimes, they do not include shallow depth to groundwater models that could be utilised for more detailed liquefaction analysis.

Table 3.6 Available groundwater studies in the study area

Title	Authors	Published date	Coverage of study area
Annual Monitoring Report 2005 – 2006	Northland Regional Council	2006	Partial
Preliminary Hydrogeological Investigations - Four Northland Aquifers: Three Mile Bush Groundwater Resource For Northland Regional Council	Donna Jones, Blair Thornburrow SKM	March 2006	Partial
Preliminary Hydrogeological Investigations - Four Northland Aquifers: Maungakaramea groundwater resource For Northland Regional Council	Zeljko Viljevac, Blair Thornburrow, Donna Jones SKM	March 2006	Partial
Maunu – Maungatapere – Whatitiri Aquifers: Sustainable Yield Assessment For Northland Regional Council	Gillian Holmes SKM	April 2010	Partial

Currently available information about groundwater in the Whangarei region indicates that there is a reasonable database of groundwater records in the region. Where available this information could be utilised to support further assessment of shallow groundwater levels. The uncertainty associated with the issues highlighted in this section is discussed further in Section 3.3.4.

3.2.5 Seismic hazard

Soils that are susceptible to liquefaction require a certain level of earthquake shaking (duration and intensity) to cause them to liquefy. A key input into the analysis of liquefaction is the intensity of shaking that is expected to occur at a particular location in future earthquake events. The following seismic hazard information is provided as background to the triggering component of the liquefaction analysis.

Regional setting

In a national context, the Northland region is an area of relatively low seismic activity, with no noted occurrences of earthquakes exceeding Magnitude 5.0 in recent history. Despite this, local seismographs have recorded a number of smaller earthquakes in the region, with epicentres noted at locations including Ruakaka, Maungaturoto and off the coast of Whangarei.

Two earthquakes are described in detail in a study of Northland seismicity (Eiby, 1964), recorded in Peria and Mangonui from November to December 1963, with damage to structures being reported in local areas including Peria, Kaeo and Kerikeri.

A search of the Geonet New Zealand earthquake database (GNS, 2020) was undertaken as part of this study. A list of notable seismic events with magnitude greater than 4.0 from the database is provided below in Table 3.7.

Table 3.7: Summary of notable historic earthquakes in the Northland region

Date	Location	Earthquake Magnitude	Earthquake Depth (km)
1 March 1830	65 km East of Kaitaia	4.5	25
18 January 1844	65 km east of Kaitaia	4.5	25
13 September 1942	65 km south-east of Whangarei	4.7	100
11 November 1963	30 km north-east of Kaitaia (Mangonui)	4.5	12
22 December 1963	20 km east of Kaitaia (Peria)	4.8	12
25 April 1964	40 km east of Kaitaia	4.7	25
18 September 1964	30 km east of Kaitaia	4.5	25
11 February 1975	45 km south-east of Whangarei	4.4	12

The New Zealand Active Faults database (GNS Science, 2020), indicates that there are no known active faults within the Whangarei District. The nearest active fault within the GNS database is the Waikopua fault, located some 150 km southeast of Whangarei City. While geological studies have identified numerous faults within the Whangarei region, all to date have been classified as inactive faults (i.e., showing no evidence of movement within the past 100,000 years).

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. The Z Factor map for the North Island is provided for regional context below as Figure 3.7, and provides a visual overview of the anticipated seismic hazard of the Whangarei District in the context of the North Island.

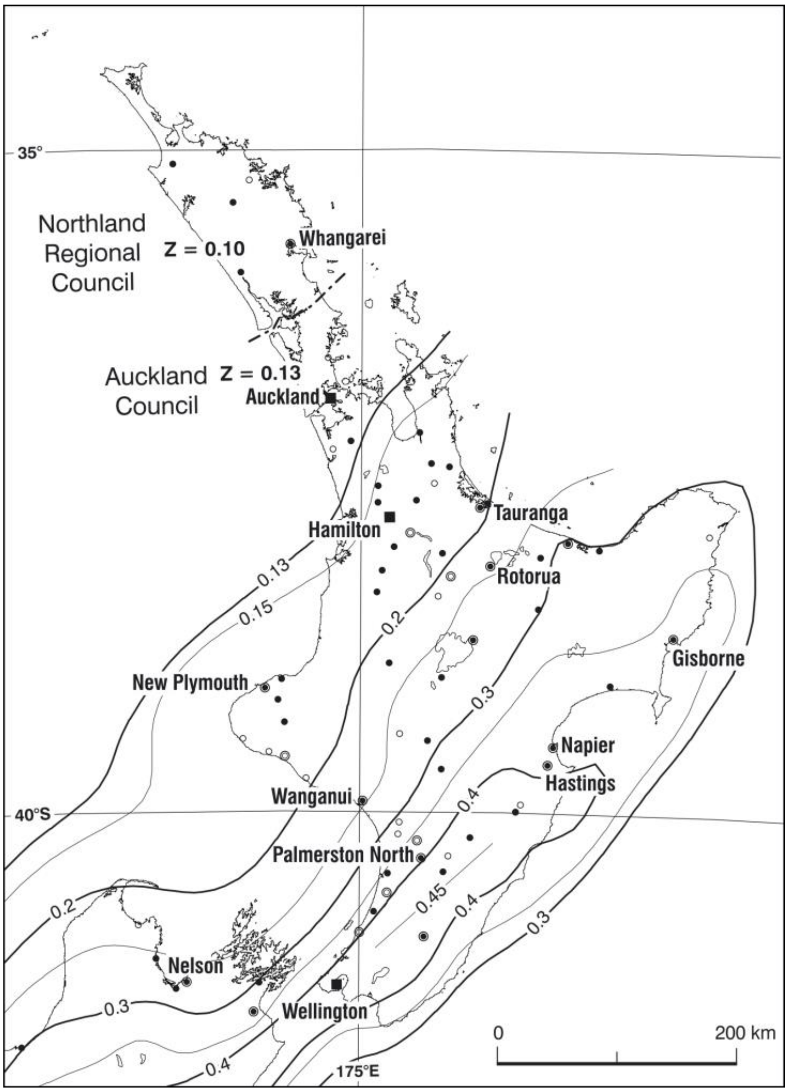


Figure 3.7: Z Hazard Factor map for the North Island. (Source: Standards New Zealand NZS 1170.5:2004).

High-level seismic ratings (MBIE, 2018) for New Zealand based on Z Factor values are provided below for context in Table 3.8.

Table 3.8: 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

While the available evidence indicates that seismic hazard of the Northland region is low relative to other parts of New Zealand, in a wider global context the potential for seismic events to occur is still significant and requires due consideration. In common New Zealand engineering practice the procedure for calculating seismic hazard is adopted from the NZTA Bridge Manual (NZTA, 2018), which gives an earthquake magnitude of 5.8 for the Whangarei region and a range of peak ground acceleration (PGA) values depending on the design scenario required. Derivation of seismic hazard parameters is discussed further in the following section.

Seismic hazard parameters

In the absence of a site specific assessment or regional study (NZGS/MBIE, 2016) the NZTA Bridge Manual (NZTA, 2018) is the commonly accepted method for the determination of seismic parameters for use in liquefaction assessment for routine engineering projects in New Zealand.

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 3.9.

Table 3.9: Seismic parameters (NZTA Bridge Manual)

Design Case	Magnitude (M_{eff})	Peak Ground Acceleration, PGA (g)		
		Soilsoil Class A & B	**Subsoil Class C**	**Subsoil Class D & E**
1 in 25 Years	5.8	0.03	0.03	0.03
1 in 100 Years	5.8	0.05	0.07	0.06
1 in 250 Years	5.8	0.08	0.10	0.09
1 in 500 Years	5.8	0.10	0.13	0.12
1 in 1000 Years	5.8	0.13	0.17	0.16
1 in 2500 Years	5.8	0.18	0.24	0.22
Lower bound for Damage Control Limit State design (refer below)	6.5	0.14	0.19	0.16

The NZTA Bridge Manual requires that bridge designers control damage resulting from a magnitude 6.5 earthquake at 20km distance as a deterministic lower bound check, even if the probabilistic seismic hazard model indicates a lower level of shaking. This emphasises the importance of considering uncertainty in the seismic hazard model and is particularly relevant for Whangarei District where the modelled seismic hazard is low relative to elsewhere in New Zealand. This acknowledges that it is possible that unmapped faults capable of generating significant earthquakes could be present anywhere across New Zealand. As an example, the Canterbury Earthquake sequence included earthquakes up to magnitude 6.2 on previously unmapped faults directly beneath Christchurch City.

While it is possible that unmapped faults capable of generating significant earthquakes could be present in Whangarei District, there is a very low probability of such an earthquake affecting a specific site in any given year. This means a balanced pragmatic approach is needed to take this uncertainty into account without unreasonably over-estimating the seismic hazard.

The MBIE/MfE Guidance (2017) notes that for routine situations it will often be most appropriate for extreme earthquake scenarios such as this to be considered as a sensitivity check to provide additional background information (e.g. “what if” questions) to help guide development of natural hazard management strategies, rather than as a primary factor determining the liquefaction categorisation. If the extreme scenario results in a large step-change worsening of land performance compared to the 500-year scenario (e.g. enough to materially impact the engineering solution that would be adopted), then this might indicate higher liquefaction vulnerability than a situation where there is only a minor incremental change to the land performance.

3.2.6 Historical observations of liquefaction

A review of the historical earthquake records of the area indicates that there are no recorded observations of liquefaction related damage in the region. The Beetham Natural Hazards Report (2004) does document observations of other forms of damage from the 1963 Peria Earthquakes as shown in Figure *3.8*, but these do not appear to be the consequences of liquefaction.

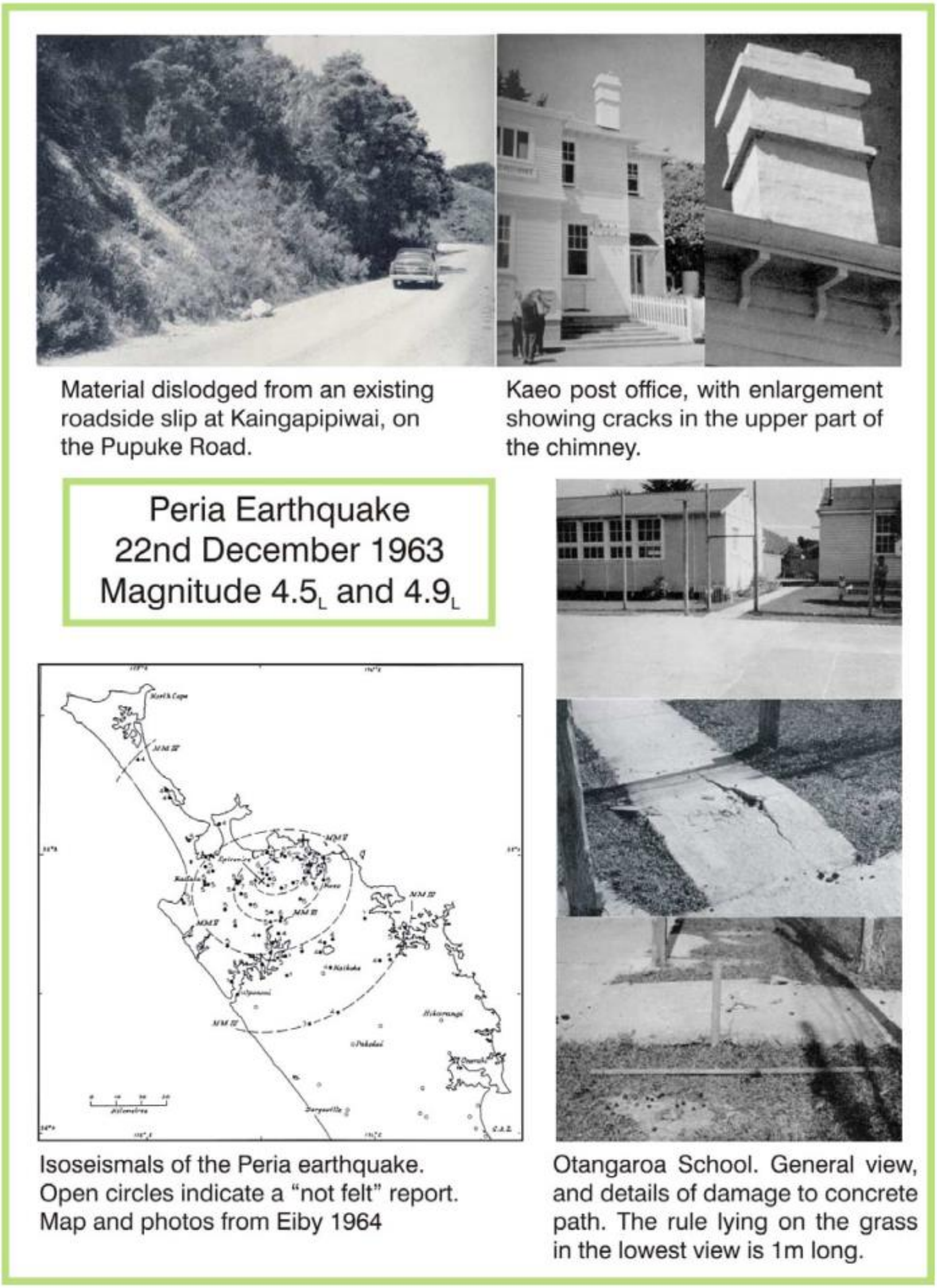


Figure 3.8*: Examples of damage caused by the 1963 Peria earthquakes - reproduced from Beetham (2004).*

3.3 Uncertainty assessment

This section presents an assessment of the uncertainty associated with the base information currently available in the WDC 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 relatively high resolution and considered fit for the purposes of this liquefaction assessment, the following accuracy issues 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.

In most cases these limitations will have a relatively minor effect on the representation of the ground surface. 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.

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.

As discussed in Section 3.2.2, anthropogenic features have been identified while undertaking the geomorphic mapping and have been utilised in the liquefaction vulnerability classification process. Note that mapping from historic aerial imagery is unlikely to capture all areas of anthropogenic modification. The historic images may not cover the period when modification 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).

As discussed above this source of uncertainty can be partially managed by mapping anthropogenic features as identified from historic aerial imagery and appropriately classifying these according to the liquefaction vulnerability performance criteria. However, this mapping process is unlikely to capture all areas of anthropogenic landform change.

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 (both quantitatively and qualitatively) 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 issues in data quality. Some of these are readily identifiable, are logged as part of the investigation and can be allowed for in the analysis (e.g. post-ground improvement investigations and portions of predrilled CPT). 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 means that this is not a significant source of uncertainty in this study.

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 beach and dunes, 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 reclamation fill and the alluvial terrains, 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 discussed with reference to the spatial density below.

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 3.9.

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 km²	1 to 10 km	–
Level B **Calibrated desktop assessment**	0.5 to 20 per km²	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 3.9: 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. As shown in Figure 3.5, the few available investigations are predominantly located within Whangarei City and within the area to the south along Bream Bay. For the areas where a Level A level of detail is targeted (refer to Figure 3.2), this spatial density issue means it is not possible to reliably calibrate the soil conditions from the available geotechnical investigations.

For example, as noted in Section 3.2.3 a significant proportion of the geotechnical investigations within the alluvial flood plains have been undertaken on a single site at Whangarei Boys High School. While this tells us a lot about the ground conditions at that particular location, there would be a high degree of uncertainty associated with using this information to infer the ground conditions in the remaining 132 km^2 (approx.) of mapped alluvial flood plains in the study area. The other available geotechnical investigations are similarly clustered around project specific locations.

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”.

For the areas in this study where a Level B level of detail is targeted this issue is also a significant source of uncertainty. Table 3.10 shows the borehole and CPT count and density in the areas where a Level B level of detail is targeted. Note this table only shows borehole and CPT data where the depth exceeds 10m. This is because these investigations are typically the most useful deep investigation methods for assessing liquefaction and 10-15 m is the minimum depth typically required for liquefaction assessment.

Table 3.10: Land area, borehole and CPT investigation count, borehole and CPT investigation density in the target Level B areas in the areas where a Level B level of detail is targeted

Location	**Land area (km2)**	**Number of borehole and CPT with depth more than 10m**	**Borehole and CPT density (per km2)**
Whangarei City CBD	1.3	10	7.8
North Port Commercial/Industrial Area	2.4	23	9.6
One Tree Point/Marsden Cove Residential Area	5.9	0	0
Marsden Point Commercial/Industrial Area	10.1	0	0
Ruakaka Residential Area	2.1	0	0

Inspection of Table 3.10 shows that there are no deep borehole or CPT in the One Tree Pont/Marsden Cove Residential Area, Marsden Commercial/Industrial Area or the Ruakaka Residential Area therefore the indicative spatial density for a Level B level of detail (0.5 to 20 per km^2) is not satisfied in these areas. Whereas, at face value the indicative spatial density for a Level B level of detail study is satisfied in the Whangarei City CBD and the North Port Commercial/Industrial Area.

To explore these areas in more detail, Figure 3.10 shows the Whangarei CBD and the Northport Commercial/Industrial Area with geomorphology, CPT and borehole investigations on the NZGD and the areas where a Level B level of detail is targeted. Note that this map does not show investigations from T+T’s internal records because we do not have permission to publish the locations of these investigations.

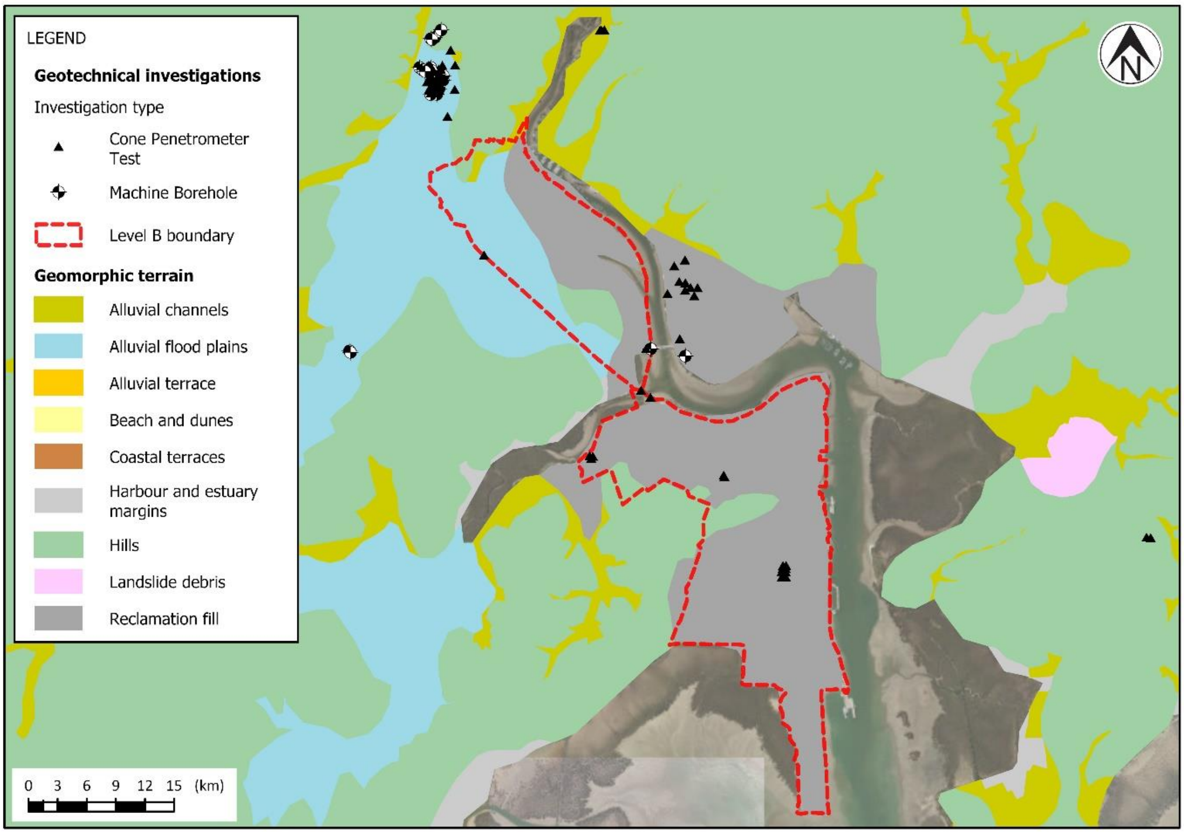


Figure 3.10: Whangarei CBD and the Northport Commercial/Industrial Area with geomorphology, NZGD CPT and borehole investigations and the areas where a Level B level of detail is targeted.

Inspection of Figure 3.10 shows the investigations that are available are clustered around specific locations. The investigations on T+T's internal records follow a similar pattern. This is because these investigations were undertaken to satisfy the requirements of specific projects and not for the purposes of this study. For the complex ground conditions that are likely to be prevalent within the reclamation fill that is predominantly found in these areas, the spatial distribution is not considered sufficient for adequate ground characterisation to a Level B level of detail extrapolated across the geomorphic terrain. While the available investigations are extremely valuable, to satisfy the indicative spatial density for a Level B level of detail, additional deep investigations would be required in these two areas.

Review of the studies supplied by WDC (refer to Section 2.4) demonstrated that there are existing geotechnical investigations within the district that could be uploaded onto the NZGD. If WDC intends to undertake future higher-level studies, T+T would recommend locating and uploading historic geotechnical investigations in areas where these are targeted. Furthermore, WDC may wish to consider encouraging the uploading of supporting geotechnical investigations onto the NZGD as part of the process of evaluating resource and building consents. Undertaking these steps would also be of benefit to other projects that utilise geotechnical investigation data. Once these steps have been undertaken it may be necessary to supplement these investigations with new geotechnical investigations to achieve the target level of detail required for WDC's intended purposes.

3.3.4 Groundwater

As discussed in Section 3.2.4, there are a number of in-situ groundwater data records within the WDC region, the majority of which are single measurements from boreholes that are sourced from the NRC 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 region 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. However, to date T+T has not been able to access monitoring data. 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:

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.

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. Therefore, in the areas where a Level A level of detail is 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 assessment. Similarly, for the areas where a Level B level of detail is targeted this uncertainty in seismic hazard can be managed with sensitivity testing of any quantitative liquefaction analysis undertaken. For example, as discussed in Section 3.2.5, a sensitivity check could be made using an extreme earthquake scenario to see if it results in a large step-change worsening of land performance. If it does not, then more refined analysis is unlikely to be warranted.

Refinement of this source of uncertainty becomes more important at higher levels of detail (such as Level C or D) when the main objective is to differentiate between areas of medium and high liquefaction vulnerability, so the return period of liquefaction-induced damage is important. In these situations, further study into the seismic hazard of the Whangarei area could be undertaken to reduce uncertainty in the seismic hazard, via the commissioning of a site-specific Probabilistic Seismic Hazard Assessment (PSHA). Such an approach is preferred for more significant projects, more complex sites, or other cases where advanced analysis can be justified (NZGS/MBIE, 2016) however it is unlikely to be warranted to satisfy WDC's intended purposes for this study.

3.3.6 Assess ground damage response against the performance criteria

The MBIE/MfE Guidance (2017) provides the performance criteria shown in Figure 3.11 to determine the liquefaction vulnerability category for a particular area of land.

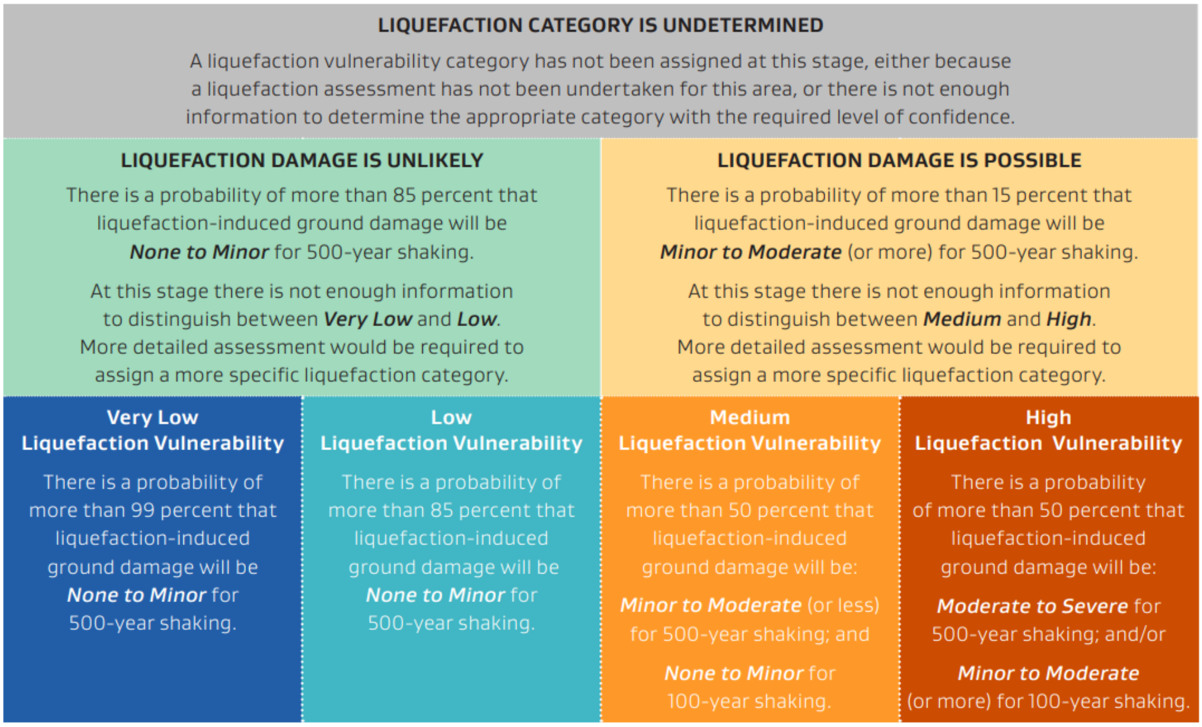


Figure 3.11: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017)

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 3.11.

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 these areas 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" at the present time. This lack of a definitive category might at first 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 could be provided via the GIS metadata which accompanies each sub area of similar expected performance (refer Section 4.3).

3.4 Level of detail supported by the currently available base information

The assessment of uncertainty described above has been used to inform the level of detail in the assessment supported by the currently available base information shown in Figure 3.12 and Figure A6 in Appendix A.

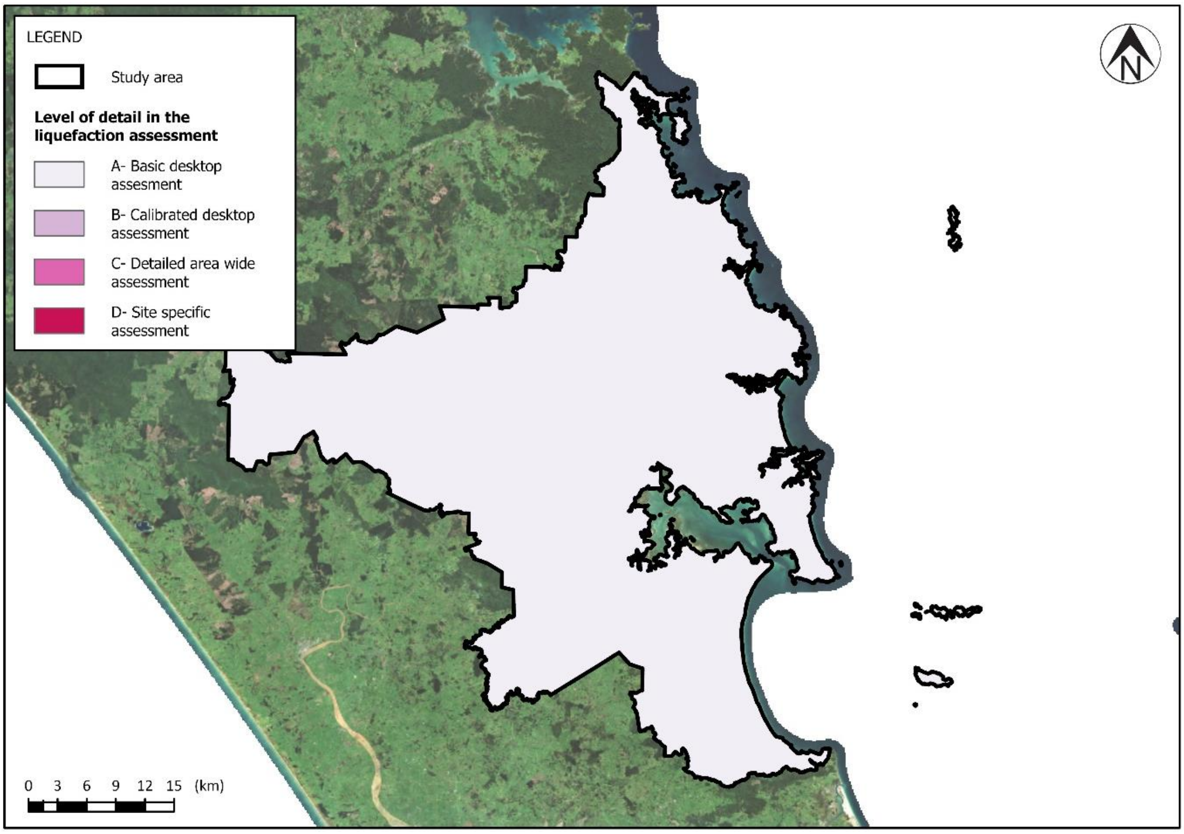


Figure 3.12: Level of detail supported by currently available base information (Level A throughout study area).

Figure 3.12 shows that the highest level of detail supported by the currently available information is Level A throughout the entire study area. In areas where more detailed assessment was initially targeted, the key sources of uncertainty that prevent a Level B level of detail being achieved are:

- The relatively limited number of geotechnical investigations available.
- The complex nature of the ground conditions in the areas where investigations are available.
- The uncertainty associated with the depth to groundwater in these areas.

4 Risk analysis

4.1 Groundwater levels for analysis

As described in Section 3.2.4 and 3.3.4, within the study area there are relatively few in-situ groundwater data points available, T+T has not been able to access longer term groundwater monitoring records and T+T is not aware of any shallow surface depth to groundwater models in the area. This makes it particularly challenging to establish precise groundwater levels for analysis and make allowance for seasonal fluctuations. However assumptions can be made for the purposes of qualitative screening and engineering judgement has been applied to estimate the typical range of depth to groundwater in each of the geomorphic terrains as shown in Table 4.1. An accompanying evaluation of the potential effects of sea level rise has also been made.

Table 4.1: Assumed depth to groundwater and potential influence of sea level rise in each geomorphic terrain

Geomorphic terrain	Assumed depth to groundwater	Potential influence of sea level rise
Reclamation fill	Less than 4 m	Likely to become shallower
Landslide debris	Undetermined	Undetermined
Alluvial channels	Less than 4 m	Areas of low elevation adjacent to coastal margins are likely to become shallower Areas of higher elevation are likely to be unaffected
Alluvial flood plains	Less than 4 m	Areas of low elevation adjacent to coastal margins are likely to become shallower Areas of higher elevation are likely to be unaffected
Alluvial terraces	More than 4 m	Areas of low elevation adjacent to coastal margins are likely to become shallower Areas of higher elevation are unlikely to be affected
Beach and dunes	Less than 4 m	Likely to become shallower
Harbour and estuary margins	Less than 4 m	Likely to become shallower
Coastal terraces	More than 4 m	Areas of low elevation adjacent to coastal margins are likely to become shallower Areas of higher elevation are unlikely to be affected
Hills	Hilltops, ridges and elevated areas assumed to be more than 8 m Sloping land assumed to be highly variable depending on antecedent rainfall and position on slope Bottom of gullies and ravines assumed to be less than 4 m	Areas of low elevation adjacent to coastal margins are likely to become shallower Areas of higher elevation are unlikely to be affected

4.2 Earthquake scenarios for analysis

For the purposes of this liquefaction vulnerability study we have adopted the seismic hazard parameters shown in Table 3.9.

Table 4.2: Earthquake scenarios for analysis

Design Case	M_{eff}	PGA (g)
500-year return period	5.8	0.12
Extreme (low probability) scenario	5.8	0.18

The 500-year return period is considered because this is the recommended minimum earthquake scenario for Level A and B studies. The values for site soil class D/E values based on the NZTA Bridge Manual methodology are adopted because these are the most likely site soil class that would be encountered when liquefiable soils are present.

The extreme (low probability) scenario is used as a sensitivity test for the liquefaction vulnerability classification. It is calculated by multiplying the 500-year return period PGA by 150 percent as recommended in Section 4.3 of the MBIE/MfE Guidance (a similar outcome would result from the lower bound values for Damage Control Limit State design discussed in 3.2.5). This sensitivity test is used as a means of managing the uncertainty in the estimation of seismic hazard described in Section 3.3.5. This test is particularly relevant in this case because the design seismic hazard parameters calculated using the Bridge Manual methodology for 500-year return period earthquake are only just on the threshold of triggering liquefaction in typical susceptible soils.

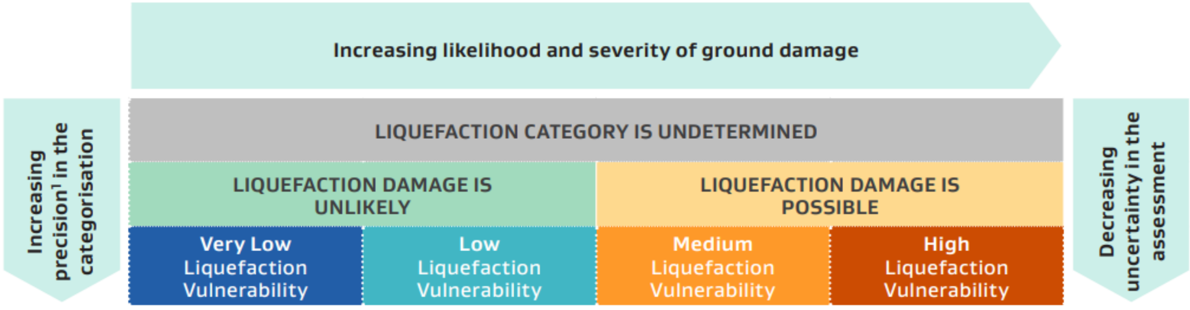
4.3 Sub areas of similar expected performance

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 region. This is used as the primary basis for evaluating the likely soil conditions within each sub-area of similar expected performance. Where available geotechnical investigations have been utilised to calibrate this assessment**.**
- **Topographic screening** – the LiDAR derived DEM has been processed using GIS analytical tools to divide the study area into hilltops, ridges and elevated land, sloping land and flat lowland areas. This is a useful means of subcategorization because it allows qualitative assessment of the typical range of depth to groundwater.
- **Lateral spread screening** – a high level screening of areas where lateral spreading is more likely to be possible has been undertaken by applying a 200m buffer to the mapped water bodies from the QMAP 1:250,000 scale. This high-level mapping of water bodies was utilised because inspection of the other available data sources (e.g. the MfE River Environment Classification system) indicates significant discrepancies between the mapped locations of streams and the available aerial photography.

4.4 Liquefaction vulnerability assessed against performance criteria

Based on the available information the liquefaction vulnerability of each sub area has been assessed against the performance criteria. The end result of the assessment against the performance criteria is the assigned liquefaction vulnerability categories shown in *Figure 4.1*, Figure 4.2 and Figure B1 in Appendix B.



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).

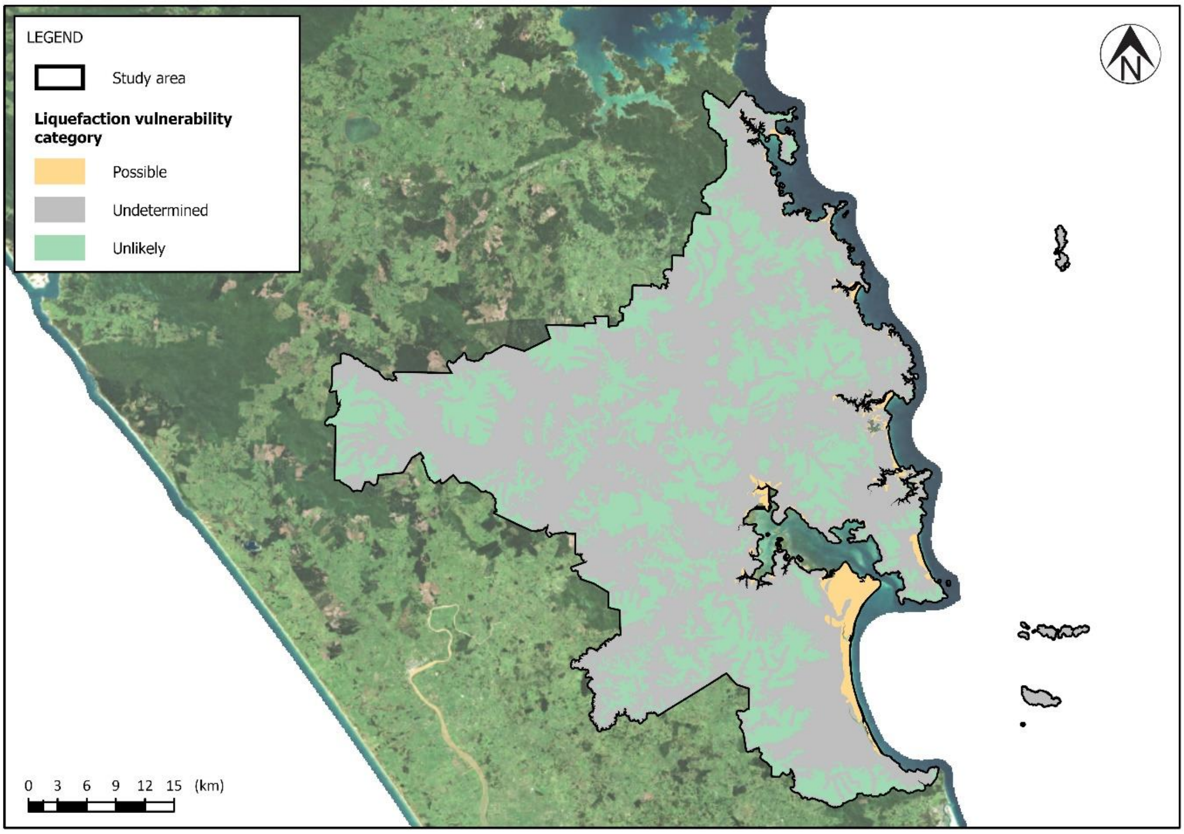


Figure 4.2: Liquefaction vulnerability classification assessed against performance criteria

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

4.4.1 Reclamation fill

Typically, reclaimed land is formed by placing uncompacted or poorly compacted fills within existing waterways. These deposits are considered particularly susceptible to liquefaction as they are often loose and saturated (refer to Section 2.3 of the MBIE/MfE Guidance (2017)).

The available geotechnical investigations indicate that the reclamation fills in the study area are composed of plastic soils (which are not susceptible to liquefaction) interbedded with silt and sand layers (which are susceptible to liquefaction). Reclamation fills are typically highly variable in nature which means there is a high degree of uncertainty associated with using the available geotechnical investigations (which are clustered around project specific locations) to calibrate the liquefaction performance of the remaining reclamation fill.

The reclamation fills mapped in this study are low lying and found adjacent to the upper reaches of the Whangarei Harbour and are therefore likely to have shallow depth to groundwater (<4m) with the potential to be influenced by sea level rise.

In the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200m of free-faces more than 2m high (such as the harbour edge).

Under 500-year levels of earthquake shaking and the extreme (low probability) scenario, based on engineering judgement, there is a probability of more than 15% that liquefaction-induced ground damage will be Minor to Moderate (or more). Therefore, the reclamation fills have been classified as "Liquefaction Damage is Possible".

4.4.2 Landslide debris

The landslide debris are areas of mapped historic slope instability and are typically found within the hills geomorphic terrain. There is only limited information about the soil and groundwater conditions in this terrain and they are both likely to be 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, 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 plasticity and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

4.4.3 Alluvial channels and floodplains

Typically, soils found in alluvial channels and floodplains are geologically young and deposited in low energy environments forming loose and soft layers. The depth to groundwater is also likely to be shallow (<4m) because they are associated with waterbodies and they are found in the bottom of valleys. They are two of the main landforms that are typically considered susceptible to liquefaction (refer to Section 2.3 of the MBIE/MfE Guidance (2017)).

However, within the Whangarei district the limited available geotechnical information indicates that the soils at the investigation locations in these terrains are predominantly composed of clay-like (plastic) materials that are not considered to be susceptible to liquefaction. This introduces a significant degree of uncertainty into this qualitative Level A assessment.

Within both terrains free faces associated with riverbanks, streams and drainage ditches are visible in the available aerial photography. 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.

However as described above there is currently significant uncertainty as to whether liquefaction-susceptible soils are present in the alluvial channels and alluvial floodplains.

Due to the uncertainty associated with whether liquefaction-susceptible soils are present, there is currently insufficient information to characterise the expected land performance. Therefore, in these terrains "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 soil types means that if more detailed site-specific assessment was undertaken in 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 plasticity will efficiently determine which liquefaction vulnerability category applies.

4.4.4 Alluvial terraces

The alluvial terraces consist of elevated land above the current alluvial channels and floodplains. The terraces typically contain Pleistocene-age or older alluvium and colluvium. Based on the available geotechnical information and local knowledge they are likely comprised of similar clay-like (plastic) soils to the alluvial channels and floodplains. This combined with the older age of these materials means they are less likely than the alluvial channels and floodplains to contain liquefaction-susceptible soils. However, there are currently no geotechnical investigations in this terrain on either the NZGD or T+T's accessible internal records which introduces significant uncertainty into the assessment.

Due to the higher elevation, the depth to groundwater is likely to be deeper (>4 m) than the groundwater level in the alluvial channels and floodplains. The main exception to this is the gullies associated with streams that intersect the alluvial terraces where the 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 them 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 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 plasticity and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

4.4.5 Beach and dunes, and harbour and estuary margins

The beach and dune, and harbour and estuary margin terrains are likely to be predominantly composed of thick (>10 m) deposits of sands and silts (which are susceptible to liquefaction) and are unlikely to contain a significant proportion of clay-like (plastic) materials (which are not susceptible to liquefaction). While there are relatively few geotechnical investigations in these terrains on the NZGD and within T+T's internal records, these terrains are relatively easy to map from aerial photography and typically have consistent soil conditions.

The primary differences between the two terrains are as follows:

- Beach and dune terrains are typically deposited in a higher energy environment which means the soils are typically denser than those found in the lower energy harbour and estuary margins. The densest soils are typically found within dune deposits adjacent to the open coast
- Harbour and estuary margins are more likely to contain soft silts that exhibit clay-like (plastic) behaviour than the beach and dune terrains

Groundwater is also generally shallow (<4 m) in these terrains because they are typically flat and close to the coastal margins. This proximity to coastal margins means that the depth to groundwater is likely to become shallower with sea level rise. For these reasons, these terrains are identified as landforms that are commonly susceptible to liquefaction in Section 2.3 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 (such as the harbour edge or dune ridges).

Based on the information considered in this liquefaction assessment, at 500-year levels of earthquake shaking and the extreme (low probability) scenario, there is a probability of more than 15% that of liquefaction-induced ground damage will be Minor to Moderate (or more). Therefore, the mapped beach and dunes, and harbour and estuary margins, have been classified as "Liquefaction Damage is Possible".

4.4.6 Coastal terraces

The coastal terraces comprise terraced land along the coastal margin approximately 3 m above the current sea level. They are differentiated from the alluvial terraces because they are likely to or have been subjected to coastal processes and may contain relic sand dune deposits. There are currently no geotechnical investigations in this terrain on either the NZGD or T+T's accessible internal records which introduces significant uncertainty into the assessment.

Like the alluvial terraces, the higher elevation of the coastal terraces means the depth to groundwater is likely to be deeper (>4 m) than the groundwater level in the beach and dunes, and harbour and estuary margins. The main exception to this is the gullies associated with streams that intersect the coastal terraces where the 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 in many cases they have not been mapped at the target scale for the geomorphic mapping (1:25,000). The proximity to coastal margins means that the depth to groundwater is likely to become shallower with sea level rise. These factors also introduce a significant source of uncertainty into the assessment.

In the presence liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free-faces more than 2 m high. However as described above there is currently significant uncertainty as to whether liquefaction-susceptible soils are present in the coastal 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 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 plasticity and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

4.4.7 Hills

The hills terrain comprise elevated landforms characterised by highly dissected hills with many gullies, as well as hills that are more rolling in nature, depending on the underlying geological units. The ground conditions vary from exposed rock to thick (>10 m) deposits of residual soils.

The exposed rock is not considered susceptible to liquefaction. However, based on the information available it is not possible to differentiate with a significant degree of certainty between these areas and the residual soils. This is to be expected for a desktop study at the target scale of the geomorphic mapping (1:25,000).

Based on the available information it is likely that the residual soils are predominantly comprised of clay-like (plastic) materials that are not considered to be susceptible to liquefaction. However, considering this terrain comprises approximately 84% of the study area, there are relatively few geotechnical investigations available to calibrate this assumption. This introduces additional uncertainty into the assessment.

The depth to groundwater is highly variable across this geomorphic terrain. As described in Section 4.1 and 4.3 it has been categorised as follows:

- In the hilltops, ridges and elevated areas the depth to groundwater is likely to be more than 8 m
- In the sloping land the depth to groundwater is highly variable depending on antecedent rainfall conditions and position on slope

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 gullies). However as described above there is currently significant uncertainty as to whether liquefaction-susceptible soils are present in the hills.

Based on the information considered in this liquefaction assessment, the liquefaction vulnerability of the hills has been categorised as follows:

- In the hilltops, ridges and elevated areas there is a probability of more than 85% that liquefaction induced ground damage will be none to minor for both 500 year levels of earthquake shaking and the extreme (low probability) scenario. Therefore, these areas are classified as “Liquefaction Damage is Unlikely.”
- In the sloping land, 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 future then this would likely indicate a category of “Low Liquefaction Vulnerability”. For future assessments, it is likely that site walkovers to confirm exposed rock or simple shallow hand auger boreholes to confirm soil plasticity and/or groundwater depths will efficiently determine which liquefaction vulnerability category applies.

5 Conclusions and recommendations

T+T has undertaken a liquefaction vulnerability study in accordance with the MBIE/MfE Guidelines (2017) for the study area covering the entire Whangarei District. The following are the key conclusions and recommendations from this study:

- The current LiDAR derived DEM that is available for the study area provides a valuable tool both for assessing liquefaction vulnerability and other applications. One of the key limitations associated with any DEM (regardless of the survey source) is the potential for temporal changes in the ground surface elevation due to landform modification from both natural (e.g. erosion) and anthropogenic (e.g. land development) processes. To manage this source of uncertainty T+T recommends that WDC require liquefaction assessments accompanying resource and building consent applications consider the proposed finished ground surface elevation.
- 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 applications (e.g. slope instability assessment).

  To help facilitate the collection of more geotechnical investigation data WDC may wish to consider the following:
  - Identify geotechnical investigations from historic projects within the study area and upload these investigations onto the NZGD.
  - Encourage the uploading of supporting geotechnical investigations onto the NZGD as part of the process of evaluating resource and building consents.
  - Engage suitably competent geo-professionals to undertake geotechnical investigations within the study area where more information about the ground conditions is required (e.g. areas where a Level B level of detail is targeted).
- A key source of uncertainty in this liquefaction assessment is the relatively 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 studies (e.g. areas where a Level B level of detail is targeted). It also provides a valuable data source for other purposes such as asset management.

  To help facilitate the collection of more detailed groundwater data WDC may wish to consider installing a network of piezometers to monitor groundwater level fluctuations over time and developing depth to groundwater surface models from this data.
- The key output from this study is the categorisation of the land in the study area 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 precision in the categorisation of liquefaction vulnerability is generally consistent with a regional scale study such as this undertaken to a Level A level of detail. The mapped output provides a valuable tool for WDC’s intended purpose of informing policy, planning and consenting processes.

  T+T recommends that WDC incorporate this information into their current business processes to inform policy, planning and consenting processes. This is particularly relevant with respect to the processing of building consent applications as changes to the definition of “good ground” in the Building Code are due to take effect by 28 November 2021.

6 Applicability

This report has been prepared for the exclusive use of our client Whangarei 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.

This assessment has been made at a broad scale across the defined study area and is intended to approximately describe the typical range of liquefaction vulnerability across areas of similar ground conditions. 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

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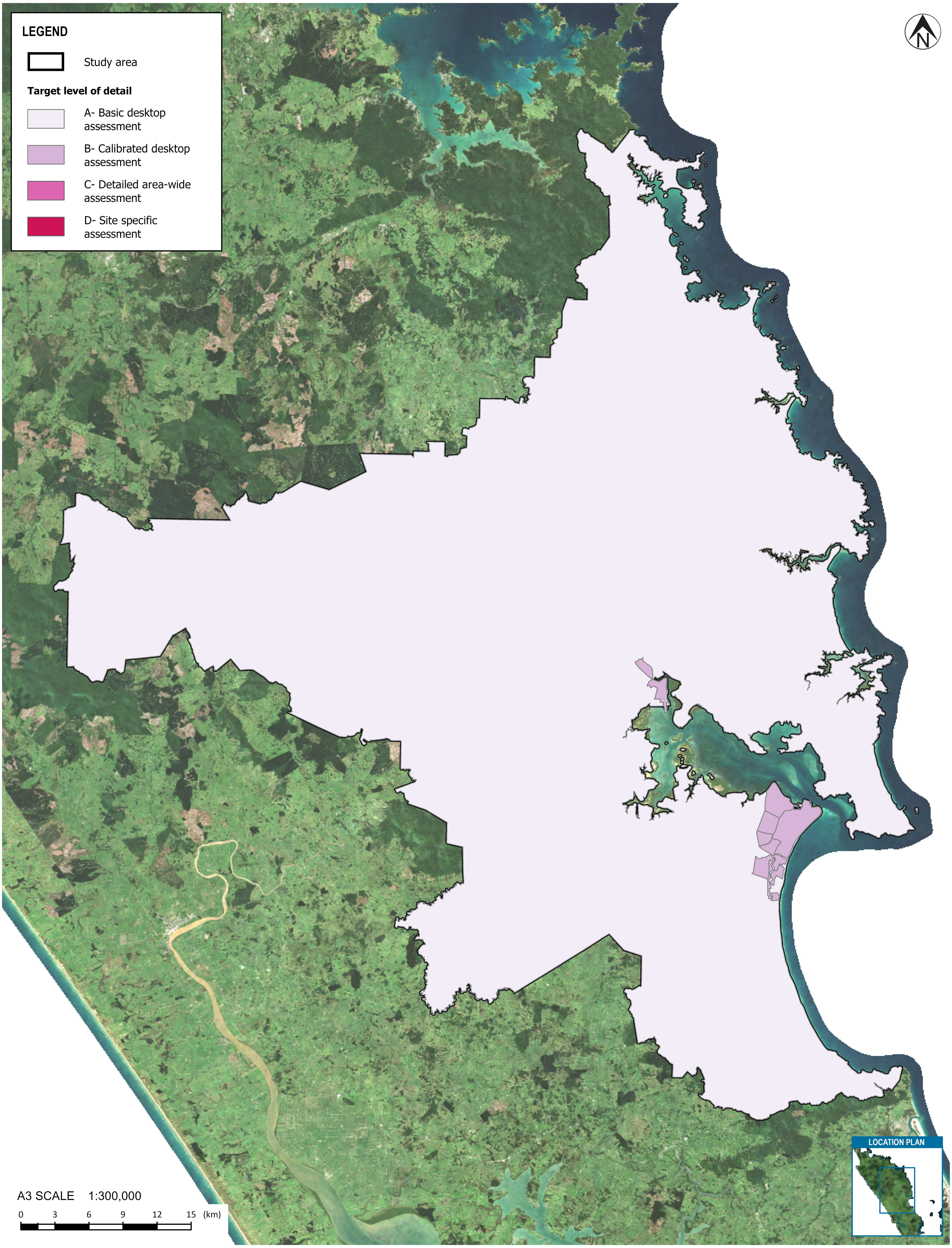
Appendix A: Risk identification

- **Figure A1: Target level of detail**
- **Figure A2: Ground surface elevation (2019 LiDAR survey)**
- **Table A1: Simplified geological model of Whangarei District**
- **Figure A3: Geomorphology map**
- **Table A2: Description of geomorphic terrains shown in Figure A3**
- **Figure A4: NZGD geotechnical investigations**
- **Figure A5: In-situ groundwater data and recorded locations of surface water bodies**
- **Figure A6: Level of detail supported by the available base information**



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PROJECT **LIQUEFACTION VULNERABILITY MAPPING**
TITLE TARGET LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT
SCALE (A3) 1:300,000 FIG No. FIGURE A1 REV 0

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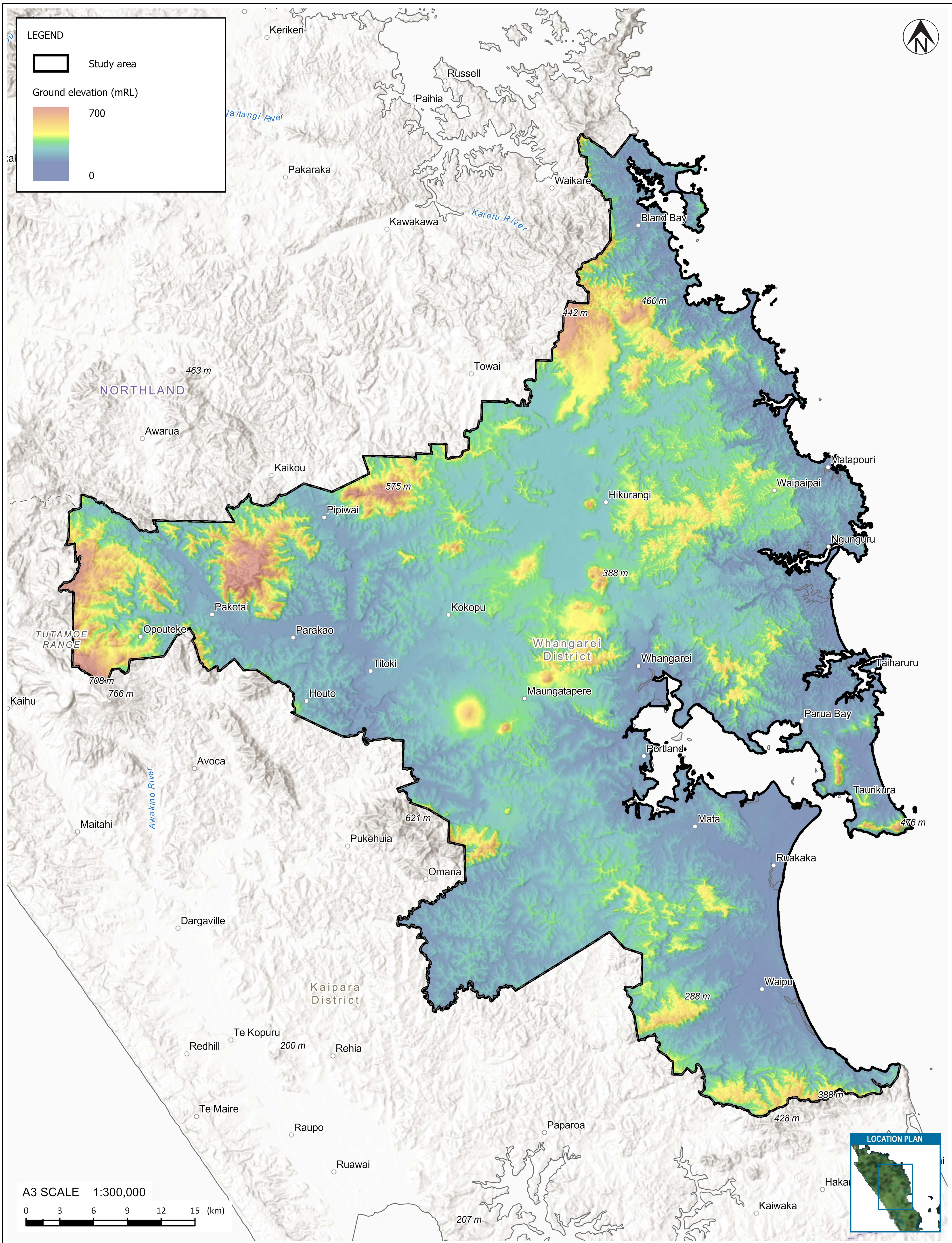

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TITLE GROUND SURFACE ELEVATION (2019 LIDAR SURVEY)

SCALE (A3) 1:300,000 FIG No. FIGURE A2 REV 0

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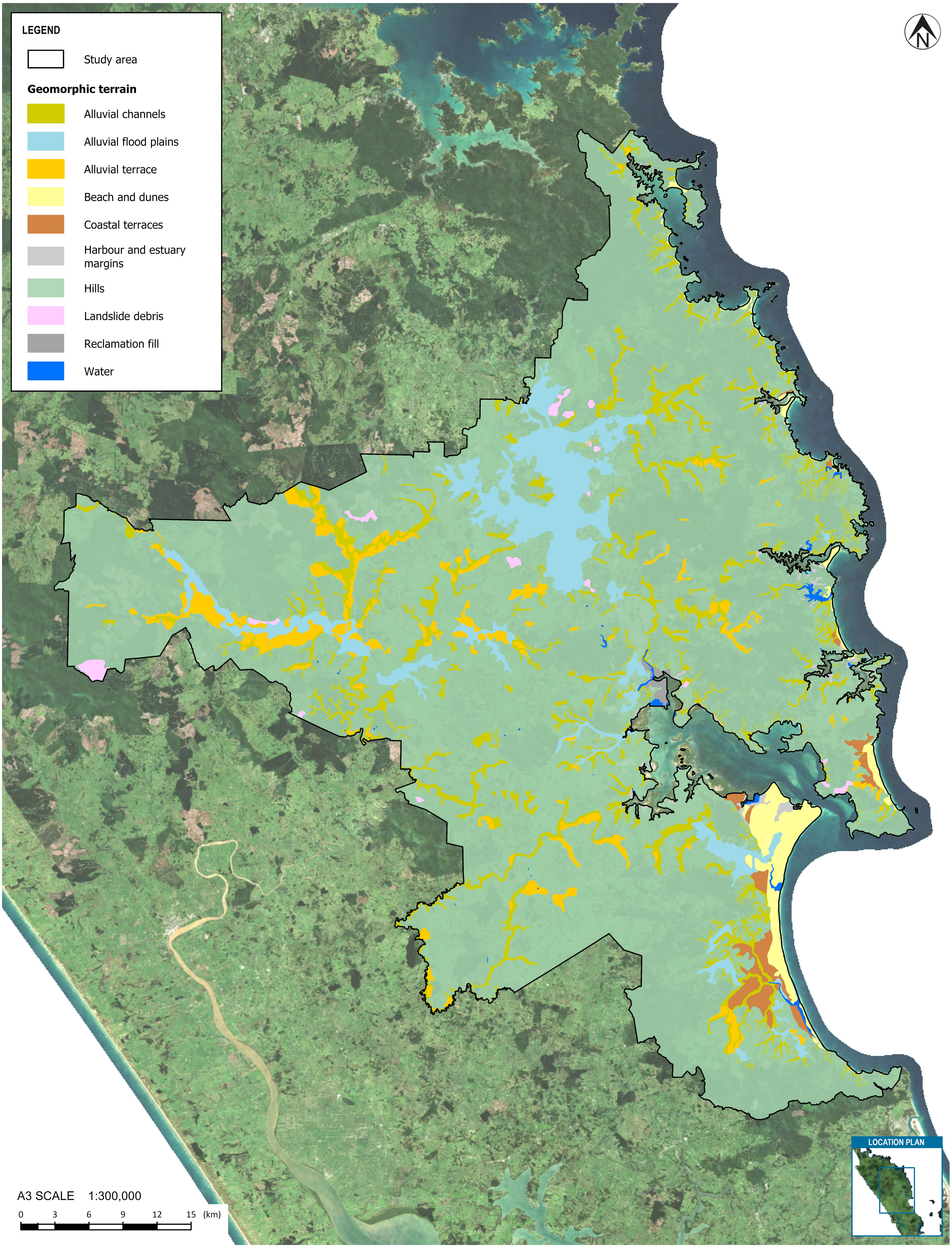
Appendix A Table A1: Simplified geological model of Whangarei District

Geological Unit	Main rock types	Age (Ma)[1]	Depositional environment	Typical extent in Whangarei District
Landslide Debris	Colluvium	Recent	Sloping land throughout the district where land instability occurred.	Landslides have been mapped on sloping land throughout the district, occurring on various older geological units.
Reclamation Fill	Clays, sands and gravels	Recent	Man-made construction fill or land reclamation in areas typically around the harbour at the port, that are likely to have been dredged from the Whangarei Harbour.	The main area of this unit is located at the port in Whangarei. Other areas have been identified at dams and landfills.
Tauranga Group	Silt, sands, gravels and local peat	Early Pleistocene to Holocene 1.8 Ma to Present	Alluvial deposits along stream/river channels, flood plains and gullies, typically relating to river sediment deposition or erosional processes from hillsides.	These units cover the majority of the region in flood plains, alluvial channels, gullies in the hills and incorporate alluvial terraces.
Karioitahi Group	Beach and dune sands	Early Pleistocene to Holocene 1.8 Ma to present	Dune complexes formed as sea level remained steady in the region and sands were deposited along the coastline. Older dunes are inland of the current coastline, with active sand dunes and beaches along the coast, either in bays between headlands or long beaches.	These units are typically observed along the eastern coastline and within the harbour.
Kerikeri Volcanic Group	Basalts and scoria cones	Late Miocene to Quaternary 11.2-1.8 Ma	Volcanism occurred in the Northland Volcanic Arc as a result of subduction of the Pacific Plate beneath the Australian Plate. Uplift of the existing land resulted in deposition of volcanic sediments on the existing landforms.	These volcanic deposits are typically located in the central parts of the region, and are typically identified capping the hills.
Coromandel Group	Rhyolite domes	Early to Middle Miocene 23.8-11.2 Ma	Volcanism occurred in the Northland Volcanic Arc as a result of subduction of the Pacific Plate beneath the Australian Plate. Uplift of the existing land resulted in deposition of volcanic sediments on the existing landforms.	These volcanic deposits are located in the Whangarei Heads region.
Waitemata Group	Sandstone	Late Eocene to late Oligocene 23.8-11.2 Ma	These units were formed in a deep marine environment of the Northland Basin, and are found beneath, within and on top of the Northland Allochthon sediments.	This unit is typically located to the south of the region, adjacent to Te Kuiti Group and Waipapa Group rocks.
Northland Allochthon	Marine sandstone and mudstone	Early Cretaceous to Miocene 145-23.8 Ma	The Northland Allochthon units were originally deposited in marine environments to the north-east of the area, and were tectonically emplaced in thrust slices into the Northland Basin over the region as the basin likely subsided.	These units cover the majority of the western part of the region, with some traces of these units to the east and along the coastline.
Unconformity – emplacement of Northland Allochthon				
Te Kuiti Group	Limestone	Late Eocene to late Oligocene 55.5-23.8 Ma	Swamp deposits formed at the start of a period of continental extension and subsidence in the region, which resulted in rising sea levels. As the sea level rose or land subsided, marine sediments were deposited over the area.	These rocks are observed to the west of the Waipapa Group rocks, in the centre of the region.
Regional Unconformity				
Waipapa Group	Greywacke	Permian to Jurassic 299-145.5 Ma	The sandstone likely accumulated on the ocean floor along the eastern margin of Gondwanaland, which became accreted onto the continental margin as part of an arc-trench complex resulting in metamorphism and uplift.	These rocks form the hills in the east of the region, north of the Whangarei Harbour, with some outcrops to the south of the Harbour.

[1] Ma = Million years, inferred from Edbrooke & Brooke (2009)



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TITLE GEOMORPHOLOGY MAP
SCALE (A3) 1:300,000 FIG No. FIGURE A3 REV 0

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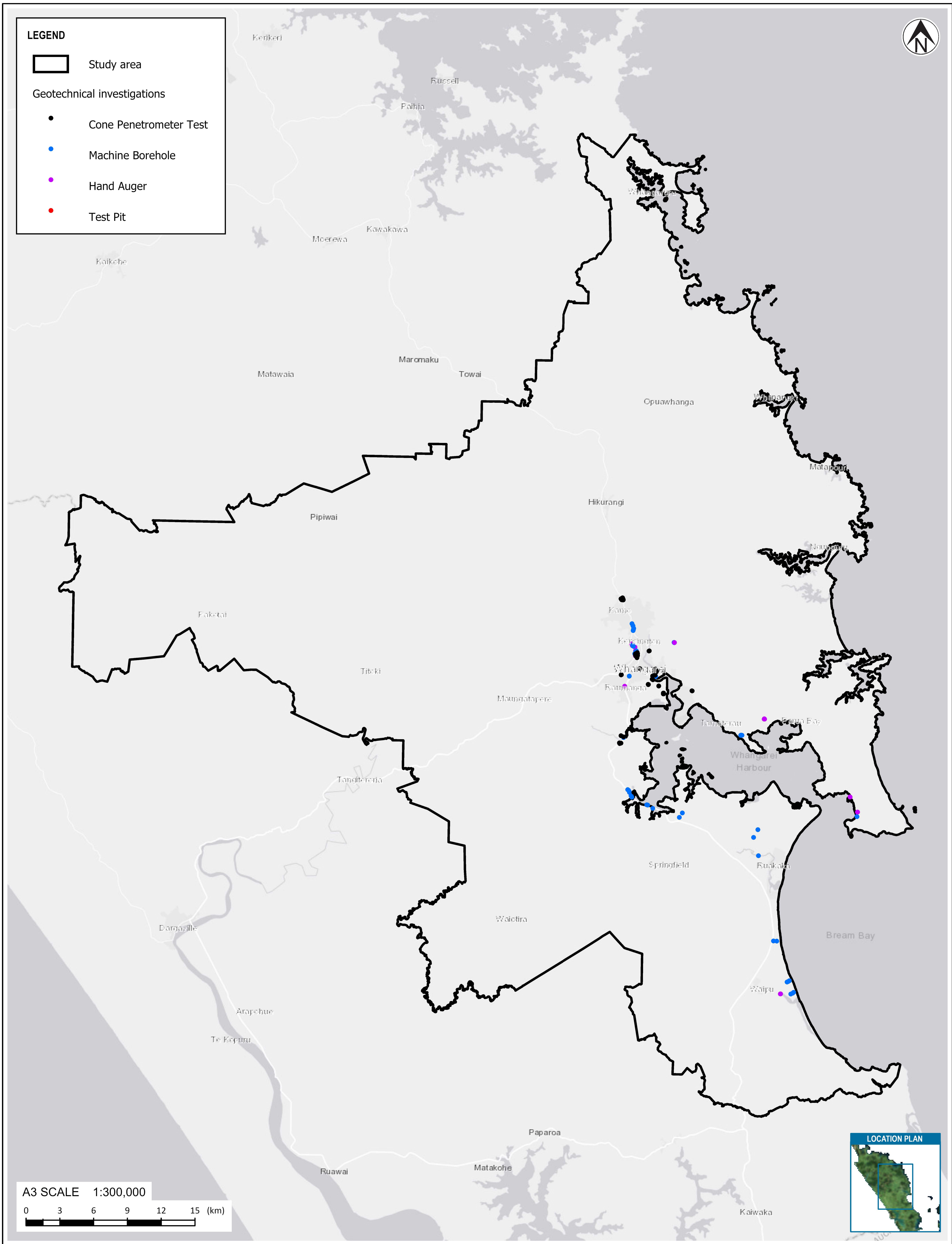
Appendix A Table A2: Description of geomorphic terrains shown in Figure A3

High level environment	Terrain Code	Colour	Geomorphic Terrain	Landform description
Reclamation Fill	RL		Reclamation Fill	Variable landforms associated with coastal reclamation around harbour and estuary margins, based on previous mapping by others[1] or historic aerial mapping.
Landslide Debris	LS		Landslide Debris	Landforms with hummocky, gently to steeply sloping topography mapped as landslides. These areas are based on mapping by others from a range of sources [1,2,3] and are not expected to be a complete record of all landslides in the area.
Alluvial	AC		Alluvial Channels	The base of valleys and channels, typically where alluvium and potentially colluvium has accumulated. Alluvial channels have narrow valley floors relative to the alluvial flood plains which are wider.
	AF		Alluvial Flood Plains	Flat to gently sloping topography on plains and wide valley floors, typically dominated by alluvial processes. Wetlands and swamps are also included.
	AT		Alluvial Terraces	Elevated terraces above the current alluvial channels and floodplains. The terraces typically comprising Pleistocene-age or older alluvium and colluvium.
Coastal	BD		Beach/dunes	Coastal landforms associated with beach and sand dune processes, both active and relict. Found along the eastern coastline.
	HE		Harbour and Estuary Margins	Low-lying areas surrounding the present-day shoreline of the coastal margins and harbours, typically influenced by low energy estuarine and tidal processes.
	CT		Coastal Terraces	Terraced land along the coastal margin approximately 3 m above the current sea level.
Hills	HS		Hills	Elevated landforms characterised by highly dissected hills with many gullies, as well as hills that are more rolling in nature, depending on the underlying geological units. Isolated cone or dome shaped landforms can represent hills of volcanic origin such as scoria cones.

1. Edbrooke SW & Brook FJ (compilers) 2009. *Geology of the Whangarei Area*. Institute of Geological & Nuclear Sciences 1:250,000 Geological Map 2.
2. White PJ & Perrin ND 2003. *Geology of the Whangarei Urban Area*. Institute of Geological & Nuclear Sciences 1:25,000 Geological Map 26
3. GNS Landslide Database accessed from https://data.gns.cri.nz/landslides/wms.html



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Geotechnical investigations: sourced from the New Zealand Geotechnical database.
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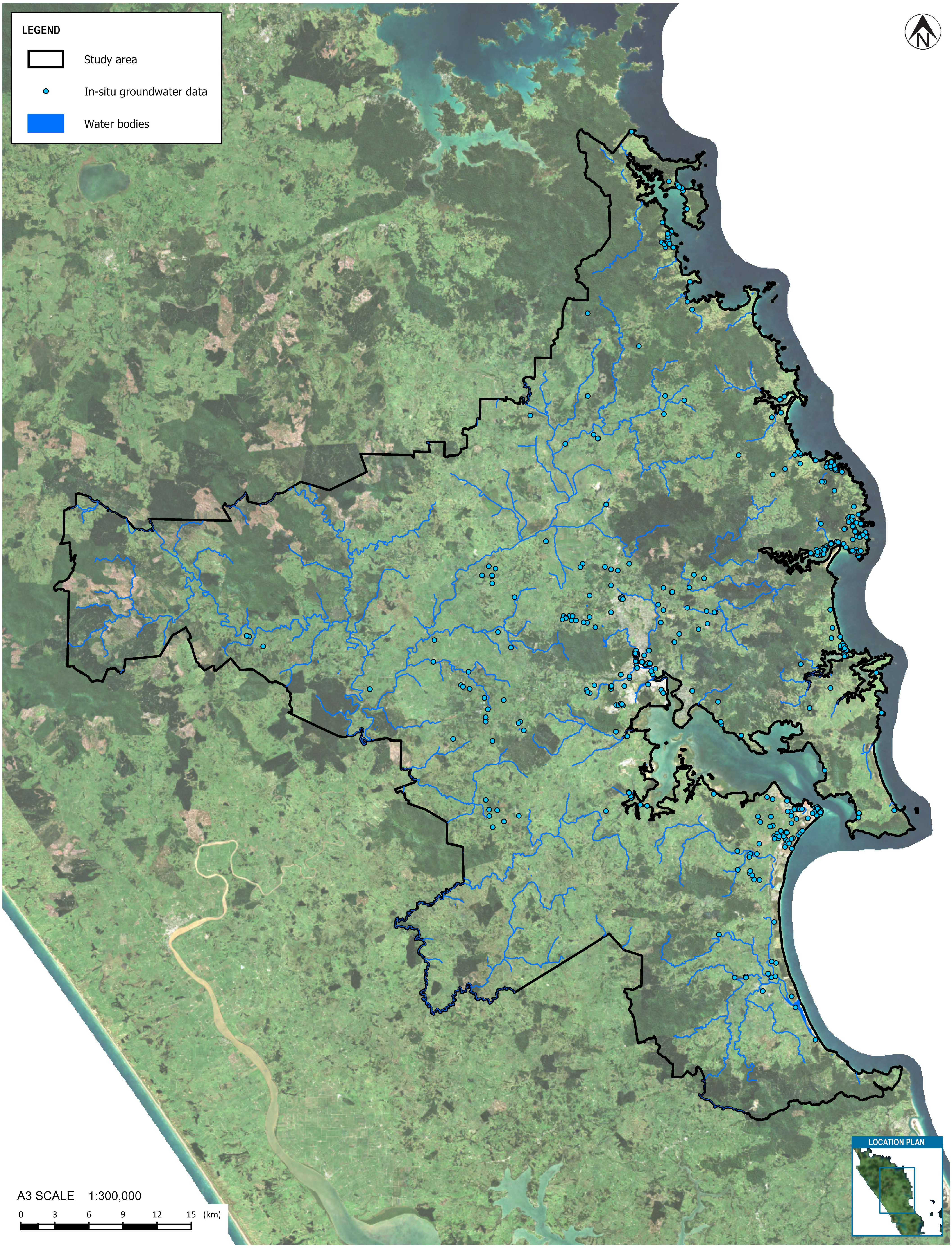
SCALE (A3) 1:300,000 FIG No. FIGURE A4 REV 0



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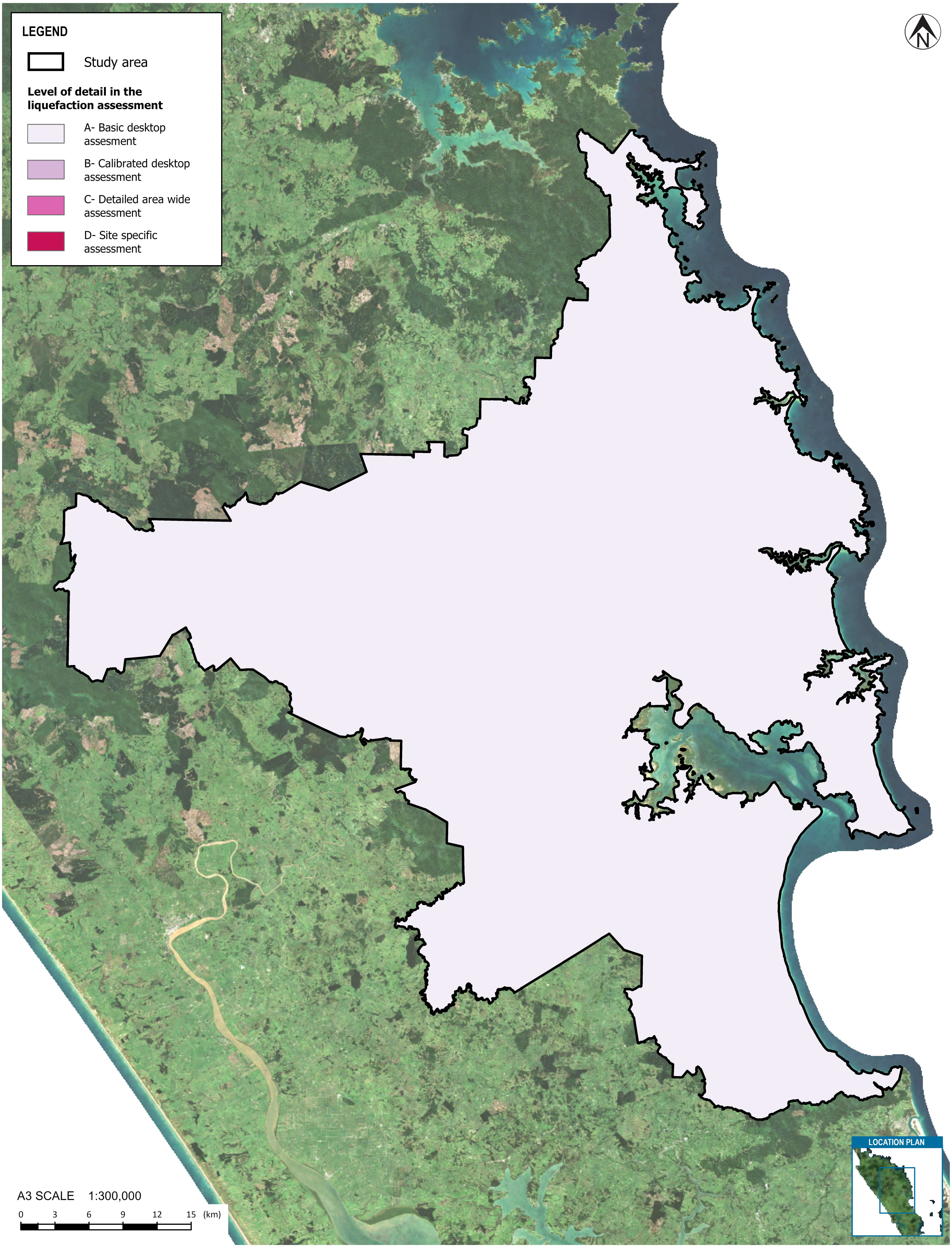
PROJECT LIQUEFACTION VULNERABILITY MAPPING
TITLE SHALLOW GROUNDWATER MONITORING LOCATIONS

SCALE (A3) 1:300,000 FIG No. FIGURE A5 REV 0



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Map indicates the level of detail in the liquefaction assessment that is supported by current available base information. Refer to Table 3.3 of the MBIE Guidelines (2017) for further information about the detail in the liquefaction assessment.
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TITLE	LEVEL OF DETAIL SUPPORTED BY THE CURRENTLY AVAILABLE BASE INFORMATION
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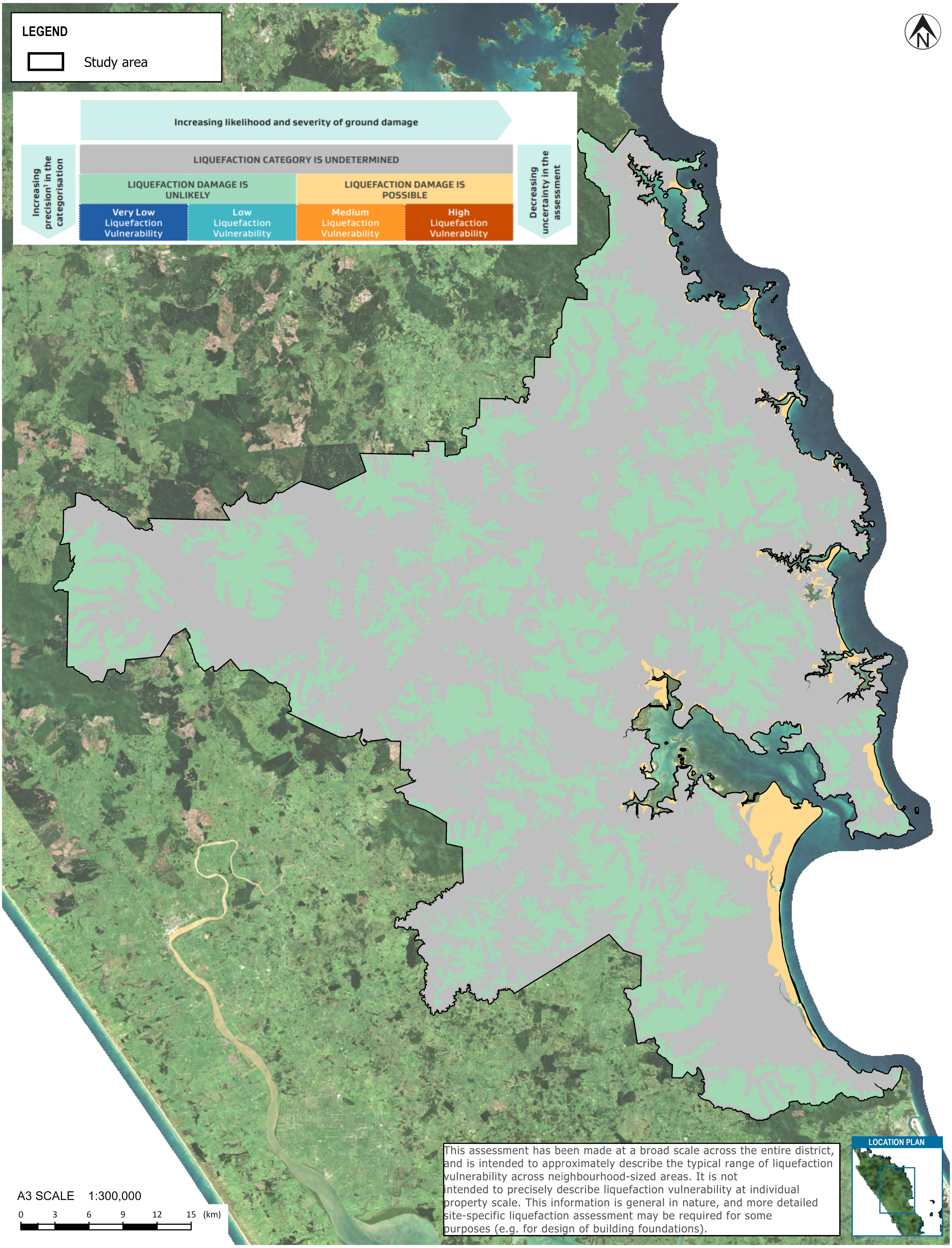
Appendix B: Risk analysis

- **Figure B1 – Mapped liquefaction vulnerability categories**



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TITLE LIQUEFACTION VULNERABILITY CATEGORIES

SCALE (A3) 1:300,000 FIG No. FIGURE B1 REV 0

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