Auckland Liquefaction Assessment

Technical Report TR2021/19

November 2021

Cover photo: Jay Farnworth

Auckland Liquefaction Assessment

November 2021
Auckland Council
Technical Report TR2021/19

ISSN 2230-4533 (Online)

ISBN 978-1-99-100282-2 (PDF)

Reviewed and recommended for publication by:

Name: Branko Veljanovski

Position: Head of Engineering Design and Asset Management, Resilient Land and Coasts

Approved for publication by:

Name: Paul Klinac

Position: General Manager, Resilient Land and Coasts

Recommended citation:

Brightman, C and R Roberts (2021). Auckland liquefaction assessment. Auckland Council technical report, TR2021/19

© 2021 Auckland Council, New Zealand

Auckland Council disclaims any liability whatsoever in connection with any action taken in reliance of this document for any error, deficiency, flaw or omission contained in it.

This document is licensed for re-use under the Creative Commons Attribution 4.0 International licence.

In summary, you are free to copy, distribute and adapt the material, as long as you attribute it to the Auckland Council and abide by the other licence terms.

Acknowledgements

This document was prepared with technical input from Auckland Council and industry experts including the following individuals:

Author

Charlie Brightman

Authors (Liquefaction Vulnerability Maps for the Auckland Region Report - Appendix C)

Omer Altaf, Liam Wotherspoon, Rolando Orense

Contributors

Ross Roberts

Thanks are extended to industry professional who contributed to this document, Greg Pinches and the authors of the Liquefaction Vulnerability Maps for the Auckland Region report, on which this the summary report is based.

Thanks also to Auckland Council staff, both past and present, and industry experts who contributed to the development of the Liquefaction Vulnerability Maps. The project team acknowledges the work undertaken by many individuals and organisations over the years to provide technical content for this document.

Contents

Figures

Tables

Abbreviations

Acronym	Definition
BCA	Building Consent Authority
CPT	Cone penetration test
DEM	Digital elevation model
EQC	Earthquake Commission
GIS	Geographic information system
MBIE	Ministry of Business, Innovation and Employment
MfE	Ministry for the Environment
MSF	Magnitude scaling factor
PGA	Peak ground acceleration
RMA	Resource Management Act
TA	Territorial Authority

Executive Summary

Liquefaction occurring beneath buildings and other structures can cause major damage during earthquakes. Although Auckland is, relative to most of New Zealand, a low-risk area for ground shaking, this hazard does exist in our region.

In response to lessons from the Canterbury earthquakes, in 2019 the Ministry of Business, Innovation and Employment (MBIE) advised all New Zealand councils to undertake hazard mapping to identity liquefaction-prone areas. MBIE advised that these regional hazard maps should be prepared in advance of changes to the Building Code coming into effect after 28 November 2021.

To satisfy this requirement, maps of liquefaction vulnerability categories for the Auckland region have been produced and are available on the Auckland Council GeoMaps service. The maps were developed to inform RMA and Building Act planning and consenting processes. This report presents the methodology used to prepare these maps and summarises how the maps are expected to be used.

These maps have been prepared in accordance with the guidance published by MBIE in 2017, '*Planning and engineering guidance for potentially liquefaction-prone land*'[1]. This document proposed four levels of detail for liquefaction assessment studies:

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

Data availability defined the level of assessment detail that was appropriate across the Auckland region based on the guidance. At the highest level of assessment (Level A), the assessment is based on geological, groundwater and seismic hazard data.

To refine the Level A classification, qualitative screening was carried out using geotechnical investigation and topographic data (Level B) in areas where sufficient data was available.

It is expected that these levels of detail will be sufficient for many purposes. For some developments, a more detailed Level C or D assessment may be required. This would normally be undertaken by a developer as part of their consent application.

[1] MBIE/MfE/EQC 2017

1.0 Introduction

1.1 Technical background

Liquefaction occurring beneath buildings and other structures can cause major damage during earthquakes.

Liquefaction is the process which causes soil to behave more like a liquid than a solid during an earthquake. The shaking rearranges sand and silt grains in the soil, and the water between the grains is squeezed. Pressure builds up until the soil loses all its strength. Water (laden with sand and silt) is forced up to the surface through the easiest path it can find, often through cracks in the ground or concrete. The rising water takes silt and sand with it, forming sand boils or volcanos. The ground surface above liquefied soil often tilts and sinks, damaging buildings, roads, pipes and tanks.

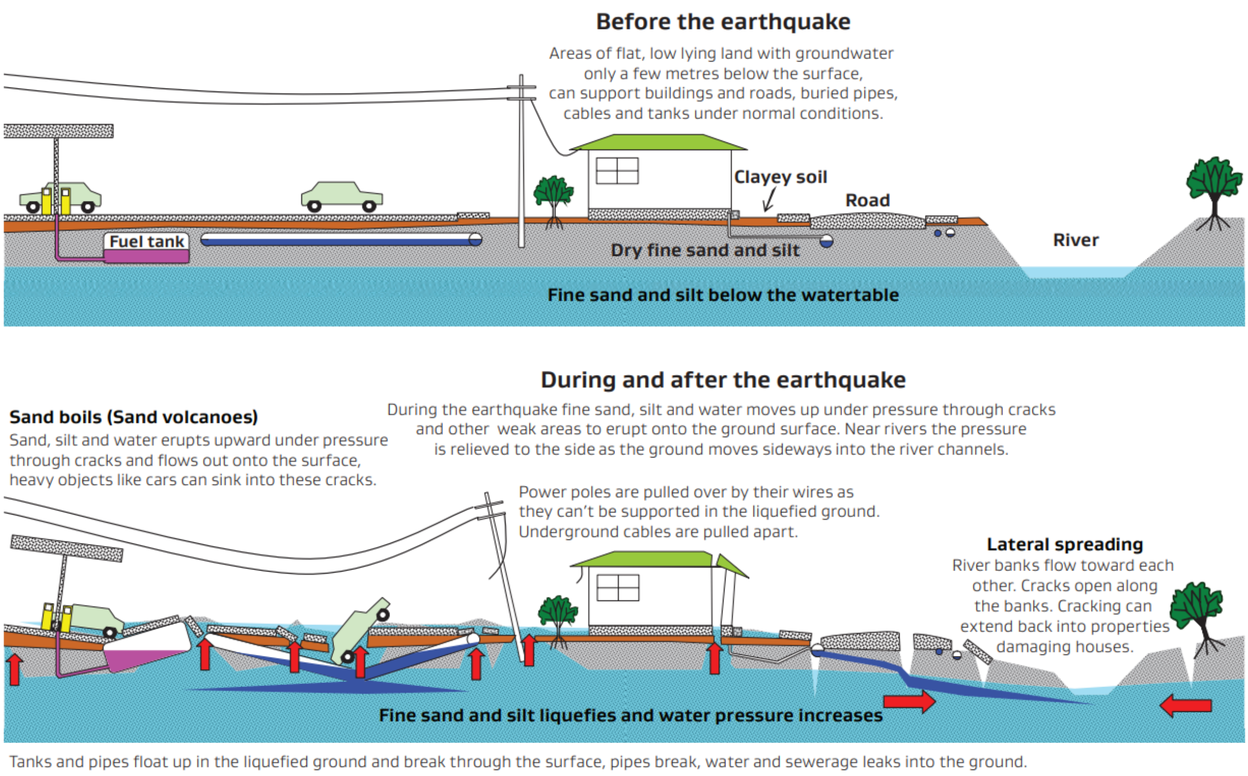


Figure 1: Illustration of liquefaction and its effects. Source: IPENZ technical fact sheet Liquefaction, 2012

Whether liquefaction can occur depends on the geological conditions. Soils that are sandy or silty, loose, and wet (below the water table) are most likely to liquefy. Clay and gravel tend not to liquefy.

Liquefaction usually only happens in susceptible soils in moderate to strong ground shaking (when it is difficult to stand up, things are being moved around, and buildings and infrastructure are being damaged).

Figure 2: Liquefaction caused by the 2010–11 Canterbury earthquakes created large holes in streets around Christchurch. This car toppled into a hole near Shortland Street in the suburb of Aranui following the 22 February 2011 earthquake. Source: Te Ara (the Encyclopaedia of New Zealand)

1.2 Legislative background

In November 2019, the Ministry of Business, Innovation and Employment (MBIE) made a change to Acceptable Solution B1/AS1 preventing it from being used on liquefaction-prone ground. This change takes effect from 29 November 2021. The change was made as a result of the experience of the Canterbury earthquakes, and subsequent recommendations made by the Royal Commission of Inquiry.

The change to B1/AS1 was intended to help those building on liquefaction-prone ground select foundations for residential homes. The change also revoked the use of a 'deemed to comply' pathway for foundations unless the ground has been assessed and/or categorised as not being liquefaction-prone, i.e. 'good ground'.

To ensure readiness for this change, councils were advised to undertake hazard mapping and identity liquefaction-prone areas. MBIE advised that these regional hazard maps should be prepared using the Ministry of Business, Innovation and Employment (MBIE) / Ministry for the Environment (MfE) liquefaction mapping guidance to allow a smooth transition for this change coming into effect after 28 November 2021.

MBIE advised that these maps will typically be published in one of the following forms:

- Maps that are prepared to capture knowledge and understanding of natural hazard processes in a particular area or location (hazard maps)
- Maps that contain information about management responses or controls for a particular area or location (hazard management maps).

Auckland Council has adopted the hazard maps approach.

1.3 Purpose of this report

This report summarises the methodology used in the Auckland Council liquefaction vulnerability assessment and has been issued to support the GIS maps made available at the same time. The study area comprises the Auckland Council administered region. This report presents a summary of the following information for the study area:

- Geological and geotechnical conditions
- Near-surface groundwater characteristics
- Seismic shaking hazard
- An assessment of the likelihood of liquefaction-induced land damage based on the above information.

1.4 Scope of work

The work presented in this report comprises the collation of readily available data within the study area to inform a liquefaction vulnerability assessment based on the publication '*Planning and engineering guidance for potentially liquefaction-prone land*'[2]. This is referred to as the MBIE / MfE Guidance throughout the remainder of this report. The extent of the study area is summarised in Figure 3.

The following data was collated to inform this study:

- Geological maps published by GNS Science
- Digital elevation model data from Auckland Council
- Geotechnical site investigation data from the New Zealand Geotechnical Database and from the Tonkin + Taylor in-house geotechnical database
- Groundwater information from hydrologic observation wells and geotechnical sources from the New Zealand Geotechnical Database and from the Tonkin + Taylor in-house geotechnical database.

[2] MBIE/MfE/EQC 2017

The extent and quality of available data was used to inform the appropriate level of assessment detail across the study area based on the MBIE / MfE Guidance. Liquefaction vulnerability categories have been assigned using geological, groundwater and seismic hazard data through a high-level assessment for the Auckland region. Qualitative calibration using geotechnical investigations and a regional digital elevation model inform this high-level assessment.

The output of this work is a GIS map of liquefaction vulnerability categories for the study area based on geology, with this supporting report.

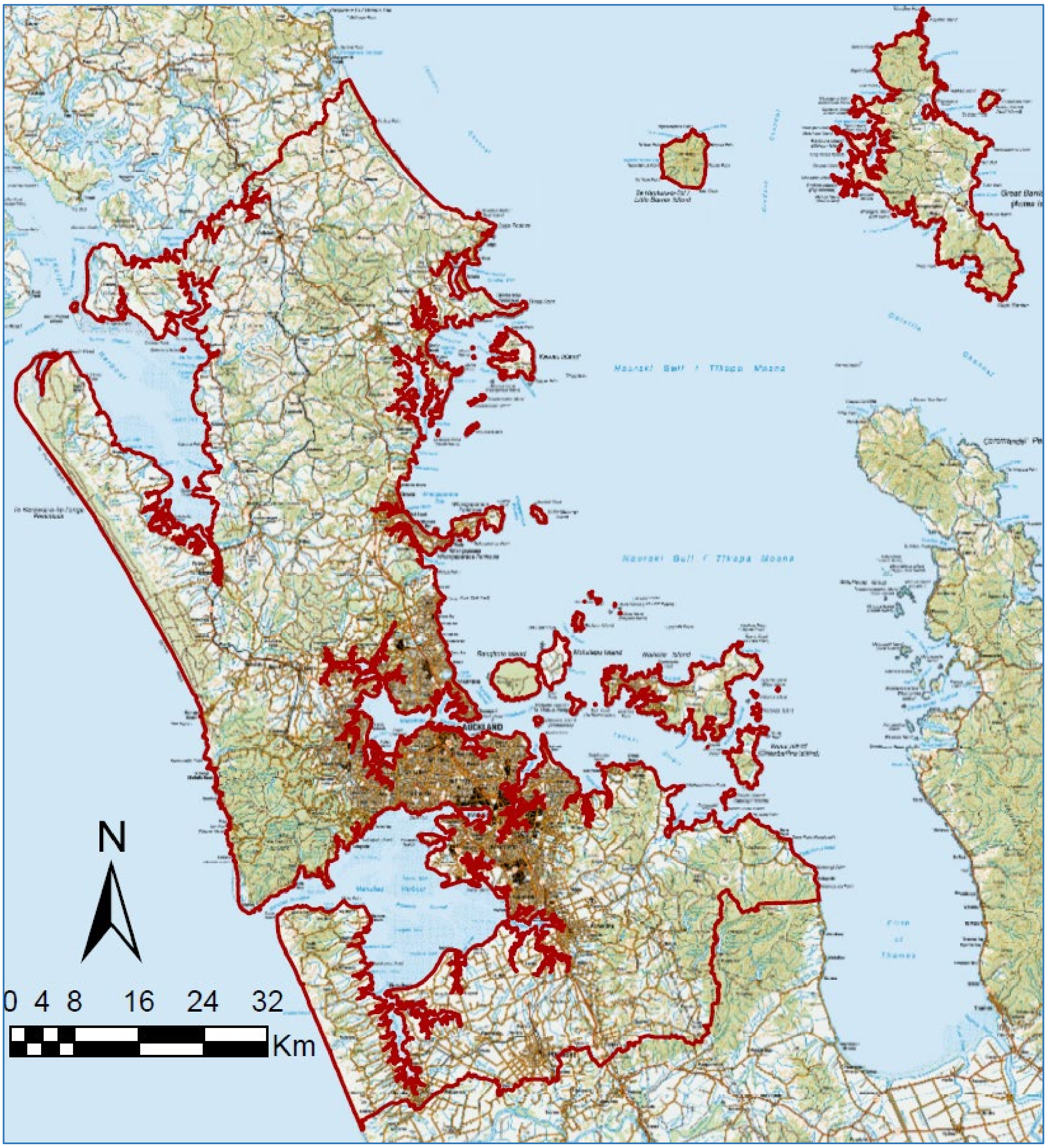


Figure 3: Geographic location and extent of the study area - Auckland Council region

1.5 How these maps may be used

There are numerous ways information about the potential for liquefaction-induced ground damage might be used, for example:

- Long-term strategic land use 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 lifeline resilience
- Civil defence and emergency management planning
- Catastrophe loss modelling for insurance, disaster risk reduction and recovery planning.

The maps presented on Auckland Council's GeoMaps were developed to inform RMA and Building Act planning and consenting processes.

1.5.1 Use of these maps for building consent applications

These maps can be used to support building consent applications by enabling developers to identify whether sufficient data exists to make an assessment of the liquefaction vulnerability of a site.

MBIE developed the process shown in the flowchart below, and this is defined in more detail in the following sections.

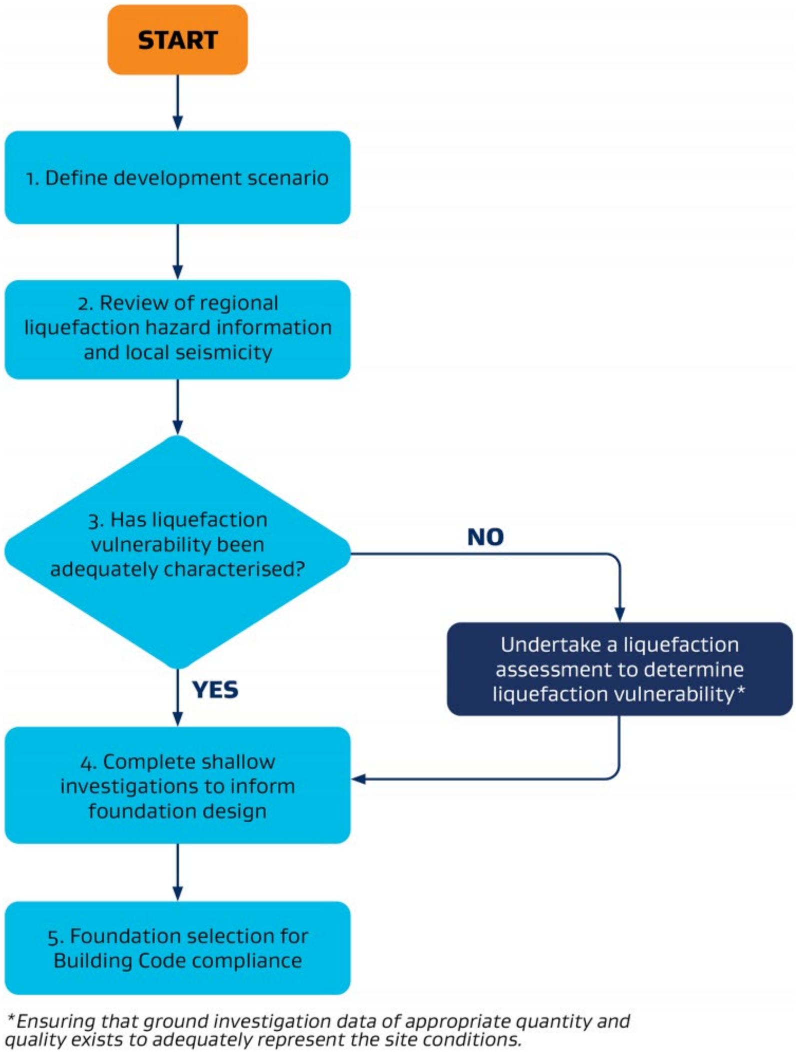


Figure 4: Overview of the recommended process to determine liquefaction vulnerability at building consent stage. Retrieved from https://www.building.govt.nz/building-code-compliance/geotechnical-education/ensuring-new-buildings-can-withstand-liquefaction-risks/

1.5.2 Step 1 – Define the development scenario

The development scenarios are presented below. The various development scenarios have been separated into categories based on the level of capital investment and total exposure to a single event. The assessment levels are indicative only. Designers, engineers and BCAs/TAs should apply discretion when undertaking geotechnical investigation and design review.

Note: Please refer to all the footnotes as prescribed under Table 3.7 on page 26 of MBIE / MfE Guidance.

STEP 1 – Define development scenario (refer to Table 3.7 of MBIE/MfE Guidence (2017)

Increasing likelihood and severity of ground damage →

Increasing new capital investment and total exposure to a single event ↓

	LIQUEFACTION VULNERABILITY CATEGORY			
	LIQUEFACTION CATEGORY IS UNDETERMINED			
	LIQUEFACTION DAMAGE IS UNLIKELY		LIQUEFACTION DAMAGE IS POSSIBLE	
DEVELOPMENT SCENARIO[2]	Very Low	Low	Medium	High
Sparsely populated rural area (lot size more than 4 Ha) eg A new farm building	Level A	Level A	Level A	Level A
Rural-residential setting (lot size of 1 to 4 Ha) eg A 'lifestyle' property	Level A	Level B	Level B	Level B
Small-scale urban infill (original lot size less than 2500 m2) eg Demolish old house and replace with four townhouses	Level B	Level B	Level B	Level D
Commercial or industrial development[7] eg A warehouse building in an industrial park	Level B	Level B	Level C	Level D
Urban residential development (lot size less than 1 Ha; typically <1000 m2) eg Home in a new subdivision	Level B	Level C	Level C	Level D

Figure 5: Defining the development scenario. Retrieved from https://www.building.govt.nz/building-code-compliance/geotechnical-education/ensuring-new-buildings-can-withstand-liquefaction-risks

1.5.3 Step 2 – Review of regional liquefaction hazard information and local seismicity

See Auckland Council GeoMaps to identify which level assessment has been undertaken for your site, and to confirm the liquefaction vulnerability category that has been applied.

1.5.4 Step 3 – Identify if liquefaction assessment is required

The following flowchart was provided by MBIE to identify if further assessment is required. The iterative process to provide a liquefaction vulnerability category is to continually refine the liquefaction assessment to the next higher level of detail until a vulnerability category can be confirmed with sufficient detail for the purpose of demonstrating compliance with the performance objectives of the Building Code.

Because Level A (and in some areas Level B) assessments have already been carried out by Auckland Council there is no need to repeat these high-level assessments unless new information is available which renders the existing maps obsolete.

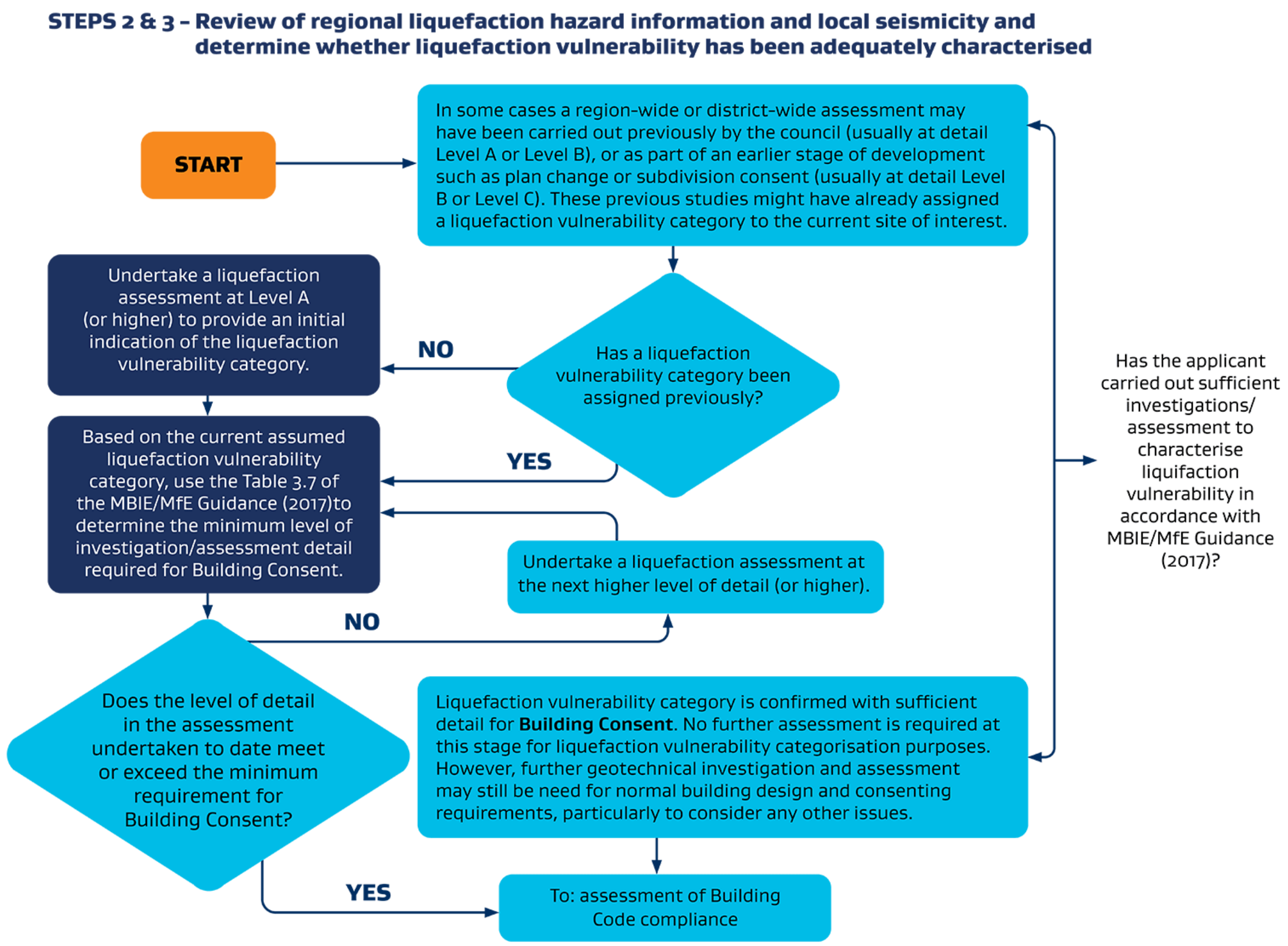


Figure 6: Defining liquefaction vulnerability. Retrieved from https://www.building.govt.nz/building-code-compliance/geotechnical-education/ensuring-new-buildings-can-withstand-liquefaction-risks

1.5.5 Step 4 – Ground investigation

A ground investigation is likely to be required for foundation design and may also be required to increase the data available for sites where a more detailed liquefaction assessment is required. Section 3.4 of the MBIE / MfE Guidance provides recommendations for ground investigation density for liquefaction assessments.

These recommendations are minimums for liquefaction assessment; additional investigation may be required for other purposes such as foundation design. Reasonable inquiry is expected to include shallow investigations, as a minimum, to establish the near surface ground conditions, bearing capacity and depth to groundwater.

Further information on appropriate ground investigation is available in the Auckland Council Code of Practice for Land Development Chapter 2 (Earthworks and Geotechnical).

1.5.6 Step 5 – Foundation selection

Where the local seismicity is low, and regional mapping has been completed to a low level of precision (i.e. *liquefaction damage is possible*, *liquefaction damage is unlikely*) and reasonable inquiry confirms that liquefaction risk is unlikely to exceed a 'medium' vulnerability class; MBIE recommends that foundation options outlined within Section 5.3.4 of the Canterbury Guidance be adopted (i.e. TC2 foundation options).

Figure 7 shows how the liquefaction vulnerability classes can be used to select foundation options presented within the MBIE Canterbury Guidance (i.e. TC1, TC2 and TC3 foundations). Subject to project requirements, additional investigation and specialist geotechnical input may be appropriate to assess whether a more optimised foundation solution can be adopted.

Residential Building Consent Pathway (small scale urban infill or minor alterations)

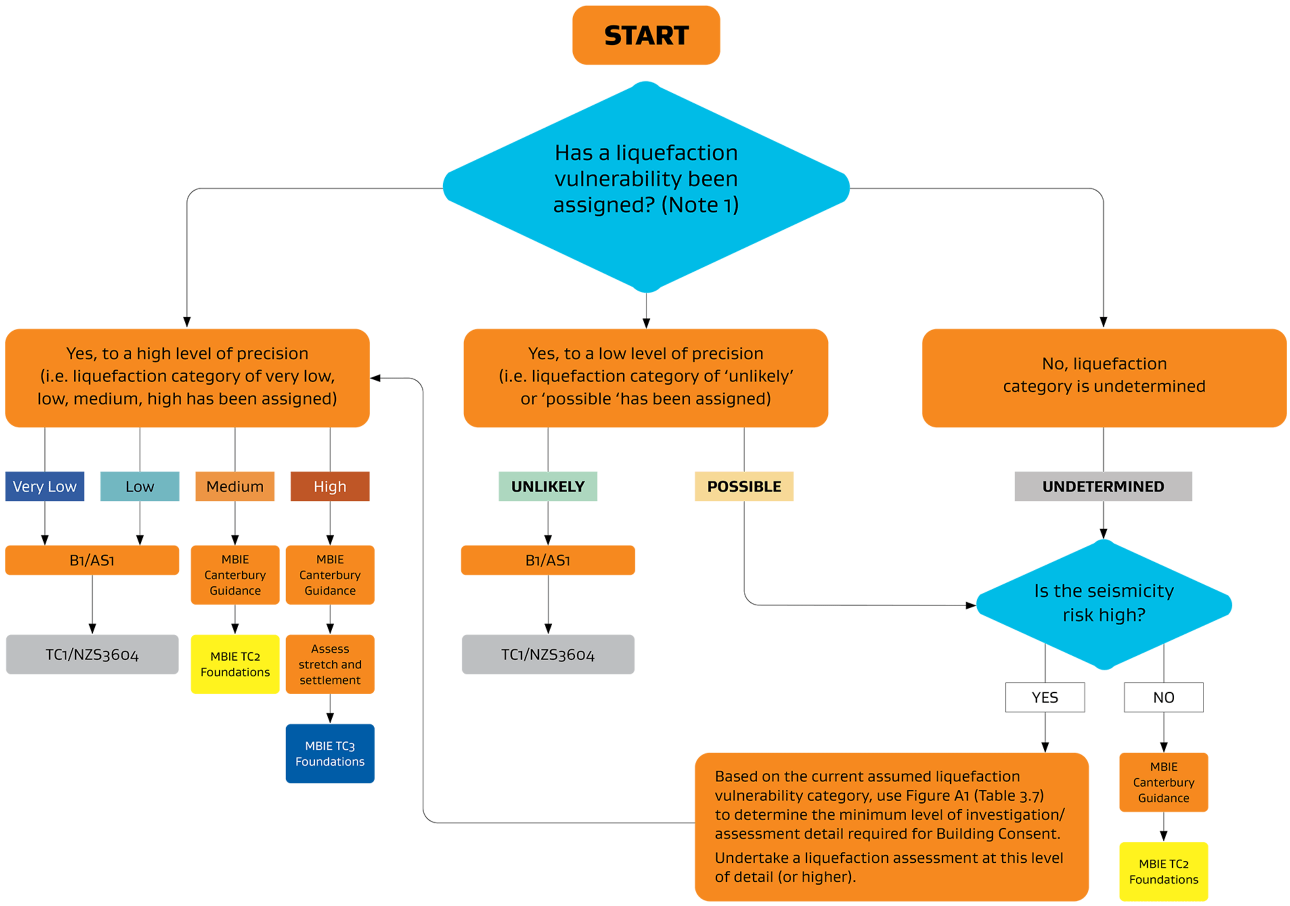


Figure 7: Residential Building Consent Pathway for small scale urban infill or minor alterations. Retrieved from https://www.building.govt.nz/building-code-compliance/geotechnical-education/ensuring-new-buildings-can-withstand-liquefaction-risks/

Geotechnical investigation and professional input should inform foundation design for sites subject to 'medium' and 'high' liquefaction potential.

2.0 Methodology

The methodology presented in the MBIE / MfE Guidance (summarised in Figure 8) was applied to develop liquefaction vulnerability categories for the Auckland region. Liquefaction vulnerability categories are based on performance criteria that relate a category to the probability of different levels of liquefaction-induced ground damage severity for a given return period of ground shaking.

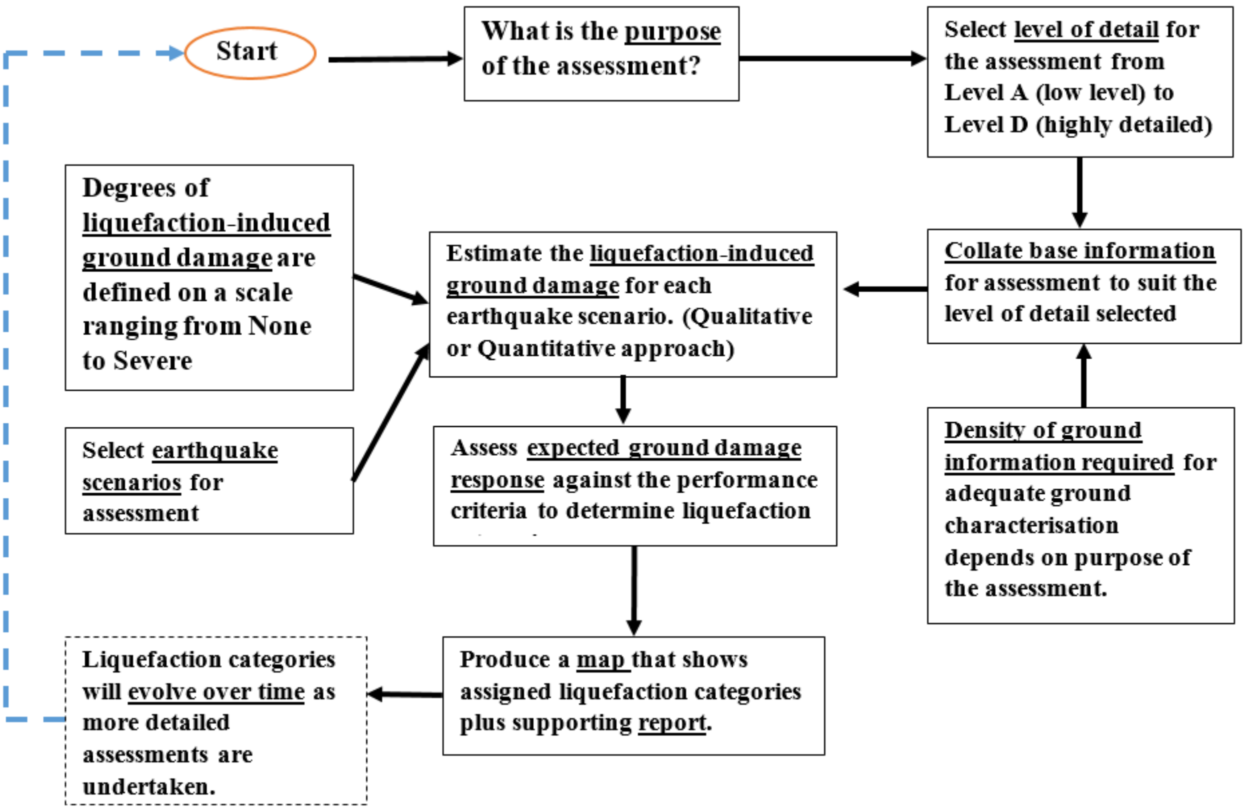


Figure 8: Overview of the recommended process for categorizing the potential for liquefaction-induced ground damage (MBIE / MfE Guidance)

Figure 9 summarises the different levels of detail of the liquefaction assessment approach from the MBIE / MfE Guidance. Two levels of assessment have been undertaken and are presented in this study:

- Level A - basic desktop assessment (full Auckland region)
- Level B - calibrated desktop assessment (localised areas within Auckland where appropriate data was available).

The liquefaction vulnerability categories assigned in each level of assessment are summarised in Figure 10. As the spatial density of available information increases, the precision of categorisation can increase.

The default vulnerability category is "*Liquefaction Category is Undetermined*". This is assigned to areas where a liquefaction assessment has yet to be undertaken, or if there is not enough information to define an appropriate category. The remaining categories are defined based on the probability of different ground damage severities for 500-year return period ground shaking, and in some cases, 100-year return period ground shaking. When undertaking a liquefaction assessment using a desktop approach, it is typical to focus on whether liquefaction damage is unlikely, where there is a greater than 85% probability of none-minor ground damage for a 500-year event, or liquefaction damage is possible, where there is a greater than 15% probability of minor-moderate ground damage for a 500-year event.

For Level A and Level B assessments, it is often not possible to assign liquefaction vulnerability categories with any more precision than this. In some cases, a more precise category can be assigned with confidence, such as a '*Very Low*' category for exposed rock outcrops. Due to the large extent of the study area and lack of required density of geotechnical investigation data across most of the region, liquefaction vulnerability maps can only be produced based on Level A and B assessments.

The probabilities used as part of the liquefaction vulnerability assessment are intended to be a general guidance framework rather than targets for a specific calculation. They are used along with qualitative and quantitative estimates of the uncertainty associated with the input data used to define an appropriate liquefaction vulnerability category. This is discussed in relation to each level of assessment applied in this report.

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 9: Levels of detail for liquefaction assessment studies (MBIE / MfE Guidance)

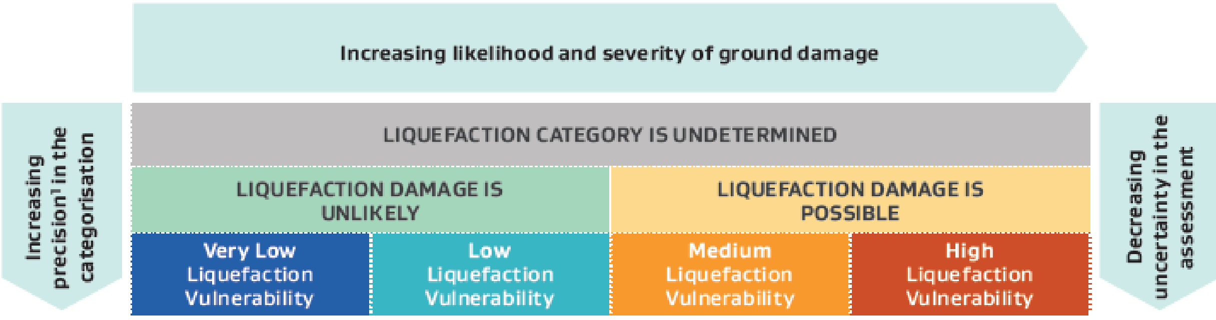


Figure 10: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform the planning and consenting process (MBIE / MfE Guidance)

2.1 'Level A' assessment

The Level A assessment is a basic desktop study that utilises surface geology, groundwater and seismic hazard characteristics to classify the liquefaction potential. One of the primary focuses of this assessment is to identify land where liquefaction damage is unlikely so that it can be removed from further assessment. Where there is enough confidence in the available data, the remaining areas can be classified as '*Liquefaction damage is possible*'. Areas where there is not enough information to determine an appropriate category can be classified as '*Liquefaction category is undetermined*'.

Potentially liquefiable deposits are defined based on the classification by Youd & Perkins (1978) and other researchers[3]. This geology-based classification considers the regional seismic hazard and the depth to groundwater in conjunction with the age and depositional processes that formed the soil deposits. A semi-quantitative screening criterion illustrated in Table 1 is used in the MBIE / MfE Guidance to identify geological units where liquefaction-induced ground damage is unlikely to occur. A specific soil deposit can be assigned a liquefaction vulnerability category of '*Liquefaction damage is unlikely*' if the 500-year return period peak ground acceleration (PGA) is less than the value listed, or if the depth to groundwater is greater than the value listed. The listed PGA values in Table 1 correspond to a moment magnitude (Mw) 7.5 earthquake. For screening purposes using this table, earthquake scenarios with different magnitudes may be scaled using the magnitude scaling factor (MSF) proposed by Boulanger and Idriss (2008):

$$MSF = [6.9 \exp(-Mw/4) - 0.058], \text{ up to a maximum value of } 1.8.$$

For example, for a region where the design magnitude is less than 7.5, the limit for a Mw7.5 in Table 1 will be multiplied by the MSF to define the limit for an equivalent earthquake. This will result in a larger PGA, such that the two situations have a similar PGA-Mw combination outcomes in terms of input energy from the earthquake.

[3] Pyke 2003, Youd et al. 2001

Table 1: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely based on a Mw7.5 earthquake (MBIE / MfE Guidance)

Types of soil deposit	A liquefaction vulnerability category of *liquefaction damage* is unlikely can be assigned if either of these conditions are met:	
	Design peak ground acceleration (PGA) for the 500-year intensity of earthquake shaking	Depth to groundwater
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	< 0.1 g	> 8 m
Holocene age Less than 11,000 years old	< 0.2 g	> 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.3 g	> 4 m

2.2 'Level B' assessment

The Level B assessment is a calibrated desktop assessment, where the details from the Level A assessment are further refined using additional datasets that can clarify the subsurface characteristics and land performance. Qualitative assessment using simple screening criteria based on a digital elevation model and geotechnical investigations can identify areas where there is potential for liquefaction-induced ground damage to occur, or where the landform suggests it may have occurred in the past. This can inform the calibration of the liquefaction vulnerability categories from Level A, with any other regional information on subsurface deposits fed into this calibrated assessment.

3.0 Ground conditions

3.1 Auckland geology

The deposits of the Auckland region sit upon a basement of Greywacke rock that outcrop at many of the islands in the Hauraki Gulf, the Hunua Ranges, and land south of Port Waikato. The Waitakere Ranges in the west are the re-deposited remains of a large andesitic volcano. The main isthmus and North Shore are underlain by Waitemata Group sandstone and mudstone, and portions of the Northland Allochthon that extend as far south as Albany. The regions where these materials outcrop are often highly weathered at the ground surface, generally forming firm to very stiff clay.

The Manukau Harbour and South Kaipara Harbour are protected by the recent sand dune deposits of the Awhitu and South Kaipara Peninsulas. Figure 11 presents the geology for the Auckland region based on Edbrooke et al. (2003), and Figure 12 presents the geology of Auckland's main urban regions.

Alluvial deposits are present across the region as a part of the Puketoka Formation and more recent Quaternary deposits. These deposits are present in valleys and in low-lying areas, with large swamps and peat deposits also present[4].

Recent basaltic volcanic activity has produced a number of volcanic cones throughout the Auckland region. The Auckland volcanic field has a great influence on the overall geological setting of the Auckland region. Highly variable basaltic deposits are present at many locations and overlie the original strata. These volcanic deposits consist of tuff, basalt, ash, pumice and scoria[5].

Figure 13 shows the distribution of different volcanic deposits and deposits with volcanic content in the Auckland region.

[4] Kermode, 1992; Edbrooke et al., 2003

[5] Searle and Mayhill 1981; Balance and Smith 1982

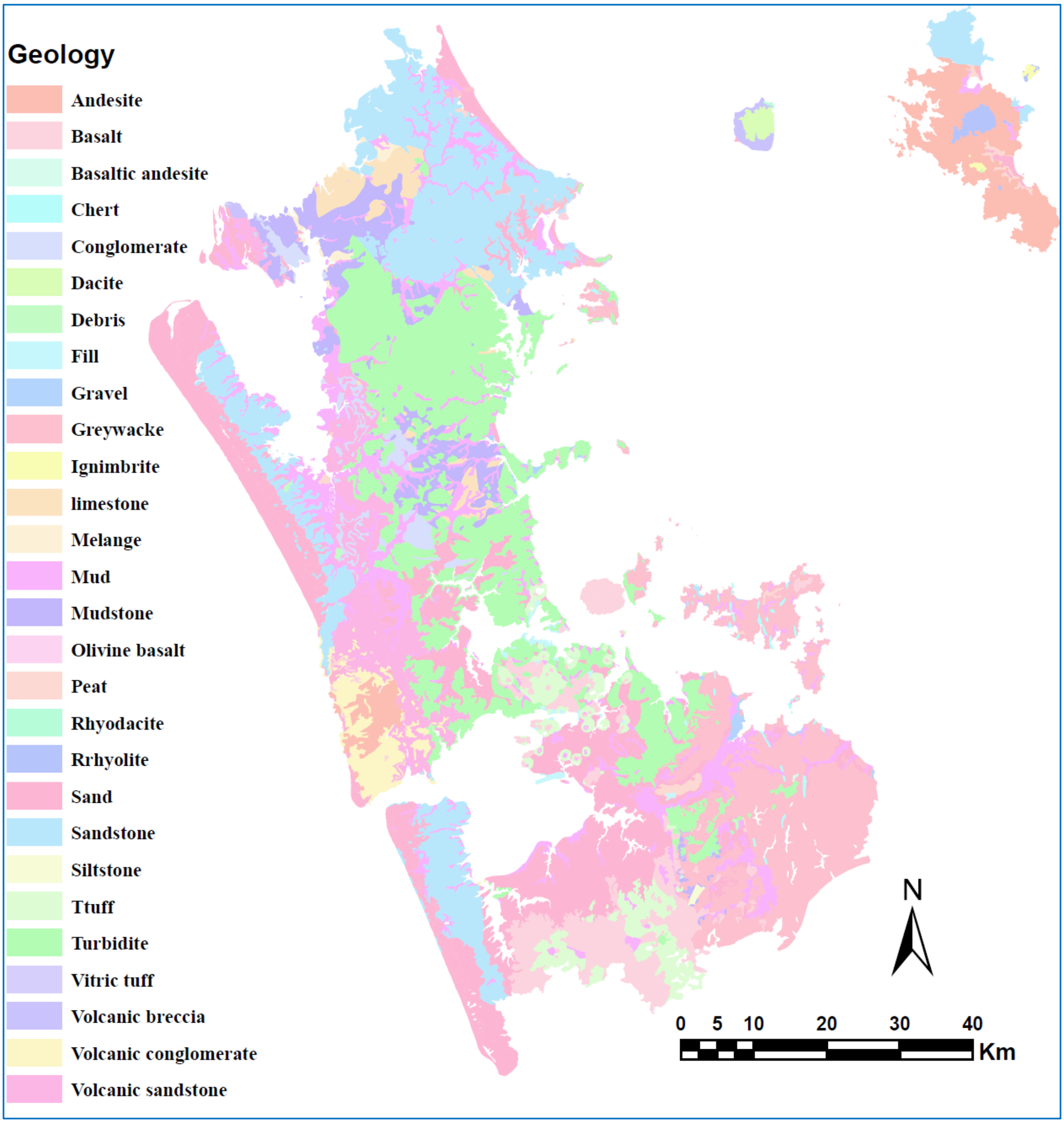


Figure 11: Geological map of the Auckland region (based on Edbrooke et al., 2003)

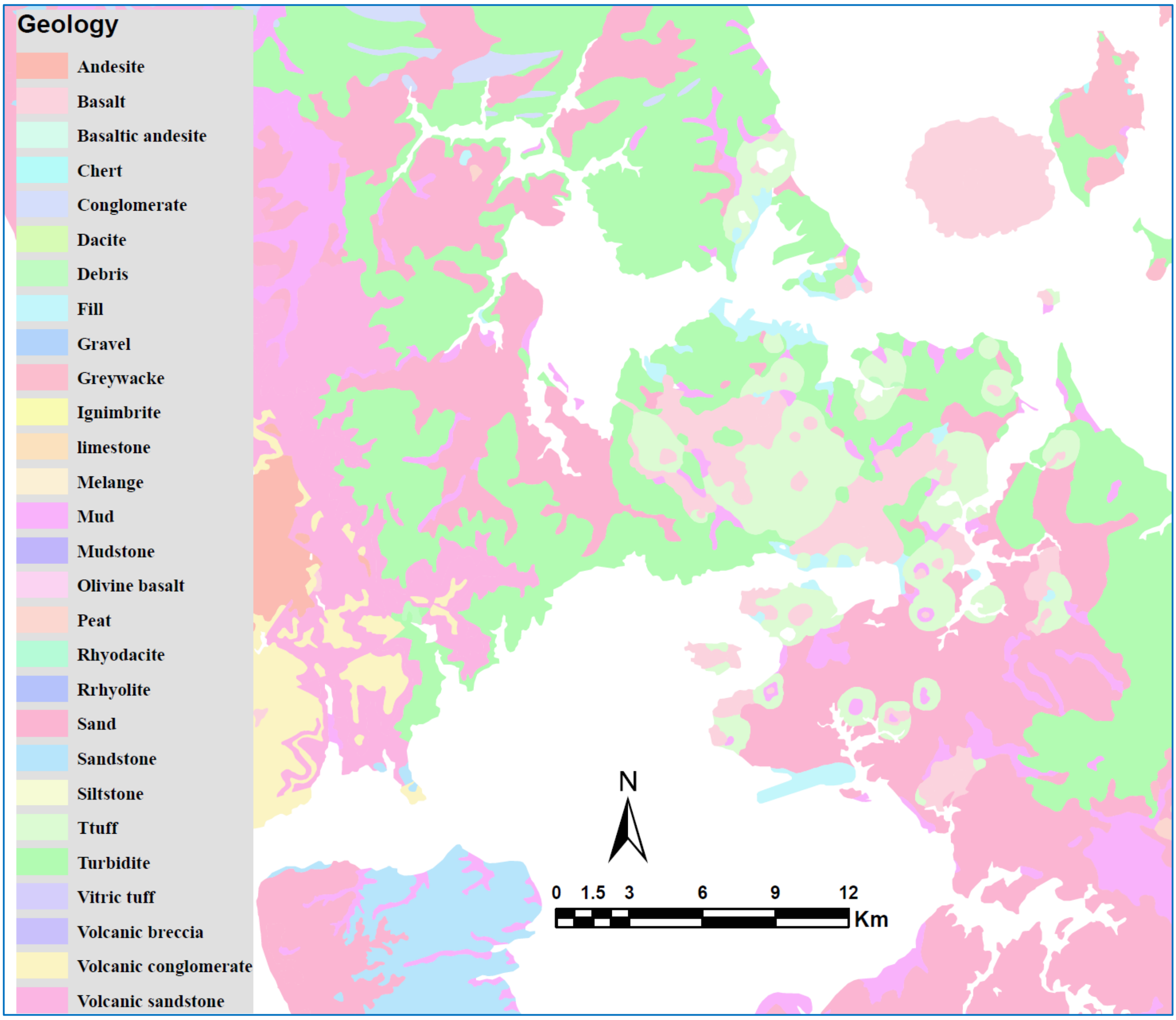


Figure 12: Geological map of Auckland's main urban region. (based on Edbrooke et al., 2003)

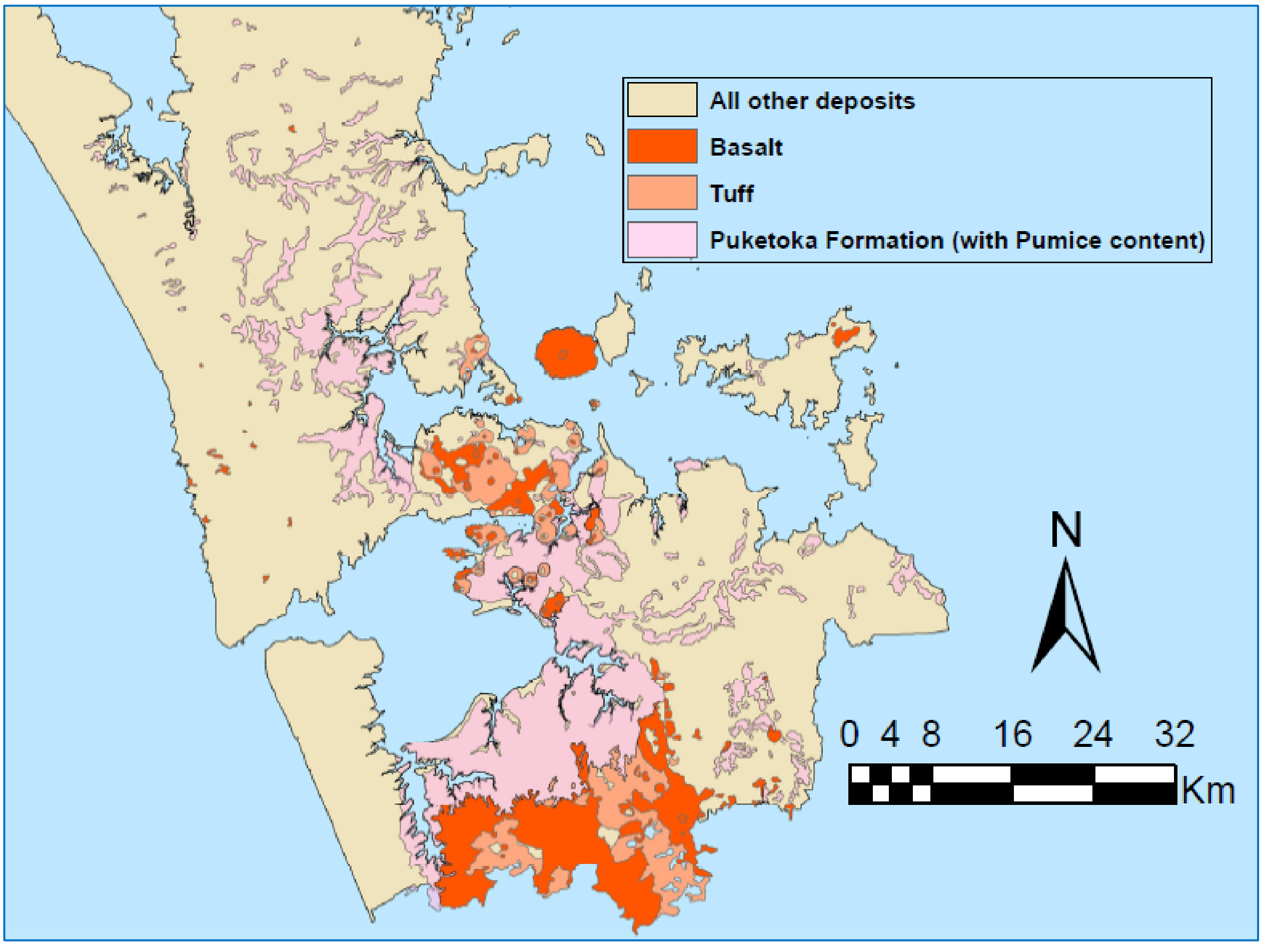


Figure 13: Distribution of areas of volcanic deposits and deposits with volcanic content in the Auckland region

3.3 Groundwater

Near-surface groundwater conditions are an important consideration for liquefaction vulnerability assessment and can be informed through the collation of geotechnical investigation data, observation monitoring wells and other hydrogeological information. However, the reliability of specific groundwater data for application in this context can be influenced by changes in groundwater regimes, climate influences, and shallow groundwater readings due to perched groundwater. It is possible that many of the groundwater monitoring wells are associated with groundwater abstraction from the regional aquifer and may be more representative of regional deep groundwater rather than near-surface perched groundwater. Due to these issues, it is not possible to develop a near-surface groundwater model with currently available information across the region. Nonetheless, based on published geotechnical investigation reports across different areas of Auckland, the following generalised groundwater conditions can be expected:

- Groundwater levels within coastal areas are likely to be within 2-3 m of the existing ground level (shallow depth to groundwater). The groundwater within low-lying coastal areas is likely to be influenced by tidal effects
- Groundwater levels further inland will likely be present at depths of 3 m or more below ground level (deeper depth to groundwater)
- Groundwater flow is typically from elevated areas toward streams and creeks (river recharge from the surrounding environment), with resulting groundwater levels being closer to the surface near streams and creeks and within gullies
- Groundwater aquicludes (less permeable materials between beds of more permeable material) may exist in some areas allowing for the development of perched water tables and zones of seepage where intersected by sloping ground.

The above assumptions for groundwater are reasonable and care was taken in assigning liquefaction vulnerability categories in Level A semi-quantitative criteria in this study.

3.4 Seismicity

It is generally considered that the Auckland region is one of New Zealand's least seismically active regions, located approximately 300 km away from the boundary between Australian and Pacific tectonic plates[6]. Table 2 and Figure 14 summarise the recorded earthquakes in the Auckland region from the period of 1850 until the present[7]. In the GNS Active Faults Database (GNS 2019) there is only one fault identified in close vicinity to the Auckland region, the Wairoa North Fault, approximately 30 km from the Auckland central business district.

However, the recent recognition of at least one other active fault close to the urban area, the Drury Fault, has changed the perception of seismic hazard[8], and other active faults have been postulated in new maps of South Auckland being prepared by GNS Science. Moreover, faults further afield, such as

[6] Dowrick 1992, Kenny et al. 2011, Stirling et al. 2012

[7] Auckland Council 2019

[8] Al-Salim, 2000; Edbrooke et al., 2003

the Kerepehi Fault in the Hauraki Plains, have the potential to generate damaging ground motions within the Auckland region[9].

As the Auckland region has the largest population concentration in New Zealand and is the hub of New Zealand's major commercial activities[10], the seismic and co-seismic hazards in the region cannot be disregarded, given the potential social and economic impacts. Figure 15 shows the location of known active faults in the vicinity of the Auckland region.

Table 2: Historic earthquakes felt in the Auckland region (Auckland Council 2017)[11]

Earthquake date	Location	Magnitude	Shaking felt In Auckland
23-Jan-1855	Wairarapa	8.1-8.2	MM4
18-Oct-1868	Cape Farewell	7.0-7.5	MM4-5
23-June-1891	Waikato Heads	5.5-6.0	MM5-6
11-Feb-1893	Nelson	6.6-6.9	MM3-4
6-Oct-14	East Cape	6.7	MM4
28-Oct-14	East Cape	6.5	MM3
28-Jun-21	Hawkes Bay	7	MM3
9-Mar-29	Arthurs Pass	7.1	MM2-3
16-Jun-29	Buller	7.8	MM3
21-Sep-31	Bay of Plenty	6.75	MM2-3
20-Jul-32	Taranaki	6.3	MM2-3
5-Mar-34	Pahiatua	7.6	MM2-3
15-Mar-34	Hawkes Bay	6.4	MM3
24-Jun-42	Wairarapa	7.2	MM2-3
1-Aug-42	Wairarapa	7	MM2
29-Sep-53	Bay of Plenty	7.2	MM3
18-Oct-53	Taranaki	5.3	MM3-4
30-Jan-56	Bay of Plenty	5.8	MM2-3
23-Jan-62	Aria	5.5	MM3-4
23-May-68	Inangahua	7.0-7.1	MM3
11-Feb-75	Hen and Chickens Islands	4.4	MM3
2-Mar-87	Edgecumbe	6.1	MM3

9 Dempsey et al. 2020

10 Auckland Council 2014: https://www.aucklandcouncil.govt.nz/plans-projects-policies-reports-bylaws/our-plans-strategies/auckland-plan/about-the-auckland-plan/Documents/aucklandprofileinitialresults2013census201405.pdf

11 https://teara.govt.nz/en/historic-earthquakes/page-9

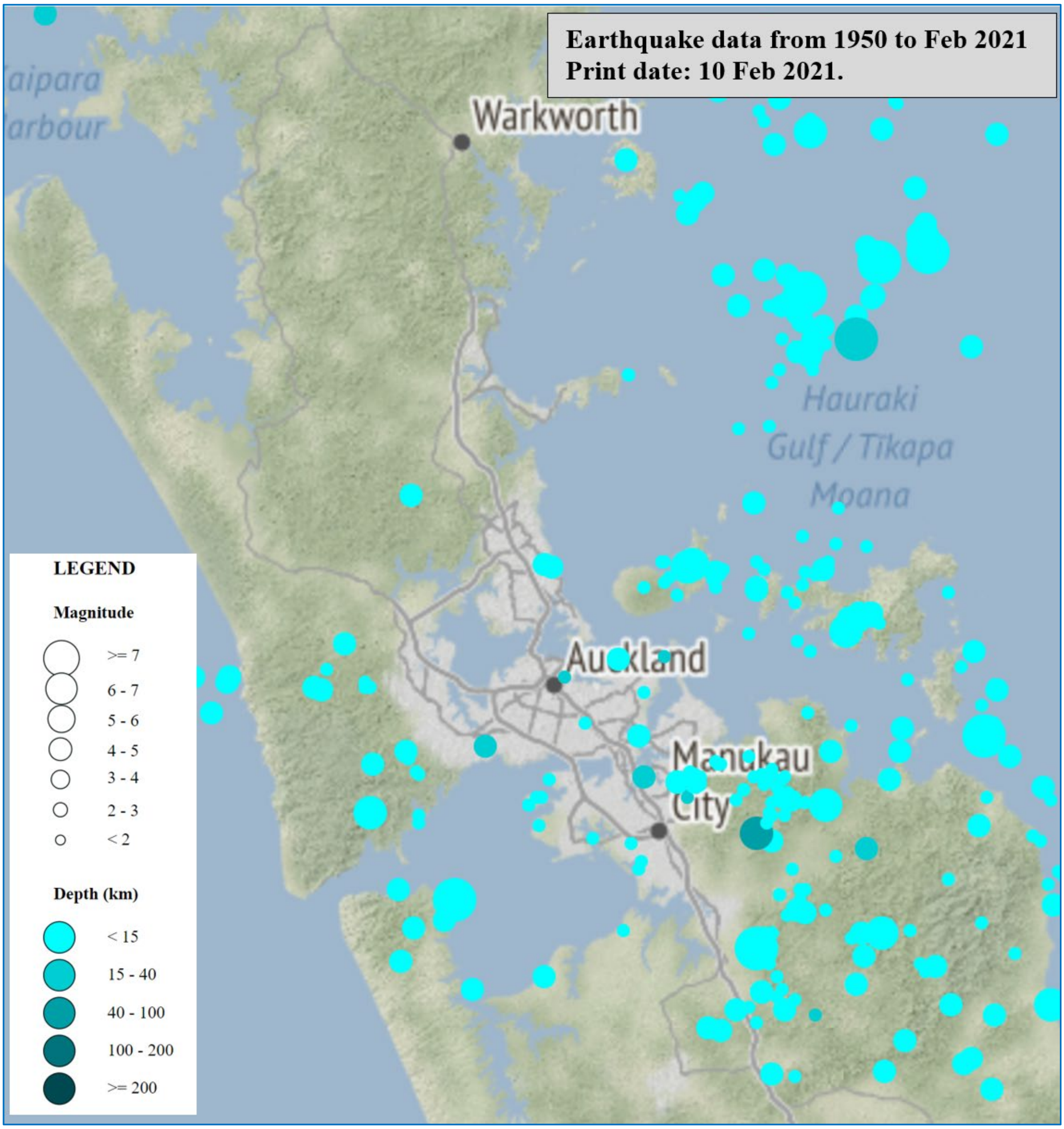


Figure 14: Historical recorded earthquakes in the Auckland region from the 1950s to present (http://quakesearch.geonet.org.nz)

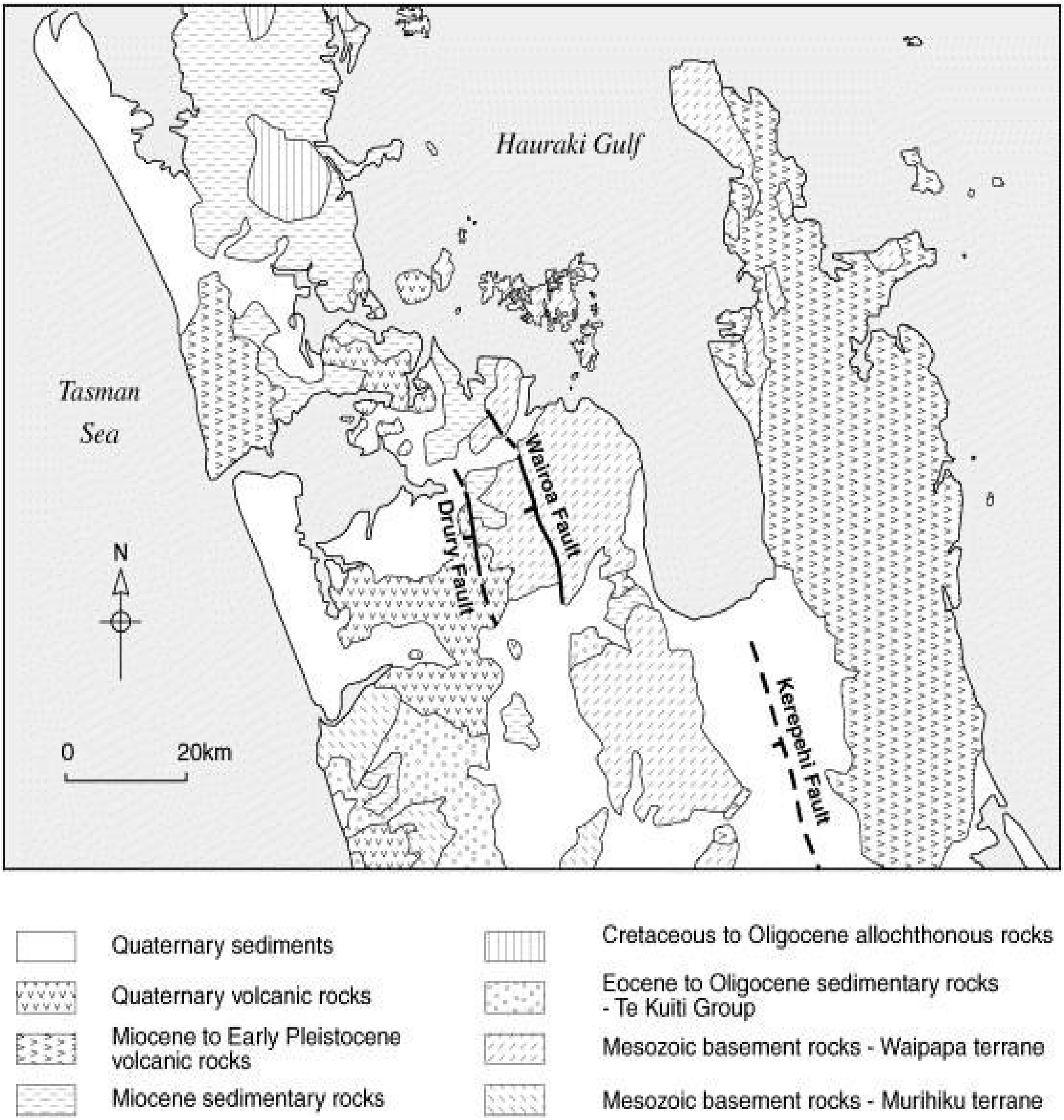


Figure 15: Active faults around the Auckland region and geologic deposit types (adapted from Edbrooke et al. 2003)

The MBIE / MfE Guidance recommends the assessment of liquefaction-induced ground damage for different ground shaking return period to categorize liquefaction vulnerability. According to the NZTA Bridge Manual SP/M/022 (2013), the peak ground accelerations (PGA) applied should be 'unweighted' and derived for the relevant return period as follows:

$$PGA = C_{0,1000} \times \frac{R_u}{1.3} \times f \times g$$

where:

$C_{0,1000}$ = 1000-year return period PGA coefficient

R_u = Return period factor derived from NZS 1170.5 Structural design actions part 5 Earthquake actions – New Zealand (SNZ 2004)

f = Site subsoil class factor, equal to 1.0 for Site subsoil class A, B, D and E soil sites, and 1.33 for a site subsoil class C site.

Based on this, the PGA characteristics for the Auckland region using a site subsoil class C site are:

- For 1000-year return period: PGA= 0.2 x (1.3/1.3) x 1.33 = 0.27 g
- For 500-year return period: PGA = 0.2 x (1.0 /1.3) x 1.33 = 0.205 g
- For 100-year return period: PGA = 0.2 x (0.5 /1.3) x 1.33 = 0.10 g
- For 25-year return period: PGA = 0.2 x (0.25 /1.3) x 1.33 = 0.05 g

For liquefaction triggering analysis, the magnitude for the Auckland region defined by the NZTA Bridge manual is M_w 5.9 and is used for all return period events. When applied to the semi-quantitative criteria from Table 1, the PGA values from the 500-year return period are scaled using MSF of 1.52. Table 3 summarises the revised PGA boundaries for a M_w 5.9 earthquake for the semi-quantitative criteria to inform liquefaction vulnerability categories.

Table 3: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely for MW 5.9. (MBIE / MfE Guidance)

Types of soil deposit	A liquefaction vulnerability category of *liquefaction damage* is unlikely can be assigned if either of these conditions are met:	
	Design peak ground acceleration (PGA) for the 500-year intensity of earthquake shaking	**Depth to groundwater**
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	< 0.15 g	> 8 m
Holocene age Less than 11,000 years old	< 0.25 g	> 6 m

Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.35 g	> 4 m

4.0 'Level A' - Basic desktop assessment

This section presents the development of the liquefaction vulnerability categories based on the Level A desktop approach based on geological maps, groundwater, and seismic hazard for the Auckland region following the MBIE / MfE Guidance.

A geological desktop assessment was undertaken based on published national and regional surface geological maps and reports to characterise liquefaction. Q-Maps developed by GNS Science were used to create geological layers for the Auckland region. The output of this initial assessment is a geology-based liquefaction vulnerability map defining areas in the Auckland region where *Liquefaction damage is possible* and *Liquefaction damage is unlikely*. The primary aim of this initial screening is to identify geological units that are not expected to be susceptible to liquefaction.

4.1 Qualitative screening

Using qualitative criteria, soil types susceptible to liquefaction include fills, reclaimed land, sands and silt deposits of Quaternary age, estuarine deposits of Holocene age[12]. Most liquefaction-induced failures and nearly all case history data compiled in empirical charts for liquefaction evaluation were in Holocene deposits or constructed fills[13].

Based on the above discussion, areas of the following geological deposits are categorised as *Liquefaction damage is possible*:

- Fills
- Sand, silt, gravel, swamps deposits of Holocene age
- Landslide deposits (debris).

In general terms, the basement, Late Pliocene, and Early Pleistocene deposits are rock or relatively well consolidated and will not liquefy under strong ground shaking. Because of their age, the early and middle Pleistocene non-marine and marine deposits, the last interglacial marine deposits, and the alluvial materials of the early and middle last glaciation are old enough to have been consolidated by natural processes. Their liquefaction susceptibility is regarded as negligible[14]. Using this criterion, the following regional deposits are assigned the category *Liquefaction damage is unlikely*:

- Greywacke
- East Coast Bays Formation containing sandstone and mudstone deposits
- Tuff
- Basalt
- Firm to stiff Pleistocene age alluvium.

[12] Pyke 2003, Youd et al., 2001, Youd and Perkins, 1978

[13] Seed and Idriss, 1971; Seed et al., 1985; Boulanger and Idriss, 2008

[14] Youd and Perkins 1978

Figure 16 summarises the potentially liquefiable soils in the Greater Auckland region and Figure 17 shows the same for Auckland's main urban region.

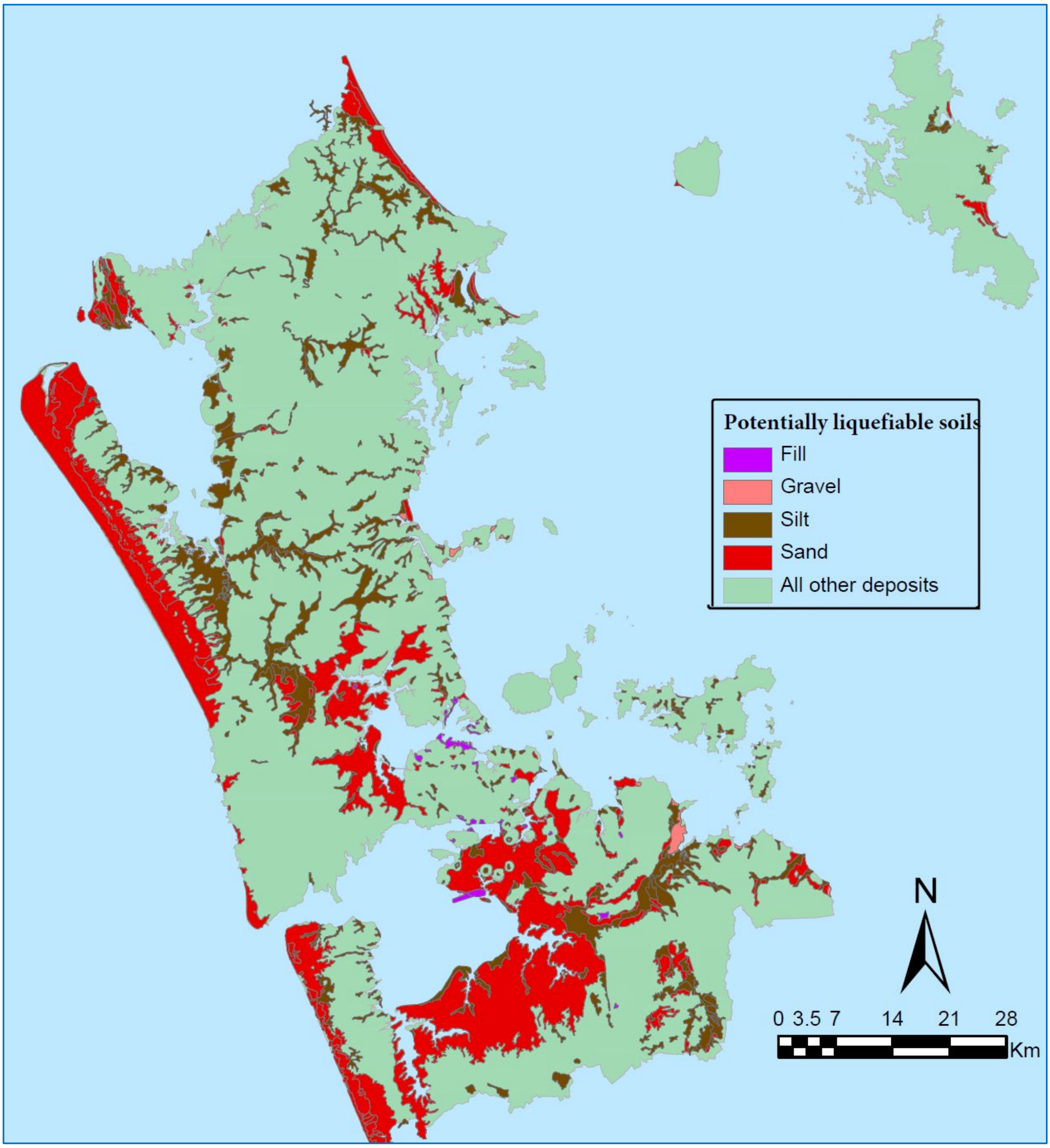


Figure 16: Summary of potentially liquefiable deposits in the Greater Auckland region

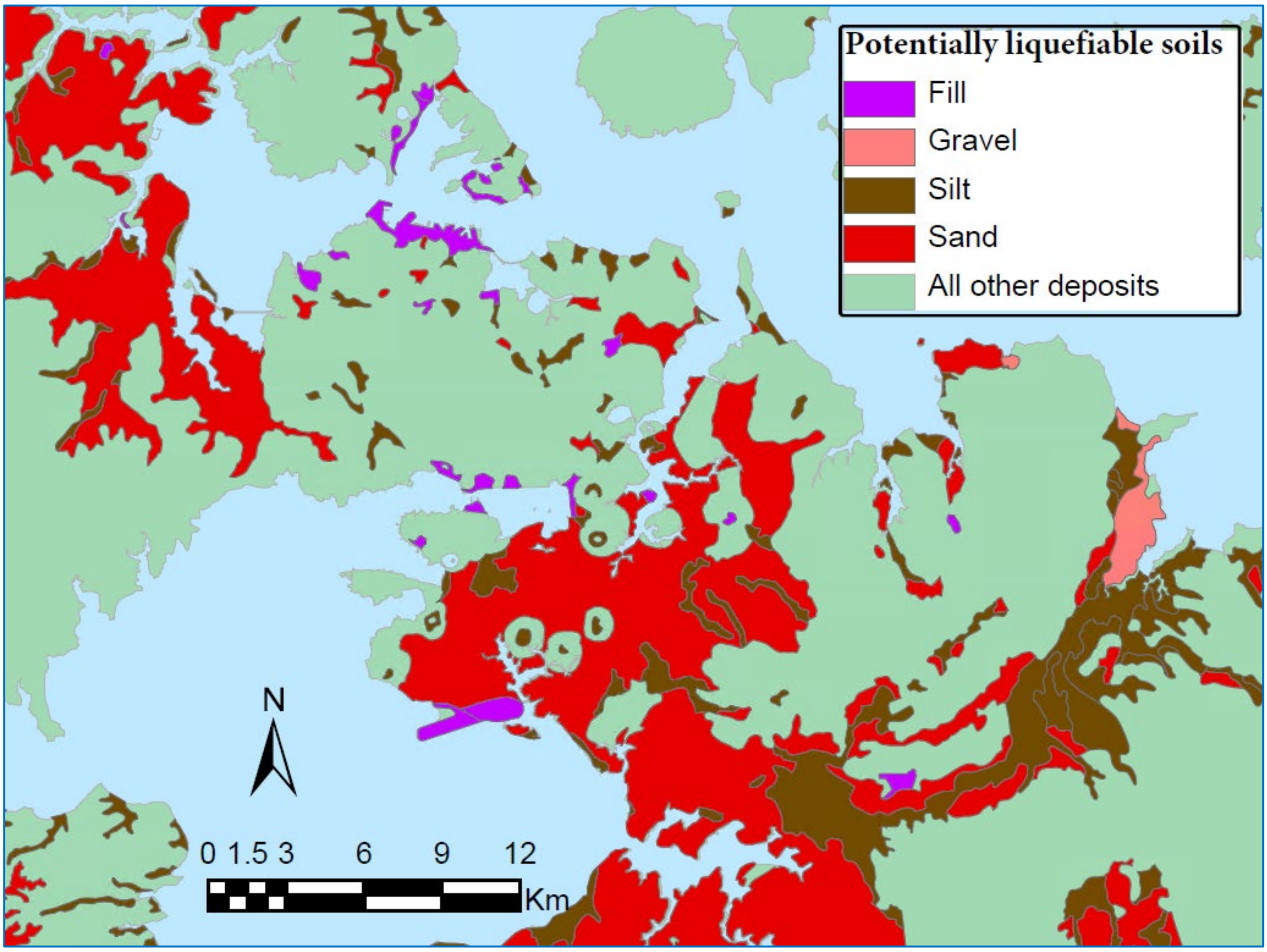


Figure 17: Summary of potentially liquefiable deposits in Auckland's main urban region

4.2 Semi-quantitative screening

By considering the regional seismic hazard and depth to groundwater, in conjunction with the depositional process and the age of soil deposits, the semi-quantitative screening criteria in Table 3 is used to identify geological units where significant liquefaction-induced ground damage is unlikely to occur. A soil deposit of the specified type is assigned a liquefaction vulnerability category of *Liquefaction damage is unlikely* if the 500-year return period PGA is less than the limit for the age of that deposit, or if the depth to groundwater is greater than the limit.

As geological age is one of the main factors in the semi-quantitative criteria to assess the liquefaction vulnerability of the deposits, Figure 18 summarises the geological age associated with each deposit in the study area identified as potentially liquefiable based on qualitative criteria. Figure 19 presents the depositional age of potentially liquefiable deposits in Auckland's main urban regions.

Holocene deposits are dominated by fill and silt material, while most of the sand deposits belong to the Puketoka Formation. Although the Puketoka Formation deposits consist of sandy, silty volcanic soils with tephra, pumice, and lignite, their Late Pliocene to Middle Pleistocene depositional age screens these deposits out from the initial level A assessment, as the 500-year return period PGA is less than the 0.35 g cut-off value.

An aspect of the Puketoka Formation in the Auckland region is that in some areas it contains pumice and other volcanic deposits, with behaviours that may differ from the rest of the deposits without these volcanic materials. As an example, the 1987 Edgecumbe earthquake resulted in widespread liquefaction of sands of volcanic origin. At this level of assessment, these deposits are not treated separately, and the Q-Map polygons and classifications are applied.

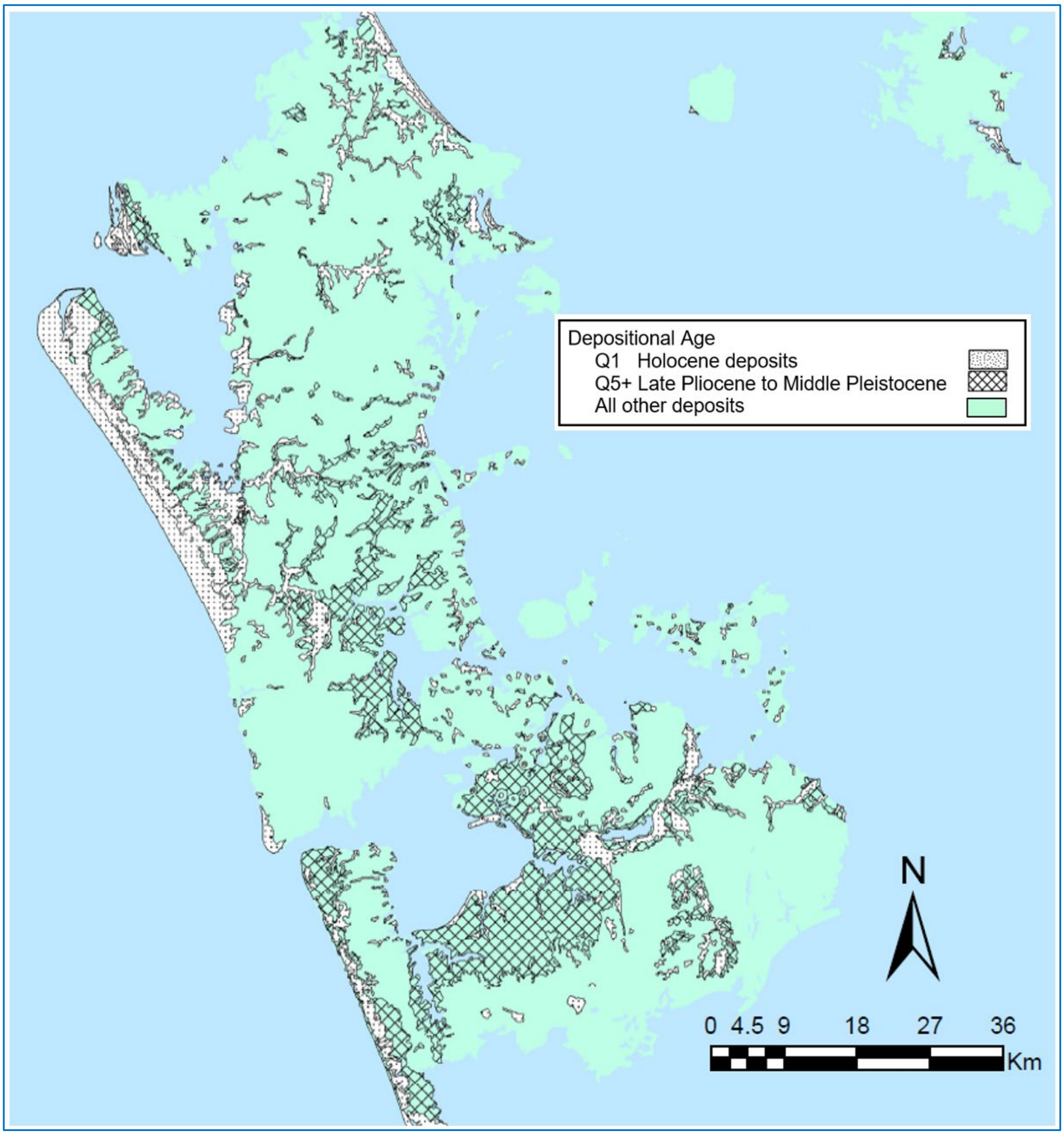


Figure 18: Depositional age of potentially liquefiable soils in the Greater Auckland region

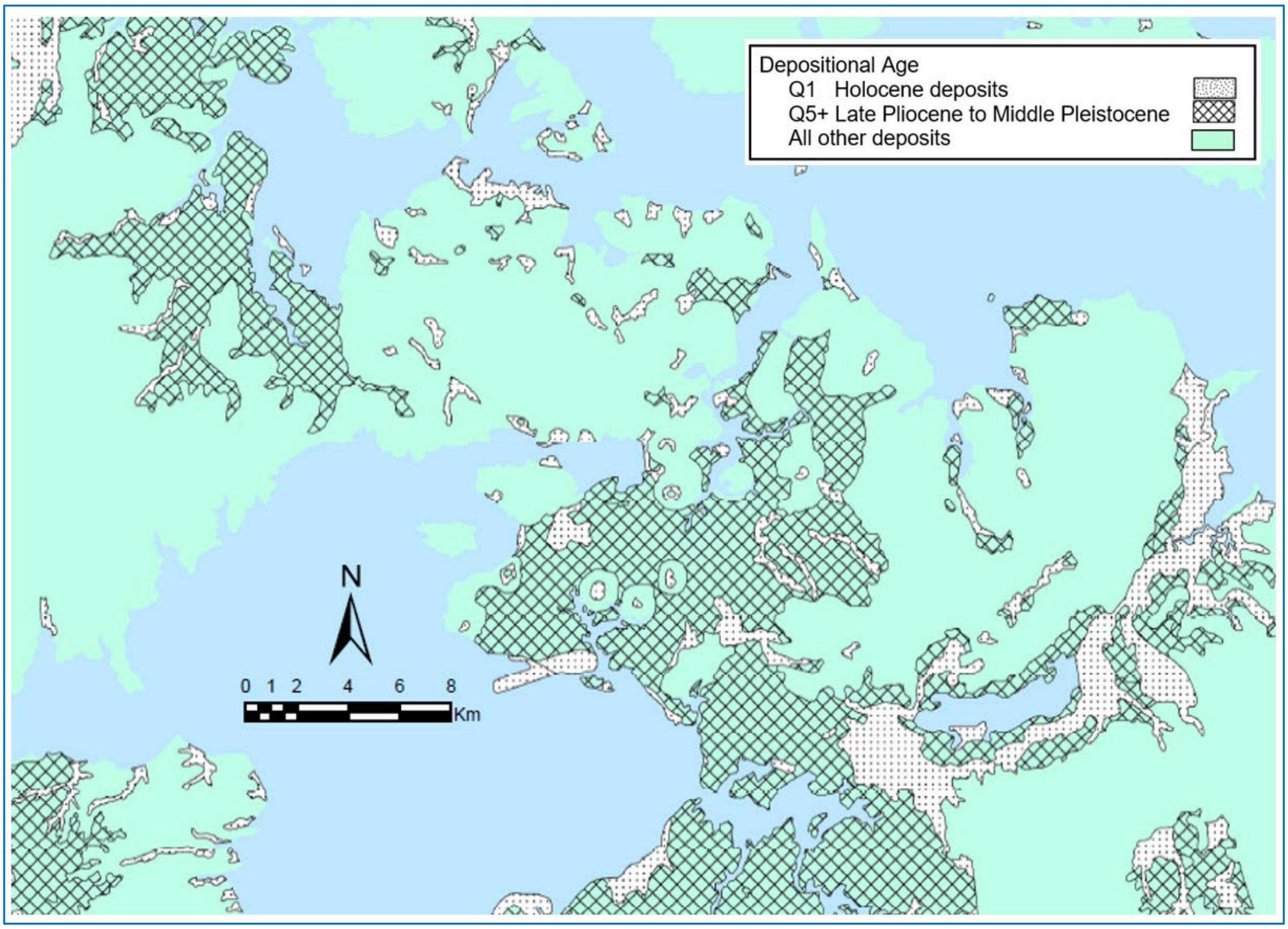


Figure 19: Depositional age of potentially liquefiable soils in Auckland's main urban area

The rock deposits in the region are rock or relatively well consolidated and will not liquefy under strong ground shaking. Therefore, exposed rock deposits can be assigned a liquefaction vulnerability category of *Very Low*. This includes Late Pliocene rock, Early Pleistocene rock, Allochthonous rocks, Basement rock, basaltic rock deposits, and igneous and sedimentary rocks of Neogene and Pliocene age.

As defined in Section 4, the 500-year return period PGA value is 0.20 g for the Auckland region, less than 0.25 g cut-off value for Holocene deposits. This is the main governing criteria for this semi-quantitative assessment, as no detailed groundwater models have been developed. There is uncertainty regarding subsurface conditions elsewhere, but the nature of these deposits means that *Liquefaction damage is possible* is an appropriate classification for Holocene deposits. These deposits include alluvial deposits of fine-grained silts and sands and fills, that are inter-fingered with mud, sands, silts, pumice and gravels.

Figure 20 summarises the liquefaction vulnerability categories that are assigned for the Greater Auckland region based on semi-quantitative geological screening (Level A) and Figure 21 shows the categories for Auckland's main urban region.

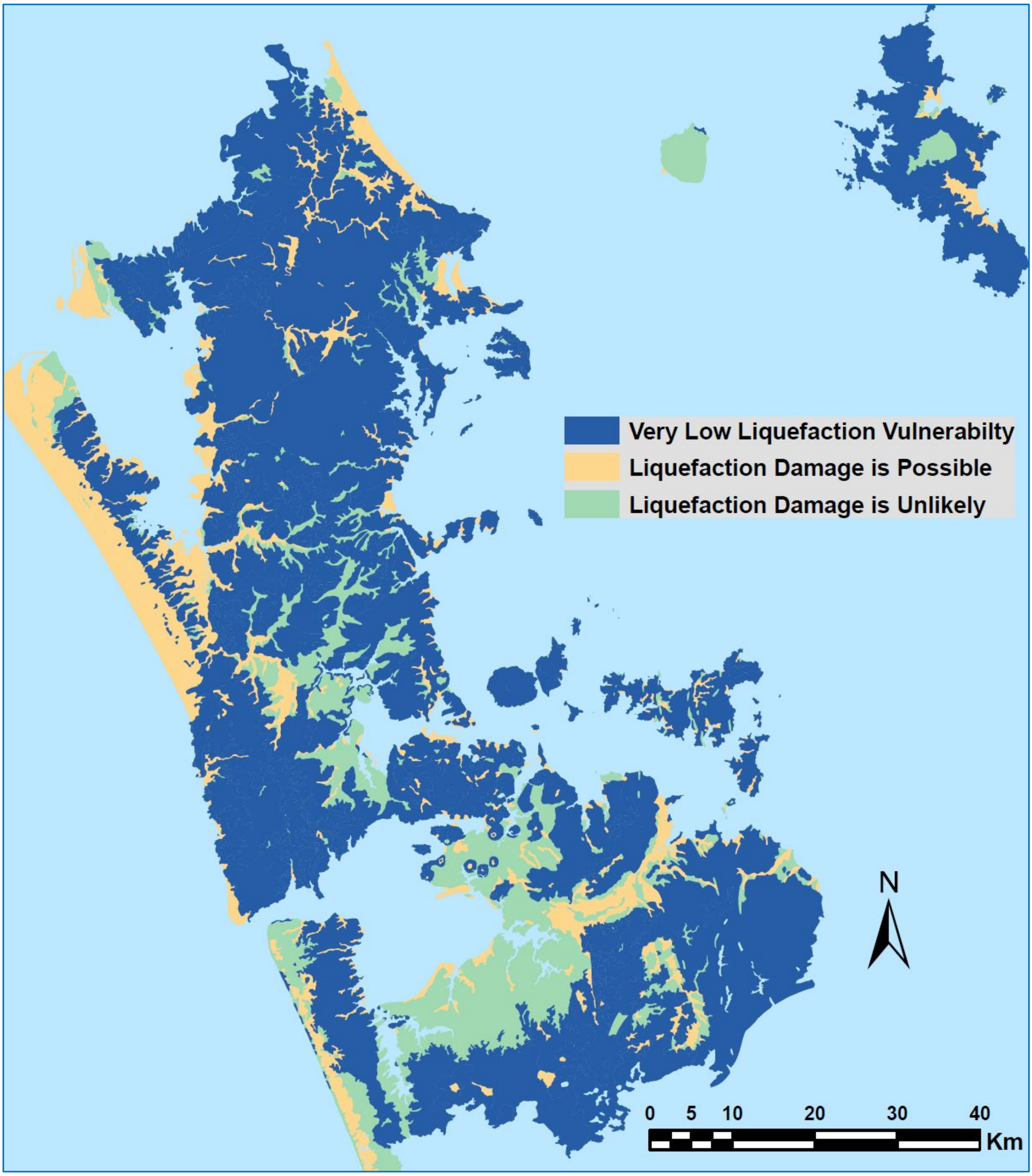


Figure 20: Geology-based liquefaction vulnerability category map for the Greater Auckland region

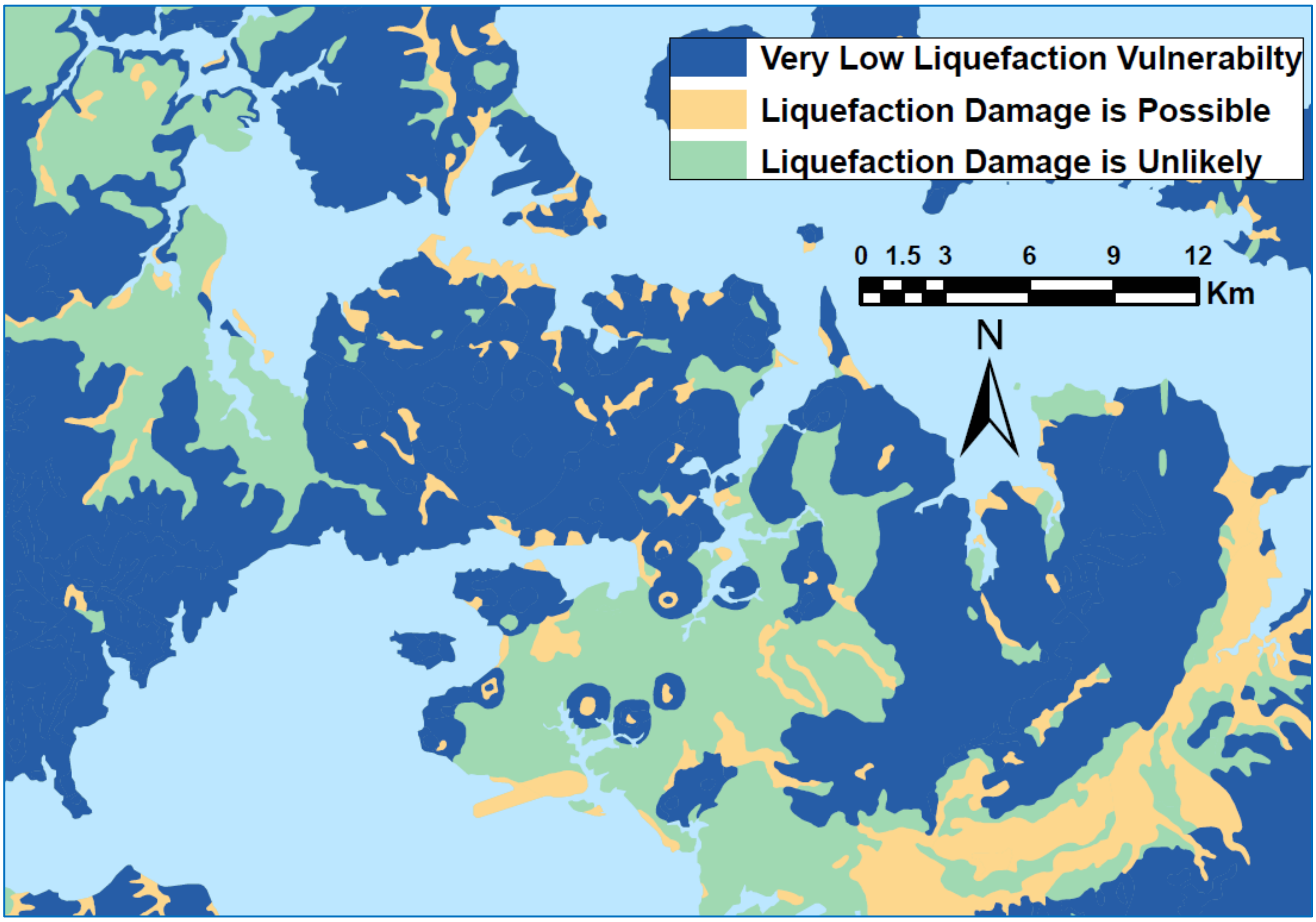


Figure 21: Geology-based liquefaction vulnerability category map for the Auckland main urban area

5.0 'Level B' geotechnical and elevation-based screening

The screening presented in this section follows the Level B calibrated desktop assessment guidelines from MBIE. Level B assessments have been undertaken where appropriate, for targeted areas of Auckland. Areas for Level B assessment were selected on the basis that there is sufficient geotechnical data available to inform the assessment.

This section includes high-level calibration of geological maps with available geotechnical data and topographical information in the region, including digital elevation model (DEM) data. Qualitative assessment of subsurface investigations provides a better understanding of liquefaction susceptibility for the mapped deposits and underlying ground profile. It can reduce the uncertainty in areas where existing information is sparse.

As there is uncertainty in relation to liquefaction vulnerability, how it varies across each mapped area and the delineation of boundaries between areas, a Level B assessment is only appropriate in areas with a good density of geotechnical investigation data. This section highlights some areas where more robust geotechnical screening with increased density of data has been carried out. There may be some areas where the surface geological maps may not justify the choice of liquefaction vulnerability category because of the characteristics of the underlying soil profile (e.g. recent fill or underlying liquefiable deposits). Suggestions are made for each area where a reasonable density of geotechnical investigations are present.

A large amount of geotechnical investigation data was sourced from the New Zealand Geotechnical Database and the Tonkin + Taylor geotechnical database for this study. The available geotechnical investigations in the region are shown in Figure 22. Although there is a large amount of data, the density of this is low in most areas.

The areas with an elevation greater than 20 m are shown by crosshatch in Figure 22 in the regions with the same liquefaction vulnerability category, with 20 m elevation used as a coarse indicator for areas where liquefaction may be less likely because there is probably a greater depth to the groundwater table.

To assess the above factors in detail across the Auckland region, focus areas have been defined, the locations and extents are shown in Figure 23. The locations outside of the focus areas do not have any geotechnical investigation data, and as such, they can only be categorised according to geological data (Level A).

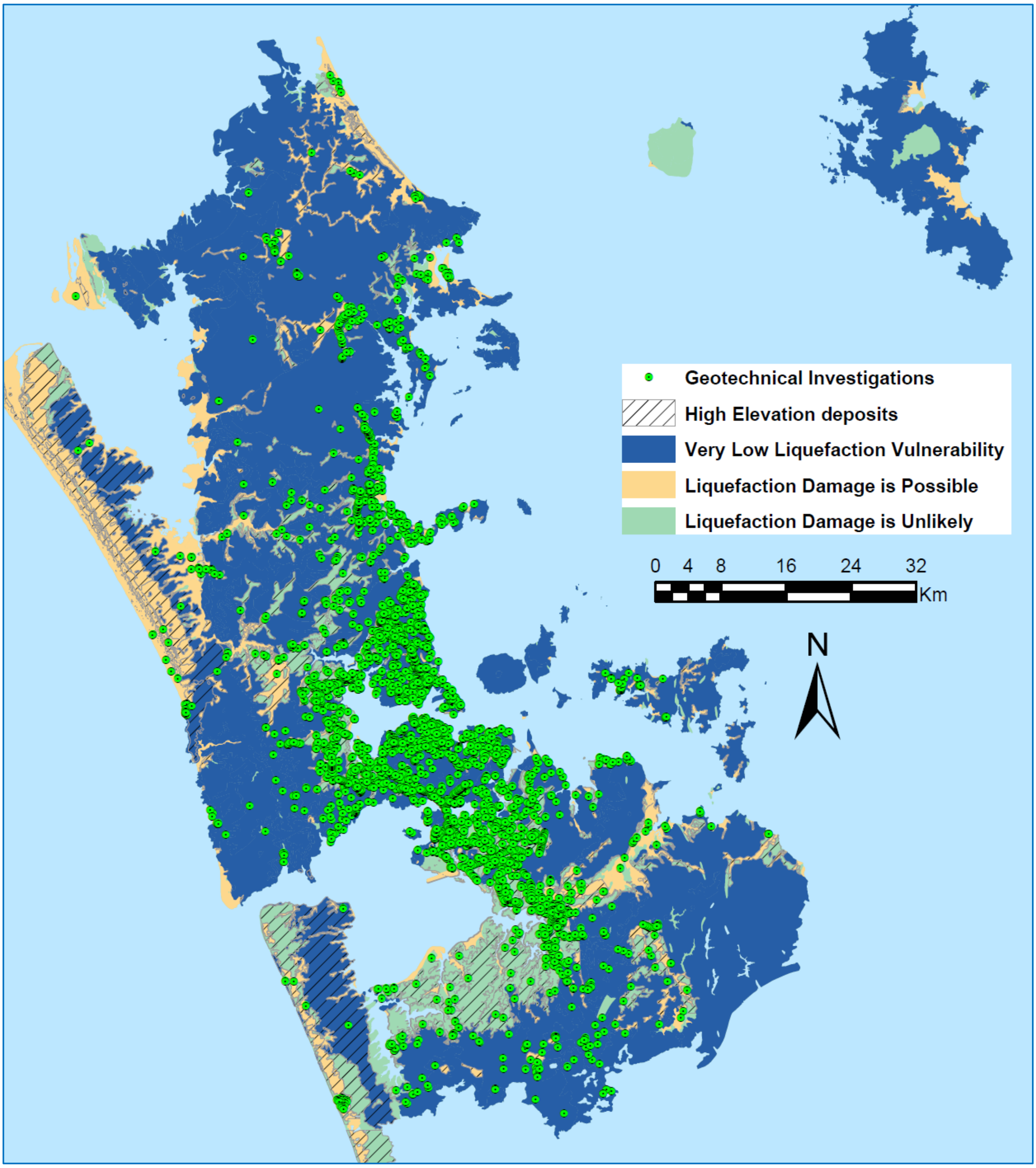


Figure 22: Summary of available geotechnical investigations and high elevation regions (>20 m) in the Greater Auckland region

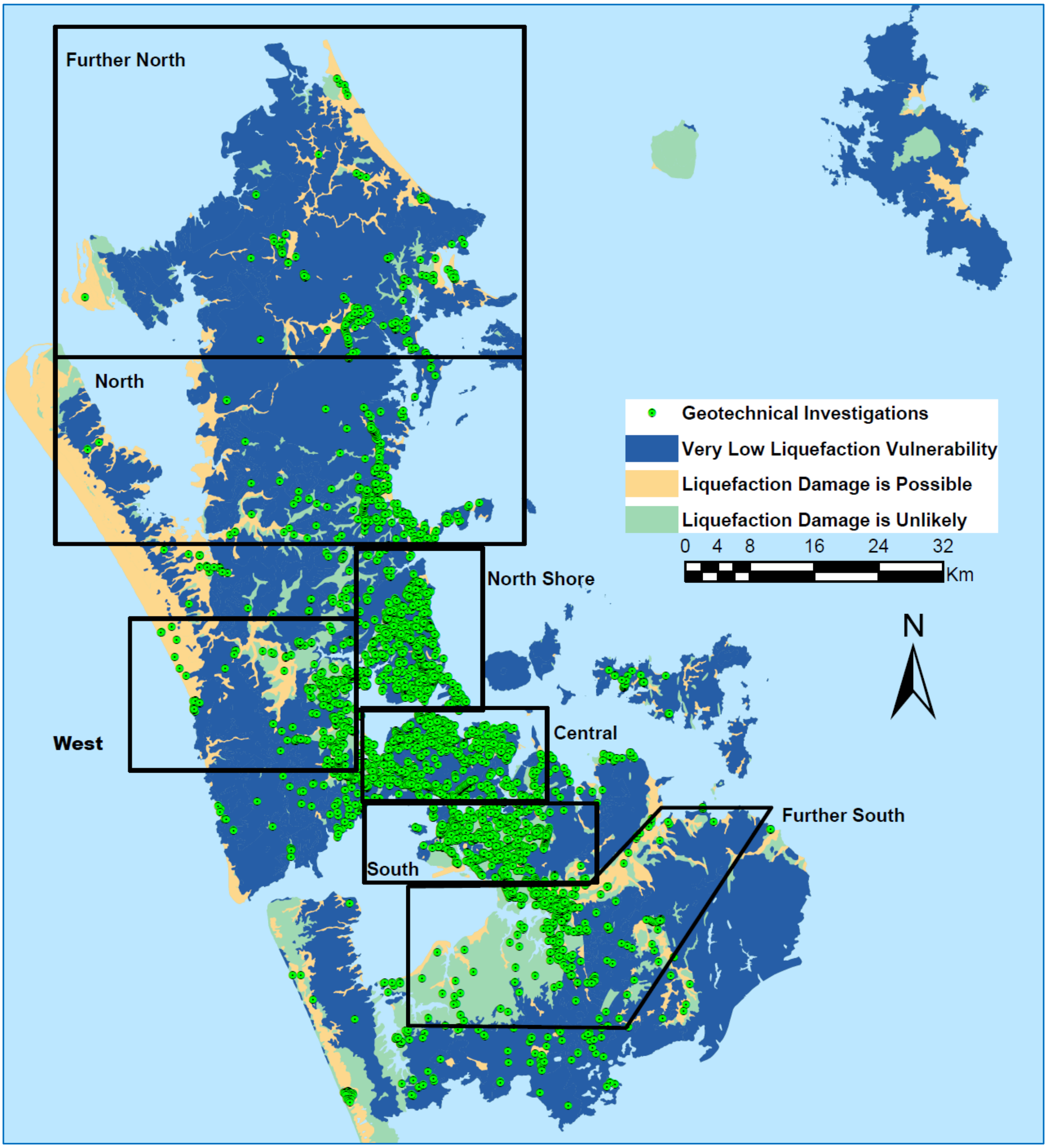


Figure 23: Summary of Focus Areas in the Greater Auckland region for Level B (Geotechnical calibration) liquefaction assessment

5.2 'Further North' Focus Area

Figure 24 shows the Level A categories for the most northern Auckland suburbs along with the locations of available geotechnical investigation data. These locations include areas in the proximity of **Mangawhai, Warkworth, Wellsford** and **Omaha**. Areas with an elevation >20 m are also shown in Figure 24, as a coarse indicator for areas where liquefaction may be less likely as a result of the greater depth of the groundwater table.

Warkworth and Wellsford investigations mostly identify clay at or near the ground surface and silt underlying silty sandy material of low plasticity. Although these areas are at a higher elevation, investigation data shows the presence of sandy, silty material below the water table at shallow depth. This data confirms the *Liquefaction damage is possible* category and a more refined category cannot be assigned at this level. This disproves the general assumption that areas of >20 m height are where liquefaction may be less likely as a result of the greater depth of the groundwater table

Similarly, deposits at **Mangawhai** have an elevation greater than 20 m. However, a more refined category cannot be assigned due to a low density of geotechnical investigations. The existing geological mapping information confirms the *Liquefaction damage is possible* category.

All geotechnical investigations in **Omaha** show alluvial deposits with low elevation and shallow groundwater depth, which confirms the category of *Liquefaction damage is possible*.

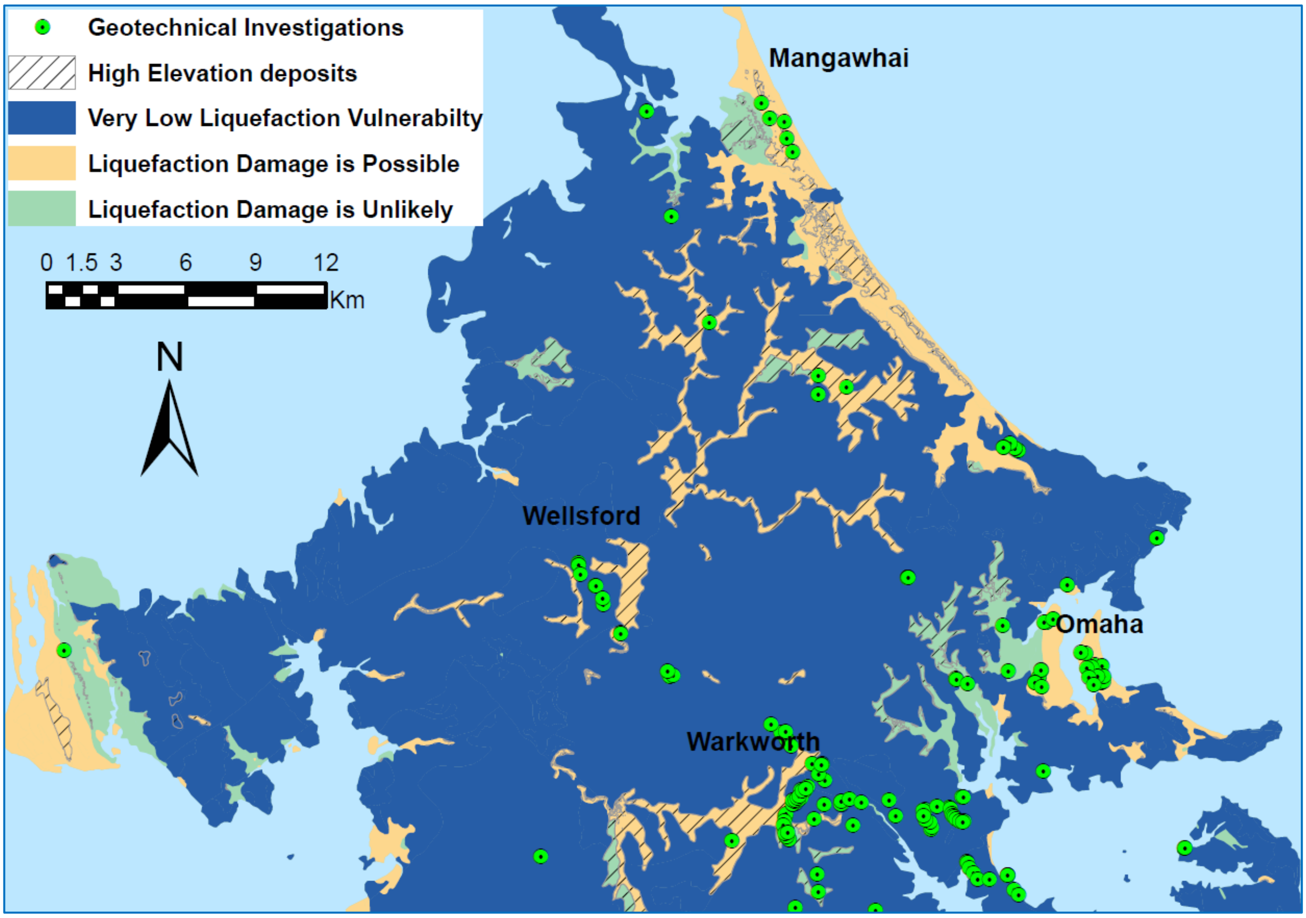


Figure 24: 'Further North' Focus Area suburbs investigated under Level B liquefaction assessment

5.3 'North' Focus Area

Figure 25Figure 25 shows the Level A categories in the North Auckland suburbs and the available geotechnical investigations. These locations include areas in the proximity of **Puhoi, Waiwera, Orewa, Red Beach, Silverdale** and **Whangaparaoa**. The density of investigations in this area is not sufficient to update the liquefaction vulnerability categorisation. Areas with an elevation >20 m are also shown in Figure 25.

Boreholes in the area adjacent to **Puhoi** show alternate layers of clayey silt and silty clay, becoming gravely with siltstone and sandstone. Near the river and beach, there is likely to be sandy, silty material, but there is no investigation data in these areas. Small areas in **Waiwera** have clayey silt with layers of gravels and stiff silt. However, investigation data is sparse in this region. Only two boreholes available in **Orewa** show sandy layers of 3-4 m thickness underlying near-surface soil deposits that behave in a plastic manner up to 2 m thick. Other areas with no investigation data, especially near beaches, may have soils susceptible to liquefaction. **Red Beach** investigations show sandy/silty clay with moderate plasticity at locations away from the coast. The **Silverdale** area has mainly silty sandy soil deposits. Available data points in **Whangaparaoa** areas indicate that silty sandy soil layers are present.

Based on the above discussion and the low density of geotechnical investigations, no update in Level A assessment is applied for locations within the North Area.

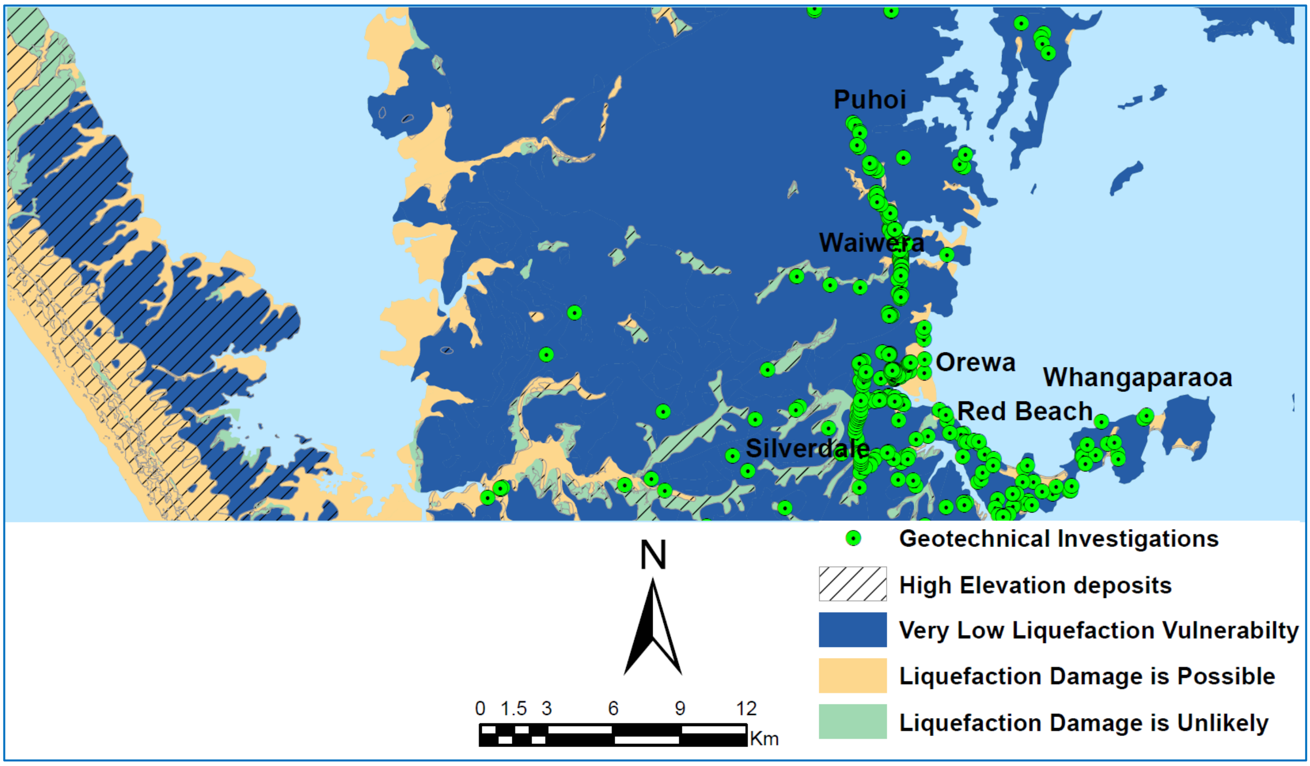


Figure 25: 'North' Focus Area suburbs investigated under 'Level B' liquefaction assessment

5.4 'North Shore' Focus Area

Figure 26 shows the Level A categories in North Shore suburbs with the available geotechnical investigations. These locations include areas in the proximity of **Long Bay, Browns Bay, Torbay, Takapuna, Devonport, Northcote**, and **Forest Hill**. Areas with an elevation >20 m are also shown in Figure 26.

Some of the regions in **Glenfield** and **Takapuna** in Figure 26 have some areas of high elevation up to 30-40 m. The water table depth is 2-3 m in most locations. The **Glenfield** area has two types of deposits. High elevation areas have Neogene sedimentary rocks (with volcanic content) while low elevation areas have Holocene River deposits. Sandy and silty deposits are present.

All the coastal areas shown in Figure 26 are Holocene River deposits. **Torbay** has silty layers up to 5 m in thickness over East Coast Bay Formation. **Browns Bay** has fill material up to 3 m and overlying silty layers up to 10-11 m thick. Highlighted areas of **Devonport** and **Northcote** have sandy, silty soils of thickness 4-5 m. **Takapuna** has fill material up to 4-5 m, which are comprised of silty and sandy loose soils. Below that, there are silty clayey soils with low plasticity up to 12 m depth.

Based on the above, the high elevation area in **Glenfield** is assigned a refined *Low liquefaction vulnerability* category, with the subsurface data identifying areas that do not align with the geological mapping. For all other locations, the *Liquefaction damage is possible* category is not modified.

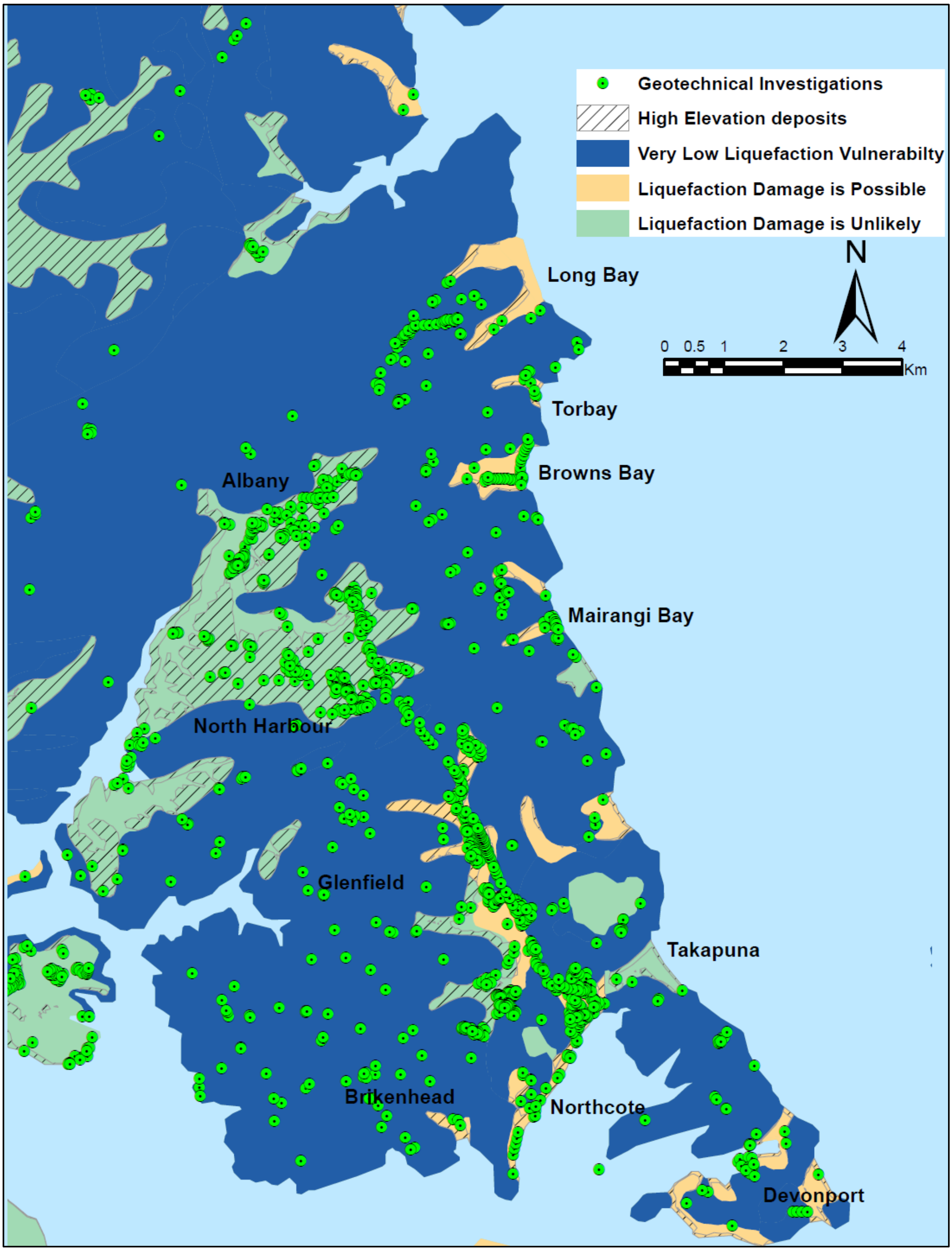


Figure 26: 'North Shore' Focus Area suburbs investigated under Level B liquefaction assessment (overlain on Level A assessment mapping)

5.5 'West' Focus Area

Figure 27 shows the Level A categories in the West Auckland suburbs with the available geotechnical investigations. These locations include areas in the proximity of **Te Atatu Peninsula, Henderson, Hobsonville, Kumeu, New Lynn and Kelston**. Areas with an elevation >20 m are also shown in Figure 27.

Te Atatu Peninsula has few data points, mostly indicating sandy silty soils with some interbedded clayey and peaty layers and elevation 21-30 m. The **Henderson** highlighted area has layers of loose silt and sand, interbedded with clay and gravels. Available boreholes in **Hobsonville** show the presence of silty sandy layers with alternate layers of plastic clay. Highlighted areas in **Kumeu** have silty and sandy soil layers with a layer, near the ground surface, of plastic clay (1-3 m) but high elevation. As the density of available geotechnical investigation is low in these areas, and available boreholes show the presence of potentially liquefiable deposits, no refined classification is used for this area.

In this area, one of the important aspects to explore further is the liquefaction potential of the Puketoka Formation. This formation covers a large area of the West Auckland suburbs, which are all categorised as *Liquefaction damage is unlikely* based on semi-quantitative criteria in the Level A assessment. Geotechnical investigations in **New Lynn** and **Te Atatu South** show 3-4 m plastic clayey soil overlying 5-6 m of sandy soil layers. **Kelston** has 1-2 m of clayey soil of a volcanic nature above sandy, silty soil layers. These deposits consist of mostly loose sandy, silty soils, suggesting that their behaviour should be evaluated with further site-specific investigations to provide more confidence in the liquefaction vulnerability classification. These deposits are of Late Pliocene to Middle Pleistocene age and would therefore be less likely to liquefy, however there is some uncertainty in this classification based on the evidence from site investigation data. As this indicates less confidence in the classification of these deposits based solely on the Level A approach, a *Liquefaction category is undetermined* classification is used for the Puketoka Formation.

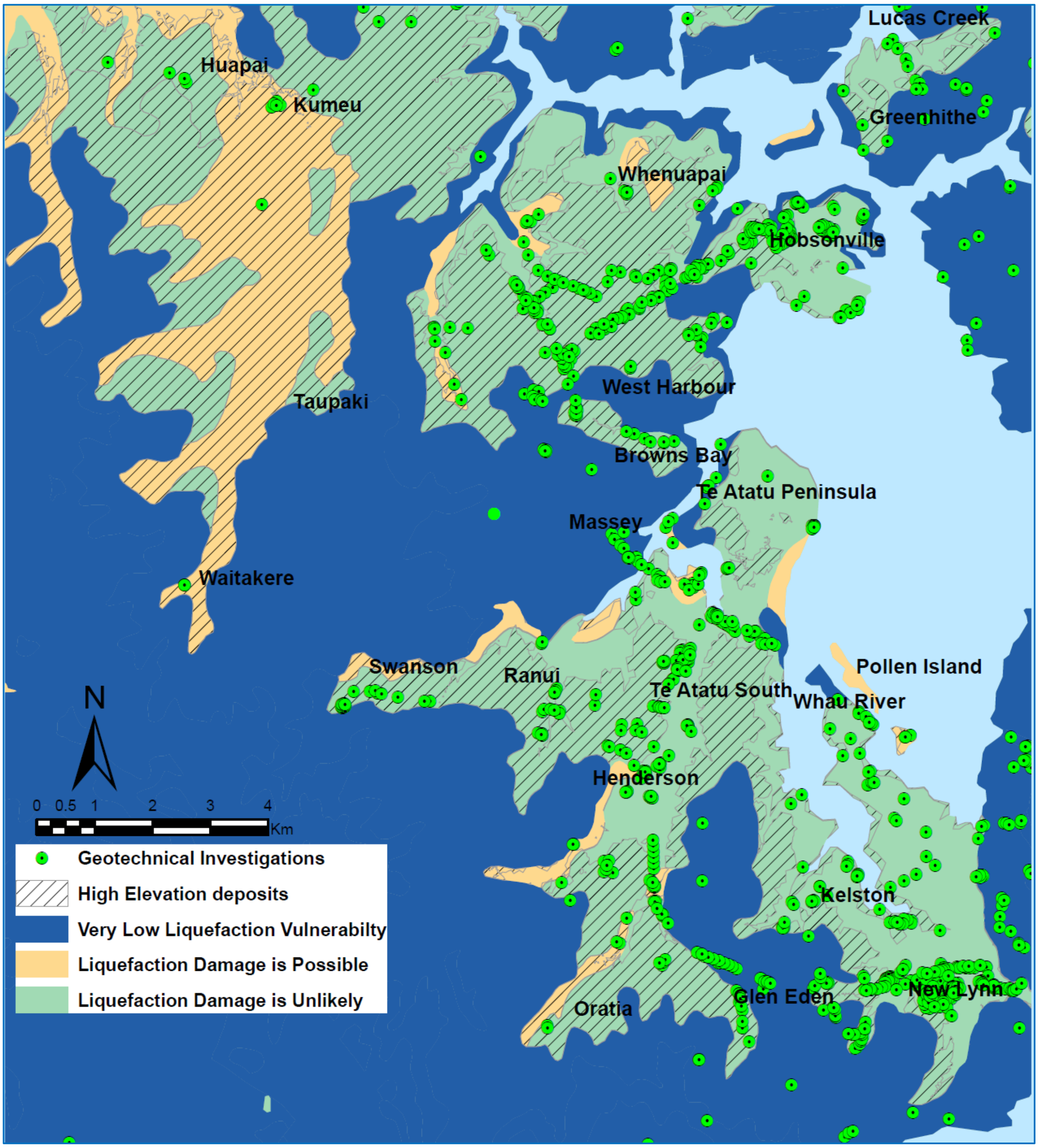


Figure 27: 'West' Focus Area suburbs investigated under Level B liquefaction assessment

5.7 'Central' Focus Area

Figure 28 shows the Level A categories in the Central Auckland suburbs with the available geotechnical investigations. These locations include areas in the proximity of the **Auckland Waterfront, Point Chevalier, Grey Lynn, Newmarket, Sandringham, Mission Bay, Mount Roskill, Ellerslie, Panmure, Mount Wellington, Kohimarama, Orakei Reserve, St Helier's Bay** and **Onehunga**. Areas with an elevation >20 m are also shown in Figure 28.

The **Auckland Waterfront** reclamation fills have been deposited over an extended time period and they are situated over Tauranga Group alluvium of varying thickness and East Coast Bays Formation. This fill consists of four major types: construction fill, excavated rockfill, hydraulic fill and industrial and domestic waste. The reclaimed areas along the waterfront from Mechanics Bay to Herne Bay have highly variable surface deposits across the different ages of reclamation. All these deposits conform to the *Liquefaction damage is possible* category. As there are a higher density of CPT soundings available in these areas, a detailed investigation (Level C) could inform a more refined category. However, this detail is outside the scope of the current project.

The **Point Chevalier** area has stiff clayey layers and sediments with volcanic content. The **Grey Lynn** area has surface fill that is plastic with volcanic content overlying ECBF. The **Newmarket area** has sandy, silty material, and although elevation is greater than 50 m the groundwater depth is shallow.

The areas along the waterfront in **Orakei Reserve, Mission Bay, Kohimarama** and **St Helier's Bay** all have loose sandy, silty soil layers overlying weathered ECBF.

The **Sandringham** area has basaltic ash and some organic clay. In the **Mount Roskill** area, the dominant near-surface stratigraphy is comprised of basalt and tuff, with the upper 8 m consisting of organic silt and peat. The average elevation is 60 m with shallow groundwater. Sand and silt layers are present at depths greater than 15 m, situated below volcanic deposits. **Onehunga** has fill material comprised of refuse, plastic ash layers, and sands, silts and clays.

Boreholes in **Ellerslie** show that the dominant deposits are tuff and basalt, although not indicated by geology maps. Soft silt deposits of thickness 1.5-2 m are also present up to depths of 3 m. The tuff material is highly weathered, weak and fine-grained.

Mt Wellington has silty clay and clayey silt with variable plasticity volcanic ash and Tauranga group deposits. **Panmure** has stiff clay and basaltic material. **Otahuhu** has a gravelly fill and also some sandy, silty soil layers.

Based on the above; **Point Chevalier, Panmure, Ellerslie, Mt Wellington, Mt Roskill** and **Sandringham** have some mixed stratigraphy which suggests that *Low liquefaction vulnerability* may be appropriate in some areas classified as *Liquefaction damage is possible*. However, there is still uncertainty in the overall material characteristics in these polygons based on limited number of investigation locations. Therefore, no refined classification is proposed for any of these areas. The investigation of boreholes in Puketoka Formation which were assigned *Liquefaction damage is unlikely* suggest that their behaviour should be evaluated with site-specific investigations for further revisions of the liquefaction maps, similar to the deposits in West Auckland. A *Liquefaction category is undetermined* classification is proposed for the Puketoka Formation in Central Auckland.

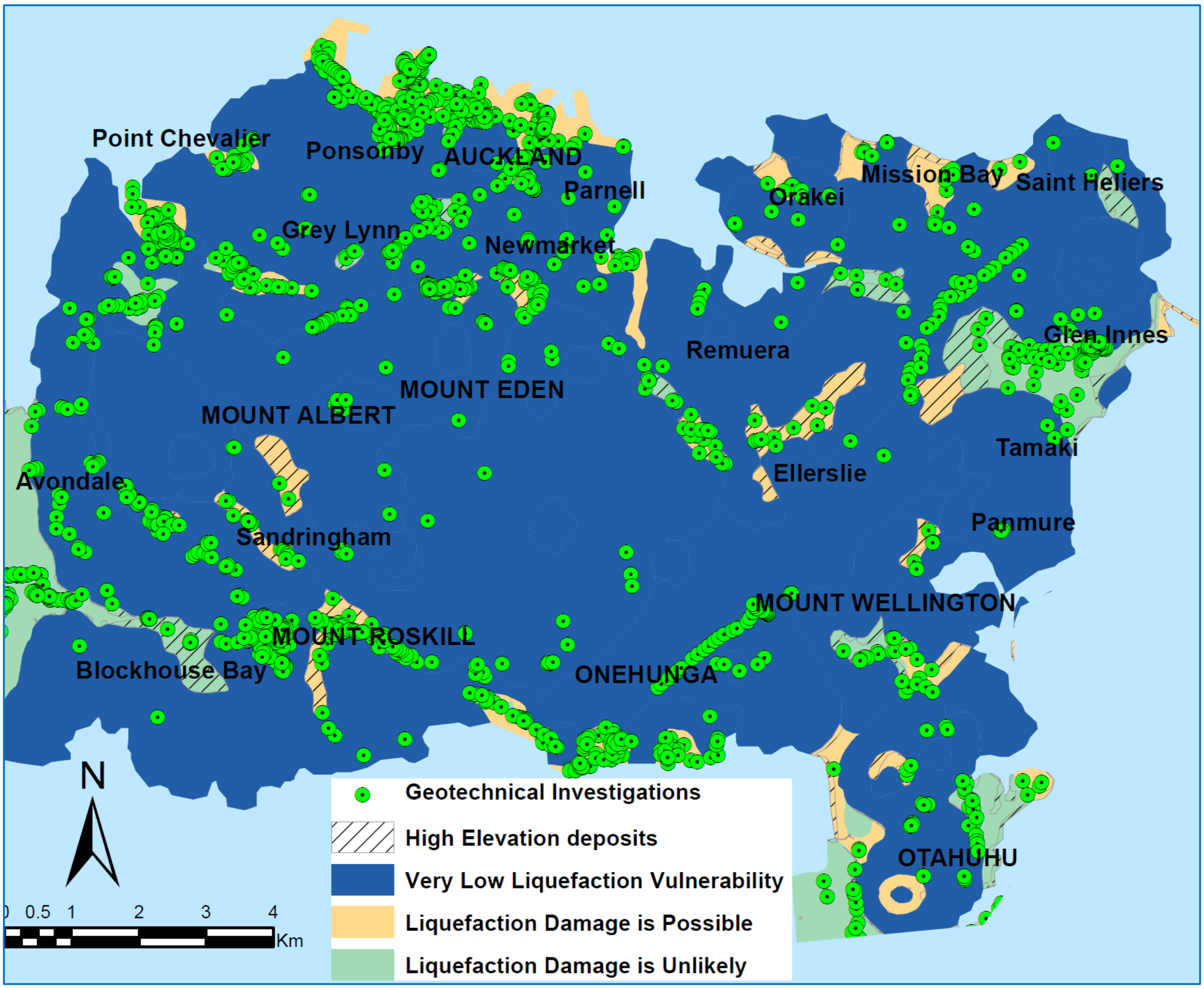


Figure 28: 'Central' Focus Area suburbs investigated under Level B liquefaction assessment

5.9 'South' Focus Area

Figure 29 shows the Level A categories in the South Auckland suburbs with the available geotechnical investigations. These locations include areas in Pakuranga, East Tamaki, Flat Bush, Mangere, Middlemore, Papatoetoe and Ormiston. Areas with an elevation >20 m are also shown in Figure 29.

The Pakuranga area shows the presence of clayey soil, and volcanic ash with high plasticity across discrete investigation locations, and elevations of 21-25 m. Part of East Tamaki in the focus area has some layers of silty, sandy soils with layers of peat and clay. The density of investigations is too low to assign a refined liquefaction vulnerability for these locations.

Ambury Regional Park has loose layers of sandy and silty soils with some volcanic ash and basalt which is not indicated by the geology map. The area towards Mangere Bridge has gravelly silty, sandy layers up to 2-3 m depth overlying basaltic layers. The Mangere area has more prominent sand layers at shallow depth with some clay intrusions.

Papatoetoe area has silty-sandy loose layers 6-7 m thick underlying 4-5 m of clayey soils. Investigation data shows that the Otara and East Tamaki areas have fill material (sandy) and sandy, silty loose layers. Gravelly deposits at the surface become sandy with some peat layers below 2-3 m depth.

The investigations near Wiri and Flat Bush area have silty soil layers to a depth of 5-6 m with surficial organic deposits of thickness 1-1.5 m. The investigation data towards the Ormiston area has upper layers of clay 3-4 m thick overlying silty layers 5-6 m in thickness. Overall, there is no significant variation in stratigraphy and material type across all investigation points.

This area is dominated by Puketoka Formation deposits that have been classified as *Liquefaction damage is unlikely* in the Level A assessment because of their depositional age. However, boreholes in the area indicate the presence of fill material with sand and silt, similar to observations from the West Auckland area. *Liquefaction category is undetermined* is used for the Puketoka Formation in this level of assessment as further detailed quantitative assessment will give confidence in assigning a liquefaction vulnerability category. A refined classification is not used for any of the other areas that have been assigned a *Liquefaction damage is possible* category under Level A assessment.

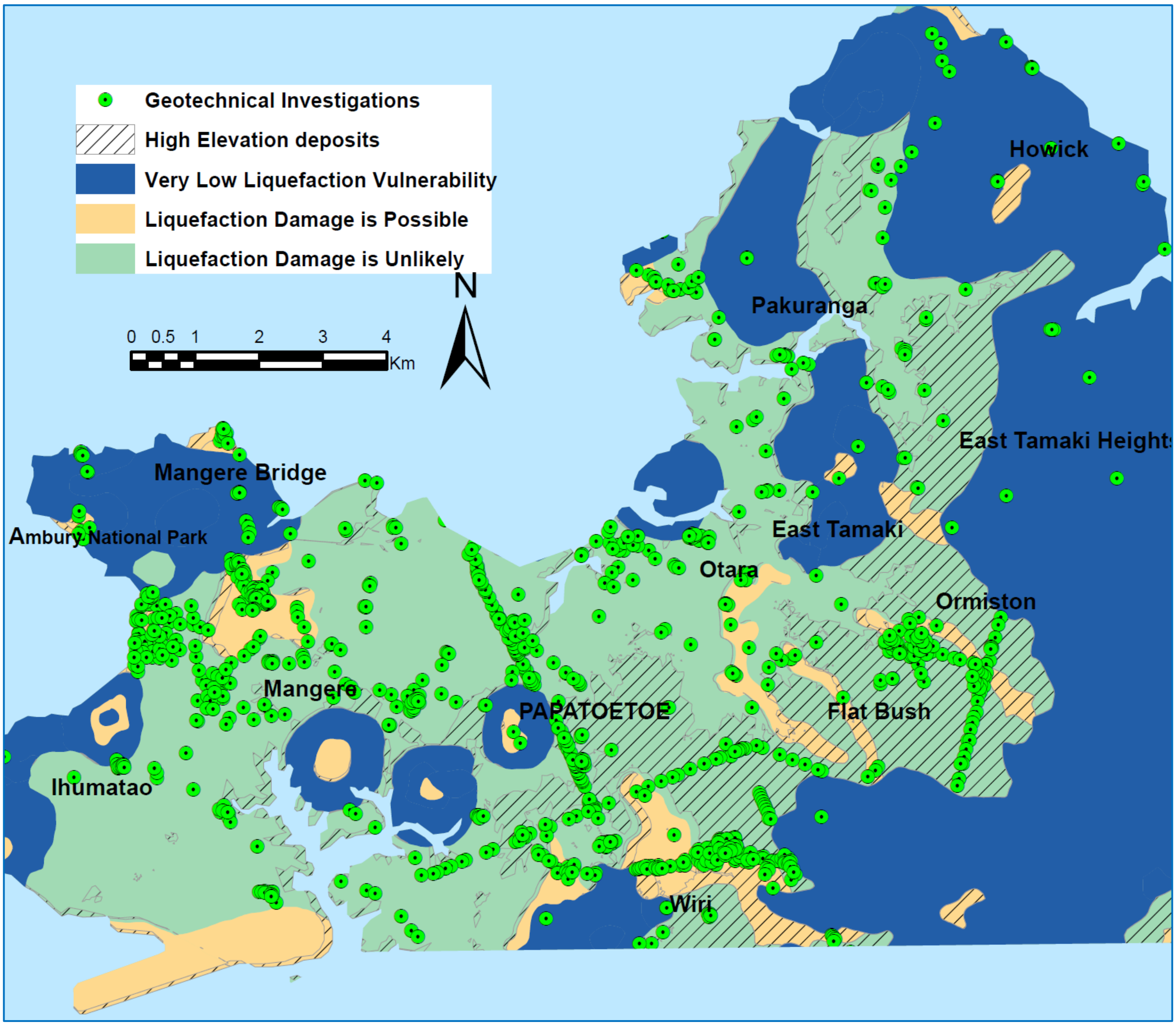


Figure 29: 'South' Focus Area suburbs investigated under Level B liquefaction assessment

5.10 'Further South' Focus Area

Figure 30 shows the Level A categories in the 'Further South' suburbs with available geotechnical investigations. These locations include areas in the suburbs of **Manurewa, Takanini,** and **Ardmore**. Areas with an elevation >20 m are also shown in Figure 30.

The Manurewa area has plastic clayey soil deposits up to 4 m thick, while below this there are volcanic sand deposits up to 5-8 m thick below the water table. Areas between **Takanini** and **Papakura** have high elevation >30 m with a stratigraphy that is changing significantly. There are deposits of sands, silts and organics, with some volcanic content. Few boreholes in Ardmore region show the presence of weathered gravelly silty material with volcanic content of plastic nature.

Based on the soils present and the density of investigations, no modifications have been applied to the Level A categorisation in this area.

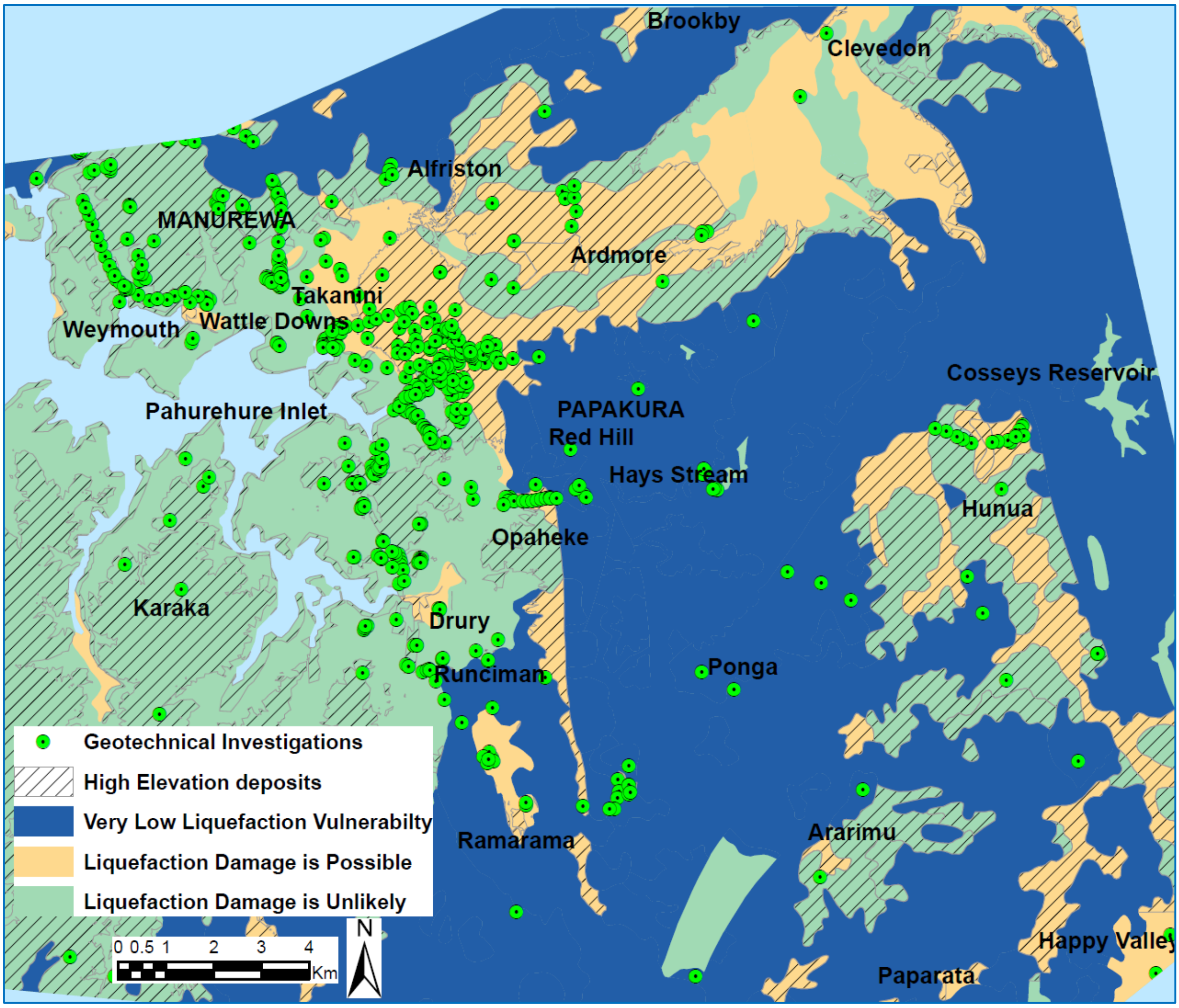


Figure 30: 'Further South' Focus Area suburbs investigated under Level B liquefaction assessment

5.11 Level B assessment summary

Geotechnical site investigation data in some areas that are classified as *Liquefaction damage is possible* according to a Level A assessment suggests that a refined category of *Low liquefaction vulnerability* is more appropriate given the deposits that are encountered in these areas. This is possible only for the areas where a good density of subsurface investigations is available. Being a regional level study, it is not possible to apply this change from *Liquefaction damage is possible* to *Low liquefaction vulnerability* to the whole region due to the current inconsistency in the density of the subsurface investigation data across the whole region. The updated categories used for the region for all the areas with a good density of investigations are shown in Figure 31, and Figure 32 shows the Level B categories for the Auckland's main urban region.

The Puketoka Formation deposits, which can be a loose sandy material with volcanic content, are prevalent across the region. Although the semi-quantitative criteria used in the Level A assessment suggests that these deposits are less likely to liquefy, geotechnical site investigation data indicates that they may liquefy and therefore there is less confidence in the Level A category of *Liquefaction damage is unlikely*. Given this lack of confidence, an updated classification of *Liquefaction category is undetermined* is used for these deposits.

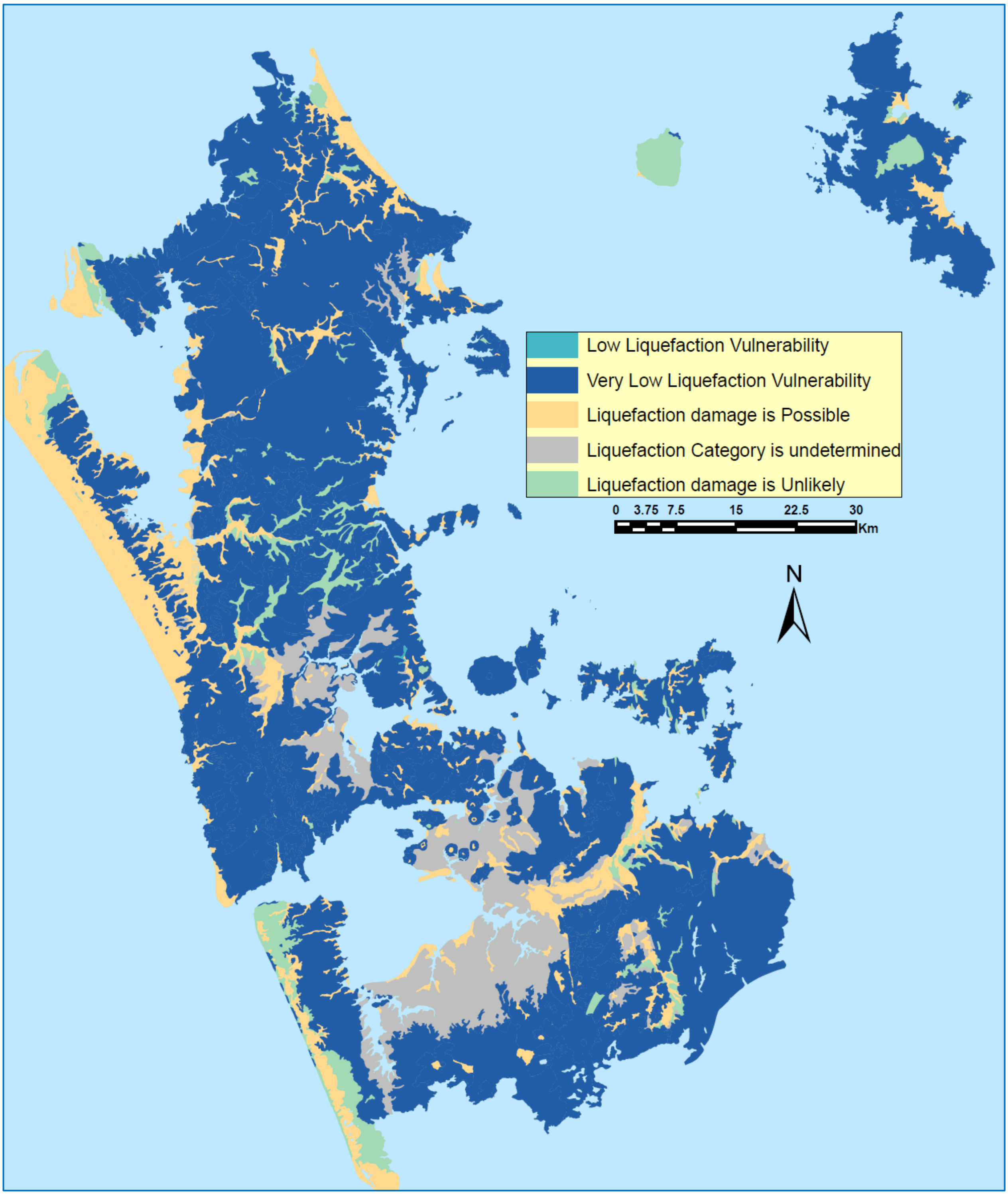


Figure 31: Summary of Level B assessment categories for the Greater Auckland region

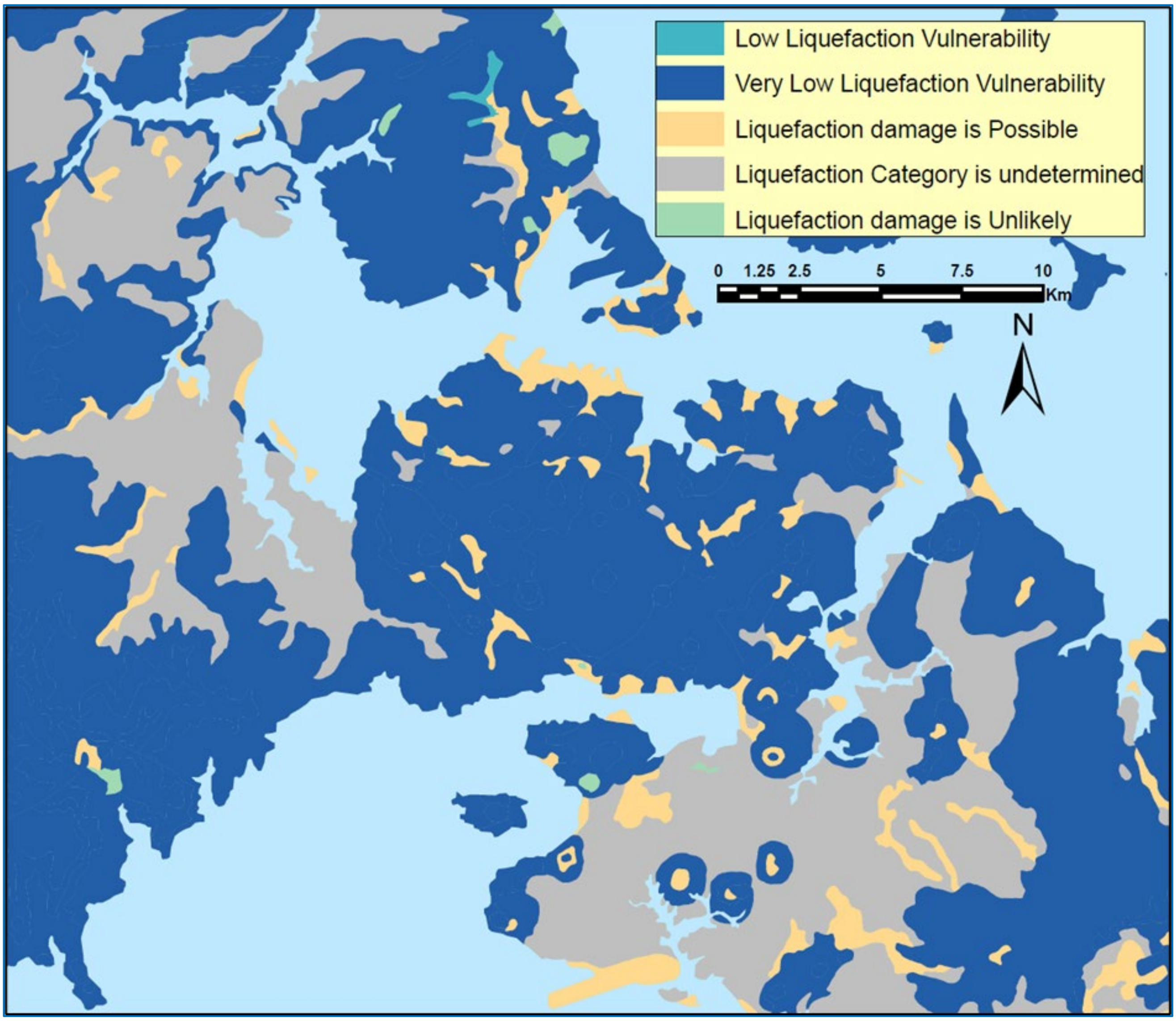


Figure 32: Summary of Level B assessment categories for Auckland urban region

6.0 Summary

This report has presented a liquefaction-induced ground damage assessment for the Auckland region based on the document *'Planning and engineering guidance for potentially liquefaction-prone land'* (MBIE/MfE/EQC 2017). Level A and Level B assessments are presented for the whole Auckland region.

The Level A geology-based assessment using geological maps, regional groundwater and seismic hazard information provided a high-level representation of the liquefaction vulnerability categories across the Auckland region. Exposed rock deposits that are not expected to liquefy were given a *Very Low* classification, removing them from further assessment. Young geological deposits were classified as *Liquefaction damage is possible* based on the simple screening assessment, with the remaining deposits in the region classified as *Liquefaction damage is unlikely*.

Geotechnical investigation data from across the region was used in Level B assessment to refine the Level A liquefaction vulnerability categories using qualitative screening approach. The changes in classification between Level A and B were discussed, in particular the areas where the liquefaction vulnerability of the soil profile was likely dominated by the presence of Puketoka Formation. All these deposits were assigned *Liquefaction damage is unlikely* in the Level A assessment because of their Late Pliocene to middle Pleistocene geologic age, however subsurface investigation data in these areas showed the presence of loose sandy, silty soils with pumice content in some areas. Based on the current understanding of the behaviour of the Puketoka Formation, there is insufficient investigation data to better refine their liquefaction potential. As a result, their classification based on Level B assessment has been changed to *Liquefaction category is undetermined*. For a large part of the remaining Auckland region there were no investigations available to be able to apply the Level B assessment, meaning no changes to the Level A assessment classifications could be made.

Glossary

Term	Definition
Desktop assessment	An assessment of land characteristics using information available without site work.
Digital elevation model	A topographic model of the ground surface.
Groundwater	Water held underground in pores in soil or rock.
Liquefaction	The process which causes some soil types to behave more like a liquid than a solid during an earthquake.
Liquefaction vulnerability	The potential for a particular location to experience liquefaction during an earthquake.
Hazard map	A hazard map shows the spatial extent of a specific hazard. It does not take into account the consequences of the hazard, which vary depending on the use of each site.
GeoMaps	Auckland Council's online mapping platform.
Groundwater abstraction	Removal of groundwater from the ground for human use or to change the characteristics of a site.
Ground acceleration	The acceleration experienced by the ground during an earthquake.
Groundwater aquiclude	Less permeable materials between beds of more permeable material which prevent or slow groundwater flow.
Perched groundwater	A zone of groundwater separated from an underlying body of groundwater by an unsaturated zone. It occurs when subsurface water percolating downward is held by a groundwater aquiclude.
Plasticity	Plasticity is the ability of a material to undergo permanent deformation under stress without cracking. Fine-grained soils often behave in plastic manner when wet, and this behaviour can reduce the susceptibility to liquefaction.
Q-map	A series of geological maps produced by GNS Science.
Qualitative assessment	An assessment of liquefaction potential using empirical data and expert judgement.
Quantitative assessment	An assessment of liquefaction potential using numerical data and mathematical models.
Seismic hazard	The probability of an earthquake of a particular size occurring in a given location.

References

Altaf, O., Wotherspoon L., Orense, R. (2021) *Liquefaction Vulnerability Maps for the Auckland Region,* Version 0.2. University of Auckland Uniservices

Auckland Council Code of Practice (2013). Land Development and Subdivision Chapter 2: *Earthworks and Geotechnical*

Auckland University Report *"Liquefaction Vulnerability Maps for the Auckland Region"* (2021)

Auckland Council (2014). *Auckland Profile: Initial results from the 2013 census*. Auckland.

Balance, P.F., Smith, I.E.M. (1982). *Walks through Auckland's geological past: a guide to the geological formations of Rangitoto, Motutapu, and Motuihe Islands*. Geoscience Society of New Zealand.

Boulanger, R. W., & Idriss, I. M. (2014). CPT and SPT-based liquefaction triggering procedures. Rep. No. UCD/CGM-14, 1

Building Government NZ; *Ensuring new buildings can withstand liquefaction effects*, https://www.building.govt.nz/building-code-compliance/geotechnical-education/ensuring-new-buildings-can-withstand-liquefaction-risks/#jumpto-changes-to-foundation-design

Dempsey, D., Eccles, J. D., Huang, J., Jeong, S., Nicolin, E., Stolte, A., & Bradley, B. A. (2020). Ground motion simulation of hypothetical earthquakes in the upper North Island of New Zealand. *New Zealand Journal of Geology and Geophysics*, 1-19

Dowrick, D.J. (1992). Seismic hazard estimates for the Auckland area, and their design and construction implications. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 25(3): 211-221.

Edbrooke, SW, Mazengarb, C & Stephenson, W (2003). 'Geology and geological hazards of the Auckland urban area, New Zealand', *Quaternary International*, Vol. 103, No. 1, pp. 3–21.

Kenny J.A., Lindsay J.M., Howe T.M. (2011). *Large-scale faulting in the Auckland region*. Technical Report 1-2011.04 Institute of Earth Science and Engineering (IESE)

Kermode, L. (1992). *Geology of the Auckland Urban Area: Sheet R11: 1: 50 000*. Institute of Geological & Nuclear Sciences.

Ministry of Business, Innovation and Employment (MBIE) document *"Planning and engineering guidance for potentially liquefaction-prone land"* (MBIE/MfE/EQC 2017).

NZ Transport Agency (2013). *Bridge Manual*, SP/M/022 Version 3.

Pyke, R. (2003). Discussion of "*Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils*" by TL Youd, IM Idriss, Ronald D. Andrus, Ignacio Arango, Gonzalo Castro, John T. Christian, Richardo Dobry, WD Liam Finn, Leslie F. Harder Jr., Mary Ellen Hynes, Kenji Ishihara, Joseph P. Koester, Sam SC Liao, William F. Marcuson III, Geoffrey R. Martin, James K. Mitchell, Yoshiharu Moriwaki, Maurice S. Power, Peter K. Robertson, Raymond B. Journal of Geotechnical and Geoenvironmental Engineering, 129(3), 283-284.

Searle, E.J & Mayhill, R.D. (1981).*City of Volcanoes: A Geology of Aucklan*d (2nd edition), Longman Paul.

Seed, H. B., and Idriss, I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. J. Soil Mechanics and Foundations Div., ASCE 97(SM9), 1249–273.

Seed, H. B., Tokimatsu, K., Harder, L. F. Jr., and Chung, R. (1985). Influence of SPT procedures in soil liquefaction resistance evaluations, *J. Geotechnical Eng*., ASCE 111(12), 1425–445

Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Van Dissen, R., Berryman, K. & Jacobs, K. (2012). National seismic hazard model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America,* 102(4), 1514-1542.

Youd, T. L., & Idriss, I. M. & NCEER workshop Participants (2001). Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental Engineering*, 127(4), 297-313.

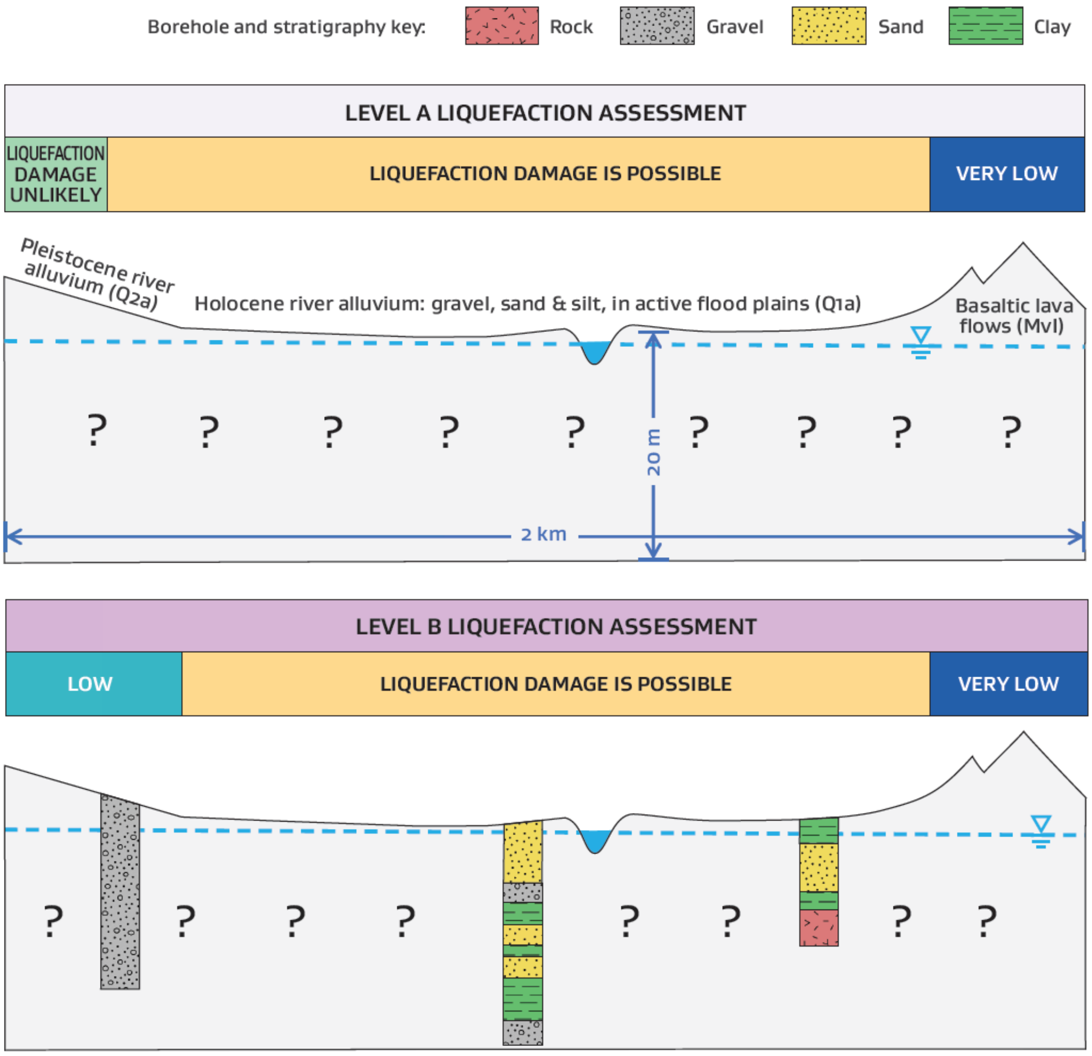
Youd, T. L., & Perkins, D. M. (1978). Mapping liquefaction-induced ground failure potential. *Journal of the Soil Mechanics and Foundations Division*, 104(4), 433-446.Idriss and Boulanger (2008)

Appendix A: Conceptual example of difference in subsurface ground information

Conceptual example of the difference in subsurface ground information for Level A, B, C and D liquefaction assessments:

Level A – Only basic surface geology and groundwater information is available. Areas are identified where ***Liquefaction Damage Is Unlikely*** (Pleistocene deposits with groundwater deeper than 4 m) and with ***Very Low*** liquefaction vulnerability (exposed rock). Substantial uncertainty remains regarding subsurface conditions elsewhere, but the nature of the deposits means that ***Liquefaction Damage Is Possible***.

Level B – A small number of subsurface investigations provides a better understanding of liquefaction susceptibility for the mapped deposits. This shows that the Pleistocene deposits comprise gravel to the surface, with ***Low*** liquefaction vulnerability. Significant uncertainty remains regarding the level of liquefaction-related risk for the Holocene deposits and how ground conditions vary across the area.



Explanation of Level A and Level B assessment (MBIE / MfE Guidance Figure 3.1)

Appendix B: Degrees of liquefaction-induced ground damage

DEGREE OF LIQUEFACTION-INDUCED GROUND DAMAGE (example photographs)	TYPICAL CONSEQUENCES AT THE GROUND SURFACE These are examples of the type of damage that would be expected, they are not intended to be criteria for calculation
None to Minor 	– ***None to Minor*** no signs of ejected liquefied material at the ground surface[1]. – No more than minor differential settlement of the ground surface (eg undulations less than 25 mm in height). – No apparent lateral spreading ground movement (eg only hairline ground cracks). – Liquefaction causes no or only cosmetic damage to buildings and infrastructure (but damage may still occur due to other earthquake effects).
Minor to Moderate 	– ***Minor to Moderate*** quantities of ejected liquefied material at the ground surface (eg less than 25 percent of a typical residential site covered[2]); and/or – Moderate differential settlement of the ground surface (eg undulations 25–100 mm in height). – No significant lateral spreading ground movement (eg ground cracks less than 50 mm wide may be present, but pattern of cracking suggests the cause is primarily ground oscillation or settlement rather than lateral spreading). – Liquefaction causes moderate but typically repairable damage to buildings and infrastructure. Damage may be substantially less where liquefaction was addressed during design (eg enhanced foundations).
Moderate to Severe 	– Large quantities of ejected liquefied material at the ground surface (eg more than 25 percent of a typical residential site covered[2]); and/or – ***Moderate to Severe*** differential settlement of the ground surface (eg undulations more than 100 mm in height); and/or – Significant lateral spreading ground movement (eg ground cracks greater than 50 mm wide, with pattern of cracking suggesting direction of movement downslope or towards a free-face). – Liquefaction causes substantial damage and disruption to buildings and infrastructure, and repair may be difficult or uneconomic in some cases. Damage may be substantially less, and more likely to be repairable, where liquefaction was addressed during design (eg enhanced foundations and robust infrastructure detailing).

Notes:

1 An absence of ejecta at the ground surface does not necessarily mean that liquefaction has not occurred. Liquefaction may still occur at depth, potentially causing ground settlement.

2 The coverage of the site with ejected liquefied material does not in itself represent ground damage in an engineering sense, however there is a strong correlation between the volume of ejecta and the severity of differential ground settlement and foundation/infrastructure damage.

Degrees of liquefaction-induced ground damage used in the land performance framework. (MBIE / MfE Guidance Figure 41)

Appendix C: Liquefaction vulnerability maps for the Auckland region

Auckland University Report “Liquefaction Vulnerability Maps for the Auckland Region” (2021)

Liquefaction Vulnerability Maps for the Auckland Region

Omer Altaf, Liam Wotherspoon, Rolando Orense

University of Auckland

Uniservices

V 0.2

This page is intentionally left blank.

Executive Summary

This report summarises a liquefaction-induced ground damage assessment for the Auckland Region based on the 'Planning and engineering guidance for potentially liquefaction-prone land' (MBIE/MfE/EQC 2017). The methodology and datasets that were used are summarised in this report and a suite of maps of liquefaction vulnerability categories presented.

Data availability defined the level of assessment detail that was appropriate across the region based on the guidance. At the highest level (Level A), this is based on geological, groundwater and seismic hazard data. Exposed rock deposits will not liquefy and are assigned a liquefaction vulnerability category of *Very Low*. Areas having young geologic deposits of fills, sand, silt, gravel, swamps, deposits of Holocene age are categorised as *Liquefaction damage is possible*. Other areas with older deposits or deeper groundwater tables are classified as *Liquefaction damage is unlikely* based on the Level A classification approach.

To refine the Level A classification, qualitative screening is carried out using geotechnical investigation and topographic data (Level B). The key changes were in areas where the liquefaction vulnerability of the soil profile is dominated by the Puketoka Formation. This formation contains pumice in some areas, with behaviours that may differ from deposits without these volcanic materials. Based on the current understanding of the behaviour of the Puketoka Formation, more investigation is needed to better constrain their liquefaction potential. For these reasons the classification in these areas is changed to *Liquefaction category is undetermined.*

The most detailed liquefaction vulnerability classifications are defined using CPT-based liquefaction assessment procedures (Level C). As detailed liquefaction assessment for the entire Auckland region is not possible given the low density of CPT soundings in most areas, this is only applied to a few select areas A demonstration of the application of the Level C assessment in two areas with a good density of CPTs is presented, showing how classifications can change as more investigation data becomes available.

Table of Contents

1 INTRODUCTION

This report summarises a liquefaction vulnerability assessment for the Auckland region. The primary objective of this assessment is the development of a representation of the spatial distribution of liquefaction vulnerability across the region. This report includes the following information for the study area:

- Geological and geotechnical conditions
- Near-surface groundwater characteristics
- Seismic shaking hazard
- Assessment of the likelihood of liquefaction-induced land damage

1.1 Background

Existing liquefaction susceptibility mapping in the Auckland region was developed as part of the Auckland Engineering Lifelines Project-stage 1, 1997 (ARC 1997). Liquefaction susceptibility mapping of the Auckland region was developed with consideration of the geology of the region is shown in Figure 1. Soils were categorized into four liquefaction susceptibility classes. Class A were non-liquefiable deposits and classes B, C and D were soils susceptible to liquefaction, including pumiceous deposits, coastal and dune deposits, fills, alluvial and Holocene age estuarine deposits. This map was developed based on the identification of soils potentially susceptible to liquefaction as a result of ground shaking associated with a 2000-year return period earthquake in the Auckland region. The liquefaction susceptibility map was assessed both in terms of a uniform hazard model for the Auckland region and a scenario earthquake of magnitude 6.0 with an epicentre within 20 km of Auckland. The report provides a high-level review of the hazards, however, this report was produced in 1997, and therefore precedes the current New Zealand national seismic hazard model (Stirling et al. 2012). In addition, the understanding of land response to earthquake shaking and liquefaction potential has evolved significantly since the Canterbury earthquake sequence.

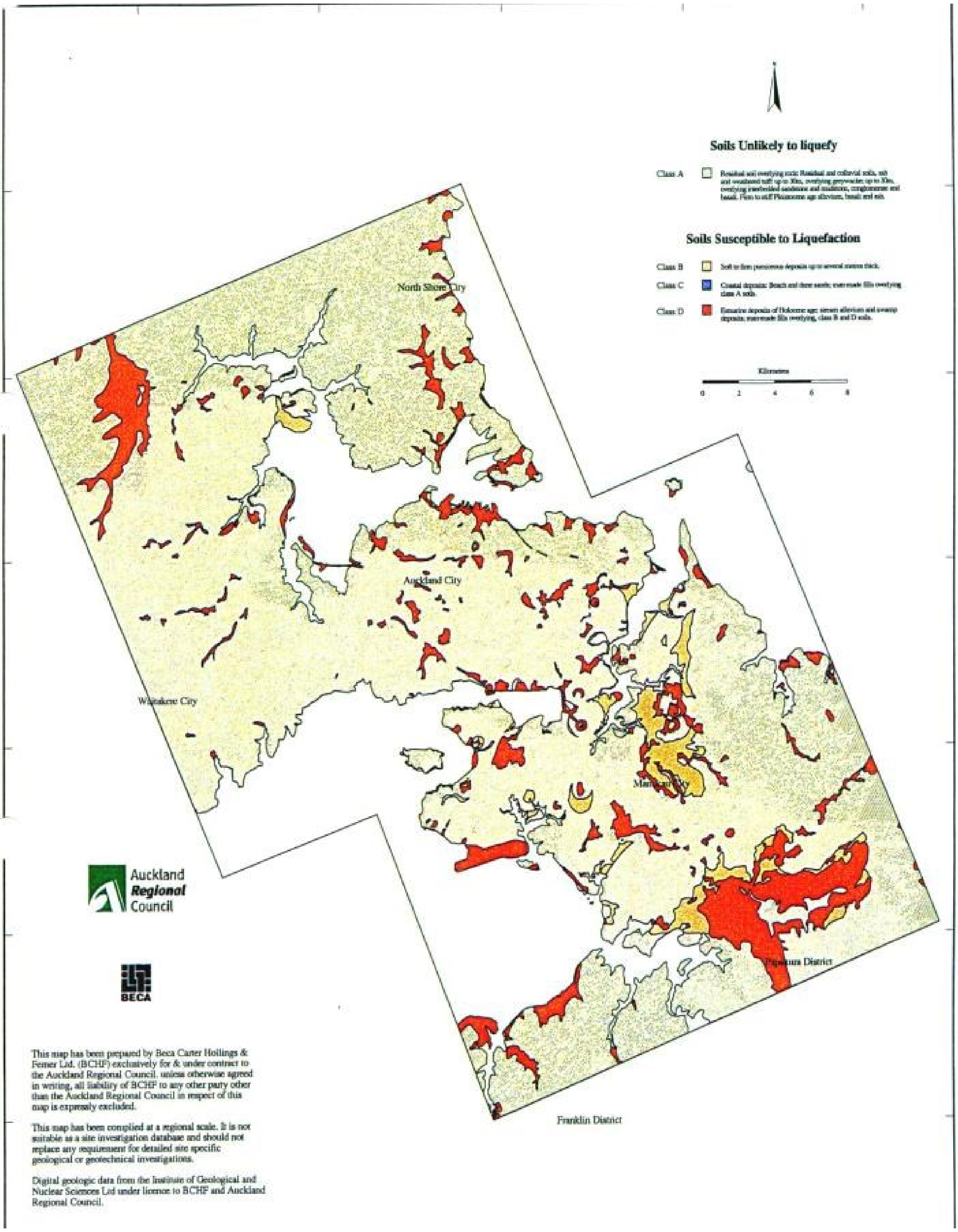


Figure 1: Liquefiable soils in Auckland main urban region identified in AELP stage 1 report, 1997 (ARC 1977).

1.2 Scope of work

The scope of work presented in this report comprises the collation of all available data within the study area to inform a liquefaction vulnerability assessment based on the 'Planning and engineering guidance for potentially liquefaction-prone land' (MBIE/MfE/EQC 2017). This is referred to as the MBIE Guidance throughout the remainder of this report. The extent of the study area is summarised in Figure 1.

The following data was collated to inform this study:

- Geological and digital elevation model data
- Geotechnical site investigation data
- Groundwater information from hydrologic observation wells and geotechnical sources

This data was used to inform the appropriate level of assessment detail across the study area based on the MBIE Guidance. Liquefaction vulnerability categories are developed for using geological, groundwater and seismic hazard data through a high-level assessment for the Auckland region. Qualitative calibration using geotechnical investigations and a regional digital elevation model inform this high-level assessment.

Based on the limited availability and density of geotechnical investigations compared to the extent of the study area, a detailed investigation is provided only as a demonstration of the application of MBIE guidelines but was not used to reclassify the geology-based high-level classification. For this, a cone penetration test (CPT) dataset was used with the seismic hazard and groundwater data to provide an assessment of the liquefaction hazard for a range of return period shaking scenarios.

The output of this scope of work is a GIS layer of liquefaction vulnerability categories for the study area based on geology, with this supporting report.

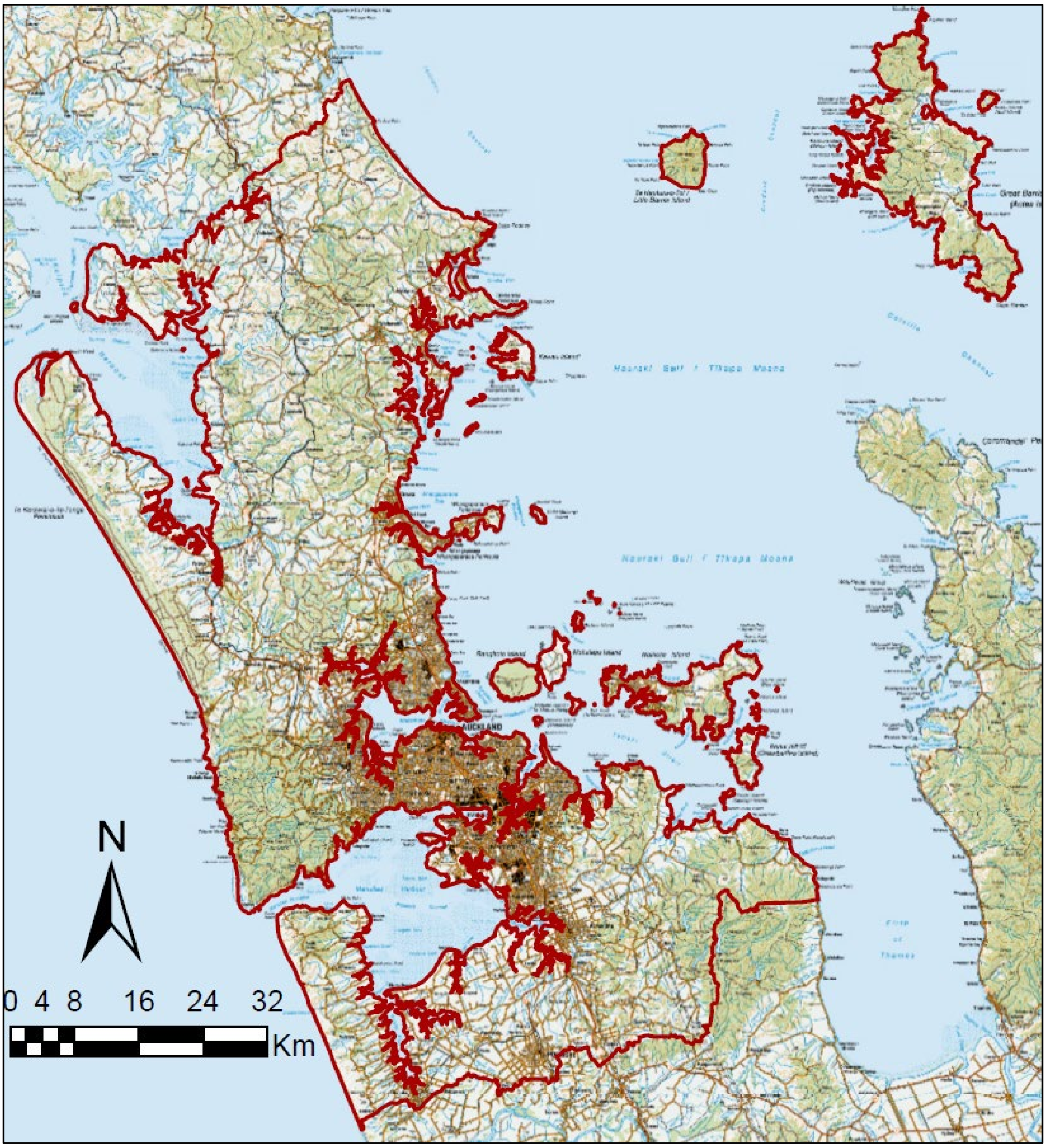


Figure 2: Geographic location and extent of the study area - Auckland region

2 METHODOLOGY

In order to develop liquefaction vulnerability categories for the Auckland region, the methodology presented in MBIE Guidance summarised in Figure 3 is applied. Liquefaction vulnerability categories are based on performance criteria that relate a category to the probability of different levels of liquefaction-induced ground damage severity for a given return period of ground shaking.

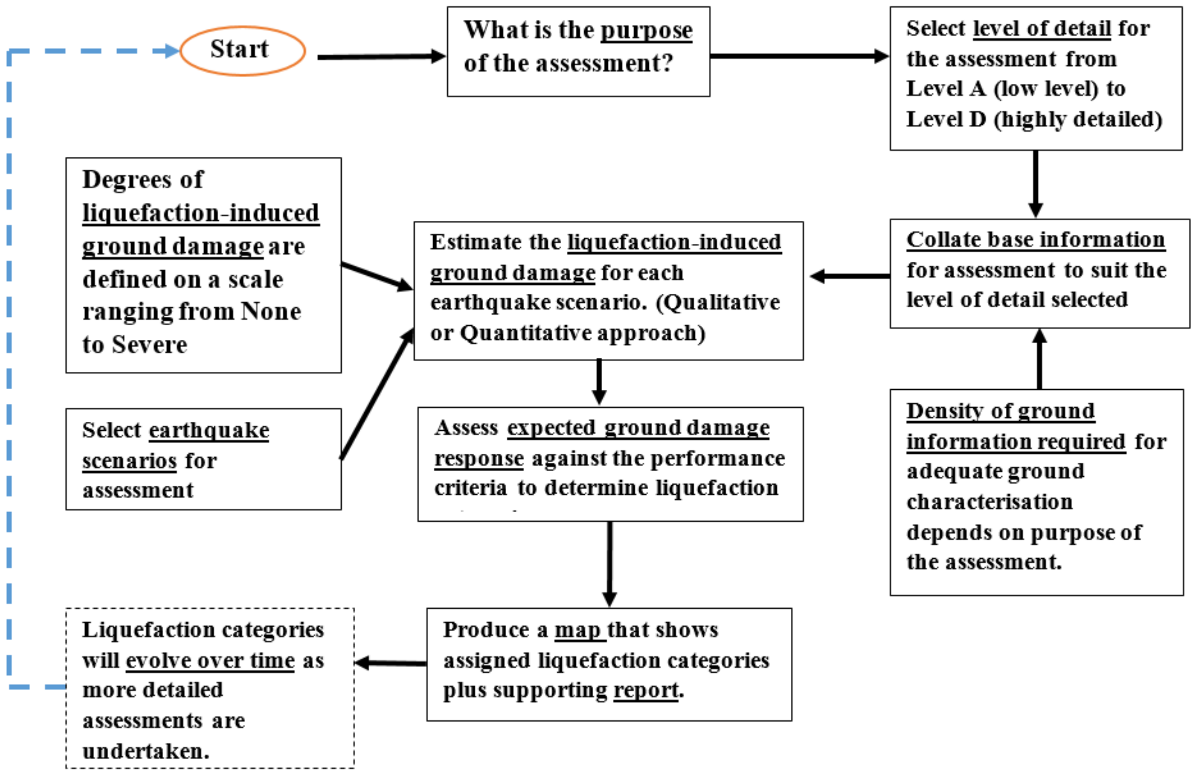


Figure 3: Overview of the recommended process for categorizing the potential for liquefaction-induced ground damage (MBIE/MfE/EQC 2017).

The first step in this methodology is the definition of the level of detail for the assessment so that the required level of data and resources can be defined. Figure 4 summarises the different levels of detail of the liquefaction assessment approach from the MBIE Guidance. Three levels of assessment are discussed in this study: Level A, B and C.

Level A is a basic desktop assessment, Level B is a calibrated desktop assessment and Level C is a detailed region-wide assessment. These are discussed in more detail in the following sections.

The liquefaction vulnerability categories assigned in each level of assessment are summarised in Figure 5. As the spatial density of available information increases, the precision of categorisation can increase. The default vulnerability category is *Liquefaction category is Undetermined*. This is assigned to areas where a liquefaction assessment has yet to be undertaken, or if there is not enough information to define an appropriate category. The remaining categories are defined based on the probability of different ground damage severities for 500-year return period ground shaking, and in some cases, 100-year return period ground shaking. When undertaking a liquefaction assessment using a desktop approach, it is typical to focus on whether *Liquefaction damage is unlikely*, where there is a greater than 85% probability of none-minor ground damage for a 500-year event, *or Liquefaction damage is possible*, where there is a greater than 15% probability of minor-moderate ground damage for a 500-year event. For Level A and Level B assessments, it is often not possible to assign liquefaction vulnerability categories with any more precision than this. In some cases, a more precise category can be assigned with confidence, such as a *Very Low* category for exposed rock outcrops. Due to the large extent of the study area and lack of required density of geotechnical investigation data across most of the region, liquefaction vulnerability maps can only be produced based on Level A and B assessments. Level C assessments can shift the classification to more refined categories of *Very Low*, *Low*, *Medium* and *High* for areas where a high spatial density of site investigation data is available. These details are discussed in subsequent sections of the report. As a demonstration of the application of MBIE guidelines, detailed level-C assessment based on CPT soundings and performance criteria is provided in this report for the areas where a higher density of investigations are available.

The probabilities used as part of the liquefaction vulnerability assessment are intended to be a general guidance framework rather than targets for a specific calculation. They are used along with qualitative and quantitative estimates of the uncertainty associated with the input data used to define an appropriate liquefaction vulnerability category. This is discussed in relation to each level of assessment applied in this report.

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 4: Levels of detail for liquefaction assessment studies (MBIE/MfE/EQC 2017).

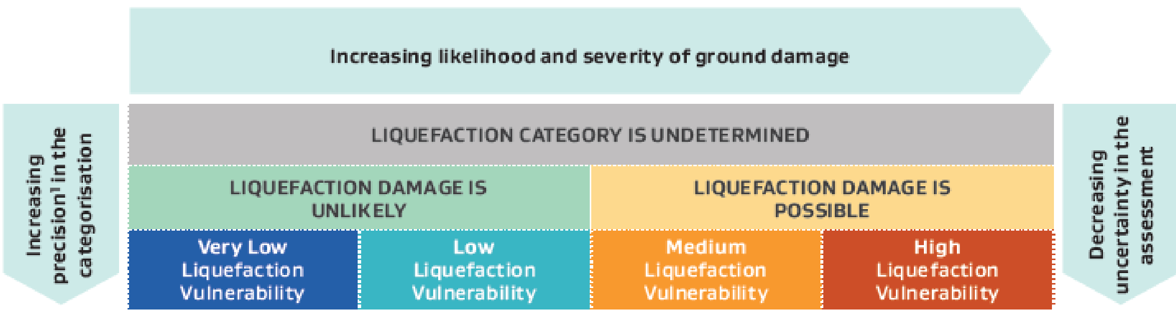


Figure 5: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform the planning and consenting process (MBIE/MfE/EQC 2017).

2.1 Level A assessment

The Level A assessment is a basic desktop study that utilises surface geology, groundwater and seismic hazard characteristics to classify the liquefaction potential. One of the primary focuses of this assessment is to identify land where *Liquefaction damage is unlikely* so that it can be removed from further assessment. Where there is enough confidence in the available data, the remaining areas can be classified as *Liquefaction damage is possible*. Areas where there is not enough information to determine an appropriate category can be classified as *Liquefaction category is undetermined*.

Potentially liquefiable deposits are defined based on the classification by Youd & Perkins (1978) and other researchers (Pyke 2003, Youd et al. 2001). This geology-based classification considers the regional seismic hazard and the depth to groundwater in conjunction with the age and depositional processes that formed the soil deposits. A semi-quantitative screening criterion illustrated in Table 1 is used in the MBIE Guidance to identify geological units where liquefaction-induced ground damage is unlikely to occur. A specific soil deposit can be assigned a liquefaction vulnerability category of *Liquefaction damage is unlikely* if the 500-year return period peak ground acceleration (PGA) is less than the value listed, or if the depth to groundwater is greater than the value listed. The listed PGA values in Table 1 correspond to a moment magnitude (M_w) 7.5 earthquake. For screening purposes using this table, earthquake scenarios with different magnitudes may be scaled using the magnitude scaling factor (MSF) proposed by Idriss and Boulanger (2008):

MSF = [6.9 exp (-Mw/4) – 0.058], up to a maximum value of 1.8.

For example, for a region where the design magnitude is less than 7.5, the limit for a M_w7.5 in Table 1 will be multiplied by the MSF to define the limit for an equivalent earthquake. This will result in a larger PGA, such that the two situations have a similar PGA-M_w combination outcomes in terms of input energy from the earthquake.

Table 1: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely based on a M_w7.5 earthquake (MBIE/MfE/EQC 2017).

Type of soil deposits	A Liquefaction Vulnerability category of *Liquefaction damage is unlikely* can be assigned if either of these conditions are met:	
	Design peak ground acceleration (PGA) for the 500-year intensity of earthquake shaking	**Depth to groundwater**
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	< 0.1 g	> 8 m
Holocene age Less than 11,000 years old	< 0.2 g	> 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.3 g	> 4 m

2.2 Level B assessment

The Level B assessment is a calibrated desktop assessment, where the details from the Level A assessment are further refined using additional datasets that can clarify the subsurface characteristics and land performance. Qualitative assessment using simple screening criteria based on a digital elevation model and geotechnical investigations can identify areas where there is potential for liquefaction-induced ground damage to occur, or the landform suggests it may have occurred in the past. This can inform the calibration of the liquefaction vulnerability categories from Level A, with any other regional information on subsurface deposits fed into this calibrated assessment.

2.3 Level C assessment

The Level C assessment is a detailed area-wide assessment based on cone penetration test (CPT) soundings and applies a quantitative approach. These CPT soundings from across the region are used to estimate the degree of liquefaction-induced ground damage for a range of peak ground accelerations (PGA) and earthquake magnitudes that are representative of the seismic hazard for the region. There are currently not enough CPT soundings to apply this level of classification over the entire Auckland region. Therefore, a demonstration of this assessment is provided in this report and information on more refined liquefaction vulnerability categories for the areas where high enough density of CPT soundings are available. These outputs can also be fed back into the calibrated desktop assessment as the level of certainty is not high enough to inform the *Very Low – High* vulnerability categories.

CPT sounding data, the seismic hazard and the groundwater data discussed in the Level A assessment are used to estimate where liquefaction is expected to trigger (occur) within the soil profile of a particular site. The combined effect of this triggering throughout the soil profile is used to estimate the severity of liquefaction-induced land damage at the ground surface.

3 GROUND CONDITIONS

3.1 Auckland Geology

The deposits of the Auckland Region sit upon a basement of greywacke rock that outcrop at many of the islands in the Hauraki Gulf, the Hunua Ranges, and land south of Port Waikato. The Waitakere Ranges in the west are the remains of a large andesitic volcano. The main isthmus and North Shore are composed of Waitemata group sandstone and mudstone, and portions of the Northland Allochthon extend as far south as Albany. The Manukau and South Kaipara Harbours are protected by the recent sand dune deposits of the Awhitu and South Kaipara Peninsulas. Recent basaltic volcanic activity has produced a number of volcanic cones throughout the Auckland Region. Figure 6 presents the geology for the Auckland region based on Edbrooke et al. (2003), and Figure 7 presents the geology of Auckland’s main urban regions.

The basement of the region is composed of greywacke as part of Waipapa group. East Coast Bays Formation interbedded with sandstone and mudstone are present above the basement. The regions where this material outcrops are highly weathered at the ground surface. Alluvial deposits are present across the region as a part of the Puketoka Formation. These deposits are present in valleys and in low-lying areas, with large swamps and peat deposits are also present (Kermode, 1992; Edbrooke et al., 2003).

One of the main features of Auckland geology is Auckland Volcanic Field. The Auckland Volcanic Field is an area of monogenetic volcanoes that covers much of the metropolitan area of Auckland. These have produced a diverse array of explosion craters, tuff rings, scoria cones, and lava flows. Each volcano has erupted for just one period, lasting for weeks to several years, except for Rangitoto Island, which erupted repeatedly. The field is fuelled entirely by basaltic magma, unlike the explosive subduction-driven volcanism in the central North Island, such as at Mount Ruapehu and Lake Taupo. The Auckland Volcanic Field has a great influence on the overall geologic setting of the Auckland region. Highly variable basaltic deposits are present at many locations and overlie the original strata. These volcanic deposits consist of tuff, basalt, ash, pumice and scoria (Searle and Mayhill 1981; Balance and Smith 1982). Figure 8 shows the distribution of different volcanic deposits and deposits with volcanic content in the Auckland region.

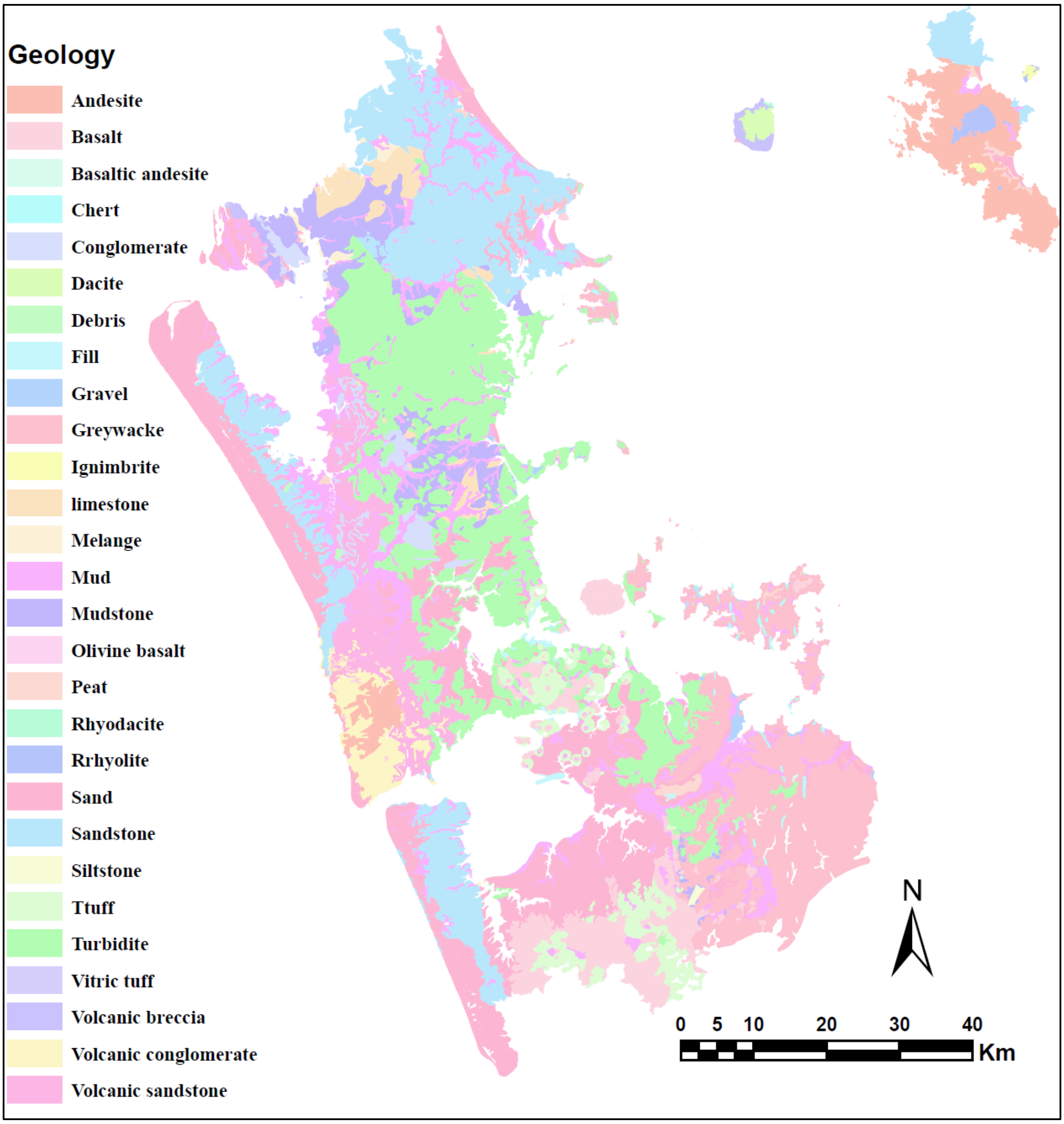


Figure 6: Geologic map of the Auckland Region (based on Edbrooke et al., 2003).

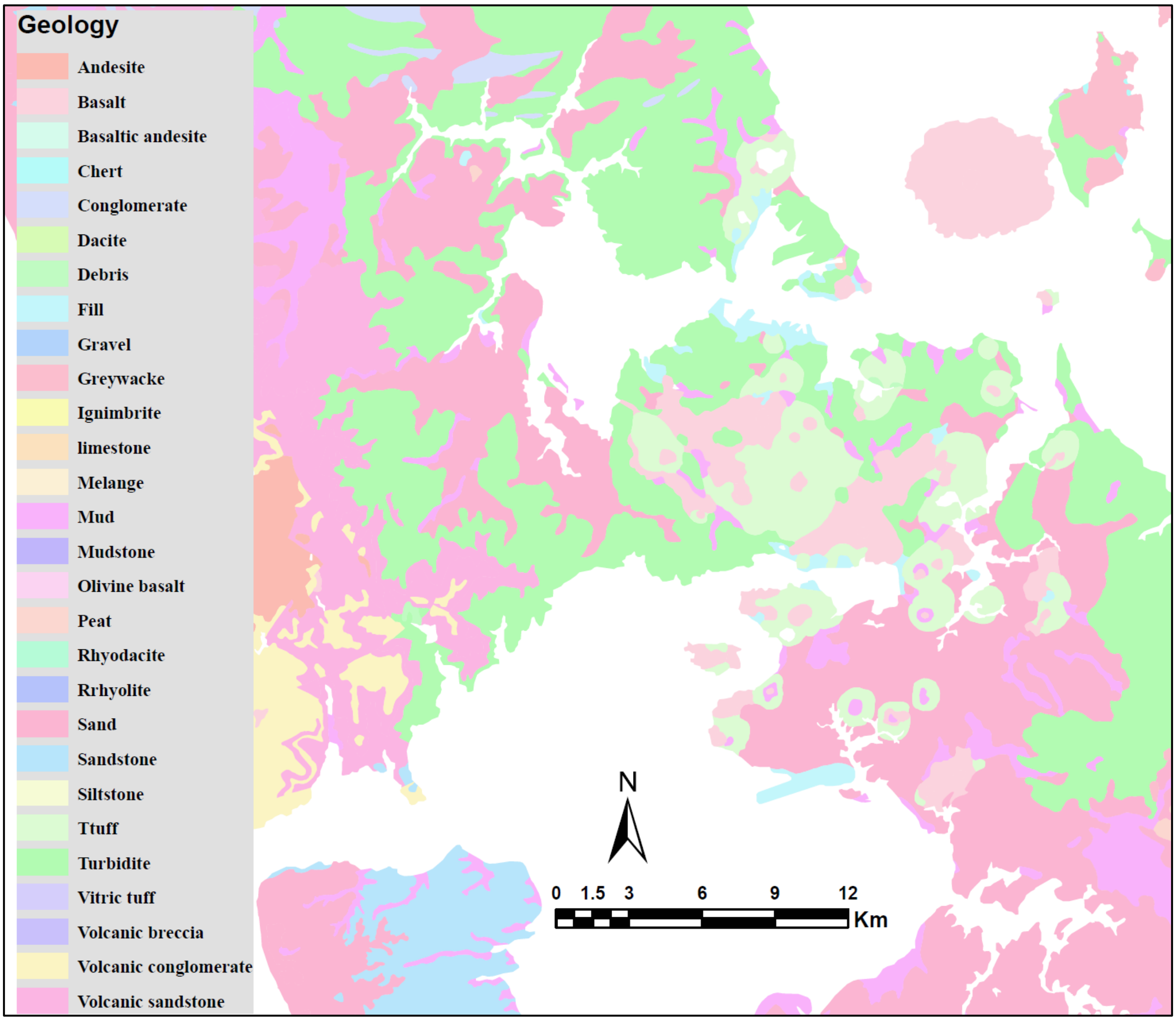


Figure 7: Geologic map of Auckland's main urban region (based on Edbrooke et al., 2003).

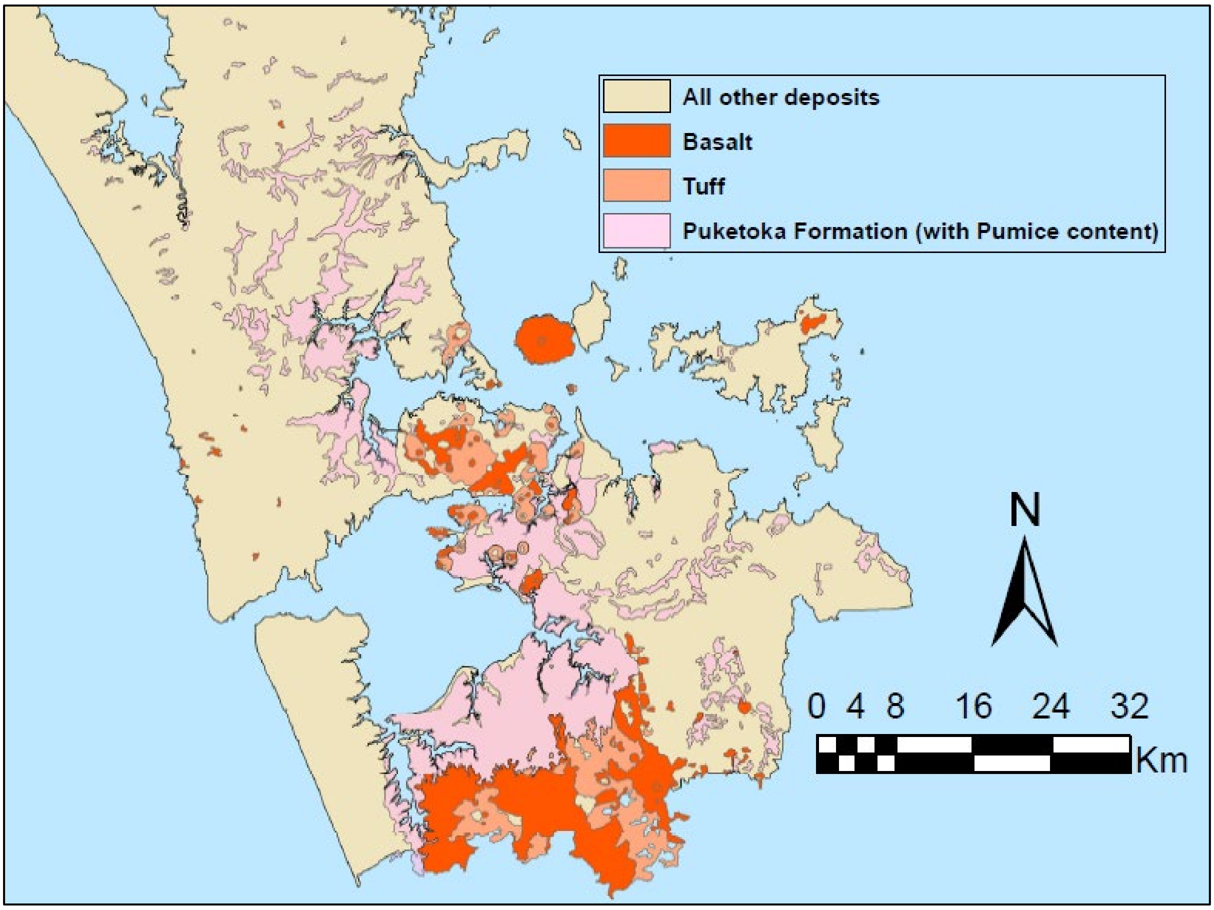


Figure 8: Distribution of areas of volcanic deposits and deposits with volcanic content in the Auckland Region.

3.2 Groundwater

Near-surface groundwater conditions are an important consideration for liquefaction vulnerability assessment and can be informed through the collation of geotechnical investigation data, observation monitoring wells and other hydrogeological information. However, the reliability of specific groundwater data for application in this context can be influenced by changes in groundwater regimes, climate influences, and shallow groundwater readings due to perched groundwater. It is possible that many of the groundwater monitoring wells are associated with groundwater abstraction from the regional aquifer and may be more representative of regional deep groundwater rather than near-surface perched groundwater. Due to these issues, it is not possible to develop a near-surface groundwater model with currently available information across the region.

Nonetheless, based on published geotechnical investigation reports across different areas of Auckland the following generalised groundwater conditions can be expected:

- Groundwater levels within coastal areas are likely to be within 2-3 m of the existing ground level (shallow depth to groundwater). The groundwater within low-lying coastal areas is likely to be influenced by tidal effects.
- Groundwater levels further inland will likely be present at depths of 3 m or more below ground level (deeper depth to groundwater).
- Groundwater flow is typically from elevated areas toward streams and creeks (river recharge from the surrounding environment), with resulting groundwater levels being closer to the surface near streams and creeks and within gullies.
- Groundwater aquicludes (interbedded less permeable materials) may exist in some areas allowing for the development of perched water tables and zones of seepage where intersected by sloping ground.

The above assumptions for groundwater are reasonable and care was taken in assigning liquefaction vulnerability categories both in Level A semi-quantitative criteria and demonstration of Level C detailed assessments in this study. It is recommended that groundwater monitoring instruments (piezometers) be installed during future geotechnical investigations to provide design inputs and confirm the assumed near-surface groundwater conditions outlined above for future detailed assessments.

3.3 Seismic hazard

It is generally considered that Auckland Region is one of New Zealand’s least seismically active regions, located approximately 300 km away from the boundary between Australian and Pacific tectonic plates (Dowrick 1992, Kenny et al. 2011, Stirling et al. 2012). Table 2 and Figure 9 summarise the recorded earthquakes in the Auckland region from the period of 1850 until the present (Auckland Council 2019). In the GNS Active Faults Database (GNS 2019) there is only one fault identified in close vicinity to the Auckland Region, the Wairoa North Fault, approximately 30 km from the Auckland Central Business District. However, the recent recognition of at least one other active fault close to the urban area, the Drury Fault, has changed the perception of seismic hazard (Al-Salim, 2000; Edbrooke et al., 2003). Moreover, faults further afield, such as the Kerepehi Fault in the Hauraki Plains, have the potential to generate damaging ground motions within the Auckland region (Dempsey et al. 2020). As the Auckland region has the largest population concentration in New Zealand and is the hub of New Zealand’s major commercial activities (Auckland Council, 2014), the seismic and co-seismic hazards in the region cannot be disregarded, given the potential social and economic impacts. Figure 10 shows the location of active faults in the vicinity of the Auckland region.

Table 2: Historic Earthquakes felt in the Auckland Region (Auckland Council 2017).

Earthquake Date	**Location**	**Magnitude**	**Shaking Felt In Auckland**
23-Jan-1855	Wairarapa	8.1-8.2	MM4
18-Oct-1868	Cape Farewell	7.0-7.5	MM4-5
23-June-1891	Waikato Heads	5.5-6.0	MM5-6
11-Feb-1893	Nelson	6.6-6.9	MM3-4
6-Oct-14	East Cape	6.7	MM4
28-Oct-14	East Cape	6.5	MM3
28-Jun-21	Hawkes Bay	7	MM3
9-Mar-29	Arthurs Pass	7.1	MM2-3
16-Jun-29	Buller	7.8	MM3
21-Sep-31	Bay of Plenty	6.75	MM2-3
20-Jul-32	Taranaki	6.3	MM2-3
5-Mar-34	Pahiatua	7.6	MM2-3
15-Mar-34	Hawkes Bay	6.4	MM3
24-Jun-42	Wairarapa	7.2	MM2-3
1-Aug-42	Wairarapa	7	MM2
29-Sep-53	Bay of Plenty	7.2	MM3
18-Oct-53	Taranaki	5.3	MM3-4
30-Jan-56	Bay of Plenty	5.8	MM2-3
23-Jan-62	Aria	5.5	MM3-4
23-May-68	Inangahua	7.0-7.1	MM3
11-Feb-75	Hen and Chickens Islands	4.4	MM3
2-Mar-87	Edgecumbe	6.1	MM3

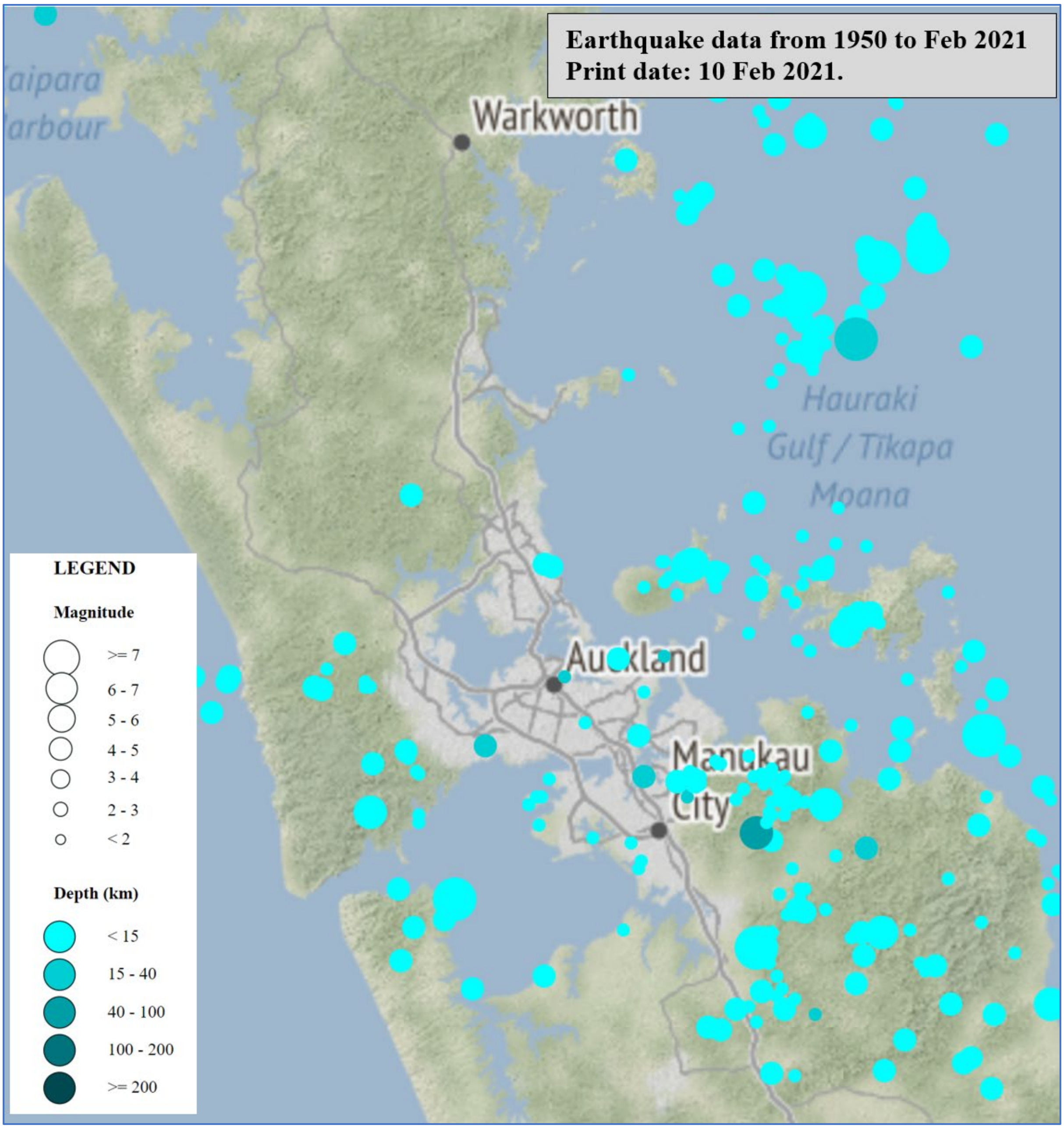


Figure 9: Historical recorded earthquakes in the Auckland Region from the 1950's to present (http://quakesearch.geonet.org.nz).

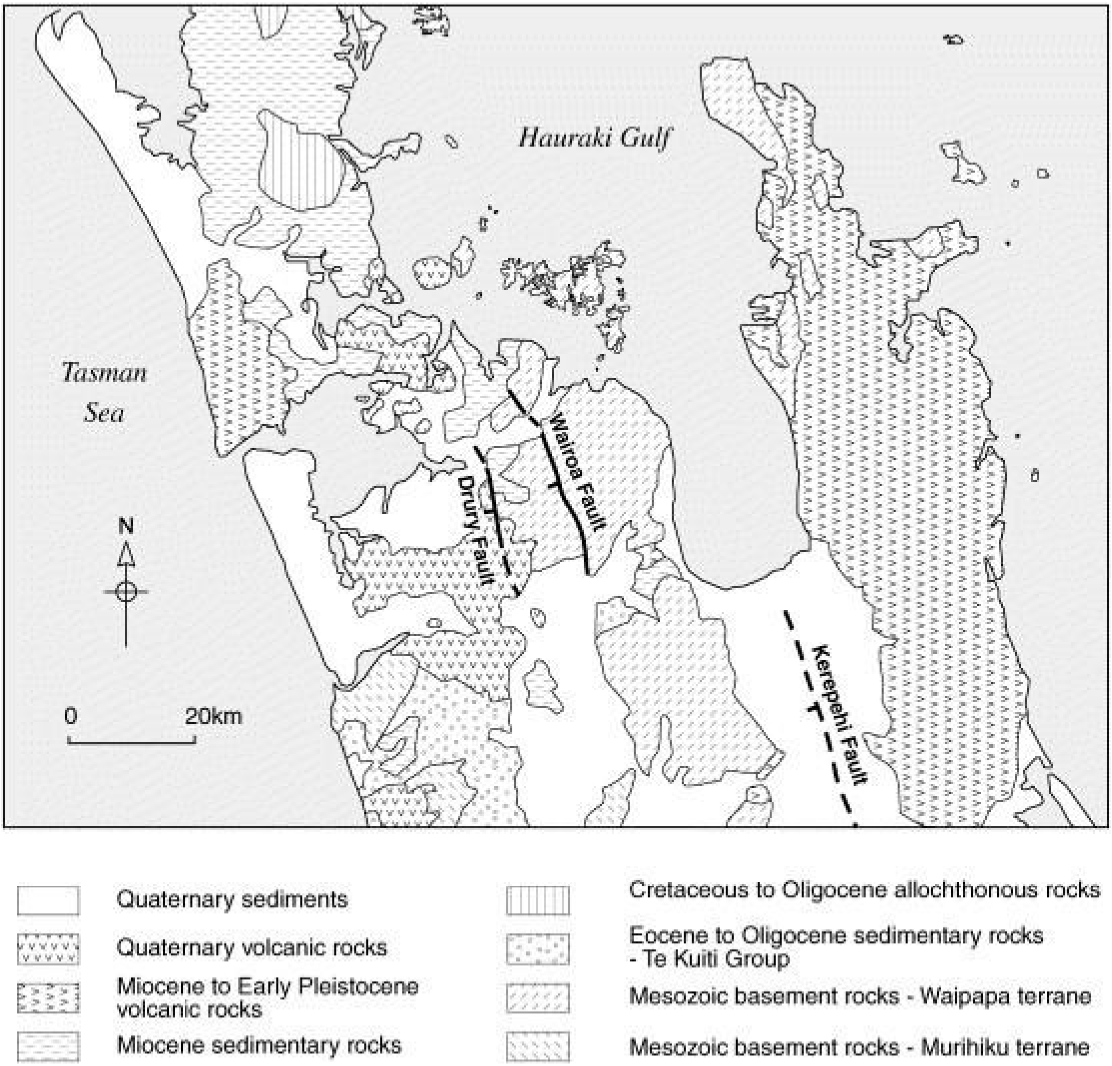


Figure 10: Active faults around Auckland Region and geologic deposits types (adapted from Edbrooke et al. 2003).

The MBIE Guidance recommends the assessment of liquefaction-induced ground damage for different ground shaking return period to categorize liquefaction vulnerability. According to the NZTA Bridge Manual SP/M/022 (2013), the peak ground accelerations (PGA) applied should be 'unweighted' and derived for the relevant return period as follows:

$$PGA = C_{0,1000} \times \frac{R_u}{1.3} \times f \times g$$

where:

$C_{0,1000}$ = 1000 year return period PGA coefficient

R_u = return period factor derived from NZS 1170.5 Structural design actions part 5 Earthquake actions – New Zealand (SNZ 2004)

f = Site subsoil class factor, equal to 1.0 for Site subsoil class A, B, D and E soil sites, and 1.33 for a site subsoil class C site.

Based on this, the PGA characteristics for the Auckland region using a site subsoil class C site are:

For **1000-year** return period: PGA= 0.2 x (1.3/1.3) x 1.33 = 0.27g

For **500-year** return period: PGA = 0.2 x (1.0 /1.3) x 1.33 = 0.205g

For **100-year** return period: PGA = 0.2 x (0.5 /1.3) x 1.33 = 0.10g

For **25-year** return period: PGA = 0.2 x (0.25 /1.3) x 1.33 = 0.05g

For liquefaction triggering analysis, the magnitude for the Auckland region defined by the NZTA Bridge manual is M_w 5.9, and is used for all return period events. When applied to the semi-quantitative criteria from Table 1, the PGA values from the 500-year return period are scaled using MSF of 1.52. Table 3 summarises the revised PGA boundaries for a M_w 5.9 earthquake for the semi-quantitative criteria to inform liquefaction vulnerability categories.

Table 3: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely for M_W 5.9 (MBIE/MfE/EQC 2017).

Type of soil deposits	**A Liquefaction Vulnerability category of *Liquefaction damage is unlikely* can be assigned if either of these conditions are met:**	
	Design peak ground acceleration (PGA) for the 500-year intensity of earthquake shaking	**Depth to groundwater**
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	< 0.15 g	> 8 m
Holocene age Less than 11,000 years old	< 0.25 g	> 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.35 g	> 4 m

4 BASIC DESKTOP ASSESSMENT

This section presents the development of the liquefaction vulnerability categories based on the Level A desktop approach based on geological maps, groundwater, and seismic hazard for the Auckland region following the MBIE Guidance.

A geological desktop assessment is undertaken based on published national and regional surface geological maps and reports to characterise liquefaction. Q-Maps developed by GNS Science are used to create geological layers for the Auckland region. The output of this initial assessment is a geology-based liquefaction vulnerability map defining areas in the Auckland region where *Liquefaction damage is possible* and *Liquefaction damage is unlikely*. The primary aim of this initial screening is to identify geological units that are not susceptible to liquefaction.

4.1 Qualitative screening

Using qualitative criteria, soil types susceptible to liquefaction include fills, reclaimed land, sand, silts, quaternary deposits and estuarine deposits of Holocene age (Pyke 2003, Youd et al., 2001, Youd and Perkins, 1978). Most liquefaction-induced failures and nearly all case history data compiled in empirical charts for liquefaction evaluation were in Holocene deposits or constructed fills (Seed and Idriss, 1971; Seed et al., 1985; Boulanger and Idriss, 2008).

Based on the above discussion, areas of the following geological deposits are categorised as *Liquefaction damage is possible*:

- Fills
- Sand, silt, gravel, swamps, deposits of Holocene age.

In general terms, the basement, Late Pliocene, and Early Pleistocene deposits are lithified or relatively well consolidated and will not liquefy under strong ground shaking. Because of their age, the early and middle Pleistocene non-marine and marine deposits, the last interglacial marine deposits, and the alluvial materials of the early and middle last glaciation are old enough to have been consolidated by natural processes. Their liquefaction susceptibility is regarded as negligible (Youd and Perkins 1978). Using this criterion, the following regional deposits are assigned the category *Liquefaction damage is unlikely*:

- Greywacke

- East Coast Bays Formation containing sandstone and mudstone deposits
- Tuff,
- Basalt,
- Firm to stiff Pleistocene age alluvium.

Figure 11 summarises the potentially liquefiable soils in the Auckland region and Figure 12 shows the same for Auckland's main urban region.

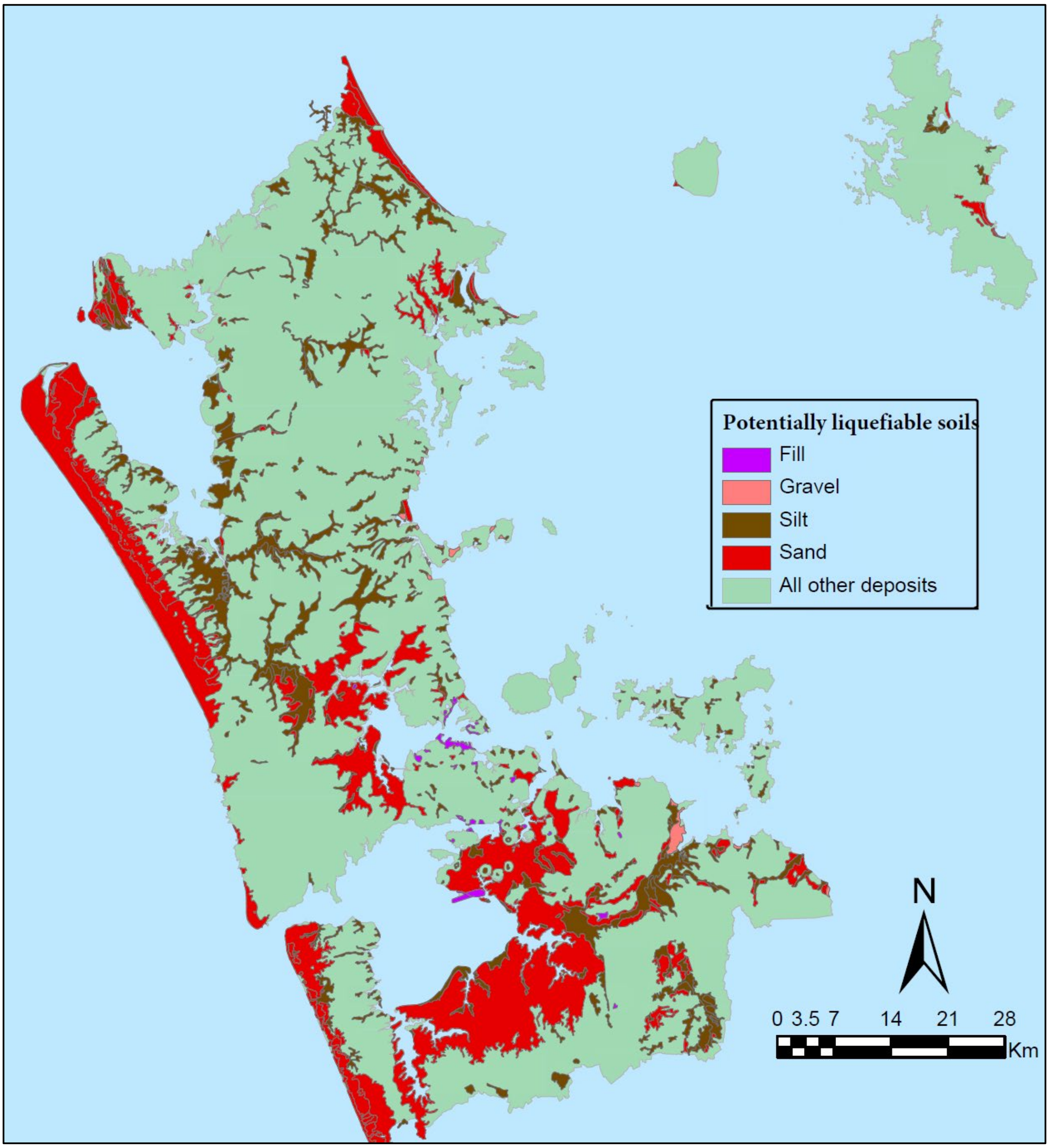


Figure 11: Summary of potentially liquefiable deposits in the Auckland Region.

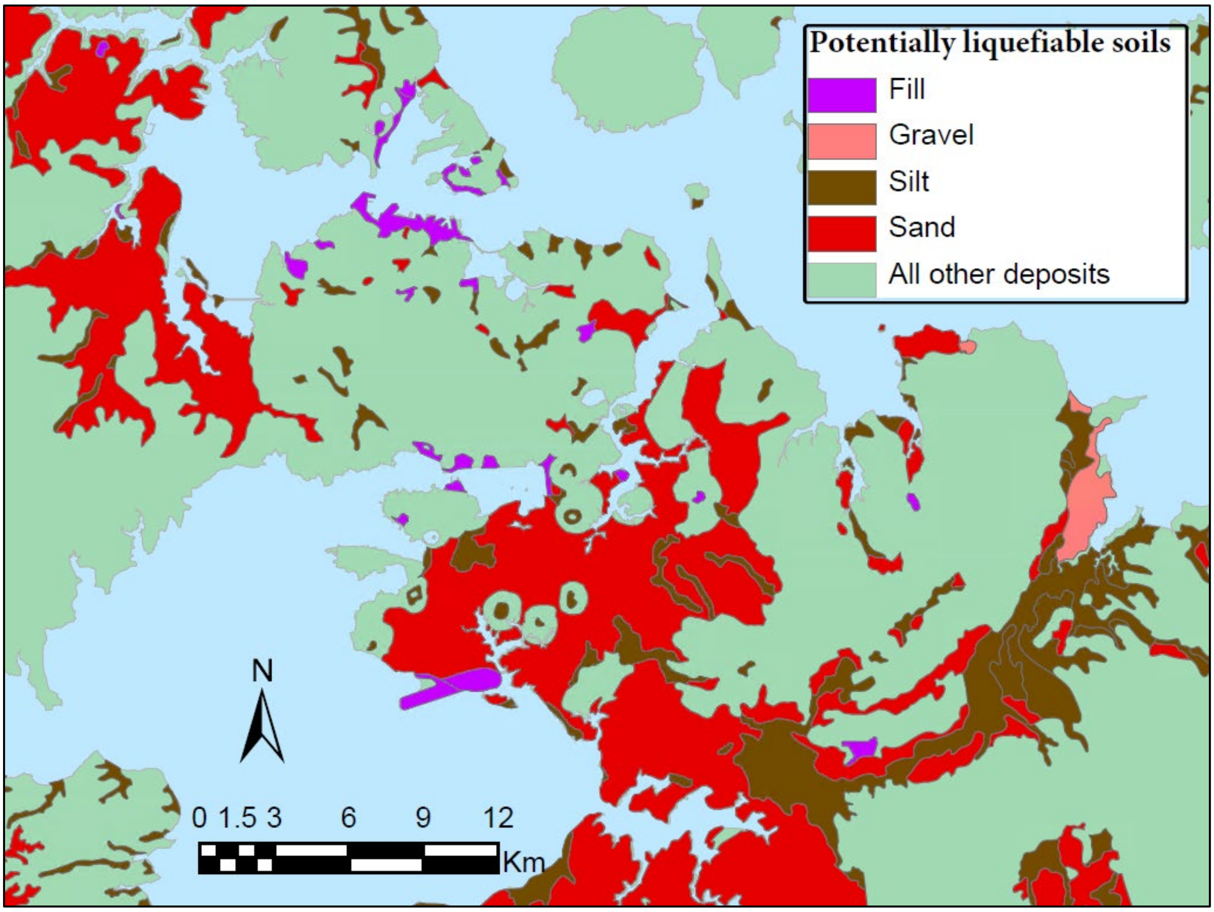


Figure 12: Summary of potentially liquefiable deposits in Auckland's main urban region.

4.2 Semi-quantitative screening

By considering the regional seismic hazard and depth to groundwater, in conjunction with the depositional process and the age of soil deposits, the semi-quantitative screening criteria in Table 3 is used to identify geological units where significant liquefaction-induced ground damage is unlikely to occur. A soil deposit of the specified type is assigned a liquefaction vulnerability category of *Liquefaction damage is unlikely* if the 500-year return period PGA is less than the limit for the age of that deposit, or if the depth to groundwater is greater than the limit.

As geological age is one of the main factors in the semi-quantitative criteria to assess the liquefaction vulnerability of the deposits, Figure 13 summarises the geological age associated with each deposit in the study area identified as potentially liquefiable based on qualitative criteria. Figure 14 presents the depositional age of potentially liquefiable deposits in Auckland's main urban regions.

Holocene deposits are dominated by fill and silt material, while most of the sand deposits belong to the Puketoka Formation. Although the Puketoka Formation deposits consist of sandy, silty volcanic soils with tephra, pumice, and lignite, their Late Pliocene to Middle Pleistocene depositional age screens them out from the initial level A assessment as the 500 year return period PGA is less than the 0.35g cut-off.

An interesting aspect of the Puketoka Formation in the Auckland region is that in some areas it contains pumice and other volcanic deposits, with behaviours that may differ from the rest of the deposits without these volcanic materials. As an example, the 1987 Edgecumbe earthquake, resulted in widespread liquefaction of sands of volcanic origin. It is recommended that based on the current understanding of the behaviour of the Puketoka Formation, more investigation needs to be carried out to better constrain the liquefaction potential of these deposits. Even so, at this level of assessment, these deposits are not treated separately and the QMap polygons and classifications are applied.

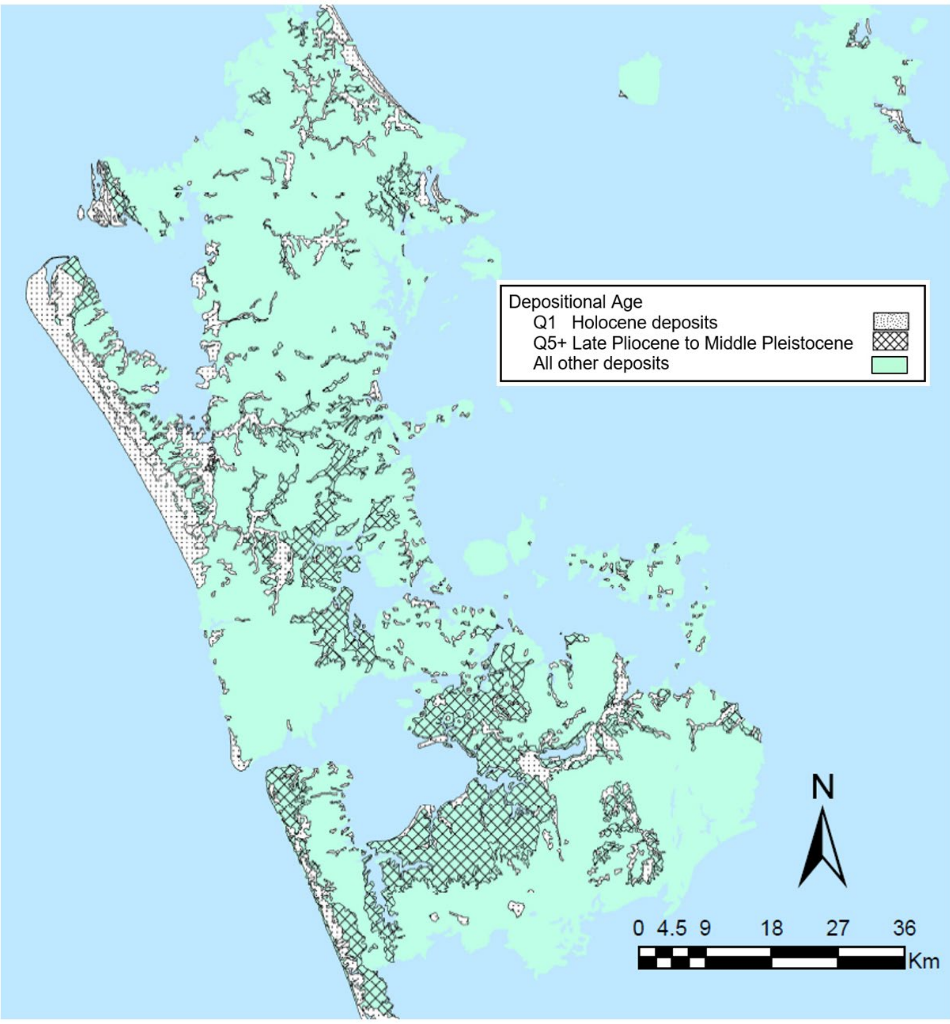


Figure 13: Depositional age of potentially liquefiable soils in the Auckland Region.

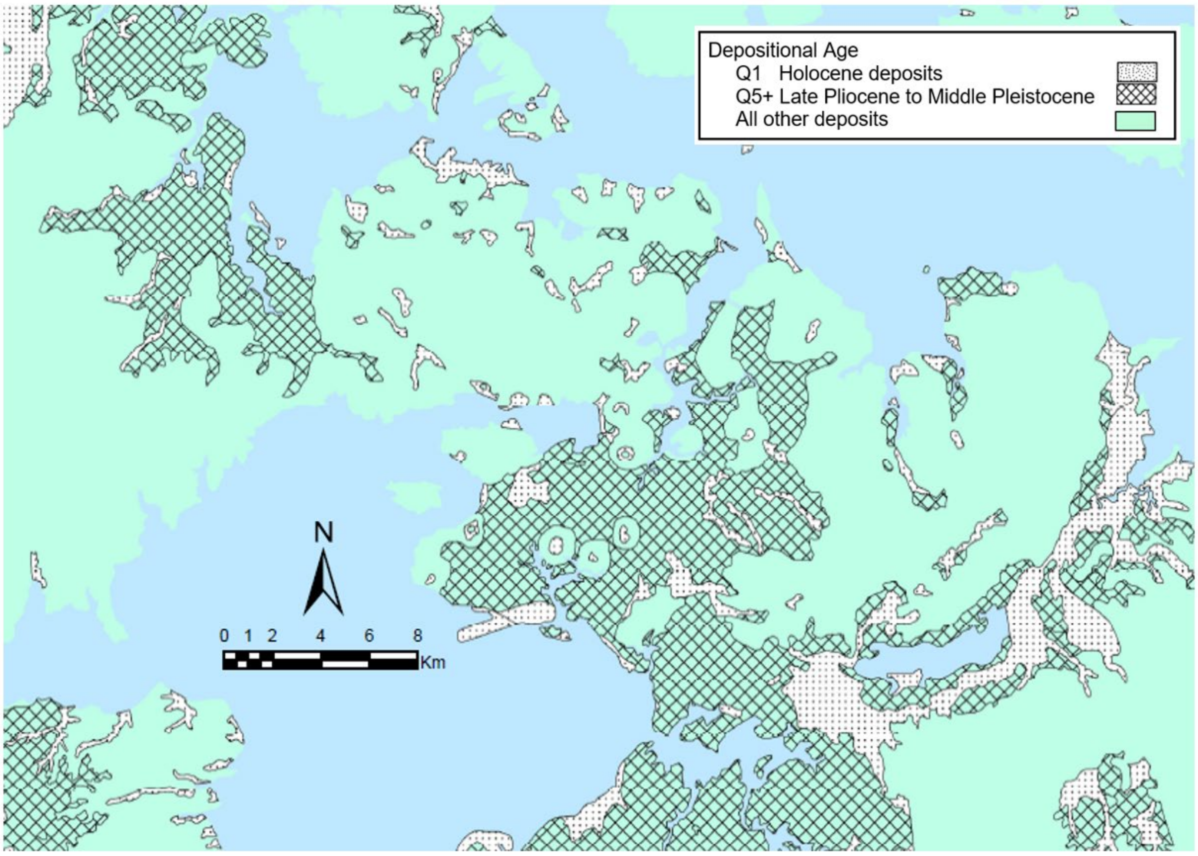


Figure 14: Depositional age of potentially liquefiable soils in Auckland's main urban area.

The rock deposits in the region are lithified or relatively well consolidated and will not liquefy under strong ground shaking. Therefore, exposed rock deposits can be assigned a liquefaction vulnerability category of *Very Low*. This includes Late Pliocene rock, Early Pleistocene rock, Allochthonous rocks, Basement rock, basaltic rock deposits, and igneous and sedimentary rocks of Neogene and Pliocene age.

As defined in Section 4, the 500-year return period PGA value is 0.20g for the Auckland region, less than 0.25g cut-off value for Holocene deposits. This is the main governing criteria for this semi-quantitative assessment, as no detailed groundwater models have been developed. There is uncertainty regarding subsurface conditions elsewhere, but the nature of these deposits means that *Liquefaction damage is possible* is an appropriate classification for Holocene deposits. These deposits include alluvial deposits of fine-grained silts and sands and fills, that are inter-fingered with mud, sands, silts, pumice and gravels.

Figure 15 summarises the liquefaction vulnerability categories that are assigned for the Auckland region based on semi-quantitative geological screening (Level A) and Figure 16 shows the categories for Auckland's main urban region.

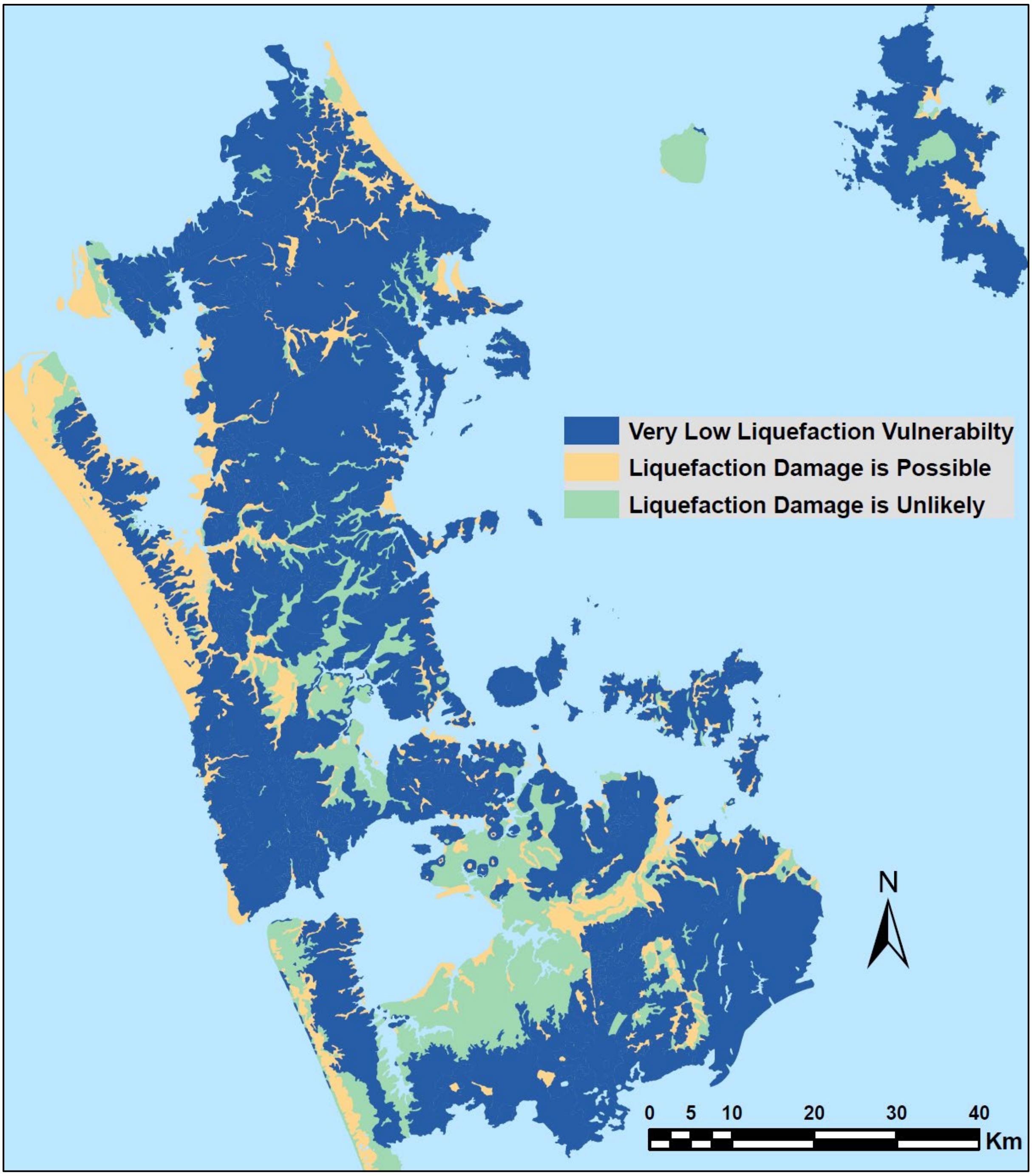


Figure 15: Geology-based liquefaction vulnerability category map for the Auckland Region.

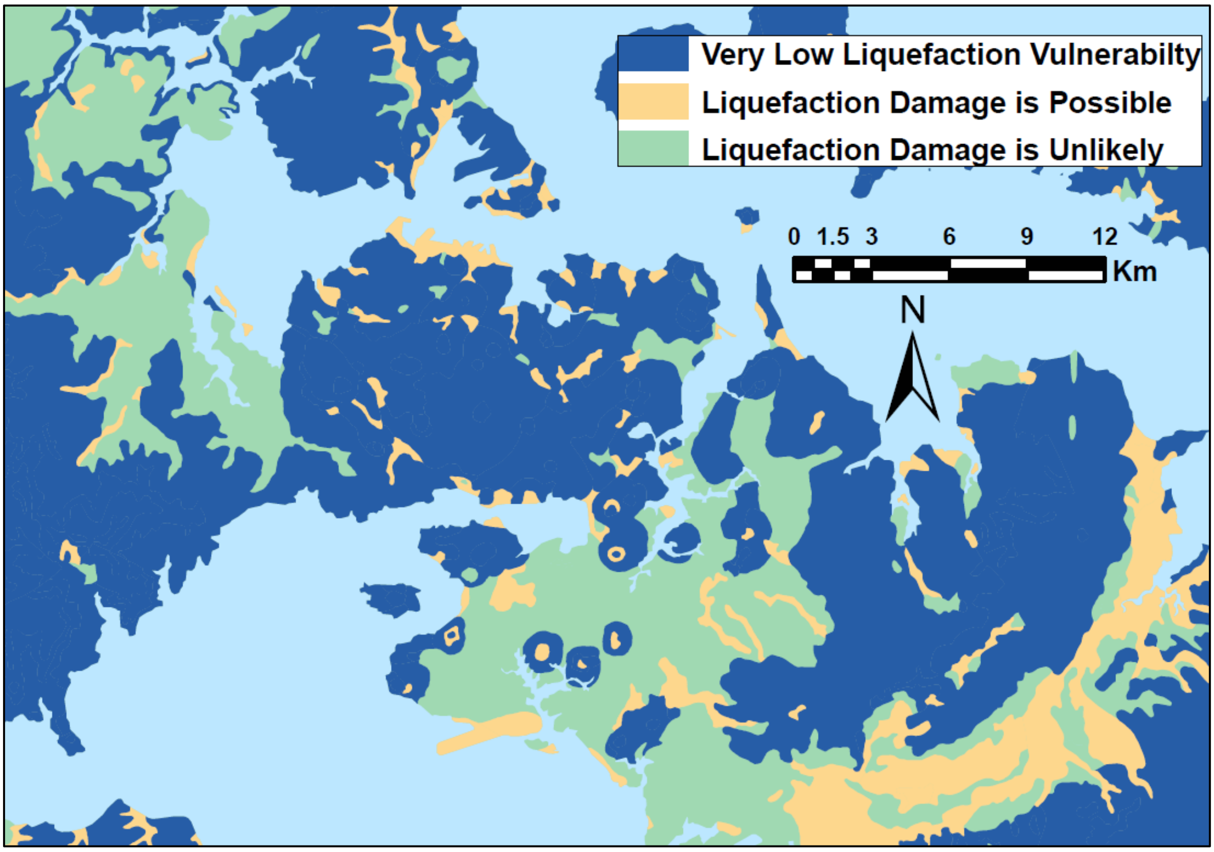


Figure 16: Geology-based liquefaction vulnerability category map for the Auckland's main urban area.

5 GEOTECHNICAL AND ELEVATION BASED SCREENING

This screening presented in this section follows the Level B calibrated desktop assessment guidelines from MBIE. This section includes high-level calibration of geological maps with available geotechnical data and topographical information in the region, including digital elevation model (DEM) data. Qualitative assessment of subsurface investigations provides a better understanding of liquefaction susceptibility for the mapped deposits and underlying ground profile. It can reduce the uncertainty in areas where existing information is sparse by using the targeted collection of new information.

As there is uncertainty in relation to liquefaction vulnerability, how it varies across each mapped area and the delineation of boundaries between areas, an update on geology-based liquefaction vulnerability categories is only suggested in areas with a good density of geotechnical investigation data. This section highlights some areas where more robust geotechnical screening with increased density of data should be carried out. There may be some areas where the surface geological maps may not justify the choice of liquefaction vulnerability category because of the characteristics of the underlying soil profile. Suggestions are made for each area where a reasonable density of geotechnical investigations are present.

A large amount of geotechnical investigation data in the form of boreholes with or without SPTs, CPTs, hand augers, trenches and others are available in the New Zealand Geotechnical Database and the Tonkin & Taylor Geotechnical database. The available geotechnical investigations in the region are shown in Figure 17, and although there is a large amount of data, the density of this is low is the vast majority of areas. The areas with an elevation greater than 20 m are also shown by cross-hatch in Figure 17 in the regions with the same liquefaction vulnerability category, with 20 m elevation used as a coarse indicator for areas where liquefaction may be less likely as a result of the greater depth of the groundwater table. As per the MBIE guidance (as shown in Appendix 9.1), the liquefaction vulnerability category of "Low" can be assigned to areas where geotechnical investigations are available and stratigraphy to a certain depth can be determined. In order to discuss the above factors in detail across the Auckland region, focus areas have been defined and are summarized in Figure 18. The locations outside of the focus areas do not have any geotechnical investigation data, and as such, they can only be categorised according to geologic data (Level A).

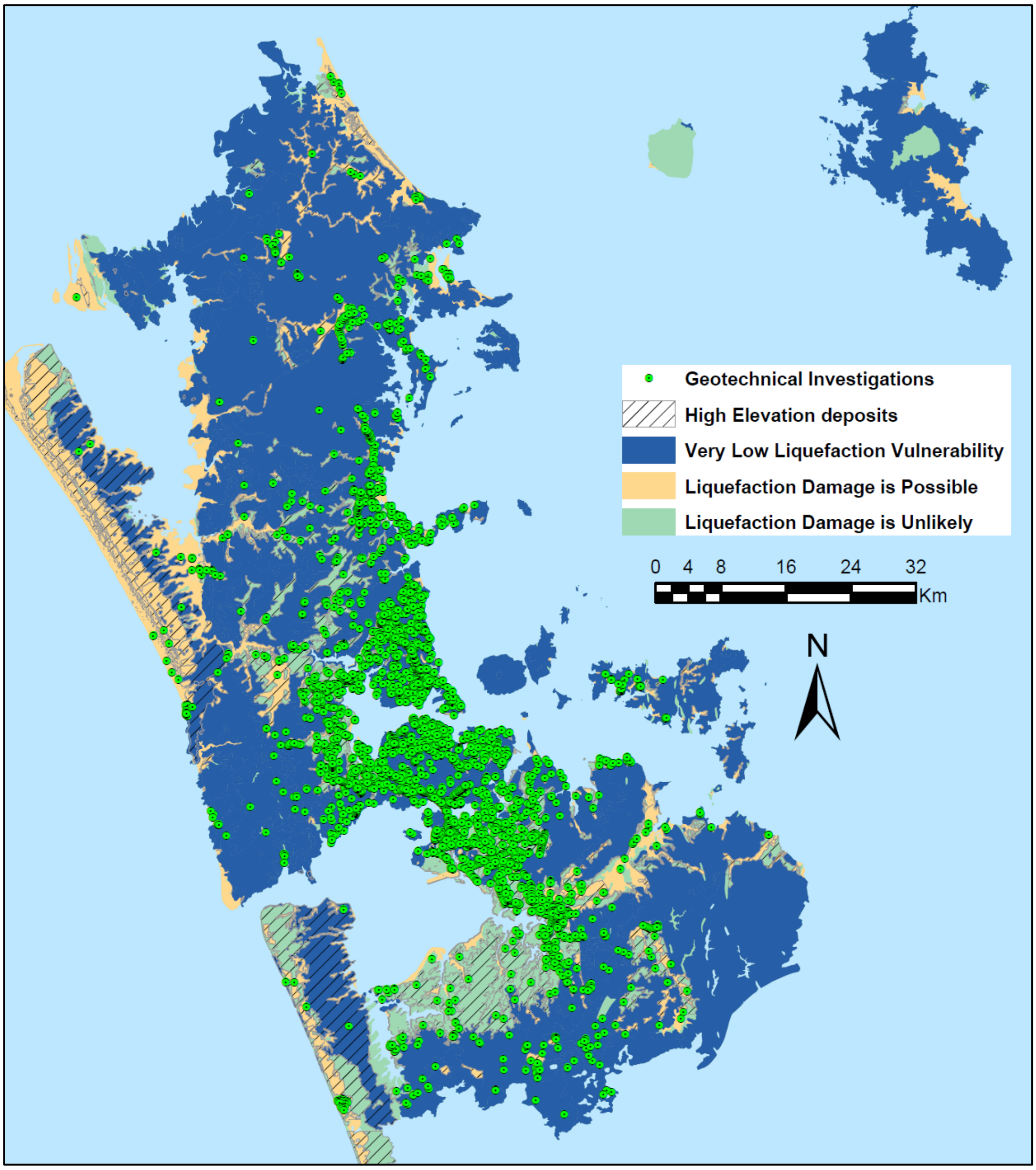


Figure 17: Summary of available geotechnical investigations and high elevation regions (>20 m) in the Auckland Region.

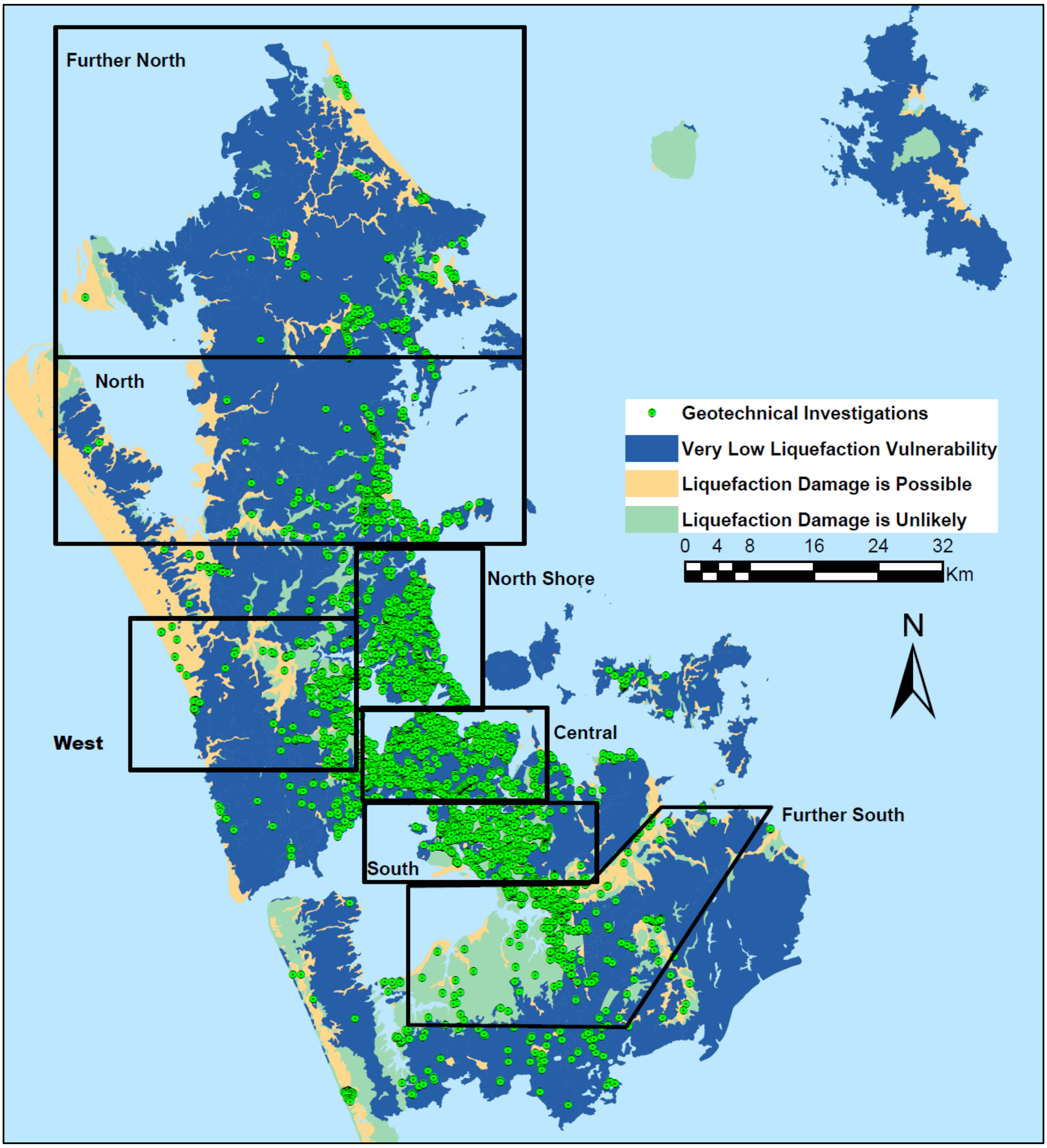


Figure 18: Summary of focus areas in the Auckland Region for Level B (Geotechnical calibration) liquefaction assessment.

5.1 Further North areas

Figure 19 shows the Level A categories for the most northern Auckland suburbs along with the locations of available geotechnical investigation data. These locations include areas in the proximity of Mangawhai, Warkworth, Wellsford and Omaha. Areas with an elevation >20 m are also shown in Figure 19.

Warkworth and Wellsford investigations mostly consist of surficial clay and silt underlying silty sandy material of low plasticity. Although these areas are at a higher elevation investigation show the presence of sandy, silty material below the water table at shallow depth. This data confirms the *Liquefaction damage is possible* category and a more refined category cannot be assigned at this level.

Similarly, deposits at **Mangawhai** have an elevation greater than 20 m and but due to a low density of geotechnical investigations, a more refined category cannot be assigned. The existing information confirms the *Liquefaction damage is possible* category.

All geotechnical investigations in **Omaha** show alluvial deposits with low elevation and shallow groundwater depth, which confirms the category of *Liquefaction damage is possible*.

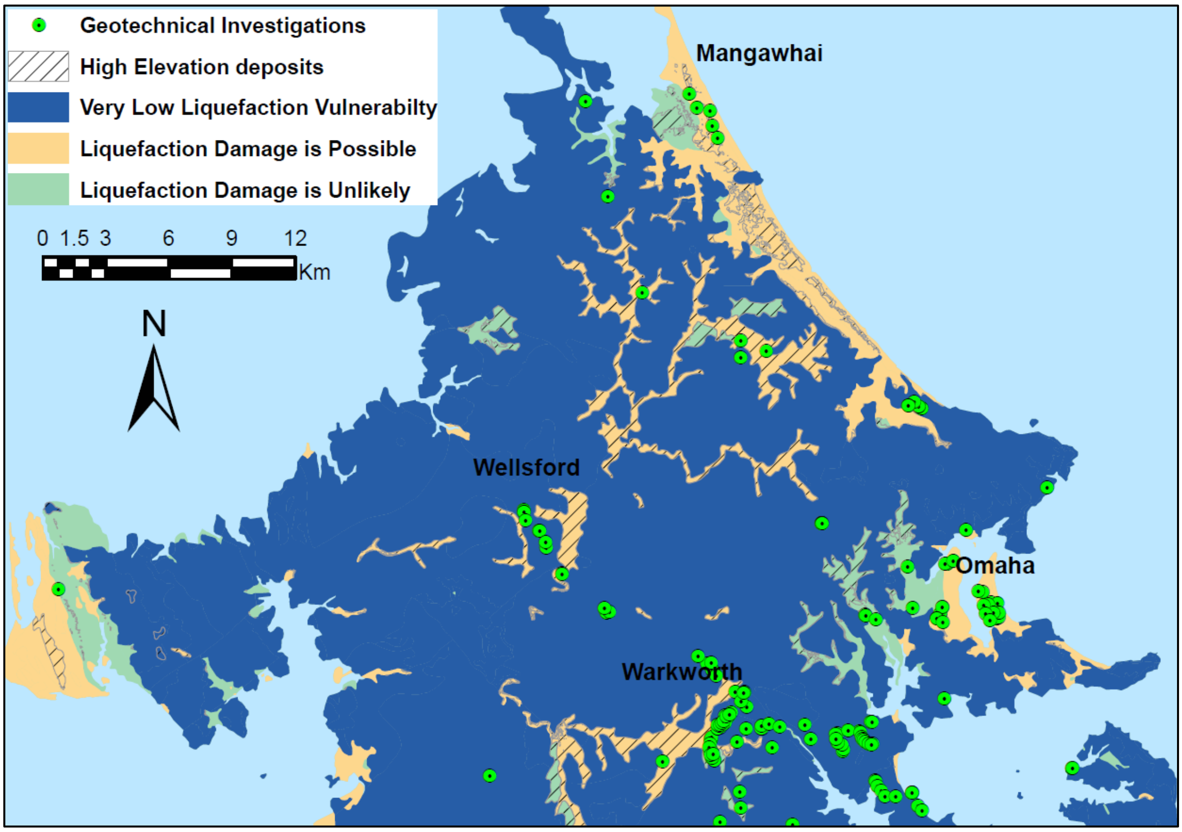


Figure 19: Summary of Further North areas investigated under Level B liquefaction assessment.

5.2 North Area

Figure 20 shows the Level A categories in the North Auckland suburbs and the available geotechnical investigations. These locations include areas in the proximity of **Puhoi, Waiwera, Orewa, Red Beach, Silverdale and Whangaparaoa.** The density of investigations in this area is not enough to update the liquefaction vulnerability categorisation. Areas with an elevation >20 m are also shown in Figure 20.

Boreholes in the area adjacent to **Puhoi** show alternate layers of clayey silt and silty clay, becoming gravely with siltstone and sandstone. Near the river and beach, there is likely to be sandy, silty material, but there is no investigation data in these areas. Small areas in **Waiwera** have clayey silt with layers of gravels and stiff silt. However, investigation data is sparse in this region Only two boreholes available in **Orewa** shows sandy layers of 3-4 m thickness underlying surficial plastic deposits up to 2 m thick. Other areas with no investigation data, especially near beaches, may have soils susceptible to liquefaction. **Red Beach** investigations show sandy/silty clay with moderate plasticity at locations away from the coast. The **Silverdale** area has mainly silty sandy soil deposits. Available data points in **Whangaparaoa** areas indicate that silty sandy soil layers are present.

Based on the above discussion and the low density of geotechnical investigations, no update in Level A assessment is recommended for locations within the North Area.

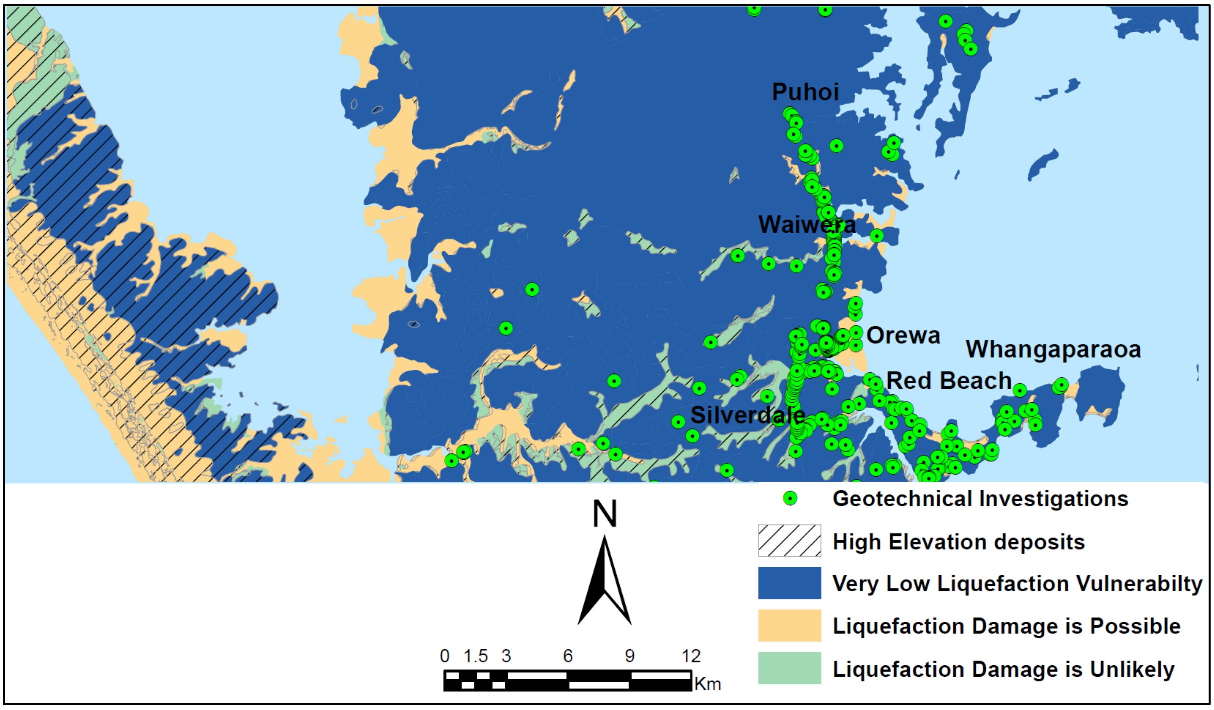


Figure 20: Summary of North Auckland suburbs investigated under Level B liquefaction assessment.

5.3 North Shore

Figure 21 shows the Level A categories in North Shore suburbs with the available geotechnical investigations. These locations include areas in the proximity of **Long Bay, Browns Bay, Torbay, Takapuna, Devonport, Northcote,** and **Forest Hill**. Areas with an elevation >20 m are also shown in Figure 21.

Some of the regions in **Glenfield** and **Takapuna** in Figure 21 have some high elevation pockets up to 30-40 m. The water table depth is 2-3 m in most locations. The **Glenfield** area has two types of deposits. High elevation areas have Neogene sedimentary rocks (with volcanic content) while low elevation areas have Holocene river deposits. Sandy and silty deposits are present.

All the coastal areas shown in Figure 21 are Holocene river deposits. **Torbay** has silty layers up to 5 m in thickness over East Coast Bay Formation. **Browns Bay** have fill material up to 3 m and overlying silty layers up to 10-11 m thick. Highlighted areas of **Devonport and Northcote** have sandy, silty soils of thickness 4-5 m. **Takapuna** has fill material up to 4-5 m, which are comprised of silty and sandy loose soils. Below that, there are silty clayey soils with low plasticity up to 12 m depth.

Based on the above the High elevation area in Glenfield is assigned a refined *Low* liquefaction vulnerability category, with the subsurface data identifying areas that do not align with the geologic mapping. For all other locations, the *Liquefaction damage is possible* category is not modified.

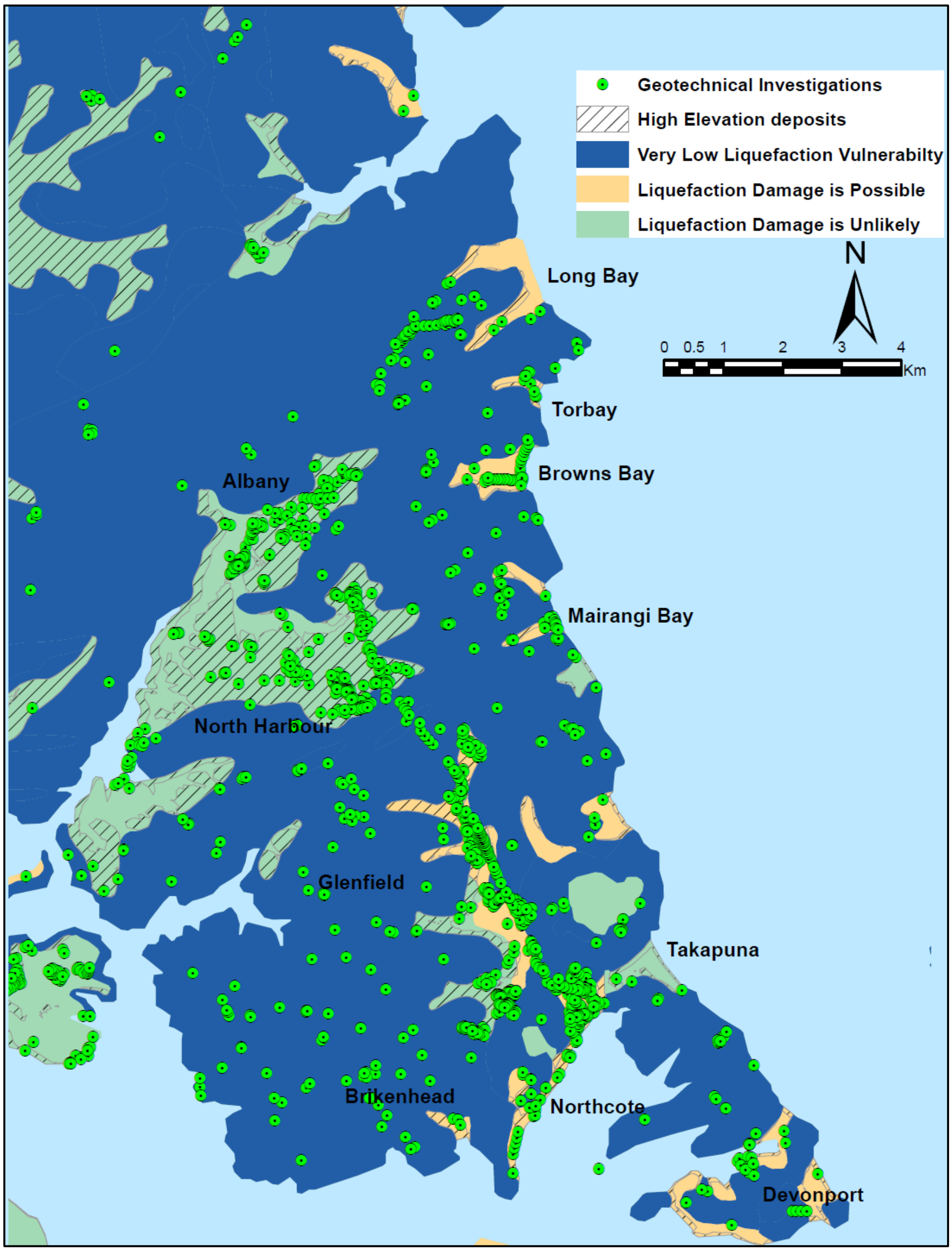


Figure 21: Summary of North Shore areas investigated under Level B liquefaction assessment.

5.4 West Auckland

Figure 22 shows the Level A categories in the West Auckland suburbs with the available geotechnical investigations. These locations include areas in the proximity of **Te Atatu Peninsula, Henderson, Hobsonville, Kumeu, New Lynn and Kelston**. Areas with an elevation >20 m are also shown in Figure 22.

Te Atatu Peninsula has few data points, mostly indicating sandy silty soils with some interbedded clayey and peaty layers and elevation 21-30 m. The **Henderson** highlighted area has layers of loose silt and sand, interbedded with clay and gravels. Available boreholes in **Hobsonville** show the presence of silty sandy layers with alternate layers of plastic clay.

Highlighted areas in **Kumeu** have silty and sandy soil layers with a surficial layer of plastic clay (1-3 m) but high elevation. As the density of available geotechnical investigation is low in these areas, and available boreholes show the presence of potentially liquefiable deposits, no refined classification is suggested for this area.

In this area, one of the important aspects to explore further is the liquefaction potential of the Puketoka Formation. This formation covers a large area of the West Auckland suburbs, which are all categorised as *Liquefaction damage is unlikely* based on semi-quantitative criteria in the Level A assessment. Geotechnical investigations in **New Lynn** and **Te Atatu South** show 3-4 m plastic clayey soil overlying 5-6 m of sandy soil layers. **Kelston** has 1-2 m of clayey soil of a volcanic nature above sandy, silty soil layers. These deposits consist of mostly loose sandy, silty soils, suggesting that their behaviour should be evaluated with further site-specific investigations in order to provide more confidence in the liquefaction vulnerability classification. These deposits are of Late Pliocene to Middle Pleistocene age and would therefore be less likely to liquefy, however there is some uncertainty in this classification based on the evidence from site investigation data. As this points towards less confidence in the classification of these deposits based solely on the Level A approach, a *Liquefaction category is undetermined* classification is suggested for the Puketoka Formation.

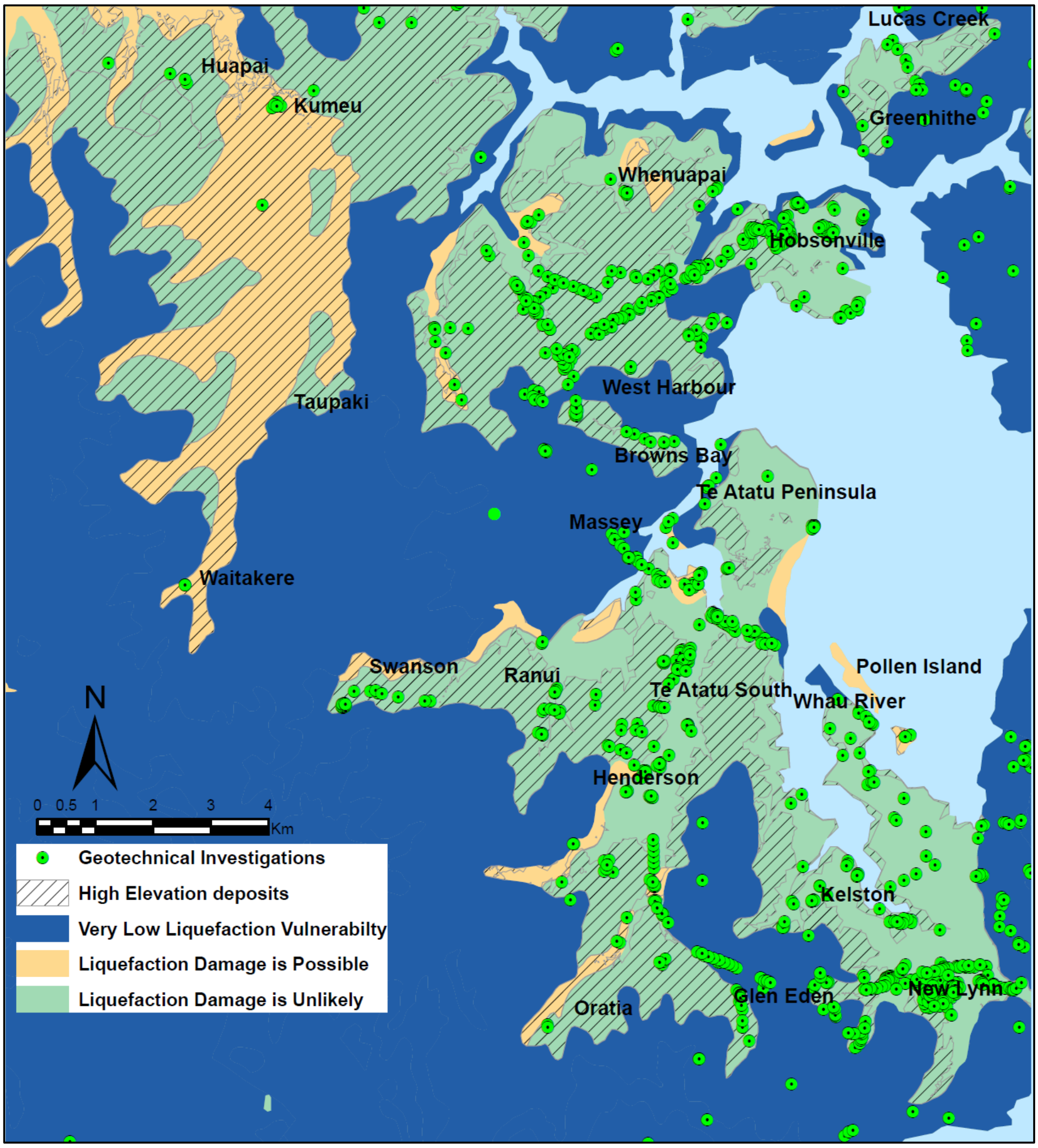


Figure 22: Summary of West Auckland areas investigated under Level B liquefaction assessment.

5.5 Central Auckland

Figure 23 shows the Level A categories in the Central Auckland suburbs with the available geotechnical investigations. These locations include areas in the proximity of the **Auckland Waterfront, Point Chevalier, Grey Lynn, Newmarket, Sandringham, Mission Bay**, **Mount Roskill, Ellerslie, Panmure, Mount Wellington, Kohimarama**, **Orakei Reserve**, **St Helier's Bay and Onehunga**. Areas with an elevation >20 m are also shown in Figure 23.

The **Auckland Waterfront** reclamation fills have been deposited over an extended time period and they are situated over Tauranga Group alluvium of varying thickness and East Coast Bays Formation. This fill consists of four major types: construction fill, excavated rockfill, hydraulic fill and industrial and domestic waste. The reclaimed areas along the waterfront from Mechanics Bay to Herne Bay have highly variable surface deposits across the different ages of reclamation. All of these deposits conform to the *Liquefaction damage is possible* category. As there are a high density of CPT soundings available in these areas, a detailed investigation (Level C) could inform a more refined category (discussed in the subsequent section of this report).

Point Chevalier area has stiff clayey layers and sediments with volcanic content. The **Grey Lynn** area has surface fill that is plastic with volcanic content overlying ECBF. The **Newmarket** area has sandy, silty material, and although elevation is greater than 50 m the groundwater depth is shallow.

The areas along the waterfront in **Orakei Reserve, Mission Bay, Kohimarama** and **St Helier's Bay** all have loose sandy, silty soil layers overlying weathered ECBF.

Sandringham area has basaltic ash and some organic clay. In the **Mount Roskill** area the dominant near-surface stratigraphy is comprised of basalt and tuff, with the upper 8 m consisting of organic silt and peat. The average elevation is 60 m with shallow groundwater. Sand and silt layers are present at depths greater than 15 m, situated below volcanic deposits. **Onehunga** has fill material comprised of refuse, plastic ash layers, and sands, silts and clays.

Boreholes in **Ellerslie** show that the dominant deposits are tuff and basalt, although not indicated by geology maps. Soft silt deposits of thickness 1.5-2 m are also present up to depths of 3 m.. The tuff material is highly weathered, weak and fine-grained.

Mt Wellington has silty clay and clayey silt with variable plasticity volcanic ash and Tauranga group deposits. **Panmure** has stiff clay and basaltic material. **Otahuhu** has a gravelly fill and also some sandy, silty soil layers.

Based on the above **Point Chevalier, Panmure, Ellerslie, Mt Wellington, Mt Roskill and Sandringham** have some mixed stratigraphy which suggests that *Low liquefaction vulnerability* may be appropriate in some areas classified as *Liquefaction damage is possible*. However, there is still uncertainty in the overall material characteristics in these polygons based on limited number of investigation locations. Therefore, no refined classification is suggested for any of these areas. The investigation of boreholes in Puketoka Formation polygons which were assigned *Liquefaction damage is unlikely* suggest that their behaviour should be evaluated with further site-specific investigations, similar to the deposits in West Auckland. A

Liquefaction category is undetermined classification is again suggested for the Puketoka Formation in Central Auckland.

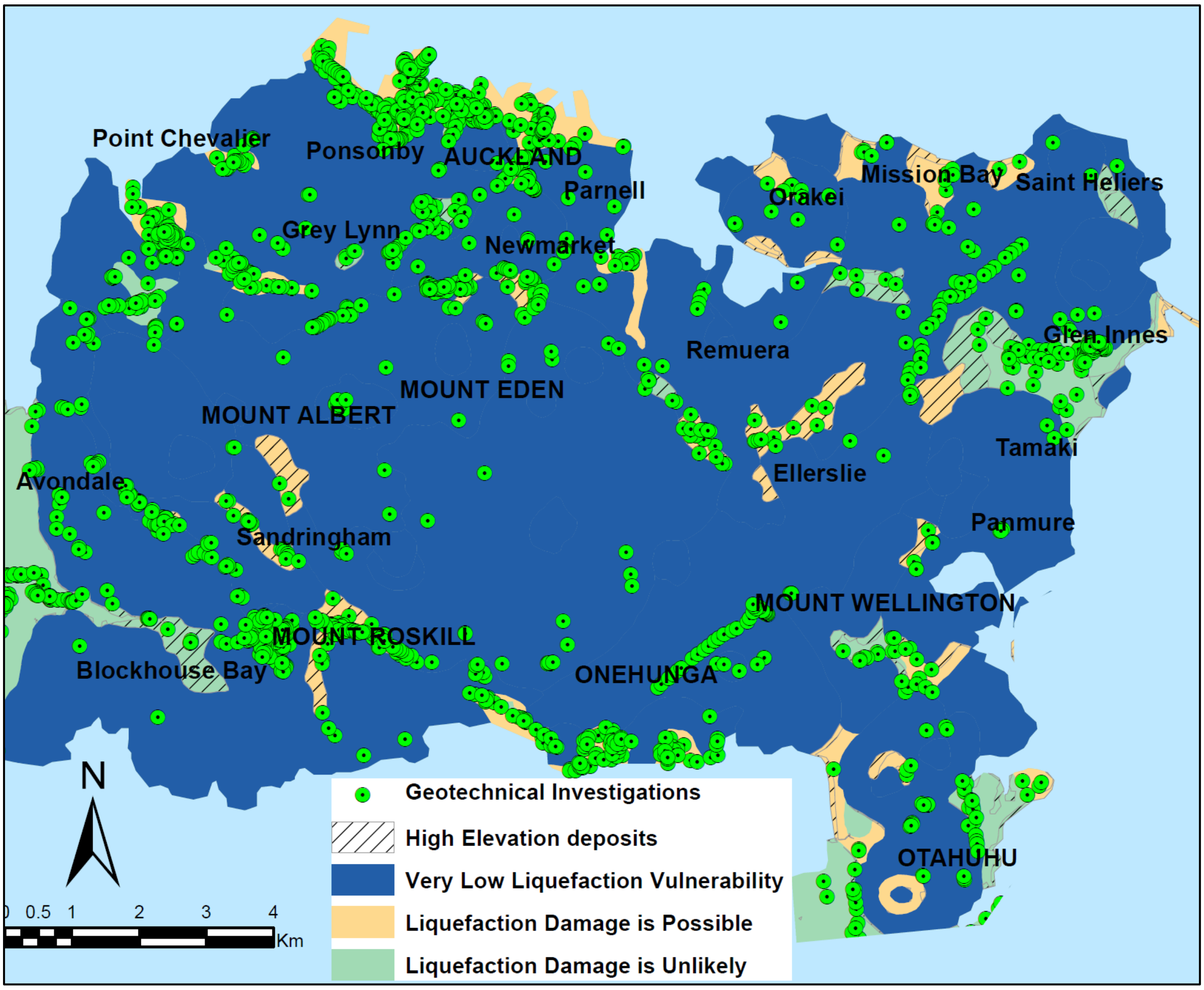


Figure 23: Summary of Central Auckland areas investigated under Level B liquefaction assessment.

5.6 South Auckland

Figure 24 shows the Level A categories in the South Auckland suburbs with the available geotechnical investigations. These locations include areas in **Pakuranga, East Tamaki, Flat Bush, Mangere, Middlemore, Papatoetoe and Ormiston**. Areas with an elevation >20 m are also shown in Figure 24.

Pakuranga area shows the presence of clayey soil, and volcanic ash with high plasticity across discrete investigation locations, and elevations of 21-25 m Part of **East Tamaki** in the focus area has some layers of silty, sandy soils with layers of peat and clay. The density of investigations is too low to assign a refine liquefaction vulnerability for these locations.

Ambury Regional Park has loose layers of sandy and silty soils with some volcanic ash and basalt which is not indicated by the geology map. The area towards **Mangere Bridge** has gravelly silty, sandy layers up to 2-3 m depth overlying basaltic layers. The **Mangere** area has more prominent sand layers at shallow depth with some clay intrusions.

Papatoetoe area has silty-sandy loose layers 6-7 m thick underlying 4-5 m of clayey soils. Investigation data shows that the **Otara** and **East Tamaki** areas have fill material (sandy) and sandy, silty loose layers. Gravelly deposits at the surface become sandy with some peat layers below 2-3 m depth.

The investigations near **Wiri and Flat Bush** area have silty soil layers to a depth of 5-6 m with surficial organic deposits of thickness 1-1.5 m. The investigation data towards the **Ormiston** area has upper layers of clay 3-4 m thick overlying silty layers 5-6 m in thickness. Overall there is no significant variation in stratigraphy and material type across all investigation points.

This area is dominated by Puketoka Formation deposits that have been classified as *Liquefaction damage is unlikely* in the Level A assessment because of their depositional age. However, boreholes in the area indicate the presence of fill material with sand and silt, similar to observations from the West Auckland area. *Liquefaction category is undetermined* is suggested for the Puketoka Formation in this level of assessment as further detailed quantitative assessment will give confidence in assigning a liquefaction vulnerability category. A refined classification is not suggested for any of the other areas that have been assigned a *Liquefaction damage is possible* category under Level A assessment.

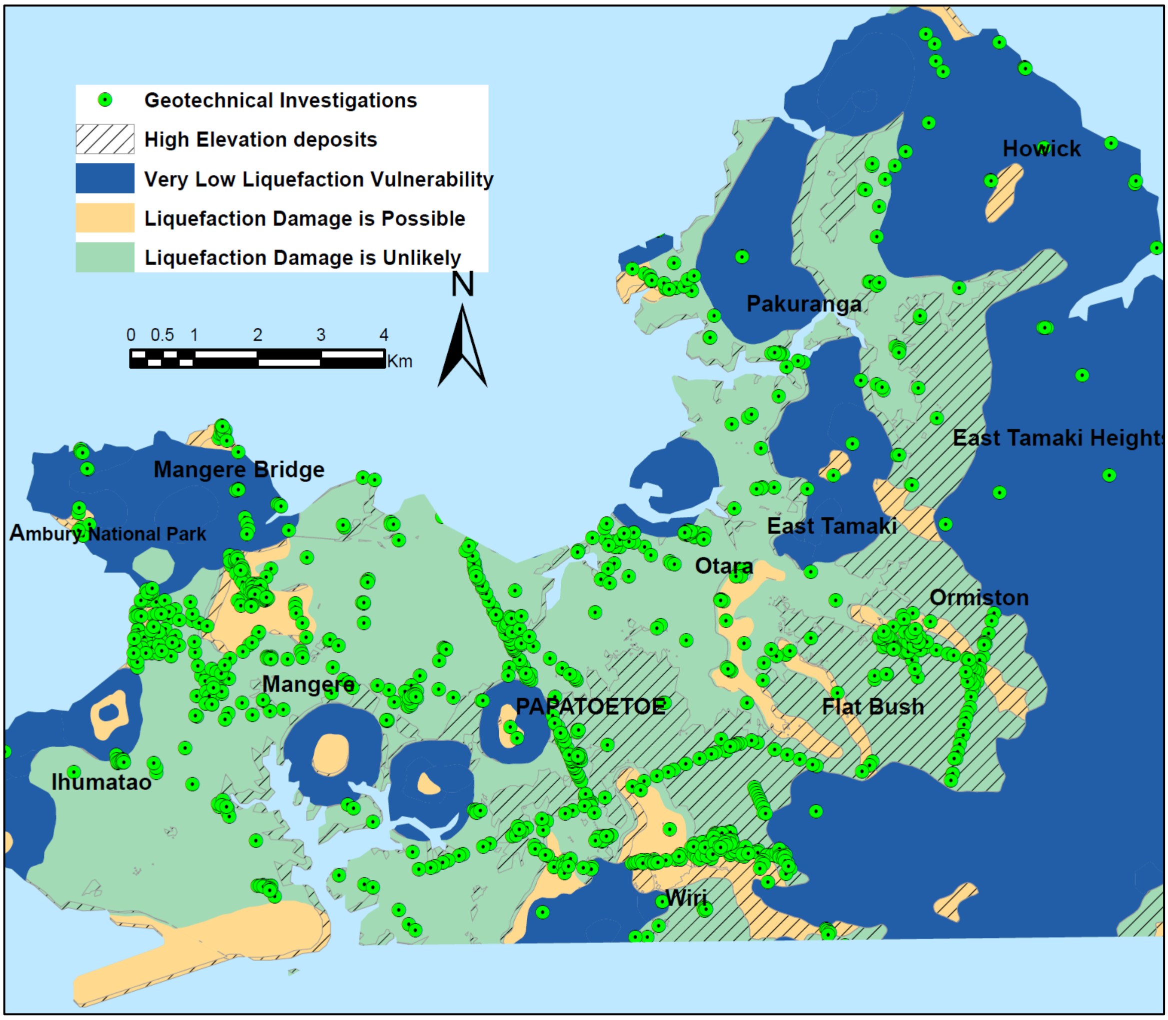


Figure 24: Summary of South Auckland areas investigated under Level B liquefaction assessment.

5.7 Further South

Figure 25 shows the Level A categories in the Further South suburbs with available geotechnical investigations. These locations include areas in the suburbs of **Manurewa, Takanini, and Ardmore.** Areas with an elevation >20 m are also shown in Figure 25.

Manurewa areas have plastic clayey soil deposits up to 4 m thick, while below this there are volcanic sand deposits up to 5-8 m thick below the water table. Areas between **Takanini and Papakura** has high elevation >30 m with a stratigraphy that is changing significantly. There are deposits of sands, silts and organics, with some volcanic content. Few boreholes in **Ardmore** region show the presence of weathered gravelly silty material with volcanic content of plastic nature.

Based on the soils present and the density of investigations no modifications are applied to the Level A categorisation in this area.

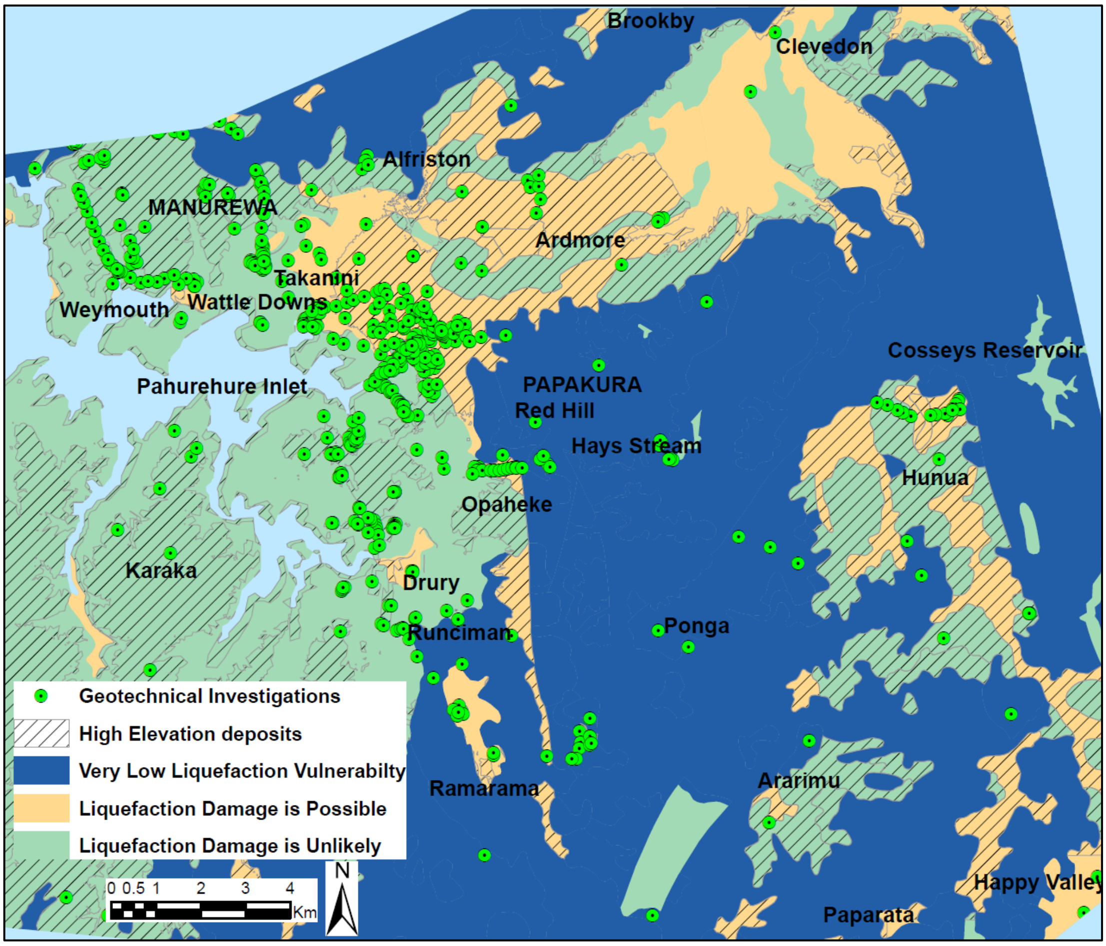
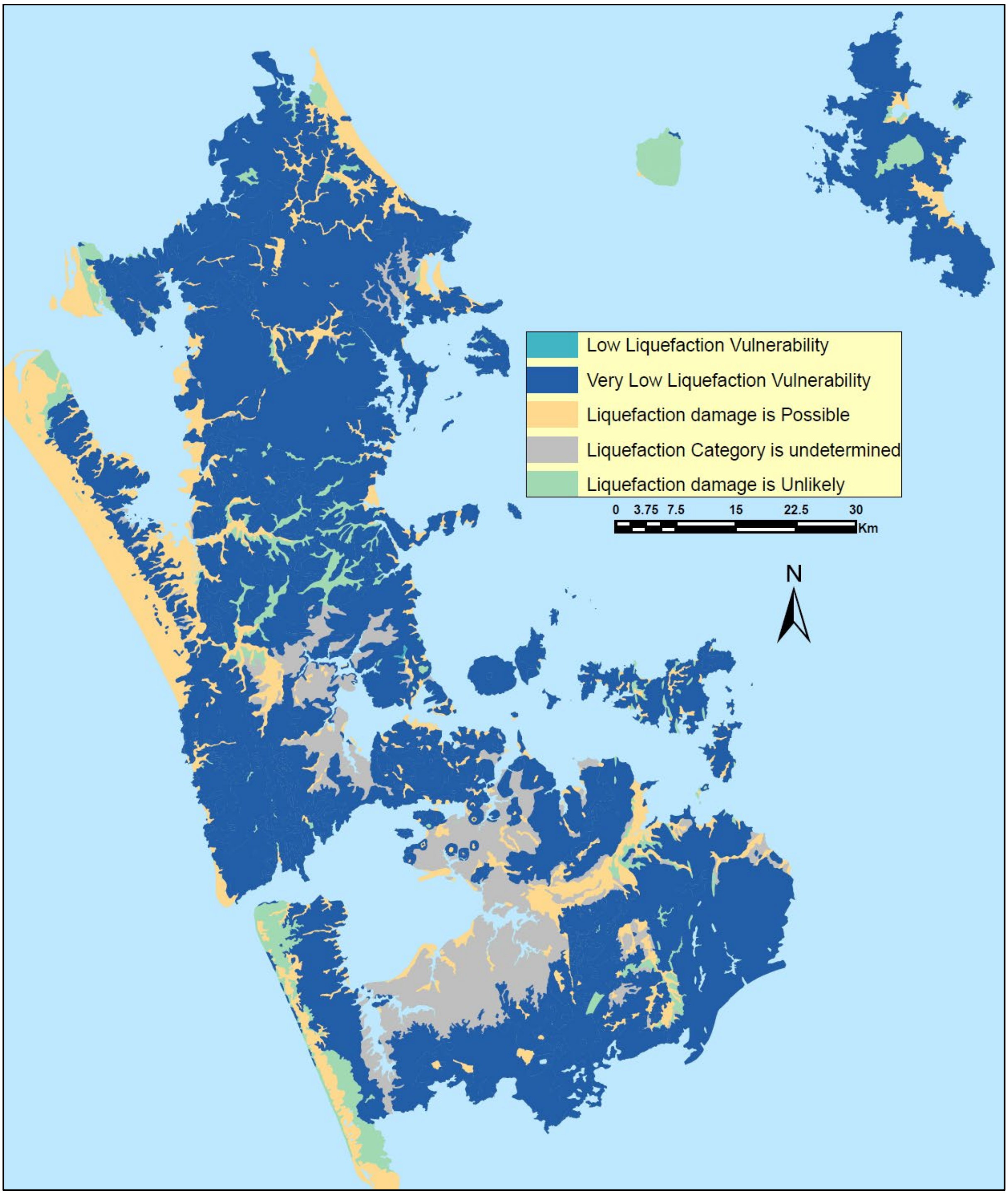


Figure 25: Summary of Further South areas investigated under Level B liquefaction assessment.

5.8 Summary

This section summarises the application of a Level B assessment using qualitative screening criteria. Geotechnical site investigation data in some areas that are classified as *Liquefaction damage is possible* according to a Level A assessment suggests that a refined category of *Low* liquefaction vulnerability is more appropriate given the deposits that are encountered in these areas. This is possible only for the areas where a good density of subsurface investigations are available. Being a regional level study, it is not possible to apply this to the whole region. The updated categories suggested for the region for all the areas with a good density of investigations are shown in Figure 26, and Figure 27 shows the Level B categories for the Auckland's main urban region.

The Puketoka Formation deposits, which can be a loose sandy material with volcanic content, are prevalent across the region., Although the semi-quantitative criteria used in the Level A assessment suggests that these deposits are less likely to liquefy, geotechnical site investigation data suggests that they may liquefy and therefore there is less confidence in the Level A category. Given this lack of confidence, an updated classification of *Liquefaction category is undetermined* is suggested for these deposits.



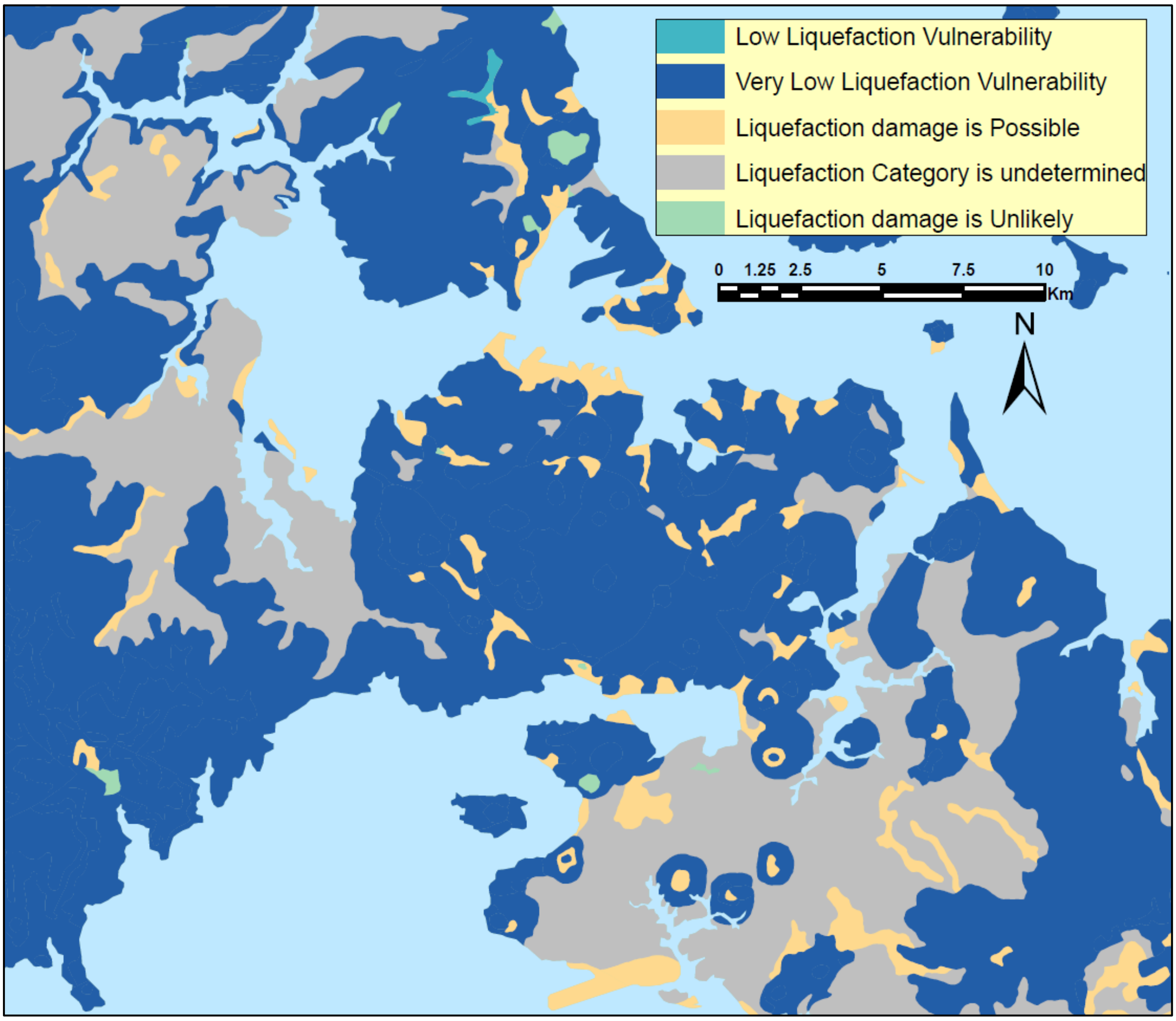


Figure 27: Summary of Level B assessment categories for Auckland's main urban region.

6 DETAILED LIQUEFACTION ASSESSMENT (LEVEL C)

Detailed liquefaction assessment for the entire Auckland region is not possible given the low density of CPT soundings in most areas. This section provides a demonstration of the application of the Level C detailed liquefaction assessment using CPT data available in the region. The areas identified as *Liquefaction damage is possible* in Level-A geology-based classification can be assigned refined liquefaction vulnerability categories of *Low, Medium, High, or Very High*.

6.1 PGA and Magnitude

The PGA and magnitudes described in Section 3 are used in this Level C assessment. For liquefaction triggering analysis, the magnitude for the Auckland region defined by the NZTA Bridge manual is M_w5.9 across all return period events. A PGA of 0.205g is used for the **500-year** return period and for the **100-year** return period the PGA is equal to 0.10g.

6.2 Triggering and Surface Manifestation Severity

The triggering of liquefaction for each soil layer is assessed using the simplified liquefaction triggering methodology proposed by Boulanger and Idriss (2014). This method is an empirical approach that estimates whether liquefaction will trigger in the different layers of a soil profile. The input parameters that have been adopted for the Boulanger and Idriss (2014) liquefaction triggering assessment for this study are listed in Table 4.

One of the key aspects of a quantitative liquefaction assessment is understanding the relationship between liquefaction triggering analysis and the potential for damage at the ground surface. A common approach is to select threshold values of a calculated index parameter that estimates the degree of liquefaction-induced ground damage severity. This study uses the Liquefaction Severity Number (LSN) to provide this estimate, based on the results of the liquefaction triggering analysis for a given level of shaking and a given groundwater level. The LSN parameter has been correlated with evidence of surface ground damage in Christchurch (Tonkin + Taylor, 2015), with a higher LSN value indicating a greater likelihood of liquefaction-induced ground damage. MBIE Guidance recommends that the degree of liquefaction-induced ground damage is split into three categories:

- none to minor
- minor to moderate
- moderate to severe

Table 4: Input parameters for CPT liquefaction triggering analysis.

Input parameter	Default value adopted	Comments
Soil density	18 kN/m^3	Triggering is typically not sensitive to the typical soil density values.
FC-Ic correlation	0	Appropriate upper bound value for regional soils in an absence of other data.
Ic-cut off	2.6	An appropriate value for regional soils in an absence of other data.
Magnitude of earthquake shaking	M_w = 5.9	Recommended by the NZTA Bridge manual.
Peak ground acceleration (g)	0 to 0.8 with an increment of 0.05	Range of PGAs are used.
Probability of liquefaction, P_L (%)	P_L =15%	Based on standard engineering design practice P_L=15% is discussed in this report.
Depth to groundwater (m)	Varies	A range of groundwater depths are used based on the regional model, and the sensitivity of these values is assessed.

Explanation of the typical manifestations of damage at the ground surface and example photos are described in MBIE Guidance and also presented in the Appendix 9.2 of this report. Characteristic LSN ranges for each degree of liquefaction-induced damage category adopted for this assessment are summarised in Table 5 These are used to define a degree of severity of ground damage for each soil profile and scenario, and eventually a liquefaction vulnerability category.

To provide a visual representation of the relationship between liquefaction-induced ground damage and intensity of earthquake shaking for a range of PGA values, ground damage response curves are developed. Examples of different ground damage response curves are presented in Figure 28. Here a range of PGA values for a particular magnitude earthquake are used (as summarised in Table 4), extending beyond the values defined for each return period earthquake. These curves are used to assign a liquefaction vulnerability category based on the MBIE Guidance, with the vulnerability category to be used at each site:

- If less than minor ground damage at 500-year Level of shaking, then the liquefaction vulnerability category is *Low* (Curve 1 in Figure 28)

- If more than Moderate ground damage at 500-year Level of shaking, then the liquefaction vulnerability category is *High* (Curve 2 in Figure 28)
- If more than Minor ground damage at 100-year Level of shaking, then the liquefaction vulnerability category is *High* (Curve 3 in Figure 28)
- If none of the above apply, the liquefaction vulnerability category is *Medium*

Table 5: Characteristic LSN boundaries adopted for the purpose of this study (Ogden 2018).

Degree of liquefaction-induced ground damage	Approximate characteristics LSN ranges used for this high-level hazard study
None to minor	<13
Minor to moderate	13-18
Moderate to severe	>18
Note: These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).	

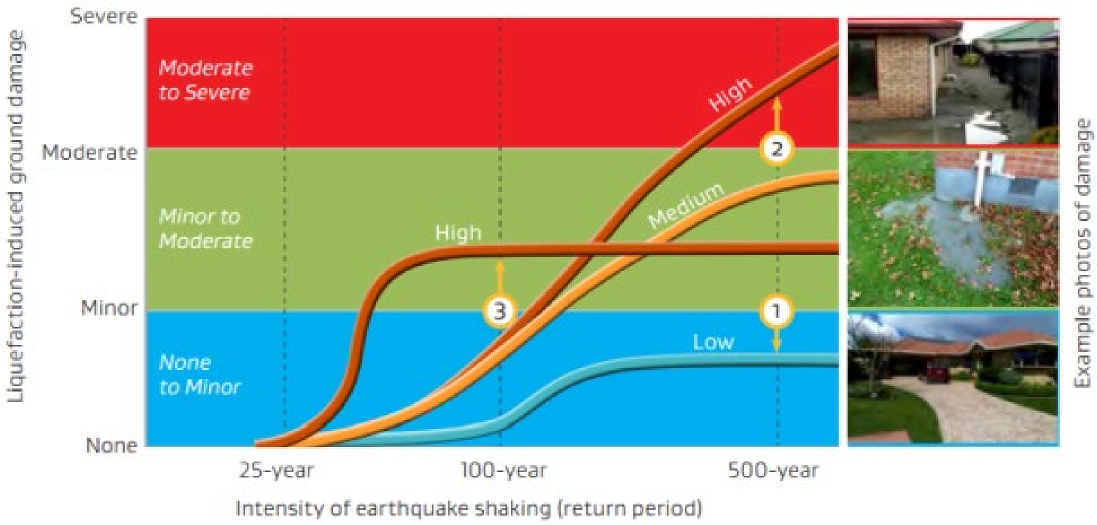


Figure 28: Conceptual example of ground damage response curves for low, medium and high liquefaction vulnerability categories, and performance criteria for liquefaction categorisation (MBIE/MfE/EQC 2017).

To account for the spatial variability in results within each focus area the 50_{th}, 15_{th} and 85_{th} percentile ground damage response curves for each grouping of CPT soundings are defined and presented with the individual CPT soundings-based ground damage response curves. It gives a good overview to assign classification and how outliers showing very high or very low LSN values impacted the overall classification.

To classify the liquefaction vulnerability category for each focus area, LSN values corresponding to 100-year and 500-year return period events were determined for the 50th and 85th percentile ground damage response curves. The upper boundaries between the liquefaction-induced ground damage categories for the 50_{th} and 85_{th} percentile LSN values for each region were defined in accordance to the values presented in Table 5:

- less than minor $50_{th} \leq 10$, $85_{th} \leq 15$
- less than moderate $50_{th} \leq 20$, $85_{th} \leq 25$
- greater than moderate $50_{th} > 20$, $85_{th} > 25$

In cases where the categories differed between the 50_{th} and the 85_{th} percentile curves, the 85th percentile curve was used.

As outlined in the MBIE Guidance, when assigning liquefaction vulnerability categories for an area-wide hazard assessment it is important to account for the uncertainties associated with the assessment, and the potential consequences of over-estimating or under-estimating the liquefaction vulnerability. To understand the potential liquefaction vulnerability of the study area, LSN values were calculated at each CPT location for a range of groundwater depths. This approach develops ground response curves that define the relationship between LSN values and PGA for each CPT. Ground damage response curves are developed at each CPT location, and these are grouped by geomorphic zone.

6.3 Demonstration of Level C detailed assessment

The following section provides a demonstration of the application of the qualitative criteria described above on two areas of Auckland where a high density of CPT data is available. In each area, further sub-areas are assigned when there is evidence of spatial variability.

6.3.1 Auckland waterfront

Figure 29 shows the locations of CPTs in the Auckland waterfront and the Level A liquefaction vulnerability classification. Auckland waterfront reclamation fills deposited since 1859 are present above Tauranga Group alluvium and East Coast Bays Formation. The fills consist of four major types: Construction fills, excavated rock fills, hydraulic fills and industrial and domestic wastes. A high density of CPTs is available and these are divided into three sub-areas according to the nature of the fill material.

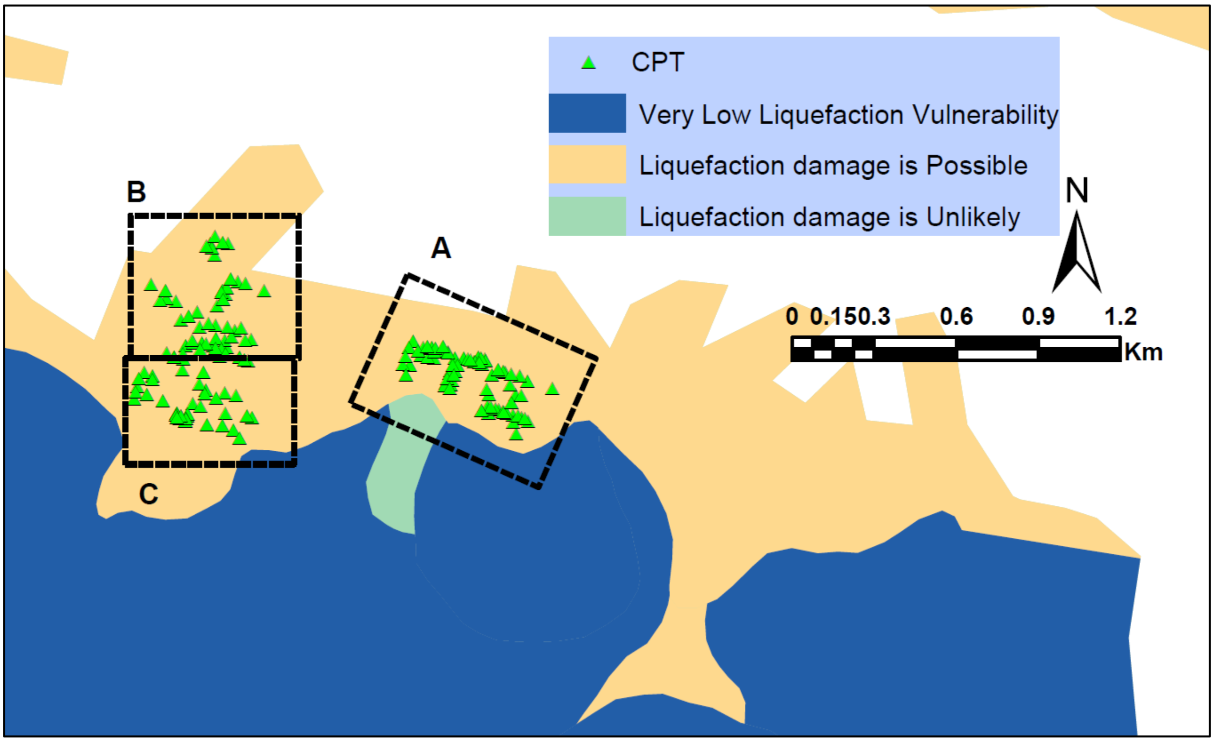


Figure 29: Summary of the Auckland waterfront area with CPT sounding locations and sub-areas used in the Level C assessment.

Sub-area A is loose alluvial, hydraulic fill, with the ground damage response curves in Figure 30 indicating that the estimates of liquefaction-induced damage is less than moderate but higher than minor for the 500-year level of shaking. Therefore a category of *Medium* can be assigned to this sub-area. The outliers with very high or very low LSN values can be ignored as these are few and the criteria described is based on the 85th and 50th percentile curves that represent the categories for the majority of the curves for this area.

Sub-area B is loose alluvial hydraulic fill, with the ground damage response curves in Figure 31 indicating that there is significant variability across the LSN curves for each CPT sounding. The estimate of liquefaction-induced ground damage is less than minor for the 500-year level of shaking for sub-area C. Therefore, a liquefaction vulnerability category of *Low* can be assigned to this sub-area.

Deposits in sub-areas C are rockfill, hard stiff and waste material. Ground damage response curves summarised in Figure 32 show that the estimate is less than minor for the 500-year level of shaking for sub-area C. Therefore, a liquefaction vulnerability category of *Low* can be assigned to this sub-area.

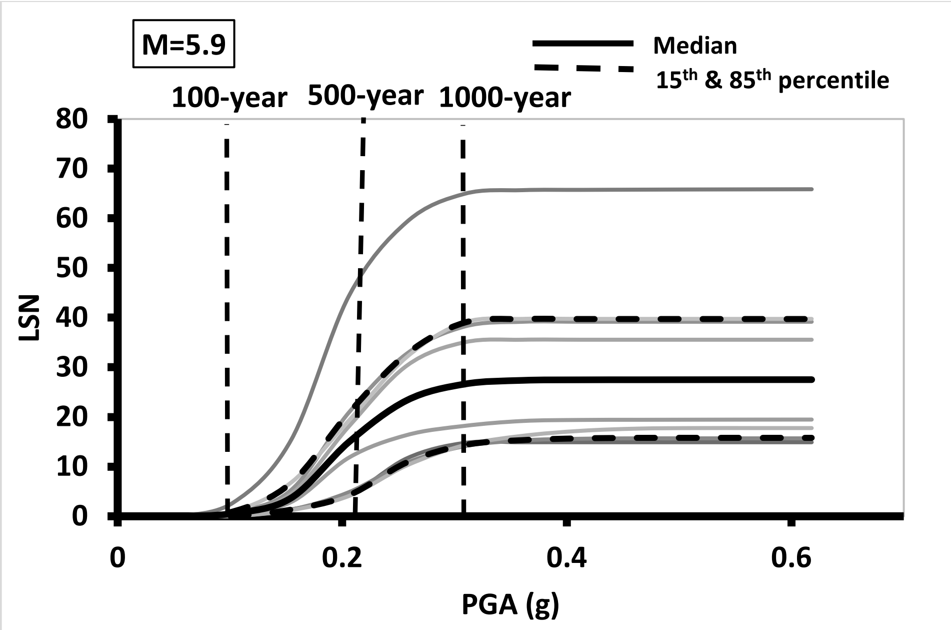


Figure 30: Ground damage response curves for CBD and waterfront sub-area A.

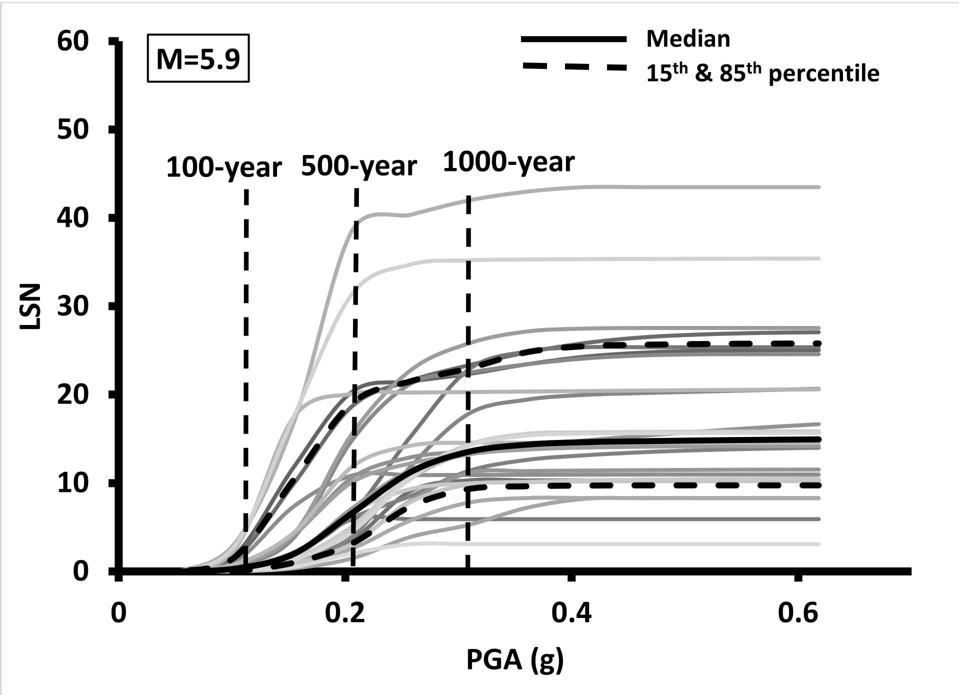


Figure 31: Ground damage response curves for CBD and waterfront sub-area B.

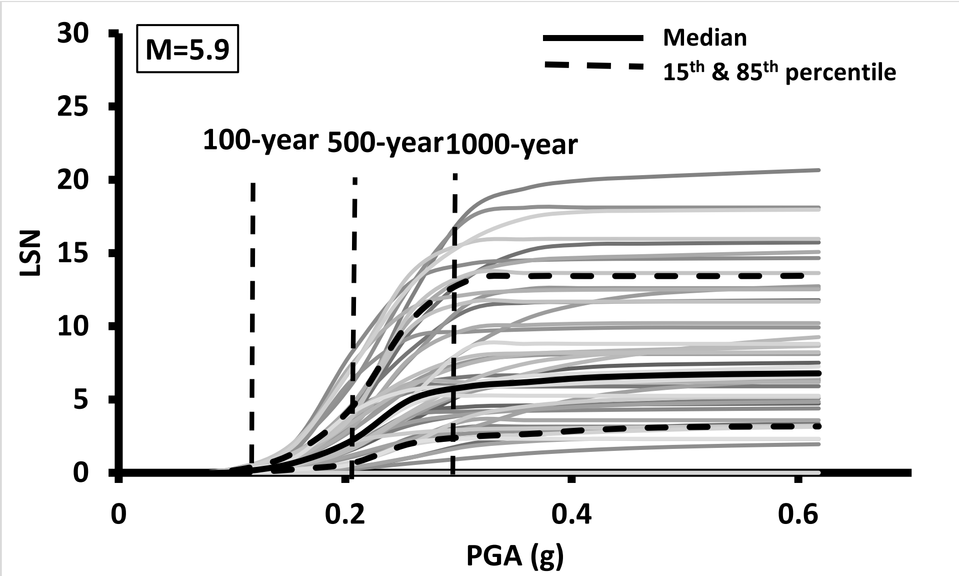


Figure 32: Ground damage response curves for CBD and waterfront sub-area C.

6.3.2 Mangere

The Mangere area of interest is dominated by Puketoka Formation deposits. These have been classified as *Liquefaction damage is unlikely* based on the Level A classification using semi-quantitative criteria. The Level B classification indicated that as these deposits are dominated by sandy material with some pumice content, a classificaiton of *Liquefaction category is undetermined* was appropriate given the potential uncertainy in their performance. For the Level C assessment, this can be further investigated to assign a more precise category based on CPT data.

A large number of CPTs are available in this area as shown in Figure 33 and ground damage response curves cannot be summarized into a single grouping. Therefore, CPTs in this area were divided into sub-areas a-g. The geologic characteristics of all CPTs in this area are similar and grouping is done on the basis of proximity only (this has little influence on the classification as demonstrated).

The ground damage response curves in the Mangere area are presented in Figure 34 to Figure 40, and all the 50th and 85th percentile curves have similar characteristics. There are a few outliers with high values, however this should not affect the classification for each area.

Liquefaction-induced ground damage is less than minor for the 500-year level of shaking. Therefore, a category of *Low* can be applied across this area.

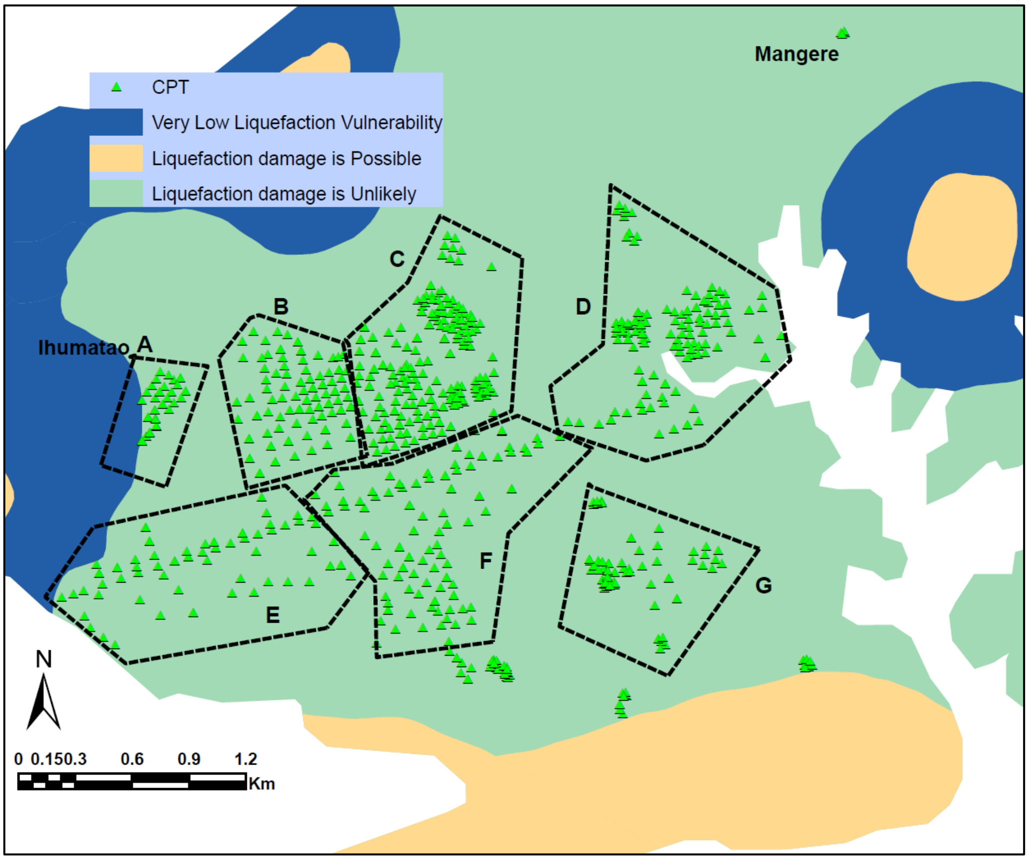


Figure 33: Summary of the Mangere area with CPT sounding locations and sub-areas used in the Level C assessment.

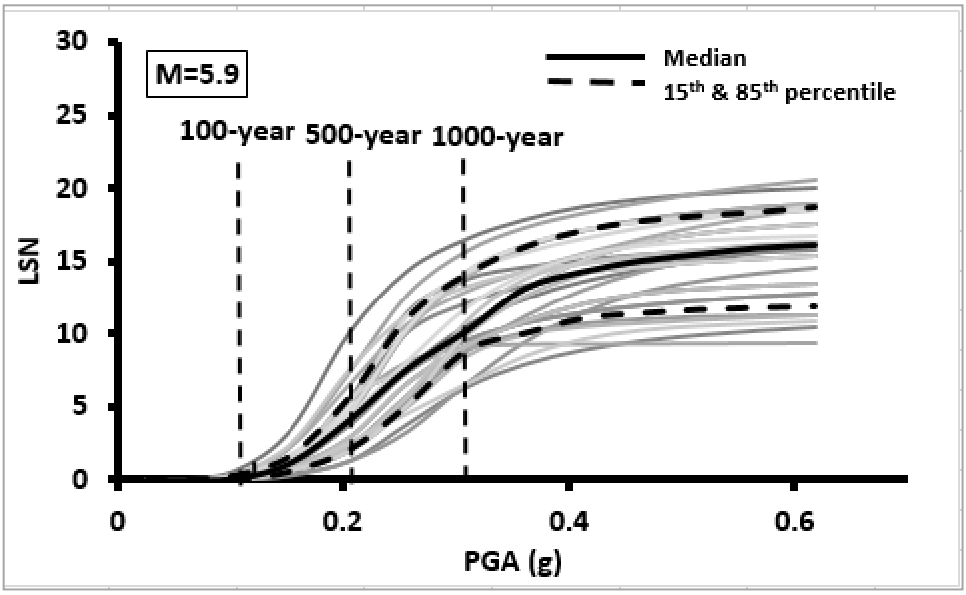


Figure 34: Ground damage response curves for Mangere sub-area a.

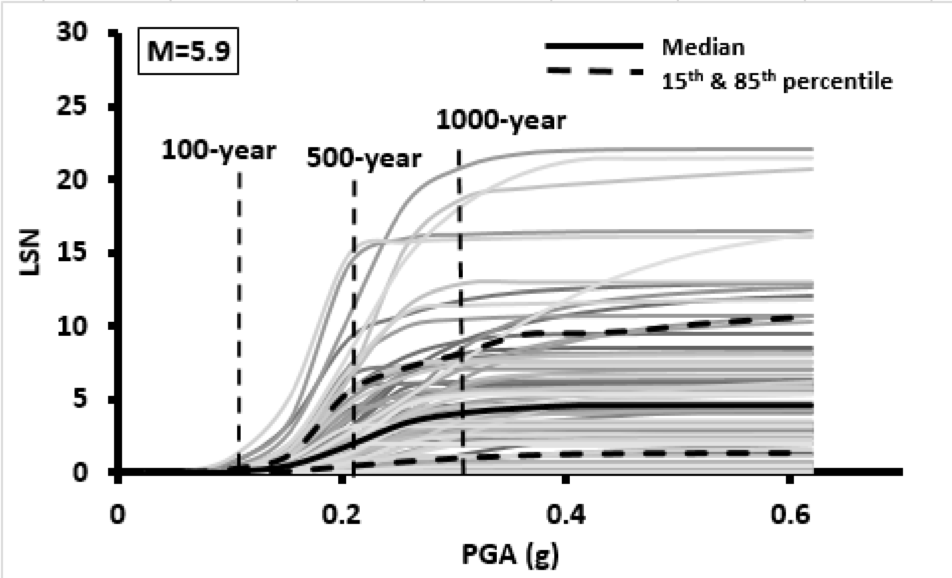


Figure 35: Ground damage response curves for Mangere sub-area b.

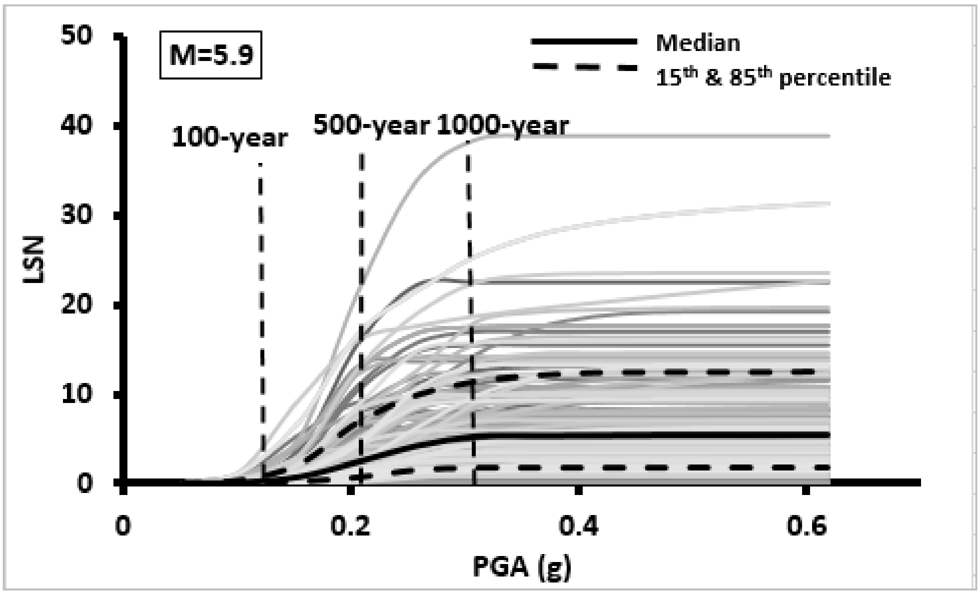


Figure 36: Ground damage response curves for Mangere sub-area c.

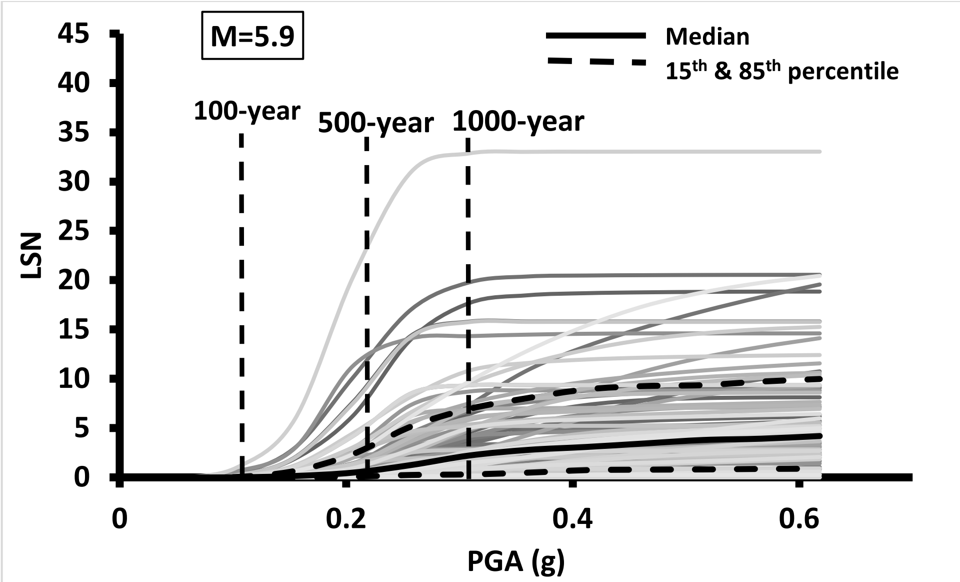


Figure 37: Ground damage response curves for Mangere sub-area d.

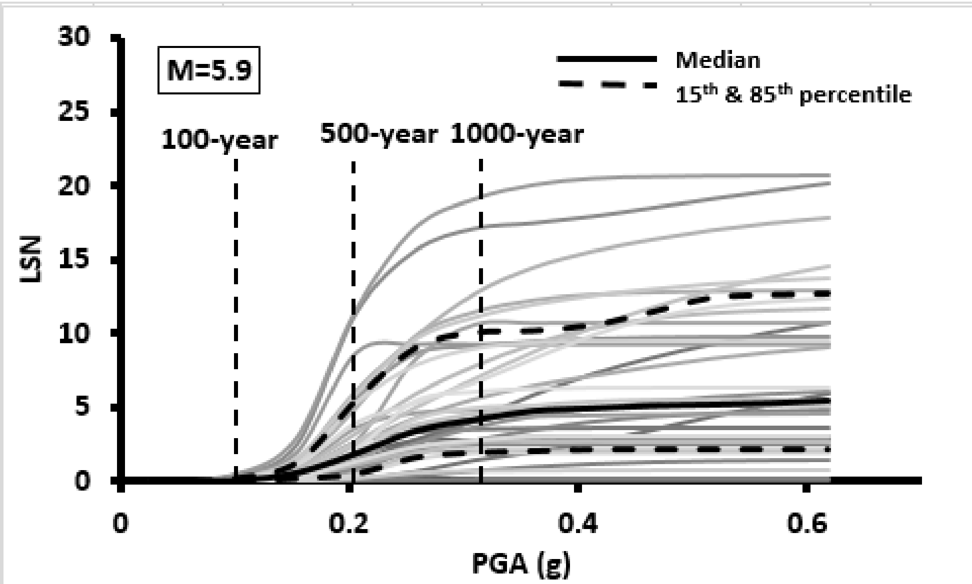


Figure 38: Ground damage response curves for Mangere sub-area e.

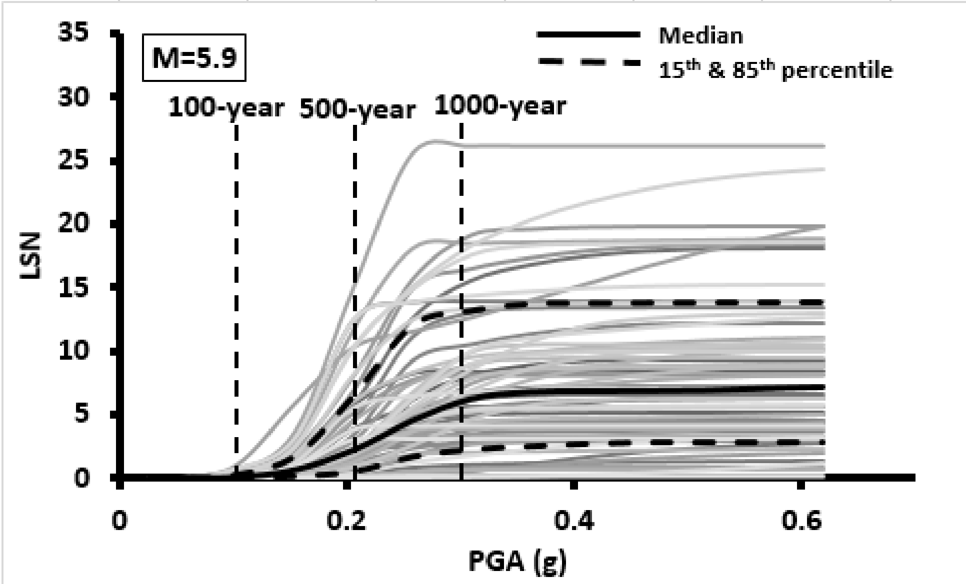


Figure 39: Ground damage response curves for Mangere sub-area f.

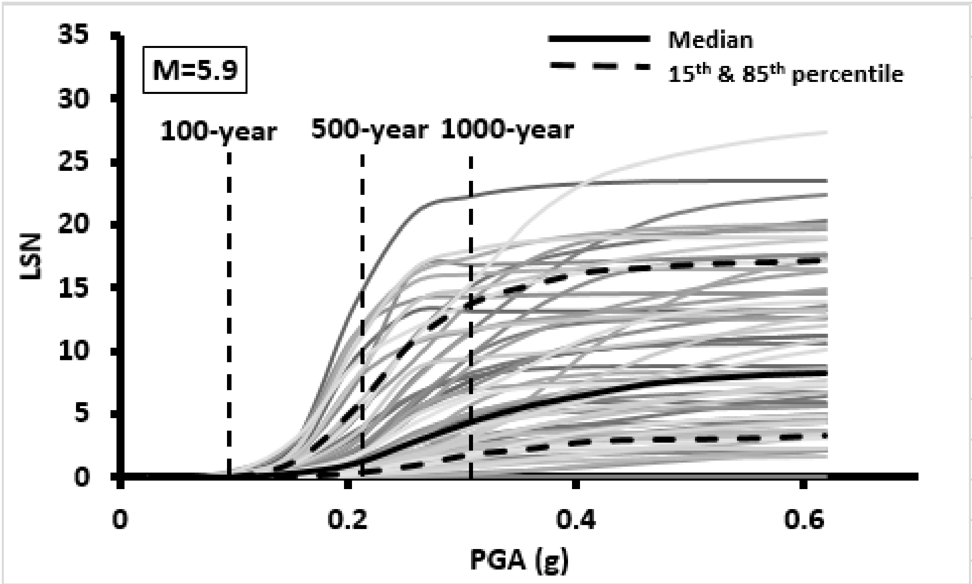


Figure 40: Ground damage response curves for Mangere sub-area g.

6.4 Summary

This section provides a demonstration of the application of Level C liquefaction vulnerability assessment based on CPT soundings. Two areas with a high density of CPT soundings are presented, showing how more refined categories can be assigned to a area using performance-based quantitative criteria.

The Auckland waterfront has a high density of CPT soundings and variable fill material at the near-surface. This area has been identified as *Liquefaction damage is possible* based on Level A assessment, and then qualitative calibration in Level B assessment confirmed this classification. Using a Level C assessment, more precise categories of *Medium* and *Low* are assigned to these areas.

A portion of the Mangere region has a high density of CPTs and is dominated by the Puketoka Formation. This sandy material has been assigned as *Liquefaction damage is unlikely* in Level A assessment, based on the age of these deposits. However, Level B assessment qualitative calibration suggested that these deposits may still be susceptible to liquefaction, noting the presence of loose alluvial deposits and a high groundwater table. Because of this uncertainty across classifications, *Liquefaction category is undetermined* was assigned to the Puketoka Formation. Level C assessment provides an opportunity to assign a category to these areas with more confidence based on CPT data, and it suggests that *Low* liquefaction vulnerability would be suitable for this area.

Table 6 summarises the liquefaction vulnerability categories for these two examples across the Level A, B and C assessments. This provides a good demonstration of the progression of classification from Level A to Level C as more information is used to reduce uncertainty and refine the classification.

Table 6 : Summary of liquefaction vulnerability categories for the Auckland waterfront and Mangere region as a demonstration of the application of different levels of assessment.

Regions	Liquefaction vulnerability categories		
	Level A	Level B	Level C
CBD Waterfront a	Liquefaction damage is possible	Liquefaction damage is possible	Medium
CBD Waterfront b and c			Low
Mangere	Liquefaction damage is unlikely	Liquefaction category is undetermined	Low

7 Summary

This report has presented a liquefaction-induced ground damage assessment for the Auckland Region based on the Planning and engineering guidance for potentially liquefaction-prone land' (MBIE/MfE/EQC 2017). Level A and Level B assessment is presented for the whole region and a demonstration of the application of Level C assessment is presented for two areas.

Level A geology-based assessment using geologic maps, regional groundwater and seismic hazard information provided a high level representation of the liquefaction vulnerability categories across the Auckland Region. Exposed rock deposits that are not expected to liquefy were given a *Very Low* classification, removing them from further assessment. Young geologic deposits were classified as *Liquefaction damage is possible* based on the simple screening assessment, with the remaining deposits in the region classified as *Liquefaction damage is unlikely*.

Geotechnical investigation data from across the region was used in Level B assessment to refine the Level A liquefaction vulnerability categories using qualitative screening approach. The changes in classification between Level A and B were discussed, in particular, the areas where the liquefaction vulnerability of the soil profile was likely dominated by the Puketoka Formation. All these deposits were assigned *Liquefaction damage is unlikely* in the Level A assessment because of their Late Pliocene to middle Pleistocene geologic age, however subsurface investigation data in these areas showed the presence of loose sandy, silty soils with pumice content in some areas. Based on the current understanding of the behaviour of the Puketoka Formation, more investigations are needed to better constrain their liquefaction potential. As a result their classification based on Level B assessment has been changed to *Liquefaction category is undetermined.* For a large part of the remaining Auckland Region there were no investigations available to be able to apply the Level B assessment, meaning no changes to the Level A assessment classifications could be made.

Detailed Level C liquefaction assessment for the entire Auckland Region using CPT-based liquefaction assessment procedures was not possible given the low density of CPT soundings in most areas. A demonstration of the application of the Level C assessment in two areas with a high density of CPTs was presented. Both these examples clearly demonstrated the influence of different levels of assessment detail and increased density of investigation data on the classification outcome. Maps developed for each level of assessment will benefit planners, asset owners, emergency managers, and engineers in assessing the vulnerability of their projects and assets with respect to liquefaction. Further collation of geotechnical investigation data will help to further refine the liquefaction vulnerability categories across the region.

8 REFERENCES

Alloway, B. V., Lyall, J.A., & Kozuch, M.J. (1998). Mapping and characterisation of the Drury Fault. *Issue 96 of Technical Publication,* Auckland Regional Council.

Al-Salim, M.A. (2000). A geophysical and geological investigation of the Drury Fault and related block faulting, south-east Auckland, *MSc Thesis*, University of Auckland.

Auckland Council (2014). *Auckland Profile: Initial results from the 2013 census*. Auckland.

Auckland Council (2014). *South Auckland Rural Urban Boundary project*, Report by Tonkin& Taylor

Auckland Council website (2017) (http://www.aucklandcouncil.govt.nz)

Auckland Regional Council (1997). *Final Report-Stage 1, Auckland Engineering Lifelines Project*.

Balance, P.F., Smith, I.E.M. (1982). *Walks through Auckland's geological past: a guide to the geological formations of Rangitoto, Motutapu, and Motuihe Islands*. Geoscience Society of New Zealand.

Boulanger, R. W., & Idriss, I. M. (2014). CPT and SPT-based liquefaction triggering procedures. *Rep. No. UCD/CGM-14, 1*.

Creinarz (2010). Soil liquefaction," EERI Chile Earthquake Clearinghouse "Earthquake Actions – *New Zealand; Standards* New Zealand

Dempsey, D., Eccles, J. D., Huang, J., Jeong, S., Nicolin, E., Stolte, A., & Bradley, B. A. (2020). Ground motion simulation of hypothetical earthquakes in the upper North Island of New Zealand. *New Zealand Journal of Geology and Geophysics*, 1-19.

Dowrick, D.J. (1992). Seismic *hazard estimates for the Auckland area, and their design and construction implications. Bulletin of the New Zealand National Society for Earthquake Engineering*, 25(3): 211-221.

Edbrooke, SW, Mazengarb, C & Stephenson, W (2003). 'Geology and geological hazards of the Auckland urban area, New Zealand', *Quaternary International*, Vol. 103, No. 1, pp. 3–21.

ESRI (2011). *ArcGIS Desktop: Release 10. Redlands*, CA: Environmental Systems Research Institute.

GNS Science (2017). *Auckland Geological Maps* (http://data.gns.cri.nz/af/)

Japan Society of Civil Engineers-Japanese Geotechnical Society (2003). *Damage Investigation Report of the May 26 2003 off Miyagi Prefecture Earthquake* (in Japanese).

Kenny J.A., Lindsay J.M., Howe T.M. (2011). *Large-scale faulting in the Auckland region*. Technical Report 1-2011.04 Institute of Earth Science and Engineering (IESE)

Kermode, L. (1992). *Geology of the Auckland Urban Area: Sheet R11: 1: 50 000*. Institute of Geological & Nuclear Sciences.

Langridge, R. M., et al. (2016) "The New Zealand active faults database." *New Zealand Journal of Geology and Geophysics* 59.1: 86-96.

Leonard, G. S., Calvert, A. T., Hopkins, J. L., Wilson, C. J., Smid, E. R., Lindsay, J. M., & Champion, D. E. (2017). High-precision 40Ar/39Ar dating of Quaternary basalts from Auckland

Volcanic Field, New Zealand, with implications for eruption rates and paleomagnetic correlations. *Journal of Volcanology and Geothermal Research*, 343, 60-74.

Lindsay, J. M., Leonard, G. S., Smid, E. R., & Hayward, B. W. (2011). Age of the Auckland Volcanic Field: a review of existing data. *New Zealand Journal of Geology and Geophysics*, *54*(4), 379-401.

Ministry of Business, Innovation and Employment New Zealand report, (2017) "*National Framework for assessment of Liquefaction-Induced Ground Damage to inform planning Processes*". (https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land)

NZ Transport Agency (2013). *SP/M/022 Version 3*. Bridge Manual.

Okabayashi, T., Hyodo, M., Yasufuku, N., & Murata, H. (1994). Monotonic and cyclic undrained shear behaviour of volcanic soil "SHIRASU". *Doboku Gakkai Ronbunshu, 1994(499), 97-106.*

Pyke, R. (2003). Discussion of "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils" by TL Youd, IM Idriss, Ronald D. Andrus, Ignacio Arango, Gonzalo Castro, John T. Christian, Richardo Dobry, WD Liam Finn, Leslie F. Harder Jr., Mary Ellen Hynes, Kenji Ishihara, Joseph P. Koester, Sam SC Liao, William F. Marcuson III, Geoffrey R. Martin, James K. Mitchell, Yoshiharu Moriwaki, Maurice S. Power, Peter K. Robertson, Raymond B. *Journal of Geotechnical and Geoenvironmental Engineering*, *129*(3), 283-284.

Searle, E.J & Mayhill, R.D. (1981).*City of Volcanoes: A Geology of Auckland* (2nd edition), Longman Paul.

Seed, H. B., and Idriss, I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. *J. Soil Mechanics and Foundations Div., ASCE 97(SM9)*, 1249–273.

Seed, H. B., Tokimatsu, K., Harder, L. F. Jr., and Chung, R. (1985). Influence of SPT procedures in soil liquefaction resistance evaluations, *J. Geotechnical Eng., ASCE* 111(12), 1425–445.

Standards New Zealand (2004). *NZS 1170.5: Structural Design Actions, Part 5: Earthquake actions.*

Stringer, M. E., Bastin, S., McGann, C., Cappellaro, C., El Kortbawi, M., McMahon, R., & McGlynn, L. (2017). Geotechnical aspects of the 2016 Kaikōura Earthquake on the South Island of New Zealand. Bulletin- *New Zealand Society for Earthquake Engineering* 50(2): 117-141.

Stirling, M., McVerry, G., Gerstenberger, M., Litchfield, N., Van Dissen, R., Berryman, K. & Jacobs, K. (2012). National seismic hazard model for New Zealand: 2010 update. *Bulletin of the Seismological Society of America*, 102(4), 1514-1542.

Uzuoka, R., Sento, N., Kazama, M. & Unno, T. (2005). Landslides during the earthquakes of May 26 and July 26, 2003, in Miyagi," *Soils and Foundations,* Vol. 45, No. 4, 149- 164.

van Ballegooy, S, Malan, P, Lacrosse, V, Jacka, ME, Cubrinovski, M, Bray, JD, O'Rourke, TD, Crawford, SA, and Cowan, H. (2014) Assessment of liquefaction-induced land damage for residential Christchurch. *Earthquake Spectra*, 30(1): 31-55.

Yamanouchi, T. (1968). *Ground failure due to the Ebino earthquake*, Report of the JSSMFE Technical Committee on Shirasu, Tsuchi-to-Kiso, JSSMFE, 16(9), 47-59 (in Japanese).

Youd, T. L., & Idriss, I. M. & NCEER workshop Participants (2001). Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *Journal of Geotechnical and Geoenvironmental*

Engineering, 127(4), 297-313.

Youd, T. L., & Perkins, D. M. (1978). Mapping liquefaction-induced ground failure potential. *Journal of the Soil Mechanics and Foundations Division*, 104(4), 433-446.

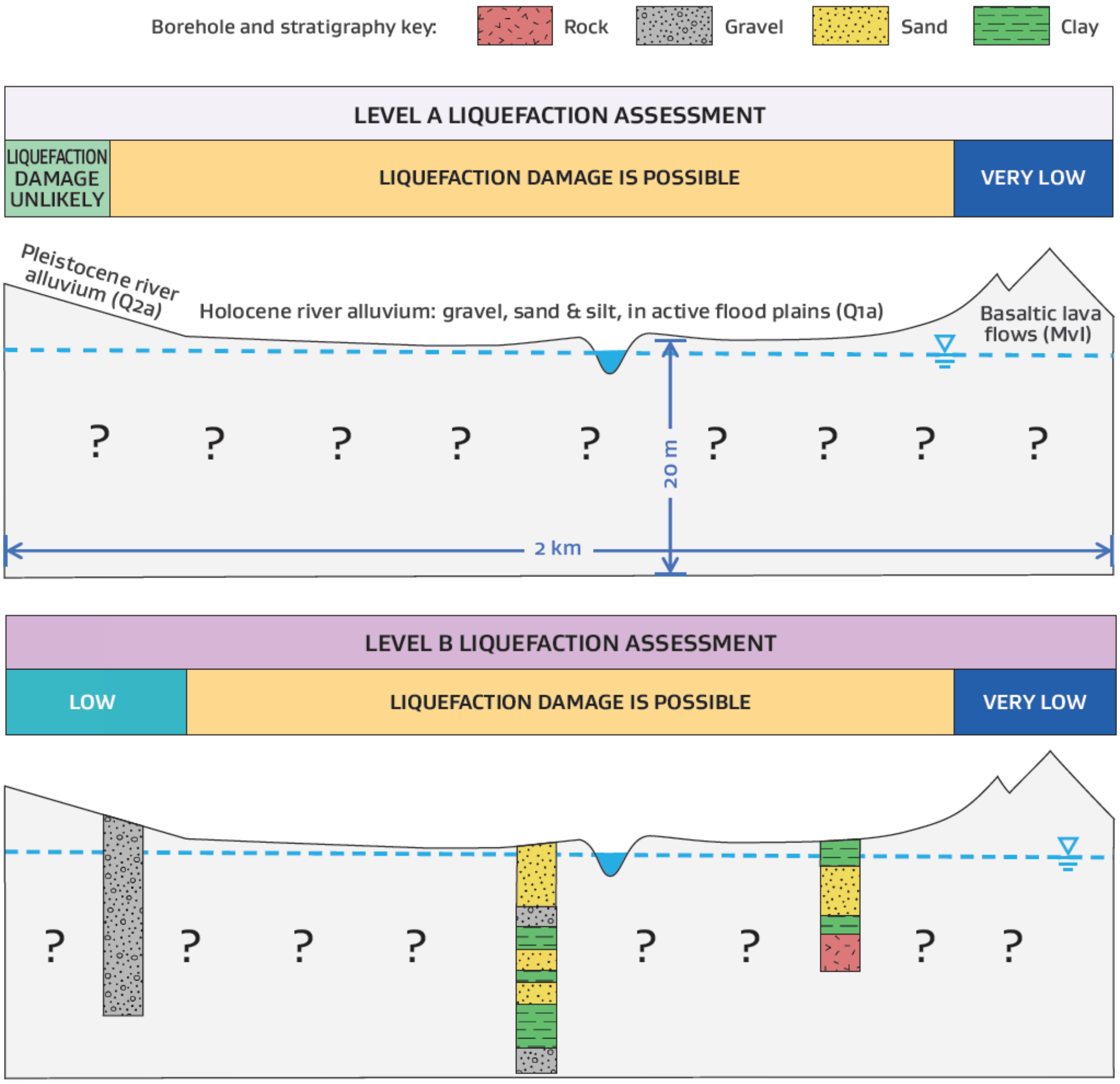
9 Appendix

9.1 Explanation of Level A and Level B assessment (extracted from *MBIE/MfE/EQC 2017)*

Conceptual example of the difference in subsurface ground information for Level A, B, C and D liquefaction assessments:

Level A – Only basic surface geology and groundwater information is available. Areas are identified where ***Liquefaction Damage Is Unlikely*** (Pleistocene deposits with groundwater deeper than 4 m) and with ***Very Low*** liquefaction vulnerability (exposed rock). Substantial uncertainty remains regarding subsurface conditions elsewhere, but the nature of the deposits means that ***Liquefaction Damage Is Possible***.

Level B – A small number of subsurface investigations provides a better understanding of liquefaction susceptibility for the mapped deposits. This shows that the Pleistocene deposits comprise gravel to the surface, with ***Low*** liquefaction vulnerability. Significant uncertainty remains regarding the level of liquefaction-related risk for the Holocene deposits and how ground conditions vary across the area.



9.2 Examples of different degrees of liquefaction-induced ground damage

DEGREE OF LIQUEFACTION-INDUCED GROUND DAMAGE (example photographs)	TYPICAL CONSEQUENCES AT THE GROUND SURFACE **These are examples of the type of damage that would be expected, they are not intended to be criteria for calculation**
None to Minor 	– ***None to Minor*** no signs of ejected liquefied material at the ground surface[1]. – No more than minor differential settlement of the ground surface (eg undulations less than 25 mm in height). – No apparent lateral spreading ground movement (eg only hairline ground cracks). – Liquefaction causes no or only cosmetic damage to buildings and infrastructure (but damage may still occur due to other earthquake effects).
Minor to Moderate 	– ***Minor to Moderate*** quantities of ejected liquefied material at the ground surface (eg less than 25 percent of a typical residential site covered[2]); and/or – Moderate differential settlement of the ground surface (eg undulations 25–100 mm in height). – No significant lateral spreading ground movement (eg ground cracks less than 50 mm wide may be present, but pattern of cracking suggests the cause is primarily ground oscillation or settlement rather than lateral spreading). – Liquefaction causes moderate but typically repairable damage to buildings and infrastructure. Damage may be substantially less where liquefaction was addressed during design (eg enhanced foundations).
Moderate to Severe 	– Large quantities of ejected liquefied material at the ground surface (eg more than 25 percent of a typical residential site covered[2]); and/or – ***Moderate to Severe*** differential settlement of the ground surface (eg undulations more than 100 mm in height); and/or – Significant lateral spreading ground movement (eg ground cracks greater than 50 mm wide, with pattern of cracking suggesting direction of movement downslope or towards a free-face). – Liquefaction causes substantial damage and disruption to buildings and infrastructure, and repair may be difficult or uneconomic in some cases. Damage may be substantially less, and more likely to be repairable, where liquefaction was addressed during design (eg enhanced foundations and robust infrastructure detailing).

Notes:

1 An absence of ejecta at the ground surface does not necessarily mean that liquefaction has not occurred. Liquefaction may still occur at depth, potentially causing ground settlement.

2 The coverage of the site with ejected liquefied material does not in itself represent ground damage in an engineering sense, however there is a strong correlation between the volume of ejecta and the severity of differential ground settlement and foundation/infrastructure damage.

Figure 41: Degrees of liquefaction-induced ground damage used in the land performance framework. (MBIE/MfE/EQC 2017).

Find out more: phone 09 301 0101
or visit www.aucklandcouncil.govt.nz and
www.aucklanddesignmanual.co.nz