REPORT

Tonkin+Taylor

# Bay of Plenty Regional Liquefaction Vulnerability Assessment

**Prepared for**
Bay of Plenty Regional Council
**Prepared by**
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## Document Control

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<table>
<tr><th colspan="2">LIQUEFACTION ASSESSMENT SUMMARY</th></tr>
<tr><td colspan="2">This liquefaction assessment has been undertaken in general accordance with the guidance document ‘Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes’ published by the Ministry for the Environment and the Ministry of Business, Innovation and Employment in 2017.<br>https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land/</td></tr>
<tr><td>Client</td><td>Bay of Plenty Regional Council (BOPRC)</td></tr>
<tr><td>Assessment undertaken by</td><td>Tonkin & Taylor Ltd, PO Box 317, Tauranga 3140</td></tr>
<tr><td>Extent of the Study Area</td><td>The Study Area aligns with the Bay of Plenty Regional Council boundary excluding the Tauranga City Council territory. The Study Area also includes two areas outside of the regional boundary, that being a small area to the west of Mamaku and a large area south of Lake Rotorua to incorporate all of the Rotorua Lakes Council Territory.</td></tr>
<tr><td>Intended RMA planning and consenting purposes</td><td>To provide BOPRC with a region-wide liquefaction vulnerability assessment to identify areas of land susceptible to liquefaction as required in the Regional Policy Statement (RPS). The technical report and resulting map outputs will be used to inform land use, subdivision and building consent applications. In particular the vulnerability assessment outputs will be utilised by stake holders to inform the risk assessment requirements for liquefaction prone land.</td></tr>
<tr><td>Other intended purposes</td><td>Not applicable</td></tr>
<tr><td>Level of detail</td><td>Level A (basic desktop assessment)</td></tr>
<tr><td>Notes regarding base information</td><td>The available base information provides enough information for a Level A (basic desktop assessment) level of detail across the Study Area. The main factor controlling this level of detail is the spatial extent of the available geotechnical investigations and groundwater information across the Study Area. There are some small areas (e.g. parts of Whakatāne and Rotorua) where higher levels of detail could be supported by the available base information. Undertaking these studies at a higher level of detail is outside of the scope of work for this project.</td></tr>
<tr><td>Other notes</td><td>This assessment has been made at a broad scale across the entire region and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations).<br>A key consideration of the liquefaction vulnerability categorisation undertaken in accordance with the MBIE/MfE Guidelines (2017) is the degree of uncertainty in the assessment. Discussion about the key uncertainties in this assessment is provided in sections 3.3 and 3.4 of this report.</td></tr>
</table>

# Table of contents

# 1 Introduction

The purpose of this report is to summarise the approach adopted for the assessment of liquefaction vulnerability in the Bay of Plenty region by Tonkin & Taylor Ltd (T+T) and the associated results. This assessment has been undertaken in accordance with the Ministry of Business Innovation and Employment (MBIE) & Ministry for the Environment (MfE) guidance document: *Planning and engineering guidance for potentially liquefaction prone land* (referred to as the MBIE/MfE Guidance (2017)). This assessment provides a risk-based assessment of liquefaction vulnerability across the region.

As shown in Figure 1.1, the extent of the Study Area does not precisely match the extent of the Bay of Plenty Regional Council (BOPRC) land area. This is because the Tauranga City Council land area has been excluded because liquefaction vulnerability mapping has already been completed for this area. Parts of the Rotorua Lakes Council land area that are outside of the BOPRC regional boundary have been included to ensure full coverage of this area.

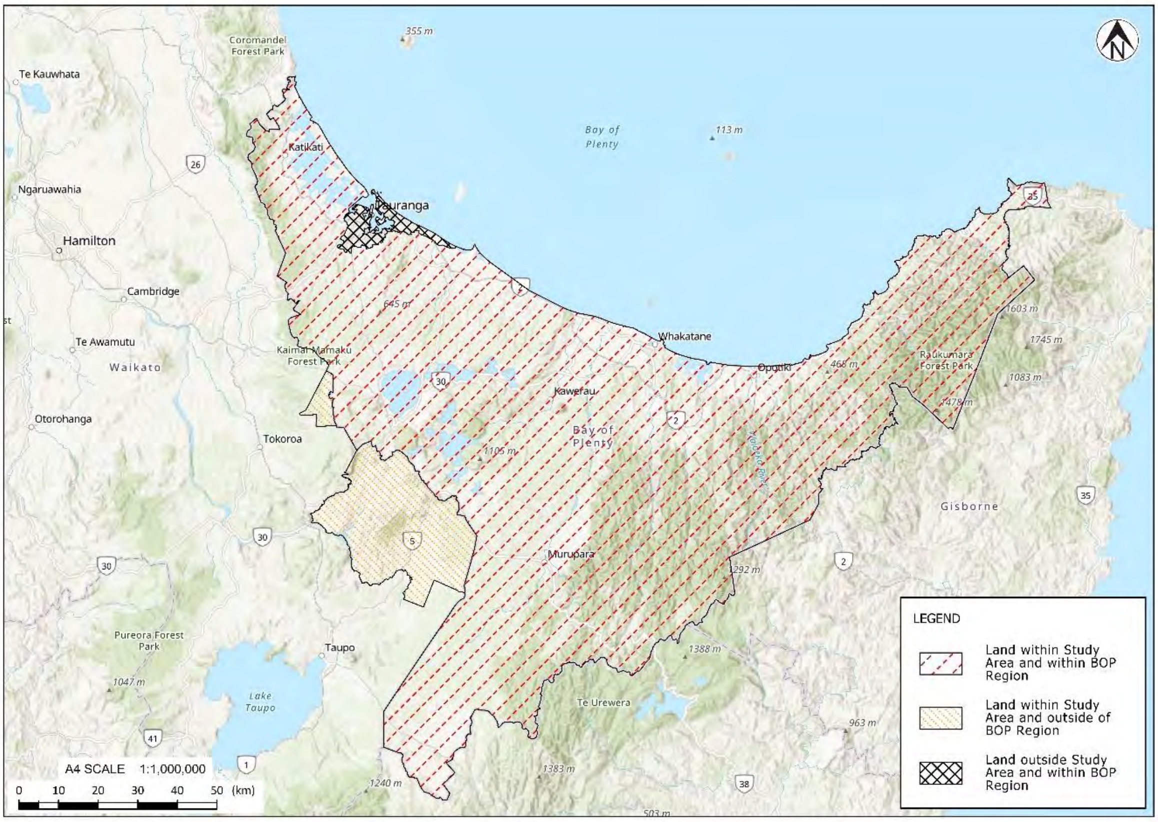



*Figure 1.1: Map showing the extent of the Study Area and the BOPRC regional boundary.*

This report includes:

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

The liquefaction vulnerability assessment and the layout of this report follows the risk management process recommended in ISO 31000:2018, as shown in Figure 1.2.

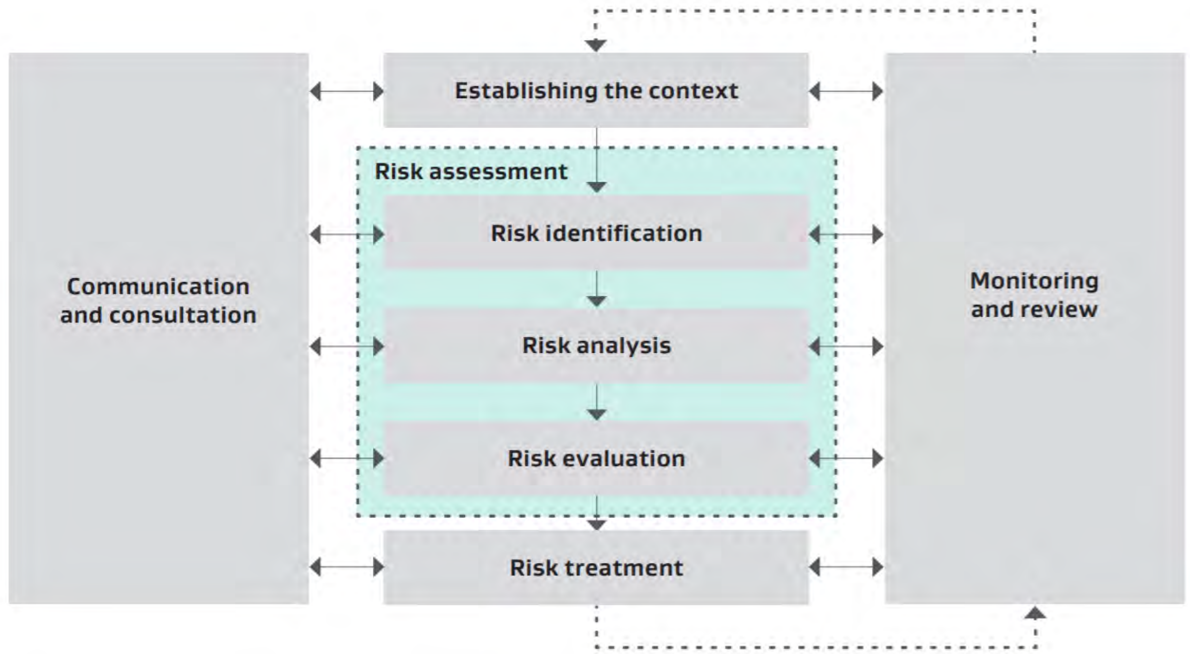



*Figure 1.2: Risk management process defined in ISO 31000:2009, which has been used to guide the liquefaction vulnerability assessment and the layout of this report - from MBIE/MfE Guidance (2017). Note, this figure has been slightly modified in the ISO 31000:2018 standard, however the general concepts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

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

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

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

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

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

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

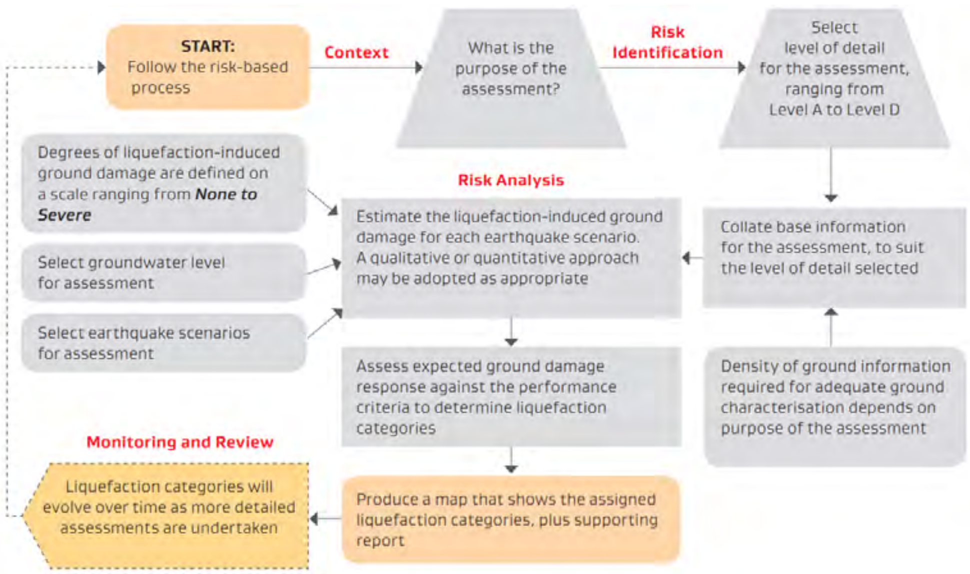
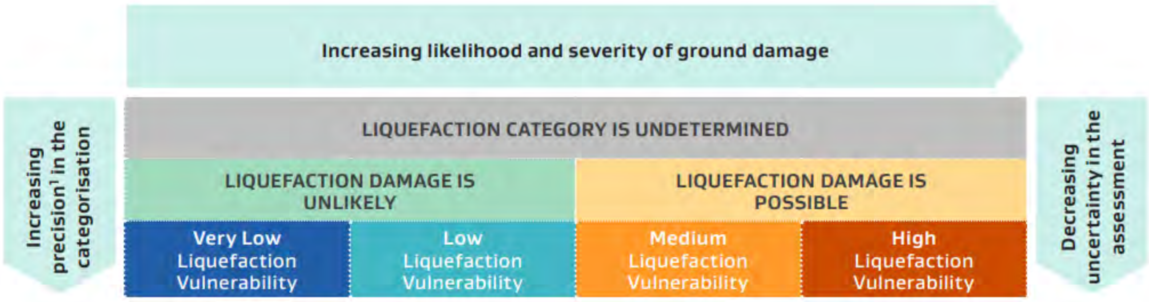



*Figure 1.3: Overview of the recommended process for categorising the potential for liquefaction-induced ground damage - from MBIE/MfE Guidance (2017).*

The MBIE/MfE Guidance (2017) provides a performance-based framework for categorising the liquefaction vulnerability of land to inform planning and consenting processes. That framework is based on the severity of liquefaction-induced ground damage that is expected to occur at various intensities of earthquake shaking. Figure 1.4 shows the recommended liquefaction vulnerability categories for use in that performance-based framework.




Note:

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

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

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

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

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

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

It is important to note that regional scale studies typically result in categorisation of the land into one of the top three vulnerability categories of "Liquefaction Category is Undetermined" or "Liquefaction Damage is Unlikely" or "Liquefaction Damage is Possible". The categorisation of the liquefaction vulnerability of the land within the Bay of Plenty Region into one of the categories shown in Figure 1.4 is one of the key deliverables of this assessment.

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

It is emphasised that the discussion in this report regarding vulnerability categories and options for further geotechnical assessment relate only to liquefaction hazard. There are various other natural hazards and geotechnical constraints which would also need to be considered as part of any future land development or building activities.

# 2 Context

## 2.1 Background to this project

Bay of Plenty Regional Council has funded this project to identify areas of land within the region that have potential for liquefaction-induced ground damage. The region spans across a variety of landscapes that have varying vulnerability to liquefaction-related hazards. Identifying areas of the region that are prone to liquefaction-induced damage will be beneficial for providing safer communities within the region and enable an appropriate land use planning response. This assessment is intended to improve the understanding of liquefaction vulnerability in the region and will produce a liquefaction vulnerability map that can be utilised by different stakeholders. The outputs of the assessment will have two specific uses, the first being related to recent changes to the Building Act and the second being Resource Management Act applications.

Regarding the Building Act changes, in November 2019 the Building Code was amended with respect to ground prone to liquefaction and/or lateral spreading. The changes were:

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

The outputs of the vulnerability assessment provide information to users that can relate to these two Building Code amendments. To date, MBIE have not provided specific recommendations to categorise land as "prone to liquefaction or lateral spreading" within the context of these Building Code amendments. However, T+T understands that further information will be forthcoming from MBIE soon. In the absence of specific advice from MBIE, we recommend the following:

- Land that has been categorised as "Liquefaction Damage is Possible" as part of this assessment is considered to be "prone to liquefaction or lateral spreading" and therefore does not meet the definition of "Good Ground" as outlined in the Building Code amendments. Note that subsequent liquefaction vulnerability assessment at a higher level of detail may result in reclassification of the land into a different category and whether it meets the definition of "Good Ground" should be reconsidered based on that new information.
- Land that has been categorised as "Liquefaction Damage is Unlikely" as part of this assessment is considered to be "not prone to liquefaction or lateral spreading" within the context of the definition of "Good Ground" as outlined in the Building Code amendments. Note there may be other reasons why the definition of "Good Ground" is not satisfied at a particular site (e.g. the presence of compressible or expansive soils) and the person specifying the foundation solution will need to undertake their own assessment for these factors.
- For land that has been categorised as "Liquefaction Category is Undetermined" as part of this assessment, there is currently insufficient information to determine whether it is "prone to liquefaction or lateral spreading" within the context of the definition of "Good Ground" as outlined in the Building Code amendments. Note that subsequent liquefaction vulnerability assessment at a higher level of detail will likely result in reclassification of the land into a different category and whether it meets the definition of "Good Ground" should be reconsidered based on that new information.

Resource Management Act applications within the Bay of Plenty region are generally undertaken in accordance with the Regional Policy Statement (RPS). T+T understands that BOPRC intends that the outputs from this liquefaction vulnerability assessment will be utilised by stakeholders to inform the risk assessment requirements for liquefaction prone land required in the RPS. Most importantly, the outputs from the assessment will relate to Policy NH 7A outlined within the RPS. Policy NH 7A requires councils to identify areas susceptible to natural hazards. The purpose of this policy is to "*Identify natural hazards and the locations where those natural hazards could affect people, property and lifeline utilities by mapping hazard susceptibility areas*". This policy relates to volcanic activity hazards, earthquake hazards, coastal/marine processes, and extreme rainfall hazards. It is important to note that this policy involves mapping hazard susceptibility to identify spatial extents of a potential hazard. It does not, however, require the representation of risk or consider the associated consequences of the hazard.

## 2.2 Liquefaction hazard

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

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

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

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

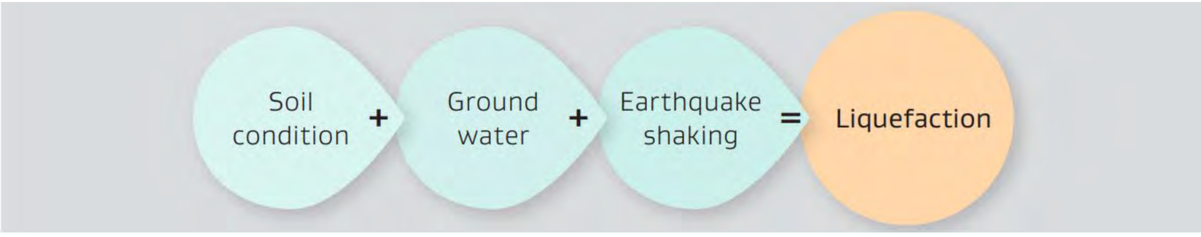



*Figure 2.1: Three key elements required for liquefaction to occur - reproduced from MBIE/MfE Guidance (2017).*

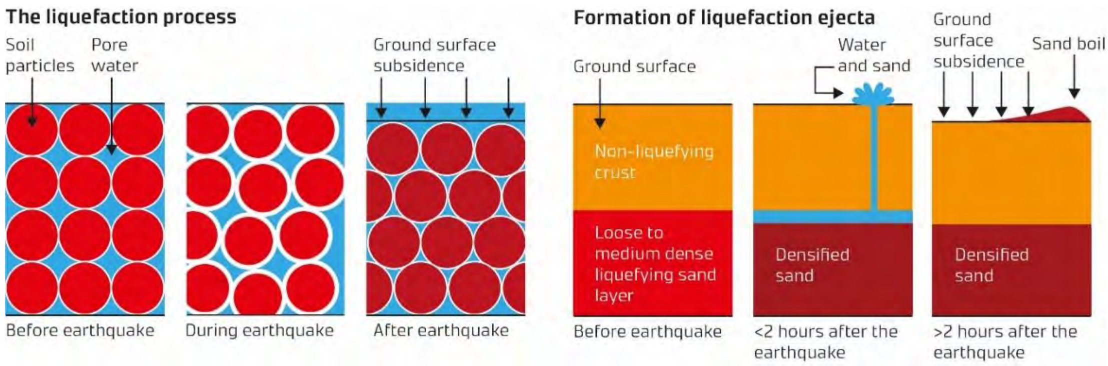



*Figure 2.2: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta - reproduced from MBIE/MfE Guidance (2017).*

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

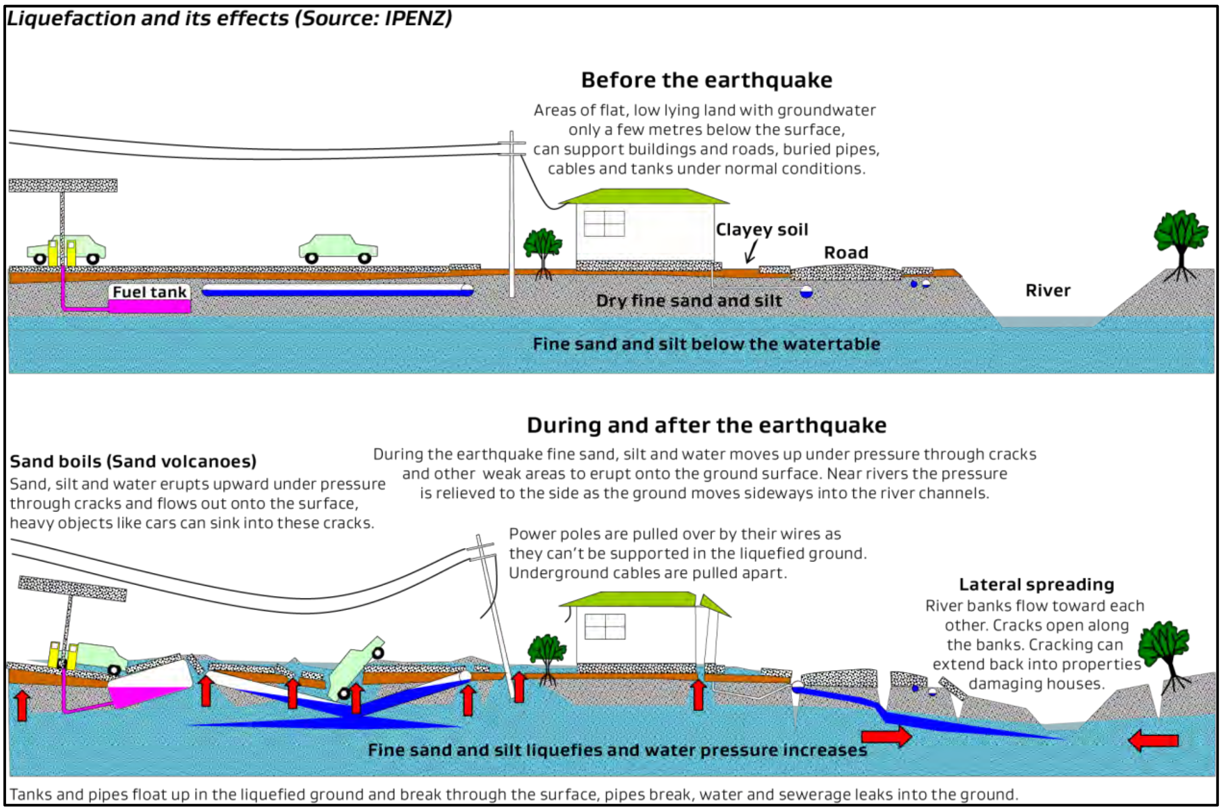



*Figure 2.3: Visual schematic of the consequences of liquefaction - reproduced from the MBIE/MfE Guidance (2017).*

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

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

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

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

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

## 2.3 Intended purpose and scope of works

The information produced from this liquefaction vulnerability assessment will be used for natural hazards planning using a risk-based approach. T+T understands that BOPRC intends to use the findings of this assessment to identify areas susceptible to liquefaction in accordance with the Regional Policy Statement (RPS), in particular, Policy NH 7A (Section 2.1).

It is also expected that the information will be utilised by other Territorial Authorities (TA) within the Bay of Plenty region to inform land use planning and consenting requirements under the RMA and Building Act. Note that a more detailed assessment of liquefaction vulnerability may be required depending on the particular activity under consideration.

The specific scope of works for this liquefaction vulnerability assessment is described in detail in the BOPRC project briefing sheet *Bay of Plenty Regional Liquefaction Hazard Assessment – 2016 0161-33 WB 2020-03* dated May 2020. The key outputs are as follows:

- A geomorphological map of the Study Area (provided in a digital format).
- Categorisation of the land in the Study Area in accordance with the MBIE/MfE Guidance (2017) into the liquefaction vulnerability categories shown in Figure 1.4 (provided in a digital format).
- Preparation of a report to accompany the liquefaction hazard risk identification and analysis.

## 2.4 Previous information about liquefaction in the Bay of Plenty region

Several previous liquefaction studies have been undertaken for various areas within the Bay of Plenty region. Table 2.2 provides a list of relevant regional scale studies that have been undertaken to date.

**Table 2.2: Previous liquefaction studies within the Bay of Plenty Region**

| Study Area | Study Title | Author(s) | Published date | Scale of Study |
|---|---|---|---|---|
| Western Bay of Plenty (WBOP) | Microzoning for Earthquake Hazards for the Western Bay of Plenty | Opus International Consultants | 2002 | 1:250,000 (at A3) |
| Rotorua area | Liquefaction potential of Rotorua Soils | Pearse-Danker, E. | 2013 | N/A |
| Whakatāne | Whakatāne Microzoning Study | GNS | 2004 | 1:25,000 (at A3) |
| Whakatāne | A 3D Geological Model of the Whakatāne Central Business District, Bay of Plenty, New Zealand – with estimate maps illustrating possible earthquake land damage | Begg, J.G., Lukovic, B., Beetham, R.D., Nikolaison, H.N. | 2015 | N/A |
| Ōmokoroa and Katikati | Liquefaction Hazard Risk Assessment for Ōmokoroa and Katikati | Tonkin + Taylor | 2020 | N/A |

The following provides a summary of each of these studies:

- **Microzoning for Earthquake Hazards for the Western Bay of Plenty** – This study focuses on the coastal lowlands between Waihī Beach in the west to Pukehina Beach in the east. Several 1:250,000 scale maps accompanied this publication, two of which include liquefaction hazard information. The study was completed for the Western Bay of Plenty Engineering Lifelines Group to provide hazard information related to lifelines in the Western Bay of Plenty area. The study pre-dated the MBIE/MfE Guidance (2017).
- **Liquefaction Potential of Rotorua Soils –** This publication was a scientific paper that addressed the liquefaction potential of diatomaceous silts and pumice sands underlying the area. There is no liquefaction hazard map associated with this paper, however, the paper concludes that the liquefaction potential of the soils around the Rotorua area is difficult to determine due to the complexity of the local soil properties. The study pre-dated the MBIE/MfE Guidance (2017).
- **Whakatāne Microzoning Study –** GNS was commissioned by Environment Bay of Plenty to undertake a detailed microzonation study of the Whakatāne urban area. This study researched the geology, the faulting history and the earthquake response of soils in the Whakatāne urban area. This study produced a liquefaction susceptibility map and undertook seismic hazard assessment for Whakatāne. The study pre-dated the MBIE/MfE Guidance (2017). The seismic hazard assessment is discussed further in Section 3.2.5.

- **A 3D Geological Model of the Whakatāne Central Business District, Bay of Plenty, New Zealand – with estimate maps illustrating possible earthquake land damage –** Builds on the original study that GNS completed for the Whakatāne and provides more quantitative information on the liquefaction hazard associated with the township. The study pre-dated the MBIE/MfE Guidance (2017).
- **Liquefaction Hazard Risk Assessment for Ōmokoroa and Katikati –** This was a project completed for BOPRC and Western Bay of Plenty District Council. The study addressed liquefaction vulnerability to inform proposed land use changes for proposed development areas in Katikati and Ōmokoroa. This work was commissioned for future population growth and associated land development. The study was undertaken in accordance with the MBIE/MfE Guidance (2017). A Level A assessment was completed for the Katikati site, and a Level B assessment was completed for the Ōmokoroa site.

# 3 Risk identification

This section outlines the risk identification that has been carried out for the liquefaction vulnerability assessment for the region.

The first task is the determination of the level of detail required for the intended purposes (refer to Section 3.1). This requires consideration of the key features associated with each level of detail as established by the MBIE/MfE Guidance (2017) and consideration of BOPRC's intended purposes for undertaking the liquefaction hazard assessment.

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

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

## 3.1 Level of detail

### 3.1.1 Level of detail hierarchy

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

| LEVEL OF DETAIL | KEY FEATURES |
|---|---|
| **Level A**<br>**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.<br><br>**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**<br>**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.<br><br>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.<br><br>**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**<br>**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.<br><br>**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**<br>**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).<br><br>**Residual uncertainty:** The information and analysis is sufficient to determine with a ***High*** degree of confidence the level of liquefaction-related risk at a specific location. However, the scientific understanding of liquefaction and seismic hazard is imperfect, so there remains a risk that actual land performance could differ from expectations even with a high level of site-specific detail in the assessment. |

**Increasing level of detail and decreasing degree of uncertainty**

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

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

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

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

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

### 3.1.2 Level of detail required for intended purposes

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

The target level of detail in the assessment (in accordance with MBIE Guidelines (2017)) that is required for BOPRC's intended purposes was developed in conjunction with TA's in the region and included a series of workshops between May and June 2019 (Tonkin + Taylor, 2019). This establishment of the target level of detail included consideration of the following:

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

As shown in Figure 3.2 and Figure A1 in Appendix A, a Level A (Desktop Assessment) level of detail was targeted for the for the Study Area.

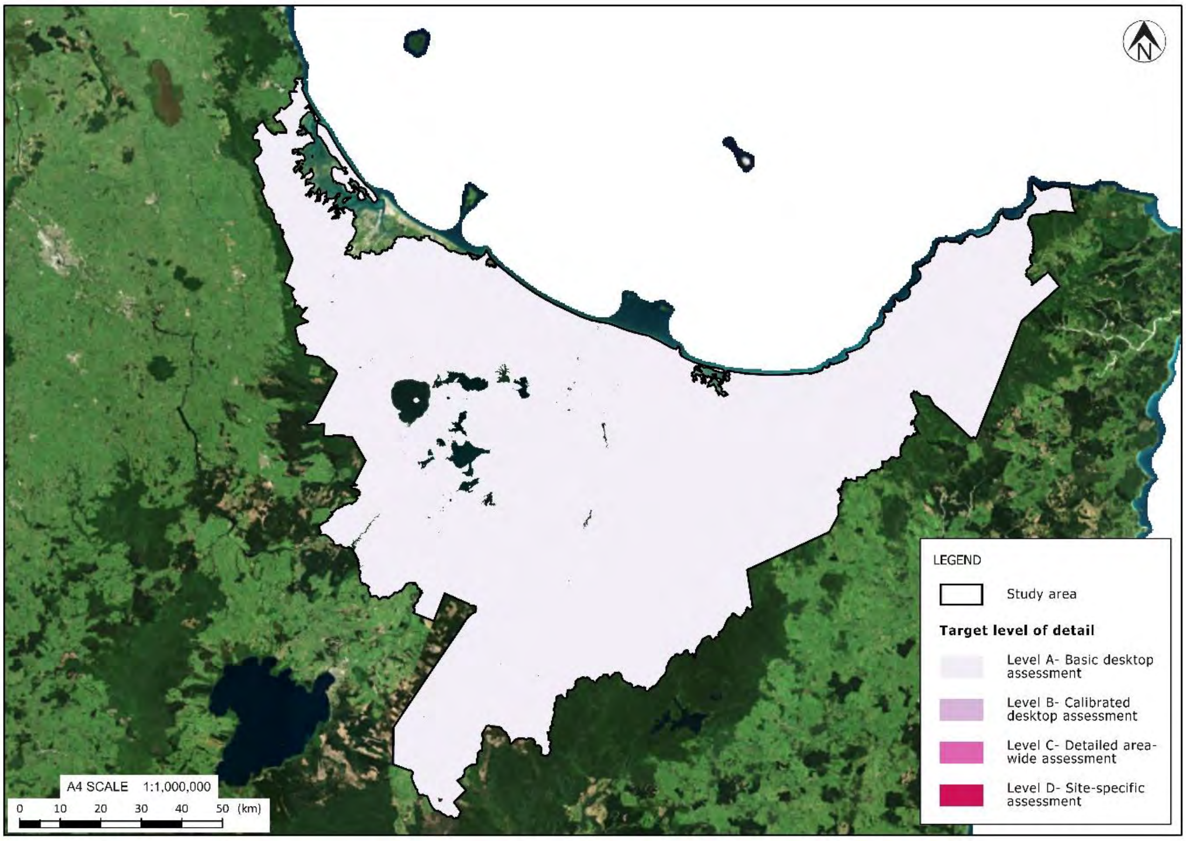



*Figure 3.2: Target level of detail for the assessment across the Study Area.*

## 3.2 Base information currently available

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

### 3.2.1 Ground surface levels

The ground surface level of the Bay of Plenty Region is characterised by a high-resolution (1.0 m – 2.0 m) LiDAR derived Digital Elevation model (DEM). Table 3.1 provides information about the LiDAR survey data that is available for this liquefaction hazard assessment and Figure 3.3 shows the extent of LiDAR survey data across the Study Area.

**Table 3.1: Recent LiDAR data acquisition for the Bay of Plenty Region**

| Year of acquisition | Acquisition by | DEM resolution (m) | Coverage of Study Area |
|---|---|---|---|
| 2010 – 2013 | BOPLASS | 2.0 | Entire |
| 2018 – 2019 | BOPLASS | 1.0 | Urban areas |
| 2019 | TCC | 1.0 | Tauranga City |
| 2020 | BOPRC | 1.0 | Maketū |

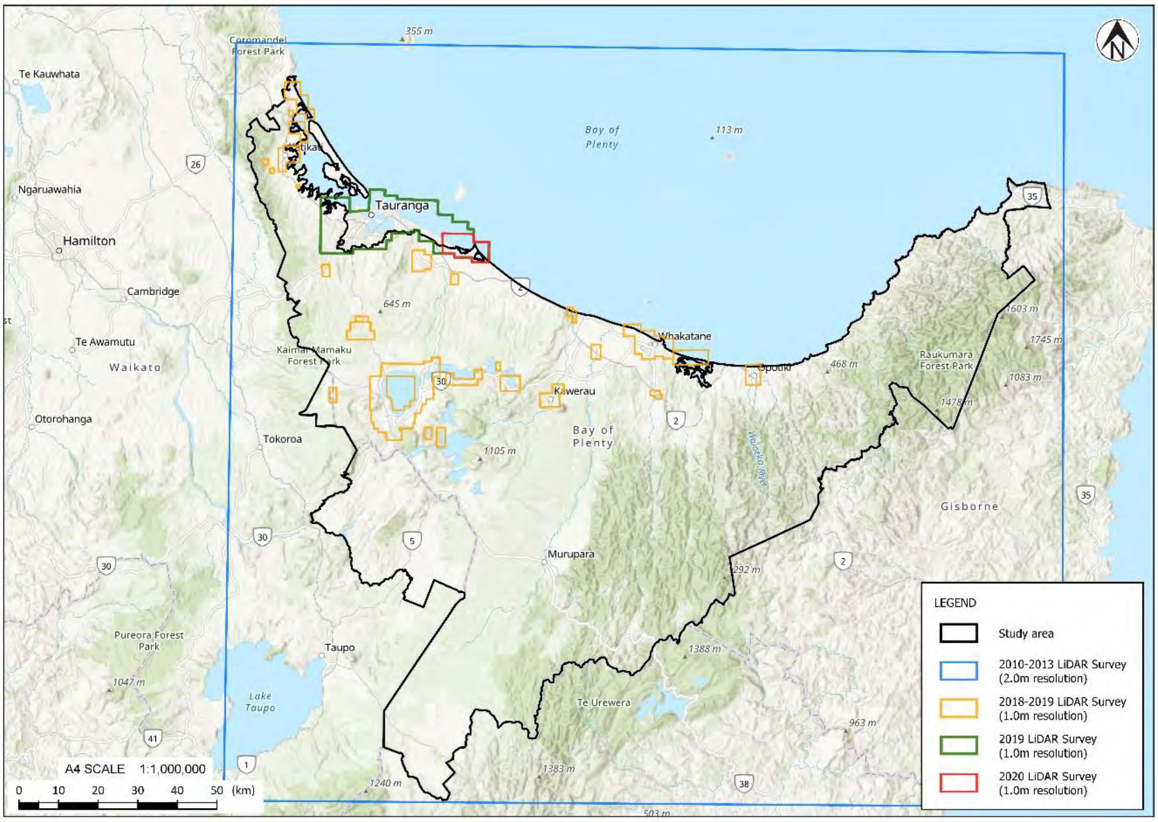



*Figure 3.3: Extent of LiDAR survey data across the Study Area.*

As shown in Figure 3.4 and Figure A2 in Appendix A, the ground surface elevation within the Bay of Plenty Region is highly variable, varying from 0 mRL along the coastline to 1,478 m RL at the highest point. The region is defined by coastal and alluvial lowlands, alluvial terraces, volcanic plateaus, volcanic ranges and greywacke ranges.

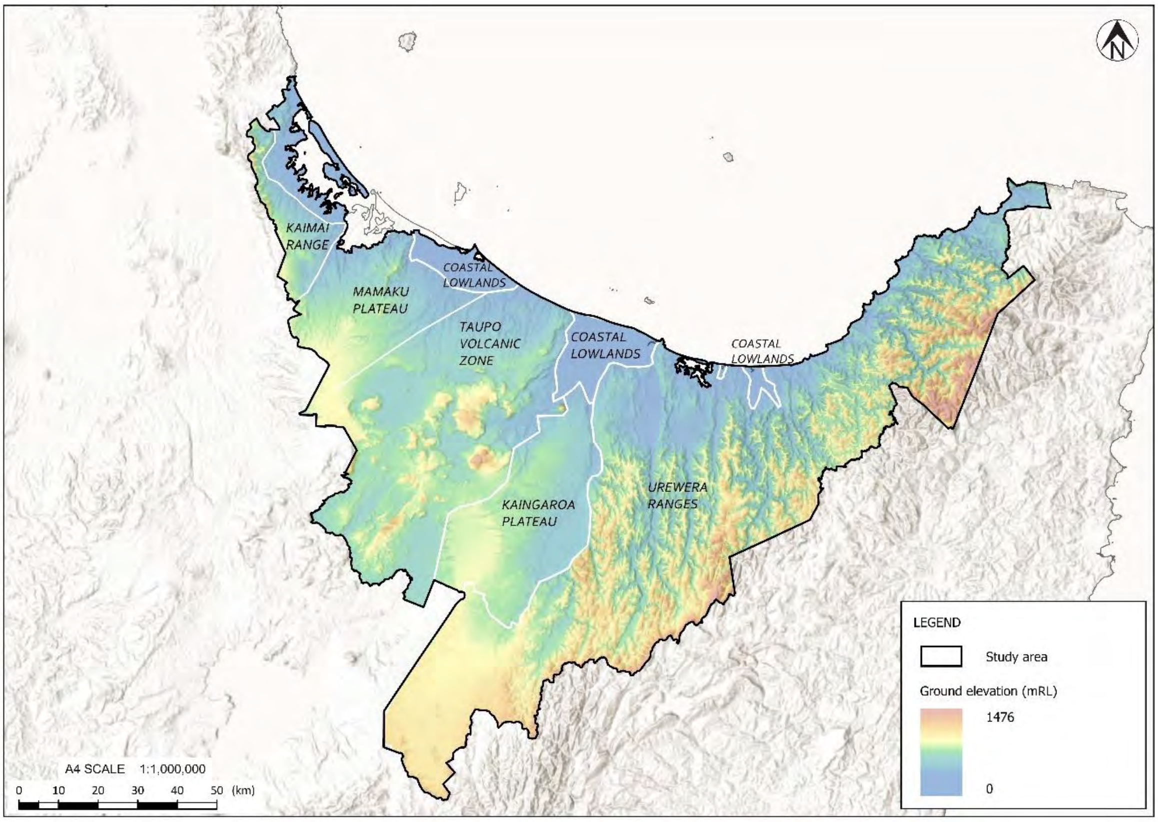



*Figure 3.4: Ground surface elevations across the Study Area.*

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

The method on which the screening tool is based was proposed by Stepiniski and Jasiewicz (2011) and considers single elevation points from a DEM dataset in relation to adjacent elevation points at a set distance. The adjacent elevation points are interpreted to be above, below or in-line with the initial elevation point and an algorithm is used to categorise these patterns into broad landform classifications, which are known as geomorphons. For the purposes of this assessment, four landform types were considered. These geomorphons were:

- Flat Land,
- Toe Slopes,
- Slopes, and
- Valleys.

The geomorphons generated from this algorithm are shown in Figure 3.5 and Figure A3 in Appendix A.

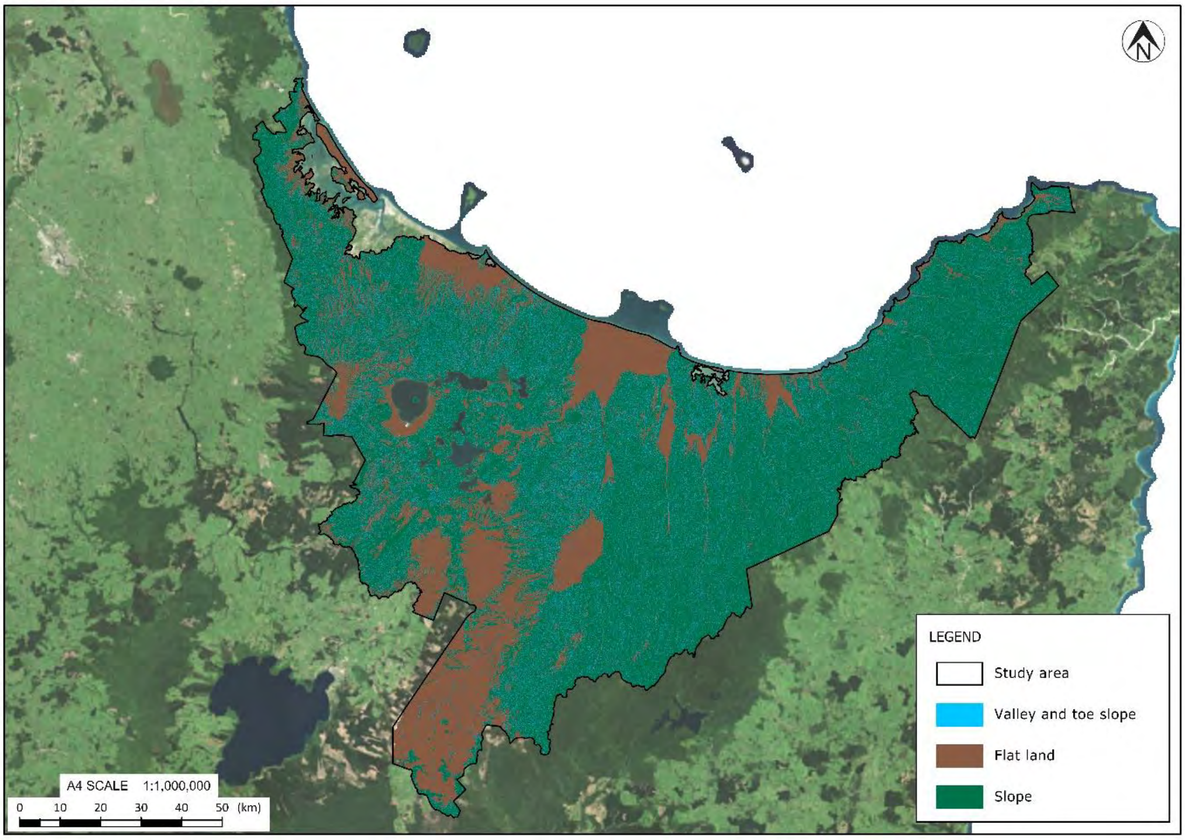



*Figure 3.5: Geomorphons produced by the screening tool across the Study Area.*

### 3.2.2 Geology and geomorphology

#### Geology

The geology of the Bay of Plenty Region is represented by three key published geological maps. As summarised in Table 3.2, these maps were published in 1996, 2010 and 2016 and cover the entire project area.

**Table 3.2: Utilised geological maps that cover the Bay of Plenty region**

| Title | Authors | Published date | Scale |
|---|---|---|---|
| Geology of the Rotorua Area (QMAP) | GNS | 2010 | 1:250,000 |
| Geology of the Raukūmara Area (QMAP) | GNS | 2016 | 1:250,000 |
| Geology of the Tauranga Area | Briggs et al | 1996 | 1:50,000 |

The QMAP series published by GNS was the main source of geological data for this liquefaction vulnerability assessment. It should be noted that sections of the QMAP series of geological maps are a compilation of many different geological maps published by various authors/institutes as well as field mapping to identify areas that were not previously mapped. For example, the Rotorua Area QMAP mentioned above was developed using 40 theses, 24 published papers, and 3 bulletins. For the purposes of this assessment (level A level of detail), the more detailed individual maps from which the QMAP series was developed were not required.

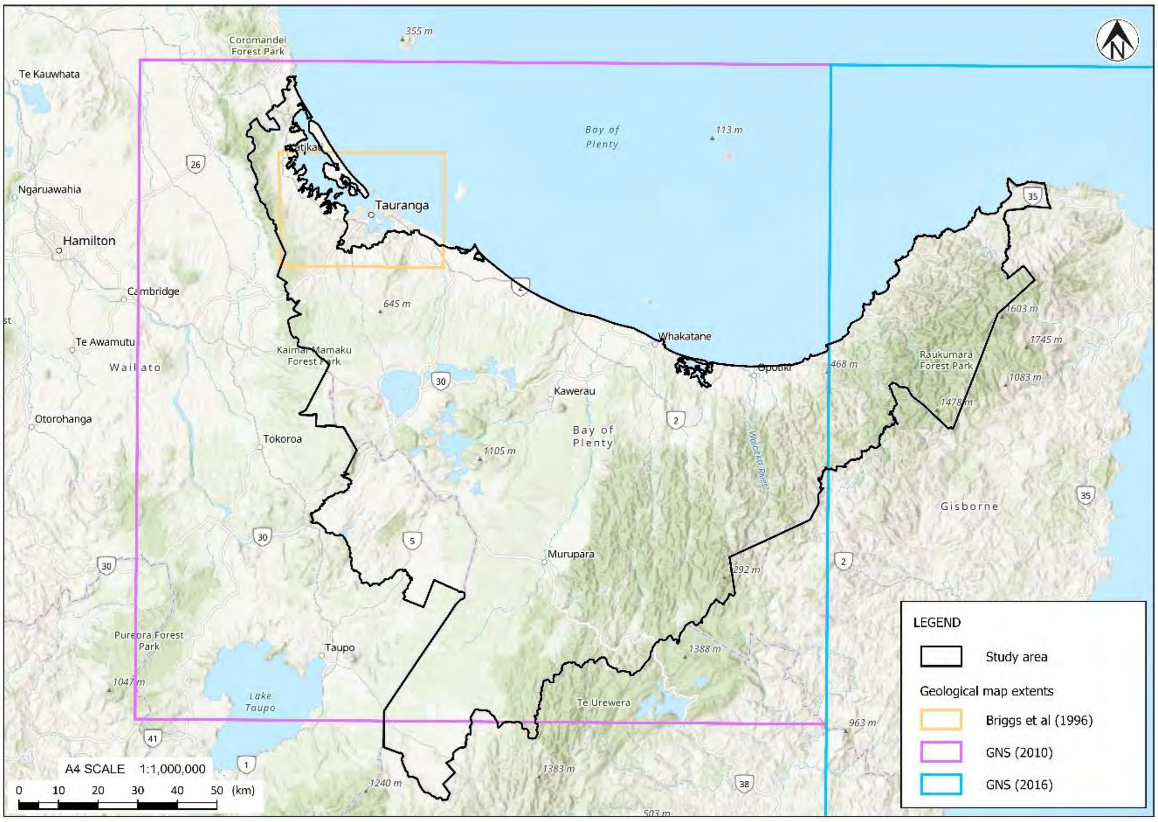



*Figure 3.6: Extents of the relevant geological maps relating to the project area.*

The Bay of Plenty region lies on the continental Australian Plate, approximately 120 – 320 km west of the Hikurangi Trough. The Hikurangi Trough is the surface manifestation of the Hikurangi Subduction Zone, where the Pacific tectonic plate subducts below the Australian tectonic plate. As a result of this subduction zone, volcanism has been and is, a common process in the Bay of Plenty region. The areas of volcanism within the Study Area are known as the Coromandel Volcanic Zone (CVZ) and the Taupō Volcanic Zone (TVZ). The CVZ is an extinct volcanic zone while the TVZ is an active extension zone that is characterised by a narrow belt of active normal faults (known as the Taupō Rift).

As a result of the volcanism described above, the surface landforms that make up the central Bay of Plenty region comprise lava flows and pyroclastic deposits related to the TVZ and CVZ, both of which are related to the Hikurangi Subduction Zone. These volcanic rocks cover approximately 60% of the QMAP Rotorua 1:250,000 geological map. The associated landforms are typically characterised by elevated plateaus, terraces, domes and mountains across the Bay of Plenty region.

The tectonic setting underlying New Zealand also formed the axial ranges present along the eastern edge of the Bay of Plenty region. These axial ranges (Te Urewera and Raukūmara) comprise Jurassic to Early Cretaceous greywacke basement terranes that underly significant portions of New Zealand.

Finally, Quaternary sediments extend across the region from its eastern (Ōpōtiki) and western (Waihī Beach) limits and are bounded to the north by the present-day Bay of Plenty shoreline. These sedimentary deposits were formed by coastal, marine and alluvial processes controlled by historic sea-level fluctuations. These sediments are Holocene-aged and lap onto the older volcanic landforms and basement greywacke across the region. These sediments cover large areas of land in the Western Bay of Plenty, Tauranga and the Rangitāiki plains.

### Geomorphology

Geomorphic terrains have been defined and mapped to help identify areas of potential liquefaction vulnerability. Terrains expected to be underlain by silt, sand and gravel sediments (e.g. flood plains etc.) are more likely to be vulnerable to liquefaction. As a result, these terrains have been categorised in more detail for this assessment compared to the various types of hill country and volcanic landforms within the region, which are less likely to be vulnerable to liquefaction. The geomorphic terrain mapping methodology is summarised in Table 3.3.

**Table 3.3: Geomorphic terrain mapping methodology**

| | |
|---|---|
| **Data sources:** | Geological maps – see this section<br>Ground surface levels – see section 3.2.1<br>Current and historical aerial imagery – supplied by BOPRC<br>Topographical screening tool and associated geomorphons – see section 3.2.1 |
| **Terrain definition:** | Geomorphic terrain categories have been defined based on their general susceptibility to liquefaction following guidance outlined in MBIE (2017) and research by Youd and Perkins (1978).<br>Areas expected to be more vulnerable to liquefaction have been divided into more detailed terrain units (i.e. alluvial channels, alluvial flood plains etc.) compared with less susceptible hill and rocky areas. |
| **Terrain mapping:** | Terrain mapping has been undertaken as a desktop assessment largely based on the ground surface levels and associated geomorphons and the QMAP geological units.<br>Surface elevation data was used to derive information of landform features, such as areas of low lying and elevated land, gently sloping to steeply sloping land, volcanic depressions and volcanic domes etc. These areas of land often control sedimentary depositional processes that relate to liquefaction vulnerability of soils.<br>The QMAP geological units have also been rationalised into the geomorphic terrain categories and incorporated into the landform feature interpretation listed above.<br>The resulting geomorphic terrains have been reviewed against aerial imagery and the geomorphons produced by the topographical screening tool. During this process, terrain extents can be modified or re-classified. |
| **Mapping Scale** | 1:25,000[2] |

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

The geomorphic mapping process identified thirteen different geomorphic terrains across the Study Area. These geomorphic terrains are described as follows:

- **Hills and Ranges:** The most extensive geomorphic terrain across the region (covers 78% of the Study Area). Represents the elevated, sloping land features that dominate the southern and western extents of the Study Area. Incised, steep, stream valleys and alluvial features are common throughout this terrain, however, they do not characterise the dominant geomorphic processes in this terrain. This terrain was differentiated into three sub-terrains which were generally based on the geological origins of the predominant landforms.
  - **Kaimai Ranges:** Extends from the north-western extent of the Study Area to the Wairoa River. This sub-terrain is characterised by early to late Pliocene-aged volcanic deposits of the Coromandel Volcanic Zone. Typically, this sub terrain has rock near the ground surface and the soils that are present are predominantly plastic. Therefore, it is less likely to contain soils that are susceptible to liquefaction.
  - **Central Volcanic Zone:** Extends from the Wairoa River in the northwest to Whakatāne and Murupara in the southeast. This sub-terrain encompasses a variety of volcanic deposits which have a spatially variable structures and depositional sequences (e.g. welded and non-welded ignimbrite, igneous domes and flows and tephra). Most of these volcanic features were formed in the middle to late Pleistocene period. It is difficult to determine the liquefaction susceptibility of this terrain due to the volcanic sediments and the localised alluvial systems that are present within it .
  - **Te Urewera/Raukūmara Ranges:** Extends from Whakatāne and Murupara to the eastern and southern limits of the Study Area. Sub-terrain is characterised by Jurassic to Cretaceous geological terranes. Typically, this sub terrain has rock near the ground surface and therefore, it is less likely to contain soils that are susceptible to liquefaction.
- **Volcanic Plateaus:** The second largest geomorphic terrain in the Study Area, covering approximately 10% of the region. This terrain comprises extensive areas of continuous flat to gently sloping land that is positioned at high elevations and is derived from volcanic material deposited in the Middle Pleistocene period. It is predominantly made up of ignimbrites with interbedded airfall tephra deposits. Localised valleys and alluvial systems can often be observed within this terrain. It is difficult to determine the typical liquefaction susceptibility of the soils in this terrain due to the volcanic sediments and the localised alluvial systems that are present within it.
- **Alluvial Plains and River Flats:** This terrain represents the Holocene sediments deposited by active and historic river systems across the region and is generally flat to gently sloping. This terrain has typically been highly valued for agricultural land uses and covers approximately 8% of the Study Area. It is likely to include sand and silt deposits that are susceptible to liquefaction.
- **Alluvial Terraces:** These terraces typically comprise Pleistocene-aged or older alluvium, with various interbedded ash and tephra deposits. This terrain is dominant in the western extent of the Study Area. Covers approximately 2% of the Study Area. It is difficult to determine the typical liquefaction susceptibility of this terrain due to the geological age of the sediments.
- **Alluvial Lowland and Swamp Deposits:** Defined by low-lying alluvial land with elevations less than 1.5 mRL, mainly associated with coastal regions of the Study Area. This terrain is characterised by present day streams, rivers and swamps that have deposited Holocene aged sediments. Similar characteristics to the Alluvial Plains and River Flats, however, the differentiating factor is the lower elevation and shallow groundwater conditions. Covers approximately 1.5% of the Study Area. It is likely to include sand and silt deposits that are susceptible to liquefaction.

- **Fixed Foredunes:** Comprise a series of Holocene-aged dune crests and troughs that generally run sub-parallel to the Bay of Plenty coastline. This terrain covers approximately 0.6% of the Study Area and presents remnant dune deposits from historic coastal regimes. These dune systems are not likely to be subject to active aeolian (wind) or coastal processes. It is likely to include sand and silt deposits that are susceptible to liquefaction.
- **Lacustrine Terraces:** Historic shorelines of several lakes within the region. These terraces are often sub-horizontal to gently sloping surfaces that are elevated above current lake levels/Lacustrine Lowlands terrain (described below) and comprise fine grained, Late Pleistocene aged sediments deposited in a lacustrine environment. This terrain covers approximately 0.5% of the Study Area. There is some uncertainty of the liquefaction susceptibility of this terrain due to age of the deposits.
- **Lacustrine Lowlands:** Characterised by the low-lying, flat land located alongside several lakes within the Study Area. This terrain represents Holocene-aged, fine grained lacustrine sediments that were deposited by recent lake shorelines. This terrain covers approximately 0.3% of the Study Area. It is likely to include sand and silt deposits that are susceptible to liquefaction.
- **Harbour Margin:** Associated with the low-lying land surrounding the present-day harbours and estuaries in the region. This terrain is inferred to be primarily formed by estuarine processes in the Holocene period, rather than by alluvial or deltaic processes. This terrain covers approximately 0.2% of Study Area. It is likely to include sand and silt deposits that are susceptible to liquefaction.
- **Alluvial Channels:** Represents active fluvial systems that erode the Hills and Ranges terrain. This erosion forms steep sided, typically narrow channels or small gullies. This terrain is characterised by Holocene-aged colluvial/alluvial deposition typically at the base of gullies or within the upper reaches of stream valleys. Also includes the deposits of side slope processes and alluvial fans. This terrain covers approximately 0.1% of the Study Area. It is likely to include sand and silt deposits that are susceptible to liquefaction.
- **Active Foredunes:** Represents the coastal dune system that is actively subject to wind/aeolian and coastal processes. Associated with the present-day shoreline along the northern extent of the Study Area. This terrain covers approximately 0.1% of the Study Area. It should be noted that the Study Area boundary often transects this terrain, with most of the Active Foredunes being positioned outside of the Study Area. The Holocene-aged silts and sands associated with this terrain are likely to be susceptible to liquefaction.
- **Debris Flows and Landslide Deposits:** Represents large mass flow/colluvium deposits that can be observed at a 1:25,000 scale. There are many smaller debris flow and landslide deposits across the Study Area, however, these deposits are not evident at a 1:25,000 scale. This terrain covers approximately 0.1% of the Study Area**.** It is difficult to determine the liquefaction susceptibility of this terrain due to variable nature of the associated sediments.
- **Reclamation Fill:** This terrain represents historic filling operations that have resulted in land being reclaimed from generally marine/estuarine areas. The fill material can be either uncontrolled or engineered. Two minor areas of reclamation fill have been mapped within Whakatāne and Ōpōtiki, covering less than 0.1% of the Study Area. As the two locations are in close proximity to the coastal environment, they are likely to include sand and silt deposits that are susceptible to liquefaction.

The larger towns and infrastructure projects throughout the Study Area are typically located within the Holocene-aged geomorphic terrains that are likely to include sand and silt deposits that are susceptible to liquefaction (e.g. Alluvial Lowland and Swamp Deposits, Alluvial Plains and River Flats). This is due to flat land in the region being historically valued for residential development and the relative ease of transportation via waterways (e.g. rivers and streams).

Once the thirteen terrains were determined, five 2D geomorphological models were constructed to illustrate how they sit spatially within the Study Area landscape. The 2D models are basic sketches that illustrate the relationships between adjacent terrains within different regions of the Study Area. An example of one of these models is shown in Figure 3.7 and the remainder are included in figures A4.1 to A4.5 within Appendix A.

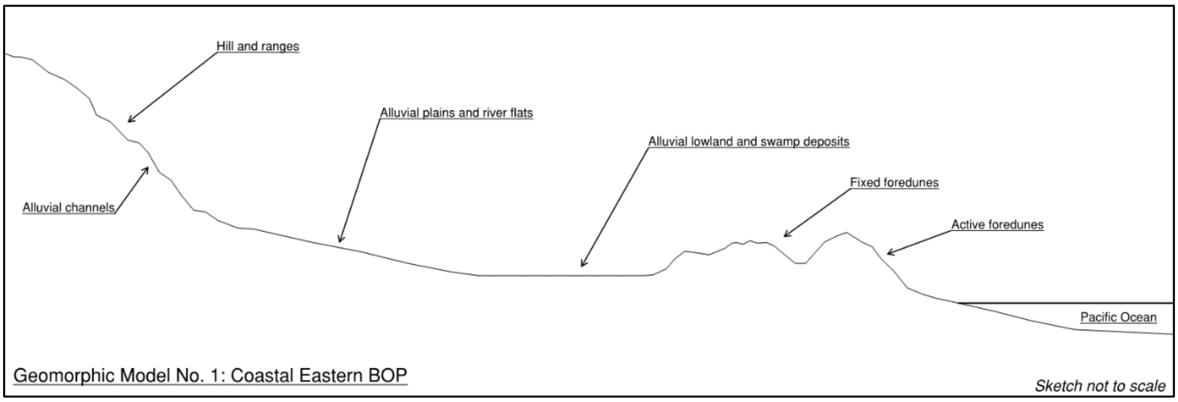



*Figure 3.7: Geomorphic model for Eastern Bay of Plenty Region (Rangitāiki Plains).*

The geomorphic map of the Study Area is shown in Figure 3.8 and Figure A5 in Appendix A.

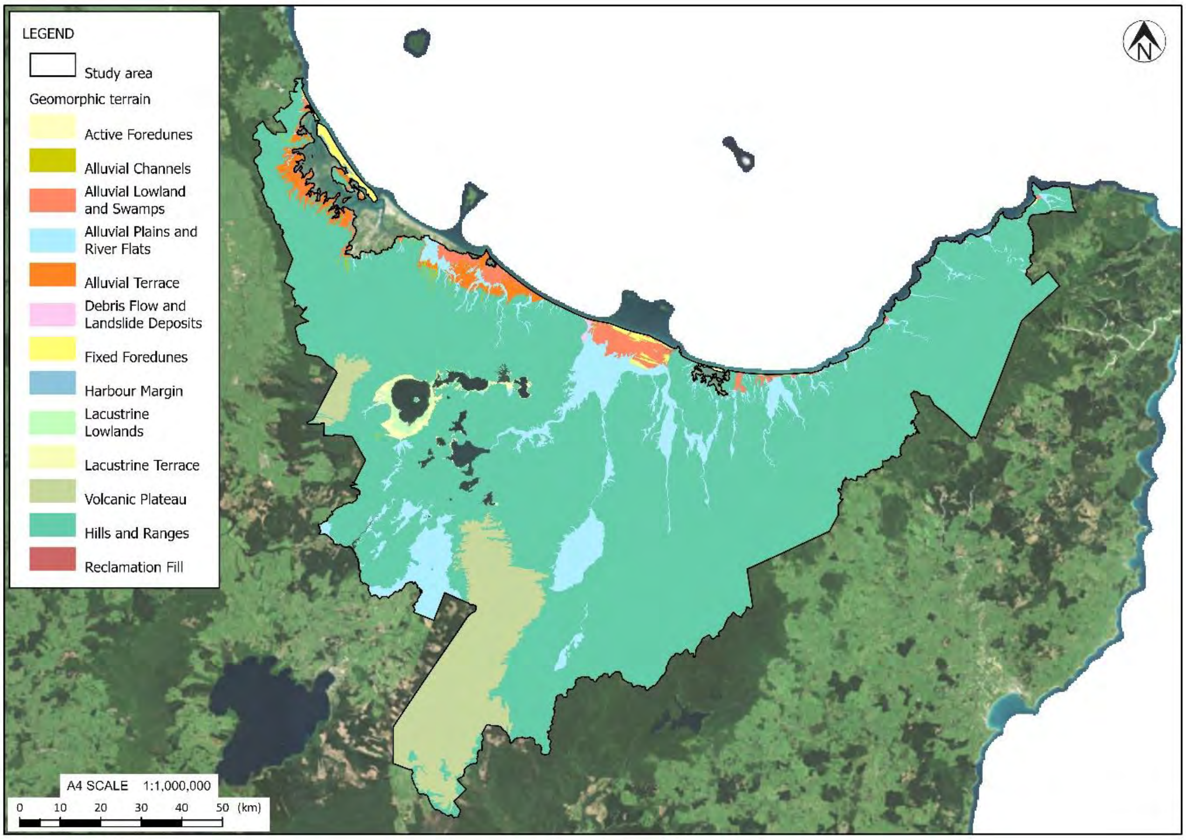



*Figure 3.8: Geomorphic map of the Study Area.*

### 3.2.3 Geotechnical investigations

Existing geotechnical investigations from the publicly available New Zealand Geotechnical Database (NZGD) and from T+T's records have been considered for this assessment, including 1869 No. Cone Penetration Tests (CPT), 460 No. Boreholes (BH), 280 No. Test Pits (TP), and 1071 No. Hand Augers (HA). The number of CPT, BH, TP, and HA within each geomorphic terrain is shown in Table 3.4.

The majority of the geotechnical investigations in the Study Area are concentrated around the larger towns (Rotorua, Whakatāne, Ōmokoroa, Waihī Beach, Edgecumbe) and recent large infrastructure projects (Tauranga Eastern Link & Rangitāiki River Stop Bank Assessment).

**Table 3.4: Geotechnical investigation count by geomorphic terrain as at 30 October 2020**

| Geomorphic terrain | CPT count (No.) | BH count (No.) | TP Count (No.) | HA count (No.) |
|---|---|---|---|---|
| Active Foredunes | 6 | 0 | 0 | 0 |
| Alluvial Channels | 36 | 7 | 7 | 6 |
| Alluvial Lowland and Swamp Deposits | 552 | 151 | 115 | 140 |
| Alluvial Plains and River Flats | 265 | 99 | 29 | 91 |
| Alluvial Terrace | 188 | 52 | 52 | 226 |
| Debris Flows and Landslide Deposits | 0 | 0 | 0 | 0 |
| Fixed Foredunes | 133 | 1 | 0 | 38 |
| Harbour Margin | 13 | 5 | 1 | 9 |
| Hills and Ranges | 136 | 83 | 37 | 271 |
| Lacustrine Lowlands | 341 | 29 | 38 | 231 |
| Lacustrine Terrace | 144 | 7 | 0 | 34 |
| Reclamation Fill | 35 | 10 | 1 | 21 |
| Volcanic Plateaus | 0 | 0 | 0 | 0 |

Figure 3.9 and Figure A6 in Appendix A show the location of the geotechnical investigations available on the NZGD as at 30 October 2020.

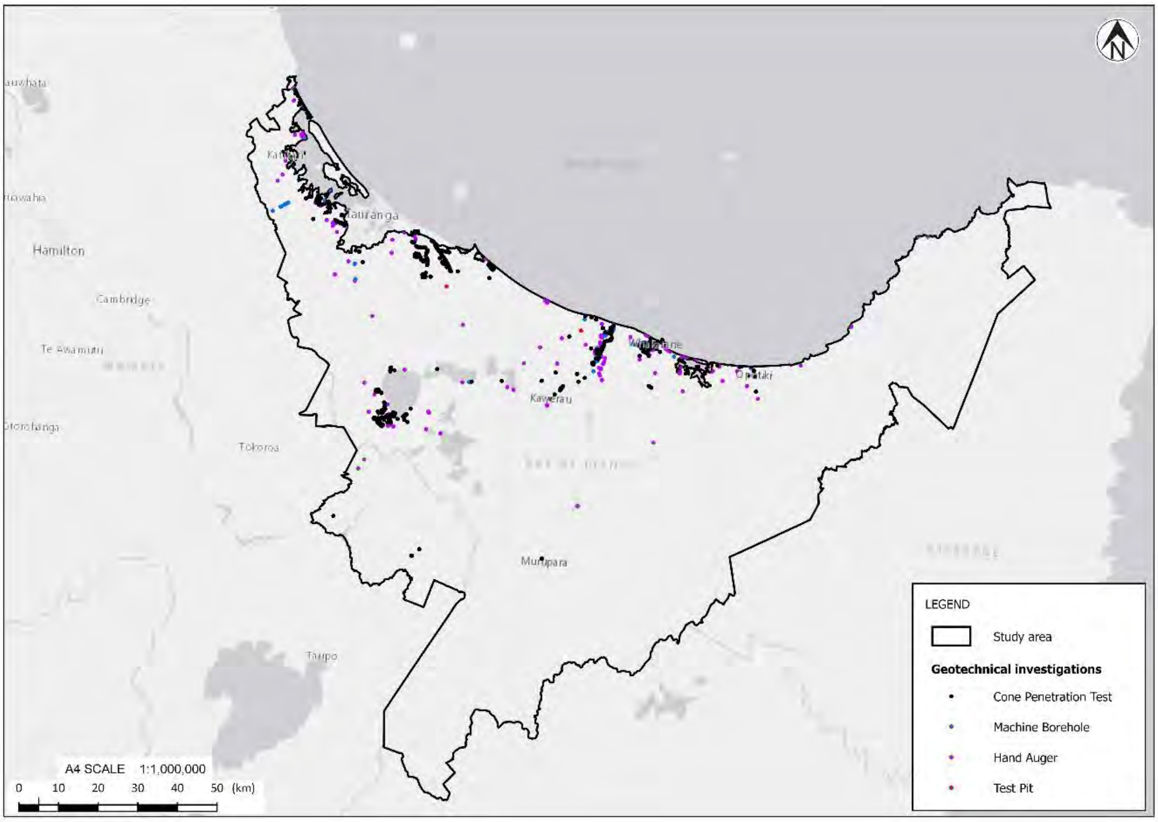



*Figure 3.9: Geotechnical investigations available on the NZGD as at 30/10/2020.*

### 3.2.4 Groundwater

**Groundwater data**

Within the Study Area, there are 5,991 bores recorded in the BOPRC GIS database as of the date of this report. These have been installed for a variety of reasons (e.g. water supply, water monitoring etc.). T+T applied the following screening criteria to estimate how many of these bores are representative of shallow groundwater (water table) and therefore can be used to provide information about the groundwater surface elevation:

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

A total of 788 investigations met these screening criteria, and of these, nine have multiple readings over a period of months to years.

In addition, based on the New Zealand Geotechnical Database, there are 2,542 geotechnical investigations within the Study Area of which 2,146 have recorded groundwater levels and the depth of the investigation is less than or equal to 20 m bgl.

The spatial distribution of the in-situ groundwater data is shown in Figure 3.10 and Figure A7 in Appendix A. The spatial distribution of water bodies across the Study Area is shown in Figure 3.11. This provides useful information because the groundwater is likely to be shallow near these mapped water bodies.

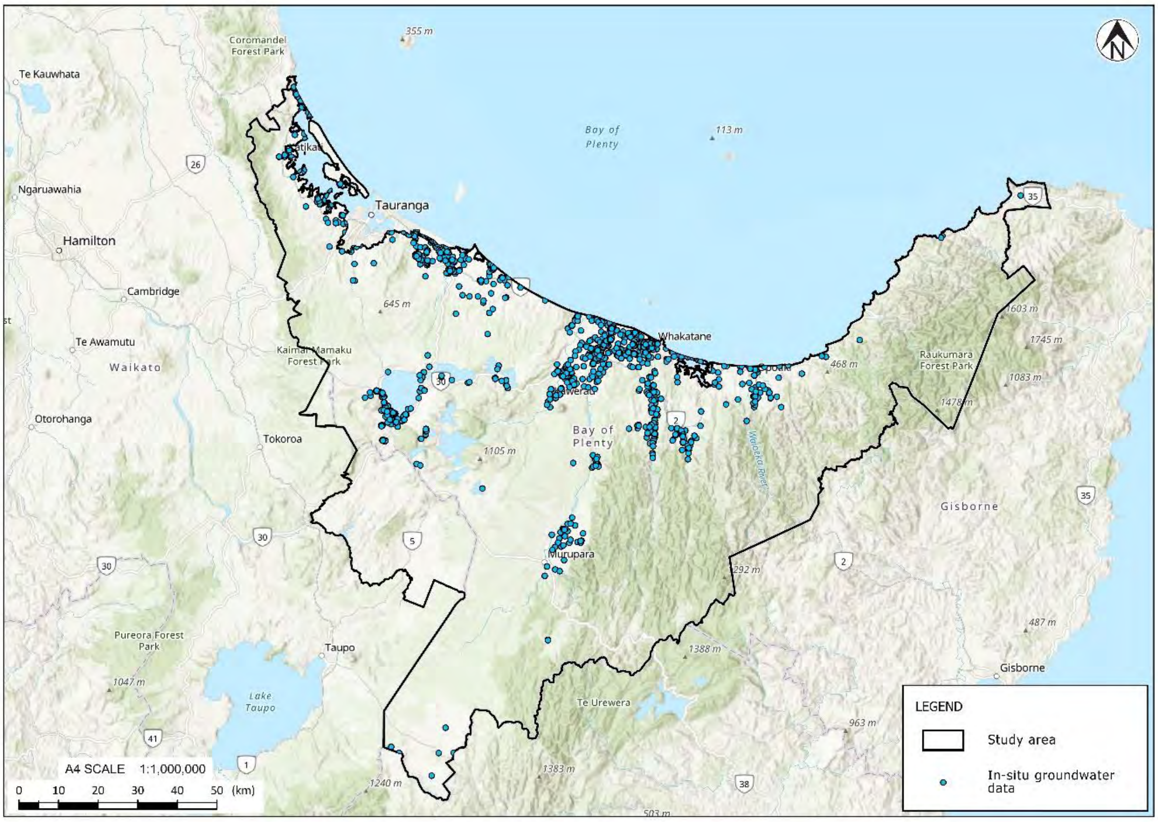



*Figure 3.10: Spatial distribution of in-situ groundwater data within the Study Area.*

**Groundwater studies**

The depth to groundwater for some areas in the Bay of Plenty Region is represented in several regional studies which are primarily based on static groundwater levels readily available from well/bore locations from the BOPRC GIS. Table 3.5 shows the known studies with mapped groundwater surfaces from within the Study Area.

**Table 3.5: Studies with mapped groundwater surfaces**

| Title | Author(s) | Published date | Resolution | Hydrological Scale | Specific to shallow groundwater |
|---|---|---|---|---|---|
| Lake Rotorua Shallow Groundwater Assessment | Zemansky, G. and Thorstad, J. | 2010 | 100 m | Local | Yes |
| Nitrogen discharge from the groundwater system to lakes and streams in the greater Lake Tarawera catchment | White, P., Toews, M., Tschritter, C., and Lovett, A. | 2016 | 100 m | Regional | Yes |
| A 3D Geological Model of the Whakatāne Central Business District, BOP | Begg, J.G., Lukovic, B., Beetham, R.D., | 2015 | NA | Local | Yes |
| Groundwater resource investigations of the Paengaroa-Matatā area stage 1 | White, P.A., Meilhac, C., Della Pasqua, F. | 2009 | NA | Regional | No |
| Groundwater resource investigations of the Western Bay of Plenty stage 1 | White, P.A., Meilhac, C., Zemansky, G., Kilgour, G. | 2008 | NA | Regional | No |

The following is a summary of the groundwater studies that are specific to shallow ground water conditions within the Study Area:

- Rotorua District Council requested a shallow groundwater study where GNS provided an assessment of locations in the vicinity of the lake where very shallow groundwater exists. Zones were identified and mapped based on contoured data of observed static water levels (through features such as seeps, springs, wetlands, bores and swamps), and developed from catchment topography of low-lying ground.
- GNS completed a characterisation of surface flows in streams and rivers which informed water budgets and understanding of groundwater inflows/outflows to the lakes within the Tarawera catchment. This information was used to inform the development of groundwater flow model based on MODFLOW-2005, which resulted in regional groundwater head map for the region.

  In general, all the lakes within this catchment are thought to be hydraulically connected to the groundwater system with the exception of Lake Rerewhakaaitu, which is thought to be perched relative to the groundwater system. This study provides critical information on surface water and groundwater interactions which can inform possible zones of shallow groundwater.
- The 3D geological model produced by GNS in 2015 for Whakatāne provides information about the shallow, unconfined water table underlying the central business district. Boreholes and

Cone Penetrometer tests provided the primary dataset related to the groundwater surface underlying the CBD.

**Sea level rise**

Sea-level rise has the potential to elevate groundwater levels in areas within close proximity to the coast. A report published by PCE (Parliamentary Commissioner for the Environment, 2015) discusses the implications of sea-level rise on groundwater and provided several land elevation maps of the Bay of Plenty Region that illustrated coastal low-lying land that could be affected. The data from these maps is reproduced in Figure 3.11. We note that the impact of sea-level rise on groundwater elevation would likely extend beyond these areas. However, these maps provide a reasonable indication of land where the groundwater levels would be most impacted.

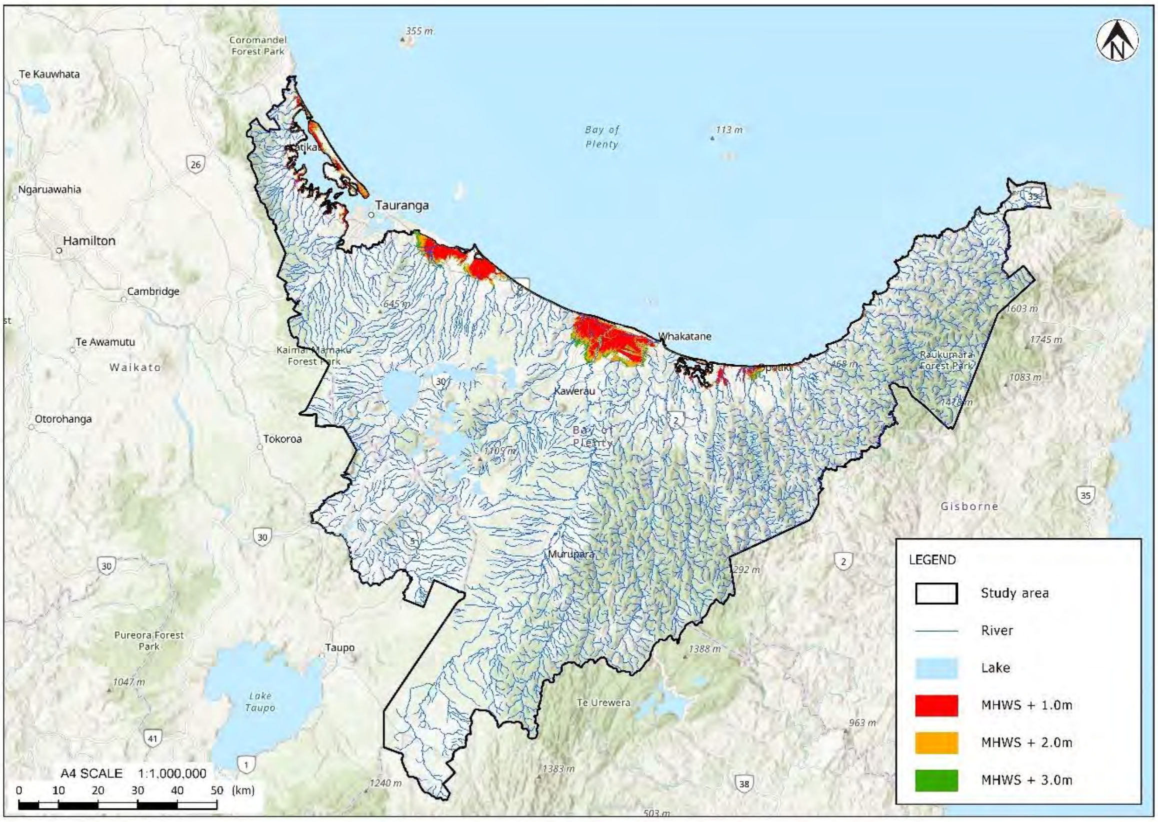



*Figure 3.11: Spatial distribution of water bodies within the Study Area, and locales within the Study Area that could be affected by sea-level rise.*

### 3.2.5 Seismic hazard

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

**Tectonic setting**

A large portion of the Bay of Plenty region is located within the Taupō Volcanic Zone which is known to be an active extension zone. This extension zone is characterised by a narrow belt of active normal faults (known as the Taupō Rift). The North Island Dextral Fault Belt[3], which is characterised by strike-slip faults also runs through the axial ranges in the eastern part of BOP.

As a result of the above, there are a significant number of known active faults within the region. Figure 3.12 below, which was taken from The National Seismic Hazard Model (NSHM) for New Zealand, illustrates the known active faults in the region.

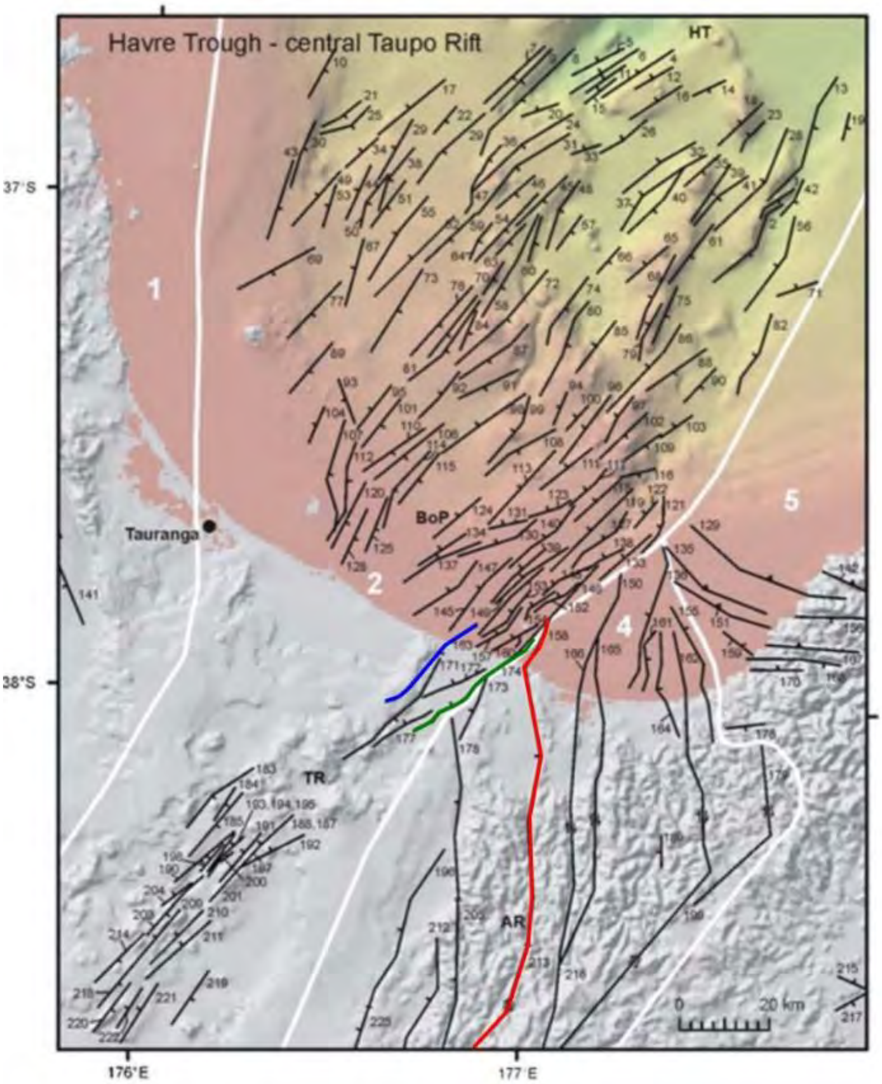



*Figure 3.12: Known active fault sources in the Bay of Plenty Region. Whakatāne Fault (red), Matatā Fault (blue) and Edgecumbe Fault (green) marked for reference (Stirling et al, 2012).*

As shown in Figure 3.12, there are many known active faults in the Bay of Plenty region located on and offshore. Some of the significant active onshore faults include the Whakatāne Fault (red), Matatā Fault (blue), and the Edgecumbe Fault (green). These are close to town centres in the Bay of Plenty region.

The following provides a summary of the characteristics these three faults:

- **Whakatāne Fault:** There is some uncertainty about the location and Recurrence Interval (RI) of the Whakatāne Fault. A recent report published by GNS in 2018 discusses several papers that each provide a different location of the Whakatāne Fault. Initial research suggested that the fault transects the Whakatāne CBD while recent research suggests that the fault is located to the east of the CBD. There is also some uncertainty associated with the RI Class of the fault, however GNS have provided evidence to suggest the Whakatāne Fault has a recurrence interval of <2000 years (which is equivalent to RI Class I).
- **Matatā Fault:** The NSHM (2012) defines the Matatā Fault as having a span of approximately 27 km and has a potential moment magnitude of 6.7. This fault is located within close proximity to the Matatā settlement and has an estimated recurrence interval of less than 2000 years (i.e. RI Class I).
- **Edgecumbe Fault**: This 19 km long normal fault has a potential moment magnitude of 6.5 and an estimated recurrence interval of <2000 years (i.e. RI Class I). This fault last ruptured in the 1987 Edgecumbe earthquake and the historical observations of liquefaction from this event are discussed in Section 3.2.6 of this report.

As illustrated in Figure 3.12 and Figure 3.13, the majority of the active faults within the region are constrained to the Taupō Volcanic Zone. The North Island Dextral Fault Belt and the Hikurangi Subduction zone shown in Figure 3.13 are features which dominate the eastern extent of the region.

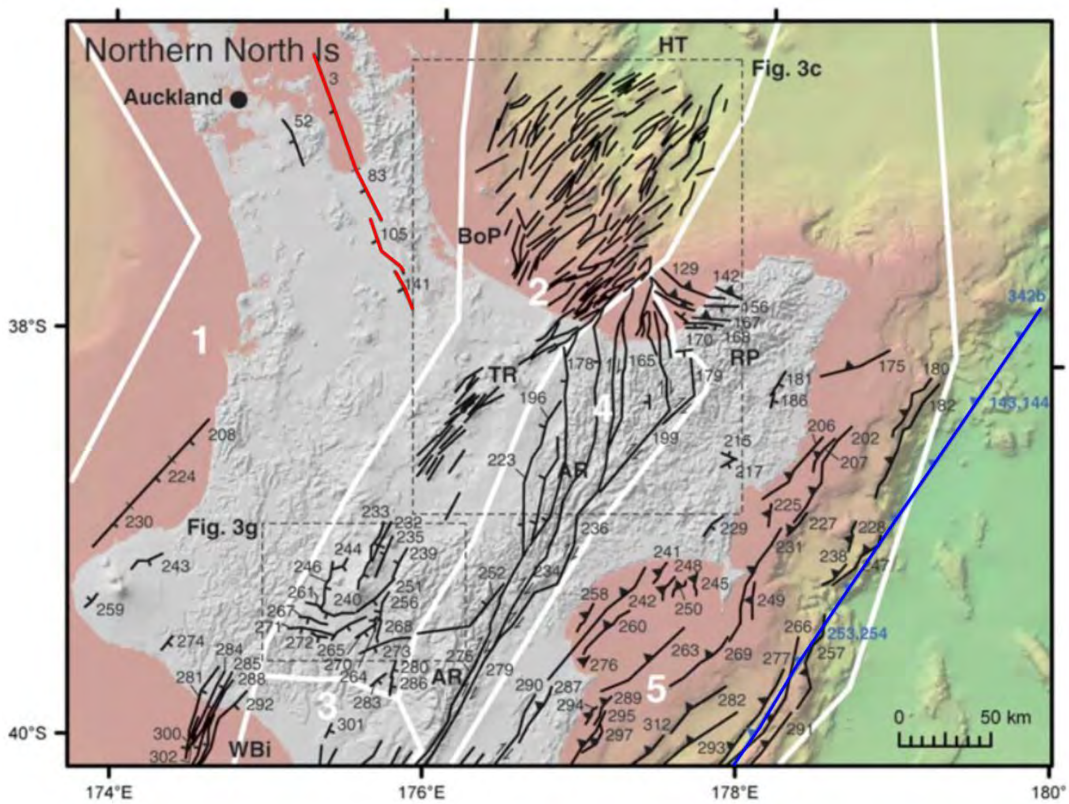



*Figure 3.13: Known active faults within Northern North Island, New Zealand. Kerepehi Fault (red) and Hikurangi Subduction Zone (blue) marked for reference to BOP region.*

The Hikurangi Subduction Zone (143, 144, 253, 254 in Figure 3.13) is not located within the BOP region however, the subduction zone does represent both a significant earthquake shaking hazard and associated tsunami hazard for the region.

This subduction zone has a potential moment magnitude of greater than 8.1 and an estimated recurrence interval of <2000 years (i.e. equivalent to RI Class I). Rupture of the Hikurangi subduction zone would likely result in earthquake shaking for an extended period that would cause damage across much of the North Island.

The western extent of the region is influenced by significantly fewer mapped faults than the eastern extent of the region (Figure 3.13). The Kerepehi Fault (3, 83, 105 and 141) runs to the west of the Kaimai Range and is the main fault contributing to the seismic risk in Western Bay of Plenty. The Kerepehi Fault has a potential moment magnitude of 6.6 – 7.2 and an estimated recurrence interval of 2000 to 3500 years (i.e. RI Class II).

The hazard assessment associated with this vulnerability assessment has taken into account the possibility of unmapped/unknown active faults within the Bay of Plenty Region by utilizing the earthquake design loadings outlined in the NZTA Bridge Manual (2018). These design loadings include a contribution from “background seismicity” to allow for the possibility of unmapped/unknown active faults.

**Seismic hazard information available for this assessment**

The primary sources of seismic hazard information used as reference for this assessment are the NZTA Bridge Manual (2018), and a regional seismic hazard study for Tauranga City undertaken by Bradley Seismic Ltd. (BSL, 2019). Each of these are summarised as follows:

- **NZTA Bridge Manual (2018)** – For routine engineering projects, the NZTA Bridge Manual (2018) is currently the commonly accepted method for determination of seismic hazard for liquefaction analysis in New Zealand in the absence of a site-specific assessment or regional study.
- **Regional Seismic Hazard Study for Tauranga City Council (2019)** –Tauranga City Council (TCC) engaged Bradley Seismic Limited (BSL) to undertake a high-level regional seismic hazard assessment (BSL, 2019) to inform a liquefaction vulnerability assessment undertaken in accordance with the MBIE/MfE Guidance (2017) (T+T, 2020). This regional seismic hazard assessment was based on the most recent version of the NSHM and utilised more current and applicable Ground Motion Prediction Equations (GMPEs).

  While the findings of this assessment are only recommended for use within the TCC area (which is out of scope for the current BOP regional liquefaction assessment), comparison of the results with the NZTA Bridge Manual methodology provides important context for the estimation of seismic hazard in the BOPRC region.

**Seismic hazard design parameters**

Estimated Peak Ground Accelerations (PGA) and Magnitude ($M_{eff}$) for 1 in 100 year and 1 in 500-year return period earthquakes for towns within the Bay of Plenty region based on the NZTA Bridge Manual methodology (NZTA, 2018) are provided in Table 3.6. These calculations have been based on Class D and Class E soils across the region. Table A2 in Appendix A provides estimates of PGA and $M_{eff}$ derived using the NZTA Bridge Manual methodology (NZTA, 2018) for a range of return period earthquake and class D (deep or soft) and E (very soft) soils.

**Table 3.6: Estimated Peak Ground Accelerations (PGA) and Magnitude ($M_{eff}$) for 1 in 100-year and 1 in 500-year return period earthquakes for towns within the Bay of Plenty region based on the NZTA Bridge Manual methodology (NZTA, 2018)**

| Town | Return Period | | |
|---|---|---|---|
| | 1 in 100 | 1 in 500 | Magnitude ($M_{eff}$) |
| Whakatāne | 0.18 | 0.35 | 6.1 |
| Kawerau | 0.17 | 0.33 | 6.2 |
| Ōpōtiki | 0.17 | 0.34 | 6.1 |
| Taupō | 0.16 | 0.32 | 6.1 |
| Ruatoria | 0.16 | 0.32 | 6.1 |
| Murupara | 0.16 | 0.32 | 6.3 |
| Rotorua | 0.15 | 0.30 | 6.0 |
| Te Puke | 0.13 | 0.27 | 6.0 |
| Tauranga | 0.13 | 0.26 | 5.9 |
| Mount Maunganui | 0.13 | 0.26 | 5.9 |
| Waihī | 0.13 | 0.26 | 5.9 |

For comparison, the Regional Seismic Hazard Study produced for Tauranga City Council (BSL, 2019), provided lower estimates for PGA in Tauranga. At return periods longer than about 250 years, the estimated PGAs reduced by up to 30%. The BSL report provided different estimates because, it was based on the most recent version of the NSHM and utilised more current and applicable ground motion prediction equations.

### 3.2.6 Historical observations of liquefaction

Review of the national catalogue of earthquakes (GNS, 2019), indicates that there have been 16 recorded earthquakes of $M_w$ 5 or greater at depths shallower than 100 km in the Study Area since records began. One of these earthquakes was the 1987 Edgecumbe Earthquake.

The Edgecumbe earthquake was a magnitude 6.3 earthquake that occurred at an estimated depth of 8 km on the 2nd of March 1987. During the earthquake, peak ground accelerations up to 0.33 g were recorded within 15 km of the earthquake epicentre. The epicentre of the earthquake was located north-west of the Edgecumbe township (Pender, M. J. & Robertson, T. W. 1987; Dowrick, D. J. 1988). Pender and Robertson (1987) also noted that the earthquake was followed by four significant aftershocks with magnitudes ranging between 5.0 – 5.6.

Dowrick (2007) published an isoseismal map related to the 1987 Edgecumbe earthquake which illustrated the Modified Mercalli intensities of the $M_w$ 6.3 earthquake felt across the Bay of Plenty region (Figure 3.14). This isoseismal map shows Modified Mercalli Intensities (MMI) of at least VI being felt from Maketū to beyond Ōpōtiki. Estimates of MMI between VIII and IX are constrained to the Rangitāiki plains, while the estimates of between VI to VIII extend towards Rotorua.

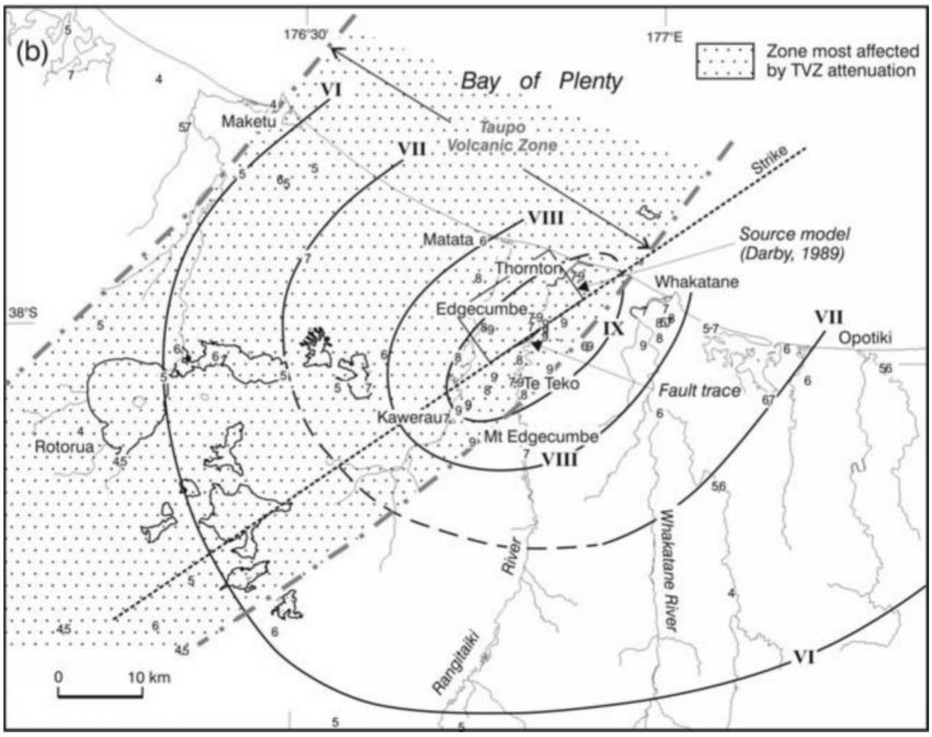



*Figure 3.14: Isoseismal map of the 1987 Edgecumbe earthquake published by Dowrick (2007)*

Extensive areas of earthquake induced ground surface movement were observed within several towns across the plains, with estimates of the magnitude of movement ranging from +0.13 to -2.05 m (Pender & Robertson, 1987). The cause of this ground surface movement is likely to be a combination of fault movement (which could be either uplift or subsidence) and liquefaction-induced subsidence, however, the literature does not provide further clarification.

As shown in Figure 3.15 and Figure A8 in Appendix A, significant liquefaction related land damage was recorded across the Rangitāiki Plains following the earthquake, spanning from Matatā in the north-west to Whakatāne in the north-east, and to Onepu/Te Teko in the south. No liquefaction related phenomena was recorded in Ōpōtiki. Rathje et al. (2010) adapted some work completed by Ambraseys to compare the extent of liquefaction ground damage in relation to distance from a given earthquake epicentre. Based on the information provided by Rathje et al., liquefaction ground damage would be expected to be observed at a maximum distance of approximately 30 km from the 1987 Edgecumbe earthquake epicentre.

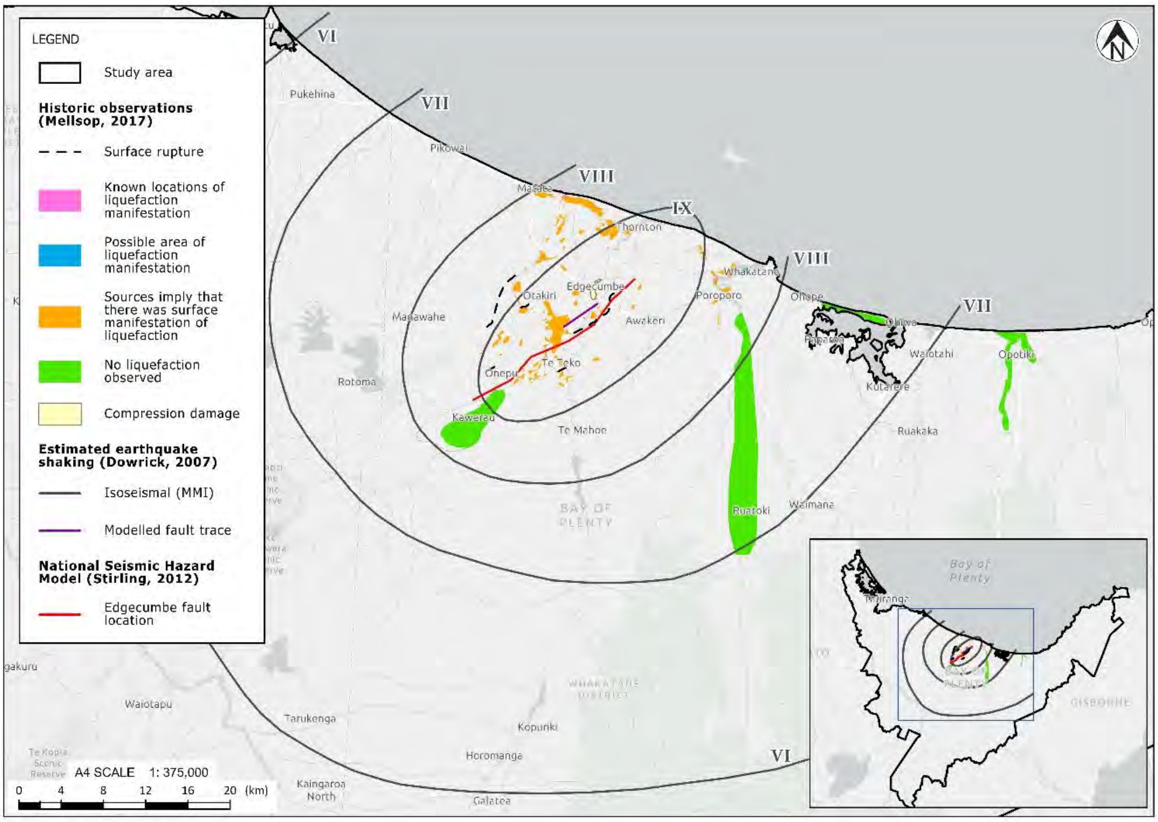



*Figure 3.15: Recorded land damage following the Edgecumbe Earthquake (data sourced from QuakeCore - 2020, based on observations from Pender, M. J. & Robertson, T. W. 1987)*

Sand boils were the most common liquefaction phenomena observed across the Rangitāiki plains. Lateral spreading associated with Tarawera River, Rangitāiki River, and Whakatāne River was also observed. Pender and Robertson (1987) noted that lateral spread was more evident along sections of the rivers where stopbanks were present. Christensen (1995) stated that following the earthquake "in excess of 26 km of stop banks required repairs and 13 drainage schemes were damaged". Robertson also noted that "…level ground liquefaction occurred corelates well with historic positions of streams and rivers of the Rangitāiki Plains. This then implies that the buried river and stream channels are highly susceptible to liquefaction."

Widespread damage to buildings, roads, railways and underground services was recorded following the earthquake event. Franks, Beetham & Salt (1989) stated that the damage following the earthquake was most severe in and around the township of Edgecumbe. The documented damage included "…severely bent and distorted railway lines, compressional ripples and tensional cracking in asphalt surfacing of roads, compressional ruptures of concrete paving and kerbs, and severe compressional damage to underground reticulation services". Franks, Beetham & Salt attribute most of this damage to earthquake shaking rather than liquefaction related phenomena. Pender and Robinson (1987) did, however, describe some damage to a council sewage pumping station in Whakatāne that was likely related to liquefaction phenomena. This damage was related to the reticulated services connected to the pump station which "…rotated excessively…" and "…floated up 2(sic) – 300 mm".

## 3.3 Uncertainty assessment

This section of the report presents an assessment of the uncertainty associated with the base information available for the Study Area. The key output from this assessment is determination of the level of detail supported by the available base information.

### 3.3.1 Ground surface levels

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

**Uncertainty due to the accuracy and limitations of LiDAR derived DEM**

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

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

In most cases these limitations will have a relatively minor effect on the representation of the ground surface. However, there are some specific applications which result in significant uncertainty in the assessment. A key example of this is the inability of LiDAR to penetrate water bodies. This limits the usefulness of LiDAR data for mapping free faces in water features because when water bodies are present at the invert of free faces, the height of the free face may be under-estimated resulting in under prediction of the extent and severity of lateral spreading.

**Uncertainty due to temporal changes in ground surface elevation**

To a greater or lesser extent, any ground surface will be undergoing change in elevation. These changes may be attributable to natural processes (e.g. tectonic movement and earthquake induced ground deformation) or anthropogenic (man-made) changes (e.g. land development activities). For example, following the 1987 Edgecumbe earthquake, earthquake-induced ground surface movement was recorded within several towns across the Rangitāiki Plains, with estimates of ground movement ranging from +0.13 to -2.05 m (Pender & Robertson, 1987). A similar seismic event within the Study Area could quite easily change the ground surface elevations again.

It is not feasible to predict with any reasonable degree of accuracy the extent and degree of future changes in ground surface elevation, although it is known that the Taupō Volcanic Zone is generally subsiding and the Te Urewera/Raukūmara Ranges are generally uplifting. However, as discussed in Section 3.2.2, areas of reclamation fill have been identified while undertaking the geomorphic mapping and have been utilised in the liquefaction vulnerability classification process. Note that mapping from historic aerial imagery may not capture all areas of reclamation fill. The historic images may not cover the period when filling occurred, or the modification was simply not visible in the imagery.

### 3.3.2 Geology and geomorphology

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

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

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

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

**Uncertainty due to anthropogenic landform changes**

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

The level of detail targeted by this assessment (i.e. Level A) means that incorporating the site-specific information that would be required to assess the effects of these landform changes is not included in the scope for this project. Except for reclamation fills (which are mapped as their own geomorphic terrain), areas of anthropogenic landform change are assessed as performing in a manner that is consistent with the geomorphic terrain within which they are situated. More detailed assessment that incorporates site specific information (i.e. Level C or D) would be required to differentiate these areas from the surrounding geomorphic terrain.

**Uncertainty due to liquefaction susceptibility of pumiceous soils**

The majority of global liquefaction research is based on empirical correlations derived from hard-grained sandy sediments. Pumiceous soils differ from these hard-grained sediments, as they are soft-grained and brittle, and are highly crushable. As a result, the empirical correlations between sandy sediments and liquefaction processes cannot be directly related to pumiceous soil deposits (Orense, Asadi, & Pender, 2019). The behaviour of these soils under seismic conditions is currently an active area of scientific research, and there is still a considerable degree of uncertainty associated with the potential for liquefaction to occur in these types of soils.

This introduces a significant source of uncertainty because pumiceous soils are likely to be present in large parts of the Study Area. This uncertainty has been managed by identifying terrains that could contain significant deposits of pumiceous sediments and qualitatively assessing the potential impact of these pumiceous deposits on the liquefaction vulnerability criteria assigned.

### 3.3.3 Geotechnical investigations

As discussed in 3.2.3, there is a range of geotechnical investigations available on the NZGD within the Study Area. These geotechnical investigations can be used to estimate (both quantitatively and qualitatively) the expected liquefaction related performance of the land. The key uncertainties associated with the geotechnical investigations are discussed below.

**Uncertainty due to geotechnical investigation data quality**

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

**Uncertainty due to variability in ground conditions within geomorphic terrains**

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

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

**Uncertainty due to spatial density of geotechnical investigations**

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

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

With that noted, it provides the indicative spatial density of deep ground investigations for adequate ground characterisation for liquefaction assessments shown in Figure 3.16.

| LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT [1,2] | AVERAGE INVESTIGATION DENSITY | AVERAGE SPACING BETWEEN | MINIMUM TOTAL NUMBER OF INVESTIGATIONS |
|---|---|---|---|
| **Level A[3]** Basic desktop assessment | 0.01 to 1 per km² | 1 to 10 km | – |
| **Level B** Calibrated desktop assessment | 0.5 to 20 per km² | 220 to 1400 m | 3 for each geological sub-unit |
| **Level C** Detailed area-wide assessment | 0.1 to 4 per Ha | 50 to 320 m | 5 if area > 1 Ha<br>3 if area 0.25 – 1 Ha<br>2 if area < 0.25 Ha |
| **Level D[4]** Site-specific assessment | 2 to 40 per Ha | 15 to 70 m | 2 within or very close to the building footprint |

Notes:

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

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

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

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

*Figure 3.16: Indicative spatial density of deep ground investigation for adequate ground characterisation for liquefaction assessments to inform planning and consenting processes*

Compared to other parts of New Zealand there are relatively few geotechnical investigations within the Study Area on the NZGD and within T+T's records. As shown in Figure 3.9, the few available investigations are predominantly associated with the main town centres (Whakatāne & Rotorua) and with significant land development projects (Tauranga Eastern Link & Rangitāiki River flood management assets). This spatial density issue means that it is not possible to reliably calibrate the soil conditions from the available geotechnical investigations for the majority of the Study Area.

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

In contrast, the variable spatial density of the geotechnical investigations could allow higher level of detail liquefaction assessments to be completed within localised areas. To understand the spatial distribution and density of CPT investigations, a map of the Study Area was prepared showing the distance from any point to the nearest CPT within the same geomorphic terrain. This map is shown in Figure 3.17 and Figure A9 in Appendix A.

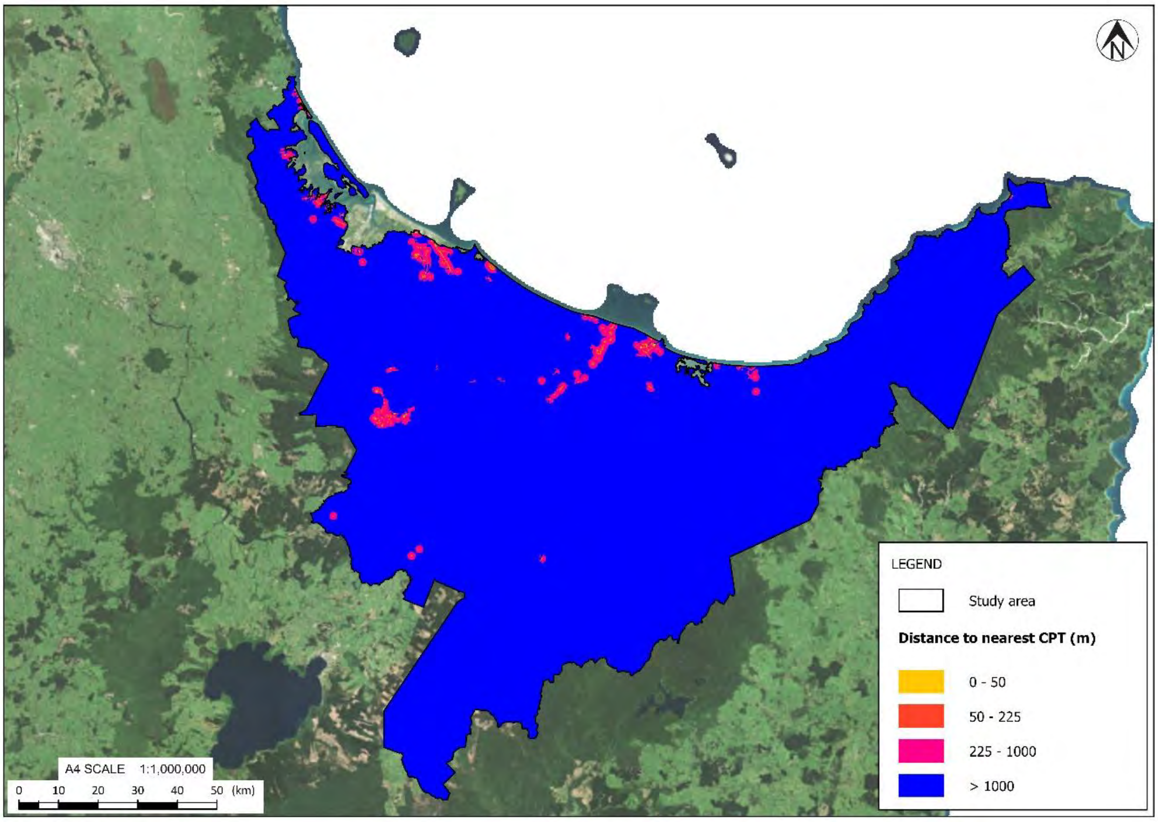



*Figure 3.17: Distance to nearest CPT within the same geomorphic terrain*

Inspection of this map shows that, there is a higher density of investigations within Waihī Beach, Katikati, Ōmokoroa, Te Puke, Rotorua, Edgecumbe, Whakatāne and Ōpōtiki. These could meet the average investigation density required for Level B or C level of detail assessments as outlined in Figure 3.16. As described in Section 3.4, this map has been used to evaluate the level of detail that could be supported in these areas following more detailed analysis.

As discussed above, it is important to recognise that "*the key features which define the level of detail for a particular assessment are the nature of the assessment undertaken and the residual uncertainties, not simply the investigation density".* Therefore, the level of detail supported by the available data in a given area can only be fully determined once that analysis is complete.

### 3.3.4 Groundwater

As discussed in Section 3.2.4, there are a number of in-situ groundwater data records within the Study Area, the majority of which are single measurements from boreholes that are sourced from the BOPRC Open Data database. The key uncertainties associated with the available groundwater data are discussed below.

**Uncertainty due to spatial density of groundwater data**

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

**Uncertainty due to length of groundwater data records**

Most of the groundwater data that T+T has been able to source to date are single point measurements of groundwater. There are only nine locations within the Study Area with multiple readings over a period of months to years. While not critical for the Level A level of detail, this information becomes increasingly important at higher levels of detail because it helps to understand the range of fluctuation in groundwater levels between seasons and years.

**Uncertainty due to the effects of climate change**

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

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

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

Such information would provide a significant reduction in uncertainty in the assessment and potentially enable more detailed classification of the liquefaction vulnerability in the area. In addition, monitoring in these areas could infer potential relationships between groundwater and sea-level rise, and provide a foundation for future management of sea-level rise hazards from groundwater. As discussed in Section 3.2.4, the data shown in Figure 3.11 can be used to identify those areas that are likely to be most sensitive to the effects of sea-level rise. In this assessment, this data has been used to identify those geomorphic units which are likely to be most sensitive to the effects of sea-level rise on groundwater. It is also useful information to inform the scope of any potential future groundwater monitoring studies.

### 3.3.5 Seismic hazard

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

1. Compatibility issues between the magnitude weighting factors embedded in the hazard evaluation and the magnitude scaling factors in the liquefaction evaluation procedures adopted in this guideline series.
2. The use of an "effective earthquake magnitude".
3. The need to incorporate updates in the National Seismic Hazard Model. The NZTA Bridge Manual methodology is based on the Stirling (2002) NSHM and not the updated Stirling et al (2012) NSHM.

It should also be noted that the National Seismic Hazard Model for New Zealand is currently being updated. This update will likely result in some locations in the Bay of Plenty Region having decreased or increased estimates of seismic hazard. These issues indicate there is a significant degree of uncertainty associated with the estimation of seismic hazard using this methodology.

The primary focus of a Level A level of detail is to identify land where there is a high degree of certainty that "Liquefaction Damage is Unlikely" (so that it can be taken off the table without further assessment) (refer to Figure 3.1). This involves the use of qualitative methods that do not rely heavily on the precise seismic hazard parameters adopted.

Regardless of the method used the 500-year level of earthquake shaking (i.e. PGA and magnitude pairing) across the Bay of Plenty Region is well above the level of shaking required to trigger liquefaction in most susceptible soils. This is the primary consideration in this qualitative assessment of liquefaction vulnerability. Therefore, due to a Level A level of detail being targeted in this assessment, the uncertainty associated with the methods used to calculate seismic hazard parameters does not contribute significantly to the residual uncertainty in the current assessment.

### 3.3.6 Historical observations of liquefaction

As detailed in Section 3.2.6, liquefaction related ground damage was observed and documented within the Study Area following the 1987 Edgecumbe earthquake. The occurrence of liquefaction-induced ground damage within the Study Area provides additional information about the liquefaction susceptibility of the geomorphic terrains within the affected area. The key uncertainties associated with the historical observations of liquefaction are discussed below.

**Uncertainty regarding the accuracy of observations and assumptions**

It is possible that observations and records were made of ground damage that wasn't related to liquefaction. The uncertainty is reduced by favouring scientific papers and documents produced by well-known professionals and companies within the geotechnical industry, which distinguish between damage from liquefaction and other earthquake effects.

**Uncertainty due to evidence of liquefaction that was not observed**

The extent of the liquefaction-induced land damage related to the Edgecumbe earthquake is based on observations made by geotechnical professionals at the time. It is possible that some of the land damage associated with the earthquake event was not observed and, as a result, was not recorded within the scientific publications. MBIE/MfE guidance (2017) provides the following examples of why liquefaction related land damage might not be observed following an earthquake even if soils are susceptible:

- It is possible that the soil is susceptible to liquefaction, but the intensity and/or duration of shaking was not sufficient to trigger liquefaction.
- It is possible that liquefaction was triggered at depth in the soil but there was no surface evidence of liquefaction, and greater intensity and/or duration of shaking may be required to induce liquefaction damage at the ground surface.
- There may have been surface evidence of liquefaction occurring, but the observation was not recorded or was attributed to some other cause such as flooding.

### 3.3.7 Assess ground damage response against performance criteria

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

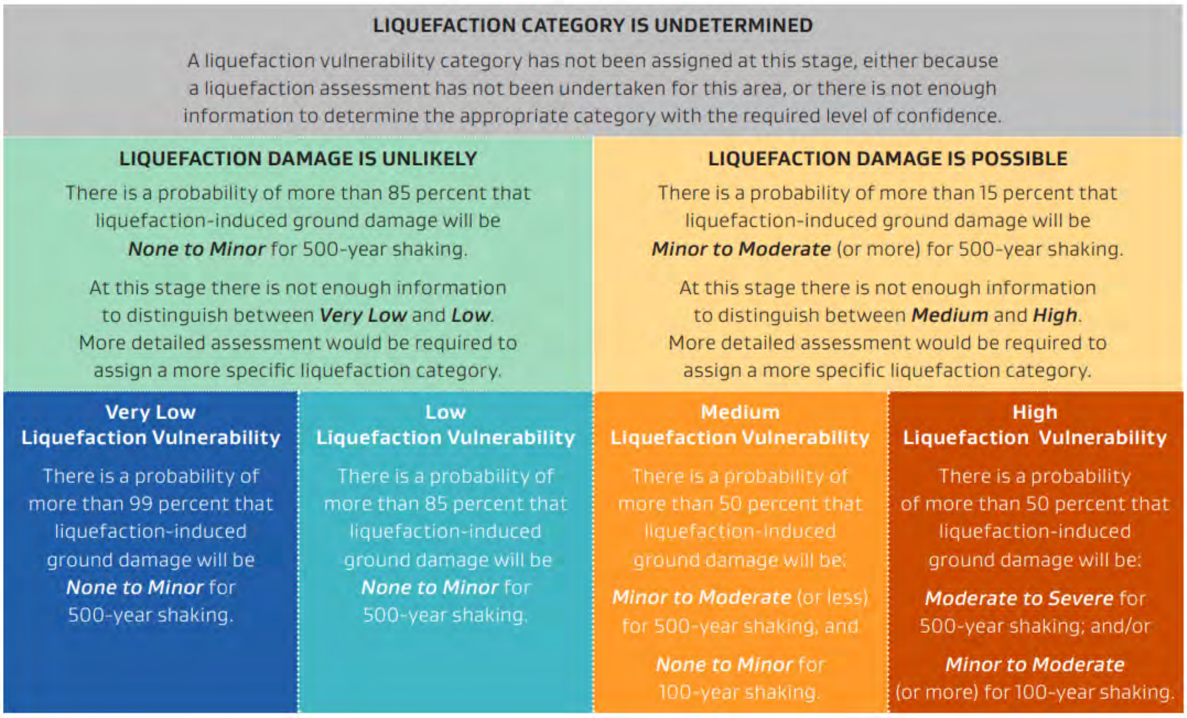



*Figure 3.18: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017).*

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

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

For typical buildings and infrastructure, the consequences (or costs) of over-predicting the hazard are incurred upfront in the form of unnecessary capital expenditure on overly robust solutions. Conversely the costs of under-prediction are incurred at some time in the future when sufficiently strong earthquake shaking occurs and the buildings and infrastructure must be rebuilt or repaired. The potential consequences of this uncertainty in characterising the liquefaction vulnerability are discussed further in Appendix J of the MBIE/MfE Guidance (2017) and are reflected in the relativity between indicative probabilities specified for various categories in Figure 3.18.

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

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

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

## 3.4 Level of detail achieved in this assessment

As shown in Figure 3.19 and Figure A1 in Appendix A, a Level A – basic desktop assessment was targeted across the Study Area and this is the level of detail that has been achieved in this assessment.

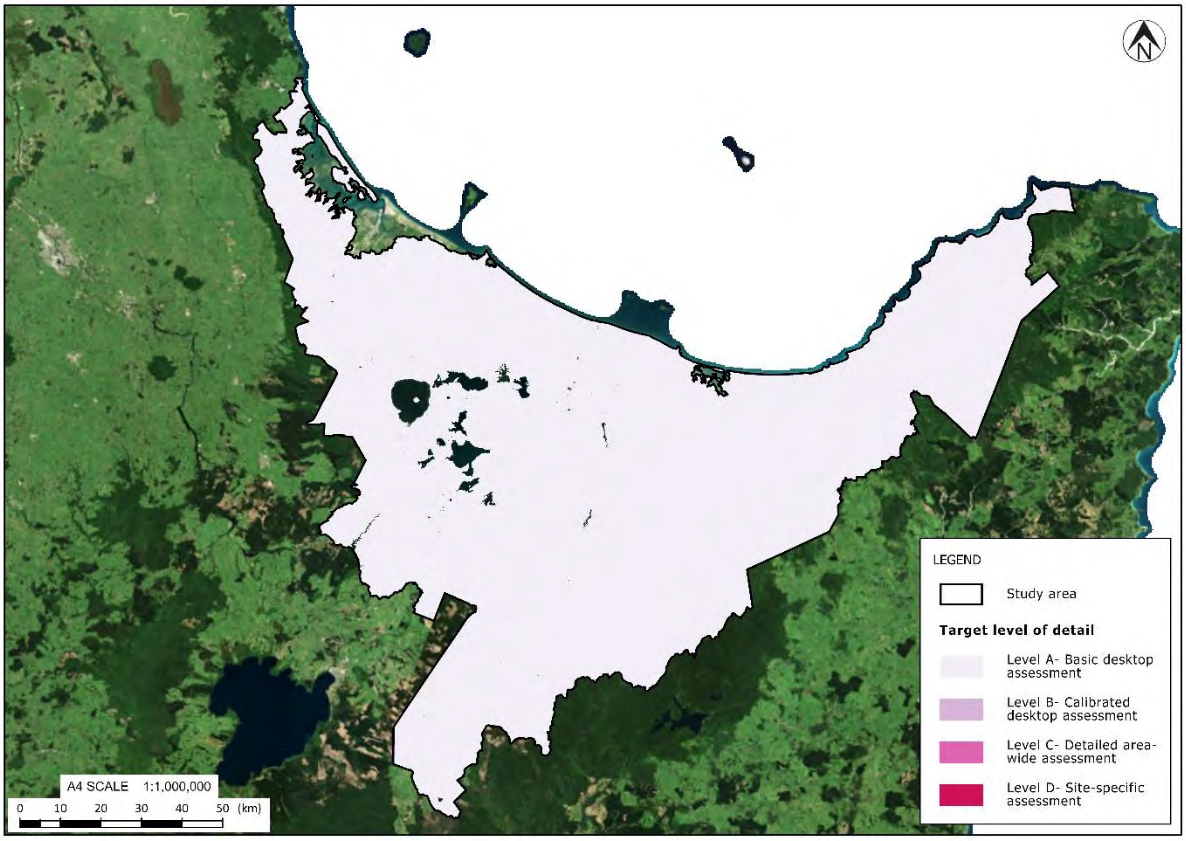



*Figure 3.19: Level of detail achieved in this assessment (Level A throughout Study Area).*

# 4 Risk analysis

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

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

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

## 4.1 Groundwater levels for analysis

As described in Section 3.2.4 and Section 3.3.4, within the Study Area there are relatively few in-situ groundwater data points available and T+T has not been able to access longer term groundwater monitoring records. These records do exist however, T+T were unable to interpret the data from these records as they are privately owned. This makes it particularly challenging to establish precise groundwater levels for analysis and to make allowances for seasonal groundwater level fluctuations. However, assumptions have been made for the purpose of qualitative screening and engineering judgement has been applied to estimate the typical range of depth to groundwater in each of the geomorphic terrains as shown in Table 4.1. An accompanying evaluation of the potential effects of sea-level rise has also been made.

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

| **Geomorphic terrain** | **Assumed depth to groundwater (below existing ground level)** | **Potential influence of sea-level rise on groundwater** |
|---|---|---|
| Reclaimed Land | Less than 4 m | Likely to become shallower. Majority of terrain within higher sensitivity zones identified by PCE. |
| Active Foredunes | Less than 4 m | Likely to become shallower. Majority of terrain within higher sensitivity zones identified by PCE. |
| Fixed Foredunes | Less than 4 m | Likely to become shallower. Majority of terrain within higher sensitivity zones identified by PCE. |
| Alluvial Lowland and Swamp Deposits | Less than 4 m | Areas of low elevation adjacent to coastal margins are likely to become shallower. Majority of terrain within higher sensitivity zones identified by PCE. |
| Alluvial Plains and River Flats | Less than 4 m (however more likely to be variable than other alluvial terrains) | Areas of low elevation adjacent to coastal margins are likely to become shallower. Some of terrain within higher sensitivity zones identified by PCE. Areas of high elevation unlikely to be affected. |
| Harbour Margins | Less than 4 m | Likely to become shallower. Majority of terrain within higher sensitivity zones identified by PCE. |
| Alluvial Terraces | More than 4 m | Areas of high elevation unlikely to be affected. |
| Alluvial Channels | Less than 4 m | Areas of low elevation adjacent to coastal margins are likely to become shallower. Areas of high elevation unlikely to be affected. |
| Debris Flows and Landslide Deposits | Undetermined | Undetermined. |
| Lacustrine Lowlands | Less than 4 m | Areas away from the coast unlikely to be affected. |
| Lacustrine Terraces | More than 4 m | Areas away from the coast unlikely to be affected. |
| Hills and Ranges | Ridge lines and elevated areas assumed to be more than 8 m depth.<br>Sloping land assumed to be highly variable depending on antecedent rainfall and position on slope.<br>Bottom of valleys and gullies assumed to be less than 4 m | Areas of low elevation adjacent to coastal margins are likely to become shallower. Areas of high elevation unlikely to be affected. |
| Volcanic Plateaus | More than 8 m | Areas away from the coast unlikely to be affected. |

## 4.2 Earthquake scenarios for analysis

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

To understand the variability across the Study Area we have considered three earthquake shaking scenarios (PGA) of 0.1 g, 0.2 g and 0.3 g (scenarios 1, 2 and 3 respectively). The approximate equivalent return periods using the NZTA Bridge Manual Methodology (2018) for each of these scenarios are shown Table 4.2. Figure B1 in Appendix B presents the information for the Study Area in a geospatial format.

**Table 4.2: Earthquake shaking scenarios for analysis**

| Town | Earthquake Shaking Scenario (Return Period) | | |
|---|---|---|---|
| | 1 (PGA = 0.1 g) | 2 (PGA = 0.2 g) | 3 (PGA = 0.3 g) |
| Waihī | 1 in 60 year | 1 in 260 year | 1 in 750 year |
| Tauranga | 1 in 60 year | 1 in 260 year | 1 in 750 year |
| Mount Maunganui | 1 in 60 year | 1 in 260 year | 1 in 750 year |
| Te Puke | 1 in 60 year | 1 in 250 year | 1 in 690 year |
| Rotorua | 1 in 50 year | 1 in 200 year | 1 in 500 year |
| Ruatoria | 1 in 40 year | 1 in 180 year | 1 in 450 year |
| Murupara | 1 in 40 year | 1 in 180 year | 1 in 430 year |
| Taupō | 1 in 40 year | 1 in 170 year | 1 in 430 year |
| Kawerau | 1 in 40 year | 1 in 160 year | 1 in 410 year |
| Ōpōtiki | 1 in 40 year | 1 in 150 year | 1 in 390 year |
| Whakatāne | 1 in 40 year | 1 in 140 year | 1 in 350 year |

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

## 4.3 Sub areas of similar expected performance

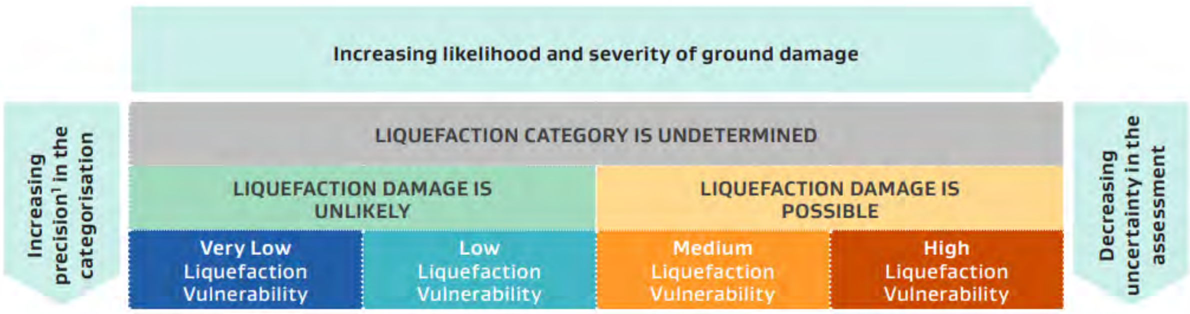
Sub-areas of similar expected performance have been created by grouping areas of land according to the following characteristics:

- **Geomorphic screening** – as described in Section 3.2.2, the Study Area has been mapped according to the dominant geomorphic processes shaping each region. This is used as the primary basis for evaluating the likely soil conditions within each sub-area of similar expected performance. Where available, selected geotechnical investigations have been utilised to inform the potential variability in soil conditions within a given terrain.
- **Topographical screening** – The LiDAR derived DEM has been processed using GIS analytical tools to divide the Study Area into Slopes, Flat Land, Valley and Toe Slope geomorphons. These subcategories have been used to qualitatively assess the typical groundwater depth ranges.
- **Lateral spread screening** – A high level screening of areas where lateral spreading is more likely to be possible has been undertaken by applying a 200 m buffer to the water bodies identified in the 1:250,000 scale topographic maps (sourced from the LINZ data service). These 1:250,000 scale maps provide a more accurate representation of the waterbodies within the Study Area when compared to other sources. For example, when comparing the PCE River Environment Classification system against aerial imagery of the Study Area, significant discrepancies of the mapped stream locations are observed.

## 4.4 Liquefaction vulnerability assessed against performance criteria

Using the available information, the liquefaction vulnerability of each sub-area has been assessed against the performance criteria. Each sub-area is then assigned one of the corresponding liquefaction vulnerability categories shown in Figure 4.1. The liquefaction vulnerability map of the Study Area is shown in Figure 4.2 and Figure B2 in Appendix B.

It is emphasised that the discussion in this report regarding vulnerability categories and options for further geotechnical assessment relate only to liquefaction hazard. There are various other natural hazards and geotechnical constraints which would also need to be considered as part of any future land development or building activities.




Note:

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

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

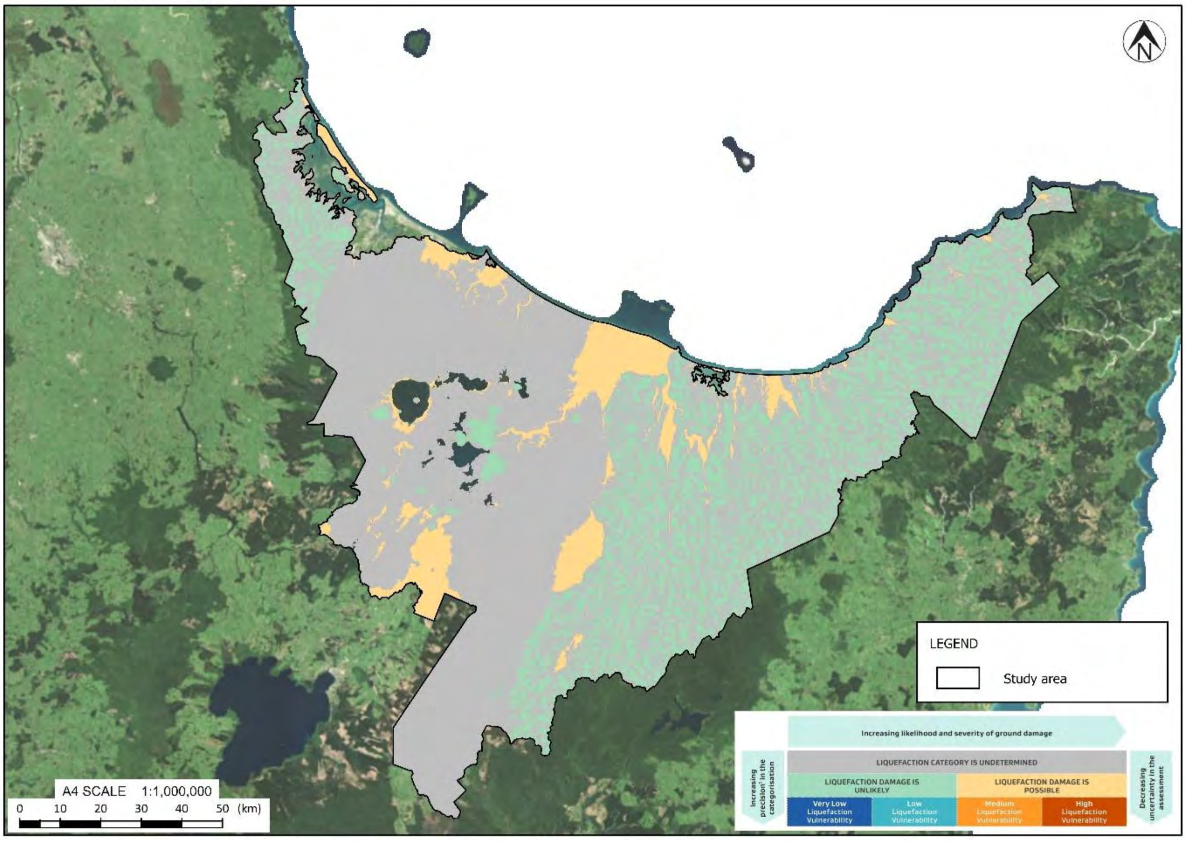



*Figure 4.2: Liquefaction vulnerability classification assessed against performance criteria.*

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

### 4.4.1 Reclamation Fill

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

Reclamation fills are typically highly variable in nature which means there is a high degree of uncertainty associated with their soil characteristics.

The Reclamation Fills mapped in the Study Area are low lying and found adjacent to major water ways (Whakatāne River and Waioeka River). They are therefore likely to have shallow depth to groundwater (< 4 m) with the potential to be influenced by sea-level rise.

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as riverbanks/stop banks).

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "…*there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*." Therefore, the reclamation fills have been classified as "Liquefaction Damage is Possible".

### 4.4.2 Active Foredunes, Fixed Foredunes and Harbour Margins

The Active Foredune, Fixed Foredune and Harbour Margin terrains are likely to comprise thick (> 10 m), Holocene age deposits of sands and silts (which are susceptible to liquefaction) and are unlikely to contain a significant proportion of plastic sediments (which are not susceptible to liquefaction). These terrains are relatively easy to map from aerial photography and typically have consistent soil conditions.

The primary differences between these terrains are as follows:

- Active Foredune and Fixed Foredune sediments are typically deposited in higher energy environments, which means the soils are typically denser than those found in lower energy environments (Harbour Margins and alluvial terrains). The densest soils are typically found within dune deposits adjacent to the open coast.
- In addition to sediments similar to those found in the foredune, the Harbour Margin terrain is more likely to contain soft silts that exhibit plastic behaviour than the dune terrains.

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

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as the harbour edge or dune ridges).

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), *"…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*". Therefore, the mapped active foredunes, fixed foredunes and harbour margin terrains have been classified as "Liquefaction Damage is Possible."

### 4.4.3 Alluvial Lowland and Swamp Deposits

Typically, soils found in this terrain are Holocene-aged and deposited in low energy environments forming loose and soft layers. The depth to groundwater is also likely to be shallow (< 4 m) within these terrains because they are generally associated with active and historic river systems. The MBIE/MfE Guidance (2017) typically associates these alluvial terrains as being susceptible to liquefaction.

The characteristics of the soils comprising these terrains are highly variable in nature and vary spatially across the landscape. Alluvial sediments typically range from non-plastic sands and silts to plastic clays and silts. These soils typically contain soil layers that are susceptible to liquefaction.

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as riverbanks, stop banks, streams and drainage ditches).

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "*…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking.*" Therefore, the mapped alluvial lowland and swamp deposit terrain have been classified as "Liquefaction Damage is Possible".

### 4.4.4 Alluvial Plains and River Flats

Under a 500-year seismic event, this terrain is expected to behave similarly to the alluvial terrain described above. However, this terrain is expected to have more variable groundwater conditions, which will likely influence the degree of liquefaction-induced ground damage. The groundwater conditions are often related to the ground elevation levels of this terrain, which are generally higher than the Alluvial Lowland and Swamp Deposits terrain such that the groundwater typically becomes deeper at higher elevations. Groundwater is also likely to be influenced by proximity to waterbodies located within this terrain, with shallower groundwater levels typically found in areas in closer proximity to waterbodies.

This terrain generally comprises Holocene-aged sediments. The depositional environments are also expected to be similar to the previously described Alluvial Lowland terrain.

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as riverbanks, stop banks, streams and drainage ditches).

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "*…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*." Therefore, the mapped alluvial plains and river flats terrain have been classified as "Liquefaction Damage is Possible".

### 4.4.5 Alluvial Terraces

This terrain comprises elevated land positioned above the previously described alluvial terrains and typically comprises Pleistocene-aged or older alluvium and volcaniclastic materials. Based on previous geotechnical information and local knowledge, this terrain comprises sediments deposited in both high energy and low energy environments, which both have plastic and non-plastic behaviours. However, the older age of these sediments means that they are less likely to contain liquefaction-susceptible soils than the alluvial terrains described above.

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

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as terrace edges).). However, as described above, there is currently significant uncertainty as to whether liquefaction-susceptible soils are present in the alluvial terraces.

Due to the uncertainty associated with whether liquefaction-susceptible soils are present and the depth to groundwater, there is currently insufficient information to characterise the expected land performance. Therefore, based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), in this terrain "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.7, in many of these areas the nature of the expected ground conditions suggests that if more detailed site-specific assessment was undertaken, a category of "Low Liquefaction Vulnerability" could be assigned. For parts of this terrain, undertaking simple shallow hand auger boreholes to confirm soil properties and/or groundwater depths may be all that is required to determine which liquefaction vulnerability category applies. Note that these comments only apply to site specific studies undertaken for the purposes of satisfying Resource and Building Consent requirements. We are not suggesting that simple shallow hand auger boreholes would enable easy refinement of the liquefaction vulnerability category at a regional level.

#### 4.4.6 Alluvial Channels

Typically, the soils found in the Alluvial Channel terrain are Holocene age and deposited in both high energy and low energy environments which results in a variety of soils being formed. Due to the alluvial processes dominating the formation of this terrain, there will be both non-plastic and plastic soils present meaning that some of the soils are likely to be susceptible to liquefaction. The depth to groundwater is also likely to be shallow (< 4 m) within this terrain because they are generally associated with active stream and river systems.

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as streams/riverbanks).

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "*…there is a probability of .more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking.*" Therefore, this mapped terrain has been classified as "Liquefaction Damage is Possible".

#### 4.4.7 Debris Flow and Landslide deposits

This terrain covers a small proportion of the Study Area (approximately 0.1%) and maps debris flows and landslide deposits that are associated with historic slope instability. There is limited information about the soil and groundwater conditions associated with this terrain with both of these factors likely being highly variable. As such, there is currently insufficient information to characterise the expected land performance. Therefore, based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), in this terrain "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.7, in many of these areas the nature of the expected ground conditions suggests that if more detailed site-specific assessment was undertaken, a category of "Low Liquefaction Vulnerability" could be assigned. For parts of this terrain, undertaking simple shallow hand auger boreholes to confirm soil properties and/or groundwater depths may be all that is required to determine which liquefaction vulnerability category applies. Note that these comments only apply to site-specific studies undertaken for the purposes of satisfying Resource and Building Consent requirements. We are not suggesting that simple shallow hand auger boreholes would enable easy refinement of the liquefaction vulnerability category at a regional level.

#### 4.4.8 Lacustrine Lowlands

The sediments comprising this terrain are expected to have been deposited in low energy environments associated with lakes within the Study Area. Soils forming in these environments typically form loose and soft layers which have both non-plastic and plastic behaviours. This terrain is also likely to have a variable pumice content. The depth to groundwater is likely to be shallow (< 4 m) and the sediments comprising this terrain Holocene aged. As a result, the soils comprising this terrain are typically susceptible to liquefaction.

Free faces are associated with this terrain in the form of lake edges, riverbanks and streams, all of which are visible on aerial photography and LiDAR imagery. In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high.

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), *"…there is a probability of more than 15 percent that liquefaction-induced ground damage will be minor to moderate (or more) for 500-year shaking*." Therefore, this terrain has been classified as "Liquefaction Damage is Possible".

### 4.4.9 Lacustrine Terraces

This terrain is very similar to the Lacustrine Lowlands terrain, however, the differentiating factors between the two terrains are their expected groundwater conditions and geological age. The depth to groundwater within the lacustrine terraces terrain is expected to be deeper than the lowlands terrain (> 4 m), due to the surface elevation being higher than the adjacent lowlands. The sediments comprising this terrain are also expected to be Late Pleistocene-age compared to the Holocene lacustrine lowlands.

Due to the properties outlined above, there is a large degree of uncertainty associated with the liquefaction susceptibility of this terrain and as a result and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.7, in many of these areas the nature of the expected ground conditions suggests that if more detailed site-specific assessment was undertaken, a category of "Low Liquefaction Vulnerability" could be assigned. For parts of this terrain, undertaking simple shallow hand auger boreholes to confirm soil properties and/or groundwater depths may be all that is required to determine which liquefaction vulnerability category applies. Note that these comments only apply to site-specific studies undertaken for the purposes of satisfying Resource and Building Consent requirements. We are not suggesting that simple shallow hand auger boreholes would enable easy refinement of the liquefaction vulnerability category at a regional level.

### 4.4.10 Hills and Ranges

This terrain comprises elevated landforms characterised by highly dissected hills with many gullies and valleys, as well as hills that are more rolling in nature, ultimately depending on the underlying geological units (which are Pleistocene-aged and older). The ground conditions vary from exposed rock at the ground surface to thick deposits of residual soils. This terrain has been sub-divided into three separate sub-terrains, the Kaimai Ranges, the Te Urewera/Raukūmara Ranges and the Central Volcanic Zone based on the geological origins of the dominant landform features.

Based on the available information, it is likely that the residual soils within the Kaimai Ranges and Te Urewera/Raukūmara sub-terrains predominantly comprise plastic soils and rock that are not considered to be susceptible to liquefaction. However, although this terrain comprises approximately 78% of the Study Area, there are relatively few geotechnical investigations available to calibrate this assumption. Furthermore, valley systems within this terrain may contain alluvial deposits that may not have been captured within the geomorphic map (due to the 1:25,000 target scale of the geomorphic map). This introduces additional uncertainty into the assessment.

The Central Volcanic Zone sub-terrain differs from the two other sub-terrains as it defines an area that encompasses a variety of volcanic deposits comprising extensive ignimbrites (both welded and non-welded) and igneous flows. This sub-terrain is expected to have significant deposits of pumiceous materials which will contribute to the uncertainty in the assessment of liquefaction vulnerability.

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

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

In this terrain the potential for lateral spreading is consistent with the definition provided in the MBIE/MfE Guidelines (2017), that is in the presence of liquefaction-susceptible soils, lateral spreading is more likely to be possible in areas within 200 m of free faces more than 2 m high (such as gullies and riverbanks). However, as described above there is currently significant uncertainty to whether liquefaction-susceptible soils are present in the hills and ranges terrain.

Based on the information considered in this liquefaction assessment, the liquefaction vulnerability of the Hills and Ranges terrain has been divided into categories as described in the following sections.

**Kaimai Ranges and Te Urewera/Raukūmara sub-terrains**

Based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), in the hilltops, ridges and elevated areas *"…there is a probability of more than 85 percent that liquefaction-induced ground damage will be none to minor for 500-year shaking."* Therefore, these areas are classified as "Liquefaction Damage is Unlikely".

Elevated areas of flat land within this sub-terrain have been classified as "Liquefaction Category is Undetermined" due to the uncertainty associated with the sediments and groundwater conditions associated with these areas.

In the sloping land and valley systems, due to the uncertainty associated with the presences/absence of liquefaction-susceptible soils the depth to groundwater, there is currently insufficient information to characterise the expected land performance. Therefore, in this terrain "Liquefaction Category Undetermined" has been assigned at this time.

**Central Volcanic Zone sub-terrain**

Due to the variability of the volcanic landforms and deposits and the uncertainty associated with whether liquefaction susceptible soils are present, there is currently insufficient information to characterise the expected land performance within this terrain. Therefore, based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), "Liquefaction Category Undetermined" has been assigned at this time.

There are minor zones within this sub-terrain that can be classified as volcanic hard rock through aerial photography and LiDAR imagery. As these features are classified as rock, *"…there is a probability of more than 85 percent that liquefaction-induced ground damage will be none to minor for 500-year shaking*." Therefore, based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), these areas are classified as "Liquefaction Damage is Unlikely".

As discussed in Section 3.3.7, in many of the 'Central Volcanic Zone' areas, the nature of the expected ground conditions suggests that if more detailed site-specific assessment was undertaken, a category of "Low Liquefaction Vulnerability" could be assigned. For parts of this terrain, undertaking simple shallow hand auger boreholes to confirm soil properties and/or groundwater depths may be all that is required to determine which liquefaction vulnerability category applies. Note that these comments only apply to site-specific studies undertaken for the purposes of satisfying Resource and Building Consent requirements. We are not suggesting that simple shallow hand auger boreholes would enable easy refinement of the liquefaction vulnerability category at a regional level.

### 4.4.11 Volcanic Plateaus

This terrain comprises extensive areas of continuous flat to gently sloping land that is positioned at high elevations. There are no geotechnical investigations within the Study Area that can be used to characterise the soils within the terrain. However, geological maps suggest the Pleistocene-aged geology is either volcanic (ignimbrites and airfall tephras) or derived from volcanic material. Minor deposits of alluvial soils may be present within the valley systems across this terrain.

Overall, it is likely that deep groundwater conditions (more than 8 m) are associated with this terrain, however, shallower groundwater conditions may be present within localised valley systems. Note that these valley systems are small and difficult to differentiate based on the information available and therefore many of them have not been mapped at the target scale for the geomorphic mapping (1:25,000). This also introduces a significant source of uncertainty into the assessment.

There is limited information about the soil and groundwater conditions associated with this terrain and both of these factors likely to be variable. As such, there is currently insufficient information to characterise the expected land performance. Therefore, based on engineering judgement and in accordance with Section 4.5.2 of the MBIE/MfE Guidelines (2017), in this terrain "Liquefaction Category is Undetermined" has been assigned at this time.

As discussed in Section 3.3.7, in many of these areas the nature of the expected ground conditions suggests that if more detailed site-specific assessment was undertaken, a category of "Low Liquefaction Vulnerability" could be assigned. For parts of this terrain, undertaking simple shallow hand auger boreholes to confirm soil properties and/or groundwater depths may be all that is required to determine which liquefaction vulnerability category applies. Note that these comments only apply to site-specific studies undertaken for the purposes of satisfying Resource and Building Consent requirements. We are not suggesting that simple shallow hand auger boreholes would enable easy refinement of the liquefaction vulnerability category at a regional level.

# 5 Discussion and recommendations

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

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

  This degree of liquefaction vulnerability categorisation precision is consistent with a regional scale assessment (such as this) undertaken to a Level A level of detail.
- The liquefaction outputs of this assessment provide a regional base layer which will be useful for Resource Management Act (RMA) applications within the Bay of Plenty Region. In particular, the outputs of this assessment relate directly to Policy NH 7A of the Regional Policy Statement (RPS), which outlines areas within the region that are prone to natural hazards. In some cases, it is likely that liquefaction vulnerability studies will need to be completed to a higher level of detail to satisfy RMA requirements.
- Local authorities within the Study Area can also use the outputs of the assessment to inform evaluation of building consent applications. To date, MBIE have not provided specific recommendations to categorise land as "prone to liquefaction or lateral spreading" as it relates to the definition of "Good Ground" in the forthcoming Building Code amendments. However, T+T understands that further information will be available from MBIE soon. In the absence of specific advice from MBIE, we recommend the following:
  - Land that has been categorised as "Liquefaction Damage is Possible" is considered to be "prone to liquefaction or lateral spreading" and therefore does not meet the definition of "Good Ground" as outlined in the Building Code amendments.
  - Land that has been categorised as "Liquefaction Damage is Unlikely" is considered to be "not prone to liquefaction or lateral spreading" within the context of the definition of "Good Ground" as outlined in the Building Code amendments.
  - For land that has been categorised as "Liquefaction Category is Undetermined" as part of this assessment, there is currently insufficient information to determine whether it is "prone to liquefaction or lateral spreading" within the context of the definition of "Good Ground" as outlined in the Building Code amendments.
- As part of the liquefaction vulnerability assessment process, we have developed a geomorphic map of the Study Area that categorises the land into the following 13 terrains: Reclaimed Land, Active Foredunes, Fixed Foredunes, Alluvial Lowland and Swamp Deposits, Alluvial Plains and River Flats, Harbour Margins, Alluvial Terraces, Alluvial Channels, Debris Flows and Landslide Deposits, Lacustrine Lowlands, Lacustrine Terraces, Hills and Ranges and Volcanic Plateaus.

  This map has been developed at a scale of approximately 1:25,000 (i.e. high-level) for the specific purpose of categorising liquefaction vulnerability, with a focus on areas of existing and currently proposed future residential development. The current geomorphic map is not intended for any other purpose, however there may be future opportunities to refine this mapping to help inform other applications (e.g. slope stability mapping).

BOPRC may choose to support Local Authorities within the Study Area to improve the resolution of the liquefaction vulnerability output to promote additional uses of the liquefaction vulnerability information. The two main areas where additional base information is required to support higher level of detail studies include geotechnical investigations and groundwater information. Potential steps to address this information limitation are as follows:

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

  To help facilitate the collection of more geotechnical investigation data, BOPRC and Local Authorities within the Bay of Plenty may wish to undertake the following:

  - Identification of geotechnical investigations from historical projects and uploading of these investigations onto the NZGD.
  - Advocation of uploading supporting geotechnical investigations onto the NZGD as part of the process of evaluating resource and building consent applications. Local engineering and scientific practitioners may need to be educated about why this sharing of information is important.
  - Engagement of suitably competent geo-professionals to undertake geotechnical investigations within given areas where more information about the ground conditions is required (e.g. areas where a Level B, C or D level of detail is targeted). Table 3.5, 3.6 and 3.7 in the MBIE/MfE Guidelines (2017) provide additional information relating to higher level of detail studies. For example, if a land use or subdivision consent application was proposed for urban residential land in the Study Area that had been categorised as "Liquefaction Damage is Possible", it would be likely that a Level B or Level C level of detail assessment would be required for the consent application.
- **Groundwater information**: A key source of uncertainty in this liquefaction vulnerability assessment is the limited amount of groundwater information in the Study Area. While not critical for this Level A assessment, detailed information about shallow groundwater levels becomes increasingly important when targeting higher level of detail liquefaction vulnerability studies. It also provides a valuable data source for other purposes such as asset management.

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

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

# 6 Applicability

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

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

This assessment has been made at a broad scale across the defined Study Area and is intended to describe the typical range of liquefaction vulnerability across areas of similar ground conditions in an approximate way only. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g. for design of building foundations).

Report prepared by:

| | |
|---|---|
| ....................................................... | ....................................................... |
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| Engineering Geologist | Senior Geotechnical Engineer |
| Report reviewed by: | Authorised for Tonkin & Taylor Ltd by: |
| ....................................................... | ....................................................... |
| Mike Jacka | David Milner |
| Technical Director | Project Director |

Tonkin & Taylor Ltd

JMB
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# Appendix A: Risk identification

- **Figure A1 – Target level of detail**
- **Figure A2 – Ground surface elevation**
- **Figure A3 – Geomorphons produced from topographical screening tool**
- **Table A1 – Geomorphic terrain descriptions**
- **Figure A4.1 to A4.5 – Geomorphic sketches**
- **Figure A5 – Geomorphic map of Study Area**
- **Figure A6 – Geotechnical investigations available on NZGD within Study Area**
- **Figure A7 – Shallow groundwater monitoring locations**
- **Table A2 – NZTA (2018) PGA calculations for Bay of Plenty Region**
- **Figure A8 – Historic liquefaction observations from 1987 Edgecumbe Earthquake**
- **Figure A9 – Distance to nearest CPT within the same geomorphic terrain**

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NOTES:
1. Basemap: sourced from Land Information New Zealand and licensed for re-use under the Creative Commons Attribution 4.0.
2. Map indicates the level of detail in the liquefaction assessment that will be targeted. Refer to Table 3.3 of the MBIE Guidelines (2017) for further information about the detail in the liquefaction assessment

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PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE TARGET LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT
SCALE (A3) 1:800,000 FIG No. FIGURE A1 REV 0

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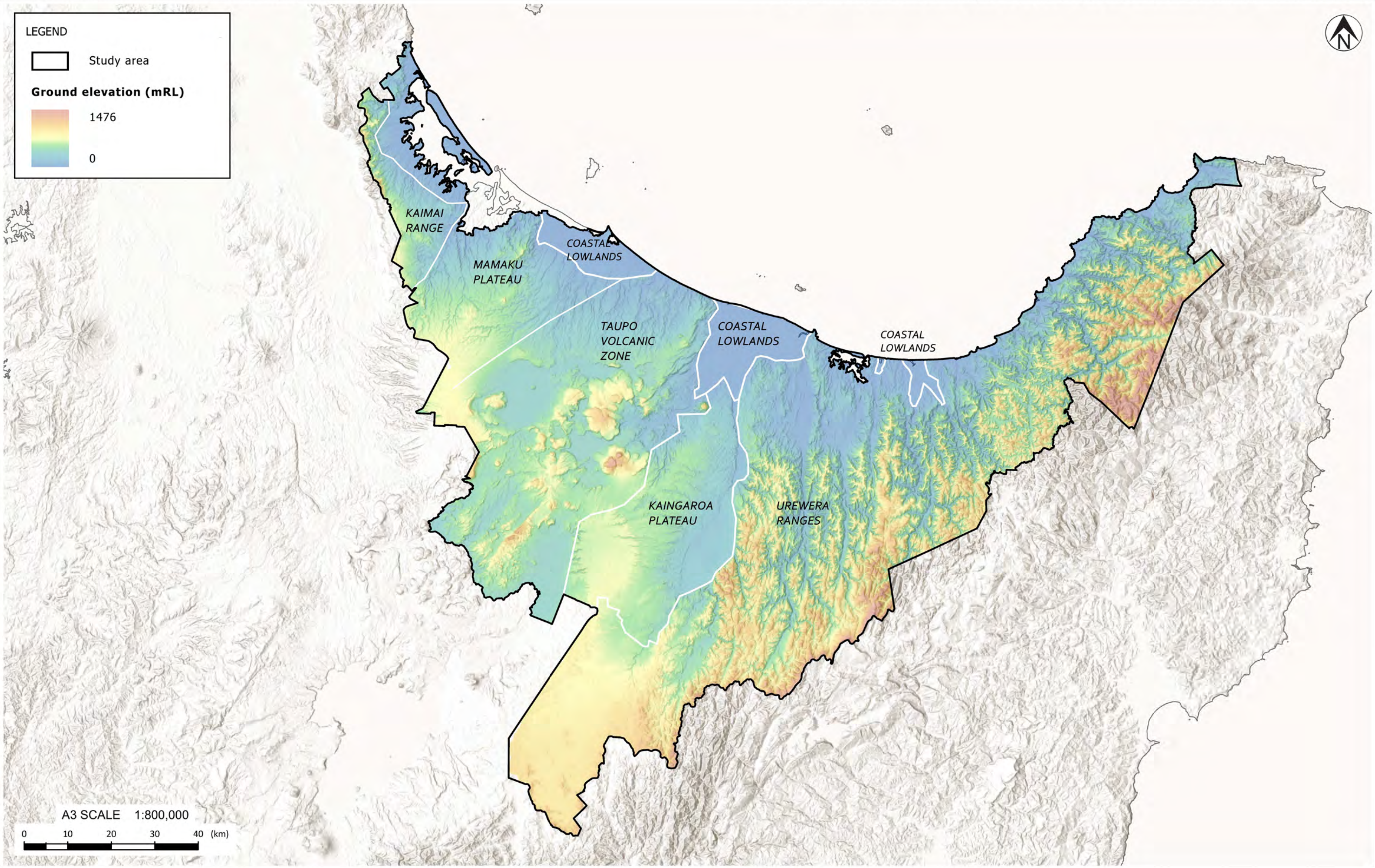


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PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE GROUND SURFACE ELEVATION (2014 LIDAR SURVEY)
SCALE (A3) 1:800,000 FIG No. FIGURE A2 REV 0

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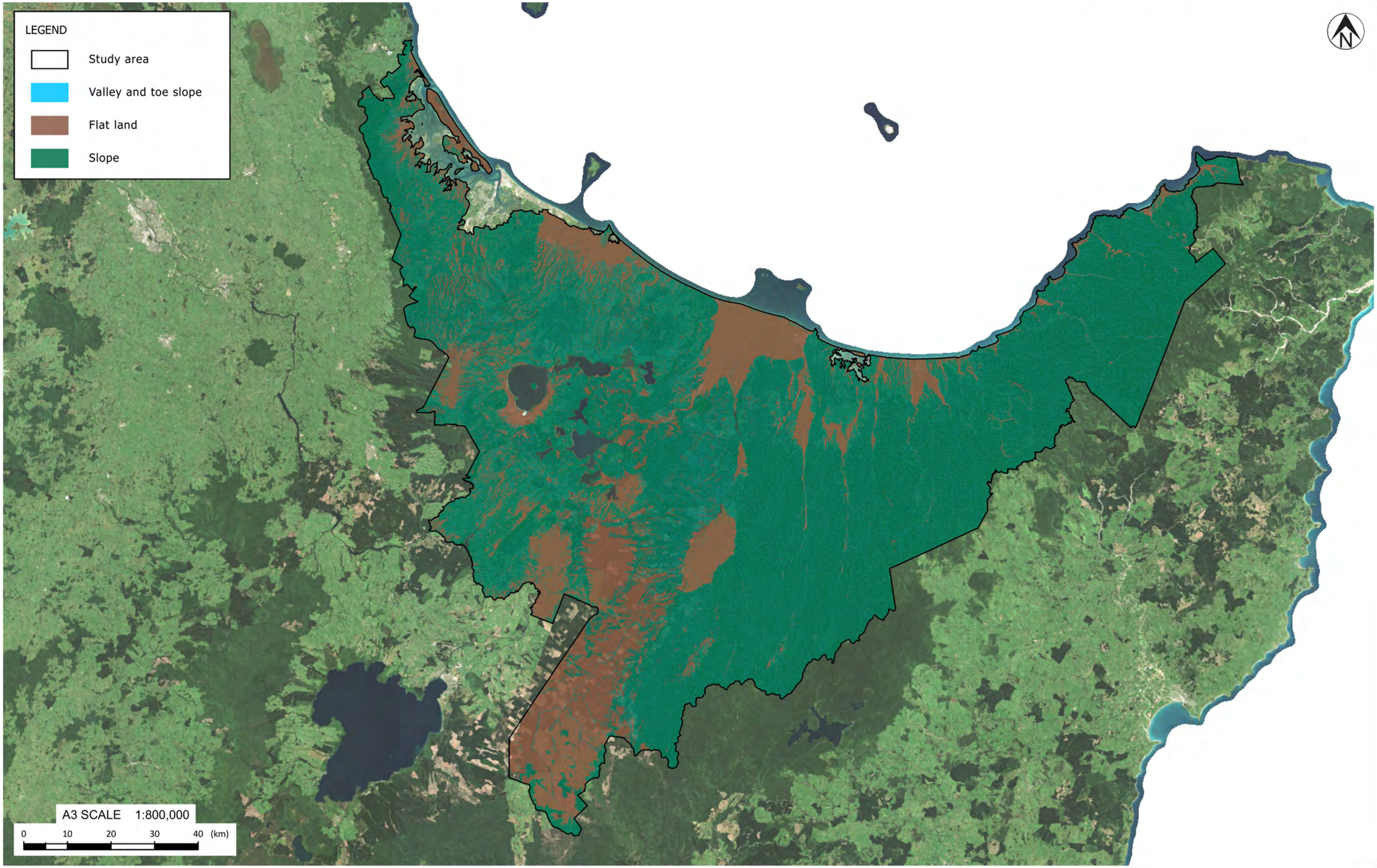


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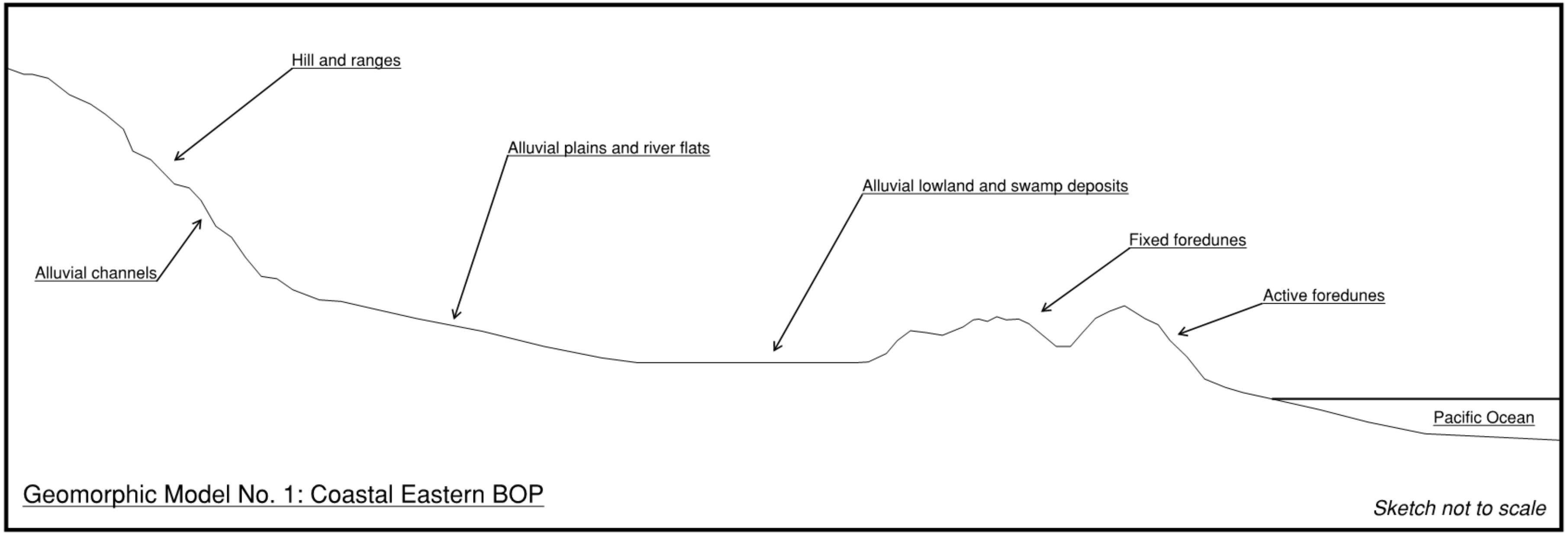
PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT

TITLE GEOMORPHONS PRODUCED FROM TOPOGRAPHICAL SCREENING TOOL

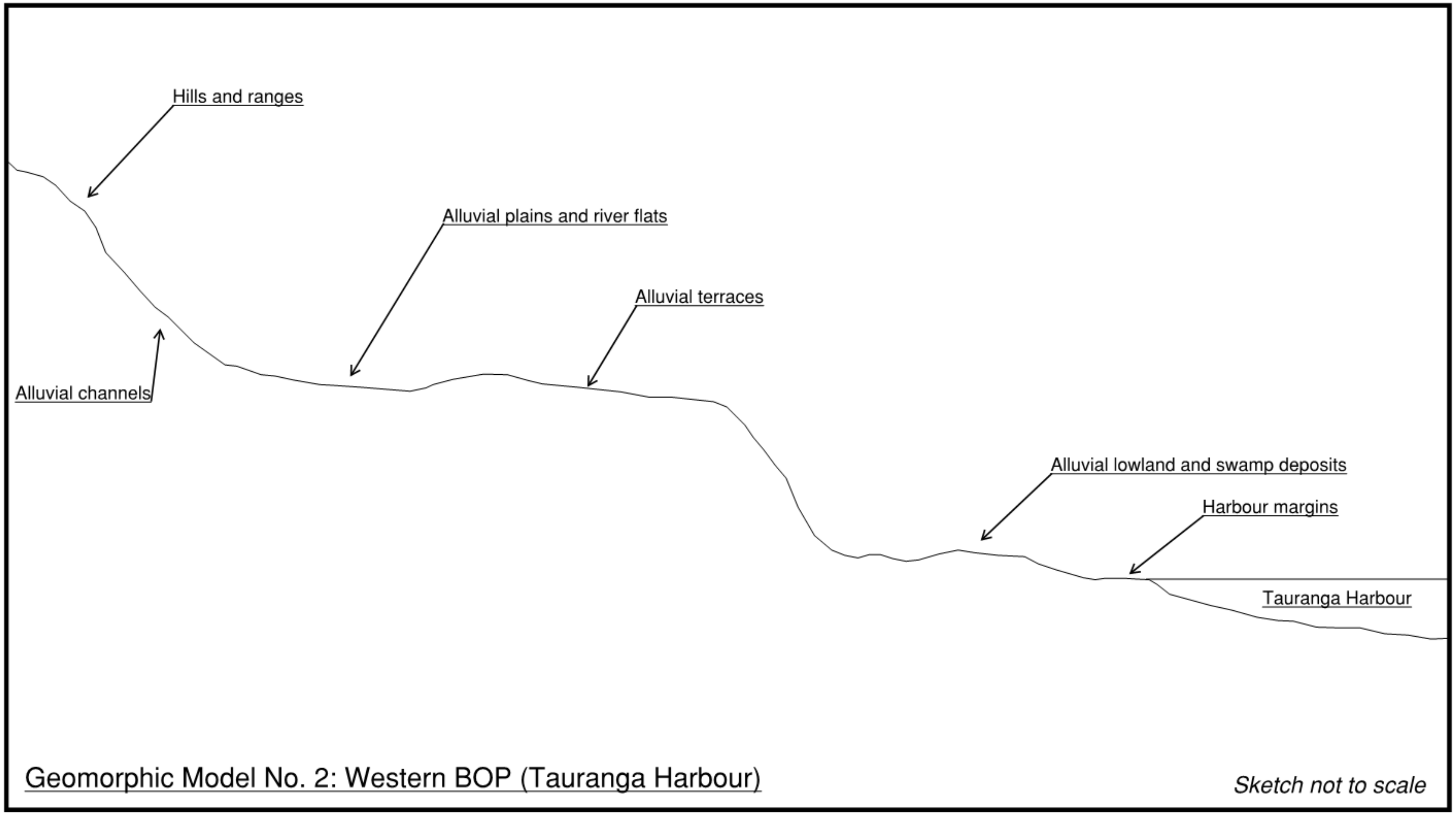
SCALE (A3) 1:800,000   FIG No. FIGURE A3   REV 0

**Appendix A Table A1: Description of geomorphic terrains**

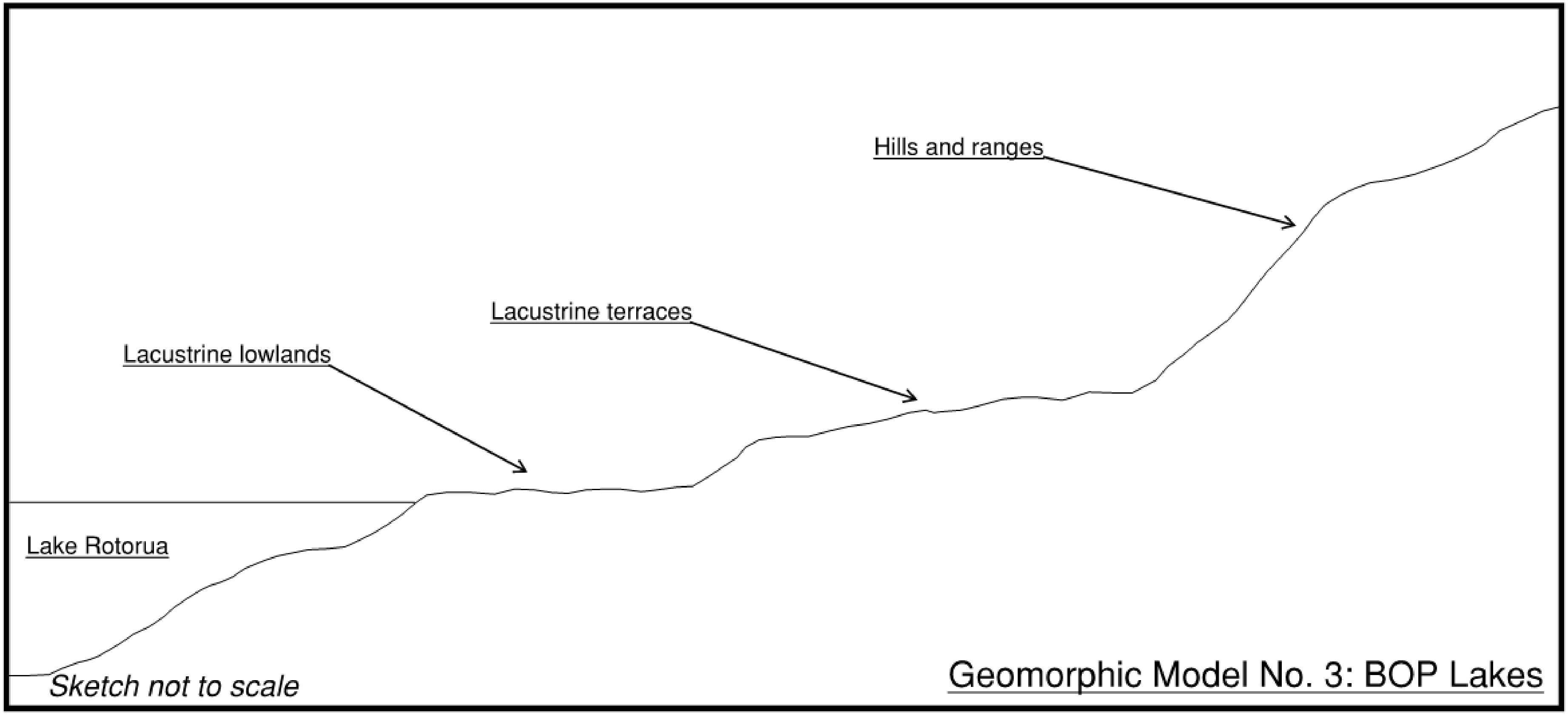
| Geomorphic Terrain | Terrain Description | GeologicalAge | Typical Groundwater Depth | Type Location | Liquefaction Vulnerability Classification |
|---|---|---|---|---|---|
| Active Foredunes | Active foredunes comprise the front coastal sand dunes which are, prior to development, actively subject to windblown and coastal processes. These dunes include the current shoreline. | Holocene | < 4 m below ground level | Waihi Beach, Pukehina, Whakatane, Opotiki | Possible |
| Fixed Foredunes | Fixed foredunes comprise a series crests and troughs, sub-parallel with the coastline. These areas extend inland from the active foredunes and are taken as remnant dune deposits from past coastal regimes which are no longer likely subject to active windblown and coastal process. | Holocene | < 4 m below ground level | Waihi Beach, Pukehina, Whakatane (inland), Opotiki | Possible |
| Alluvial Lowland and Swamp Deposits | This terrain captures the flat, low lying alluvial land that dominates the coastal areas and low-lying areas of the region. This terrain is typically characterised by low lying, flat topography comprising streams, rivers and swamps. This terrain is one of the youngest in the project area. | Holocene | < 4 m below ground level | Rangataiki Plains, Opotiki | Possible |
| Alluvial Plains and River Flats | This terrain is very similar to the alluvial lowlands and swamp deposits, however this terrain has a higher topographical elevation. This terrain represents the sediments deposited from the active and historic river systems within the region. The surface of this terrain typically increases in elevation in a landward direction from the coast. | Holocene | < 4 m below ground level | Kawerau, Te Teko, Taneatua, Murupara, Reporoa | Possible |
| Harbour Margins | Low-lying areas surrounding the present-day shorelines associated with the harbours of the Bay of Plenty region. This terrain is inferred to be primarily formed by estuarine type processes, rather than by alluvial or deltaic processes. | Holocene | < 4 m below ground level | Western Bay of Plenty (Tauranga Harbour), Ohiwa Harbour | Possible |
| Alluvial Terraces | Generally steep-sided terraces and sea cliffs. The terraces typically comprise Pleistocene-age or older alluvium, with various interbedded ash and tephra deposits. Typically positioned below the hills and ranges terrain. | Early Pleistocene - Middle Pleistocene | > 4 m below ground level | Western Bay of Plenty (Omokoroa, Katikati, Maketu) | Undetermined |
| Alluvial Channels | Active fluvial systems eroding older hills and ranges forming steep sided typically narrow channels or small gullies. Characterised by colluvial/alluvial deposition typically at the base of gullies or within the upper reaches of stream valleys. Also includes the deposits of side slope processes and fans. | Holocene | < 4 m below ground level | Small rivers and streams in hills and ranges terrain | Possible |
| Debris Flows and Landslide Deposits | Represents large mass flow/colluvium deposits that can be observed at 1:25,000 scale. Minor unit across region are not identified on the geomorphic map. | Holocene | > 4 m below ground level | Matata | Undetermined |
| Lacustrine Lowlands | Low-lying, flat land located alongside several lakes within the region. Represents recent lake sediments that were deposited by recent, historic shorelines. | Holcene | < 4 m below ground level | Rotorua CBD, Ngongotaha, Tarawera | Possible |
| Lacustrine Terraces | This terrain sits above the lacustrine lowlands and represents historic shorelines of several lakes within the region. Typically sub horizontal to gently sloping surfaces that are elevated above the current lake levels/lacustrine lowlands. | Late Pleistocene | > 4 m below ground level | Owhata (Rotorua), Western Heights | Undetermined |
| Hills and Ranges | Terrain characterised by elevated topography which is often capped with tephra and residual soils. This terrain typically sits above the alluvial terraces and covers the majority of the project area. Represents the oldest terrain in the project area. | Older than Pliocene | > 8 m below ground level | Kaimai Ranges, Te Uruwera Ranges, Raukumara Ranges | Undetermined or Unlikely |
| Volcanic Plateaus | This terrain comprises extensive areas of continuous flat to gently sloping land that is positioned at high elevations. This terrain is derived from volcanic material, predominantly comprising mass flow deposits (pyroclastic flows and airfall tephra). | Early Pleistocene - Middle Pleistocene | > 8 m below ground level | Mamaku Plateau, Kaingaroa Plateau | Undetermined or Unlikely |
| Reclaimation Fill | Uncontrolled and engineered fill, reworked natural soils or construction waste, inferred to be > 3m thick. | Holocene | < 4 m below ground level | Whakatane CBD | Possible |



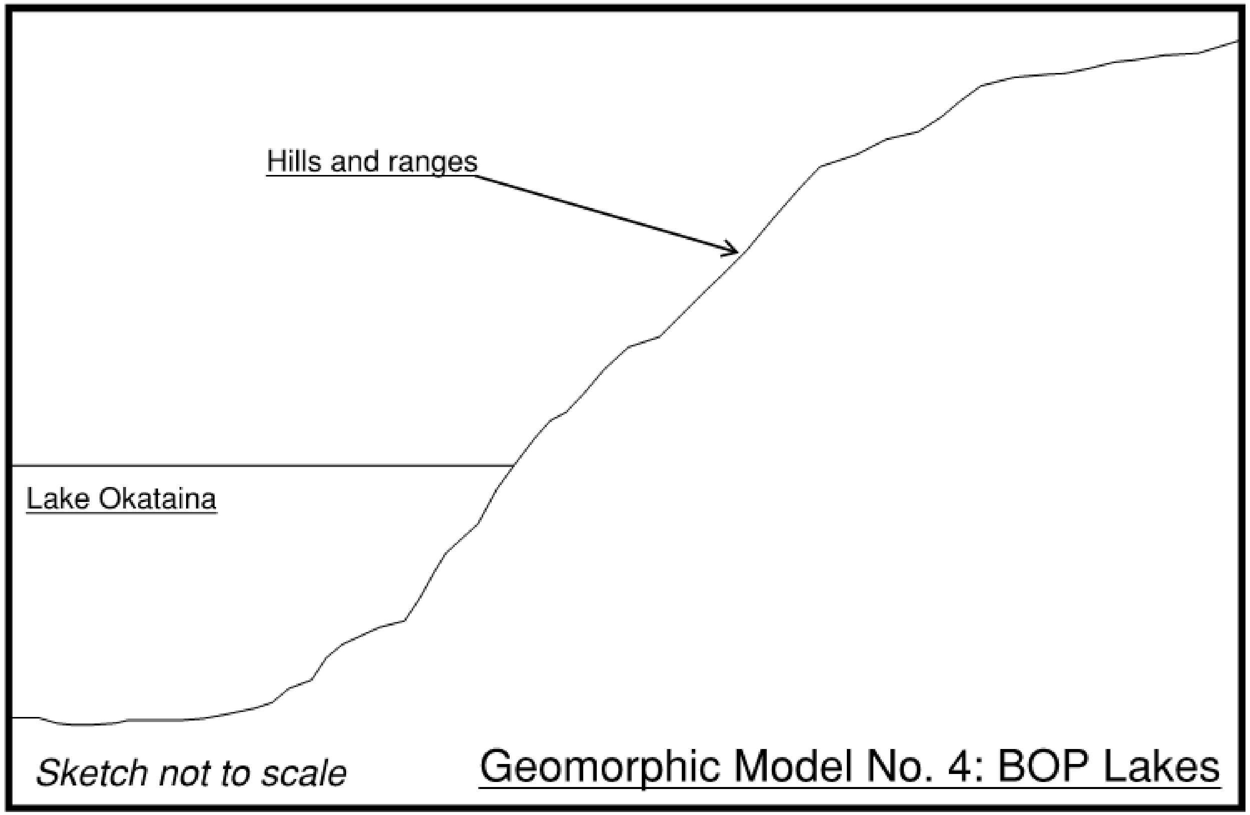

**Appendix A Figure 4.1: Geomorphic model No. 1**



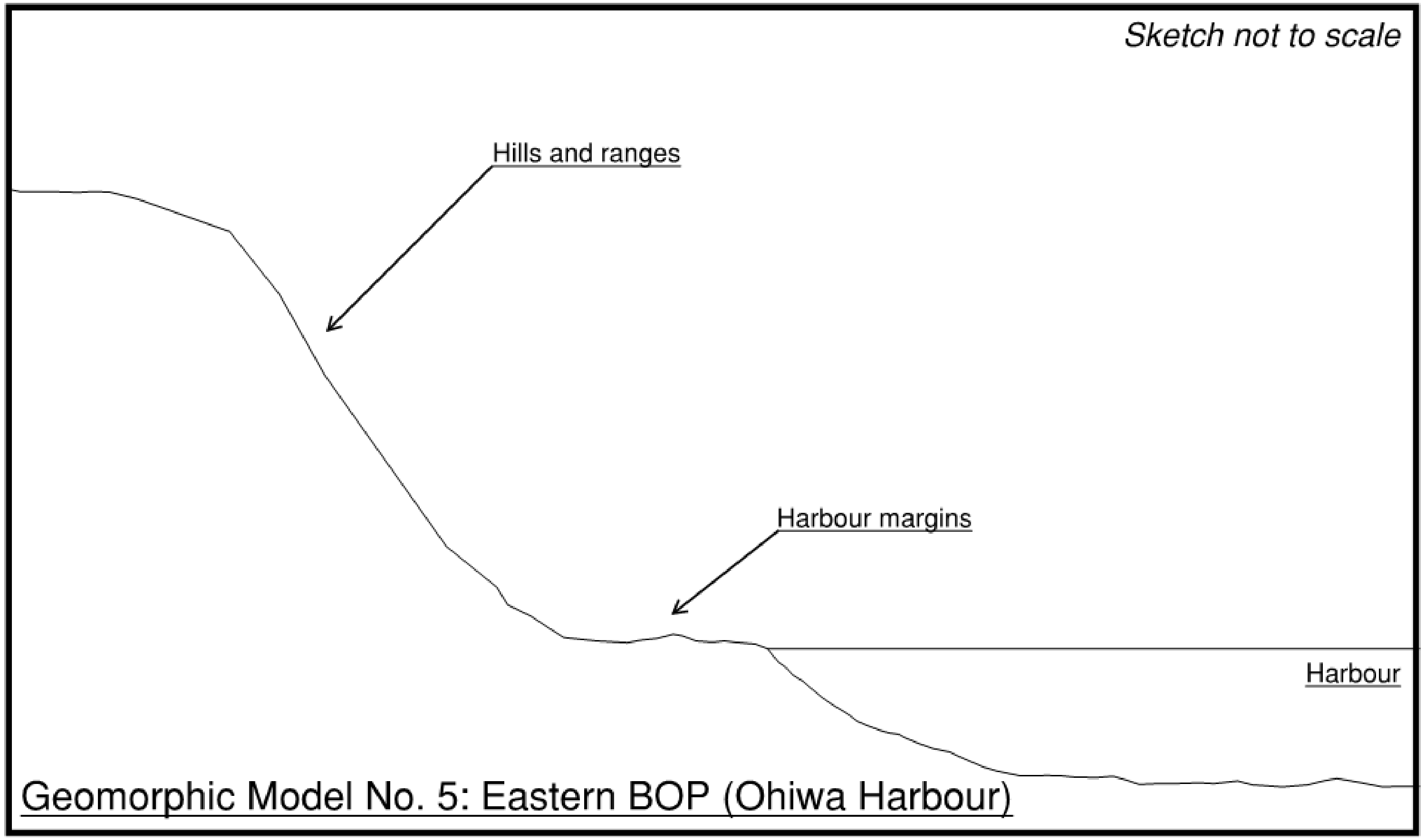

**Appendix A Figure 4.2: Geomorphic model No. 2**




**Appendix A Figure 4.3: Geomorphic model No. 3**




**Appendix A Figure 4.4: Geomorphic model No. 4**




**Appendix A Figure 4.5: Geomorphic model No. 5**

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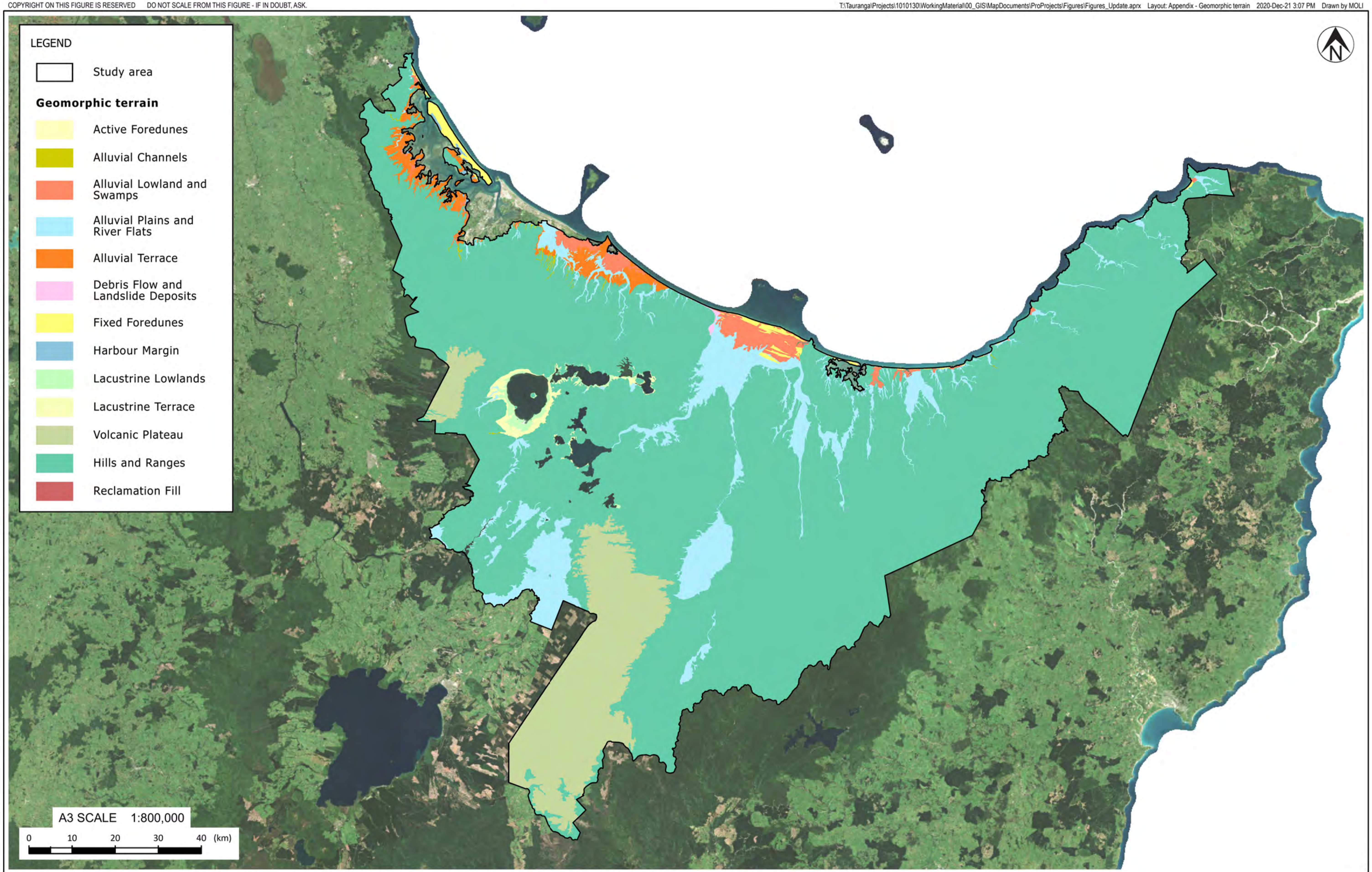


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CLIENT: BAY OF PLENTY REGIONAL COUNCIL
PROJECT: REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE: GEOMORPHIC MAP OF STUDY AREA
SCALE (A3): 1:800,000  FIG No. FIGURE A5  REV 0

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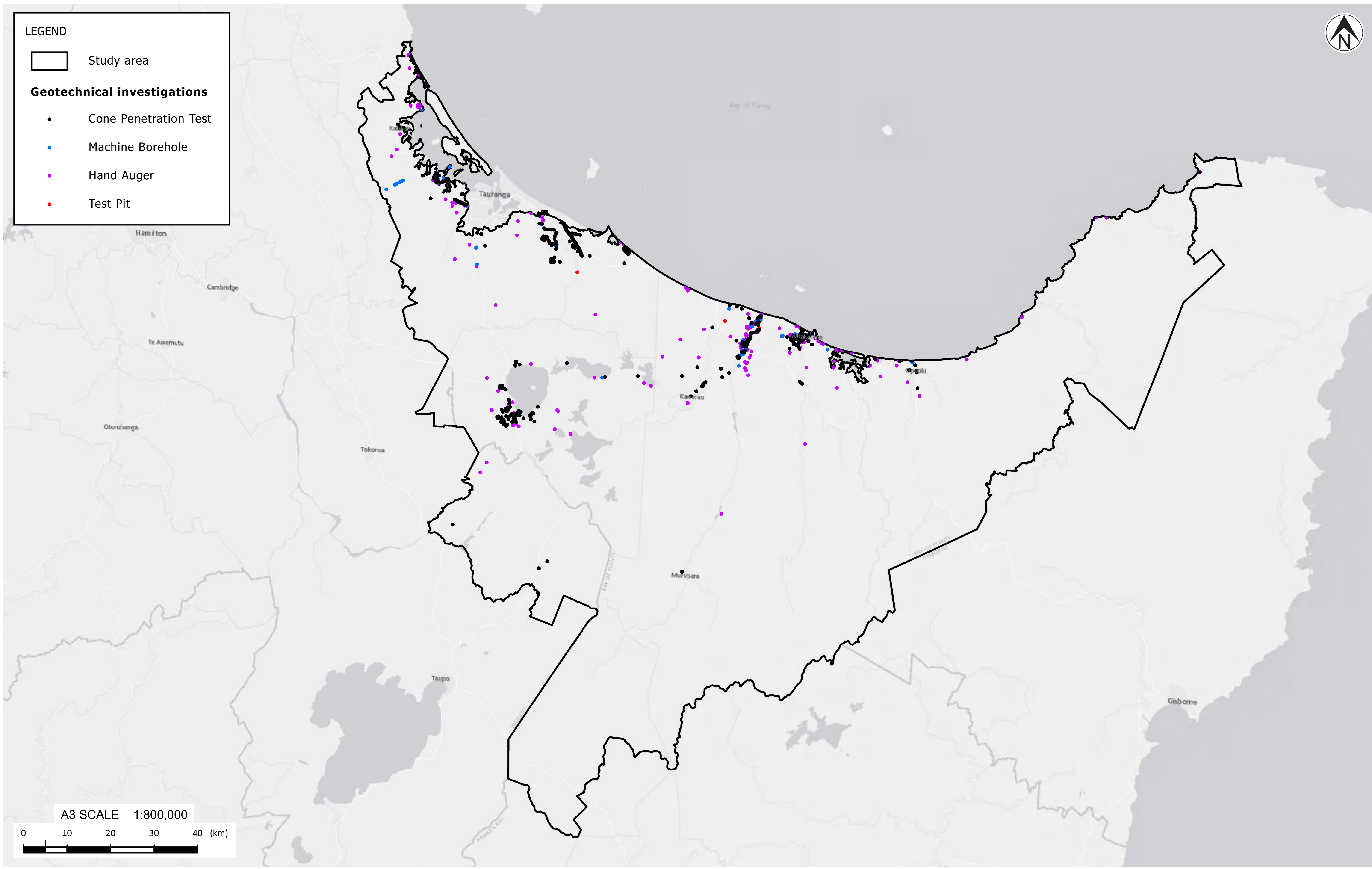


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CLIENT BAY OF PLENTY REGIONAL COUNCIL

PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT

TITLE GEOTECHNICAL INVESTIGATIONS AVAILABLE ON NZGD WITHIN STUDY AREA

SCALE (A3) 1:800,000   FIG No. FIGURE A6   REV 0

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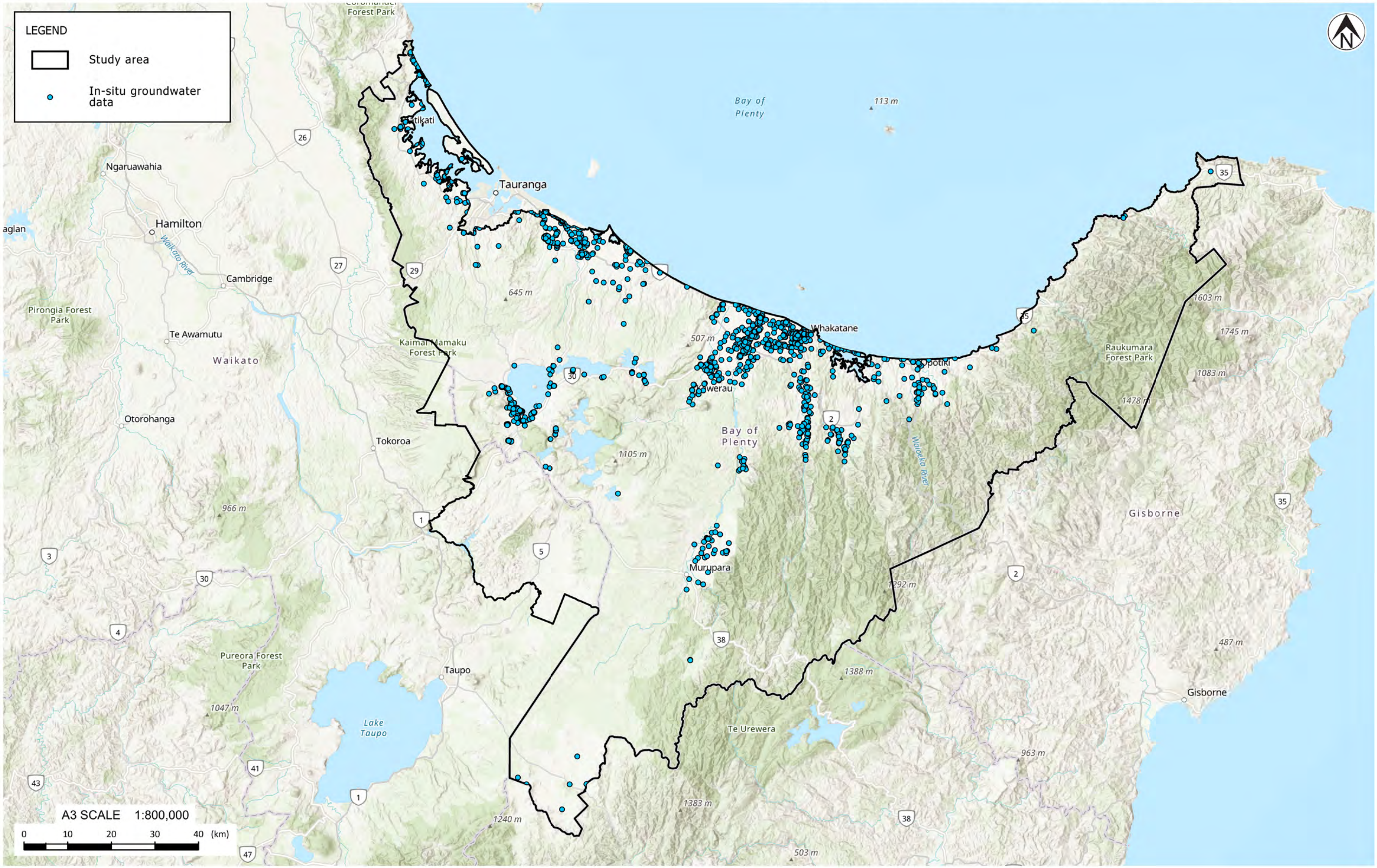


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**NOTES:**
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2. Groundwater measurement locations: sourced from Bay of Plenty Regional Council and the New Zealand Geotechnical Database.

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CLIENT **BAY OF PLENTY REGIONAL COUNCIL**
PROJECT **REGIONAL LIQUEFACTION HAZARD ASSESSMENT**
TITLE SHALLOW GROUNDWATER MONITORING LOCATIONS
SCALE (A3) 1:800,000   FIG No. FIGURE A7   REV 0

**Appendix A Table A2. Estimated Peak Ground Accelerations (PGA) and Magnitude ($M_{eff}$) for various return period earthquakes for towns within the Bay of Plenty region based on the NZTA Bridge Manual methodology (NZTA, 2018)**

| Town/ City | C0,1000 | | Effective magnitude for design return period (years | | PGA (g) 1/25 | | | PGA (g) 1/50 | | | PGA (g) 1/100 | | | PGA (g) 1/250 | | | PGA (g) 1/500 | | | PGA (g) 1/1000 | | | PGA (g) 1/2500 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Subsoil Class A/B | Subsoil Class D&E | 500 - 2500 | 50 - 100 | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E | Class A & Class B | Class C | Class D & Class E |
| **Whakatane** | 0.43 | 0.46 | 6.1 | 6.1 | 0.08 | 0.11 | 0.09 | 0.12 | 0.15 | 0.12 | 0.17 | 0.22 | 0.18 | 0.25 | 0.33 | 0.27 | 0.33 | 0.44 | 0.35 | 0.43 | 0.57 | 0.46 | 0.60 | 0.79 | 0.64 |
| **Opotiki** | 0.40 | 0.44 | 6.1 | 6.1 | 0.08 | 0.10 | 0.08 | 0.11 | 0.14 | 0.12 | 0.15 | 0.20 | 0.17 | 0.23 | 0.31 | 0.25 | 0.31 | 0.41 | 0.34 | 0.40 | 0.53 | 0.44 | 0.55 | 0.74 | 0.61 |
| **Kawerau** | 0.41 | 0.43 | 6.2 | 6.2 | 0.08 | 0.10 | 0.08 | 0.11 | 0.15 | 0.12 | 0.16 | 0.21 | 0.17 | 0.24 | 0.31 | 0.25 | 0.32 | 0.42 | 0.33 | 0.41 | 0.55 | 0.43 | 0.57 | 0.76 | 0.60 |
| **Murupara** | 0.42 | 0.41 | 6.3 | 6.3 | 0.08 | 0.11 | 0.08 | 0.11 | 0.15 | 0.11 | 0.16 | 0.21 | 0.16 | 0.24 | 0.32 | 0.24 | 0.32 | 0.43 | 0.32 | 0.42 | 0.56 | 0.41 | 0.58 | 0.77 | 0.57 |
| **Rotorua** | 0.35 | 0.39 | 6.0 | 6.0 | 0.07 | 0.09 | 0.08 | 0.09 | 0.13 | 0.11 | 0.13 | 0.18 | 0.15 | 0.20 | 0.27 | 0.23 | 0.27 | 0.36 | 0.30 | 0.35 | 0.47 | 0.39 | 0.48 | 0.64 | 0.54 |
| **Ruatoria** | 0.34 | 0.41 | 6.1 | 6.1 | 0.07 | 0.09 | 0.08 | 0.09 | 0.12 | 0.11 | 0.13 | 0.17 | 0.16 | 0.20 | 0.26 | 0.24 | 0.26 | 0.35 | 0.32 | 0.34 | 0.45 | 0.41 | 0.47 | 0.63 | 0.57 |
| **Te Puke** | 0.30 | 0.35 | 6.0 | 6.0 | 0.06 | 0.08 | 0.07 | 0.08 | 0.11 | 0.09 | 0.23 | 0.31 | 0.27 | 0.12 | 0.15 | 0.13 | 0.30 | 0.40 | 0.35 | 0.17 | 0.23 | 0.20 | 0.42 | 0.55 | 0.48 |
| **Tauranga** | 0.29 | 0.34 | 5.9 | 5.9 | 0.06 | 0.07 | 0.07 | 0.08 | 0.10 | 0.09 | 0.11 | 0.15 | 0.13 | 0.17 | 0.22 | 0.20 | 0.22 | 0.30 | 0.26 | 0.29 | 0.39 | 0.34 | 0.40 | 0.53 | 0.47 |
| **Waihi** | 0.29 | 0.34 | 5.9 | 5.9 | 0.06 | 0.07 | 0.07 | 0.08 | 0.10 | 0.09 | 0.22 | 0.30 | 0.26 | 0.11 | 0.15 | 0.13 | 0.29 | 0.39 | 0.34 | 0.17 | 0.22 | 0.20 | 0.40 | 0.53 | 0.47 |
| **Mount Maunganui** | 0.29 | 0.34 | 5.9 | 5.9 | 0.06 | 0.07 | 0.07 | 0.08 | 0.10 | 0.09 | 0.11 | 0.15 | 0.13 | 0.17 | 0.22 | 0.20 | 0.22 | 0.30 | 0.26 | 0.29 | 0.39 | 0.34 | 0.40 | 0.53 | 0.47 |

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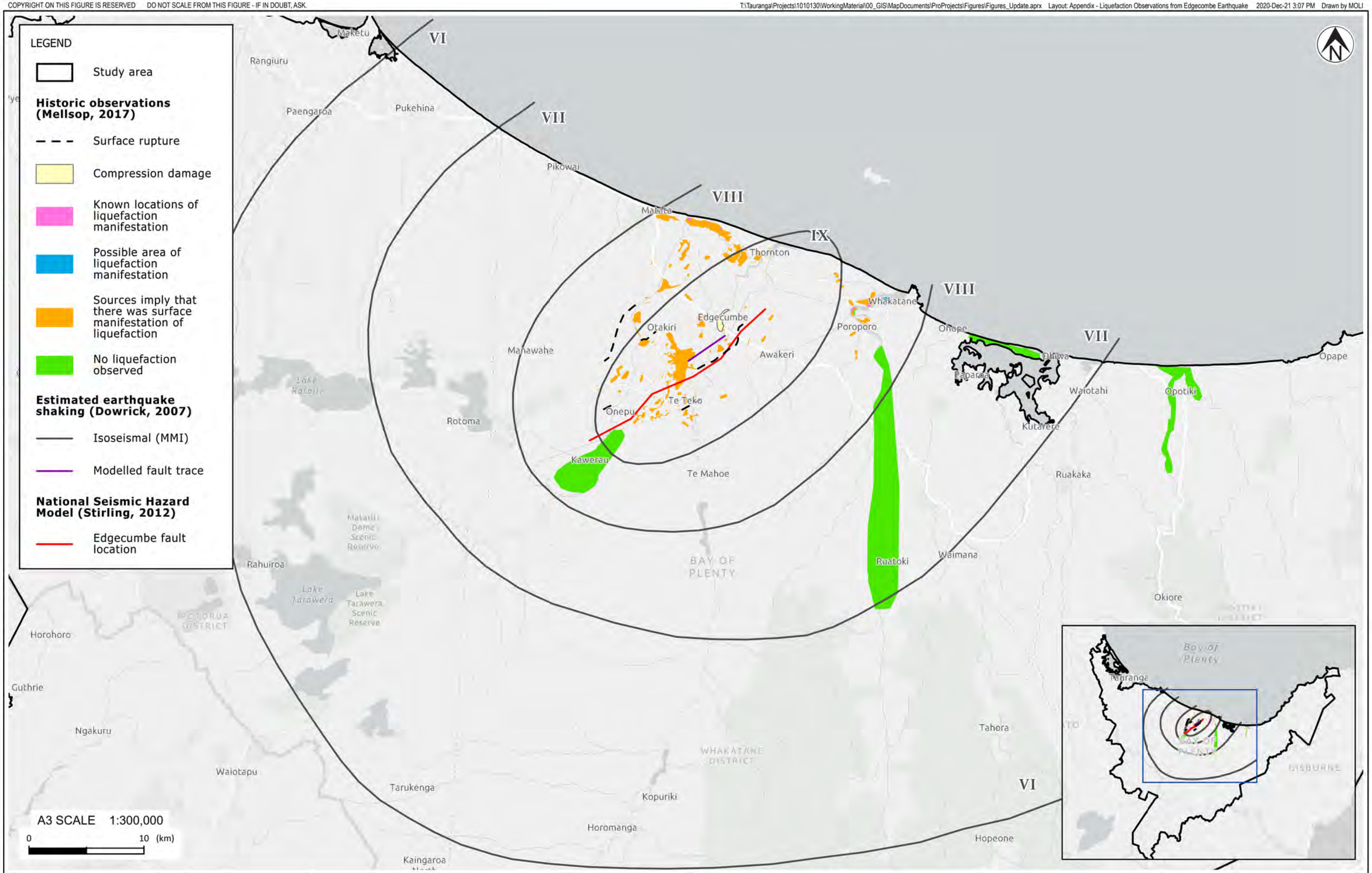


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1. Basemap: sourced from Land Information New Zealand and licensed for re-use under the Creative Commons Attribution 4.0.
2. Historic observations: sourced from QuakeCore and Mellsop, 2017.
3. Estimated earthquake shaking: sourced from Dowrick, 2007.
4. National Seismic Hazard Model faults: sourced from Stirling, 2012.

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CLIENT BAY OF PLENTY REGIONAL COUNCIL
PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE LIQUEFACTION OBSERVATIONS FROM 1987 EDGECUMBE EARTHQUAKE

SCALE (A3) 1:300,000 FIG No. FIGURE A8 REV 0

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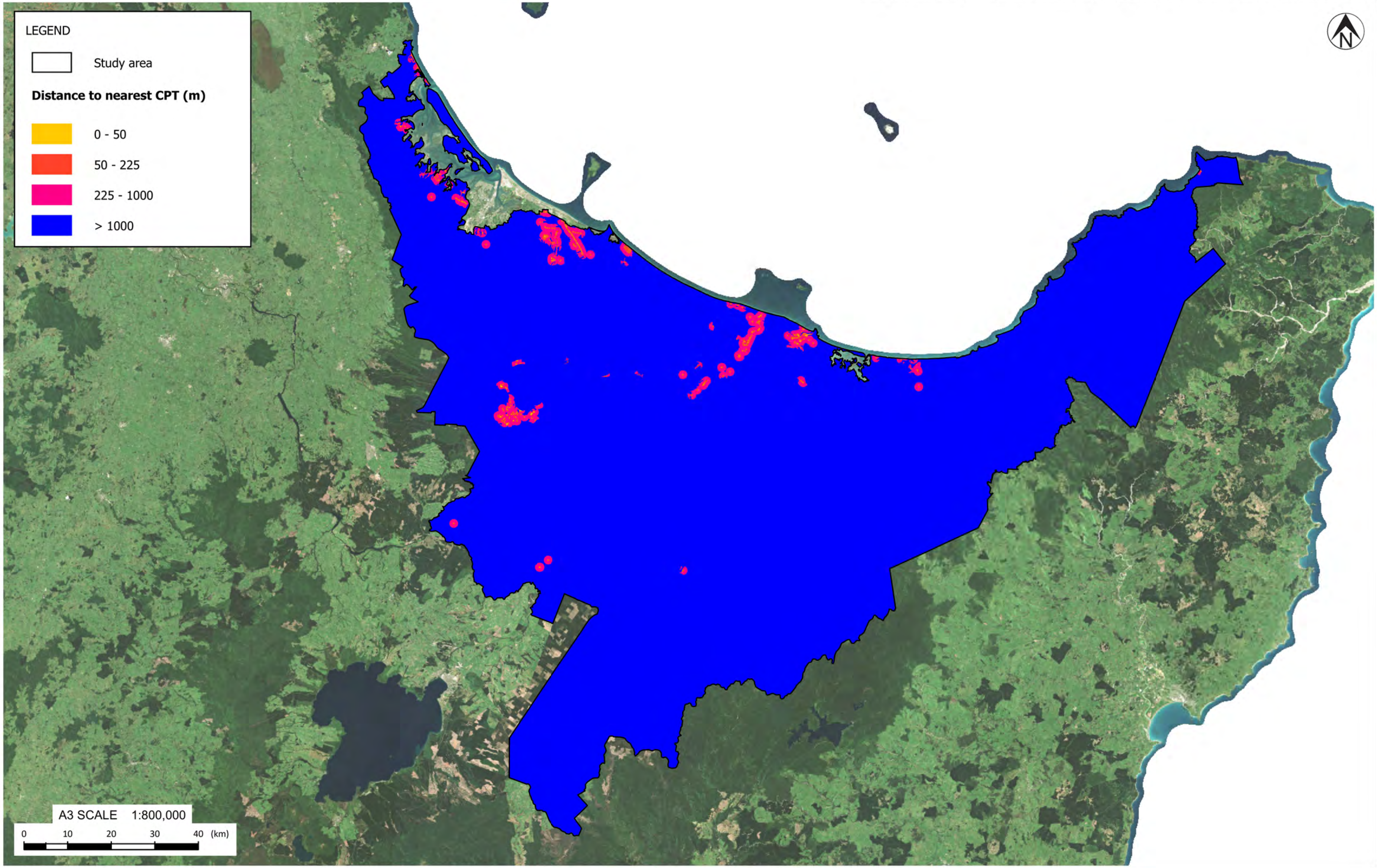


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PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE DISTANCE TO THE NEAREST CPT WITHIN THE SAME GEOMORPHIC TERRAIN

SCALE (A3) 1:800,000 FIG No. FIGURE A9 REV 0

# Appendix B: Risk analysis

- **Figure B1 – Earthquake shaking scenarios and estimated return periods**
- **Figure B2 – Liquefaction vulnerability categories**

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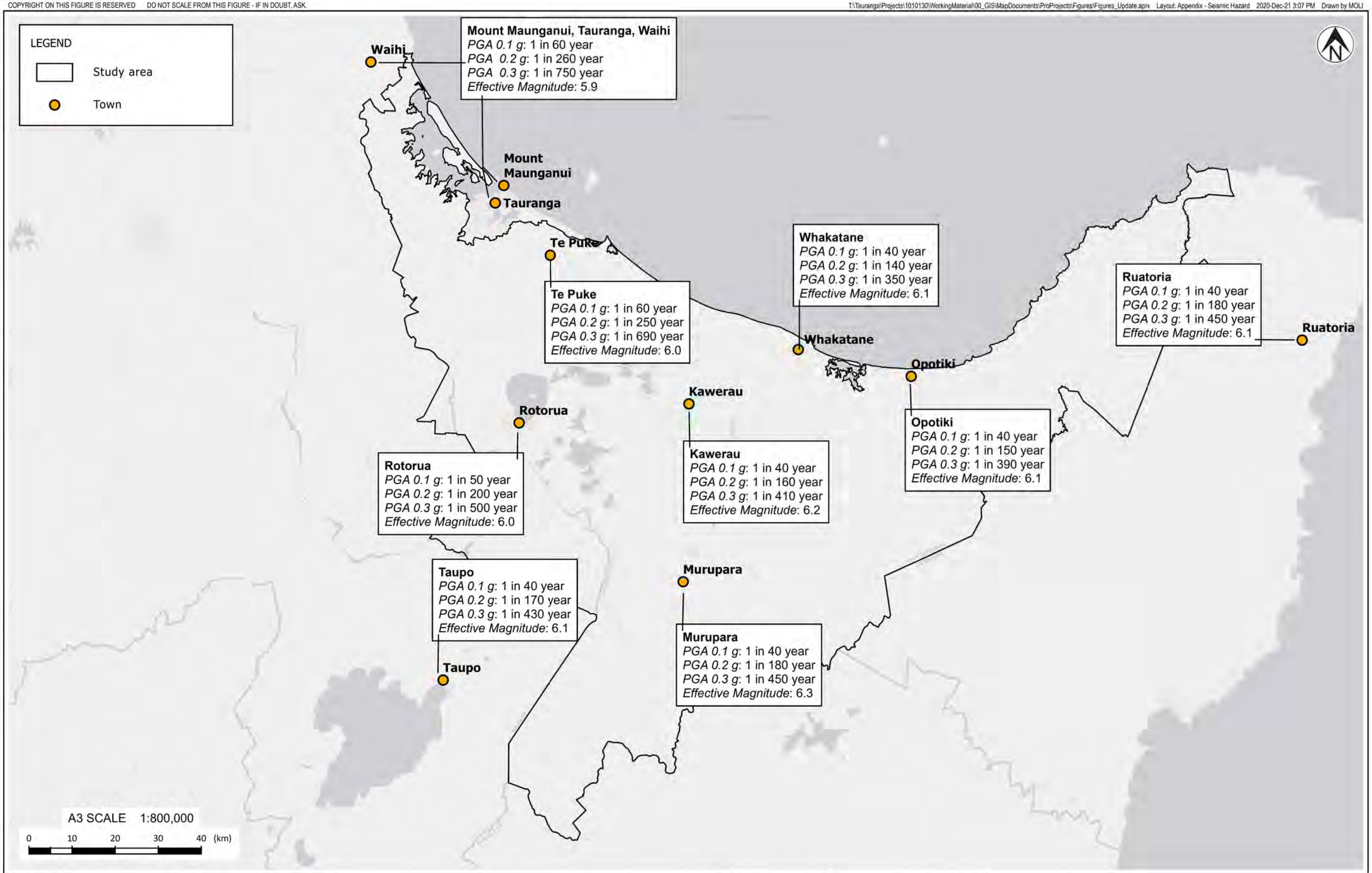


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PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE EARTHQUAKE SHAKING AND ESTIMATED RETURN PERIODS (BASED ON NZTA BRIDGE MANUAL METHODOLOGY)

SCALE (A3) 1:800,000 FIG No. FIGURE B1 REV 0

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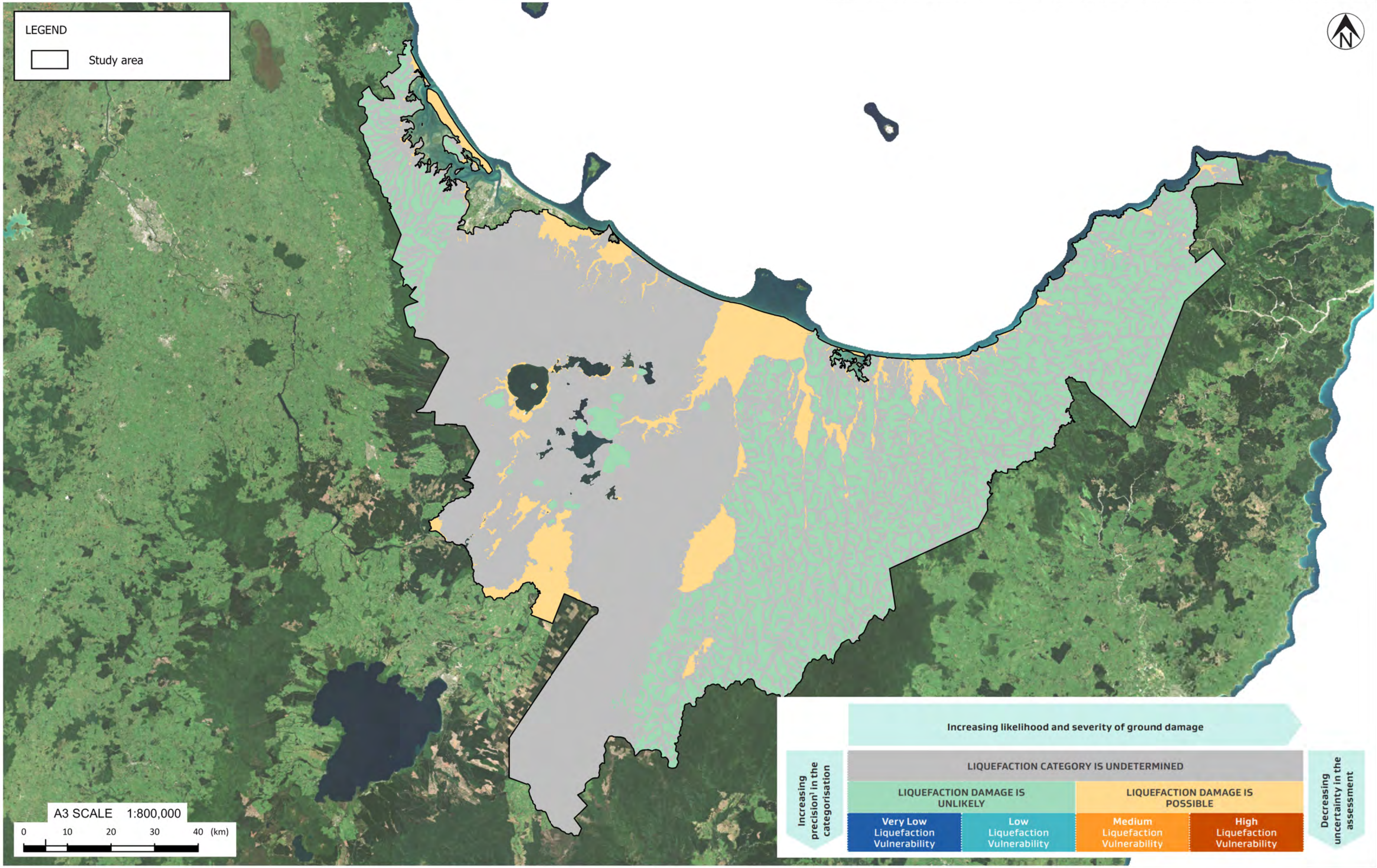


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PROJECT REGIONAL LIQUEFACTION HAZARD ASSESSMENT
TITLE LIQUEFACTION VULNERABILITY CATEGORIES

SCALE (A3) 1:800,000   FIG No. FIGURE B2   REV 0 www.tonkintaylor.co.nz