Liquefaction Vulnerability Study: Lower Wairau Plains

Prepared for:

Marlborough District Council

Prepared by:

Omer Atlaf, Liam Wotherspoon, Rolando Orense

University of Auckland

Version 1.0

May 2021

SUMMARY

This report summarises the development of liquefaction vulnerability maps for the Lower Wairau Plains in Marlborough based on the ‘Planning and engineering guidance for potentially liquefaction-prone land’ (MBIE/MfE/EQC 2017). The methodology and datasets that were used are summarised in this report and a suite of maps of liquefaction vulnerability categories presented.

Data availability defined the level of assessment detail that was appropriate across the region based on the guidance. At the highest level, this was based on geological, groundwater and seismic hazard data. Geomorphological and basin groundwater geological models were used to further refine this high-level assessment.

The most detailed assessment was based on a cone penetration test (CPT) dataset, and in combination with the seismic hazard and groundwater data provided a quantitative liquefaction assessment for a range of earthquake shaking return period scenarios. Due to the low density of CPT soundings across the region, this approach could not be used to provide more refined liquefaction vulnerability categories. For geomorphic zones where CPT data was available, potential classifications if additional investigations were undertaken are discussed.

Liquefaction vulnerability category maps for Level A and Level B assessments are presented. The age of deposits across the Wairau Plains and the relatively shallow depth to groundwater means much of the area is classified as *Liquefaction damage is possible*. The surrounding hills are classified as *Very low liquefaction vulnerability* and areas with deeper groundwater along the edge of the plains are classified as *Liquefaction damage is unlikely*. The changes in classification between Level A and B are discussed, in particular, the areas where the liquefaction vulnerability of the soil profile is likely dominated by the performance of gravels and where the profile is dominated by the performance of sand and silt deposits. Some alluvial deposits in the plains dominated by gravel are classified as *Low liquefaction vulnerability*, with investigations in this area suggesting an absence of loose sandy deposits. Combining these multiple approaches, regional liquefaction-induced ground damage maps are developed for the Lower Wairau Plains for different levels of investigation detail.

TABLE OF CONTENTS

1 INTRODUCTION

This report summarises a liquefaction vulnerability assessment of the Lower Wairau Plains in Marlborough. The primary objective of this assessment is the definition of the spatial distribution of liquefaction vulnerability across the region. This report includes the following information for the study area:

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

1.1 Scope of work

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

The following data is collated to inform this study:

- Geological and digital elevation model data
- Geomorphological mapping based on surface expression
- Regional groundwater lithology models
- Geotechnical site investigation data
- Groundwater models from hydrologic and geotechnical sources
- Case history evidence of liquefaction manifestation, with a focus on the 2016 Kaikōura earthquake

This data is used to inform the appropriate level of assessment detail across the study area based on the MBIE Guidance. Geological, groundwater and seismic hazard data is used to undertake a high-level assessment. Geomorphological and basin groundwater geological models are used to further refine this high-level assessment.

A cone penetration test (CPT) dataset is used along with the seismic hazard and groundwater data to provide an assessment of the liquefaction hazard for a range of earthquake shaking return period scenarios. CPT soundings in each geomorphic zone are grouped together to provide an indication of the representative performance of the soils in these areas. Where possible, observations from the 2016 Kaikōura earthquake are used to further inform the CPT-based liquefaction assessment.

The output of this scope of work is the report presented herein and a suite of maps of liquefaction vulnerability categories for the study area.

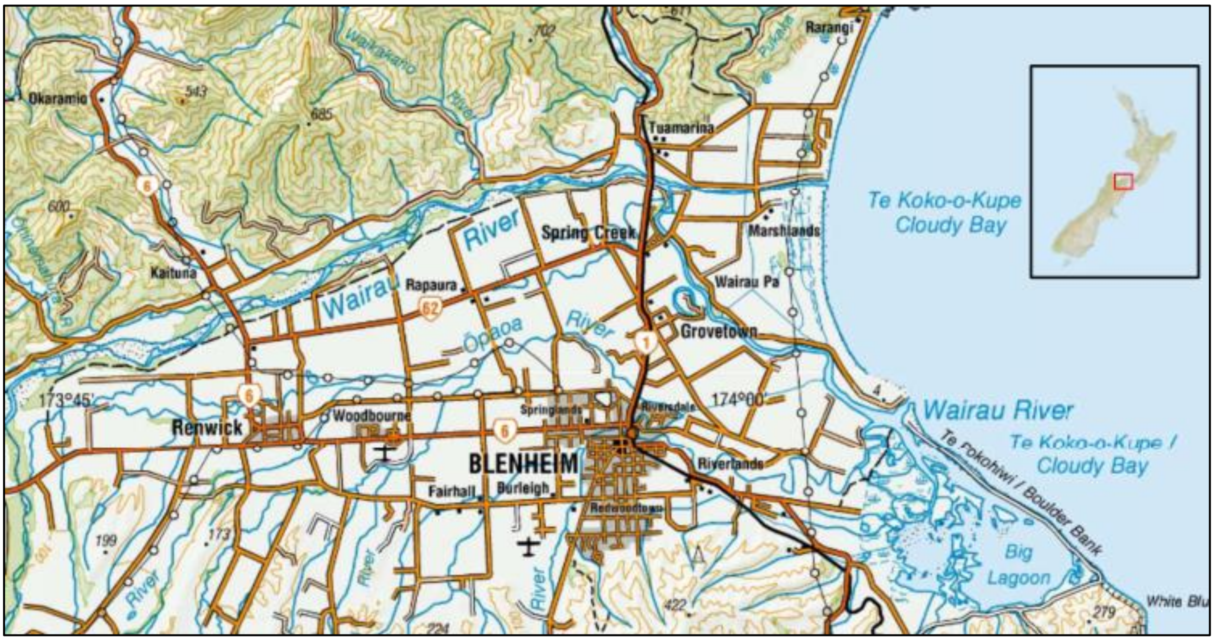


Figure 1: Geographic location of the Lower Wairau Plains and extent of the study area.

2 METHODOLOGY

In order to develop liquefaction vulnerability categories for the Lower Wairau Plains, the methodology presented in the MBIE Guidance summarised in Figure 2 is applied. Liquefaction vulnerability categories are based on performance criteria that relate a category to the probability of different levels of liquefaction-induced ground damage severity for a given return period of ground shaking.

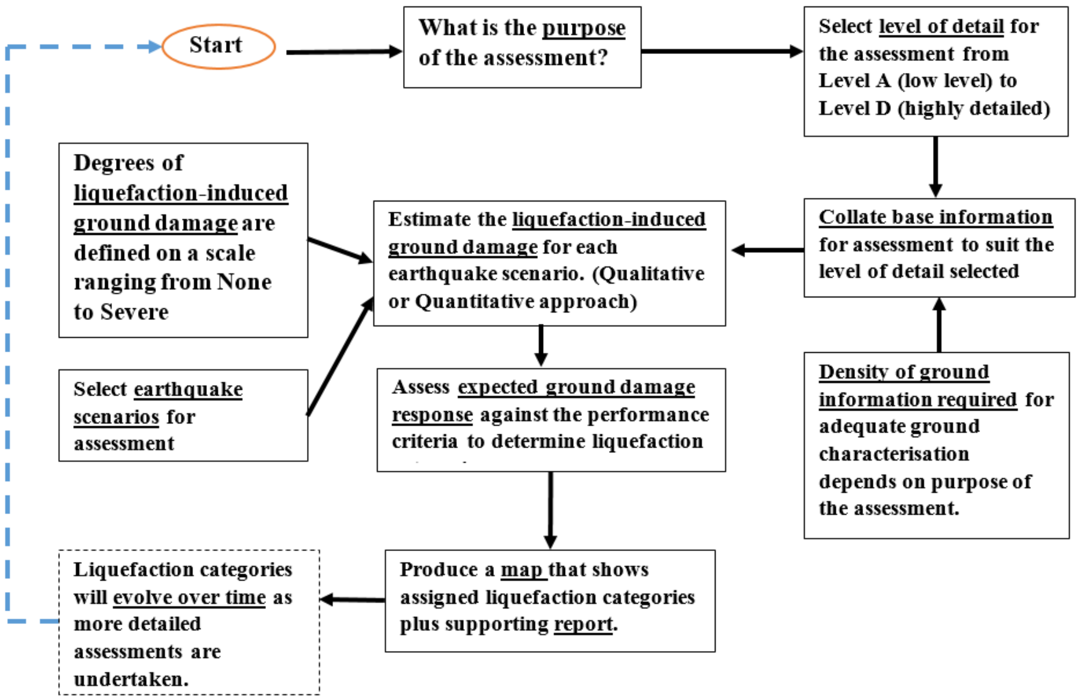


Figure 2: Overview of the recommended process for categorizing the potential for liquefaction-induced ground damage (MBIE/MfE/EQC 2017).

The first step in this methodology is the definition of the level of detail for the assessment so that the required level of data and resources can be defined. Figure 3 summarises the different levels of detail of the liquefaction assessment approaches from the MBIE Guidance. Three levels of assessment are discussed in this study: Level A, B and C. Level A is a basic desktop assessment, Level B is a calibrated desktop assessment and Level C is a detailed region-wide assessment. These are discussed in more detail in the following sections.

The liquefaction vulnerability categories (referred to as category or categories througout this report) assigned in each level of assessment are summarised in Figure 4. As the spatial density of available information increases, the precision of categorisation can increase. The default vulnerability category is *Liquefaction Category is Undetermined*. This is assigned to areas where a liquefaction assessment has yet to be undertaken, or if there is not enough information to define an appropriate category. The remaining categories are defined based on the probability of different ground damage severities for a 500 year return period ground shaking, and in some cases, 100 year return period ground shaking. When undertaking a liquefaction assessment using a desktop approach, it is typical to first focus on whether *Liquefaction damage is unlikely*, where there is a greater than 85% probability of none-minor ground damage for a 500-year return period level of ground shaking, *or Liquefaction damage is possible*, where there is a greater than 15% probability of minor-moderate ground damage for a 500-yearreturn period level of ground shaking. For Level A and Level B assessments, it is often not possible to assign liquefaction vulnerability categories with any more precision than this. In some cases a more precise category can be assigned with confidence, such as a *Very Low* category for exposed rock outcrops. Level C assessments can shift the classification to more the refined categories of *Very Low*, *Low*, *Medium* and *High* for areas where a high spatial density of site investigation data is available. The details of these are discussed in subsequent sections of the report.

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

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

Increasing level of detail and decreasing degree of uncertainty

*Figure 3: Levels of detail for liquefaction assessment studies (*MBIE/MfE/EQC 2017*).*

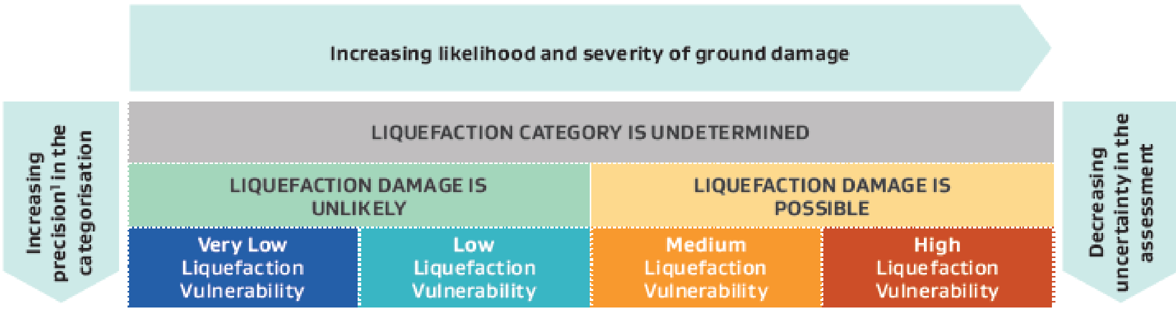


*Figure 4: Recommended liquefaction vulnerability categories for use in liquefaction assessment studies to inform the planning and consenting process (*MBIE/MfE/EQC 2017*).*

2.1 Level A assessment

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

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

$$MSF = 6.9 \exp\left(\frac{-M_w}{4}\right) - 0.058 \qquad \text{up to a maximum value of 1.8.}$$

For regions where the design moment magnitude is less than 7.5, the limits for a M_w7.5 in Table 1 is multiplied by the MSF to get the limits for an equivalent earthquake.

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

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

2.2 Level B assessment

The Level B assessment is a calibrated desktop assessment, where the details from the Level A assessment are further refined using additional datasets that can further clarify the subsurface characteristics and potential land performance. Qualitative assessment using simple screening criteria based on geomorphology can identify areas where there is potential for liquefaction induced ground damage to occur, or the landform suggests it may have occurred. Any other regional information on subsurface deposits can inform the calibration of the liquefaction vulnerability categories, such as subsurface investigation data or models derived from this data.

2.3 Level C assessment

The Level C assessment is a detailed area-wide assessment based on cone penetration test (CPT) soundings and applies a quantitative approach. These CPT soundings from across the region are used to estimate the degree of liquefaction-induced ground damage for a range of peak ground accelerations (PGA) and earthquake magnitudes that are representative of the seismic hazard across the region.

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

One of the key aspects of a quantitative liquefaction assessment is understanding the correlation between the results of liquefaction analysis and the ground damage that is likely to occur. As outlined in the MBIE Guidance, when assigning liquefaction vulnerability categories for an area-wide hazard assessment it is important to account for the uncertainties within the assessment, and the potential consequences of over-estimating or under-estimating the liquefaction vulnerability.

When there is not a high enough spatial density of CPT soundings from across a region to inform an overall Level C assessment, the outputs can be used to classify small areas where the density of investigations is adequate. These outputs can also be fed back into the calibrated desktop assessment if the level of certainty is not high enough to inform the *Very Low – High* vulnerability categories.

Observations from the 2016 Kaikōura earthquake are used in this report to assess the CPT-based liquefaction assessment. The work of Ogden (2018) highlights locations where these CPT based methods are able and unable to predict the manifestation in the Kaikōura earthquake. The CPT based classification is discussed in the context of these observations of the performance of soil profiles in the region.

3 GROUND CONDITIONS

3.1 Geology

The Lower Wairau Plains are located in the north-east of the South Island of New Zealand in the region of Marlborough. The region is intersected by many active crustal faults such as the Wairau, Awatere, and Clarence Faults (Rattenbury et al. 2006). The Lower Wairau Plains are predominantly flat to gently undulating alluvial plains, underlain by Holocene age marine and estuarine silts and sands of the Dillons Point Formation, and alluvial gravels and sands of the Rapaura Formation. The soils of the Dillons Point Formation are observed to vary significantly in their composition and degree of consolidation, varying between loose sands and soft silts to very dense sands and very dense clayey silts (MDC 2012). The alluvial sediments to the eastern margin of the Wairau Plains are inter-fingered with lagoonal muds and coastal sands, silts, and gravels which reflect coastline progradation and marine regression following the mid-Holocene high stand 6,000 years ago (Basher 1995). As shown in Figure 5, near-surface sediments present in the Lower Wairau Plains towards the coast are postglacial swamp, lagoonal estuarine and beach deposits that overlie fluvial and glacial outwash deposits. Figure 6 summarises the surface geological deposits present in the Lower Wairua Plains.

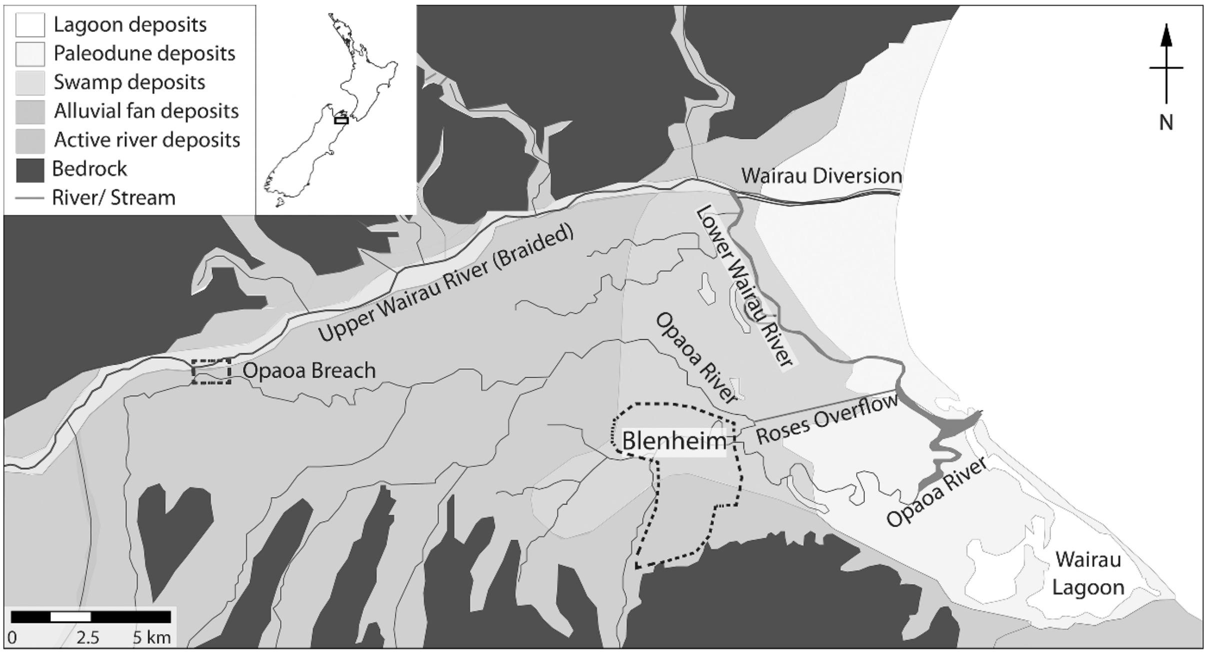


Figure 5: Near-surface sediments present in the Lower Wairau Plains (Basher et al., 1995).

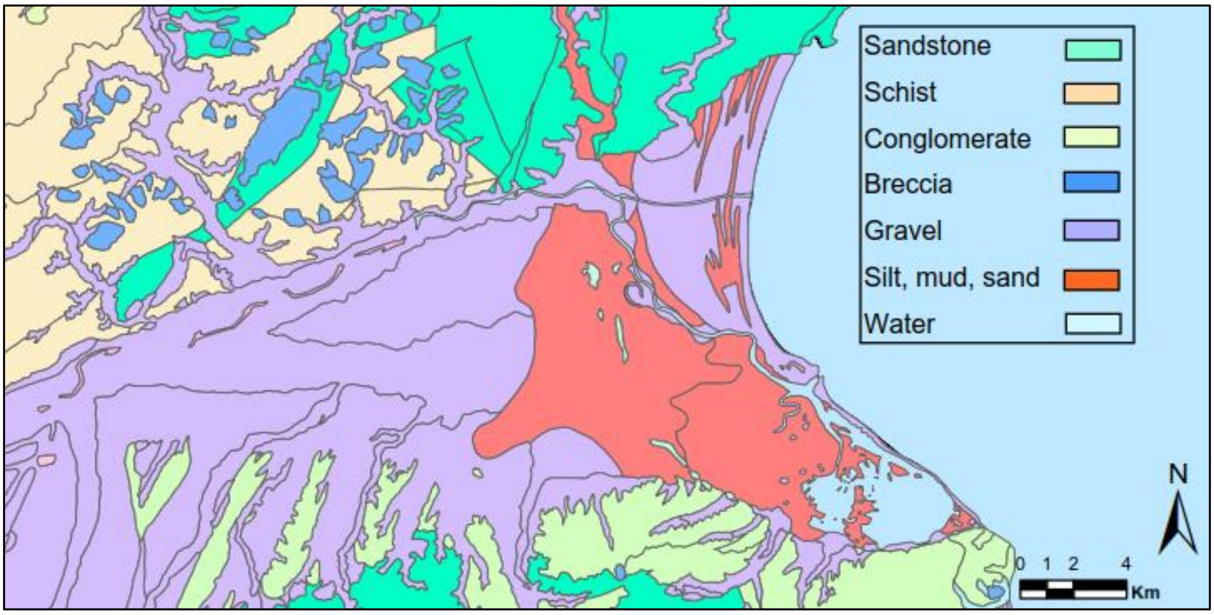


Figure 6: Surface geologic map of the Lower Wairau Plains.

3.2 Geomorphology

For liquefaction assessment of the Lower Wairau plains, the Marlborough District Council commissioned Beca Ltd to prepare a revised geomorphic map of the region and extend the initial geomorphic map of the coastal portion of the Lower Wairau Plains presented in Bastin et al., (2018). Mapping comprised a desktop-based study utilising LiDAR-based Digital Elevation Models (DEM) and aerial imagery, supplemented with the 1:250,000 geologic QMap (Begg and Johnson, 2000), the geomorphic map by Brown (1981) and literature outlining drainage modification and the history of the plains. The morphology of the Lower Wairau and Opaoa Rivers is meandering and is characterised by a single sinuous channel that forms meaner bends. The geomorphic map for the lower portion of the Lower Wairau Plains is presented in Figure 7. The level of detail and classifications of the mapped geomorphic features were selected to inform the liquefaction assessment. Mapped features were identified and characterised as follows:

3.2.1 Rapaura Formation

– ***Active flood plain*** consists of the area immediately adjacent to the braided section of the Upper Wairau River and are considered liable to flooding during bank full conditions. Deposits typically comprise alluvial gravel, sands, and silts.

– ***Recent alluvial deposits*** are identified as the low elevation areas immediately adjacent to active rivers and streams and considered liable to flooding during bank full conditions. Deposits to the west of Blenheim typically contain alluvial gravel, sands, and silts while those the east contain alluvial sands and silts.

– ***Proximal alluvial deposits*** are classified as the low elevation areas proximal to rivers and streams, typically separated from the active flood plain by a terrace riser. These areas are typically at a lower elevation than the surrounding alluvial plain suggesting re-working by the proximal river or stream. Subsurface deposits likely comprise predominantly gravels to the west of Blenheim, and alluvial sand and silt to the east.

– Overbank flood plains are subdivided into low, mid- and higher- elevation surfaces and identified as relatively flat surfaces distal to active rivers and streams.

- ***Low elevation over-bank deposits*** consist of areas of low elevation proximal to the meandering Lower Wairau River and containing alluvial landforms such as paleo-channels. Subsurface deposits likely comprise alluvial sand to silt deposited during overbank floods of the Lower Wairau River and associated tributaries. The area is indicated in the 1:250,000 QMap as comprising swamp deposits.
- ***Mid-*** and ***Higher-elevation over-bank deposits*** are identified to the west of Blenheim and likely consist of overbank deposits from the Upper Wairau River and associated tributaries. Subsurface deposits are likely predominantly gravels with localised lenses of sand to silt.

– Paleo-channels are identified as topographic depressions of similar morphologies to the active rivers and streams on the surface of the Plains.

- Paleo-channels in the mid- to higher- elevation flood plains likely contain alluvial gravels, sands, and silts and include the former southern branch of the Wairau River (***Paleo-channels with alluvial gravel, sand and silt***).
- Paleo-channels within the lower elevation flood plain are typically related to cut-off and/or abandoned channels of the meandering rivers and streams. Subsurface deposits likely comprise alluvial sand to silt (***Paleo-channels with alluvial sand, and silt***).

– ***Drained alluvial swamps*** are identified as topographic depressions distal to active rivers and streams and consist of areas where water would pool following over-bank flood events and/or heavy rainfall. Subsurface deposits likely comprise alluvial sands to silts and possibly organics.

– ***Alluvial fans*** are identified as higher elevation surfaces at the mouths of valleys containing tributary streams/ rivers, such as the Taylor River. Landforms are generally semi-circular and decrease in elevation away from the mouth of the valley. Subsurface deposits likely comprise alluvial gravels, sands, and silts.

3.2.2 Dillions Point Formation

– Dune/ beach ridges

- ***Active beach ridges*** are identified along the current coastline and are primarily composed of well sorted fine to coarse gravel.
- ***Gravel beach ridges*** are recognised as raised linear landforms orientated parallel to the existing coastline and extending approximately 5.5 km inland from the active coastline. Brown (1981) indicates that the deposits comprise well sorted fine to coarse gravel.
- ***Inter-dune swamps*** are identified in topographic depressions between the gravel beach ridges and locally contain standing water. Subsurface deposits likely comprise sand to silt.
- ***Sandy beach dunes*** consisting of linear landforms orientated parallel to the existing coastline are identified from approximately 5.5 to 7 km inland in the area north of the Wairau Lagoon. The features exhibit less prominent topography than the gravel ridges and likely consist of well graded sand to silt.

– Lagoon deposits

- ***Active lagoon deposits*** are identified in the aerial imagery as areas of mud to silt within the Wairau Lagoon. These areas may be underwater during high tide and/or storm events.
- ***Recent lagoon deposits*** are identified as vegetated low elevation areas immediately adjacent to the Wairau Lagoon. The aerial imagery indicates that the vegetation comprises short grasses typical of marshy settings. Subsurface deposits likely comprise loosely consolidated mud to silt.
- ***Mid-elevation paleo-lagoon deposits*** are identified as low elevation areas immediately inland from the Wairau Lagoon where beach ridges/ dunes were not observed. Subsurface deposits likely comprise mud to silt.
- ***Higher-elevation paleo-lagoon deposits*** are identified further inland from the existing Wairau Lagoon and adjacent to the Sandy beach dune deposits. Paleo-channels crosscut the surficial deposits suggesting that the deposits are overlain by alluvial silts.
- ***Alluvially re-worked lagoon deposits*** are identified on the inside of meander-bends of the Lower Wairau River where the river intersects the recent lagoon deposits. Landforms including scrollbars suggest the deposits have been alluvially re-worked.
- ***Active lagoon swamps*** are identified as topographic depressions within the recent lagoon deposits and locally contain standing water. Subsurface deposits likely contain muds to silts with accumulations of organics possible.

3.2.3 Speargrass Formation

This formation is identified as a relatively flat surface on the Plains that is separated from the Rapaura Formation by a degradational terrace. Extents of the surface were inferred from areas of consistent elevations and from the lack of evidence of recent fluvial re-working, such as paleo-channels.

3.2.4 Hillersden Gravel

These are present on the higher hillslopes in the south-east of the study area, as indicated in the geologic map of the region (Begg and Johnson, 2000). Deposits consist of Neogene poorly sorted and poorly bedded channelized greywacke conglomerate with lenses of sandstone and sandy siltstone. Deposits are identified from the mapped distribution in the geologic map and from the 'rolling' topography.

3.2.5 Colluvium deposits

These deposits are inferred from a step change in topography at the base of hillslopes and within valleys along the northern margin of the Plains. These deposits likely comprise gravel, sand, and silt washed off the surrounding hillslopes.

3.2.6 Marlborough Schist

Marlborough Schist is indicated in the geologic map of the region (Begg and Johnson, 2000) as present on the hillslopes along the northern margin of the valley. The unit comprises basement rock of dominantly pelitic schist derived from quartzofeldspathic sandstone and mudstone.

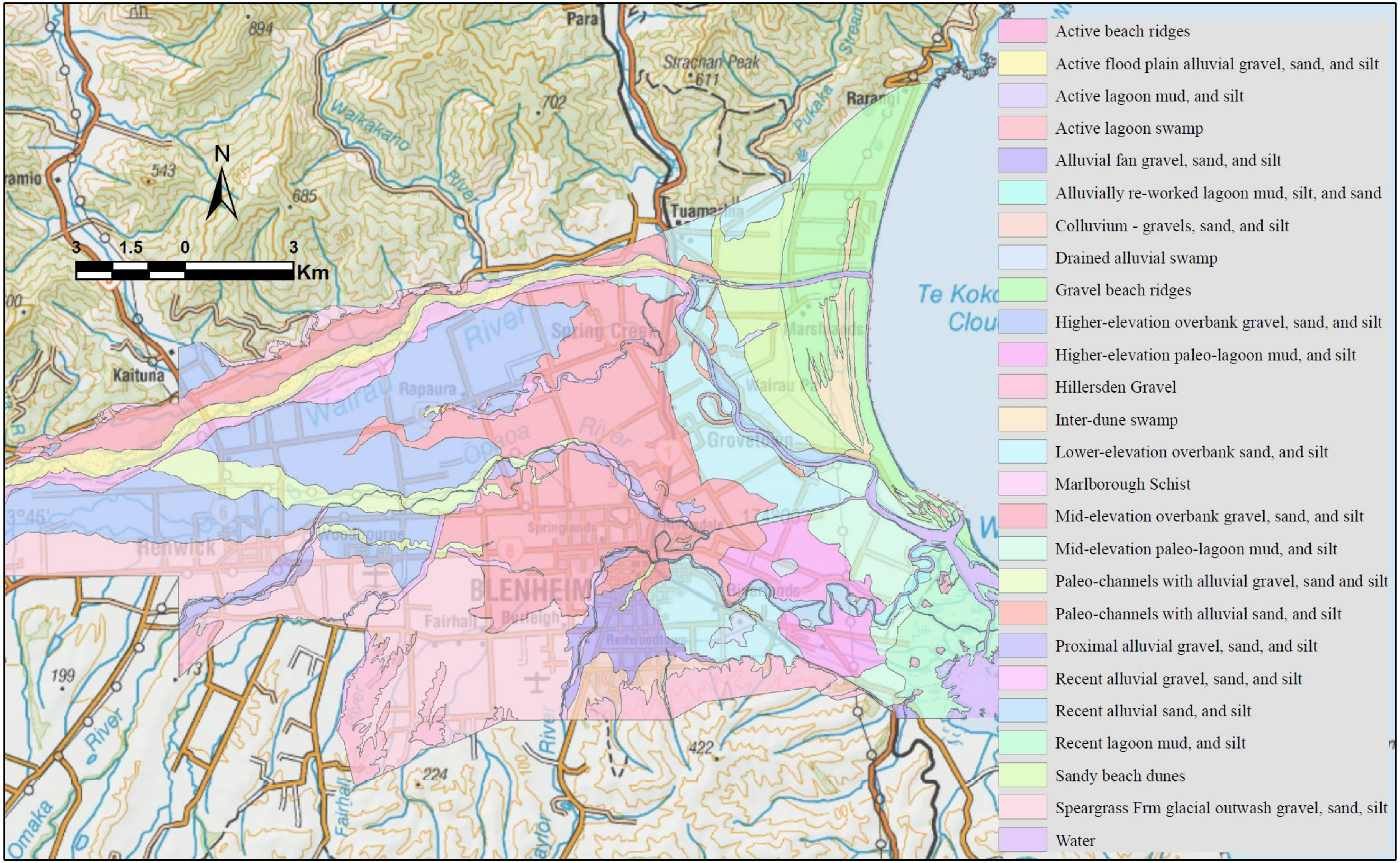


Figure 7: Geomorphic map of the Lower Wairau Plains.

3.3 Groundwater

The study of Davidson & Wilson (2011) provides a thorough description of the groundwater regime of the Lower Wairau Plains. Similarly, the groundwater model developed by Ogden (2018) indicates that GWD was approximately 2 m below ground level for much of the coastal parts of the plains and flows from west to east.

Figure 8 illustrates the median groundwater depths summarised from the available groundwater information for the region. The depositional age of the geologic deposits are also summarised in this figure. The depth increments are aligned with the depth limits used in the semi-quantitative screening criteria in Table 1, where deposits of different depositional ages can be assigned a liquefaction vulnerability category of *Liquefaction damage is unlikely*.

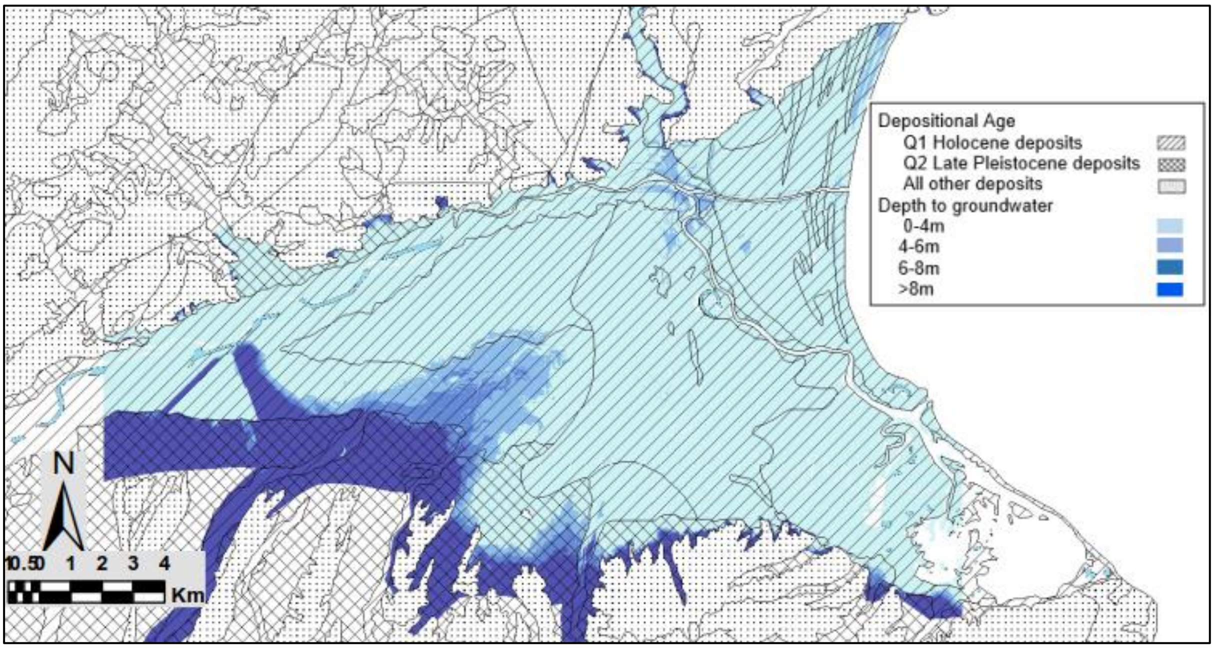


Figure 8: Median groundwater depths for the Lower Wairau Plains and depositional age of deposits.

Recently, MDC has updated the depth to static water level field for each well in the MDC Wells & Sediments database where an observation is available. Figure 9 shows that updated depth to static ground water overlaid the current ground water model used in this study. The same colours are used for the range of ground water depths for both model and static ground water observations for comparison. This shows a good agreement between the model and the observations of static ground water in the region, meaning that it can be used with confidence in this study.

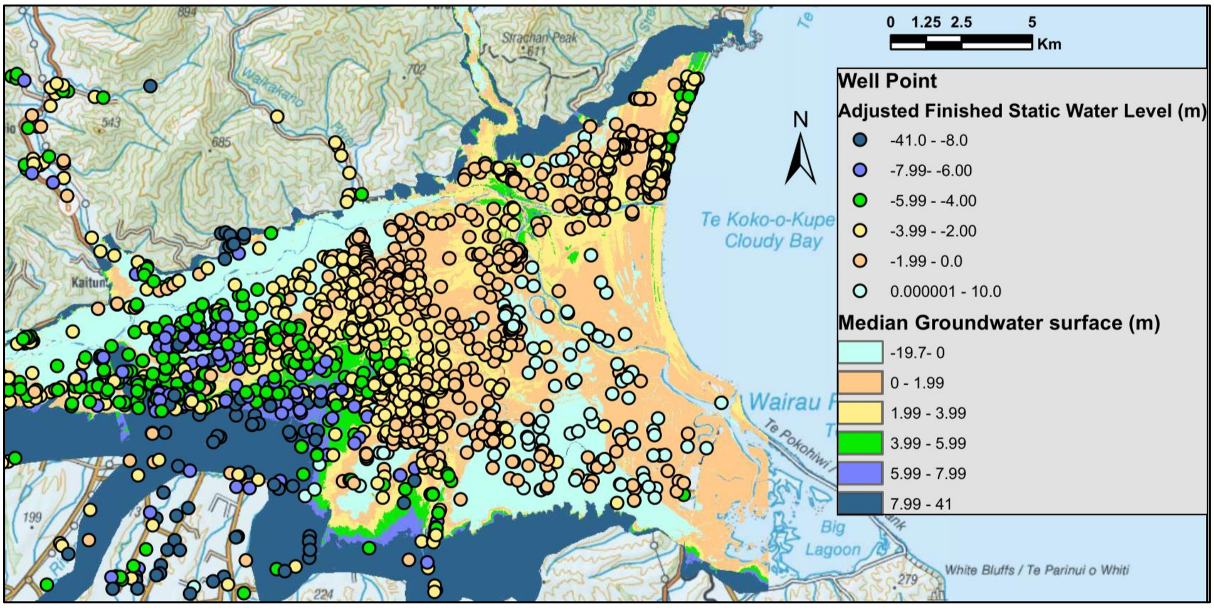


Figure 9: Depth to static water table laid over the current water table model used.

4 SEISMIC HAZARD

The plate boundary between the Pacific and Australian plates passes through the Marlborough region, and consequently, this region is an area of high seismicity. The Marlborough region consists of a series of northwest-tilted blocks forming mountain ranges, hills and drowned valleys separated by major translucent faults such as Wairau, Awatere and Clarence Faults, each of which can give rise to frequent seismic events. The Wairau Fault, which is a branch of Alpine Fault, divides Marlborough into two regions with divergent geological structures. The Wairau Plains are bounded by north-east trending mountain ranges (Richmond and Kaikoura Ranges) reflecting uplift along the Wairau and Awatere Faults which are part of the Marlborough Fault Zone (MFZ). This is a zone of north-east trending transpressional faulting associated with the offshore transition of the plate boundary (Rattenbury et al. 2006). The Wairau Fault is the closest active fault and is capable of rupturing in an earthquake event. Figure 10 shows the location of faults in the Marlborough region.

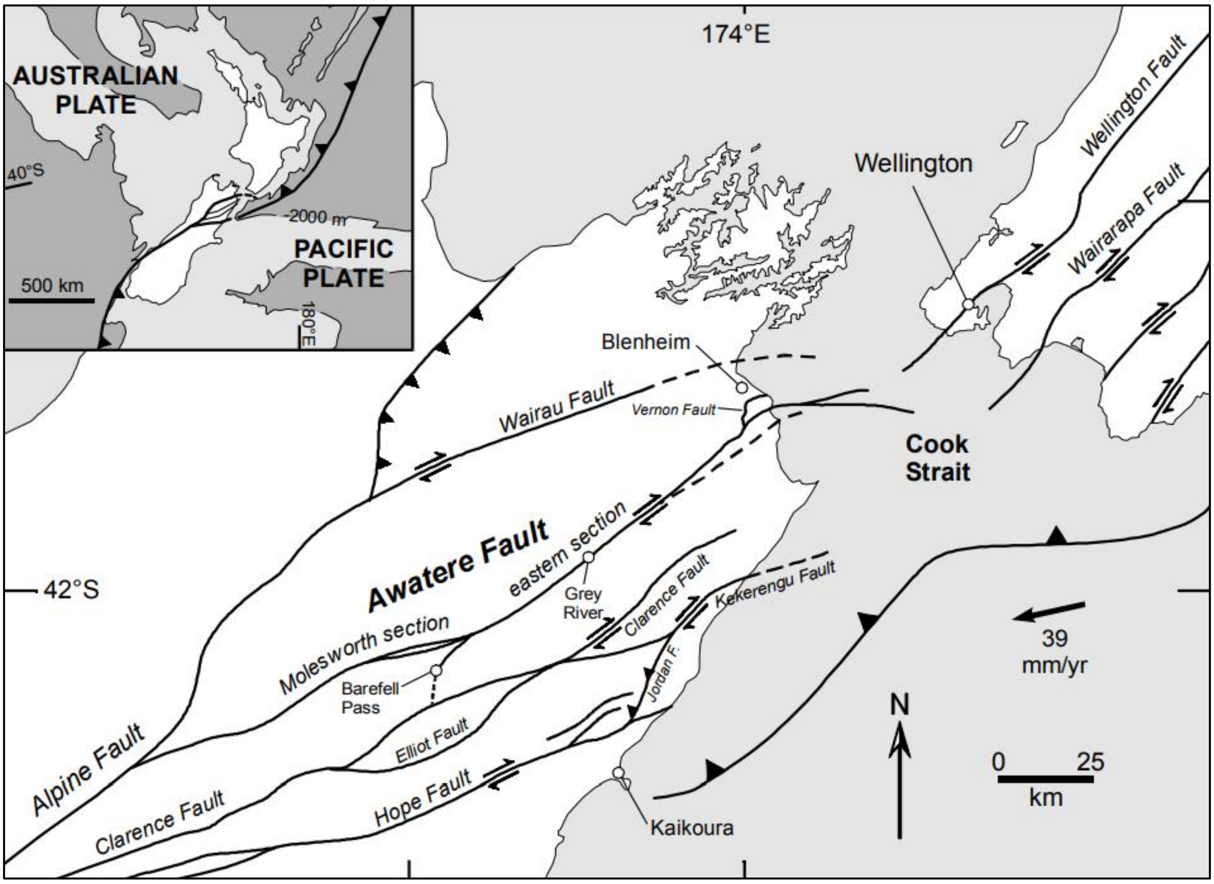


Figure 10: Location of the faults in the Lower Wairau Plains and the Marlborough Fault system (Adapted from Benson et al. 2001).

MBIE Guidance recommends the assessment of liquefaction-induced ground damage for different return periods of ground shaking intensity to categorize liquefaction vulnerability.

Peak ground acceleration (PGA) and earthquake moment magnitude (M_w) can be defined based on the New Zealand Transport Agency Bridge Manual SP/M/022 (NZTA 2013). The PGA is calculated using the following equation:

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

where:

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

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

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

g = the acceleration due to gravity (9.81 m/s^2)

A recent study by Cubrinovski et al. (2021) has identified revised PGA and Mw estimates across New Zealand based on site-specific probabilistic seismic hazard analysis, with the estimates from the Bridge Manual shown to underestimate the hazard in the Wairau Plains. Based on this updated study, the design PGA for the Lower Wairau Plains is 0.26g for a 100-year return period and 0.52g for a 500-year return period. The moment magnitude for each return period was M_w 6.8 and M_w7.3, respectively.

When applied to the semi-quantitative criteria from Table 1, the PGA values from the 500-year return period are scaled using MSF of 1.05. Table 2 summarises the revised PGA boundaries for a M_w7.3 earthquake for the semi-quantitative criteria to inform liquefaction vulnerability categories.

Table 2: Semi-quantitative screening criteria for identifying land where liquefaction-induced ground damage is unlikely for M_w7.3 (MBIE/MfE/EQC 2017).

Type of soil deposit	**A Liquefaction Vulnerability category of *Liquefaction damage is unlikely* can be assigned if either of these conditions are met:**	
	Design peak ground acceleration (PGA) for the 500-year intensity of earthquake shaking	**Depth to groundwater**
Late Holocene age Current river channels and their historical floodplains, marshes and estuaries, reclamation fills	< 0.105 g	> 8 m
Holocene age Less than 11,000 years old	< 0.21 g	> 6 m
Latest Pleistocene age Between 11,000 and 15,000 years old	< 0.315 g	> 4 m

5 OBSERVATIONS FROM 2016 KAIKŌURA EARTHQUAKE

Liquefaction has manifested in the Lower Wairau Plains following a number of earthquakes that generated significant ground shaking over the region, including the 1848 Marlborough and 1855 Wairarapa earthquakes, and most recently the 2013 Lake Grassmere and 2016 Kaikōura earthquakes. These manifestations have either been the ejection of fine-grained sand and silt in the form of sand boils, or if in close proximity to a free-face such as a river bank, the development of lateral-spreading.

Strong to severe shaking was felt across the Marlborough region during the Kaikōura earthquake. All Marlborough communities were subjected to earthquake damage. The main impact was to buildings, farm assets, horizontal infrastructure, river control works, the transportation networks and water supply networks. There are two strong motion stations (SMS) in the Lower Wairau Plains that record earthquake shaking as part of the GeoNet network. BWRS is a rock site on the edge of the Plains and MCGS is a deep soil site in Blenheim. The geometric mean horizontal peak ground accelerations recorded at these SMS were 0.15 g and 0.26 g, respectively. Across the Wairau Plains, peak ground accelerations would be expected to be slightly greater than 0.26 g moving towards the south-east of Blenheim, and would reduce moving to the west and north.

Post-earthquake reconnaissance surveys, aerial photography, and discussions with local engineers and the Marlborough District Council provided a comprehensive summary of the liquefaction related impacts and manifestations in the Wairau Plains following the 2016 Kaikōura earthquake. These are summarised in detail by Stringer et al. (2017) and in GEER (2017). Within the Wairau Plains, liquefaction and lateral spreading was the major feature of ground damage and was largely observed along the Lower Wairau and Opaoa Rivers. Figure 10 shows the location of manifestations of liquefaction in the region from this event. Severe manifestations were recorded in the area of the Equestrian Park and the Blenheim Rowing Club but as very few buildings are present in these areas, the engineering impacts were generally low. Some moderate liquefaction manifestations were observed in a few locations within Blenheim, but these again had limited impact. Localised liquefaction and associated lateral spreading occurred proximal to the Opaoa River within Blenheim as shown in Figure 11. Liquefaction and lateral spreading related damage was confined to the inner-banks of meander bends of the rivers or associated paleo-channel, with damage was observed on the outer-banks of the meander bends. Localised manifestations were also occurred adjacent to the Taylor River within central Blenheim. Sand boils were observed at Lansdowne Park which is located adjacent to the southern bank of the Opaoa River on the northern edge of Blenheim (Stringer et al. 2017, GEER 2017).

The observed distribution of liquefaction manifestations in this event further reinforces that fluvial geomorphology and the depositional processes of the meandering rivers are important factors for the interpretation of the distribution and sediment types in areas which are susceptible to liquefaction.

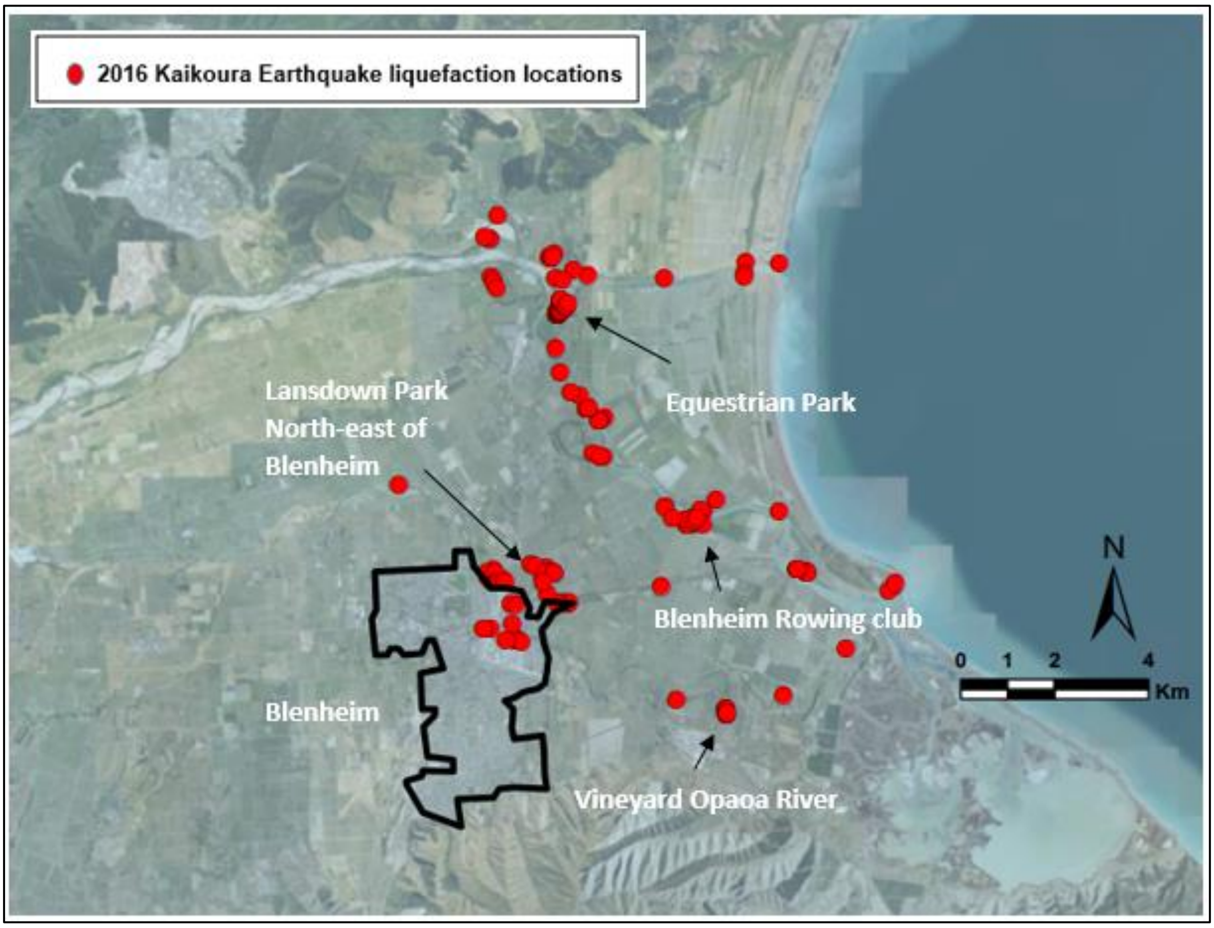


Figure 11: Locations of liquefaction manifestation from the 2016 Kaikōura Earthquake.

6 BASIC DESKTOP ASSESSMENT

In this section liquefaction vulnerability categories are defined using the Level A calibration approach based on geological maps, groundwater and seismic hazard for the Lower Wairau Plains following the MBIE Guidance.

A geological desktop assessment is undertaken based on published national and regional surface geological maps and reports to characterise liquefaction. Q-Maps developed by GNS Science are used to create geological layers for the Lower Wairau Plains. The output of this initial assessment is a geology-based liquefaction vulnerability map illustrating areas in the Lower Wairau Plains with deposits for which *Liquefaction damage is possible* and *Liquefaction damage is unlikely*. Where rock outcrops are present, a *Very Low* liquefaction vulnerability category is assigned. The primary aim of this initial screening is to identify geological units that are fundamentally not susceptible to liquefaction.

By considering the regional seismic hazard and depth to groundwater, in conjunction with the depositional process and the age of soil deposits, the semi-quantitative screening criteria in Table 2 is used to identify geological units where significant liquefaction-induced ground damage is unlikely to occur. A soil deposit of the specified type is assigned a liquefaction vulnerability category of *Liquefaction damage is unlikely* if the 500-year peak ground acceleration (PGA) is less than the limit for the age of that deposit, or if the depth to groundwater is greater than the limit presented.

Geological age is one of the main factors in the semi-quantitative criteria to assess the liquefaction vulnerability of the deposits, with Figure 12 summarising the geological age associated with each deposit in the study area. Holocene and late Pleistocene deposits are dominant in the Lower Wairau Plains, while the adjacent hills consist of basement rocks of Neogene and Mesozoic ages.

Geological maps show that alluvial deposits of Holocene age become gravel dominated towards the inland regions of the study area, as demonstrated in Figure 13. The liquefaction vulnerability of the soil profile within these alluvial deposits will either be dominated by the performance of gravels or the performance of sand and silt deposits. In general, the gravel dominated deposits are likely to be better performing, and as a result these gravel dominated areas are clearly identified in the maps presented throughout this report.

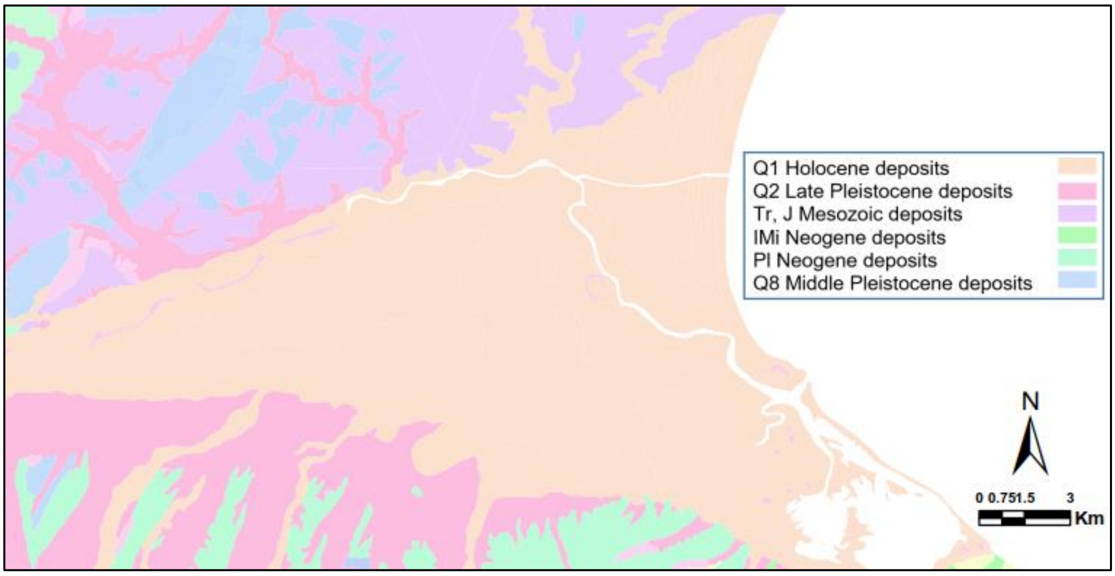


Figure 12: Depositional age of deposits in the Lower Wairau Plains based on geologic maps.

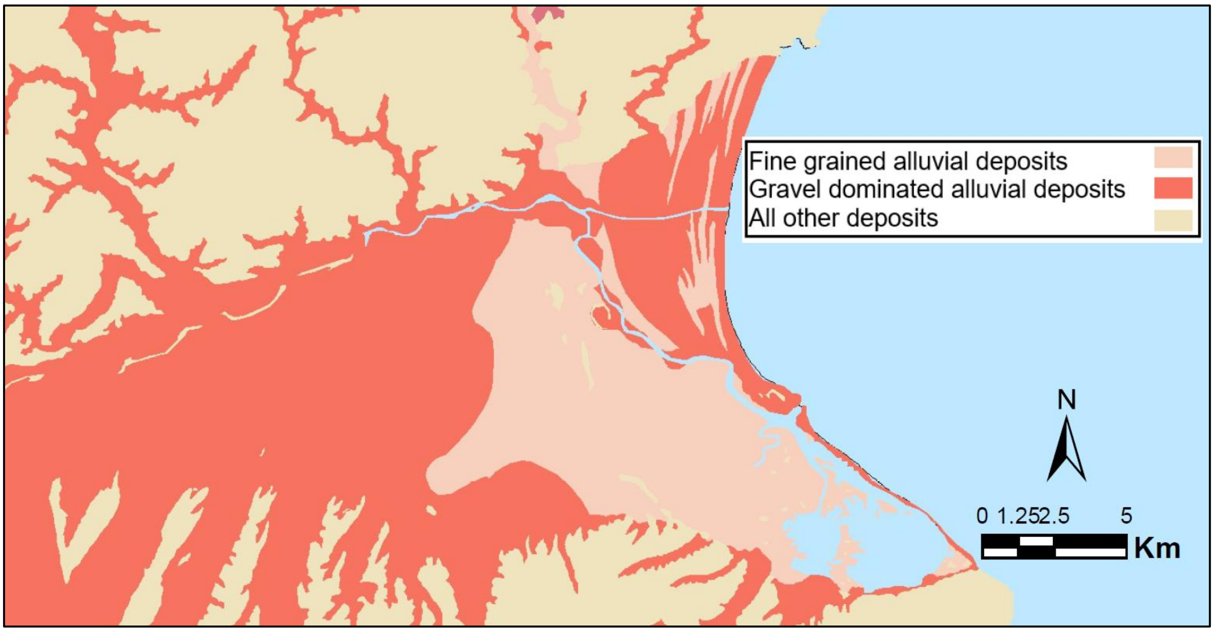


Figure 13: Characteristics of the alluvial deposits in the Lower Wairau Plains based on geologic maps.

The basement, Late Pliocene, and Early Pleistocene rocks present in this region are lithified or relatively well consolidated and will not liquefy under strong ground shaking. Therefore, exposed rock outcrops are assigned a category of *Very Low*. Because of their age, the early and middle Pleistocene non-marine and marine deposits, the last interglacial marine deposits, and the alluvial materials of the early and middle last glaciation are old enough to have been consolidated by natural processes. Their liquefaction susceptibility is typically regarded as negligible (Youd and Perkins 1978).

As defined in Section 4, the 500-year return period PGA value is greater than the cutoff value for Late Pleistocene deposits. As a result, the depth to groundwater is the governing criteria for the liquefaction vulnerability categorisation of deposits of this age. Late Pleistocene deposits with groundwater deeper than 4 m are assigned a category of *Liquefaction damage is unlikely* using the semi-quantitative criteria presented in Table 2.

The remaining deposits in the study region are of Holocene age and include alluvial deposits of fine-grained silts and sands that are present in the Lower Wairau Plains. The nature of the deposits means that *Liquefaction damage is possible* is an appropriate categorisation.

Holocene gravel-dominated deposits are also assigned a *Liquefaction damage is possible* categorisation. There is likely to be better ground performance in these areas compared to other alluvial deposits. Most gravelly soils are relatively well-drained, but drainage can be impeded if their voids are filled with finer particles or if they are surrounded by layers of less pervious soils. As discussed in MBIE Guidance, large-scale geological maps might not identify small pockets of potentially susceptible soils within larger geological units (e.g., infilled river channels). This means that there is still potential for localised areas of more severe liquefaction-induced ground damage to occur within these areas.

Figure 14 summarises the liquefaction vulnerability categories that are assigned to the Lower Wairau Plains based on semi-quantitative geological screening (Level A). The alluvial deposits dominated by gravel based on geologic maps have been highlighted by hatching.

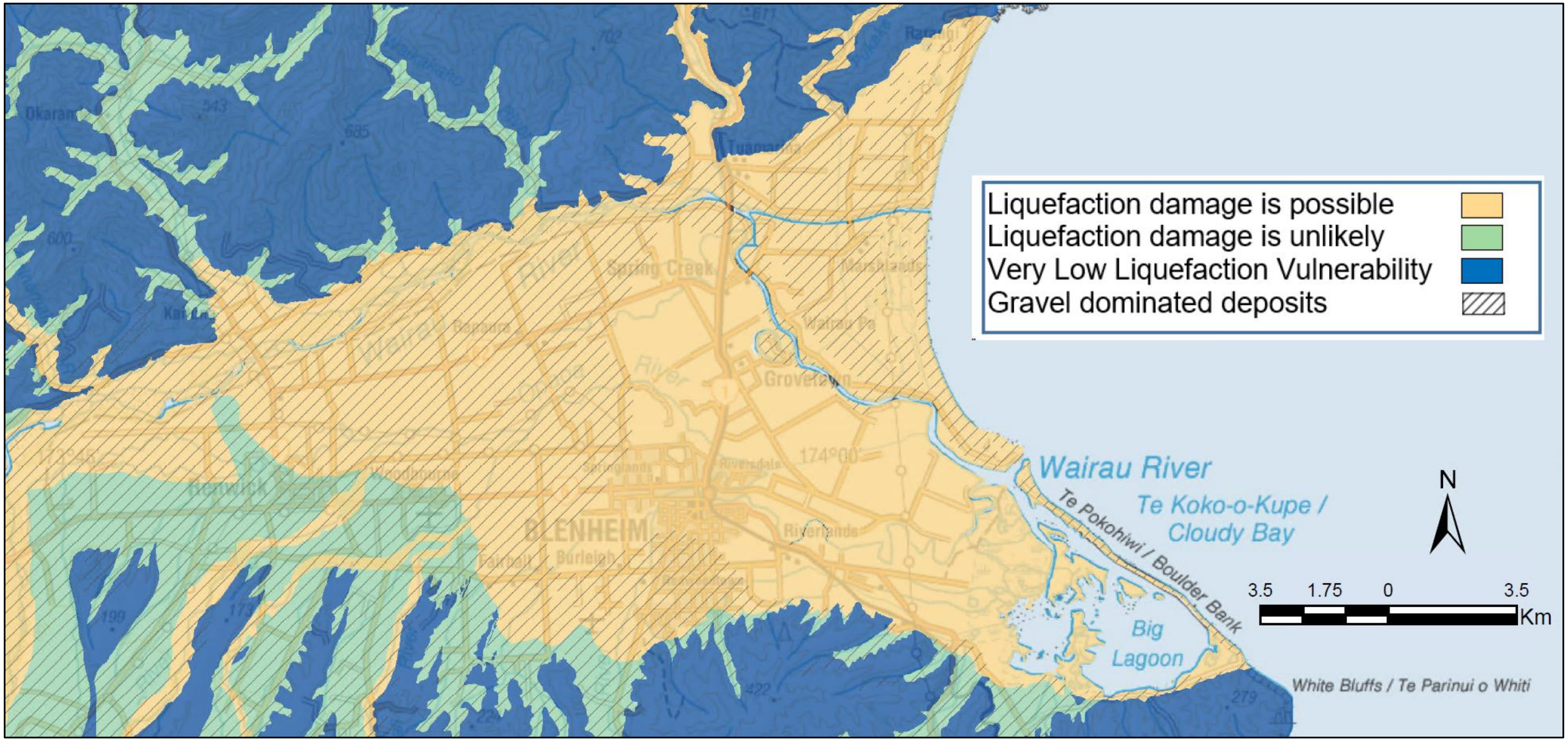


Figure 14: Level A Geology-based liquefaction vulnerability category map for the Lower Wairau Plains.

7 LEVEL B LIQUEFACTION VULNERABILTY ASSESSMENT

In this section, the liquefaction vulnerability categories from the Level A assessment are combined with other datasets in an effort to further refine this categorisation. First, the surface geomorphology of the Lower Wairau Plains presented in Section 3.2 are assessed. Second, details of the subsurface stratigraphy are assessed using a lithology model of the Wairau Plains developed for groundwater modelling. And finally, high-level 'calibration' of geological maps with available geotechnical investigation data, including boreholes, CPTs and well logs for each geomorphic zone is summarised. This approach straddles the Level A and Level B assessment levels. Qualitative assessment provides a better understanding of liquefaction susceptibility and triggering for the mapped deposits and underlying ground profile. It will reduce the uncertainty in areas where existing information is sparse by using the targeted collection of new information.

As significant uncertainty lies regarding the level of related risk, how it varies across each mapped area and the delineation of boundaries between areas, updates on the geology-based liquefaction map is only suggested in areas with a good density of geotechnical investigations as these provide a better understanding of liquefaction susceptibility for the mapped deposits. For example, deposits that were categorised as *Liquefaction damage is unlikely* in the Level A assessment is assigned a liquefaction vulnerability category of *Low* where a thick layer of gravel is present from surface as indicated by geotechnical investigations.. Suggestions are made for each geomorphic zone where a good density of geotechnical investigations are present regarding the liquefaction potential. This section highlights some areas where more robust geotechnical screening with more data needs to be undertaken Although the lithologic model only covers the central and coastal regions of the Plains, it provides an additional check in this level of assessment for thick gravel layers from the surface and confidence in the regions where a more precise liquefaction vulnerability can be suggested.

7.1 Geomorphology-based screening

In addition to surface geologic information, detailed geomorphic characteristics can be used to refine the evaluation of the liquefaction potential of soil deposits. Previous studies have shown that river migration promotes the formation and preservation of fluvial deposits prone to liquefaction, and geomorphic interpretation is a useful tool to assess liquefaction vulnerability for a region. During the Canterbury earthquake sequence, liquefaction and liquefaction-induced ground deformation were primarily concentrated near modern waterways and areas underlain by Holocene fluvial deposits with shallow water tables (< 1 to 2 m) (Wotherspoon et al. 2012, Grace 2015, Bastin et al. 2017). Similarly, a comparison of observed liquefaction manifestation in Whakatane following the Edgecumbe earthquake with local geomorphology highlighted the importance of geomorphic setting and fluvial formations in the assessment of liquefaction (Mellsop 2017, Bastin et al. 2019). Liquefaction manifestation in historical events have shown that young, unconsolidated point-bar and paleo-channel deposits are highly susceptible to liquefaction, and thus are likely to liquefy during future events.

The geomorphology of the Lower Wairau Plains discussed in Section 3.2 is assessed in this section in conjunction with the potential for liquefaction manifestation using literature related to the performance of typical geomorphological formations in recent earthquakes.

7.1.1 Lower elevation overbank gravel, Sand and silt flood plains

Low elevation overbank gravel, sand and silt deposits cover a large portion of the Lower Wairau Plains. These deposits mainly consist of fine-grained sand grading to silt. High groundwater location, low elevation and material characteristics mean these deposits are typically highly susceptible to liquefaction. Surface manifestations were observed in these areas following the 2016 Kaikōura earthquake.

7.1.2 Active floodplain alluivial gravel, sand and silt

The active floodplain of the Wairau River avulsed across the Wairau Plains prior to European settlement, as reflected by the many active and paleo-river channels that transect the surface of the plains. These gravels dominated Holocene deposits typically have less susceptibility to liquefaction than finer grained sand and silts.

7.1.3 Mid-elevation overbank gravel, sand and silt

There is high variability in content for these deposits in the Lower Wairau plains. Deposits which are distal to the river and are typically dominated by silts. The limited deposition on the outer bank and predominance of silts in these deposits typically result in lower liquefaction susceptibilities of the underlying sediments. No manifestation of liquefaction was observed in the 2016 Kaikōura earthquake in these areas. Ground water depth increases from east to west and also the Gravel content increases from low to mid-elevation floodplain deposits making these deposits typically highly dependent on other data in addition to formation to suggest liquefaction susceptibility. Therefore “less susceptibility is considered for these deposits in the Lower Wairau Plains.

7.1.4 Higher elevation overbank gravel, sand and silt

Subsurface deposits for these formations are predominately gravel and ground water depth is deep from mid to higher elevation deposits making these deposits low susceptible to liquefaction.

7.1.5 Alluvial fan gravel, sand and silt

Alluvial fan deposits are present in the southern part of the Wairau Plains. These are well-sorted floodplain gravel deposits. These are a build-up of Wairau River sediments and possesses a sloping high elevation profile with good drainage. As a result, these deposits typically have less susceptibility to liquefaction.

7.1.6 Proximal alluvial gravel, sand and silt

These deposits comprise of fine-grained sand grading to silt. They are found in the meandering Opawa and Wairau River in adjacent deposits. These deposits are geologically young, unconsolidated and saturated, and thus are typically highly susceptible to liquefaction.

7.1.7 Paleo-channels

A paleo-channel is a remnant of an inactive river or stream channel that has been filled or buried by younger sediment. These depoits are shown in two formation types i.e., Paleo-channels with alluvial gravel, sand and silts and Paleo-channels with alluvial sand and silt. The sediments that the old channel is cut into or buried are mostly unconsolidated. Paleo-channels deposits are present across the lower portion of the plains and reflect channel avulsion and bank-overtopping flood events before the settlement of the area. These deposits are geologically young, unconsolidated and saturated, making them typically highly susceptible to liquefaction.

7.1.8 Swamps

Swamps generally form distal to the river in areas where standing water remains following flood events (Fryirs and Brierley, 2012). These are shown as inter-dune swamp and active lagoon swamp in Figure 7 and are comprised of mainly silts with layers of peat and mud. These consist of flat to undulating terraces and floodplains of both Wairau and Opawa Rivers underlain by Holocene sand and silt deposits which makes them typically highly susceptible to liquefaction. During the 2010-11 Canterbury earthquake sequence areas of swamp deposits in Christchurch had significant liquefaction manifestation impacts, whereas CPT based assessments suggested they were less susceptible.

7.1.9 Recent alluvial deposits

These deposits are shown as two types in Figure 7 i.e., recent alluvial gravel, sand and silt deposits and recent alluvial sand and silt deposits. These are late Holocene deposits that are unconsolidated and saturated and typically have a high liquefaction potential.

7.1.10 Lagoon deposits

These deposits are shown as six types in Figure 7:

- Active lagoon mud and silt,
- Mid-elevation paleo-lagoon depoits
- Higher elevation paleo-lagoon deposits
- Alluvially re-worked lagoon mud, silt and sand
- Paleo-lagoon mud and sily and
- Recent lagoon mud and silt

Lagoons are formed at the tidal mouth of a large river, where the river transitions into a marine environment. The deposits from the mainland to the estuary in the northeast towards shoreline and lagoon are silty and gravelly in nature and have high liquefaction potential. Paleo-lagoon have similar soil characteristics and comprise of saturated fine-grained alluvial soils with some gravel content, meaning they are typically highly susceptible to liquefaction. Highly visible and immediate effects of liquefaction were observed in the Avon Heathcote Estuary, which is an intertidal estuary east of Christchurch city forming lagoon deposits, during the 2011 Canterbury earthquake sequence.

7.1.11 Beach ridges

These depoits are shown in three types in Figure 7:

- Active beach ridge,
- Gravel beach ridges and
- Sandy beach ridges

Holocene paleo beach ridge deposits are present in the Lower Wairau Plains and form a series of undulating gravel ridges near the coast. The**se** consist of shallow, well-drained soils that formed from semi-consolidated interbedded sandy and loamy sedimentary beds. Gravel beach ridges are present towards the shoreline are dominated by gravel deposits. Generally, these deposits typically have low liquefaction potential as they are a gravel dominated material, and due to their depositional characteristics, as they are compacted by wave action. Other beach ridge formations formations are composed of sand as well as sediment worked from underlying beach material. The beach ridges display a progressive change in orientation, with the younger ridges parallel to the coast and the older ridges parallel to the Wairau River. Sediment derived from the south (Awatere River and White Bluffs) is responsible for the development of the gravel ridges since the Wairau River does not transport gravel to the coast. Due to these depositional characteristics, these formations are typically less susceptible to liquefaction.

7.1.12 Other deposits:

Other deposits which are less susceptible to liquefaction are:

- Hillersden Gravel are higher elevation Neogene aged poorly graded gravelly deposits.
- Marlborough Schist derived from basement rocks of dominantly schist.
- Colluvium deposits that are gravel dominated.
- Speargrass Formation are well-sorted floodplain gravel deposits.

7.1.13 Summary of geomorphological screening

Based on the available geomorphological data, new sub-categories of *less susceptible* and *more susceptible* are assigned, sitting within the *Liquefaction damage is possible* category. This additional sub-categorisation can be used to guide the locations of future geotechnical site investigation to potentially refine classifications based on an increased density of site investigation data in these units. Table 3 summarises details of the sub-categorisation and Figure 15 summarises these sub-categories for the Lower Wairau Plains. Rapaura Formation deposits consists of alluvial gravel, sand and silt. These deposits are categorised based on elevation and nature of dominating deposits. Overbank alluvial deposits which are Mid- and High-elevation likely to have predominately gravel and deep water tables which makes them less susceptible. Lower elevation overbank alluvial deposits are dominated by sand and silt and are assigned *More susceptible*. Active flood plains and alluvial fans are assigned *Less susceptible* while recent, paleo and proximal alluvial deposits are assigned *More susceptible* within this formation. All deposits with beach ridges are assigned *Less susceptible* as they are well sorted alluvial material and highly compacted along the shore. Lagoon deposits are assigned *More susceptible* as these are generally overlain by alluvial sands and silts. Although some deposits have organic material and mud these can still be prone to liquefaction and has been seen in past earthquakes. Speargrass Formation deposits which are gravel dominated and originate from adjacent rock deposits in the region are assigned *Less susceptible.*

Table 3: Summary of liquefaction vulnerability sub-categories for the Lower Wairau Plains based on geology and geomorphology.

Geomorphological Unit	**Surface Geology**	**Formation type**	**Liquefaction Vulnerability category**	**Sub-category based on Geomorphology**
Active flood plain alluvial gravel,sand and silt	Holocene River deposits dominated by gravel	Rapaura Formation	Liquefaction damage is possible	Less susceptible
Alluvial fan gravel, sand, and silt	Holocene River deposits dominated by gravel	Rapaura Formation		Less susceptible
Inter-dune swamps	Holocene silty deposits with sand, gravel and peat	Dillons Point formation		More susceptible
Drained alluvial swamps	Fine sand grading to silts	Dillons Point formation		More susceptible
Active lagoon swamp	Holocene aged estuary deposits mainly consist of silts with peat and sand	Dillons Point formation		More susceptible
Active lagoon mud and silt	Holocene silty deposits with sand, mud and peat	Dillons Point formation		More susceptible
Paleo-channels with alluvial gravel, sand and silt	Holocene alluvial deposits with sand, gravel, and silt	Rapaura Formation		More susceptible
Paleo-channels with alluvial sand and silt	Holocene alluvial deposits with sand and silt	Rapaura Formation		More susceptible

Table 2 (Contd.): Summary of liquefaction vulnerability sub-categories for the Lower Wairau Plains based on geology and geomorphology.

Geomorphological Unit	Surface Geology	Formation type	Liquefaction Vulnerability category	Sub-category based on Geomorphology
Proximal alluvial gravel, sand and silt	Holocene alluvial deposits with sand, gravel and silt	Rapaura Formation	Liquefaction damage is possible	More susceptible
Lower-elevation overbank gravel mud and silt	Holocene alluvial deposits with sand and silt	Rapaura Formation		More susceptible
Mid-elevation overbank gravel, sand and silt	Holocene alluvial deposits with gravel, sand and silt	Rapaura Formation		Less susceptible
Mid-elevation paleo-lagoon mud and silt	Holocene river deposits consist of silts, mud and peat.	Dillons Point formation		More susceptible
Higher-elevation overbank gravel, sand and silt	Dominated by gravels towards the east coast and silty towards west.	Dillons Point formation		Less susceptible
Higher elevation paleo-lagoon mud and silt	Holocene River deposits dominated by Silts	Dillons Point formation		Less susceptible
Active beach ridges	Holocene shoreline deposits dominated by gravel	Dillons Point formation		Less susceptible
Sandy beach ridges	Holocene shoreline deposits dominated by gravel	Dillons Point formation		Less susceptible
Gravel beach ridges	Holocene shoreline deposits dominated by gravel	Dillons Point formation		Less susceptible

Table 2 (Contd.): Summary of liquefaction vulnerability sub-categories for the Lower Wairau Plains based on geology and geomorphology.

Geomorphological Unit	**Surface Geology**	**Formation type**	**Liquefaction Vulnerability category**	**Sub-category based on Geomorphology**
Alluvially re-worked lagoon mud, silt and sand	A mixture of river deposits with swamp deposits. Mostly silty with the inclusion of sand and gravel	Dillons Point formation	Liquefaction damage is possible	Less susceptible
Recent alluvial gravel, sand and silt	Holocene alluvial deposits with gravel, sand and silt	Rapaura Formation		More susceptible
Recent alluvial sand and silt	Holocene alluvial deposits with sand and silt	Rapaura Formation		More susceptible
Drained alluvial swamp	Holocene alluvial deposits consist of silts, mud and peat	Rapaura Formation		More susceptible
Speargrass Formation glacial outwash gravel, sand and silt	Late Pleistocene river deposits with gravel, sand and silt	Speargrass formation		Less susceptible

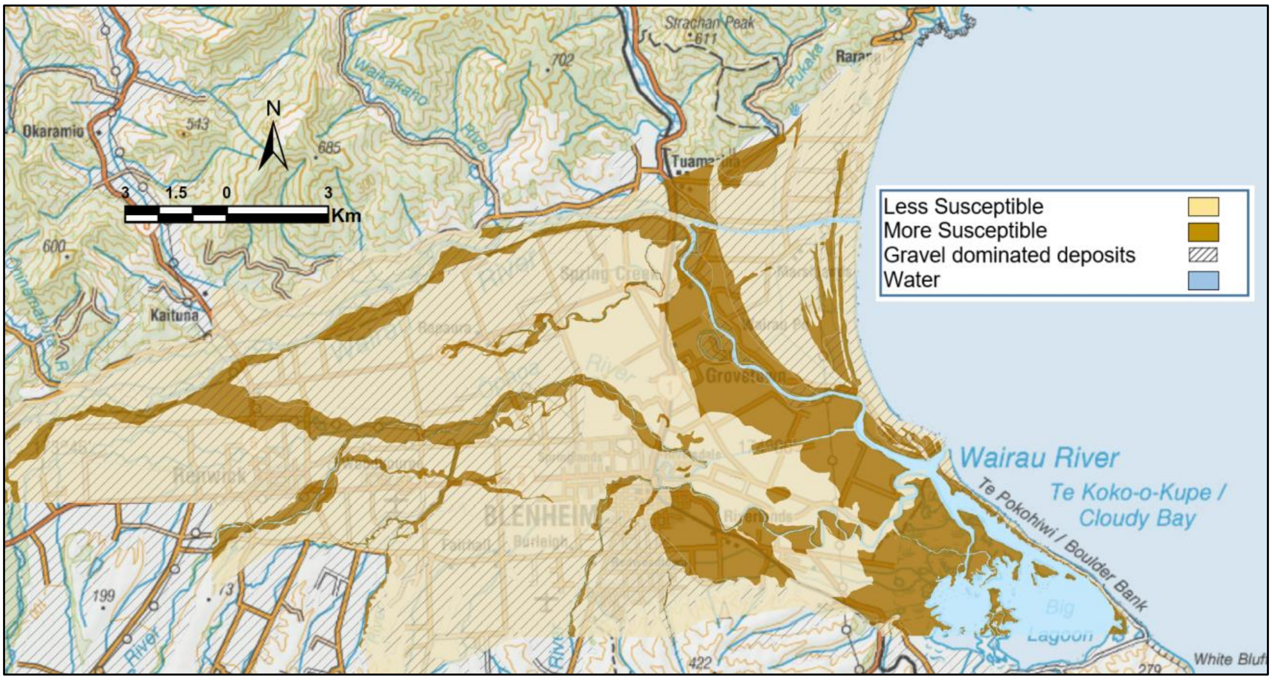


Figure 15: Summary of sub-categories within the Liquefaction damage is possible areas based on the geomorphology of the Lower Wairau Plains.

7.2 Basin geological model

Liquefaction assessments based on surface geology and geomorphology provide a high-level categorisation of liquefaction vulnerability and advancing the level of detail of this categorisation requires more information on the subsurface stratigraphy. To further this screening, a detailed geological basin model developed using groundwater observation wells is utilised to better constrain what deposits are present both across the plains and the variation of these deposits with depth.

White et al. (2016) developed a detailed geologic model of the basin beneath the Wairau Plains to better understand groundwater-surface interactions. Observations of lithology from 1,165 wells shown in Figure 16 were used to develop a continuous 3D distribution of de-facto probabilities for the occurrence of three sediment classes: gravel, sands and clays. Probability codes from 0 to 1.0 were assigned to each location on all cross-sections up to a certain depth. These codes indicate the level of confidence as to what sediment class is present, where 0 mean very low confidence and 1.0 means very high confidence. This model is used in this study to provide a more detailed representation of the stratigraphy across the Wairau Plains as related to the potential for liquefaction manifestation.

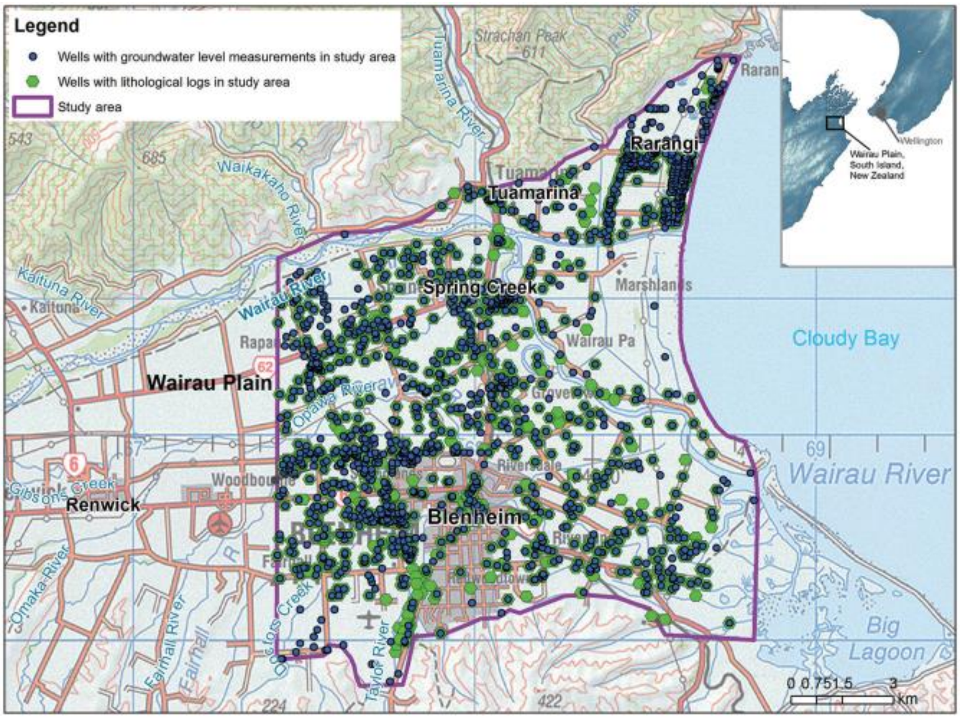


Figure 16: Location of wells used for 3D detailed geology basin model (White et al., 2016).

As the model identifies the presence of different sediment classes, it is used to differentiate between locations where surface gravels would dominate the potential surface manifestation severity and those where sands would dominate. A lack of surface manifestation of liquefaction due to the presence of an upper non-liquefiable crust is well documented by Ishihara (1985), Youd and Garris (1995), and Bouckovalas and Dakoulas (2007). To make improvements in implementing the Ishihara relationship, Maurer et al. (2015) and Towhata et al. (2016) proposed procedures that combine the thickness of the non-liquefied crust with the LPI framework. The efficacies of these two procedures were also studied by Green et. al. (2018) using case-history data from the M_w5.7 Valentine's Day earthquake that impacted Christchurch, New Zealand. These studies and field observations indicated that a crust thickness of 5 m would act to prevent surface manifestation. For the Wairau Plains case, there is the potential for young, looser surface gravels to liquefy, so here the depth to the base of the surface gravels is used to differentiate between locations where the underlying sands and silts could liquefy and control performance and those where the gravel could liquefy and control performance.

Across the Wairau Plains at the locations shown in Figure 17, cross-sections from the model are extracted to a depth of 20 m, with depths greater than this of less importance for liquefaction assessments. A number of north-south and east-west cross-sections are extracted, and a few examples are summarised in Figures 18 for both directions. A probability code of 0.8 for gravel is shown for each figure and the depth to groundwater from the model presented in Figure 8. The depth to the base of the surface gravel above sand and silt deposits at each location is controlled by either the base of the gravel layer or the water table depth. If the water table is within a non-gravel layer at the surface, the surface gravel depth is set to zero. This meant there is saturated sand or silt layers above the gravel, and this would control performance. If the water table is within a gravel layer, the depth is set to the base of the gravel deposits at that location, which is the top of the saturated sand and silt deposits below in other words. A probability code of 1.0 for gravel is also assessed, and in areas where these two probabilities showed significant differences a conservative approach is taken so as to represent the thinner estimate of the depth to the base of the surface gravel.

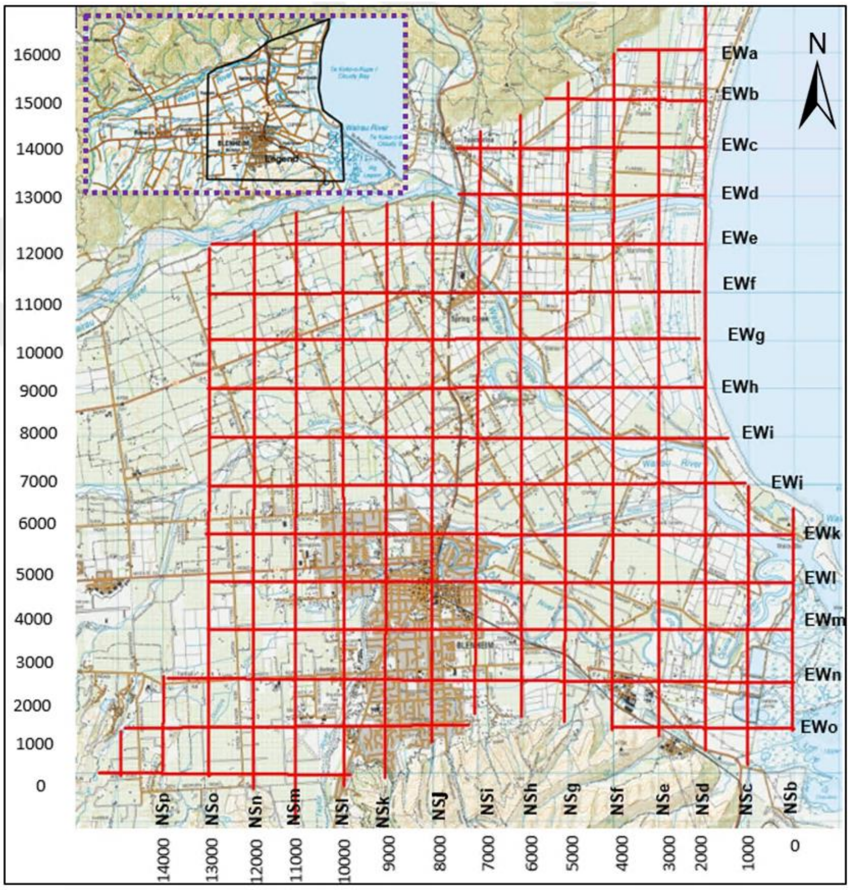


Figure 17: Location of basin model cross-sections in the east-west and north-south directions.

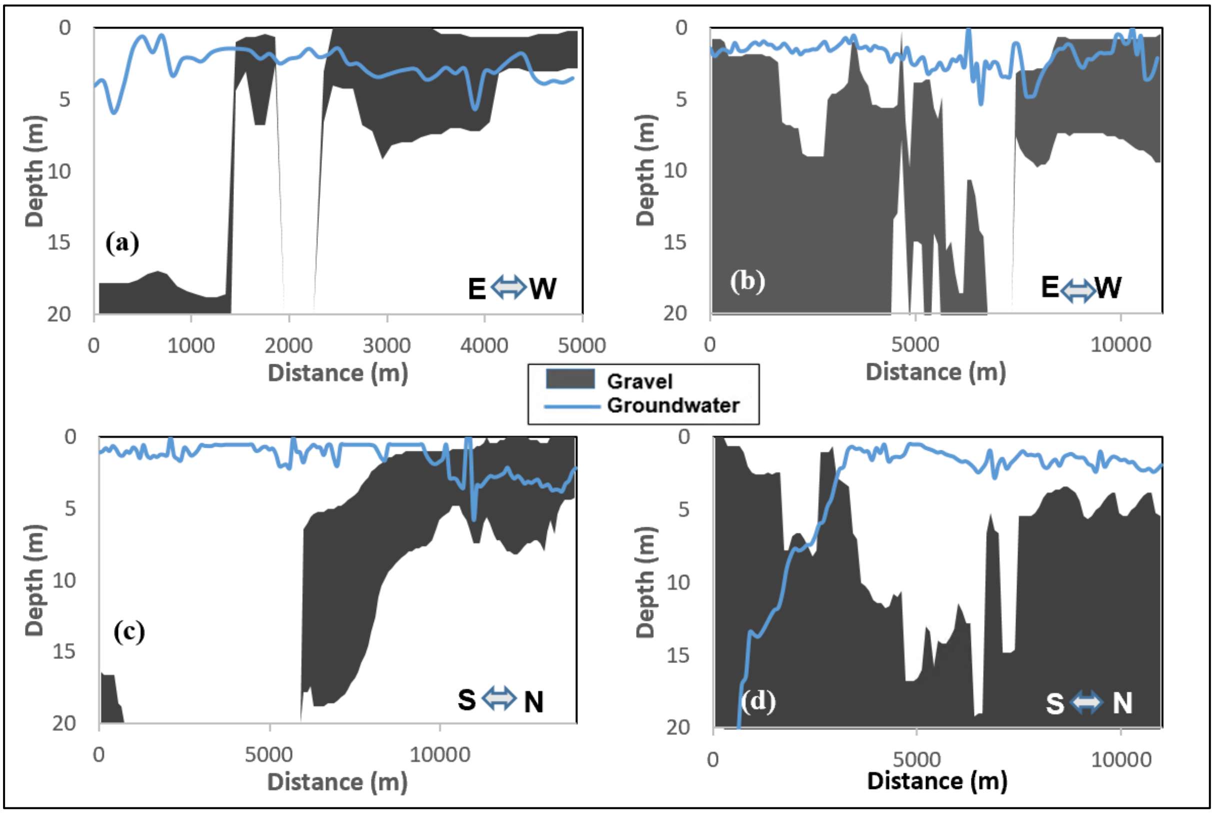


Figure 18: Location of gravel deposits and groundwater depths for cross-section (a) EWd (b) EWf (c) NSm (d)NSg

To visualise the variation in the depth to the base of the surface gravels across the region 2D surface maps are developed based on each cross-section in the east-west and north-south directions. A number of interpolation tools are assessed, but as the data available is of very high density and spatial variability is low, the *Natural Neighbours* interpolation tool is used to provide a representative surface. This tool finds the closest subset of input values and applies a weighting based on proportionate areas to interpolate values. The resulting surface using this method is presented in Figure 19, showing that the depth to the base of the surface gravels is greater than 5 m in the areas west and south of Blenheim, as well as along the coast to the north-east. There is a rapid increase in the depth to the base of the surface gravel in these areas. There are pockets of thinner surface gravels in areas and a large region where the base of the surface gravels are between 0-3 m north of Blenheim. The resulting area with surface gravel thickness >5 m is used at the end of this section to compare and make any changes to the gravel dominated deposited shown in geology based liquefaction vulnerability map.

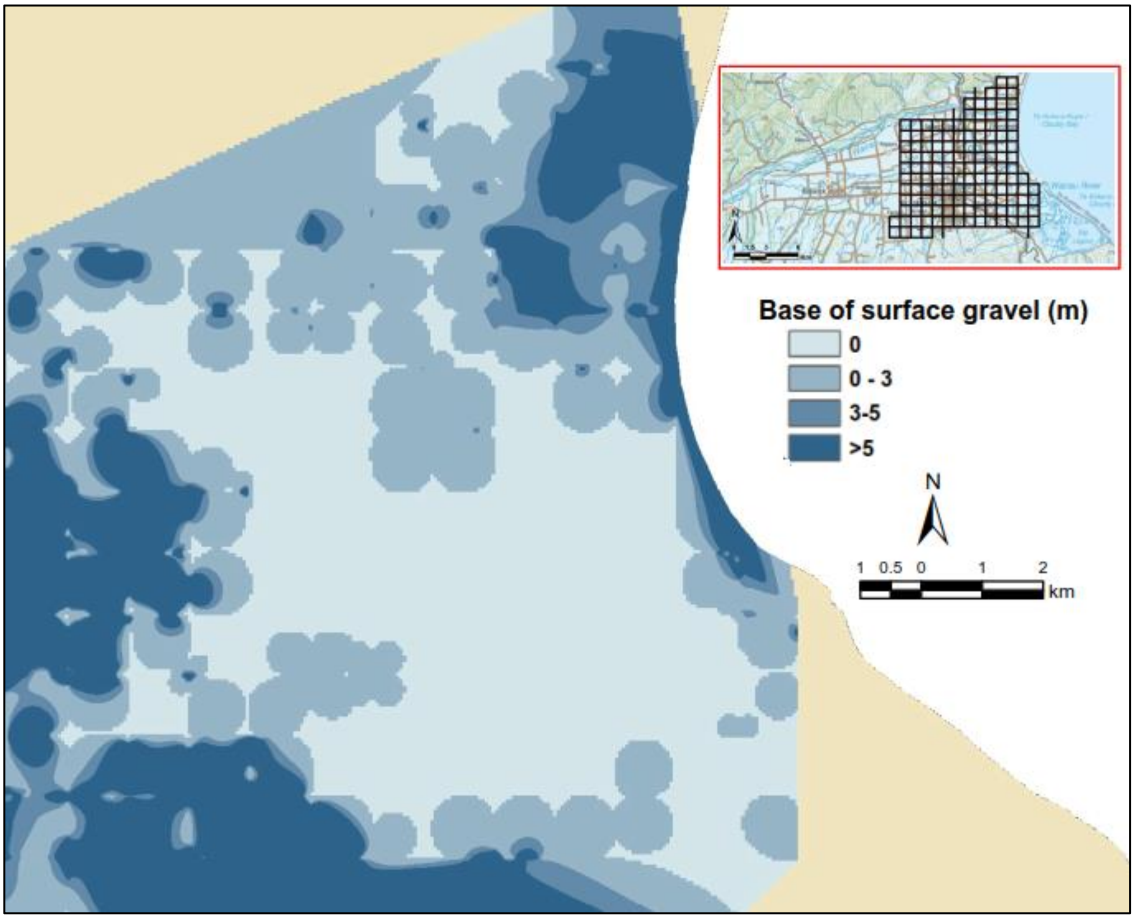


Figure 19: Interpolated map of the depth to the base of the surface gravels based on the groundwater basin model.

7.3 Geotechnical investigation data screening

Geotechnical investigation data in the form of boreholes with or without SPTs, CPTs, hand augers, trenches and others are available in the Lower Wairau Plains. Figure 20 summarises the location of the boreholes and CPTs in the region overlaid on the geomorphic zones. Existing investigations were sourced from the New Zealand Geotechnical Database and the Tonkin and Taylor geotechnical database. As part of this study, additional investigations were carried out in the western parts of the Lower Wairau Plains where no data was available. These additional investigations consisted of combined CPT and dynamic probe super heavy (DPSH) testing, with the DPSH used to characterise the gravel deposits that the CPT could not penetrate. At a selected number of sites bulk samples of the near surface gravels were collected and particle size distribution testing undertaken. Here the water and sediment database mentioned in Section 3.3 and shown in Figure 9 is also used in addition to the geotechnical investigations to inform classifications.

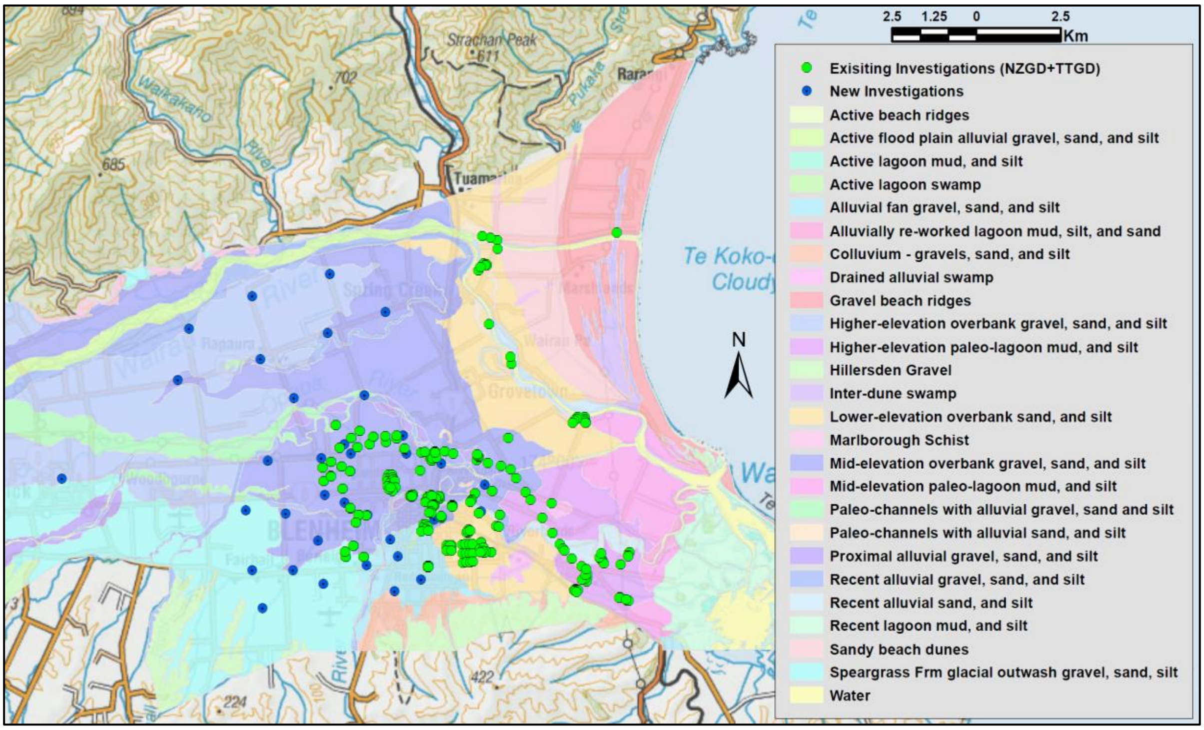


Figure 20: Summary of the location of geotechnical investigations in the Lower Wairau Plains and the geomorphic zones across the region.

The geotechnical investigations are mainly present in the following five geomorphic zones:

- Mid-elevation overbank gravel, sand, and silt
- High-elevation overbank gravel, sand, and silt
- Recent alluvial gravel, sand, and silt (including low elevation and proximal alluvial deposits)
- Speargrass Formation glacial outwash gravel, sand, and silt
- Alluvial fan gravel, sand, and silt

Recent alluvial deposits, including low elevation and proximal alluvial deposits, generally have sandy and silty material. The new data in high and mid elevation gravelly alluvial formations is useful to categorise the gravel dominated areas with increased certainty. In the Level A classification, categories of *Liquefaction damage is possible*, or *Liquefaction damage is unlikely* are assigned based on semi-quantitative criteria. At Level B we are not able to revise the categories which have been assigned in Level A, with additional data and investigations required to assign a more precise classification. As per the MBIE guidance (as shown in Appendix A), the liquefaction vulnerability category of "Low" can be assigned to areas where geotechnical investigations are available and stratigraphy to a certain depth can be determined. The following sections describe the subsurface stratigraphy for the five geomorphic zones using the geotechnical investigation data in the Lower Wairau Plains.

7.3.1 Mid-elevation overbank gravel, sand and silt

Figure 21 shows the geotechnical investigation locations and well data points in the mid-elevation alluvial deposits. The northern two new investigation locations show silt and sand mixtures from surface and gravel layers below 5 m depth intermixed with silty, clayey material. The lower three new investigation locations towards the West have gravel from the surface and have also been identified as having a gravel crust in the geologic basin model. The existing investigations in the same polygon towards the east shows silty, sandy and clayey material from the surface. Well logs and investigations in the northern polygons labelled B confirm the Level A classification of *Liquefaction damage is possible*, as these contain near surface deposits of sandy silty material.

The polygon can be divided and the regions towards the east labelled A, which have stiff gravels from the surface, can be assigned a liquefaction vulnerability category of *Low*. The new data includes DPSH that shows stiff gravel from the ground surface, which helps to assign this category. High values of DSPH blows (>20) can be seen in the logs. Similarly, some CPT investigations in this formation shows high CPT tip resistance >30 MPa at very shallow depths before reaching refusal (above the water table). This data is used along with well logs to define the boundary where these alluvial deposits become gravel dominated and can be assigned this refined liquefaction vulnerability. The grain size distribution of the samples collected from a test pit in this area at Wratts Road, Rapaura shows near surface silty sandy gravel material with 75% gravel content.

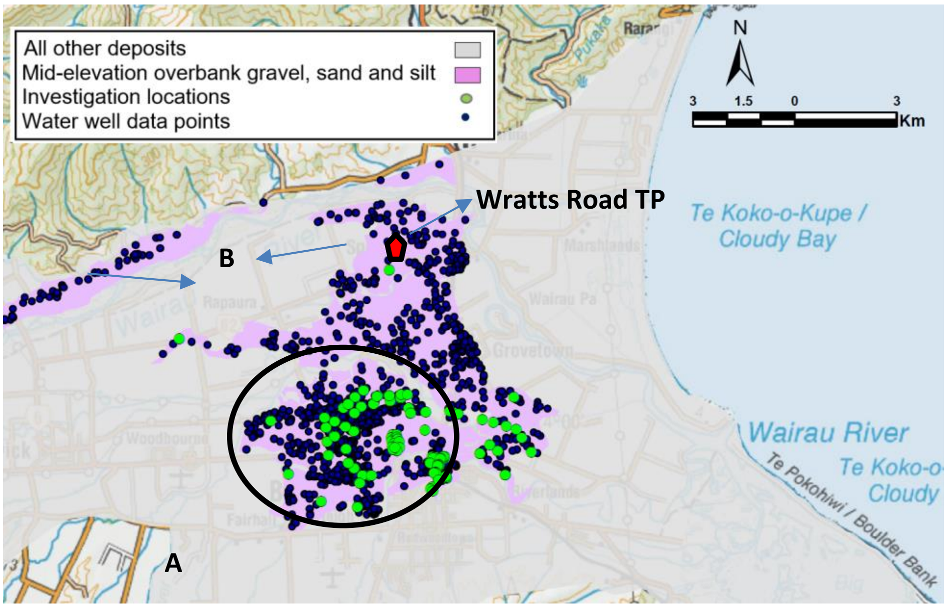


Figure 21: Geotechnical investigations in Mid-elevation overbank gravel, sand and silt deposits.

7.3.2 High-elevation overbank gravel, sand and silt

Figure 22 shows the location of geotechnical investigation in High-elevation overbank deposits. All geotechnical investigations in this formation show the presence of gravels from the surface that are often mixed with clay. Well logs shows the presence of stiff gravel and cobbles from the ground surface. DPSH in these deposits encountered stiff gravels that prevented testing beyond a few metres, with CPTs also unable to penetrate from the ground surface. Samples collected from two test pits for this formation from locations in Rapaura and Renwick show grain size distribution curves dominated by gravels. The materials in these deposits is more consistent in nature compared to the mid-elevation deposits, with little evidence of pockets dominated by sands and silts. Based on this data and the discussion in the geomorphology-based screening section a liquefaction vulnerability category of *Low* is assigned to these deposits.

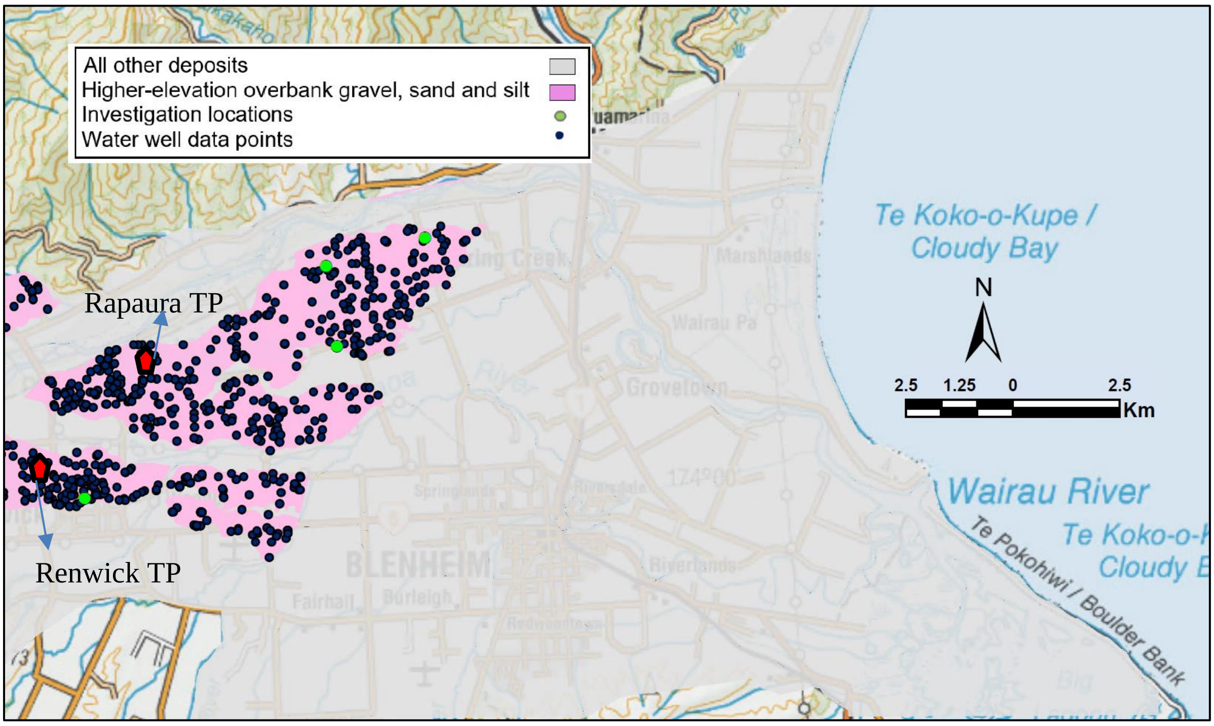


Figure 22: Geotechnical investigations in High-elevation overbank gravel, sand and silt deposits.

7.3.3 Recent alluvial gravel, sand and silt

Figure 23 shows the location of geotechnical investigations and well data points in recent alluvial deposits. Being recent deposits along the river; these deposits have a highly mixed stratigraphy, with sandy, silty deposits from surface indicted by the majority of the existing and new investigations. The water table is also shallow across these deposits, and as such the *Liquefaction damage is possible* category is still applicable.

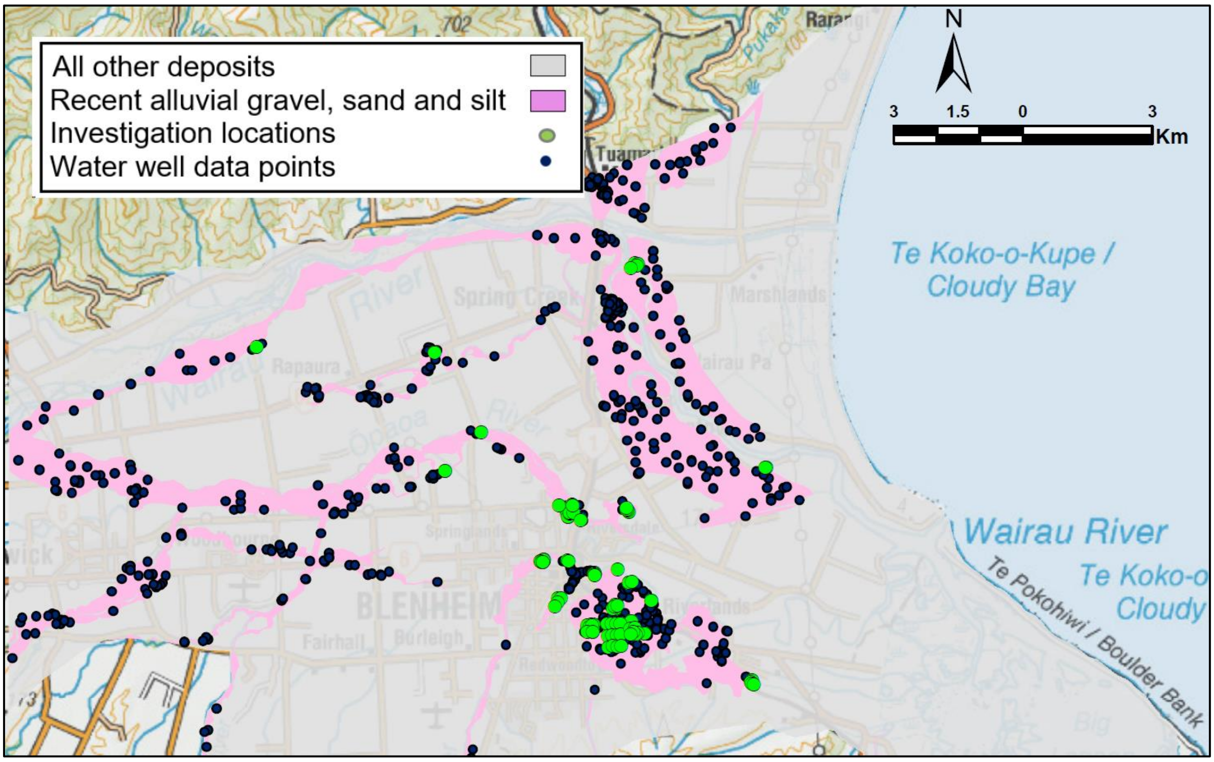


Figure 23: Geotechnical investigations in recent alluvial gravel, sand and silt deposits.

7.3.4 Speargrass Formation glacial outwash gravel, sand and silt

Figure 24 shows the location of geotechnical investigations in the Speargrass Formation deposits. Many of the investigations in the eastern and southern parts of these deposits show sands and silts from the surface with gravel layers intermixed with other alluvial material after 4-5 m depth. Most of the well logs do not have subsurface information and only provide water level readings. Although the discussion in the geomorphology screening and detailed geology basin sections suggest that these deposits may have a lower liquefaction vulnerability, there is still uncertainty about the overall stratigraphy of the deposits in the southern parts of this zone. Therefore, a more precise category cannot be assigned for these deposits and the Level A geology-based classification of *Liquefaction damage is possible* is appropriate. Some of the well logs towards the west shows stiff clay deposits, with these areas already classified as *Liquefaction damage is unlikely* based on the depth to the groundwater table in this area. The more northern parts of this zone that have not already been classified as *Liquefaction damage is unlikely* are dominated by stiff gravel, and the details of the classification revision in this area are discussed in Section 7.3.6.

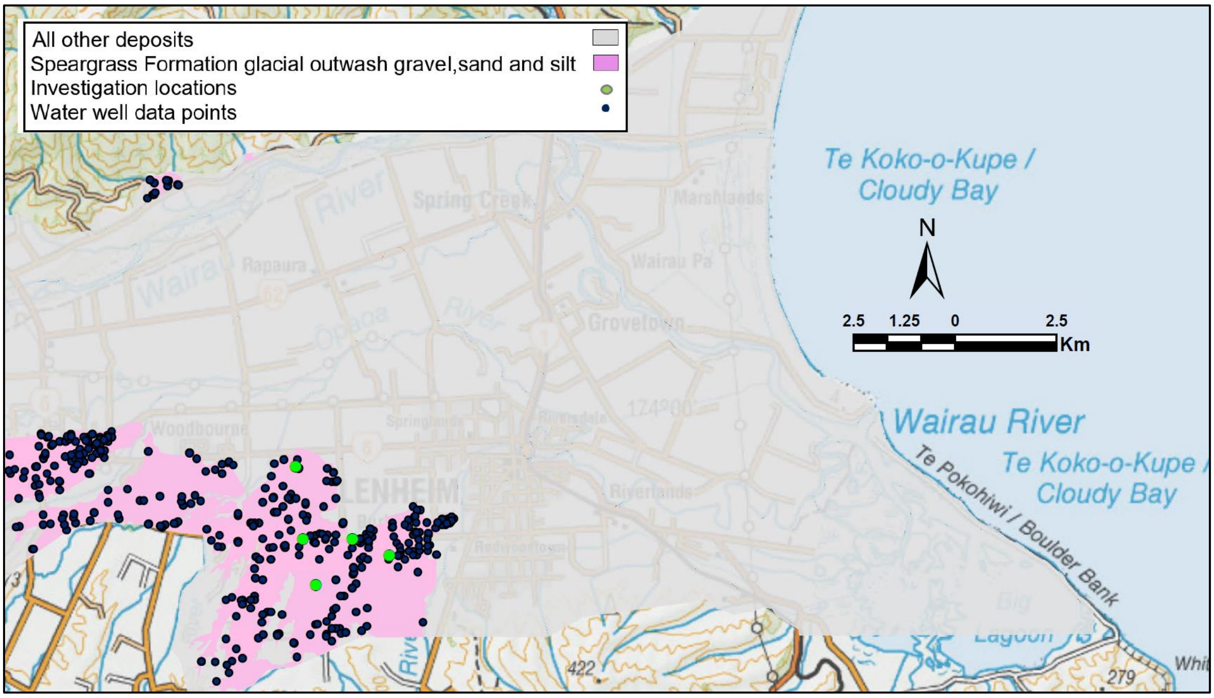


Figure 24: Geotechnical investigations in the Speargrass Formation gravel, sand and silt deposits.

7.3.5 Alluvial fan gravel, sand and silt

Figure 25 shows the location of geotechnical investigation in the Alluvial fan deposits. Two out of three new investigations show the presence of silty and sandy material from the surface with gravels at a few metres depth. The southern investigations have gravels from the surface and other existing investigations also show gravel from the surface. Similarly, well logs also show gravel dominated stratigraphy, however this is mixed with sands in a number of areas. The logs are limited and only towards the south are they dominated by gravel from the ground surface. This introduces some uncertainty, meaning that *Liquefaction damage is possible* is an appropriate classification for these deposits.

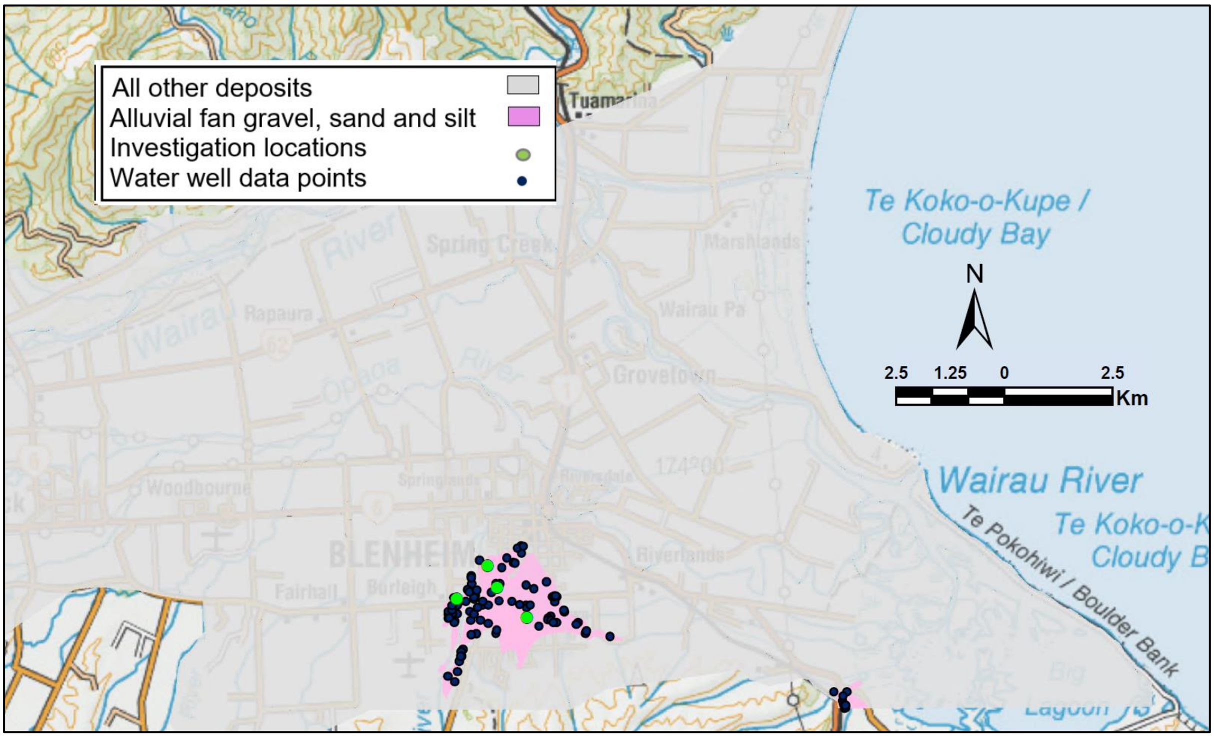


Figure 25: Geotechnical investigations in Alluvial fan gravel, sand and silt deposits.

7.3.6 Combined modifications

All the investigations in High elevation overbank gravel, sand and silt deposits show gravel from the surface or near the surface, which makes them less likely to liquefy and result in surface damage. Therefore, all these deposits are assigned a *Low* liquefaction vulnerability category. Here the recent, low and mid-elevation alluvial deposits intermixing form an irregular region between the *Low* boundary labelled as A in Figure 26. These have alluvial sandy, silty material as indicated by sub-surface investigations and will remain in the *Liquefaction damage is possible* category.

The southern two polygons can be extended to the east based on the data from investigations in this area. The strips between the polygons are channels of recent and paleo alluvial gravel, sand and silt deposits, which will remain as *Liquefaction damage is possible* as shown in Figure 26. The upper polygon labelled B has been extended over into the Mid-elevation overbank gravel, sands and silts deposits, while the lower polygon labelled C has been extended into the Speargrass Formation glacial outwash gravel, sand and silt deposits until the subsurface investigations no longer show profiles dominated by gravel from the ground surface. Here, careful consideration is given to the geomorphic characteristics and subsurface stratigraphy to set the boundaries of these two polygons.

Similarly, in the west the boundary for *Low* liquefaction vulnerability in the high elevation overbank deposits can be extended to the west until it meets the main Wairau River channel. The remainder of the Speargrass Formation and Mid-elevation overbank deposits have variable stratigraphy and density of investigations is also low (as a limited number of well logs have stratigraphic data). The uncertainty in the stratigraphy of these deposits means the *Liquefaction damage is possible* category is appropriate in these areas. Due to a lack of availability of geotechnical data in the Colluvium deposits, the liquefaction vulnerability is not updated. Figure 27 summarises the updated liquefaction vulnerability categories based on the calibration of the Level A categories.

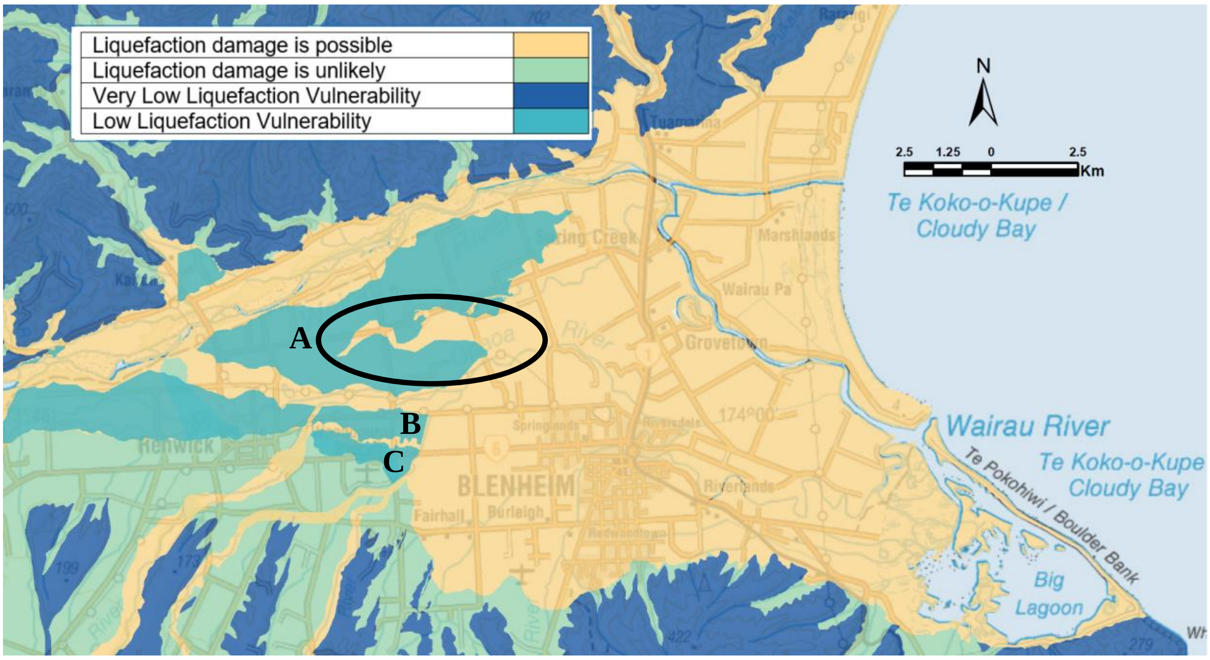


Figure 26: Details of the Low liquefaction vulnerability category for the High elevation overbank deposits.

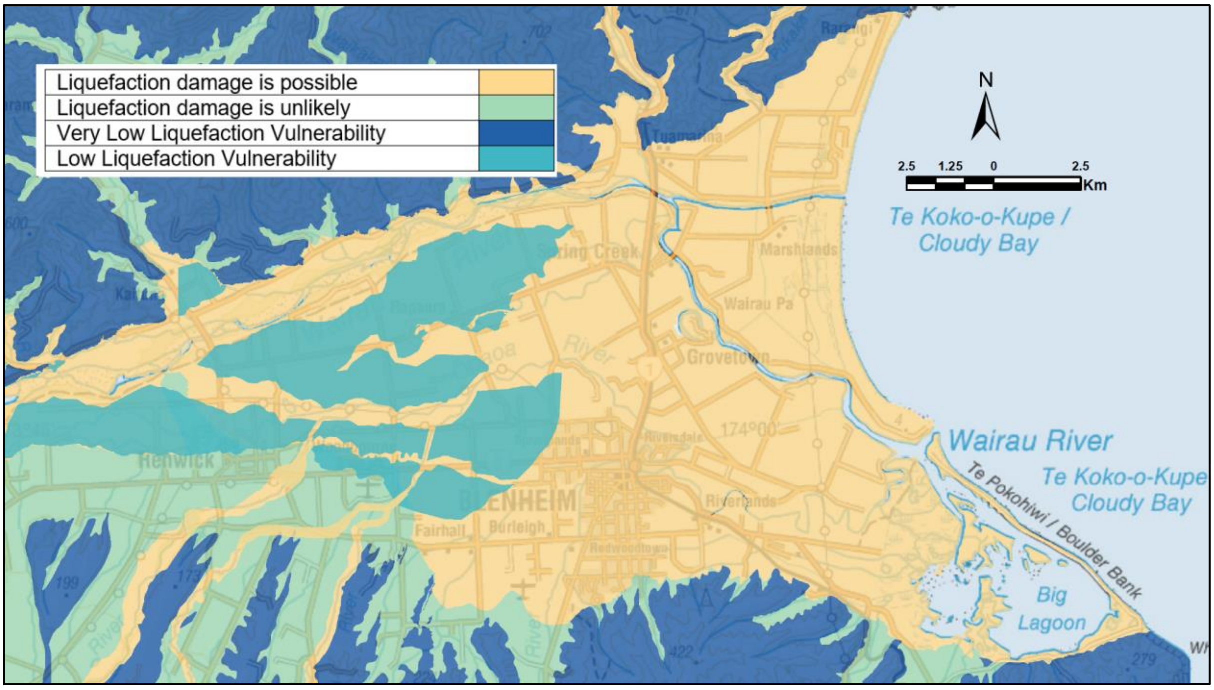


Figure 27: Details of the extension of the Low liquefaction vulnerability category for the Speargrass Formation and mid-elevation overbank deposits.

7.4 Summary

In the Level B assessment three checks using three sets of data are applied to update the Level A geology-based liquefaction maps. This provides updated maps with reduced uncertainty compared to the Level A categories, with a liquefaction vulnerability category of *Low* assigned where these screening stages have provided more confidence in the susceptibility of the deposits. Overall geotechnical investigations screening that employs existing and new data in addition to water wells data is most extensive, with detailed subsurface assessment generally agreeing with the geomorphology screening and geology basin model analysis results.

Figure 28 superimposes the depth to the base of the surface gravel onto the Level A geology-based liquefaction vulnerability map to identify areas where these approaches are in agreement and those where there are some inconsistencies. The grey polygons overlaid on the hatched areas in Figure 28 shows that regions with gravel crust greater than 5 m show good agreement with the location of gravel dominated deposits from the Level A geology-based assessment. However, there are areas to the north and northwest that are mapped as gravel dominated based on the geology-based assessment that have surface gravel layer thicknesses less than 5 m. In these areas, the detailed basin geologic analysis provides a more refined understanding of which deposits could govern the overall performance of a soil profile. However, it will not allow for a more refined vulnerability categorisation and areas with both gravel and fine-grained sand and silts are still assigned the category of *Liquefaction damage is possible*. Additional data would be required to extend this model in the western gravel dominated regions.

Figure 29 presents the areas where the surface gravel crust >5 m in thickness, overlaid on the updated liquefaction vulnerability map based on the Level B assessment. This also shows a good agreement to the precise category of *Low* liquefaction vulnerability. The boundary set in the east for this category in the mid-elevation overbank and Speargrass Formation deposits matches the surface crust area that was defined from the detailed geologic basic model. The southern polygon of the surface crust area shown in Figure 29 has been discussed in Level B assessment, and due to lack of sub-surface investigation data, a precise category is not suggested for this polygon. Figure 30 summarises the updated liquefaction vulnerability categories based on Level B assessment with the revised extent of the gravel dominated alluvial deposits. The extent of gravel in northern and eastern sides is reduced based on the detailed geologic basin model and geomorphological screening, as in these areas the performance is governed by fine grained alluvial deposits. The recent alluvial deposits, active flood plains, paleochannel deposits have fine grained silts and sands as indicted by the geotechnical investigations.

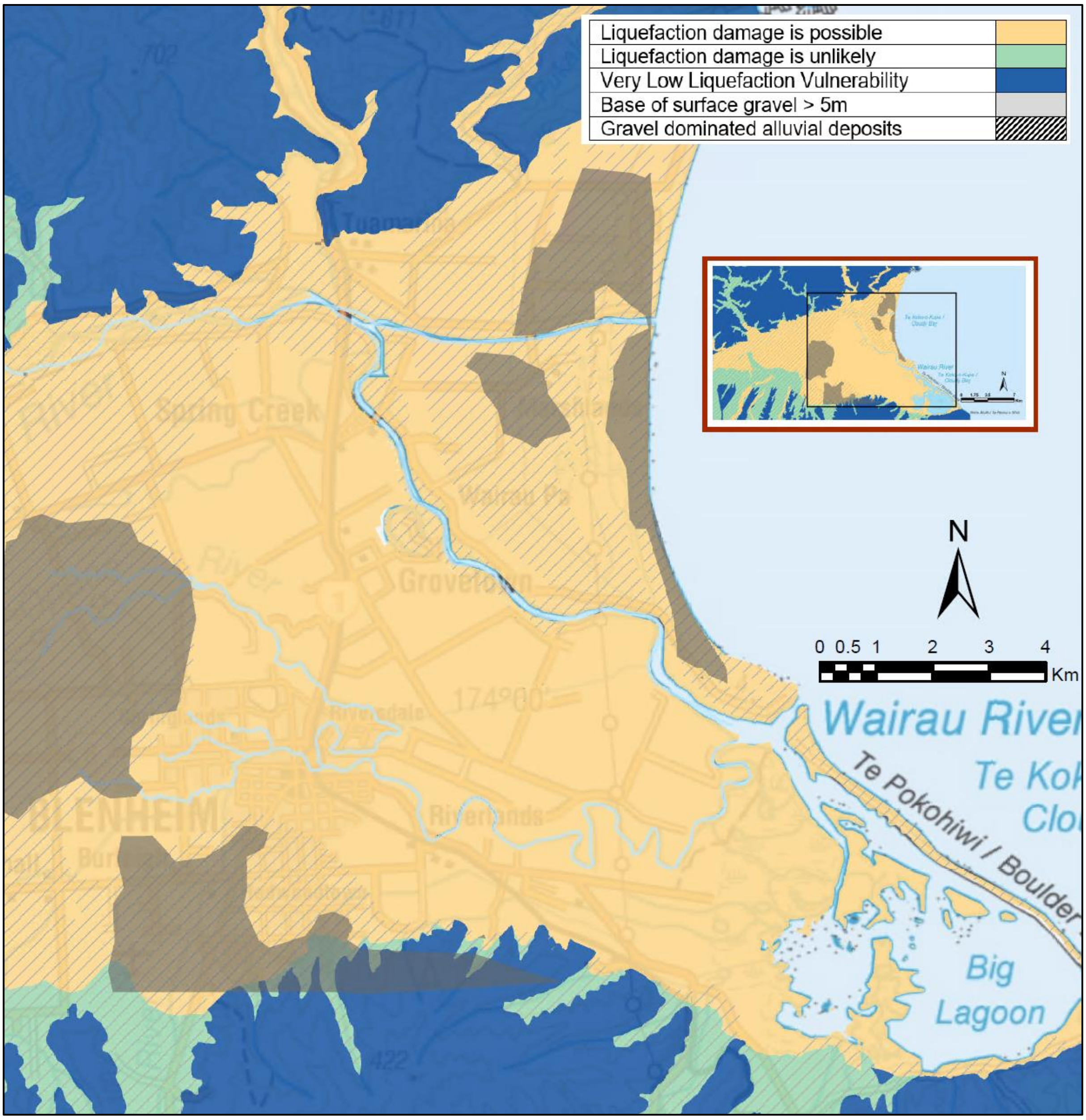


Figure 28: Depth to base of the surface gravels overlaid on the geology-based liquefaction vulnerability category map.

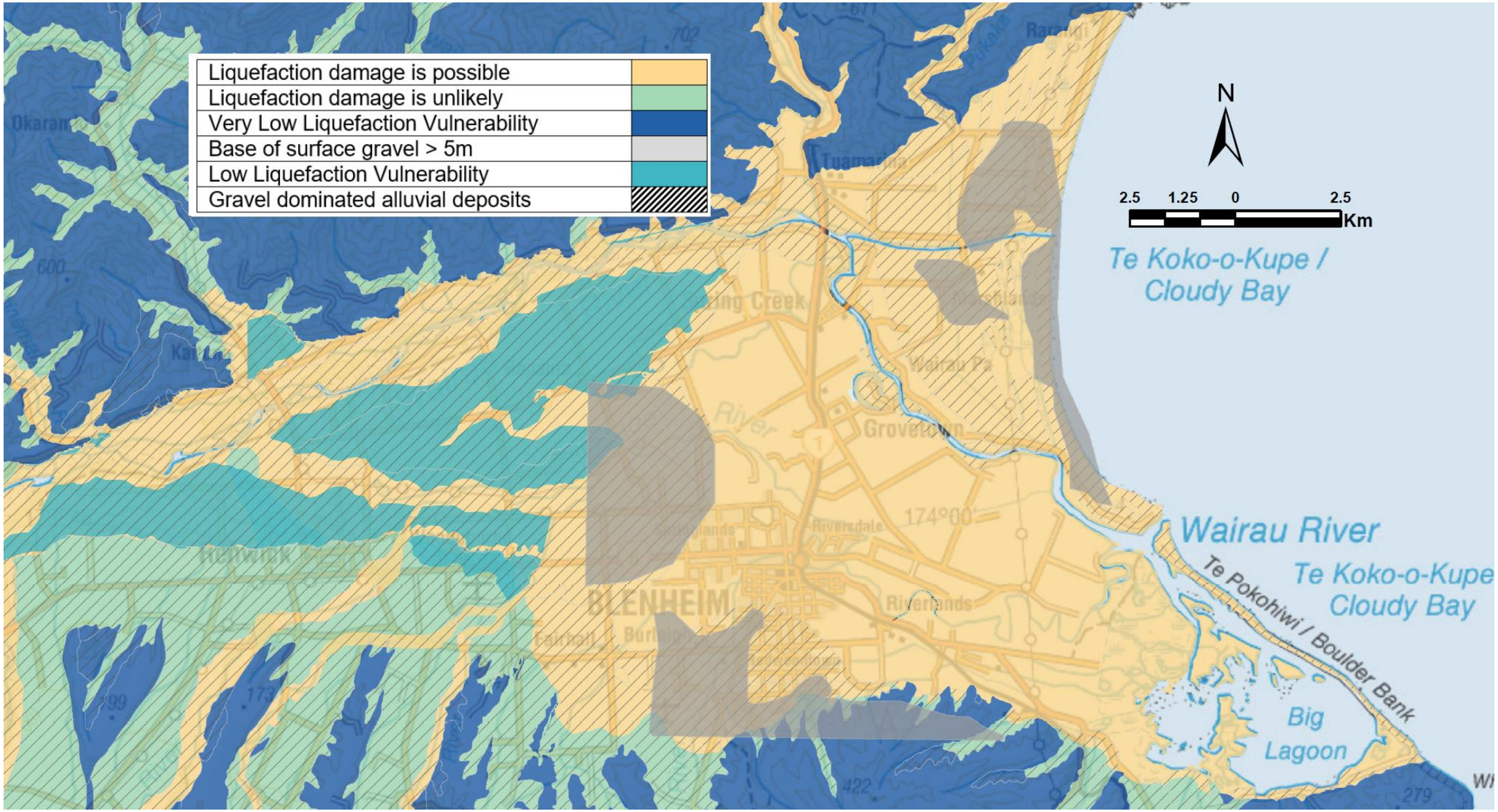


Figure 29: Summary of liquefaction vulnerability category map for the Lower Wairau Plains and base of gravel greater than 5 m.

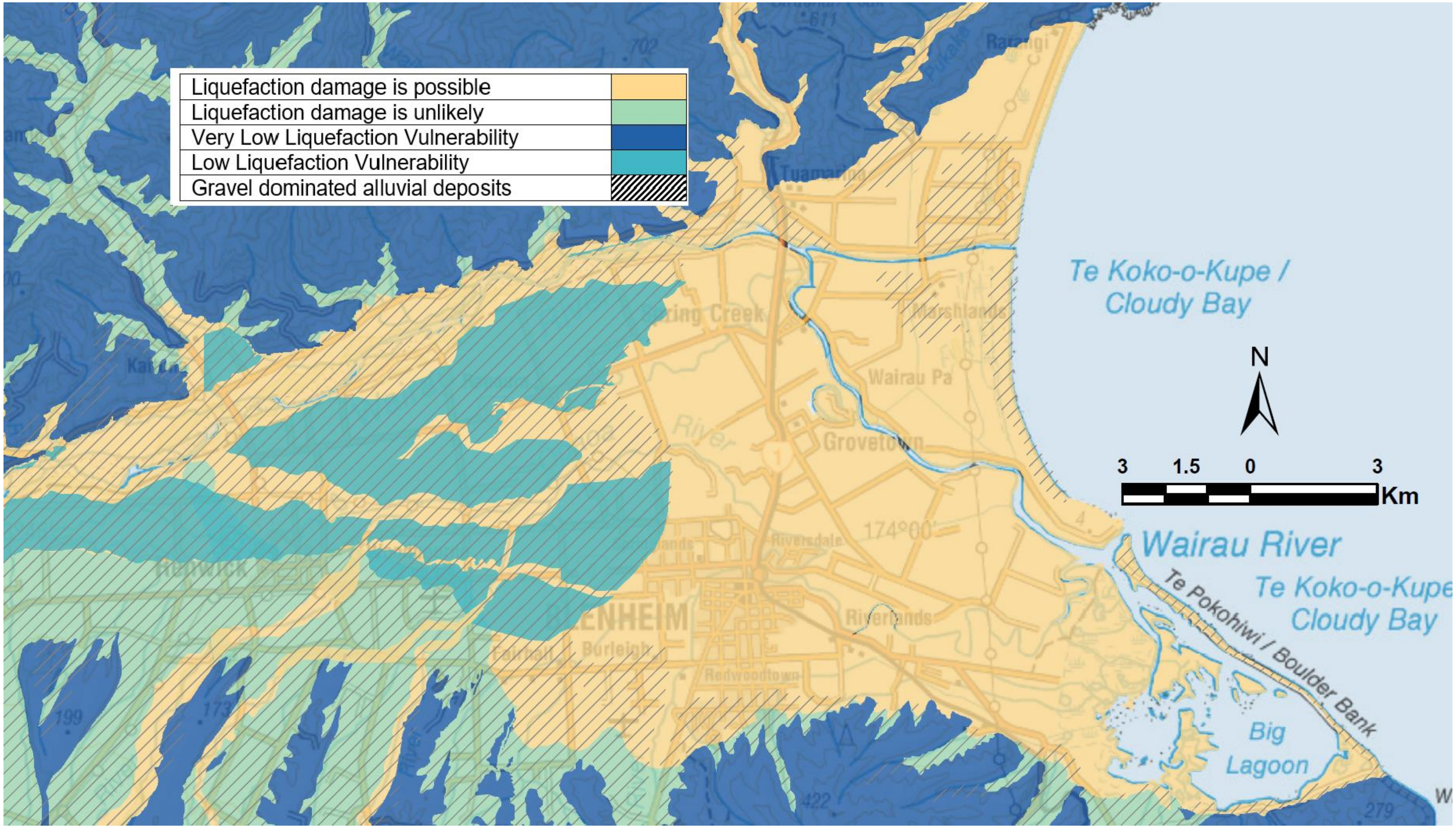


Figure 30: Level B liquefaction vulnerability category map for the Lower Wairau Plains.

8 CPT-BASED ASSESSMENT

This section summarises the outputs of the quantitative approach discussed in Section 2.3. Figure 31 summarises the location of the CPT soundings in the region that are used to undertake an estimate of the degree of liquefaction-induced ground damage for various earthquake return periods. A Level C assessment is controlled by the density of CPT investigations available across the region. The section should be used only as a demonstration of the application of Level C assessment given the low density of investigations available, and the translation of the available data to this level of assessment is discussed.

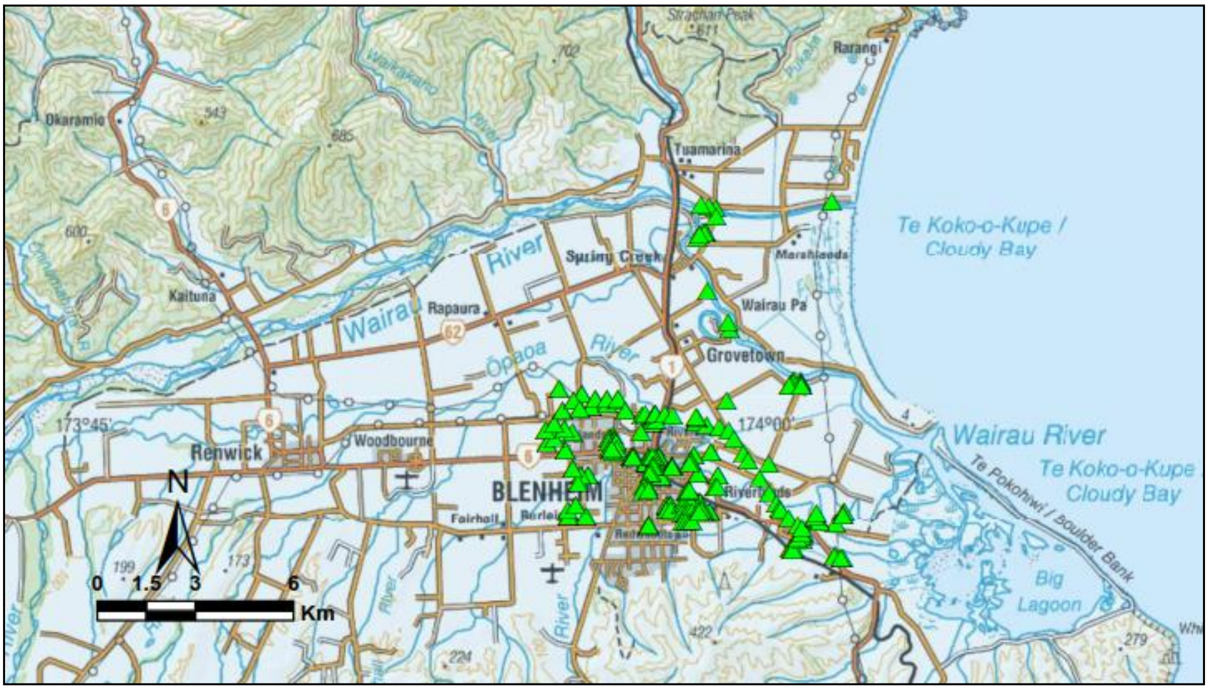


Figure 31: Location of CPT soundings in the Lower Wairau Plains.

MBIE Guidance recommends the assessment of liquefaction-induced ground damage for 100-year and 500-year return period ground motion characteristics. The PGA and M_w described in Section 4 are used in this detailed assessment. The triggering of liquefaction for each soil profile is assessed using the simplified liquefaction triggering methodology proposed by Boulanger and Idriss (2014). This method is an empirical approach that estimates whether liquefaction will trigger in the different layers of a soil profile. The input parameters that have been adopted for the Boulanger and Idriss (2014) liquefaction triggering assessment for this study are listed in Table 3.

Table 3: Input parameters for CPT liquefaction triggering analysis.

Input parameter	Default value adopted	Comments
Soil density	18 kN/m^3	Triggering is typically not sensitive to the typical soil density values.
FC-Ic correlation	0	Appropriate upper bound value for regional soils in the absence of region-specific data.
Ic-cut off	2.6	An appropriate value for regional soils in the absence of other data.
Magnitude of earthquake shaking	M_w = 6.8 and 7.3	Recommended by Cubrinovski et al (2021).
Peak ground acceleration (g)	0 to 0.8 with an increment of 0.05	A range of PGAs are used.
Probability of liquefaction, P_L (%)	P_L =15%	Based on standard engineering design practice P_L=15% is discussed in this report.
Depth to groundwater (m)	Varies	A range of groundwater depths are used based on the regional model and the sensitivity of these values.

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

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

Explanation of the typical manifestations of damage at the ground surface and example photos are described in MBIE Guidance and also presented in Appendix B of this report. Characteristic LSN ranges for each degree of liquefaction-induced damage category adopted for this assessment are summarised in Table 4. These are used to define a degree of severity of ground damage for each soil profile and scenario, and eventually a liquefaction vulnerability category.

Table 4: Characteristic LSN boundaries adopted for the purpose of this study (Ogden 2018).

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

To provide a visual representation of the relationship between liquefaction-induced ground damage and intensity of earthquake shaking for a range of PGA values, ground damage response curves are developed. Examples of different ground damage response curves are presented in Figure 32. Here a range of PGA values for a particular magnitude earthquake are used, extending beyond the values defined for each return period earthquake. These curves are used to assign a liquefaction vulnerability category based on the MBIE Guidance, with the vulnerability category to be used at each site defined based on the following:

- If less than minor ground damage at 500-year level of shaking, then the liquefaction vulnerability category is Low (Curve 1 in Figure 32)
- If more than Moderate ground damage at 500-year level of shaking, then the liquefaction vulnerability category is High (Curve 2 in Figure 32)
- If more than Minor ground damage at 100-year level of shaking, then the liquefaction vulnerability category is High (Curve 3 in Figure 32)
- If none of the above apply, then the liquefaction vulnerability category is Medium

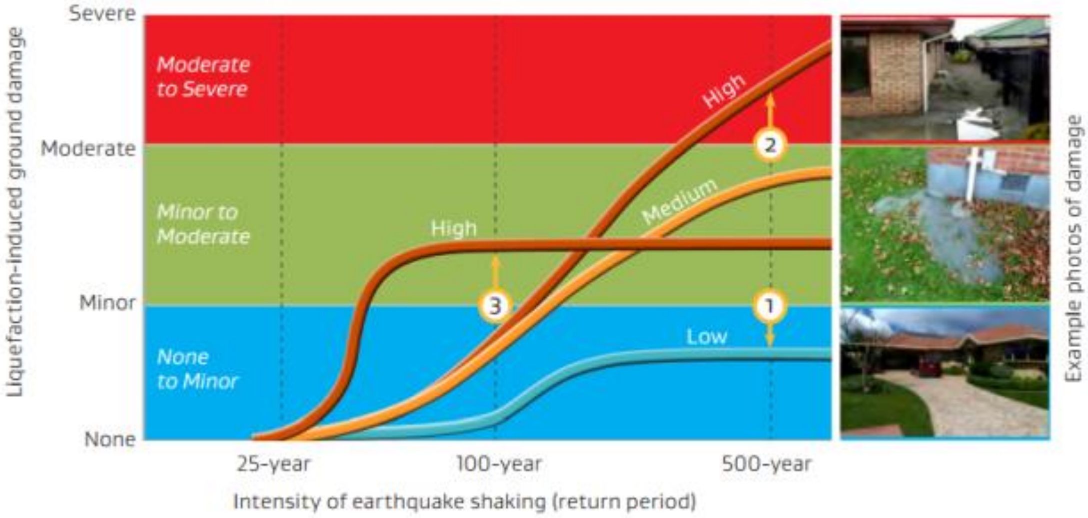


Figure 32: Conceptual example of ground damage response curves for low, medium and high liquefaction vulnerability categories, and performance criteria for liquefaction categorisation (MBIE/MfE/EQC 2017).

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

- Mid elevation overbank gravel, sand, and silt
- Low elevation overbank sand and silt
- Recent alluvial sand and silt
- Paleo channels with alluvial sand and silt
- Proximal alluvial gravel, sand, and silt

CPT soundings in each geomorphic unit are shown and discussed separately with the ground damage response curves for all CPT soundings in each unit. These curves are developed for two earthquake magnitudes of M_w6.8 and M_w7.3, matching those defined for the 100-year and 500-year return period events. As the difference between the LSN values for M_w6.8 and M_w7.3 was shown to not have a significant effect on of the resulting ground damage response curves, only M_w7.3 data is presented for each focus areas. The colour scheme from Table 3 is used in these figures to show the degree of liquefaction induced ground damage for the different LSN ranges.

To provide additional insight into the characteristics of the soils in each geomorphic zone, the variation in CPT tip resistance (q_c) and the soil behaviour type index (I_c) with depth is presented. These plots are referred to hereafter as "CPT traces". q_c is the stress reacting against the CPT tip as it is pushed into the ground and is used to determine subsurface stratigraphy and soil properties. I_c is an index based on CPT sounding data that is used to estimate the type and behaviour of soils within the sounding depth range (Robertson & Wride 1997). The bands of I_c values that are important to consider when performing a liquefaction assessment are summarised in Table 4 and adopted in this report to discuss the soil characteristics in each geomorphic unit. I_c can be used as a first-pass screening for liquefaction susceptibility, as soils which are considered too plastic to liquefy can be readily identified. To assess liquefaction susceptibility, Robertson and Wride (1998) suggested adopting a default Ic 'cut-off' value of 2.6, beyond which soil material can be assumed to be non-liquefiable (i.e., not susceptible to liquefaction). Regional liquefaction analyses carried out in Canterbury (Tonkin & Taylor, 2013; Tonkin & Taylor, 2015b, van Ballegooy, et al., 2014; van Ballegooy, et al., 2015) have also been performed assuming a default Ic cutoff of 2.6. I_c is also used to estimate the fines content of different soil based on existing empirical correlations. The CPT traces presented in this report are cut off at 10 m depth as liquefaction of soil layers at depths greater than 10 m have a negligible contribution to any liquefaction-induced damage at the ground surface. Reviewing the CPT traces grouped by geomorphic zone provides insight into the likely liquefaction-induced land damage. Looser soils are more likely to liquefy than denser soils and cohesionless soils are more likely to liquefy than cohesive soils.

Table 5: Cut-off values for I_c for soil behaviour type.

I_c	**Soil Behaviour Type**
$0 < I_c < 1.31$	Gravelly sand to dense sand
$1.31 < I_c < 2.05$	Sand – clean sand to silty sand
$2.05 < I_c < 2.6$	Sand mixtures – silty sand to sandy silt
$2.6 < I_c < 3.6$	Silt and Clay mixtures – clayey silt to clay
$I_c > 3.6$	Organic soils – clay

8.1 Paleochannels with alluvial sand and silt

Figure 33 shows the location of CPT soundings in the paleochannel formation. These soundings are mainly distributed in two focus areas labelled as "a" and "b" in Figure 33. The CPT traces in Figure 33 also shows that q_c values range from approximately 1 to 8 MPa over the top 2 m, with q_c then increasing rapidly for some traces and staying relatively low for others. The degree of scatter in these plots is high, suggesting variability in the soil profiles within the paleochannels. I_c suggests that the upper 2 m is silty sand to clayey soils and then sand and sand-silt mixture layers up to 10 m depth.

The ground response curves for paleochannel deposits are presented in Figure 34. Overall, the curves are quite scattered and there is no clear trend. The majority of ground response curves for the small area labelled as "a" in Figure 33 have a degree of liquefaction-induced damage of "none to minor" for the 100-year level of shaking and "minor to moderate" for 500-year level of shaking. The degree of liquefaction-induced damage is higher in the area labelled "b" for the majority of CPT soundings, with "moderate to severe" for both 100-year and 500-year levels of shaking. This suggests much of area "a" could have *Medium* liquefaction vulnerability, while area "b" could have *High* liquefaction vulnerability.

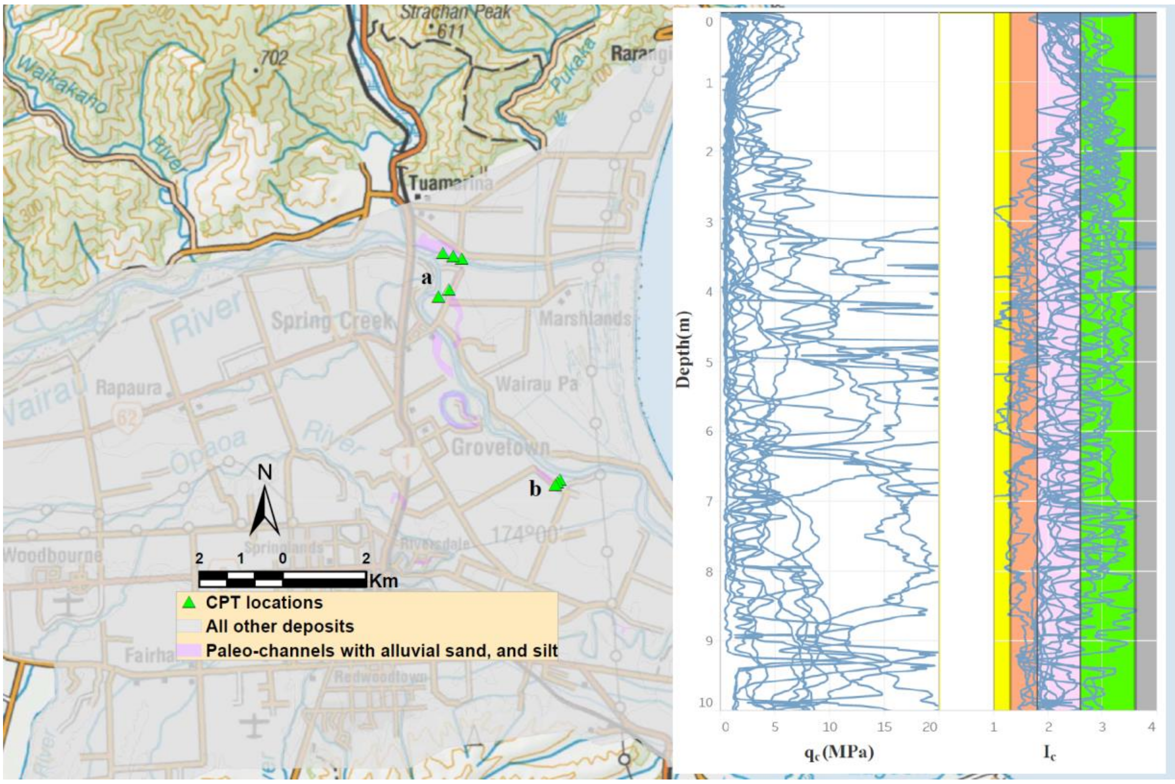
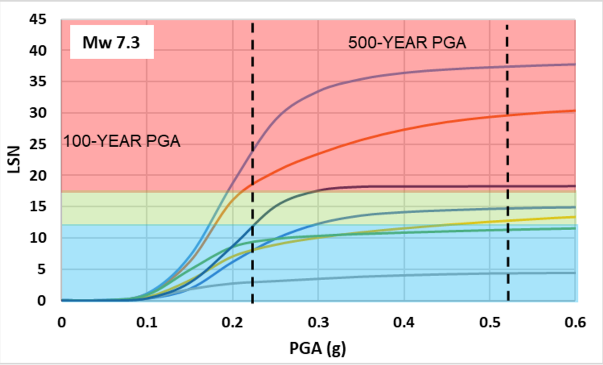
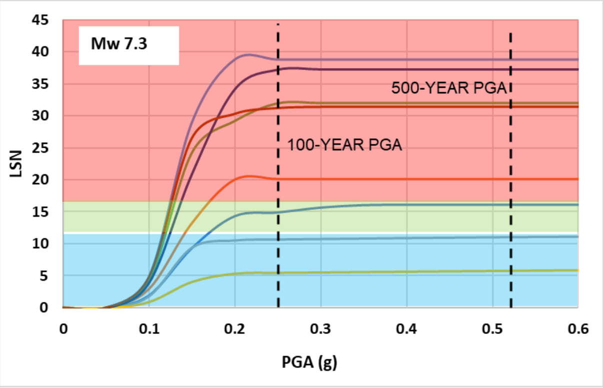


Figure 33: *Location of CPT soundings and CPT traces in the paleochannel alluvial sand and silt.*



(a)



(b)

Figure 34: Ground response curves for paleo channel alluvial sand and silt. (a) CPTs in focus area "a" for M_w7.3 (b) CPTs in focus area "b" for M_w7.3.

8.2 Proximal alluvial gravel, sand, and silt

Figure 35 shows the location of all CPT soundings available in the proximal alluvial gravel, sand silt formations. These are present proximal to both the Wairau and Opawa Rivers. The CPT traces are presented in Figure 35 and show that q_c values are 1 to 5 MPa for the upper 5 m of the soil profile, with q_c increasing below this depth for most of the soundings. I_c values range from clayey to silty soil characteristics for the upper 5 m, with traces in silt-sand mixtures. A number of traces shifts to more silty-sand characteristics below 5 m.

The ground response curves for all CPT soundings in Figure 36 shows that the degree of liquefaction-induced damage is "moderate to severe" for both the 100-year and 500-year levels of shaking for most locations, corresponding to a liquefaction vulnerability category of *High*.

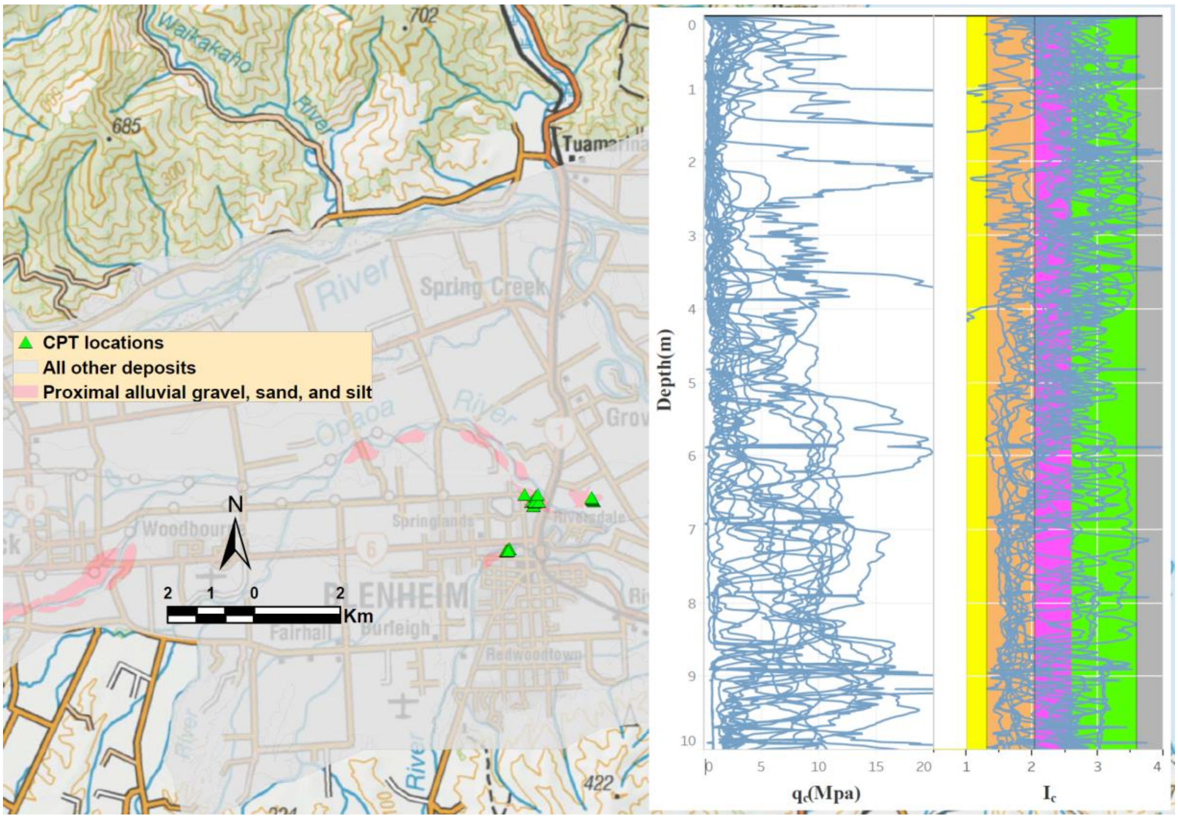


Figure 35: Location of CPT soundings and CPT traces in the proximal alluvial gravel, sand and silt deposits.

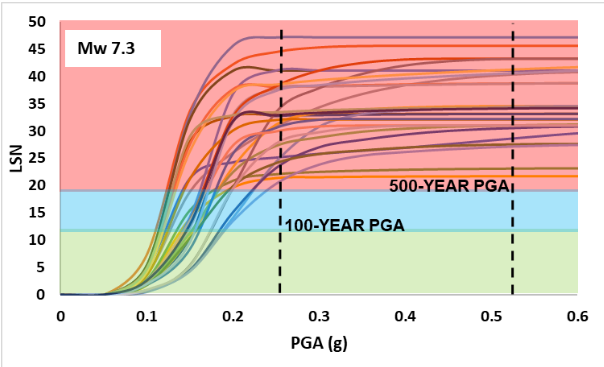


Figure 36: Ground response curves for proximal alluvial gravel, sand and silt for M_w7.3.

8.3 Low elevation overbank sand and silt

Figure 37 shows the locations of CPT soundings in the low elevation overbank sand and silt deposits. The deposits in this formation are subdivided into two focus areas and discussed. CPT traces presented in Figure 37 show a high degree of scatter, with variable intermixed soil stratigraphy throughout the 10 m depth. Values are low (1 to 6 MPa) from 0.5 to 2.5 m and after that increase rapidly for most of the traces. I_c values indicate the presence of sand-silt mixtures to silty clay behaviour for most of the traces.

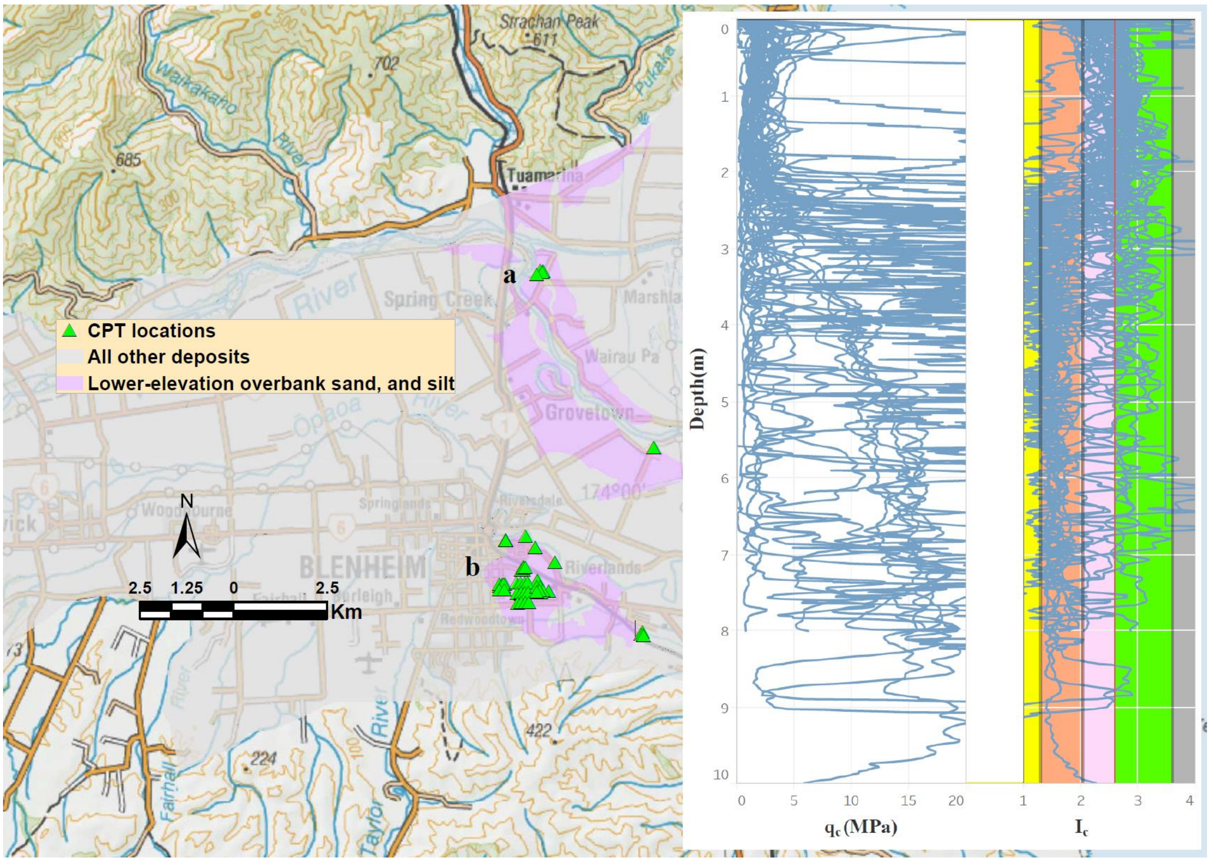


Figure 37: Location of CPT soundings and CPT traces in the low elevation overbank sand and silt deposits.

The ground damage response curves are presented in Figure 38. The degree of liquefaction-induced ground damage based on 100-year and 500-year level of shaking is “moderate to severe” for all of the CPTs at the location labelled “a” in Figure 37, suggesting that a *High* liquefaction vulnerability category could be applicable in this area. There is some scatter of the ground response curves for the CPTs at the location labelled “b”, with most of the curves falling into the “minor to moderate” and “moderate to severe” degree of liquefaction-induced ground damage zones for 500-year level of shaking. Some areas within section could have *High* liquefaction vulnerability based on overall trend of the curves.

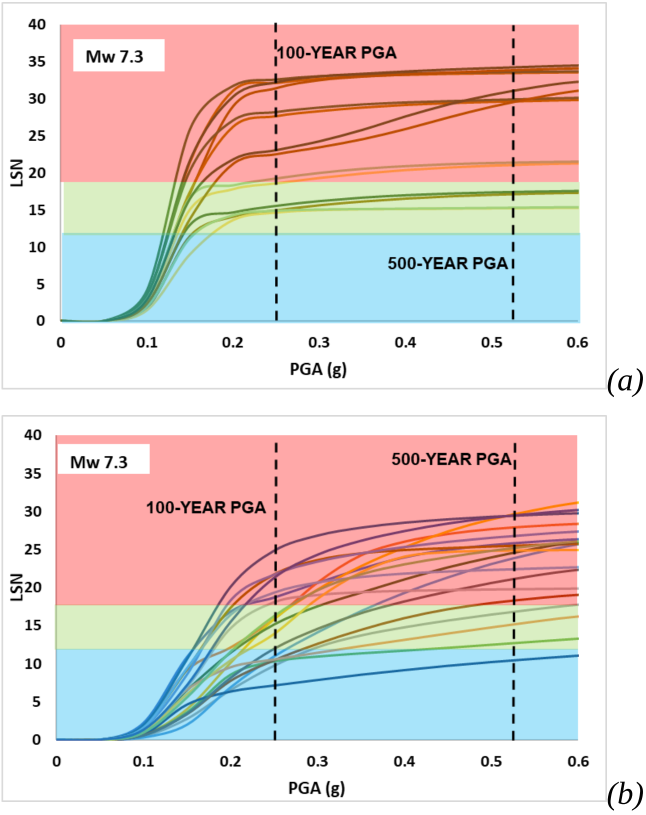


Figure 38: Ground response curves for low elevation overbank sand and silt (a) CPTs in focus area "a" for M_w7.3 (b) CPTs in focus area "b" for M_w7.3

8.4 Mid elevation overbank gravel, sand and silt

Figure 39 shows the CPT soundings available in mid-elevation overbank gravel, sand and silt formations. There are no CPTs in the northern polygons. In order to represent the trend and discuss liquefaction vulnerability, three focus areas are identified as shown in Figure 44. The CPT traces for this formation are presented in Figure 39, with q_c varying between 1 to 4 MPa to a depth of 2 m. There is a general increase in q_c with depth, albeit with a high degree of scatter. I_c values for most of the traces show that the upper 2 m is clayey silty soil and then these traces shift to sandy soil with depth.

The ground response curves in Figure 40 for these deposits show a large degree of scatter. Ground response curves for focus area "a" suggest a degree of liquefaction-induced ground damage for a 100-year level of shaking of "minor to moderate" and "moderate to severe" for most CPT soundings, shifting to "moderate to severe" for most of the CPT soundings for a 500-year level of shaking. This suggests that a liquefaction vulnerability category of *High* could be applicable to this focus area. Ground response curves for focus area "b" show that the degree of liquefaction-induced ground damage for 100-year level of shaking is "none to minor" for most of the CPT soundings and "minor to moderate" for 500-year level of shaking. This suggests a liquefaction vulnerability category of *Medium* could be applicable to this focus area. Ground response curves for focus area “c” shows that the degree of liquefaction-induced ground damage for both 100-year and 500-year level of shaking is “none to minor” for most of the CPT soundings. This suggests that a liquefaction vulnerability category of *Low* could be applicable to this focus area.

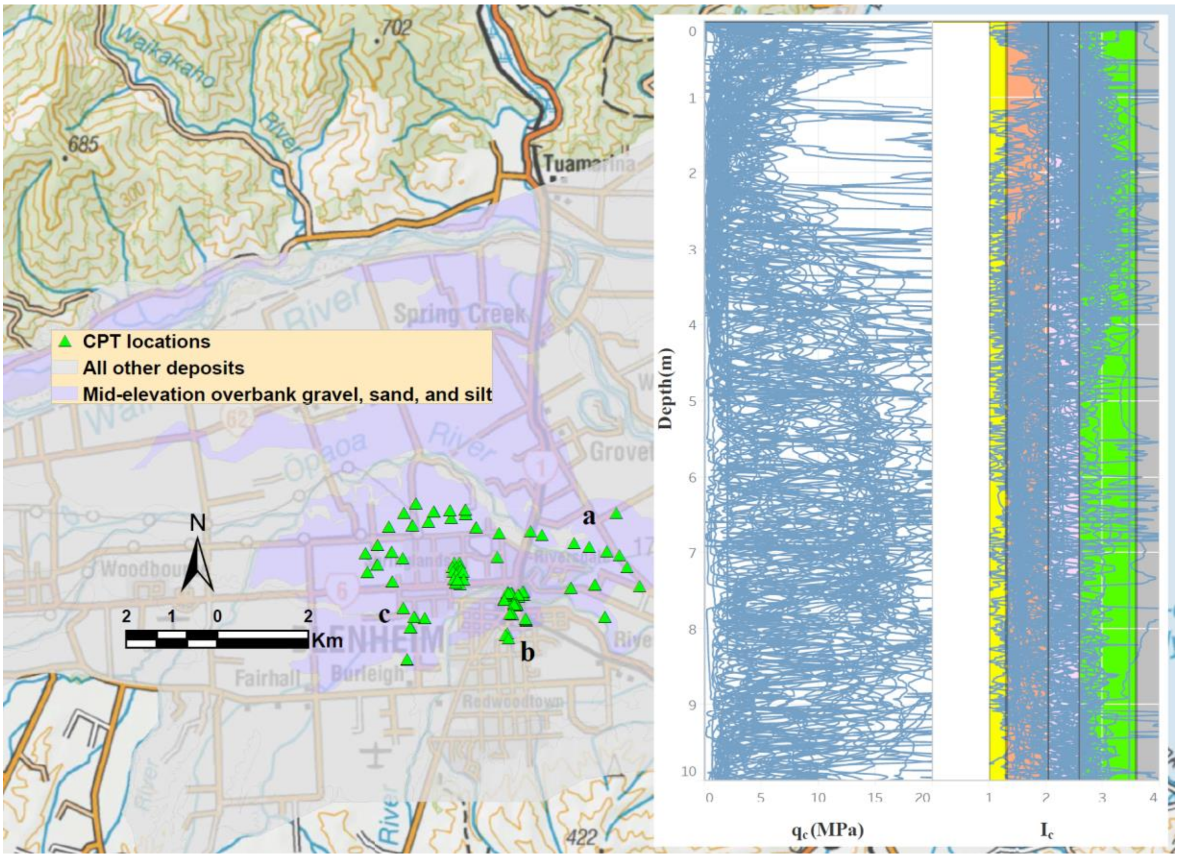
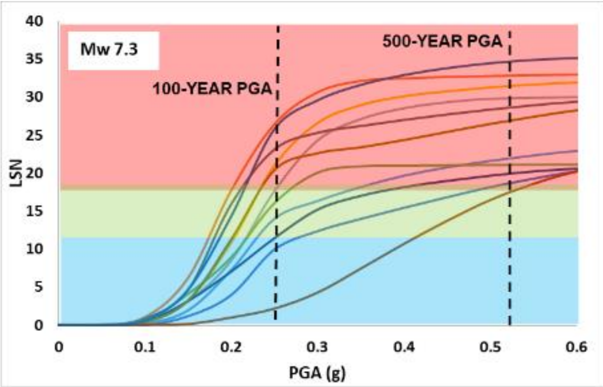
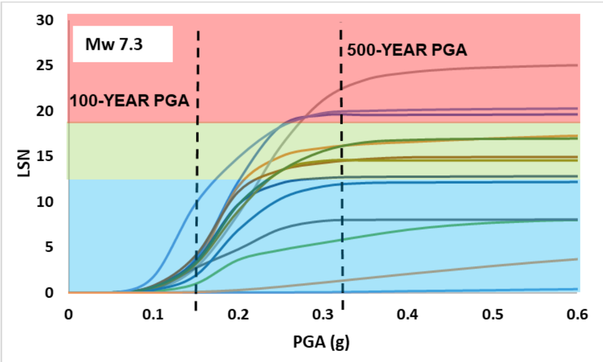


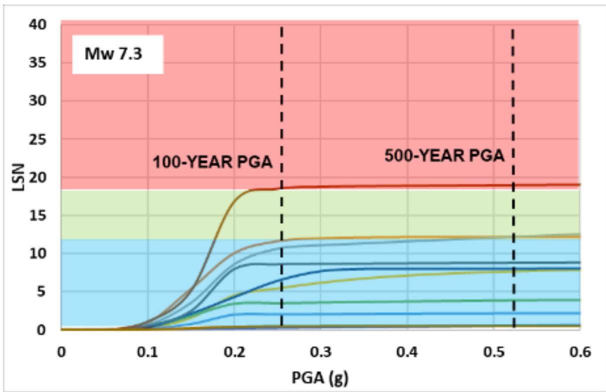
Figure 39: Location of CPT soundings and CPT traces in the mid-elevation overbank gravel, sand and silt deposits.



(a)



(b)



(c)

Figure 40: Ground response curves for mid-elevation overbank gravel, sand and silt (a) CPTs in focus area "a" for M_w7.3 (b) CPTs in focus area "b" for M_w7.3 (c) CPTs in focus area "c" for M_w7.3.

8.5 Recent alluvial sand and silt

Figure 41 shows the location of CPT soundings in recent alluvial sand and silt formations. CPT traces are presented in Figure 41 and show that q_c values are scattered with values of 1 to 3 MPa from the surface to a depth of 4 m, before increasing rapidly for most of the CPT soundings. I_c values suggest that the soil profile consists of sand-silt mixture soil types, with some clayey-silt like deposits from 1 to 3 m.

Ground response curves for this formation are presented in Figure 42. Most of the curves show that liquefaction-induced ground damage for both 100-year and 500- year level of shaking is “minor to moderate” and some curves with “moderate to severe”, with grouping of CPTs at different locations lacking any consistent trend. Due to the scatter liquefaction vulnerability is not easily assigned, with both *High* and *Medium* classifications possible across this area.

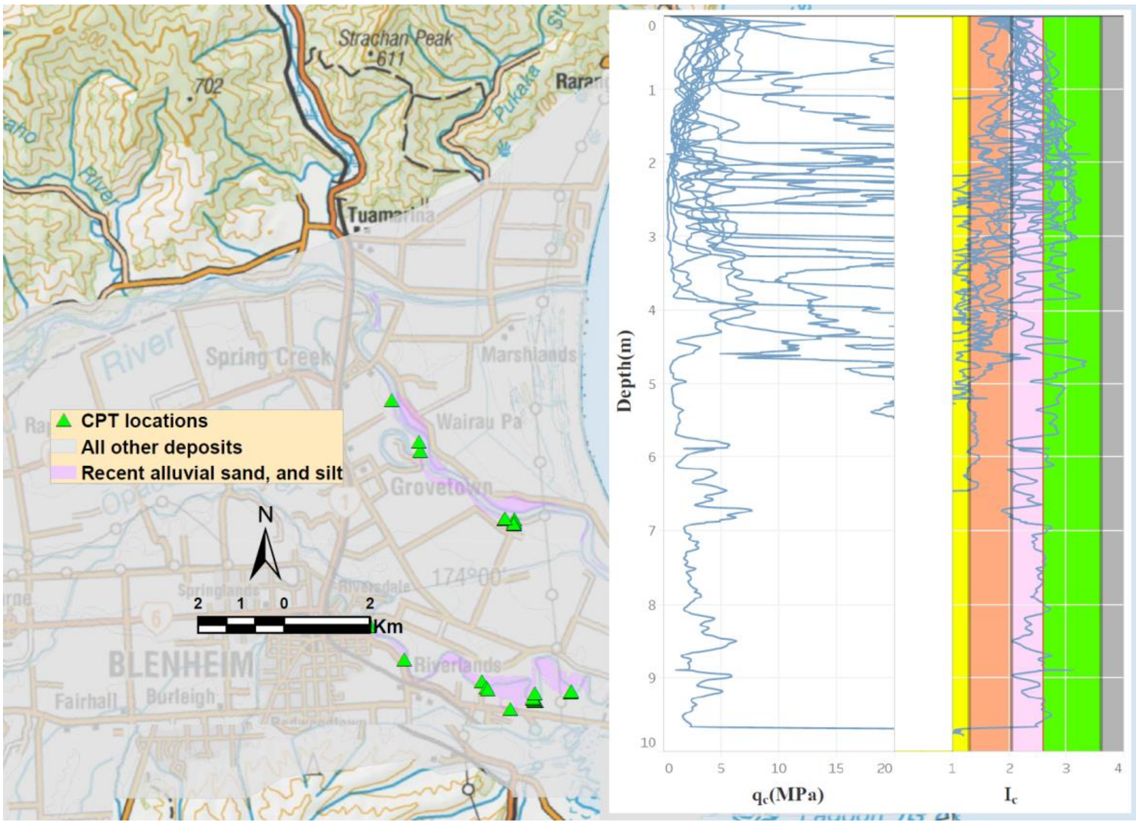


Figure 41: Location of CPT soundings and CPT traces in the recent alluvial sand and silt deposits.

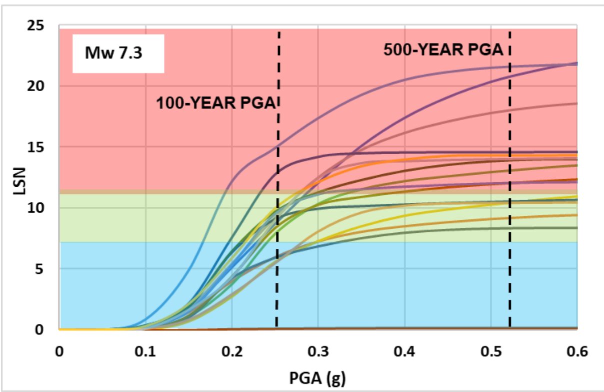


Figure 42: Ground damage response curves in recent alluvial sand and silt for M_w7.3.

8.6 Regional scenario maps

In order to summarise the overall performance, summary figures are presented for different scenarios and presented in Figures 43 to 50. LSN values are overlaid on a map of the geomorphic zones and the colour scheme from Table 3 is used to highlight the degree of liquefaction induced ground damage. Table 6 summarises the scenario details related to each of these figures. The main purpose of these scenario maps is to mix and match the M_w and PGA to see the variation of the degree of liquefaction-induced ground damage with the variation in PGA and groundwater depth. It will give the overall picture that which scenario can be most drastic in terms of liquefaction damage and also how the variation of ground water is affecting the overall response. For example, for a M_w7.3 earthquake and a PGA of 0.52g, many CPT soundings which show “moderate to severe” in Figure 44 shift to “none to minor” in Figure 48 as the groundwater depth increases from 1 m to 2 m. Similarly, Figure 44 and 46 shows the variation in the degree of liquefaction-induced ground damage as PGA shifts from 0.52g to 0.26g, keeping all other factors constant.

Table 6: Summary of the input details for the scenarios presented in Figures 43 to 50.

Figure No.	Magnitude (M_w)	Groundwater depth	PGA
43	6.8	1	0.52
44	7.3	1	0.52
45	6.8	1	0.26
46	7.3	1	0.26
47	6.8	2	0.52
48	7.3	2	0.52
49	6.8	2	0.26
50	7.3	2	0.26

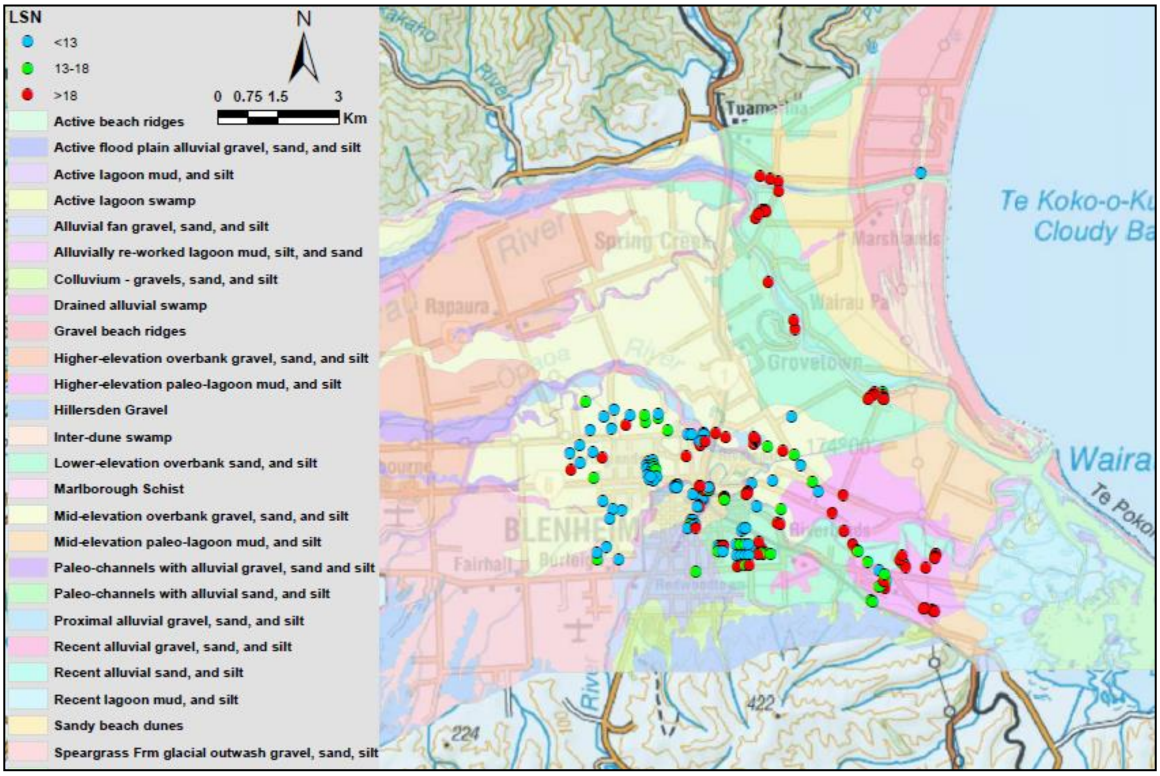


Figure 43: CPT analysis overlaid on geomorphic zones for M_w6.8, 0.52g PGA and 1 m groundwater depth.

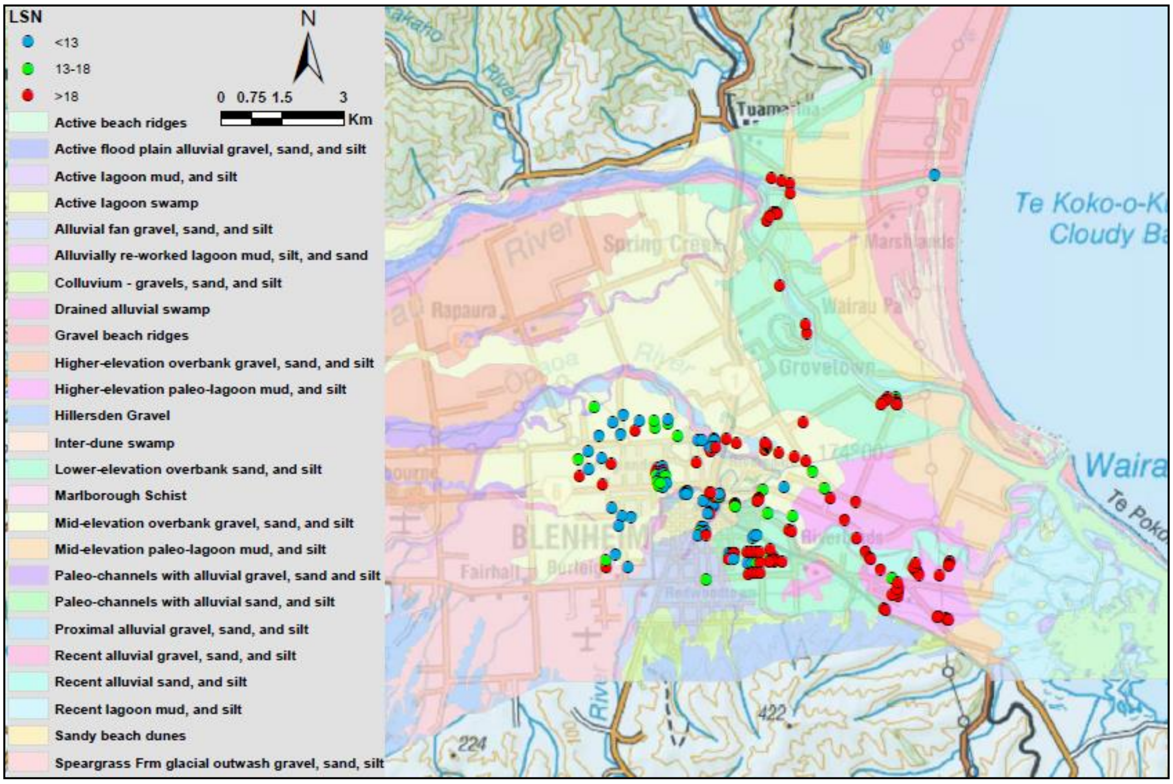


Figure 44: CPT analysis overlaid on geomorphic zones for M_w7.3, 0.52g PGA and 1 m groundwater depth.

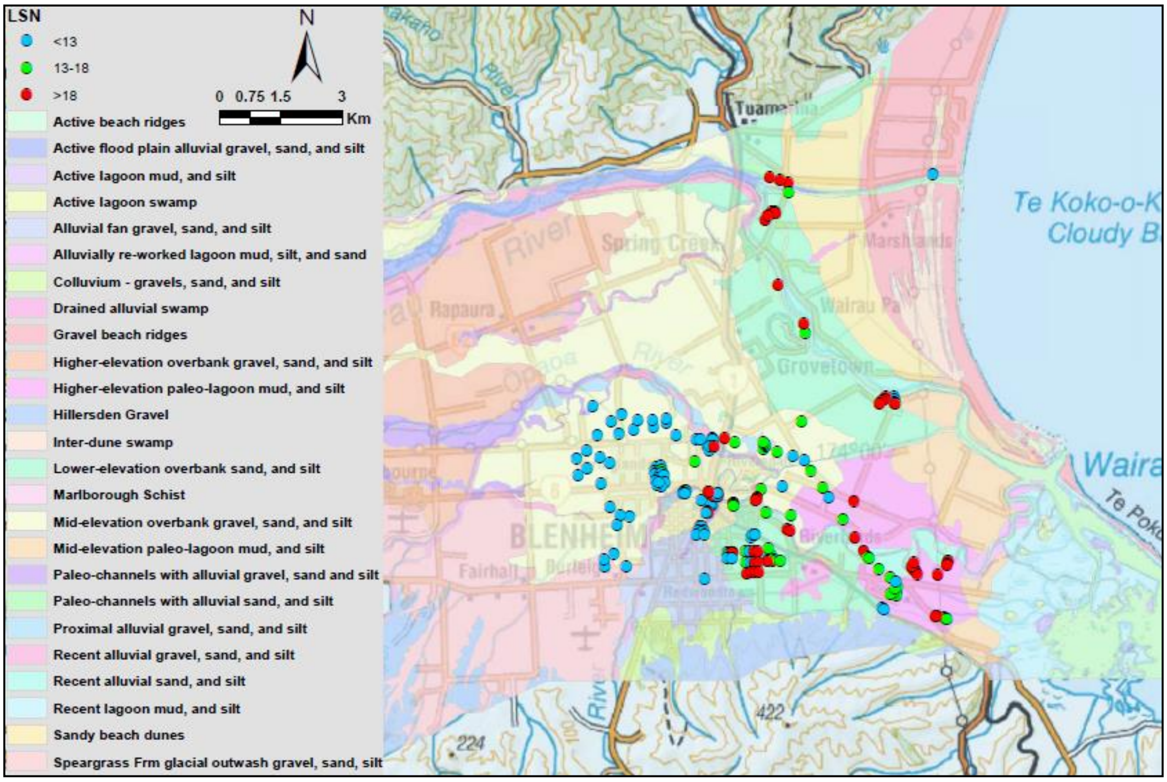


Figure 45: CPT analysis overlaid on geomorphic zones for M_w6.8, 0.26g PGA and 1 m groundwater depth.

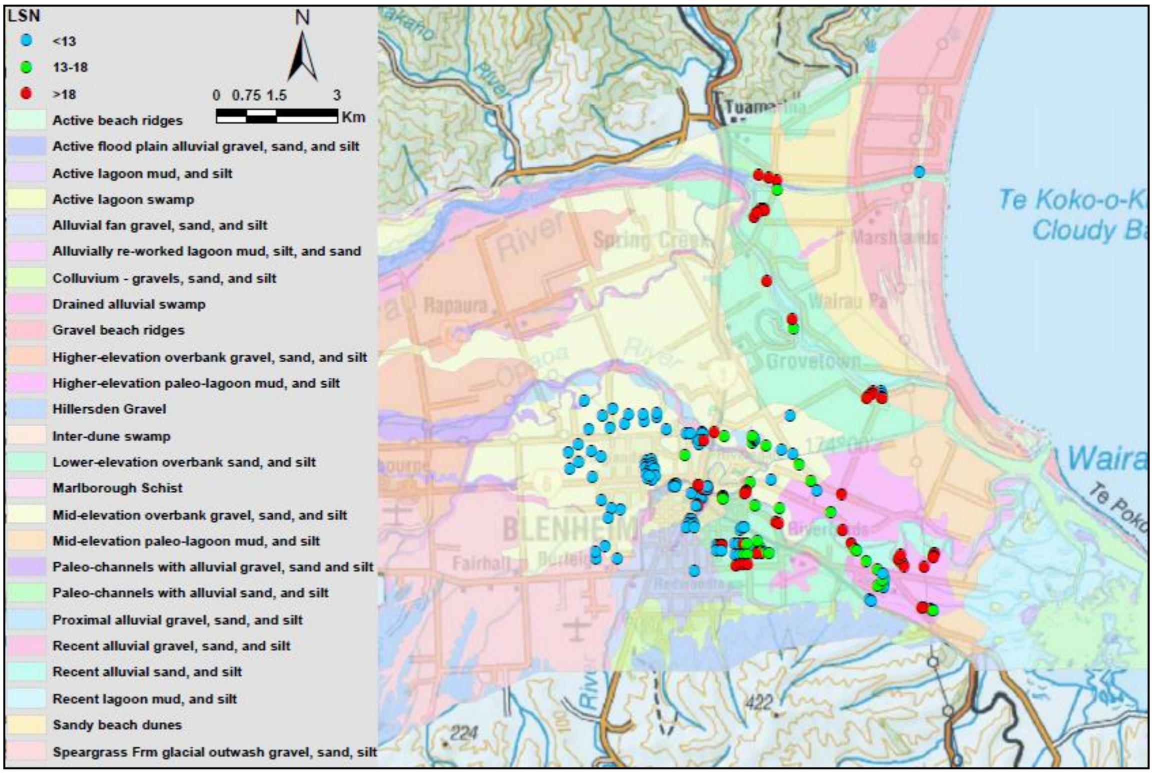


Figure 46: CPT analysis overlaid on geomorphic zones M_w7.3, 0.26g PGA and 1 m groundwater depth.

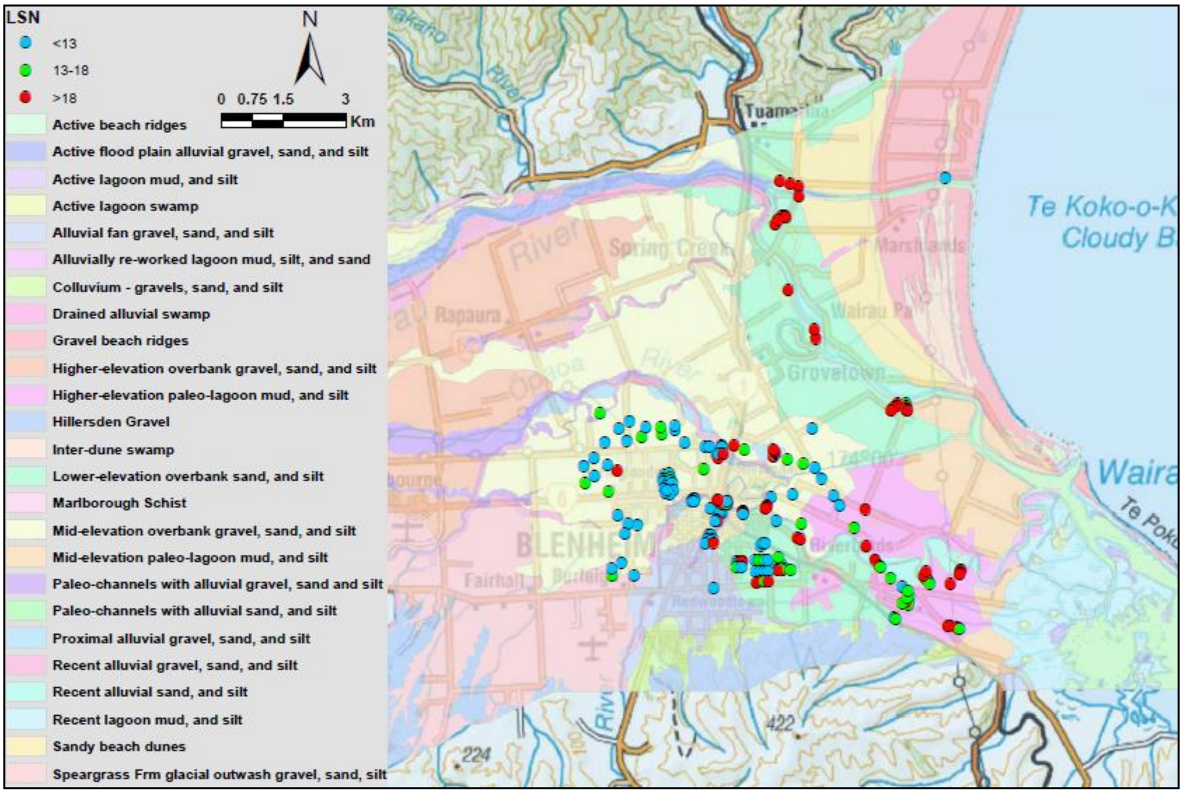


Figure 47: CPT analysis overlaid on geomorphic zones for M_w6.8, 0.52g PGA and 2 m groundwater depth.

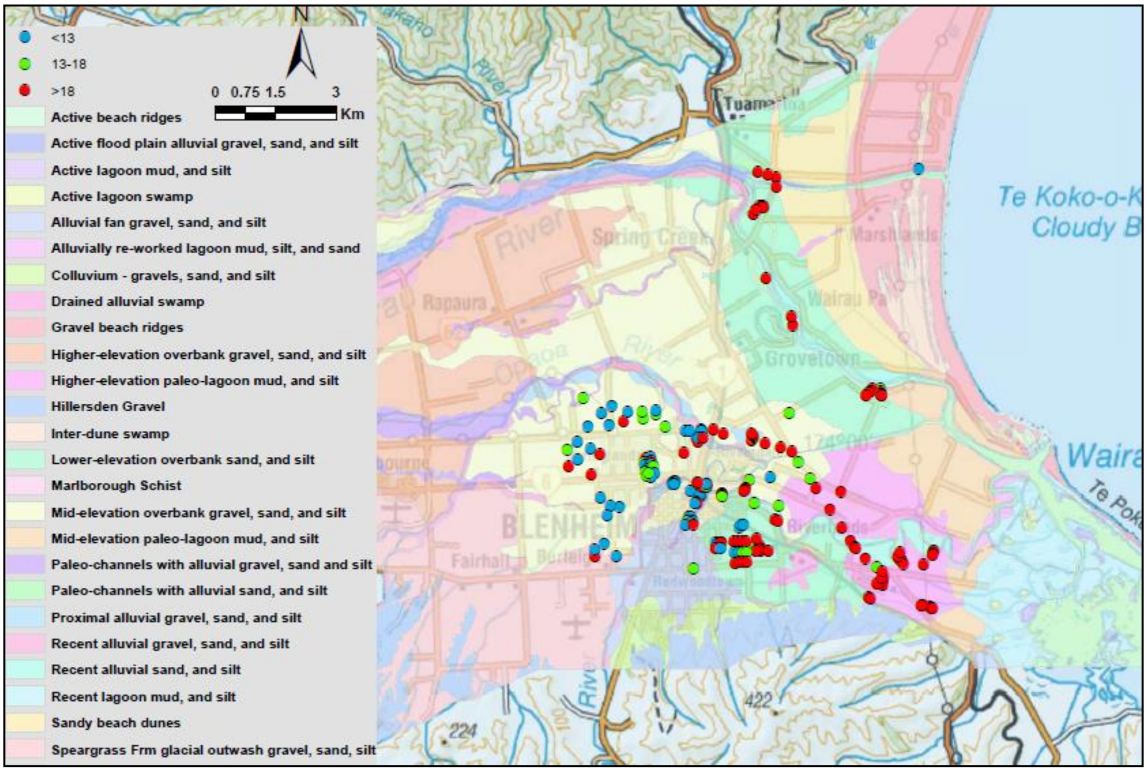


Figure 48: CPT analysis overlaid on geomorphic zones for M_w7.3, 0.52g PGA and 2 m groundwater depth.

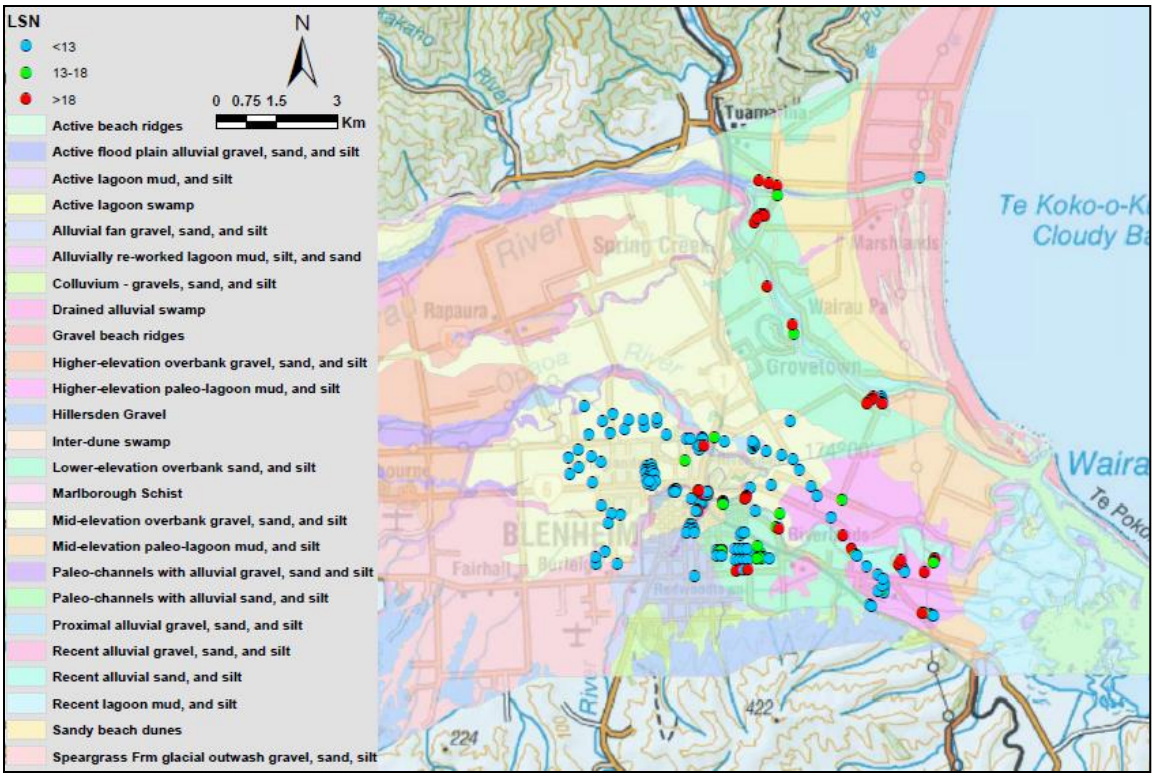


Figure 49: CPT analysis overlaid on geomorphic zones forM$_w$6.8, 0.26g PGA and 2 m groundwater depth.

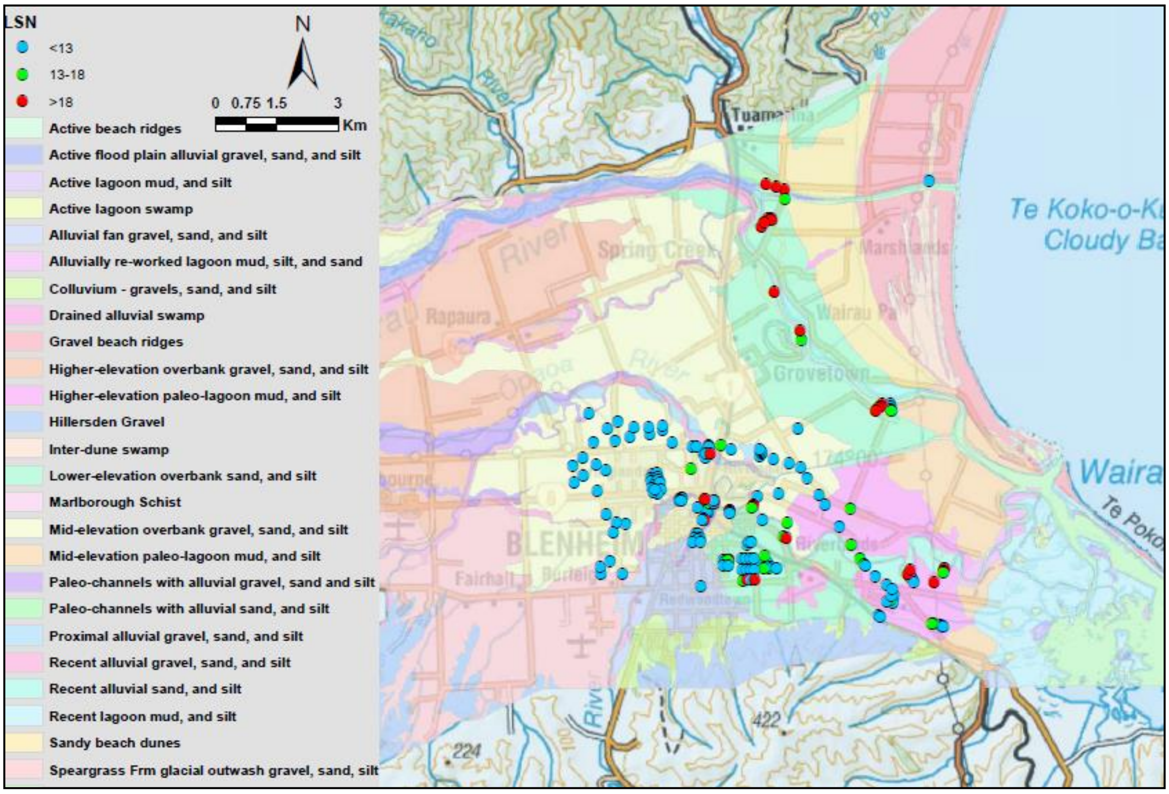


Figure 50: CPT analysis overlaid on geomorphic zones for M$_w$7.3, 0.26g PGA and 2 m groundwater depth.

8.7 Summary

The analyses described in this section provide an initial indication of the performance of the soil profiles across the region based on site investigation data. CPT soundings are only available in Blenheim and the surrounding area. As this is a regional level study and considering the overall low density of CPT soundings available across the region and within each geomorphic zone, updated categories *(Low, Medium, and High)* as the result of the Level C assessment are not able to be applied. The results from these initial CPT analyses agree well with the geomorphology-based screening presented in Section 7 of the report. In most geomorphic zones with CPT data there are areas suggesting that High liquefaction vulnerability would be appropriate. Only in the small localised areas in the vicinity of the groups of CPTs within each geomorphic zones could an updated liquefaction vulnerability category be applied. There is no CPT data available in the rest of the study area and it is recommended that more geotechnical investigations be carried out in areas with a *Liquefaction damage is possible* category to further refine the liquefaction vulnerability categories.

9 LATERAL SPREADING VULNERABILTY

Observations from previous earthquakes demonstrate that liquefaction-induced lateral spreading can cause significant damage to buildings, infrastructure and the environment. Therefore, consideration of the potential for lateral spreading should be applied when undertaking a liquefaction vulnerability assessment.

Lateral spreading can cause disproportional damage to urban infrastructure, over and above, that from the vertical settlement effects of liquefaction alone. However, lateral spreading is very difficult to accurate quantify and/or predict with any high degree of certainty, being a highly complex process dependent upon multiple variables including:

- The elevation difference between the base of the free-face (i.e., a road cutting, old terrace or a riverbank) and the elevation of the land at the point of interest;
- The distance (L) from the base of the free face to the point of interest;
- The earthquake ground motions including Peak Ground Accelerations (PGA) and earthquake magnitude (Mw);
- The thickness, relative density and location of liquefying layers within the soil profile; and
- Additional topographic and geological boundary conditions.

When considering the potential for lateral spreading adjacent to a free-face, the Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017) notes that "It is less likely (but not impossible) for lateral spreading to occur if there is no liquefied soil within a depth of 2H of the ground surface (where H is the height of the free-face. However, with the information available for this study it is difficult to accurately define the free face height (H).

Severe lateral spreading was observed as a result of the Kaikōura earthquake along the Opaoa River which greatly impacted the adjacent land and the cross-sectional characteristics of the river. The latter was identified by MDC and locals through observing flooding in the sections of the Opaoa River close to the Blenheim Township during smaller rainfall events than those prior to the Kaikōura earthquake.

Ogden (2018) identified by thorough investigation of lateral spreading manifestations in the region and predictions that for lateral-spreading no one measurement or prediction tool can be used to comprehensively model or estimate the potential effects. For example, the extent of lateral spreading along the Opaoa River is dependent on several factors that are inferred from CPT q_c and I_C traces and river cross-sections The study by Ogden (2018) also highlighted that the simplified liquefaction procedures provided a reasonable estimation of liquefaction vulnerability evaluated against observations in relatively uniform profiles comprising fine-grained non-plastic deposits. However, there was a substantial proportion of sites at which there was computed over-prediction from the simplified methods. Potential inaccuracies in the ground motion and groundwater surfaces that were developed for the region could account for a small proportion of the false positive predictions. However, the largest source of over-prediction was found at sites with significant degrees of interlayering present in the subsurface profile.

In the absence of evidence to provide region specific guidance, the MBIE guidance is applicable for the Lower Wairau Plains. This guidance suggests that there should be particular attention given to land within 100 m of a free face with a height less than 2 m, and 200 m for a free face greater than 2 m.

10 REFERENCES

Basher, L.R., Lynn, I.H. & Whitehouse, I.E. (1995). Geomorphology of the Wairau Plains: implications for floodplain management planning. *Landcare Research Science Series No. 11, Manaaki Whenua Press, Lincoln,* 42p

Bastin, S. H., Ogden, M., Wotherspoon, L. M., van Ballegooy, S., Green, R. A. & Stringer, M. (2018). Geomorphological influences on the distribution of liquefaction in the Wairau plains, New Zealand, following the 2016 Kaikōura earthquake. *Bulletin of the Seismological Society of America, 108(3B), 1683-1694.*

Bastin, S., van Ballegooy, S., Mellsop, N. & Wotherspoon, L. (2020). Liquefaction case histories from the 1987 Edgecumbe earthquake, New Zealand–Insights from an extensive CPT dataset and paleo-liquefaction trenching. *Engineering Geology*, *271*, 105404.

Bastin, S.H., van Ballegooy, S. & Wotherspoon, L. (2017). Cross-Checking Liquefaction Hazard Assessments with Liquefaction Observations from New Zealand Earthquakes and Paleo-liquefaction Trenching Proc. *20th NZGS Geotechnical Symposium.*

Benson, A., Hill, N., Little, T. & Van Dissen, (2001). *Paleoseismicity, rates of active deformation, and structure of the Lake Jasper pull-apart basin, Awatere Fault, New Zealand*. EQC research report 97/262. School of Earth Sciences, Victoria University of Wellington.

Bouckovalas, G. & Dakoulas, P. (2007). Liquefaction performance of shallow foundation in presence of a soil crust, *Earthquake Geotechnical Engineering, Chapter 11, 245-276*

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

Cubrinovski, M., Bradley, B.A., Wentz, F. & Balachandra, A. (2021). Re-evaluation of New Zealand seismic hazard for geotechnical assessment and design, *Bulletin of the New Zealand Society for Earthquake Engineering*, accepted for publication.

Davidson, P. & Wilson, S. (2011). *Groundwaters of Marlborough*. New Zealand: Marlborough District Council.

Fryirs, K. and G. Brierley (2012*). Geomorphic Analysis of River Systems: An Approach to Reading the Landscape*, John Wiley & Sons, Chichester, United Kingdom.

GEER (2017). *Geotechnical Reconnaissance of the 2016 M_w 7.8 Kaikoura, New Zealand Earthquake. Version 1: 10 June 2017,* Report of the National Science Foundation - Sponsored Geotechnical Extreme Events Reconnaissance (GEER) Team.

Grace, K. T. (2015). *Meander loop migration and liquefaction susceptibility: liquefaction along the Heathcote River during the 2010-11 Canterbury earthquake sequence*. MSc Thesis, University of Canterbury, New Zealand

Green, R. A., Maurer, B. W. & van Ballegooy, S. (2018). The influence of the non-liquefied crust on the severity of surficial liquefaction manifestations: Case history from the 2016 Valentine's Day earthquake in New Zealand. In *Geotechnical Earthquake Engineering and Soil Dynamics V: Liquefaction Triggering, Consequences, and Mitigation* (pp. 21-32). Reston, VA: American Society of Civil Engineers.

Ishihara, K., Acacio, A. A. & Towhata, I. K. U. O. (1993). Liquefaction-induced ground damage in Dagupan in the July 16, 1990 Luzon earthquake. *Soils and Foundations, 33(1), 133-154.*

Maurer, B.W., Green, R.A. & Taylor, O.-D.S. (2015). Moving Towards an Improved Index for Assessing Liquefaction Hazard: Lessons from Historical Data, *Soils and Foundations, JGS, 55(4), 778-787.*

Marlborough District Council MDC (2012). *Blenheim urban growth study geotechnical evaluation.* Marlborough New Zealand

MBIE/MfE/EQC. (2017). *Planning and engineering guidance for potentially liquefaction-prone land.* Wellington: MBIE/MfE

Mellsop, N. (2017). *Liquefaction Case Histories from the 1987 Edgecumbe Earthquake – Insights from an Extensive CPT Dataset, Direct Push Cross Hole Shear and Compression Wave Velocity (VSVP) Testing and Paleo-liquefaction Trenching*. ME Thesis, University of Auckland.

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

Ogden, M. (2018). *Assessment of Liquefaction from New Zealand Case Histories: With insights from liquefaction -induced land damage, over the Lower Wairau Plains, caused by the 2016 Kaikoura earthquake*. Master's Thesis, University of Auckland, New Zealand

Pyke R. (2003). Discussion of liquefaction resistance of soils: Summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soil. *Journal of Geotechnical and Geoenvironmental Engineering, American Society of Civil Engineers, 129(3): 283-284.*

Rattenbury, M. S., Townsend, D. B. & Johnston, M. R. (2006). Geology of the Kaikoura Area, 1: 250 000 Geological Map 13. *GNS Science, Lower Hutt, New Zealand*.

Robertson, P. K. & Wride, C. E. (1997). Cyclic liquefaction and its evaluation based on SPT and CPT: Seismic Short Course on Evaluation and Mitigation of Earthquake Induced Liquefaction Hazards. In *NCEER Workshop, San Francisco, CA*.

Robertson, P. K. & Wride, C. E. (1998). Evaluating cyclic liquefaction potential using the cone penetration test. *Canadian geotechnical journal*, *35*(3), 442-459.

Stringer, M., Beyzaei, C., Cubrinovski, M., Bray, J., Riemer, M., Jacka, M. & Wentz, F. (2015). Liquefaction characteristics of Christchurch silty soils: Gainsborough Reserve. In *6th Int. conf. on earthquake geotechnical engineering, Christchurch*.

Towhata, I., Yasuda, S., Yoshida, K., Motohashi, A., Sato, S. & Arai, M. (2016). "Qualification of residential land from the viewpoint of liquefaction vulnerability," *Soil Dynamics and Earthquake Engineering, 91, 260-271.*

Tonkin & Taylor (2013). *Liquefaction Vulnerability Study*. Report prepared for the Earthquake Commission, New Zealand., Auckland

Tonkin + Taylor (2015). *Cantebury Earthquake Sequence: Increased liquefaction vulnerability methodology*. Retrieved from The Earthquake Commission: http://www.eqc.govt.nz/ILV-engineering-assessment-methodology

Van Ballegooy, S., Lacrosse, V., Simpson, J. & Malan, P. (2015). Comparison of CPT-based simplified liquefaction assessment methodologies based on Canterbury Geotechnical Dataset. In *Proc. Of the 12th Australia New Zealand Conference on Geomechanics* (pp. 618-625).

Van Ballegooy, S., Malan, P., Lacrosse, V., Jacka, M. E., Cubrinovski, M., Bray, J. D. & Cowan, H. (2014). Assessment of liquefaction-induced land damage for residential Christchurch. *Earthquake Spectra*, *30*(1), 31-55.

White, P. A., Tschritter, C. & Davidson, P. (2016). Groundwater-surface water interaction in a coastal aquifer system, Wairau Plain, Marlborough, New Zealand. *Journal of Hydrology (New Zealand), 55(1), 25.*

Wotherspoon, L.M., Pender, M..J. & Orense, R.P. (2012). Relationship between observed liquefaction at Kaiapoi following the 2010 Darfield earthquake and former channels of the Waimakariri River, *Engineering Geology, 125: 45-55.*

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

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

Youd, T.L. & Garris, C.T. (1995). Liquefaction-induced ground surface disruption, *ASCE Journal of Geotechnical Engineering, 121 (11), 805 – 809*

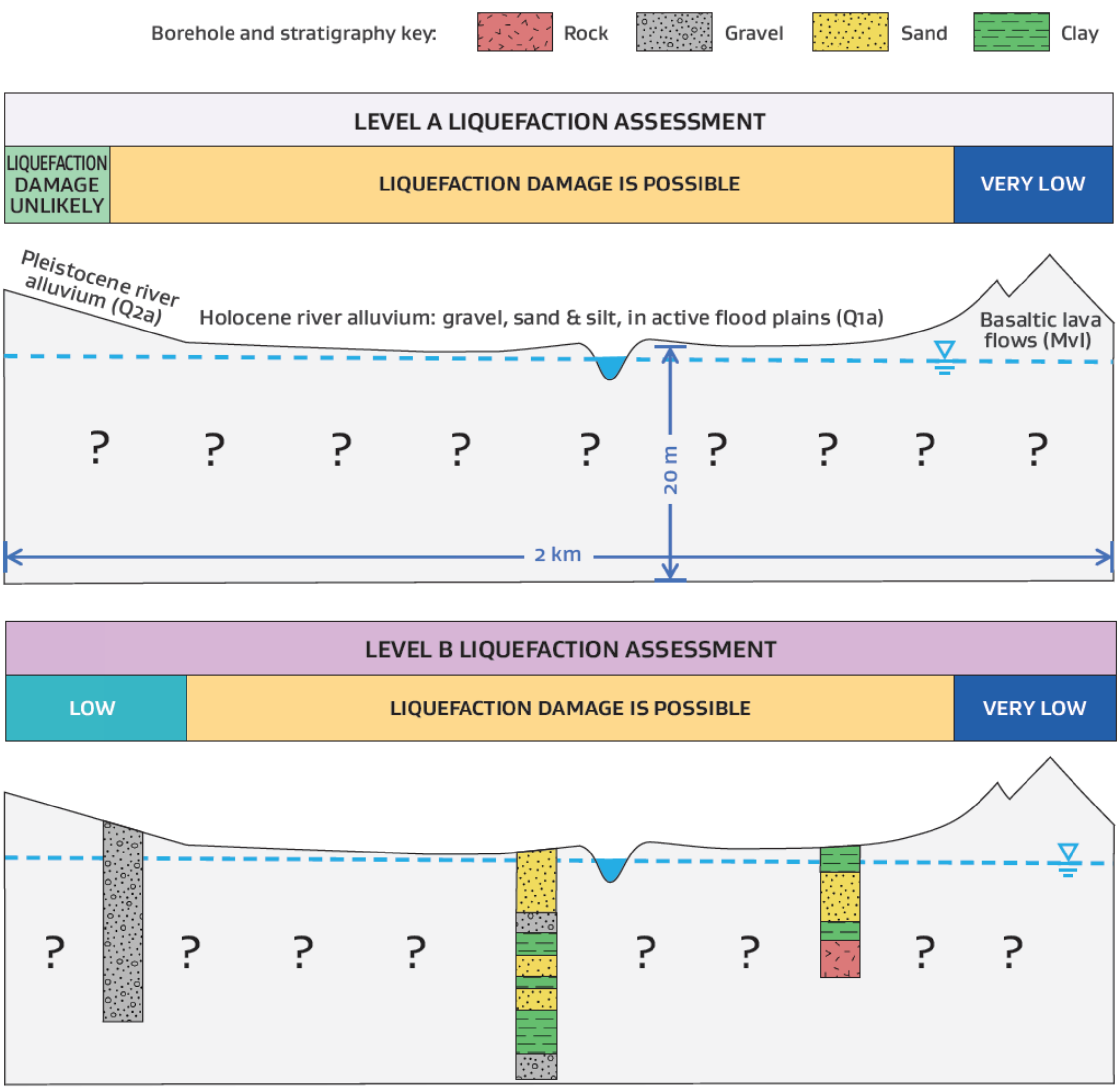
APPENDIX A

Explanation of assigning precise categories following Level B assessment (extracted from *MBIE/MfE/EQC 2017)*

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

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

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



APPENDIX B

Details of different degrees of liquefaction-induced ground damage

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

Notes:

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

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

Figure B1: Degrees of liquefaction-induced ground damage used in the land performance framework. (MBIE/MfE/EQC 2017).