Assessment of liquefaction risk in the Hawke's Bay
Volume 1: The liquefaction hazard model

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EXECUTIVE SUMMARY

This study was commissioned by Hawke’s Bay Regional Council and the Natural Hazards Research Platform to re-evaluate the liquefaction hazard across the region as described in Dellow et al (1999) and to evaluate the consequential risk posed by liquefaction. The timing of this study allowed knowledge gained from the recent experiences of the 2010-2011 Canterbury Earthquake Sequence (CES) and the 2016 Kaikoura earthquake to be used for the evaluation of the liquefaction hazard, and for damage calibration for risk analysis. GNS Science was commissioned to coordinate the study, with Tonkin + Taylor being subcontracted to bring their Canterbury and Kaikoura experience into the study and provide geotechnical input.

The objectives of this study are to:

- Refine and improve existing liquefaction susceptibility maps for the Hawke’s Bay region, including Central Hawke’s Bay and Wairoa, using existing geological and geotechnical data to identify areas prone to liquefaction.
- Define an unconfined groundwater surface for the project area using existing data.
- Develop an updated earthquake ground motion model for Hawke’s Bay, based on the National Seismic Hazard Model, and evaluate return periods/ground motions for various earthquake events.
- Produce liquefaction hazard maps for Hawke’s Bay for different return period levels of earthquake shaking based on the updated liquefaction susceptibility mapping, available geotechnical data on the NZGD and probabilistic seismic hazard model information.
- Recommend options for improving Hawke’s Bay resiliency to the effects of liquefaction during likely future earthquake events. A liquefaction land vulnerability map for the Heretaunga Plains and liquefaction planning maps for the wider Hastings District (beyond the Heretaunga Plains), Wairoa District and Central Hawke’s Bay District are presented in this report as a basis for considering options for improving the resilience of the domestic housing stock. Other options for improving Hawke’s Bay resiliency to liquefaction are included in Volume 3 of this report (e.g. via land-use planning, other building/engineering options, and pre-event response and recovery planning).

The report has been divided into four Volumes. This volume covers the derivation of the Liquefaction Hazard Model. The Appendices for Volume 1 are presented separately in volume 2. Volume 3 deals with Analysing and Managing Liquefaction Risk and the Appendices for this work are presented separately in Volume 4.

Liquefaction effects have been reported in the Hawke's Bay region during four historical earthquakes since 1840 at Modified Mercalli (MM) shaking intensities between MM7 and MM10. The reported ground damage effects include sand boils and water ejection, ground surface subsidence and settlement, fissuring and lateral spreading. Since 1840, at least seven earthquakes have produced Modified Mercalli (MM) shaking intensities of MM7 or greater in the Hawke's Bay Region. MM7 is the shaking intensity at which liquefaction generally begins to be triggered in susceptible soils.

The fundamental components of the study were the determination of the geographic distribution of the geological, geomorphological, groundwater and geotechnical conditions which affect liquefaction susceptibility and earthquake shaking intensity which dictate the severity and extent of liquefaction. This was done for each of the population centres for given

return periods of earthquake shaking. The return periods of interest agreed to for this study ranged from 25 years (10% probability of occurrence in 2.5 years) to 2500 years (10% probability of occurrence in 250 years). This range spans often-used return periods for expected damage – 25 years for the serviceability level (no damage expected) to 2500 years which is reserved for damage assessment of critical facilities (buildings such as hospitals and emergency services).

The assessment of liquefaction hazard for the Hawke's Bay region required several new datasets and models to be developed to facilitate this. They were:

- A shallow (20 m depth) 3D model of the subsurface geology.
- A model of the shallow unconfined groundwater surface developed using existing data.
- A dataset of material properties to 20 metres depth (as characterised by Cone Penetration Tests (CPTs)).
- A process to assess the liquefaction hazard at a site based on parameters at a site as determined by the above models, using the Liquefaction Severity Number (LSN).

LSN is an index developed by Tonkin + Taylor that uses the geotechnical properties and groundwater conditions at a site to estimate the potential for liquefaction ground damage to occur for a given earthquake shaking intensity. It was developed using groundwater monitoring data, and the CPT data collected after the Canterbury earthquake sequence (2010-2016), calculated based on the earthquake shaking intensity and correlated with the observed ground damage.

Shaking intensities for the main Hawke's Bay population centres were derived from the New Zealand National Probabilistic Seismic Hazard Model, which has been updated for Hawke's Bay as part of the project. Peak Ground Accelerations (PGAs) were used as a measure of ground motion for the study and were derived for five return periods: 25, 100, 500, 1000, and 2500 years. The liquefaction analyses carried out for this report showed the liquefaction hazard did not increase between the 500-year return period and the 2500-year return period so results are only presented for the 25- 100- and 500-year return periods.

The key findings from the hazard component of the study are as follows:

- There is a liquefaction hazard present in several areas of Hawke's Bay. The areas with a liquefaction hazard are mostly low-lying areas near the coastline. Liquefaction causes ground deformation that has the potential to damage buildings and infrastructure, but it is not expected to result in building collapse or to heighten life-safety risk levels for single-story timber framed residential houses.
- This report can be used to understand the variation, spatially and temporally of liquefaction hazards in Hawke's Bay. There is no unique solution as to the liquefaction hazard of any site since the liquefaction potential is driven by many variables some of which are seasonal (groundwater depth), some that are site specific (density and composition of the near-surface soil conditions), and some that are event dependent (the shaking intensity at any specific site, the magnitude of the triggering event and the source to site distance). Thus, apart from being able to identify specific site conditions where liquefaction is unlikely to occur (gravels and hilly terrain), all other sites can be expected to experience liquefaction to a greater or lesser extent when shaken severely enough and for long enough. The greatest uncertainty with respect to the liquefaction analysis undertaken for this report is in the groundwater data. Improved data showing the seasonal fluctuations of the groundwater surface could result in changes (increase or decrease) the liquefaction planning maps presented in this report.

- This report can, in conjunction with the draft liquefaction planning guidelines (Ministry for the Environment and Ministry of Business, Innovation and Employment, 2017), be used as a guide to policy and planning decisions. This report allows for liquefaction hazards to be considered and planned for prior to future residential development. The consideration of liquefaction, and mitigation of its effects, will improve the resilience of Hawke's Bay communities.
- The liquefaction land vulnerability map (Figure 8.1) is suitable for use in conjunction with the district plans for Napier City and Hastings District. The liquefaction hazard planning map can be used to delineate, at the property level on the district plan, the appropriate means to identify, investigate and/or mitigate the liquefaction hazard that may or may not be present at the property.
- The liquefaction planning maps for Wairoa District, Central Hawke's Bay District and Hastings District (beyond the Heretaunga Plains) (Figure 8.2, Figure 8.3 and Figure 8.4) are not suitable for use in conjunction with their respective district plans because of the scale difference between the underpinning geological maps (1:250,000) used to delineate the liquefaction susceptibility and most district plan maps (1:1500 to 1:25,000) and the limited datasets used to compile the maps. The liquefaction planning maps for Wairoa District, Central Hawke's Bay District and Hastings District (beyond the Heretaunga Plains) meet the requirements for a Level A liquefaction assessment, a basic desktop assessment as set out in Table 3.1 of the liquefaction planning guidelines (Ministry for the Environment and Ministry of Business, Innovation and Employment, 2017).
- The Hawke's Bay region is seismically more active than is the Canterbury region and must expect to experience shaking strong enough to initiate liquefaction more often, but perhaps with less severity than was observed in Canterbury in 2010-2011.
- The current maps are necessarily conservative to address the uncertainties in the data sources. As additional subsurface and groundwater data becomes available and the science of liquefaction prediction improves the maps presented in this report will need review and revision.

1.0 INTRODUCTION

1.1 PROJECT PURPOSE AND BACKGROUND

Since the 2010–2011 Canterbury Earthquake Sequence (CES), there has been heightened concern about liquefaction hazard throughout New Zealand. Much of the damage to residential buildings and infrastructure in Christchurch and the surrounding rural areas was caused by permanent ground damage, including liquefaction and lateral spreading in areas close to rivers, wetlands and estuaries (Brackley, 2012). The Natural Hazards Research Platform ('the Platform') was established by the Government as a vehicle for determining a natural hazards research direction having regard to its critical strategic importance to New Zealand. The Platform, in consultation with Hawke's Bay Regional Council (HBRC) (on behalf of the Local Authorities) and the Earthquake Commission (EQC), saw the merit in an assessment of the hazard and risk of the Hawke's Bay Region to earthquake induced liquefaction, for the Local Authorities. The Platform provided funding for the project, along with co-funding from EQC and the Local Authorities (HBRC, Napier City Council (NCC), and Hastings District Council (HDC). Additional co-funding was provided by GNS Science from its Crown research funding.

GNS Science, as an anchor research organisation for the Platform and as the lead Crown Research Institute in geological hazards, risk mitigation, and societal impacts of natural hazards, was requested by the Platform to lead the project. The project was developed in conjunction with HBRC, led by Lisa Pearse, acting on behalf of the Local Authorities. The scope was discussed and refined based on feedback from the Local Authorities and from a technical steering group established to guide the project. The members of the Technical Steering Group are listed in Appendix 1.

In historic times, the Hawke's Bay region has experienced moderately high levels of seismicity relative to most other areas of the country. Since 1840, at least five large, shallow earthquakes have produced shaking intensities of MM7 or greater on the Heretaunga Plains in Hawke's Bay that have resulted in liquefaction, including the damaging 1931 Napier earthquake (Dellow et al., 1999). It has long been recognised that the Hawke's Bay region has areas of land that are susceptible to liquefaction and that Napier is ranked second to Christchurch in terms of liquefaction hazard (Begg et al., 2013). The 2010-2016 Canterbury Earthquake Sequence (CES) and the 2016 Kaikoura Earthquake have provided a wealth of new data and a better understanding of the nature of liquefaction that can now be applied elsewhere in New Zealand.

1.2 SCOPE

The project predominantly used existing data, with little scope for collection of new geotechnical data. It covers Napier City and Hastings District Council parts of the Heretaunga Plains, Central Hawke's Bay and Wairoa. This report builds on and updates previous liquefaction studies that have been carried out in the Hawke's Bay region (e.g., Dellow et al., 1999, 2003). This report and appended maps provide refined and improved liquefaction hazard and risk information due to the recent availability of several important digital datasets, including LiDAR topographic coverage, soil maps (S-Map), the HBRC borehole database, and new geotechnical data available in the NZGD.

Areas susceptible to liquefaction have been identified using geomorphologic and soils maps along with information on subsurface ground conditions. A regional approach to ensure uniform coverage, if possible, to identify areas vulnerable to damaging liquefaction was an objective of the project.

Information from this project can be used by the Local Authorities for:

- Review and preparation of plans and making decisions on resource consent applications under the Resource Management Act 1991 (RMA).
- Hazard mapping for Hawke's Bay civil defence and emergency management purposes.
- Informing processes and decisions made by the Local Authorities under the Building Act and Local Government Official Information Act (LGOIA) (i.e., Building Consents and LIMS).

The project objectives were to:

- Refine and improve existing liquefaction susceptibility maps for the Hawke's Bay region, including Central Hawke's Bay and Wairoa, using existing geological and geotechnical data to identify areas prone to liquefaction.
- Define an unconfined groundwater surface for the project area using existing data.
- Develop an updated earthquake ground motion model for Hawke's Bay, based on the National Seismic Hazard Model, and evaluate return periods/ground motions for various earthquake events.
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2.0 BACKGROUND INFORMATION

2.1 THE LIQUEFACTION PHENOMENON

Earthquakes pose hazards to the built environment through five main types of processes. These processes include strong ground shaking, primary breakage of the ground surface (fault rupture), deformation of the ground surface due to fault rupture (tectonic tilting, differential uplift and subsidence), seismically-induced gravitational slope movements (slope failures), and ground surface deformation resulting from soil liquefaction. This report focuses on documenting the nature and distribution of soils that are susceptible to soil liquefaction in the Hawke's Bay Region.

The section below has mostly been adapted from the Institution of Professional Engineers of New Zealand Liquefaction fact sheet (IPENZ 2012) (Figure 2.1) and the GNS Science publication by Saunders and Berryman (2012) titled: 'Just add water: when should liquefaction be considered in land use planning?'.

In New Zealand, the most widespread observations of liquefaction since European settlement were in the CES (Cubrinovski et al., 2011, Cubrinovski et al., 2012). However, earlier instances of significant liquefaction were documented after the 1848 Marlborough, 1855 Wairarapa, 1901 Cheviot (liquefaction observed in Kaiapoi), 1929 Murchison, 1931 Napier, 1968 Inangahua, and 1987 Edgecumbe earthquakes. Most of these events generated strong shaking in coastal regions with extensive deposits of recent, cohesionless, fine-grained, sedimentary deposits (Fairless & Berrill, 1984; Hancox et al., 1997). The effects of soil liquefaction during these earthquakes were the ejection of water and sand (sand boils) and lateral spreading. These phenomena resulted in vertical and horizontal displacement of the ground surface which caused extensive damage to buildings, wharves, roads and bridges, embankments, and buried services (e.g., Hancox et al., 1997).

This section of the report provides background information on the basic principles of liquefaction science including a summary of the liquefaction process and description of the terms liquefaction susceptibility, liquefaction triggering and liquefaction vulnerability. It concludes with a discussion of historic liquefaction in the Hawke's Bay Region and a summary of previous liquefaction hazard studies in Hawke's Bay.

2.2 THE LIQUEFACTION PROCESS

It can be readily observed that dry, loose sands and silts contract in volume if shaken. However, if the loose sand is saturated, the soil's tendency to contract causes the pressure in the water between the sand grains (known as 'pore water') to increase. The increase in pore water pressure causes the soil's effective grain-to-grain contact stress (known as 'effective stress') to decrease. The soil softens and loses strength as this effective stress is reduced. This process is known as liquefaction.

The elevation in pore water pressure can result in the flow of water in the liquefied soil. This water can collect under a lower permeability soil layer and if this capping layer cracks, rush to the surface bringing sediment with it. This process causes ground failure and, with the removal of water and soil, a reduction in volume and hence subsidence of the ground surface.

The surface manifestation of the liquefaction process is the water, sand and silt ejecta that can be seen flowing up to 2 hours following an earthquake. The path for the ejecta can be a geological discontinuity or a man-made penetration, such as a fence post, which extends down to the liquefying layer to provide a preferential path for the pressurised water. The sand often forms a cone around the ejecta hole. With the dissipation of the excess pore-water pressure, the liquefied soil regains its pre-earthquake strength and stiffness.

The surface expression of liquefaction, water and sand depends on several characteristics of the soil and the geological profile. If there is a thick crust of non-liquefiable soil such as a clay, or sand that is too dense to liquefy during the particular level of shaking of the earthquake, then water fountains and sand ejecta may not be seen on the surface. The amount of ground surface subsidence is generally dependent on the density of the sand layers as well as how close the liquefying layers are to the surface. Ground surface subsidence increases with increasing looseness in the soil packing.

2.3 THE LIQUEFACTION VULNERABILITY ASSESSMENT PROCESS

The assessment of liquefaction vulnerability involves: estimating the liquefaction susceptibility of the soils being assessed; estimating whether or not liquefaction will be triggered in a susceptible soil layer for a given depth to groundwater and level of ground shaking; and estimating the vulnerability to liquefaction damage at the ground surface for a given soil profile.

For each of these steps there are several assessment methods which have been developed and these have evolved over time.

2.3.1 Liquefaction Susceptibility

Liquefaction susceptibility is a physical characteristic of a soil that determines whether it can liquefy. Soils that are susceptible to liquefaction typically have no to low plasticity, and low to moderate permeability. Liquefaction susceptibility is independent of the level of shaking required to trigger liquefaction; this is part of the assessment of the liquefaction resistance of the soil (refer to Section 2.3.2 for discussion about liquefaction triggering).

The first step in the liquefaction assessment process is to determine whether a soil layer is susceptible to liquefaction (Kramer, 1996). If a soil layer is not susceptible to liquefaction, by definition, liquefaction cannot be triggered and that layer will not contribute to liquefaction vulnerability. Therefore, liquefaction triggering assessments should only be undertaken on soil layers that have been assessed as being susceptible to liquefaction.

The susceptibility of a soil to liquefaction depends on its compositional characteristics and state in the ground. Factors affecting this include history or age and geologic environment (Idriss & Boulanger, 2008). Soils that are cohesive in nature such as clays with high plasticity are not susceptible to liquefaction. The susceptibility of soils to liquefaction can be assessed based on the plasticity of fine grained clay particles. These are combined to define a 'cut-off' between soils that are, and are not, susceptible to liquefaction.

The soil behaviour Index (I_c) as determined from Cone Penetration Tests (CPTs) is a simple screening method to identify soils that are likely to be susceptible to liquefaction. As a default parameter, an I_c value of 2.6 is considered to be indicative of soils that are not susceptible to liquefaction (Robertson & Wride, 1998) and has been used for this study. For more detailed assessments, the I_c cut-off value should be calibrated to laboratory test results that are carried out on soil samples obtained from drilling adjacent to the CPT locations. A further process of screening susceptible soils is based on plasticity of the soils, as described in terms of a soil's plasticity index (determined from the Atterberg limits) and water contents obtained from laboratory testing (Bray & Sancio, 2006).

2.3.2 Liquefaction Triggering

Liquefaction is triggered in a susceptible soil layer if the soil layer is saturated and the level of shaking (usually due to an earthquake) is sufficiently large enough to overcome the soil's resistance to liquefaction. Smaller earthquakes do not tend to trigger liquefaction as readily as larger earthquakes. The level of shaking that causes liquefaction depends on the resistance of the soil layer being assessed. This resistance is based mainly on the soil's relative density, the soil fines content (either measured in the laboratory from borehole samples or estimated from the CPT q_c and f_s profile) and the groundwater levels.

Where the soil's fines content is estimated from the CPT I_c profile, the empirical relationship used to estimate the fines content should be calibrated for the soils being assessed based on laboratory testing of borehole samples. However, this was not done for this study.

The extent of liquefaction within a soil profile is typically assessed by analysing CPT test results. This assessment uses a recognised triggering method to obtain a continuous evaluation over the full depth profile of which layers are likely to liquefy, and which are not likely, for a given level of shaking.

The main published liquefaction triggering methodologies used in practice are Robertson and Wride (1998), Moss et al. (2006) and Idriss and Boulanger (2008). Extensive studies were undertaken to determine which liquefaction triggering methodologies best fitted observations during the CES. The results from these studies showed that the Idriss and Boulanger (2008) liquefaction triggering method produced a slightly better fit compared to the other methods.

The Idriss and Boulanger (2008) methodology for predicting liquefaction triggering was updated in 2014 (Boulanger and Idriss, 2014) The methodology is based in part on an expanded international liquefaction case history database incorporating 50 case histories from the CES. This updated method provides a better correlation to the observed land damage from the CES than previous methods and has been used for the Hawkes Bay liquefaction study.

2.3.3 Liquefaction Vulnerability

Land is vulnerable to liquefaction damage when it is exposed to the risk of land damage because of liquefaction in soil layers below the ground surface.

The effects of liquefaction may include ground surface subsidence, ejecta, ground cracking, loss of strength and lateral spreading, all typically resulting in differential ground surface subsidence. A schematic representation of these effects is shown in Figure 2.1 and photographs of liquefaction ejecta and lateral spread from the CES are shown in Figure 2.2 to Figure 2.8.

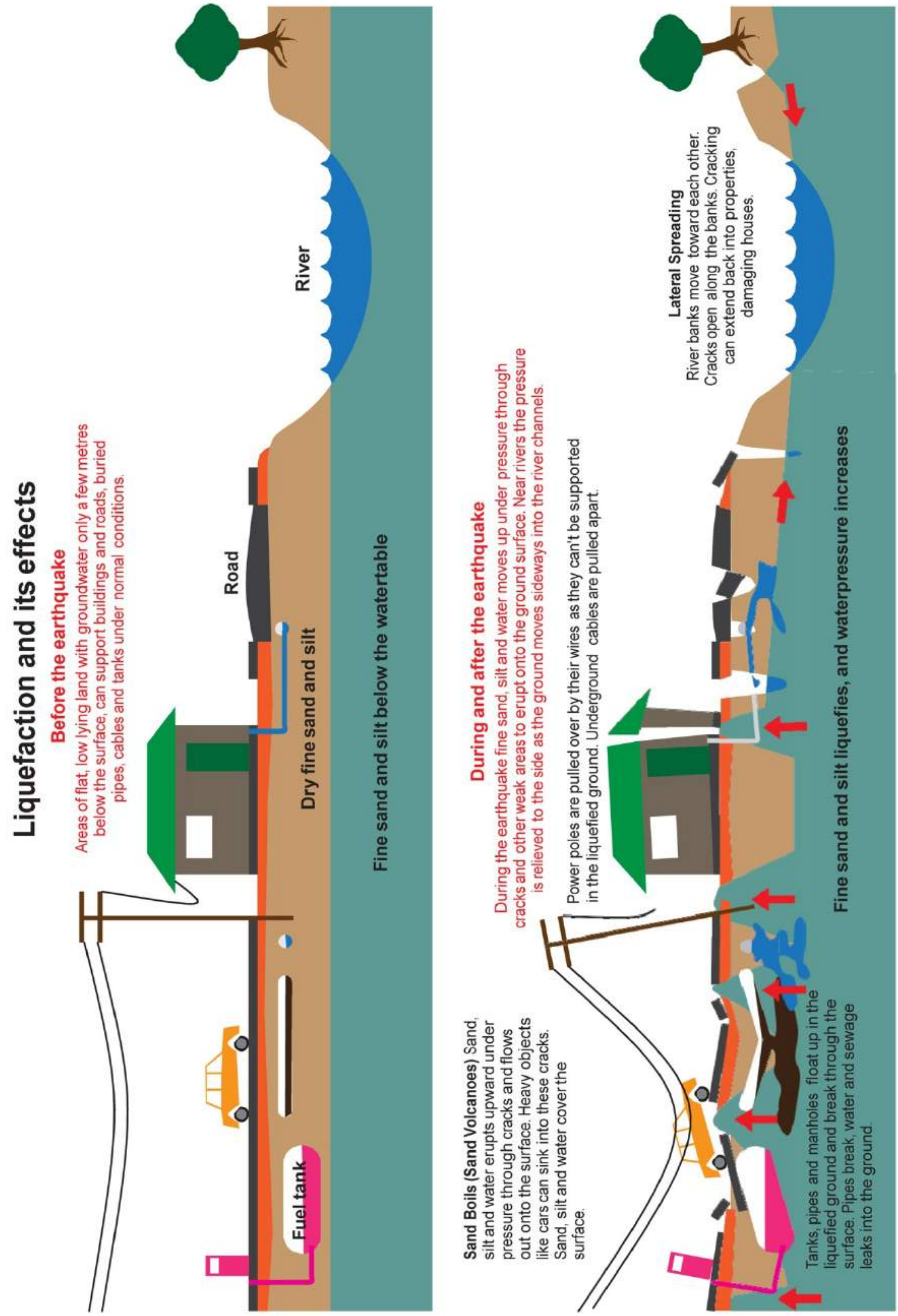

Figure 2.1 Schematic representation of liquefaction and its effects (Institution of Professional Engineers of New Zealand (IPENZ) Liquefaction fact sheet).

Figure 2.2 Liquefaction ejecta (sand boils) in Kaiapoi approximately 45 kilometres from the epicentre of the magnitude 7.1, 4 September 2010 Darfield earthquake. (Photo: N. Litchfield, GNS Science).

Figure 2.3 Liquefaction ejecta in a suburban Christchurch Street. In the suburb of Bexley, approx. 10 km from the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011. (Photo: NZ Herald).

Figure 2.4 Buoyancy of a pump-station floated up to 500 mm out of the ground by liquefaction adjacent to the Avon River near the eastern end of Morris Street, approx. 10 km form the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011. (Photo: D. Beetham, GNS Science).

Figure 2.5 Lateral spreading fissures run parallel to the Avon River in Avonside Drive, Christchurch, approx. 10 km from the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011. (Photo: D. Beetham, GNS Science)

Figure 2.6 Compression-induced buckling of a bridge over the Avon River near Medway Street due to lateral spreading displacement of the abutments approx. 10 km form the epicentre after the magnitude 6.3 Christchurch earthquake of 22 February 2011. (Photo: D. Beetham, GNS Science)

Figure 2.7 Liquefaction-induced lateral spreading through the foundation of a house in Kaiapoi approximately 45 kilometres from the epicentre of the magnitude 7.1, 4 September 2010 Darfield earthquake. (Photo: Tonkin + Taylor Ltd).

Figure 2.8 Damage to underground infrastructure from liquefaction, in this case lateral spreading has pulled a pipe joint apart in Cashmere after the magnitude 7.1 Darfield earthquake of 10 September 2010.

The extent and severity of the effects is dependent on the depth of the liquefying soil layers, their thickness and triggering shaking level, and the proximity to river banks, old river terraces and slopes and the corresponding height of these features. These effects may result in consequential land damage which in turn may result in damage to buildings situated on top of such land.

The severity of the consequential land damage depends in part on the thickness of the overlying non-liquefying soils which act as a protective raft over the liquefied soils. The greater the depth to liquefying soils, the lesser the effects observed at the surface. The amount of the consequential land damage is also dependent on the thickness of the liquefying layers and the relative density of the liquefying layers. Looser liquefying soils and thicker liquefying layers are likely to have a more adverse effect at the ground surface compared to denser liquefying layers, and liquefying layers that are deeper below the ground surface.

Also, the land in close proximity to river banks, old river terraces and slopes has a greater potential for lateral spreading damage to occur. This greater potential is dependent on the depth, thickness and relative density of the underlying liquefiable soil layers. The greater the height of these features the greater the potential for this damage to occur.

Liquefaction also causes overall ground surface subsidence. In low lying areas near rivers ground surface subsidence can result in houses becoming more flood prone and this can be exacerbated if there is accompanying tectonic subsidence. Conversely, ground subsidence caused by liquefaction can be mitigated if tectonic uplift occurs reducing the likelihood of houses becoming more flood prone.

Extensive studies have been undertaken on assessing the vulnerability of land to liquefaction damage on the flat land and lateral spreading damage (including Maurer et al., 2015, T+T, 2013 and 2015 and van Ballegooy et al., 2014b; 2015b). These liquefaction vulnerability studies show that liquefaction triggering of soil layers more than 10m below the ground surface provides a negligible contribution to liquefaction land damage at the ground surface.

CPT based methodologies commonly used to model liquefaction vulnerability include the following:

- Liquefaction settlements (S_{V1D}) calculated by integrating the one-dimensional post-liquefaction consolidation strains estimated for the soil profile using the method of Ishihara and Yoshimine (1992), as incorporated in Zhang et al. (2002);
- Liquefaction Potential Index (LPI) developed by Iwasaki (1978, 1982);
- Ishihara inspired LPI (LPI_{ISH}) developed by Maurer et al. (2015); and
- Liquefaction Severity Number (LSN) developed by Tonkin & Taylor (T+T) (2013).

For the purposes of the Hawkes Bay liquefaction study the LSN index has been used because, of the CPT-based indices, it was shown to provide the strongest correlation with land damage observations during the CES (van Ballegooy et al., 2014b, 2015a and 2015b) and the ground conditions in Canterbury are considered to be a reasonable proxy for those encountered in the Hawke's Bay region.

LSN is an index parameter based on observations in Christchurch after the CES, which characterises the vulnerability of land to damage due to liquefaction for a given level of ground shaking and a given groundwater level. The LSN parameter is defined in terms of the calculated volumetric reconsolidation strain (ε_v) integrated over the depth of the soil profile containing liquefying layers.

The LSN parameter is calculated by:

$$LSN = 1000 \int_0 \frac{\varepsilon_v}{z} dz$$

Where ε_v is calculated from Zhang et al. (2002) and z is the depth to the layer of interest in metres below the ground surface.

LSN gives a larger weighting factor to liquefying soil layers closer to the ground surface compared to liquefying layers at depth as was supported by general observations during the land mapping work in Christchurch, particularly the observation that ejection of liquefied material tended to result in significant differential settlements. It considers the balance between crust thickness and severity of underlying liquefaction. LSN allows the analysis of more complex layered soil profiles such as those commonly encountered throughout the Hawkes Bay. It incorporates the strength of the soil and assesses how severely the soil reacts once it becomes liquefied.

LSN uses the depth weighted calculated volumetric densification strain within soil layers as an indicator for the severity of liquefaction land damage likely at the ground surface. The published strain calculation techniques consider strains that occur where materials have a calculated triggering safety factor that reduces below 2.0. This means that the LSN begins to increase smoothly as factors of safety fall, rather than when the safety factor reaches 1.0 (i.e. the point at which liquefaction is triggered). One other aspect of LSN to note is that strains self-limit based on the initial relative density as the safety factor falls below 2.0, so a given soil profile has a maximum LSN that it tends towards as the PGA increases.

Studies were undertaken by van Ballegooy et al. (2014b; 2015b) to compare the estimated LSN values for the September 2010, February 2011 and June 2011 CES earthquakes with the corresponding mapped land damage. Figure 2.9 is a modified version of a figure from van Ballegooy et al. (2015b) which summarises the results.

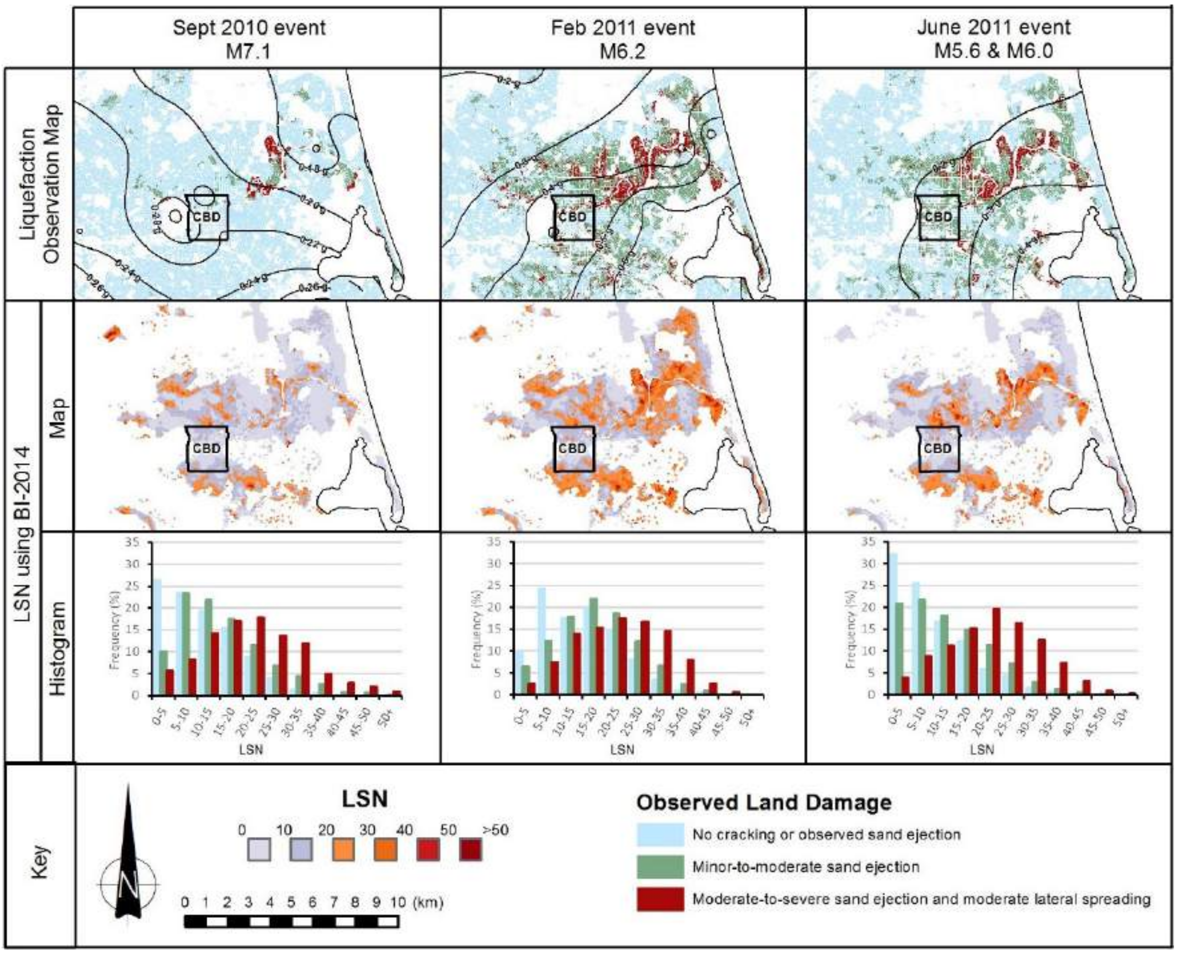

Figure 2.9 Maps of liquefaction severity observations (top row) and estimated LSN (second row) for the September 2010, February 2011 and June 2011 earthquake events. PGA contours from Bradley & Hughes (2013) are overlaid on the liquefaction severity observation maps (top row). Histograms of the liquefaction severity observations and their correlation with LSN are shown on the bottom row. This figure is modified from van Ballegooy et al. (2015b).

Figure 2.9 demonstrates a good spatial correlation between LSN and the liquefaction severity observations. Areas where high LSN values are estimated correlate well with the areas where moderate-to-severe land damage occurred. Conversely, areas where low LSN values are estimated correlate well with areas where none-to-minor land damage was observed. The frequency histograms in Figure 2.9 also produce consistent distributions of LSN values for each of the main CES events for the three different land damage groupings (i.e. none-to-minor, minor-to-moderate and moderate-to-severe). This consistent distribution of estimated land damage is a key advantage of the LSN parameter because it demonstrates that for a given estimated LSN value there is the same likelihood of liquefaction vulnerability whether for a small earthquake with a loose soil profile or a large earthquake with a medium dense to dense soil profile.

Based on the observed CES land performance compared with to the calculated LSN values, Table 2.1 provides a summary of the indicative land performance for different LSN ranges.

Table 2.1 General land performance for different LSN ranges (reproduced from New Zealand Geotechnical Society, 2016).

EFFECTS FROM EXCESS PORE WATER PRESSURE AND LIQUEFACTION	CHARACTERISTICS OF LIQUEFACTION AND ITS CONSEQUENCES	CHARACTERISTIC F_L, LPI
Insignificant	No significant excess pore water pressures (no liquefaction).	$F_L > 1.4$ LPI=0 LSN <10
Mild	Limited excess pore water pressures; negligible deformation of the ground and small settlements.	$F_L > 1.2$ LPI = 0 LSN = 5 – 15
Moderate	Liquefaction occurs in layers of limited thickness (small proportion of the deposit, say 10 percent or less) and lateral extent; ground deformation results relatively small in differential settlements.	$F_L \approx 1.0$ LPI < 5 LSN 10 – 25
High	Liquefaction occurs in significant portion of the deposit (say 30 percent to 50 percent) resulting in transient lateral displacements, moderate differential movements, and settlement of the ground in the order of 100mm to 200mm.	$F_L < 1.0$ LPI = 5 – 15 LSN = 15 – 35
Severe	Complete liquefaction develops in most of the deposit resulting in large lateral displacements of the ground, excessive differential settlements and total settlement of over 200mm.	$F_L << 1.0$ LPI > 15 LSN > 30
Very severe	Liquefaction resulting in lateral spreading (flow), large permanent lateral ground displacements and/or significant ground distortion (lateral strains/stretch, vertical offsets and angular distortion).	

2.4 HISTORIC LIQUEFACTION IN HAWKE'S BAY

Liquefaction effects have been reported in the Hawke's Bay region during historical earthquakes (Fairless and Berrill 1984, Dellow et al 1999, Hancox et al 2002, El Kortbawi 2017). The liquefaction effects and the Modified Mercalli (MM) intensity (Appendix 2) at which they occurred are summarised in Appendix 3. The reported ground damage effects include sand boils and water ejection, subsidence and settlement, fissuring and lateral spreading. The quality of the information available for the different earthquakes is highly variable and it is possible that some liquefaction-induced ground damage was not observed, recognised or reported, particularly during the early years of European colonisation (i.e., pre-1900). Since 1840, at least seven earthquakes have produced MM shaking intensities of MM7 or greater in the Hawke's Bay Region. Unequivocal liquefaction effects were reported for four of these events. However, the extent of liquefaction ground damage may be greater than has been reported because of the low population densities over much of the region, especially prior to 1900.

Historical reports show that many sites near the mouths of the rivers, or geologically very young river deposits have undergone liquefaction during these events. Areas specifically mentioned include:

- The Mahia Peninsula isthmus;
- The Whakaki lagoonal area;
- Wairoa township;
- Near the mouth of the Mohaka River;
- Near the Tongoio Lagoon;
- The former Ahuriri Lagoon;

- Along the banks of the Tutaekuri River between Taradale and the Ahuriri lagoon;
- The Heretaunga Plains as far inland as Hastings;
- Waiohiki;
- The Poukawa-Waipawa basins; and
- Near the beach at Porangahau.

The historical record confirms that liquefaction-induced ground damage is possible in the region. As the shaking intensity increases, the severity of the reported liquefaction also increases. An example of this is in the vicinity of the Tutaekuri River where sand boils were reported at MM7 (1863, 1904) and where lateral spreading occurred during MM10 shaking (1931) (Dellow et al., 1999).

In New Zealand, historical precedent evidence indicates that at least MM7 shaking is generally required for liquefaction (Hancox et al., 2002). Since 1840, at least seven and possibly nine earthquakes have generated MM7 or greater in parts of the Hawke's Bay Region. The date, epicentral location and Richter magnitude of these earthquakes are listed in Table 2.2, together with the MM intensity recorded in each of the four main population centres in the Hawke’s Bay area. More detailed descriptions of the liquefaction damage in Hawke’s Bay are contained in Appendix 3.

Table 2.2 Earthquakes generating Modified Mercalli shaking intensity 7 (MM7) or greater in the Hawke's Bay region since 1840 (from Dellow et al., 1999). Although the 1934 Pahiatua and 1990 Weber earthquakes did not produce MM7 in the main urban areas of the Hawke's Bay region, MM7 was probably reached in rural areas close to the southern boundary of the region.

Year	Date	Epicentral area	Magnitude	Maximum MM Intensity in the HBRC area Location of maximum MM Intensity in HBRC area			
				Waipawa[1]	Hastings[1]	Napier[1]	Wairoa
1855	23 January	Southern Wairarapa	M_w 8.2	7	6	6	5
1863	22 February	Otane/Waipawa	M 7.0	9	8	7	5
1904	8 August	Cape Turnagain	M_s 6.8	7	7	7	5
1914	22 November	Bay of Plenty	M ≥ 7.2	7	7	7	7
1921	28 June	Central Hawke's Bay	M_s 6.4	6	7	7	6–7
1931	3 February	Napier	M_s 7.8	8	9	10	8
1932	15 September	Wairoa	M_s 6.9	5	5–6	6–7	9
1934	5 March	Pahiatua	M_s 7.6	5-6	5–6	5–6	3–4
1990	13 May	Weber	M_s 6.4	6	5	5	4

[1] Waipawa is used to reference the Waipukurau-Waipawa-Otane urban areas; Hastings is used as the reference for the Flaxmere-Hastings-Havelock North urban areas and Napier is used to reference the Napier-Taradale urban areas.

2.5 PREVIOUS LIQUEFACTION HAZARD STUDIES IN HAWKE'S BAY

It is important to note that in previous studies the term 'liquefaction susceptibility' was used in place of 'liquefaction vulnerability'. This is because at the time the scientific fraternity had not settled on consistent terminology in the developing field of liquefaction science. For reasons of consistency, in this report, the terms liquefaction susceptibility, liquefaction triggering and liquefaction vulnerability will be used as they are defined in Sections 2.3.1, 2.3.2 and 2.3.3 respectively.

Previous studies of liquefaction hazard in Hawke's Bay are limited to a study completed by GNS Science more than a decade ago. Dellow et al. (1999, 2003), developed a deterministic method for assessing liquefaction hazard on the Heretaunga Plains, Hawke's Bay, by assigning a liquefaction damage class rating correlated with Quaternary geological units calibrated as much as possible with historical accounts of liquefaction. This enabled a liquefaction damage class to be assigned to each geological unit and regional liquefaction hazard maps to be produced for various earthquake scenarios. By implementing a classification scheme based on the cases of historical liquefaction, Quaternary geological units were differentiated by age, environmental and depositional processes, allowing estimates of liquefaction damage class to be extrapolated to areas where data were lacking.

The datasets used were:

- Historical records of liquefaction occurrences were sourced from Hancox et al. (1997), Downes (1995), Dowrick (1998) and GNS files;
- Surficial geological and soils data was compiled from published and unpublished sources prepared by the former Department of Scientific and Industrial Research (DSIR), the Institute of Geological and Nuclear Sciences, and private consulting companies;
- Topographic map and aerial photographic interpretation techniques were used to delineate landforms, such as stream terraces, marshes, and floodplains likely to be underlain by liquefiable deposits.
- The ground shaking attenuation equation of Dowrick (1995) was used for the Mohaka and Poukawa faults, and the subduction zone event;
- Limited groundwater data was sourced from Dravid and Brown (1997);
- Borehole logs and SPT data for the study area were evaluated to correlate subsurface materials to the Quaternary geological map units. Data sources included primarily the well log data base from HBRC, and GNS files;
- Mapping was completed at a scale of 1:50,000.

The analysis of liquefaction occurrence during historical earthquakes was used to establish the potential MM intensity threshold values for various geological units and formed the basis for predicting the extent and magnitude of liquefaction induced ground damage resulting from different shaking intensities. The liquefaction response of three earthquake scenarios was considered:

- Magnitude 7.5 earthquake on the Mohaka fault;
- Magnitude 7.5 earthquake on the Poukawa fault; and
- Magnitude 8.1 earthquake on the Hikurangi subduction zone.

These earthquake scenarios were selected because they are believed to represent realistic large magnitude events that have a high probability (≥10% chance in 100 years) of occurrence. Liquefaction damage was assessed by overlaying and comparing ground shaking isoseismal maps (using MMI) and the liquefaction hazard maps for the region.

At this time, only limited geotechnical data (i.e. bore logs, and SPT data) were available for the study. Where this data was available it was correlated with subsurface materials to the Quaternary geological map units. Broad scale liquefaction hazard maps for the three scenario earthquakes were prepared to show the distribution of deposits that could liquefy during strong ground shaking and the likely severity of the liquefaction induced ground damage (Figure 2.10 and Figure 2.11). The maps provide a general indication of where liquefaction will occur, and the relative extent of the liquefaction, if ground shaking above the triggering threshold were to occur. The resulting maps indicate that liquefaction could occur in the geological units classified as high and very high liquefaction vulnerability during almost any large earthquake in the region (although the extent of the liquefaction will be dependent on the intensity of the ground shaking and the location of earthquake epicentre). The units classified as moderate to low liquefaction vulnerability would only be triggered near the earthquake epicentres.

Dellow et al. (1999, 2003) concluded that in the areas identified as being highly vulnerable to liquefaction, ground deformation could occur over large areas with settlements of around 1 m, and lateral spreads of up to 15 m during ground shaking that reaches a shaking intensity of MM10. The map produced (Dellow et al, 1999, 2003) provided a basis for broad regional engineering and planning, but they were not intended to be used in place of site-specific investigations. Dellow et al. (1999, 2003) recommended implementing a programme which requires site-specific geotechnical investigations for critical or sensitive facilities located in either the high or very high liquefaction vulnerability classes to provide quantitative assessments of liquefaction hazard at a more detailed scale.

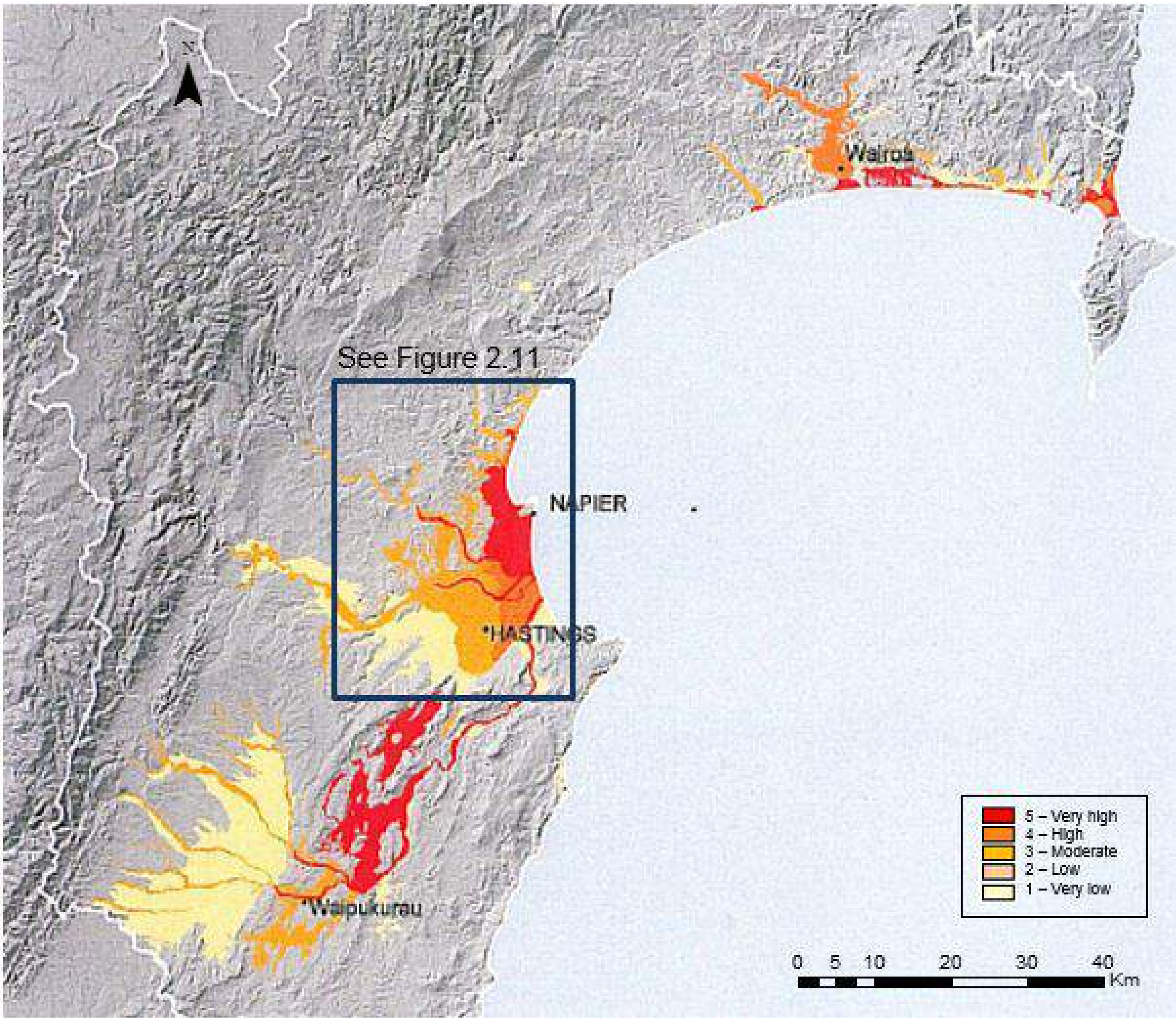

Figure 2.10 Previous regional liquefaction vulnerability hazard map from Dellow et al. (1999).

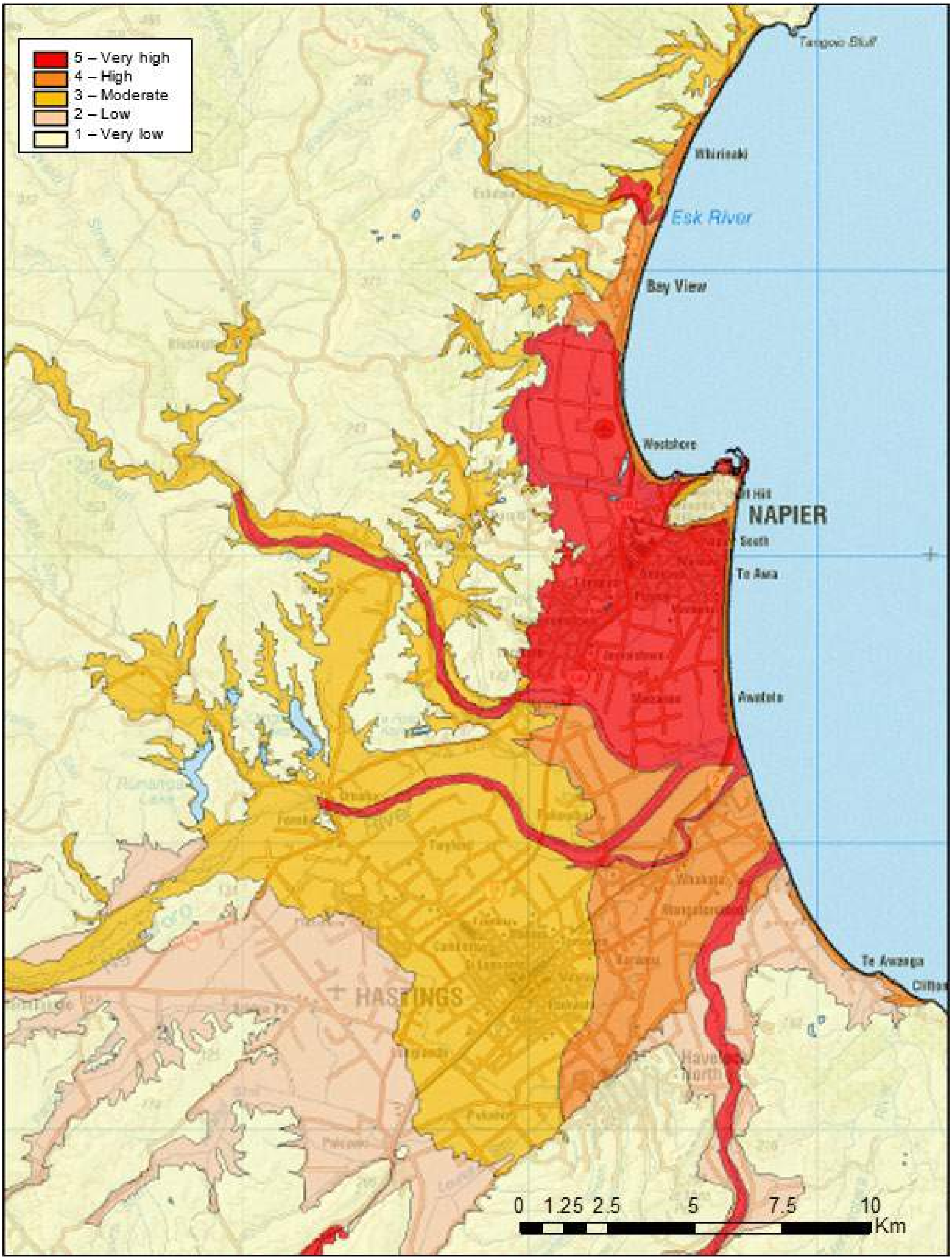

Figure 2.11 Previous Heretaunga Plains liquefaction vulnerability map from Dellow et al. (1999).

3.0 DATASETS

The key datasets used to quantify the liquefaction in the Hawke’s Bay Region are described below. The datasets are groundwater, geology, geomorphology, historical earthquake observations and geotechnical data. The groundwater, geomorphology and geotechnical datasets are used directly in the construction of the liquefaction hazard maps.

3.1 UNCONFINED GROUNDWATER SURFACE DATA

Depth to the unconfined groundwater surface (UGS) is a critical factor in determining liquefaction hazard and risk because liquefaction can occur only when sub-surface sediments are saturated. This section summarises the data and methodology used to model a surface representing this UGS, with some comparisons made to a recent UGS model created for the Christchurch region (van Ballegooy et al., 2014a). Due to the large area covered, the UGS was calculated within three different zones (Figure 3.1). The data and methods used to construct the UGS surfaces are described in more detail in Appendix 8.

Within the Hawke's Bay region, the great majority of data pertains to confined aquifers. Of the time series data available, only 15 wells within the modelled region are considered to sample the unconfined water table. The median water table level was calculated at these locations using the available data, with sampling periods ranging from 3–22 years. The exact time period used varies for each data set to ensure no bias is induced by seasonal variability. As water level measurements are taken when there is a change in level, the median calculated is for the entire time period rather than the sample set.

As the available time series measurements constitute such a small sample set, static water levels were also used to estimate the water table depth. Uncertainty arises from the use of static water levels for a number of reasons: a single measurement is taken at one point in time; as measurements are usually taken following drilling and development of a groundwater well, it is not always clear from the data whether the well was allowed sufficient time to reach equilibrium (if taken too soon following pumping then the water table depth will be overestimated); it is not always clear from the driller's notes whether the water level measured is from a confined or unconfined aquifer, and this can also be wrongly recorded.

Wells in the HBRC borehole database were classified according to whether they sampled the unconfined water table or a confined aquifer by interrogation of driller's notes and borehole logs. After datum adjustment to above mean sea level (Amsl), any static water levels within the Heretaunga Plains deeper than -1 Amsl were removed, as these were considered to be measurements taken during pumping (if the water table was below msl then there would be no flux to the sea). This reduced the original well data set of 7503 down to 449 wells. An additional set of 12 static water level measurements were added from a November 2008 GNS Science survey of the Poukawa aquifer water levels (Cameron, 2011).

During the project, the above data sets were supplemented by 24 new shallow groundwater monitoring wells that were drilled by NCC for this project in early 2014. The available time series water levels from these wells (five data points between March and October 2014) were used to derive median groundwater levels at these locations. Depth to water table estimates, from CPT data were also used as static water level measurements.

Time series data from 25 river monitoring sites were provided by Hawke's Bay Regional Council. However, the disparity between river level measurements and the DEM elevations for the corresponding locations were too large to integrate this data. The DEM used is as described in Appendix A4.2.

Mapped surface water features from the New Zealand Topo250 maps were incorporated as data points into the modelling. Due to the comparative scarcity of well data compared to mapped surface water, surface water information sampled from wells tended to bias the results too much towards a very shallow (coincident with ground level) water table. To overcome this, linear surface water features were sampled every 20 km, and polygon surface water features were sampled as a single point in the centre of the feature.

A map of all data used is displayed in Figure 3.1.

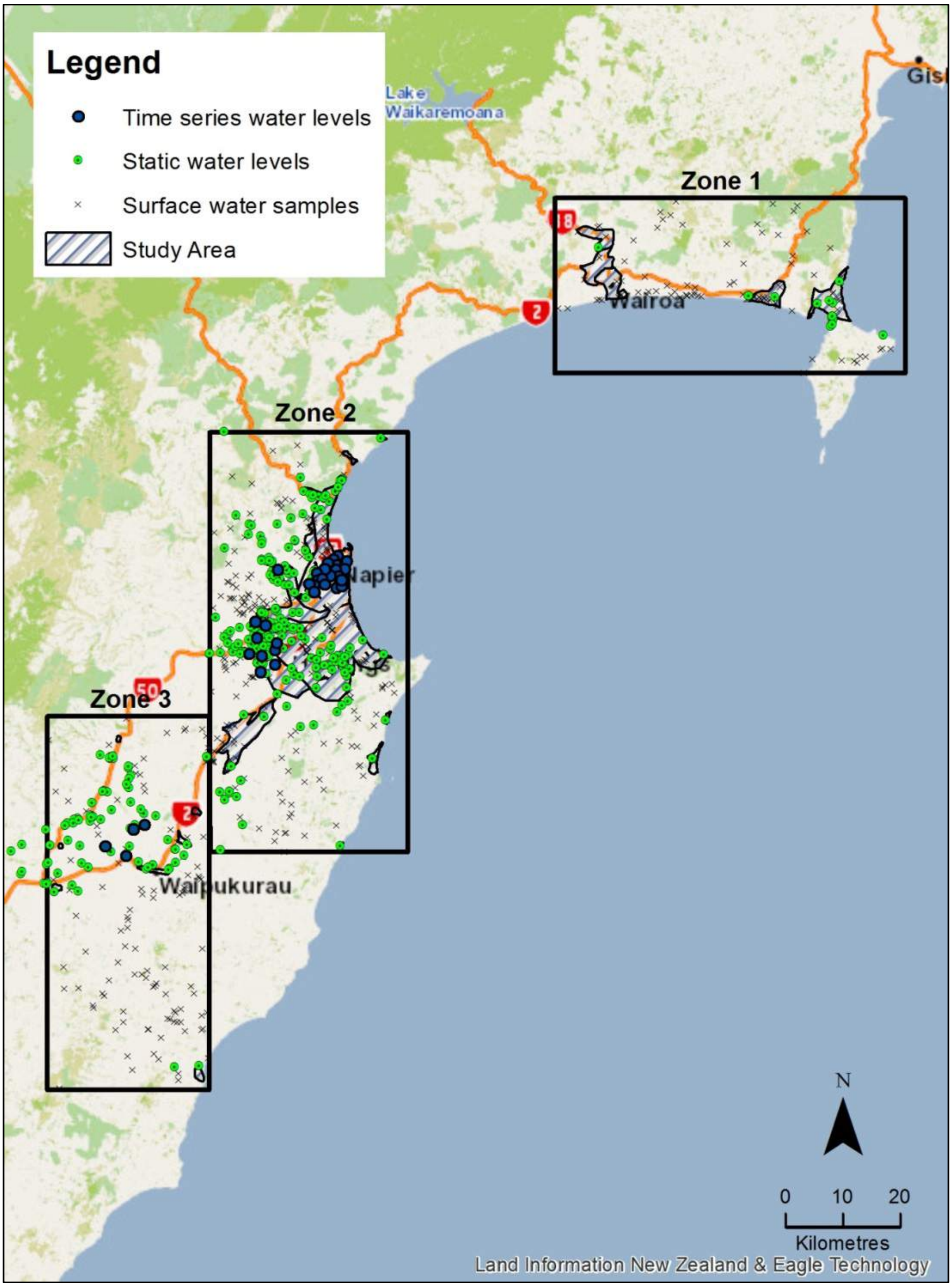

Figure 3.1 All data used to develop the unconfined groundwater surface.

3.2 SUB-SURFACE GEOLOGY

The geological setting of the Heretaunga Plains and the data and methods used to model the stratigraphy are described in more detail in Appendix 5. The surface geology of the Heretaunga Plains is shown in Figure 3.2. The Heretaunga Plains formed from the complex interaction between tectonics and glacio-eustatic sea-level changes during the Quaternary (last two million years). The interpretation of the stratigraphy beneath the Heretaunga Plains relies on a geological model based on continuing deposition within a tectonically deforming (subsiding) basin through the cyclical global climatic changes of the Quaternary Period.

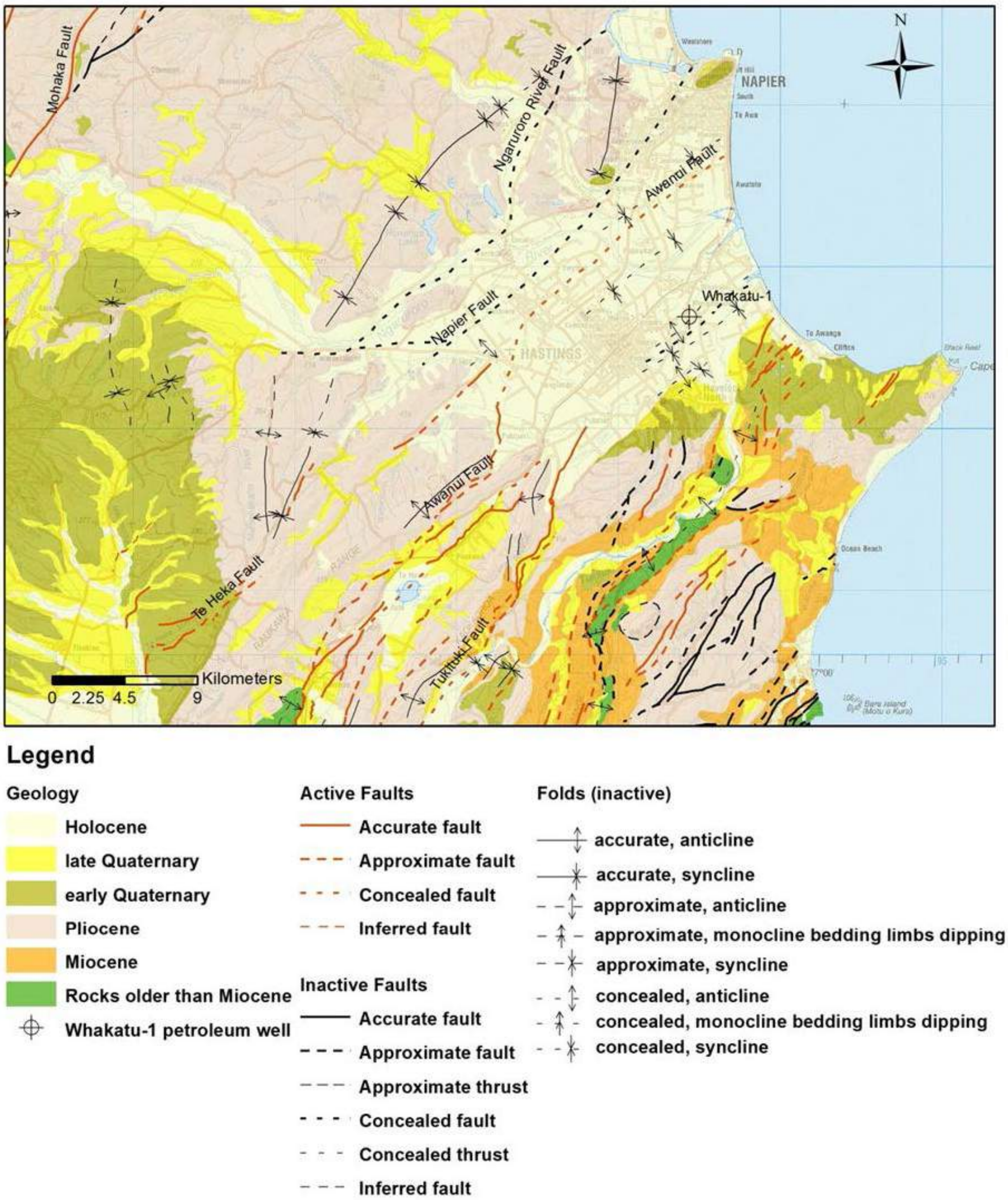

Figure 3.2 Generalised geological map of the Heretaunga Plains, divided into undifferentiated units older than Miocene, Miocene, Pliocene, Quaternary and Holocene. The geology is structurally complex as faulting and folding occurred episodically throughout the Pliocene and Quaternary. "Accurate", "approximate", "concealed" and "inferred" refer to accuracy of the location of the fault or fold. Adapted from Lee et al., 2011.

Warm climatic cycles were characterised by high sea levels, sediment carrying capacity of rivers was low (as stream gradients were low close to the coast of the day), and deposits were fine-grained. During cold climatic cycles, sea level was low, frost-related erosion in the high country was high, sediment supply to the major rivers was high, and river gradients at the Heretaunga Plains were relatively steep, because the coastline was distant near the edge of the continental shelf. Because the basin was subsiding, broad gravel plains were deposited by the braided rivers of the day. This has resulted in a complex sequence of river channel and flood plain deposits overlying shallow marine sediments. Flood plain sediments deposited in the last 10,000 years are up to 20 metres thick with shallow marine sediments ranging from 0–40 metres thick (Dravid & Brown, 1997). It is these shallow (to a depth of twenty metres), fine-grained sediments of the Heretaunga Plains, deposited since the end of the last glaciation 10,000 to 14,000 years ago that are susceptible to liquefaction today.

After the most recent large eruption from Lake Taupo c. 1,800 years ago, large quantities of Taupo Pumice Alluvium built up rapidly on the Heretaunga Plains. The pumice has been eroded in some places by alluvial processes, but up to 10 m thickness of pumice gravel and sand are found in many parts of the plains. Aggradation of the rivers has continued since the pumice deposition, with a further 5–10 m of alluvial sediment overlying the pumice in parts of the Heretaunga Plains. This thick accumulation of very young deposits provides conditions that are likely to create high susceptibilities to liquefaction in this area.

The youngest (Holocene; <10,000 years old) fluvial sediments of the Heretaunga Plains, comprise inter-fingered layers and lenses of sand, silt and gravel as interpreted from the Hawke’s Bay Reginal Council’s borehole data (Figure 3.3). The estuarine deposits in the vicinity of Napier appear to form a shallow veneer (up to 40 metres) of soft sediments which overlie the interlayered fluvial deposits (up to 20 metres thick) of the Heretaunga plains (Dravid & Brown, 1997). These in turn are overlain by coarse sands and gravels of the beach deposit (up to 20 metres thick) along Marine Parade in Napier (Dravid & Brown, 1997). At Wairoa, sub-surface investigations (Ota et al., 1989) show up to 30 metres of recent (post-glacial) fine sands and deposited in an estuarine environment.

The distributions of gravels and fine-grained materials appear to be influenced by active tectonic structures across the Heretaunga Plains, with an absence or relative scarcity of fine grained materials northwest of a line between Bridge Pa and Taradale (Figure 3.4). There is little other discernible pattern of coherent stratigraphy within the fine-grained deposits making up most of the Holocene volume. The three-dimensional distribution of Holocene shells beneath the plains is elongate to the SW, extending all the way to Pakipaki, and indicate the presence of a short-lived Holocene embayment (probably estuarine) in this area.

This lack of continuous horizons within the lithological stratigraphy of fine-grained Holocene materials contrasts with other coastal locations (Figure 3.5). In Christchurch, the Wairau Plains, Lower Hutt Valley and the Rangitaiki Plains, the Holocene stratigraphy is consistently represented by a sandy marine incursion across silty and gravelly non-marine deposits and is capped by sandy, silty and gravelly non-marine deposits. Beneath the Heretaunga Plains the only reliable indicator of the Holocene marine incursion and subsequent coastal progradation is derived from the distribution of marine shells. The interaction between fluvial systems and estuarine environments across the Heretaunga Plains because of tectonic and eustatic sea-level changes through the late Holocene produced a complex sedimentary environment. This resulted in the lack of clear differentiation in these sediments and the absence of continuous horizons with a consistent depositional origin.

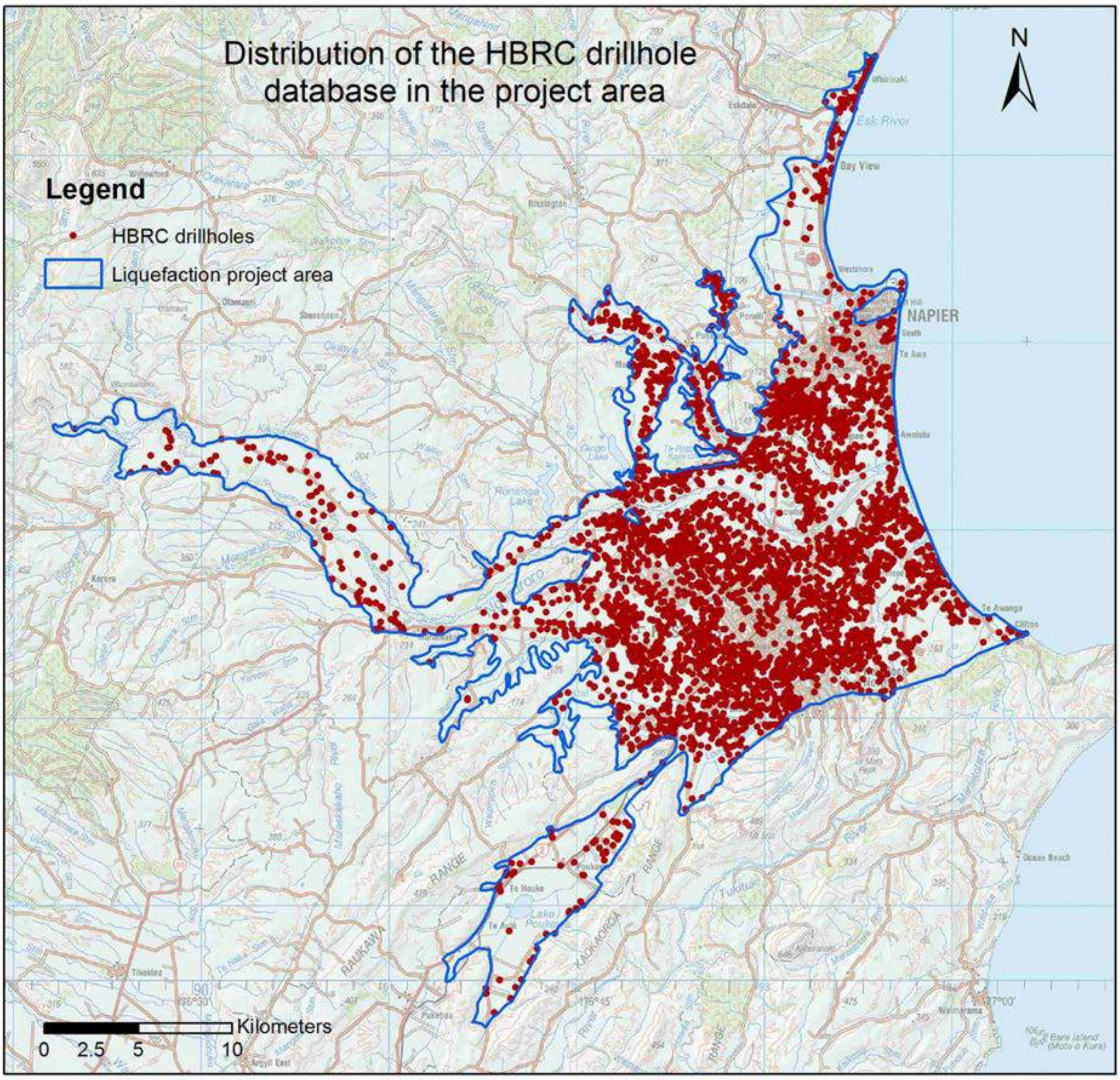

Figure 3.3 The HBRC boreholes have been clipped to the area of the Heretaunga Plains and are well distributed across the Heretaunga Plains.

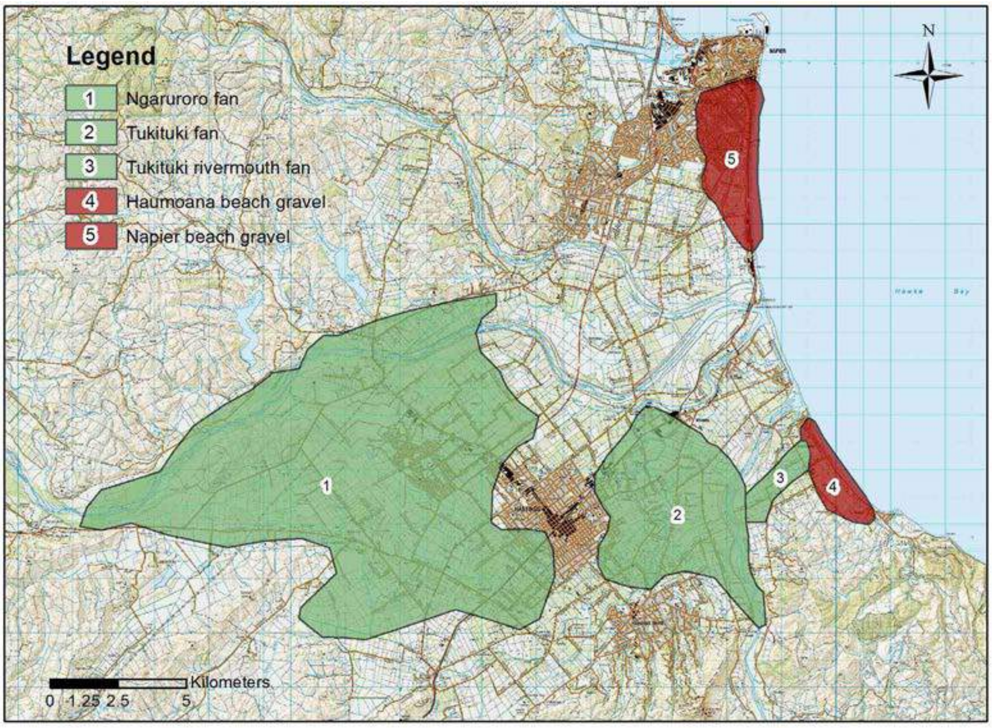

Figure 3.4 A map view of the surface and subsurface distribution of Holocene gravels identified from the boreholes. Beach barrier bar gravels are located south of Napier and at Haumoana (reddish brown). Inland alluvial fan deltas (green) were deposited by the Ngaruroro and Tukituki rivers.

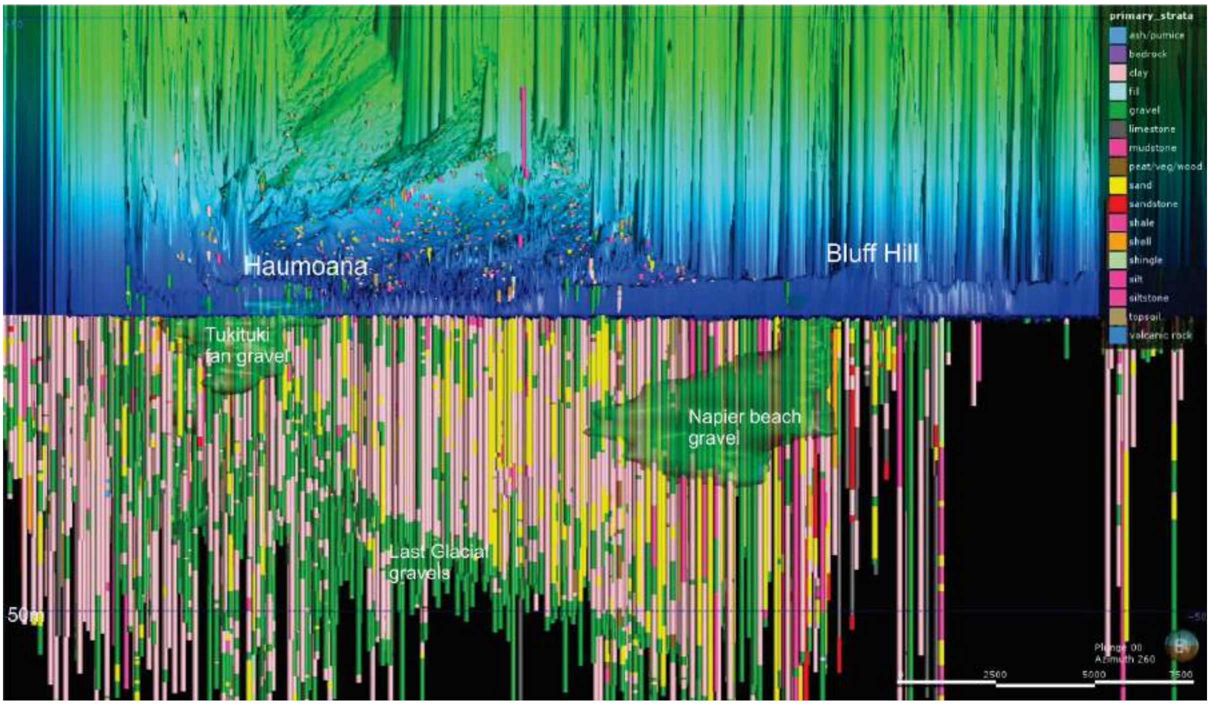

Figure 3.5 A cross section from Haumoana to Bluff Hill shows some of the Holocene gravel units identified using borehole data. Apart from gravel, other units such as sand (yellow) and silt (dark pink), do not display any coherent mappable stratigraphy. The Napier Beach gravels lie between 15–20 m below sea level. Fan gravels deposited by the Tukituki River are found up to 10 m below the ground surface.

3.3 GEOMORPHOLOGY

High quality Light Detection and Ranging (LiDAR) digital elevation models and derivative hillshade images provide a very high-resolution depiction of the form of the ground surface. They provide a basis for the interpretation of the nature and origin of landforms, which, in turn, provides a basis for inferring the likely character of the underlying geological materials. LiDAR data has been captured in 2003, 2006 and 2011–12 for the Hawke's Bay Regional Council. Data captured in 2003 and 2006 covers most of the study area except for the upper reaches of the Ngaruroro River.

The 2003 metadata sheet for this LiDAR data states that the horizontal accuracy of each laser strike was <0.55 m and the vertical accuracy was around 0.15 m. Horizontal accuracy of the 2006 laser strikes have a horizontal accuracy of <0.4 m and a vertical accuracy of 0.15 m. Again, ground elevations beneath trees may be less accurate. The 2003 and 2006 LiDAR data were merged and there are height variations in places such as riverbeds and agricultural crops. The LiDAR files were delivered as xyz point data and processed to create gridded elevation models at 2 m resolution. However, due to the low density of the data, actual resolution is more likely to be accurate to 5 m.

Outside of the LiDAR area, collar heights for borehole and geotechnical probing (including Cone Penetration Test (CPT)) data were extracted from an 8 m resolution elevation model (created by Geographx; www.geographx.co.nz). This DEM has a 22 m horizontal accuracy and 10 m vertical accuracy.

A geomorphology map was developed for the project area using the LiDAR derived topography as a base-map. Landforms of the project area were categorised according to their origins and ages, as illustrated in a generalised geomorphic map (Figure 3.6). The categories are divided into:

- Anthropogenic features;
- Dynamic features of the land surface (natural water bodies and river courses);
- Landforms of the Holocene Epoch (around the last 12,000 years), which comprise most of the river, stream, swamp, estuarine and coastal features of the Heretaunga Plains;
- Landforms of the Late Pleistocene epoch created by fluvial processes that were formed during the last glaciation; and
- Landforms of the hill country surrounding the Heretaunga Plains.

Although the surface geomorphology only maps the origin of the surfaces being examined, it provided two elements needed to more finely differentiate the liquefaction hazard. The first was to describe the sedimentary origin of the near-surface sediments (0–5 m depth). The second was to provide a basis for a more detailed spatial differentiation of the Heretaunga Plains. This detailed spatial differentiation provided a basis for examining liquefaction response using cone penetration test (CPT) data. Areas with a high density of CPT data and similar liquefaction response can be grouped together and then those with a similar geomorphology, but with few or no CPT data, can be assigned a liquefaction hazard that is likely to represent their liquefaction behaviour.

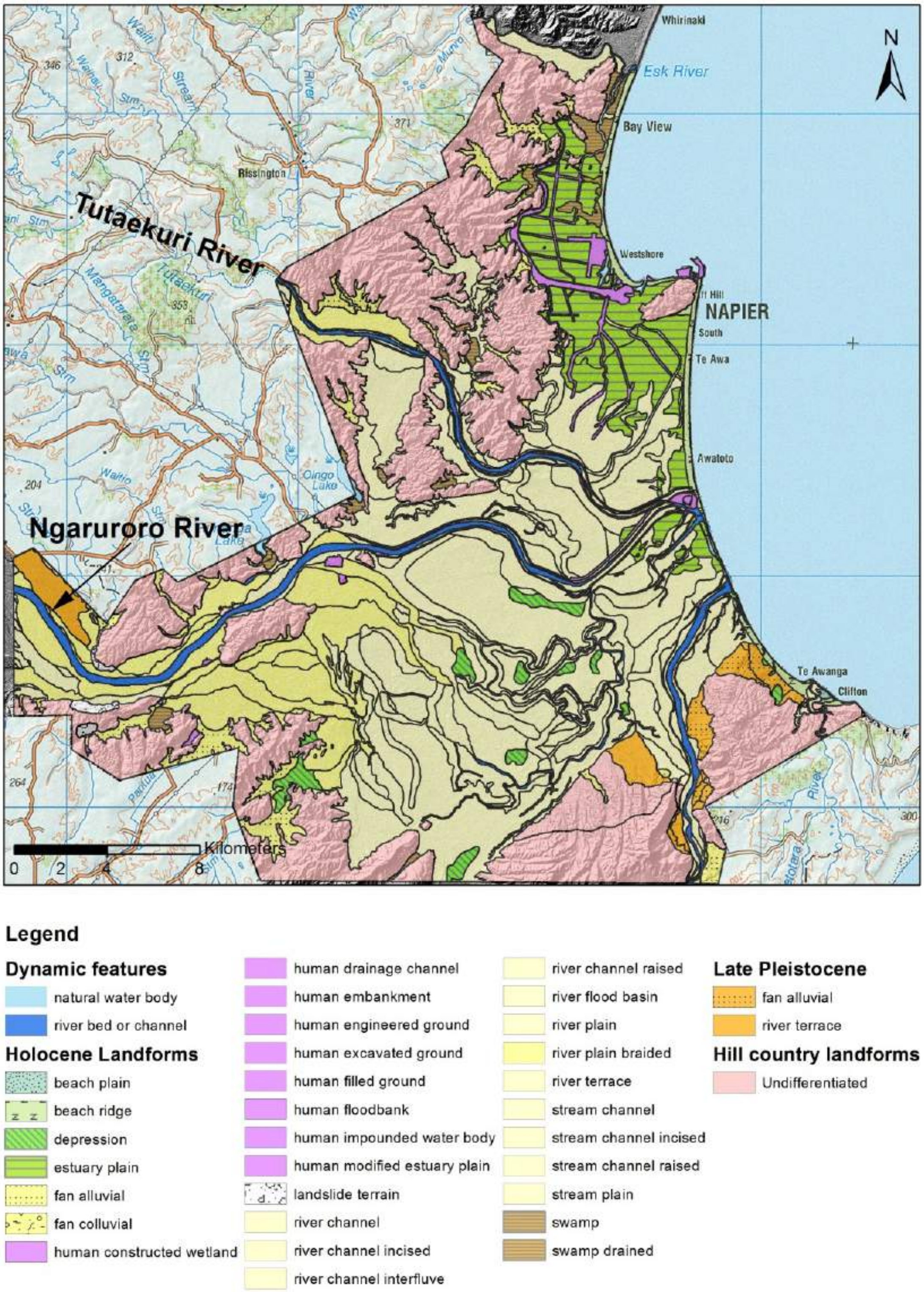

Figure 3.6 A generalised geomorphic landforms map of the Heretaunga Plains area. The dominant features are the recent and abandoned river channels and levees (yellow) from the Tutaekuri and Ngaruroro rivers cover most of the plains; and the estuary plain from of the old Ahuriri lagoon west of Napier. The hill country surrounding the plains is mostly underlain by undifferentiated Pliocene aged rock.

3.4 HISTORICAL OBSERVATIONS

Liquefaction effects have been reported in the Hawke's Bay region during historical earthquakes. The liquefaction effects and the MM intensity (Appendix 2) at which they occurred are summarised in Appendix 3. The reported ground damage effects include sand boils and water ejection, subsidence and settlement, fissuring and lateral spreading. The quality of the information available for the different earthquakes is highly variable and it is possible that some liquefaction-induced ground damage was not observed, recognised or reported, particularly during the early years of European colonisation (i.e., pre-1900). Since 1840, at least seven earthquakes have produced Modified Mercalli (MM) shaking intensities of MM7 or greater in the Hawke's Bay Region. Unequivocal liquefaction effects were reported for four of these events. However, the extent of liquefaction ground damage may be greater than has been reported because of the low population densities over much of the region, especially prior to 1900.

Historical reports show that many sites near the mouths of the rivers, or geologically very young river deposits have undergone liquefaction during these events. Areas specifically mentioned include (Table 3.1):

- The Mahia Peninsula isthmus;
- The Whakaki lagoonal area;
- Wairoa township;
- Near the mouth of the Mohaka River;
- Near the Tongoio Lagoon;
- The former Ahuriri Lagoon;
- Along the banks of the Tutaekuri River between Taradale and the Ahuriri lagoon;
- The Heretaunga Plains as far inland as Hastings;
- Waiohiki;
- The Poukawa-Waipawa basins; and
- Near the beach at Porangahau.

The historical record confirms that the occurrence of liquefaction-induced ground damage is dependent on both the shaking intensity at a site and the geological and geotechnical parameters of the site. As the shaking intensity increases, the severity of the reported liquefaction also increases. An example of this is near the Tutaekuri River where sand boils were reported at MM7 (1863, 1904) and where lateral spreading occurred during MM10 shaking (1931) (Dellow et al. 1999). More detailed descriptions of the liquefaction damage in Hawke’s Bay are contained in Appendix 3.

Table 3.1 Observations of liquefaction effects reported in the Hawke's Bay region during historical earthquakes. Sources include Hancox et al. (1997), Downes (pers. comm.), and GNS files (from Dellow, 1999).

Locality	Modified Mercalli Shaking Intensity				
	6	7	8	9	10
Wairoa – Mohaka	1904 – No liquefaction reported. 1914 – No liquefaction reported.	1921 – No liquefaction reported. 1932 – Minor sand boils near Opoutama – Mahia back road. (Mahia Peninsula isthmus).	1931 – Sand boils on Wairoa flats. Settlement of lagoonal deposits north of Wairoa. 1932 – Whole of the kerbing of the Marine Parade badly fractured. Business district moved 50–75 mm toward river (lateral spread). Subsidence in business area of 50–75 mm. Numerous cracks in all the streets. Country roads cracked in every direction. Harbour wharves damaged. Roads cracked in Frasertown.	1931 – Sand boils near Mohaka River mouth. 1932 – Railway line from Wairoa to Whakaki badly buckled in numerous places. Sand boils and fissures at Marumaru and Opoiti (inland from Frasertown on the Wairoa River).	
Napier – Taradale		1863 – Liquefaction along banks of Pirimu Stream. Road to spit cracked (Port Ahuriri). 1904 – Land at Whare-o-maraenui badly cracked with sand boils. Sand boils on the left bank of the Tutaekuri River between Taradale and Meanee. Crack in breastwork at Port Ahuriri. 1914 – No liquefaction reported. 1921 – No liquefaction reported.			1931 – Ground fissures Napier South. Westshore embankment broken in many places. Fissures run through many Napier streets either longitudinally or across. Fissures particularly well marked along the present and old infilled channel of the Tutaekuri River, roads were split, water and sewer pipes were ruptured and houses displaced (lateral spreading). Sand boils at Petane and Tangoio Lagoon. Wharf areas at Port Ahuriri badly fissured and collapsed.
Flaxmere – Hastings – Havelock North	1855 – Possible fissure on Heretaunga Plains (near Clive?). Possible gas ejection from swampy ground near Waitangi Creek (Clive). 1914 – No liquefaction reported.	1904 – No liquefaction reported from Hastings – Havelock North area. 1921 – No liquefaction reported.	1863 – Banks of the rivers broken up.	1931 – The whole of the country between Napier and Hastings is crisscrossed by fissures, some of them wide and very ugly. Slumping and fissuring of stop banks. Fissures opened at many points along the river channels, especially where these crossed the Heretaunga Flats. The swampy country and that skirting rivers between Havelock and Hastings showed many fissures. At Waiohiki fissures large and frequent with sand boils. Near Hastings low paddocks seen with water in them (sand boils).	
Waipukurau – Waipawa – Otane	1921 – No liquefaction reported from Waipukurau-Waipawa area. 1934 – No liquefaction reported from Waipukurau-Waipawa area. 1990 – No liquefaction reported from Waipukurau-Waipawa area.	1904 – Sand boils and fissures reported in old bed of Waipawa River near Otane. Crack in road between Te Aute and Te Hauke. Liquefaction at Wanstead. 1914 – No liquefaction reported. 1934 & 1990 – No liquefaction reported at Porangahau.	1904 – Liquefaction reported at Porangahau. 1931 – Railway line bent and twisted in many places, embankments slumped. Travelling Waipawa to Hastings a good many fissures were seen when the road adjoined hilly country or crossed waterlogged expanses. No ground damage reported from Waipawa or Waipukurau townships.		

3.5 GEOTECHNICAL DATASETS

Geotechnical data provide information about the geotechnical properties of materials below the ground surface. A variety of geotechnical tests are available to study liquefaction susceptibility, triggering and vulnerability including standard penetration tests (SPTs), downhole (borehole) sampling and cone penetration tests (CPTs). CPT data was used in this project to determine the geotechnical properties of subsurface materials and to assess liquefaction vulnerability. CPT were used for this purpose because of the relatively widespread use of the CPT in the Hawke's Bay Region and using modern computational techniques it is a relatively fast method for undertaking bulk analysis of liquefaction vulnerability.

Around half of these CPT are publicly available on the New Zealand Geotechnical Database (NZGD) and have been uploaded by GHD, Land Development & Exploration Ltd (LDE), Opus, Resource Development Consultants Ltd (RDCL) and Tonkin and Taylor (T+T). About a quarter of these CPT were made available by RDCL and another quarter by T+T specifically for this project.

A total of 714 CPTs were available for this project, which included 139 CPTs that are not publicly available. Of these, 590 were used as they were greater than 5 m deep. The CPT data were analysed by T+T for the top 10 m only (refer to T+T, 2013). The CPTs are largely clustered in the Hastings area, the industrial areas of Napier city and Havelock North but elsewhere are scattered or sparsely distributed (Figure 3.7). Refer to Appendix 5 for more detail on CPT analysis.

The CPT data set is a compilation of geotechnical investigation data from a variety of CPT operators undertaking these tests using different CPT rigs for projects dating back to approximately 2002. The quality of the CPT data is variable, particularly given that the standards for CPT testing have improved over time. In the CPT data set, there are known issues associated with the measurement of sleeve friction for some of the CPT operators. However, because of the significant variability in soil conditions across the study area any bias associated with these two sources of error is likely to be indiscernible relative to the background noise. Assessments were undertaken to examine whether the liquefaction analyses results were statistically different for the various subsets undertaken by different contractors and over various date ranges. While there were differences in the raw CPT data for the various subgroups examined, there were no material differences in the liquefaction analyses results for the various subgroups. Therefore, the effect of this uncertainty is considered to be negligible and the full dataset of 590 CPT have been used for the liquefaction assessment.

Detail about how the methodology applied to analyse and interpret the CPT data is available in Section 6.

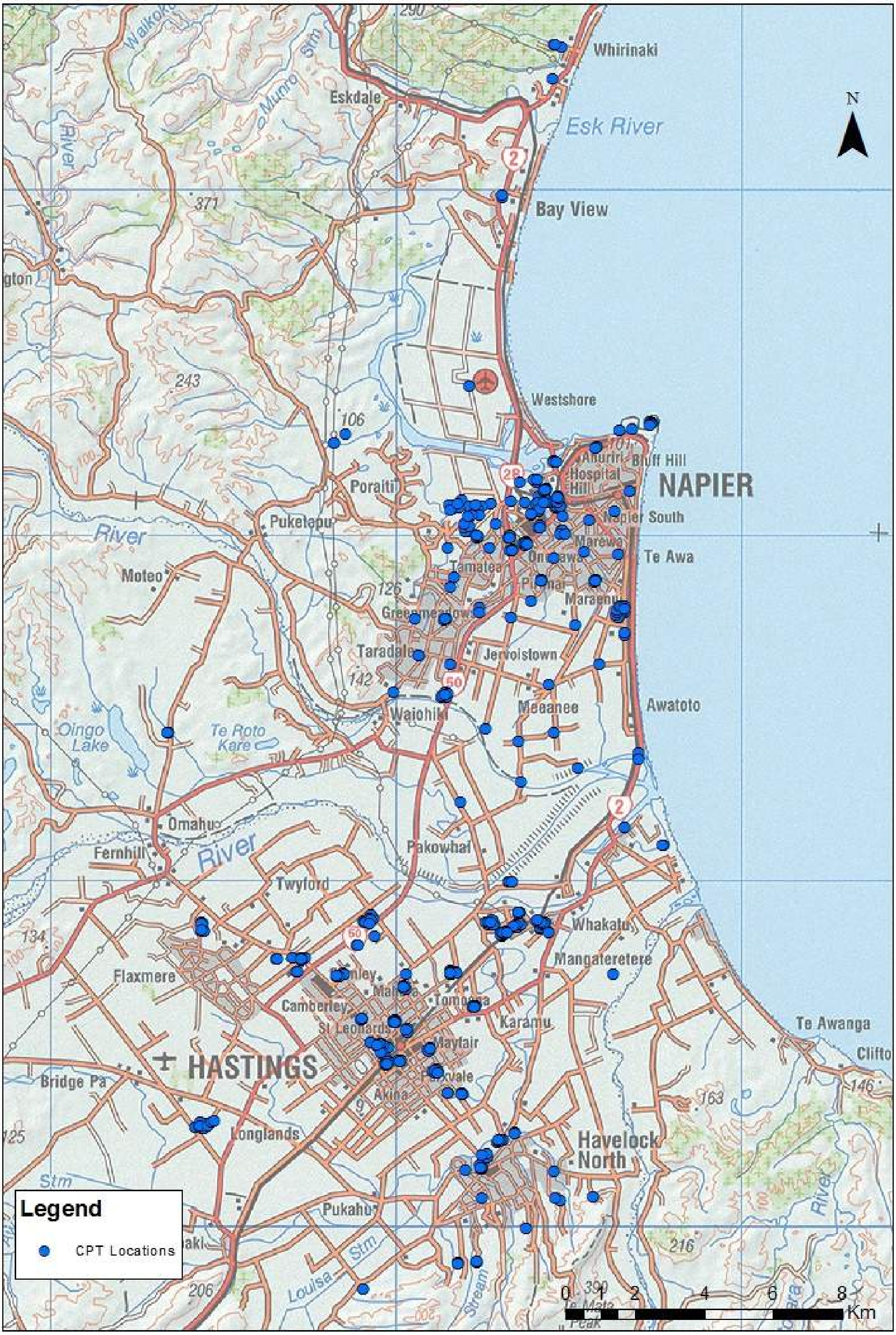

Figure 3.7 CPT locations on the Heretaunga Plains, Hawke's Bay.

4.0 GROUNDWATER MODEL

Depth to the unconfined groundwater surface (UGS) is a critical factor in determining liquefaction triggering and vulnerability, because liquefaction can occur only when materials of suitable grain-size distributions are saturated. The development of the groundwater model is described in more detail in Appendix 6 where the data and methodology used to model a surface representing the UGS, with some comparisons made to a recent UGS model created for the Christchurch region (van Ballegooy et al., 2013). Due to the large area covered, the UGS was calculated within three different zones.

The software Surfer 11.0 was used for data interpolation. van Ballegooy et al. (2014a) used the Kriging method for interpolation of the Christchurch median unconfined groundwater surface and identified three preferential interpolation methods that allow for breaklines to model rivers and the coastline and are suitable for irregularly spaced data: Kriging; Radial Basis function; and Local Polynomial. Following testing of the three methods, the Kriging method was used with a linear drift, search area of 10km, and a Gaussian variogram. The grid size used was 250 m and the coastline and major rivers were set as breaklines at ground level.

Interpolation was performed in metres below ground level (mBGL) and the UGS clipped to both the study area and the extent of mapped Quaternary geology as described by QMAP (Heron et al., 2012). Maps of the UGS in mBGL for three zones are displayed in Figure 4.1 to Figure 4.5, where the shallowest levels are shown by the dark blue and the deepest levels by the dark brown. For an overview map of the zone locations, refer to Figure 3.1.

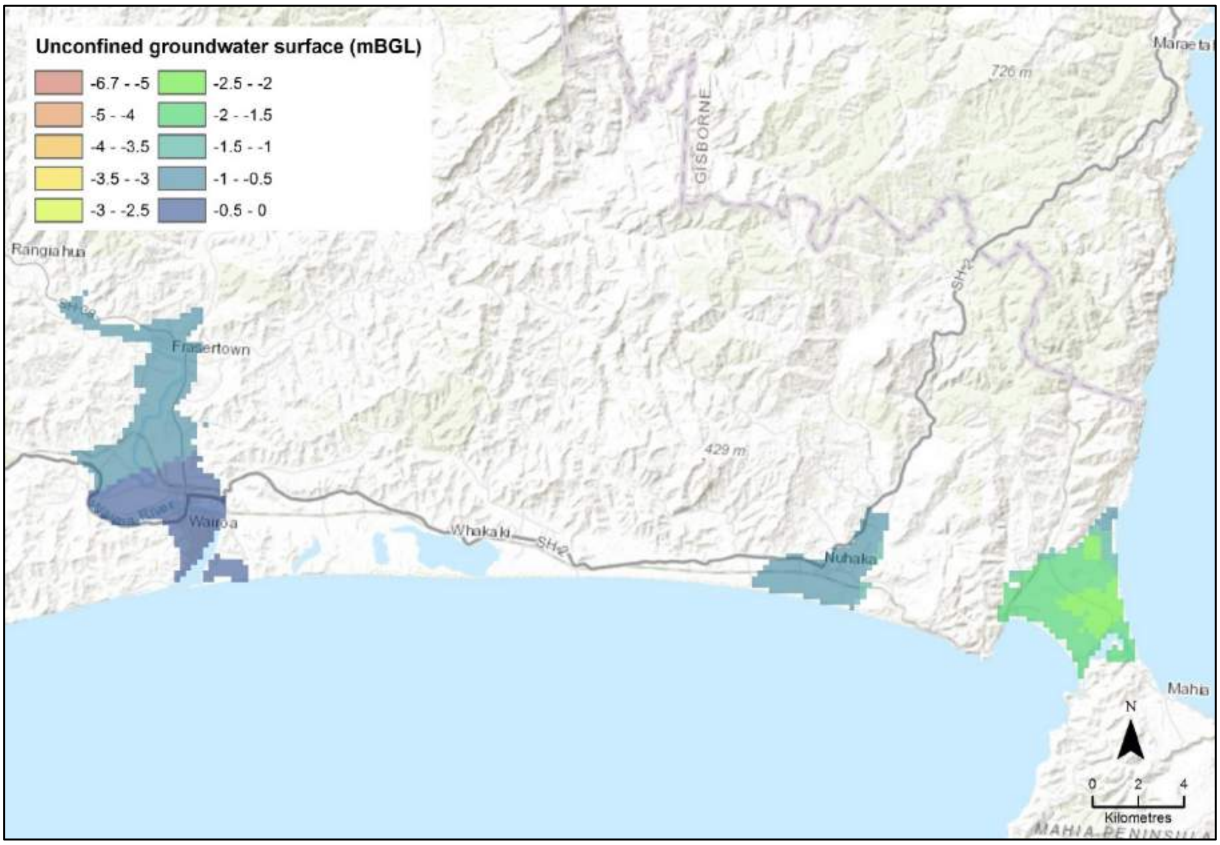

Figure 4.1 Unconfined groundwater surface for Zone 1 In northern Hawke's Bay. All the groundwater depths shown are less than three metres. These data have a high uncertainty as shown on Figure 6.9 in Appendix 6.

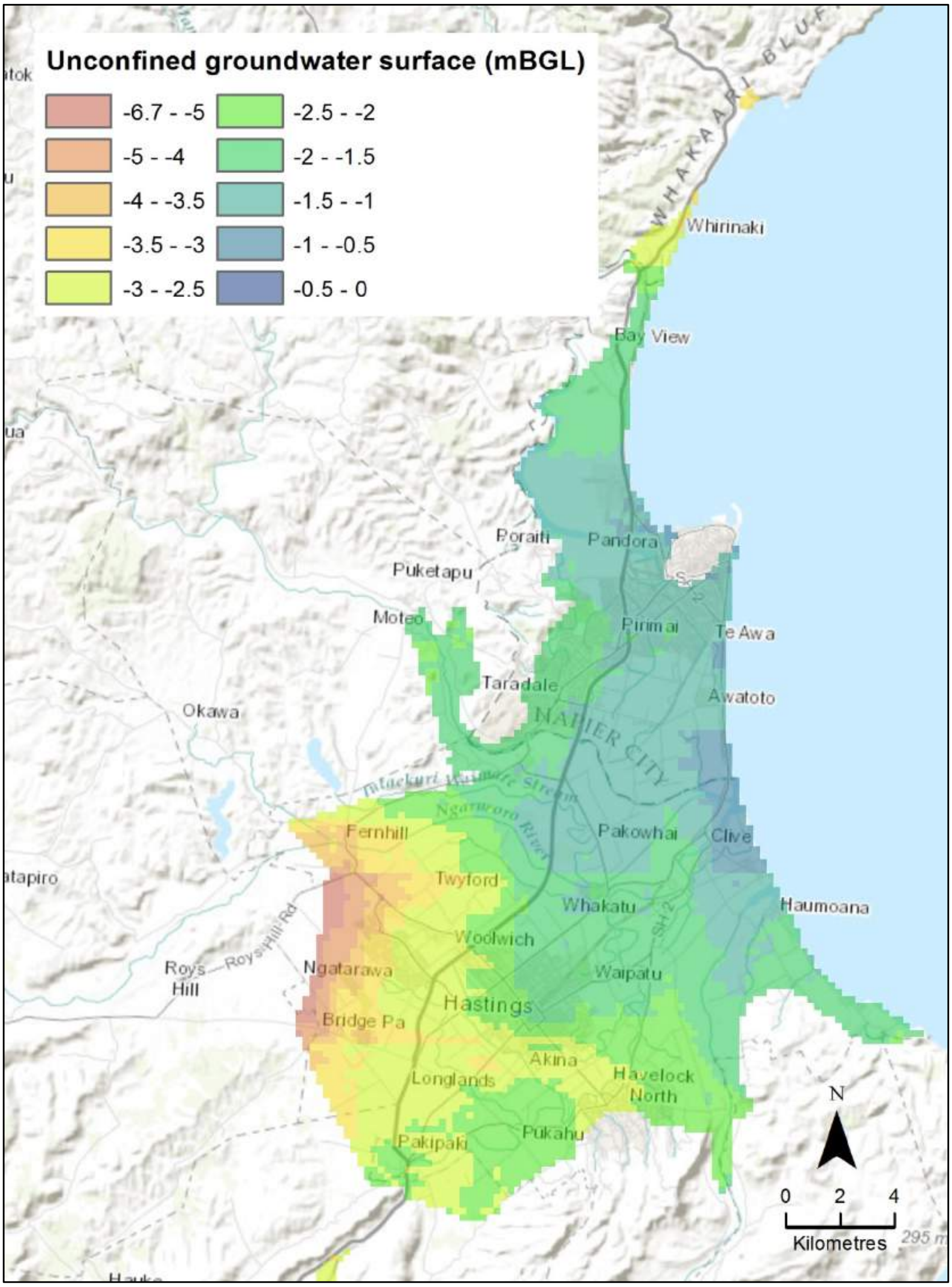

Figure 4.2 Unconfined groundwater surface for the northern portion of Zone 2. A line showing the boundary between groundwater depths greater than and less than 3 m is shown. These data have a range of uncertainty as shown on Figure 6.10 in Appendix 6.

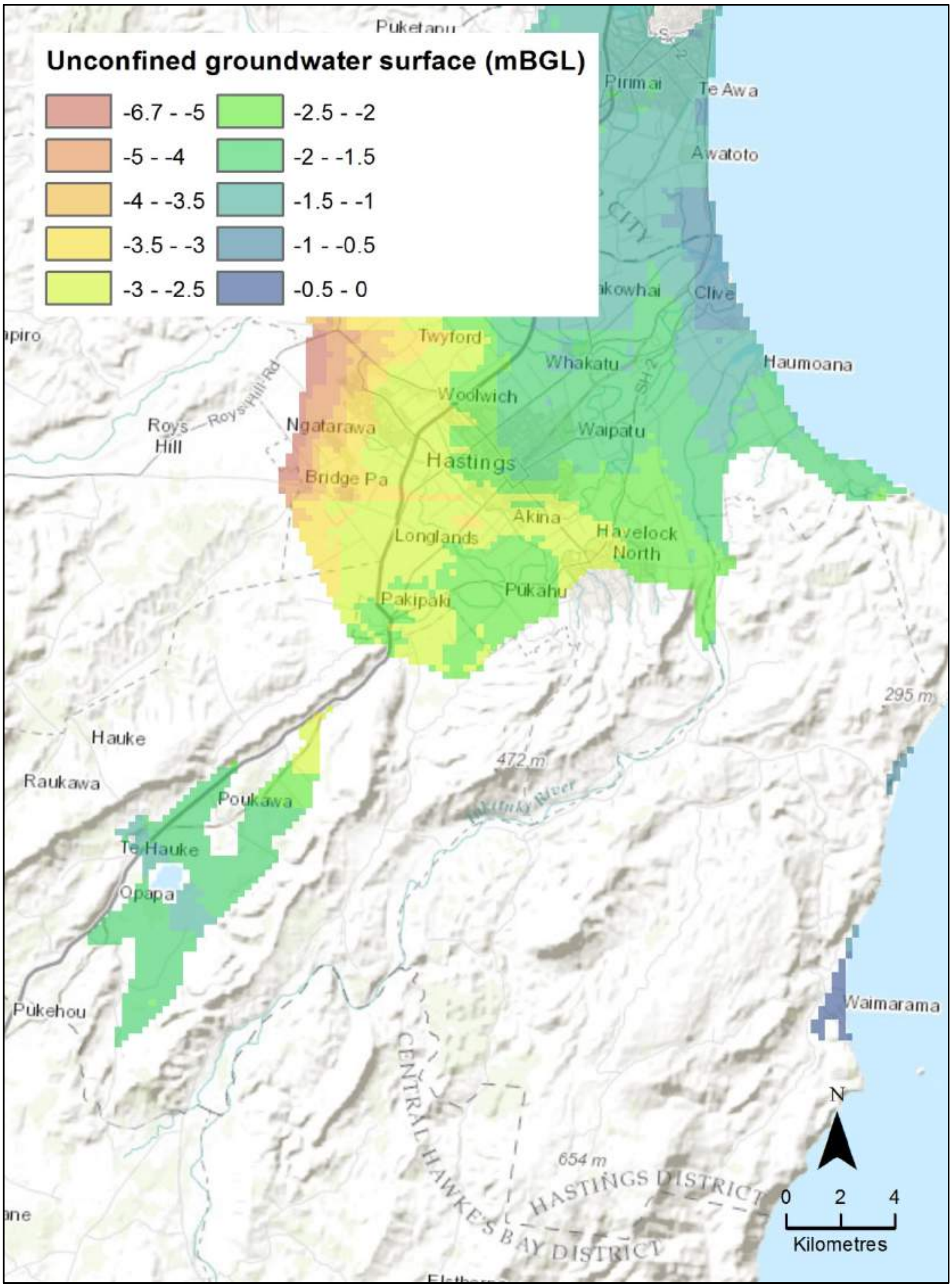

Figure 4.3 Unconfined groundwater surface for the southern portion of Zone 2. A line showing the boundary between groundwater depths greater than and less than 3 m is shown. These data have a range of uncertainty as shown on Figure 6.10 in Appendix 6.

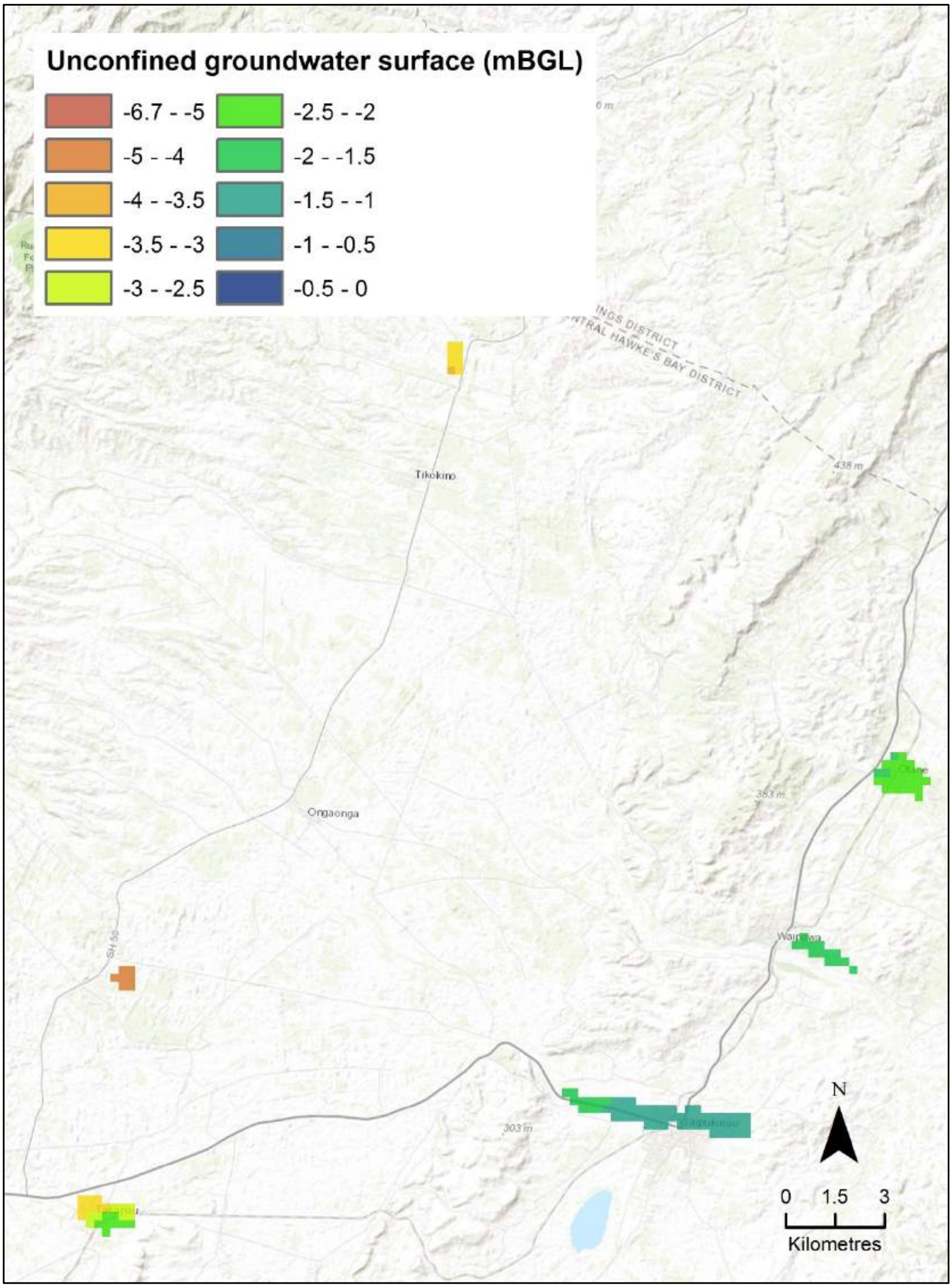

Figure 4.4 Unconfined groundwater surface for the northern portion of Zone 3. These data have a high uncertainty (Takapau and Gwavas) or moderate uncertainty (Waipukurau, Waipawa, Otane and Ashcott) as shown on Figure 6.11 in Appendix 6.

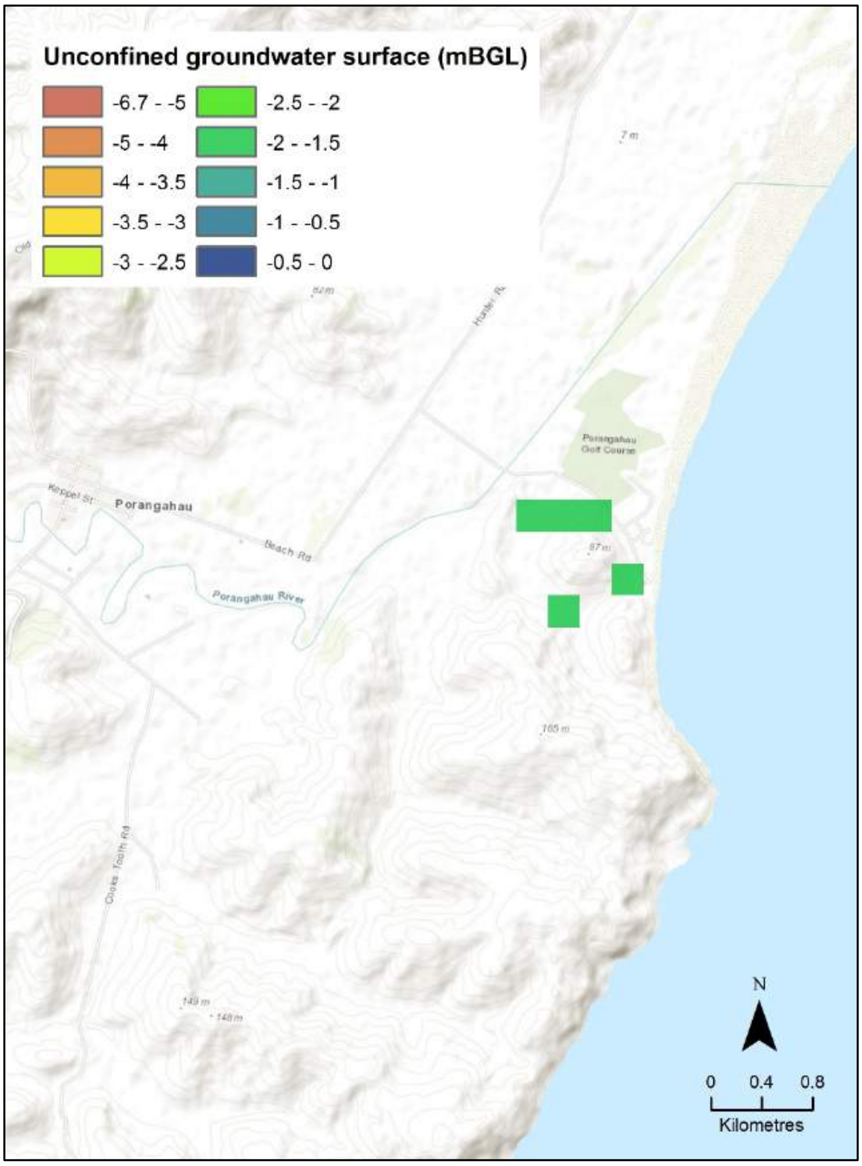

Figure 4.5 Unconfined groundwater surface for the southern portion of Zone 3. All the groundwater depths shown are less than three metres. These data have a high uncertainty as shown on Figure 6.12 in Appendix 6.

Maps of measurement uncertainty for three zones are displayed in Appendix 6 where the highest uncertainty is in the red regions, which have low measurement densities, and the lowest uncertainty is in the dark blue regions, which have high measurement densities.

There are a number of regions that are very uncertain: the whole of Zone 1 – especially Wairoa Valley, and to a lesser extent the Mahia sand aquifer; and the small coastal towns.

As shown in Appendix 6 there can be significant seasonal and yearly water level fluctuations and therefore significant deviations from the median UGS. The most appropriate quantification of hazard associated with probable water saturation would therefore take into consideration not only the median UGS, but also the minimum and maximum UGS. This is currently not possible due to the scarcity of available time series data. The new shallow groundwater monitoring wells that were drilled by NCC for this project in early 2014 provide an example of how the uncertainty of the UGS can be reduced in the future in areas of high importance. These have provided some immediate data for the UGS calculation, although the largest uncertainty reduction from these will come after several years of monitoring. The UGS has been developed in mBGL and clipped to the project area due to the DEM inconsistency between LiDAR data and the national 8x8 m DEM. LiDAR data covering the entire area of interest would be useful for obtaining a consistent DEM that would allow for a surface to be developed in mASL.

5.0 SEISMICITY AND EARTHQUAKE SHAKING

The GNS National Seismic Hazard Model (NSHM) was used to assess the level of seismic hazard at the centre of the Heretaunga Plains (SH50A bridge over the Ngaruroro River). The hazard calculations performed in this study use the 2010 version of GNS Science's National Seismic Hazard Model (NSHM) (Stirling et al., 2012). It has been significantly updated from the 2000 version of the NSHM (Stirling et al., 2002) which was used to develop the hazard section of the New Zealand Standard NZS1170.5 for earthquake loads in New Zealand (Standards New Zealand, 2004). The same overall approach is used as in the 2000 version, with the b-value of the Gutenberg-Richter distribution logN=a-bM (N=number of events > magnitude M) calculated for each seismotectonic region, and the a-value calculated at each grid point. The Gutenberg-Richter distribution is power law describing the relationship between event magnitude and frequency of occurrence. The a-value and b-values are constants that represent the seismicity of a given region.

The seismotectonic zones have been updated from those of the 2000 model, and the current version of the NSHM now uses seismicity data up to the middle of 2009. The a-value has been recalculated according to the same Gaussian smoothing method used in the earlier version (described in Stirling et al., 2002), with constant smoothing parameters at all locations. The final a-value for each grid cell is calculated by way of a maximum-likelihood method that combines the estimates from three sub-catalogues with different magnitude-completeness levels. The b-value is calculated by way of a maximum-likelihood method (Aki, 1965).

The second component of the seismicity model in the NSHM is the active fault source model. In the main, it models earthquakes associated with geologically-identified active faults. The NSHM fault sources consist of planar segments. Each of the sources is assigned a characteristic magnitude and average recurrence interval, and is modelled as producing earthquakes equal to the characteristic magnitude. Some long faults, such as the Wellington Fault, are separated into several segments, each with its own characteristic magnitude and average recurrence interval. The most recent version of the NSHM (Stirling et al., 2012) contains many potential earthquake sources in the Hawke's Bay region. These include parts of the offshore Hikurangi Subduction Zone, offshore faults that occur in the leading edge of the Hikurangi margin, onshore reverse faults including those involved in the 1931 Hawke's Bay earthquake (e.g., Waipukurau-Poukawa and Napier1931 sources), and onshore strike-slip faults (e.g. Mohaka South, the southern Mohaka Fault section).

New regression equations of moment magnitude (M_W) on fault area developed from New Zealand earthquakes were used for the fault sources (Villamor et al., 2001; Berryman et al., 2001; see also Stirling et al., 2013), along with an internationally-based regression for plate boundary strike-slip faults (Hanks & Bakun, 2002). Additionally, the active fault sources have been revised and updated as part of a separate project for HBRC (see Langridge et al., 2006, 2007, 2010, 2015). Several updates were made to individual fault sources between the 2000 NSHM (Stirling et al., 2002) and the current version of the model (Stirling et al., 2012). The 2000 NSHM used a hierarchy of methods to assign magnitudes and average recurrence intervals to each fault source. The 2010 NSHM uses a single method to estimate the characteristic magnitude (Mchar) and recurrence interval for each fault source. New regression equations of moment magnitude M_W on fault area developed from New Zealand earthquakes (Villamor et al., 2001; Berryman et al., 2001; see also Stirling et al., 2013) are used for the fault sources, along with an internationally-based regression for plate boundary strike-slip faults (Hanks & Bakun, 2002) in the case of the Alpine Fault.

Active fault mapping in the western part of Hawke's Bay has led to the definition of new active fault sources such as the Rangefront, Wakarara and Pukenui-Hinerua sources in the Makaroro area (Langridge et al., 2013). Active fault mapping in Central Hawke's Bay District (Langridge and Ries, 2014) has helped define several active fault sources that have confirmed or suspected Holocene activity (e.g., Takapau, Mangatarata, Ryans Ridge FZ, Mangaorapa). In addition, some modifications such as the splitting of the Waipukurau-Poukawa source into at least two separate fault sources reflect a different interpretation of how this reverse fault system might operate. New fault sources have also been considered within Hastings District, e.g. Te Heka FZ and length modifications have been made to the Tukituki FZ following remapping of the fault length from LiDAR (Langridge and Villamor, 2007). Each new fault source has a defined magnitude and recurrence interval so that new earthquake sources have a location, magnitude and time (recurrence) component.

For the alternative model, these changes mean that there is a larger number of earthquakes included from faults. These are concentrated along the western margin of the Hawke's Bay ranges (i.e. Wakarara area), within the central corridor of southern Hawke's Bay (Dannevirke to Poukawa), in the eastern part of the coastal ranges (SE of Waipukurau) and in the southern part of Hastings District. To balance out the expected magnitude of regional seismic moment release it is important to alter the component of background seismicity that goes into the alternative model to account for the different moment assigned to fault sources. No new fault sources are mapped across the Heretaunga Plains and within the northern half of Hastings District or Wairoa District.

5.1 MAGNITUDE FOR TARGET RETURN PERIODS

A unique earthquake magnitude for use at each return period required for this study was determined by considering the percentage contribution made to the to the seismic hazard at each magnitude interval (increments of M0.2; range M5-M9). The percentage contribution to the seismic hazard for each magnitude interval (M0.2) was multiplied by the magnitude. The results were then summed and a mean magnitude for return periods of 25, 100, 500, 1000 and 2500 years was determined. The results are shown in Table 5.1.

Table 5.1 The average magnitude of an earthquake contributing to PGA at different return periods.

Hawke's Bay Sites unweighted Site Class D Average Magnitude Contributions to PGA					
Site Number	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Napier/Hastings	6.2	6.3	6.5	6.6	6.7

5.2 PEAK GROUND ACCELERATION FOR TARGET RETURN PERIODS

The standard output from the NSHM is in the form of a set of response spectra of accelerations for different return periods. However, for liquefaction analysis we are interested in the accelerations at a return period of interest at zero second spectral period, also known as the peak ground acceleration (PGA). PGAs were calculated for the site of interest in the Heretaunga Plains for the return periods of interest (25, 100, 500, 1000 and 2500 years) (Table 5.2).

Further analysis using the NSHM has been undertaken to determine which earthquake sources, whether from the active fault model or background seismicity, contribute most to the hazard, at the specified acceleration values. This process, termed deaggregation, was used to identify the principle contributing fault sources or regional earthquakes, to the hazard. The model was run 20 times (each site at each return period) resulting in a list of potential fault sources and their respective estimated PGAs for various distances (Figure 5.1 to Figure 5.5).

The representation of fault sources in the NSHM requires considerable interpretation of the generally short, discontinuous surface fault traces contained in the GNS Science National Active Fault database (http://data.gns.cri.nz/af/), to combine them into continuous earthquake sources that are generally several tens of kilometres in length, consistent with the rupture lengths associated with the single-event displacements that are either observed in the geology or deduced from slip rates and recurrence intervals of rupture. Consequently, the NSHM fault sources differ in detail from mapped active surface fault traces represented in the Active Fault database.

The progression from the 25-year to the 2500-year hazard contributions shows the increasing contribution of larger earthquakes with a longer return period between events. At the shorter return periods, the hazard is dominated by smaller magnitude events with many sources contributing to the hazard (Figure 5.1). As the return period increases there are fewer fault sources contributing to the hazard. At the 2500-year return period two fault sources contribute over fifty per cent of the hazard (Figure 5.5). In the Heretaunga Plains area the deaggregation plots from 100 to 2500-year return period show a bi-modal distribution (Figure 5.2 to Figure 5.5). A consequence of this is that the calculated mean PGA may not represent the most likely level of shaking.

Table 5.2 PGA acceleration values from the NSHM for the Heretaunga Plains.

Hawke's Bay Sites unweighted Site Class D PGA values (g)					
Site	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Napier/Hastings	0.14	0.25	0.42	0.51	0.64

Shaking intensities for the main Hawke's Bay population centres have been derived from the New Zealand National Probabilistic Seismic Hazard Model, which has been updated as part of the project. PGAs were determined for five return periods: 25, 100, 500, 1000, and 2500 years. The return periods were nominated by the Technical Steering Group. The liquefaction analyses carried out for this report showed the liquefaction severity did not change between the 500-year return period and the 2500-year return period. Although the 1000-year and 2500-year disaggregation plots are shown here to satisfy the requirements of the Technical Steering Group they are not considered further on in the report as the liquefaction severity does not increase from the 500-year return period liquefaction hazard severity map.

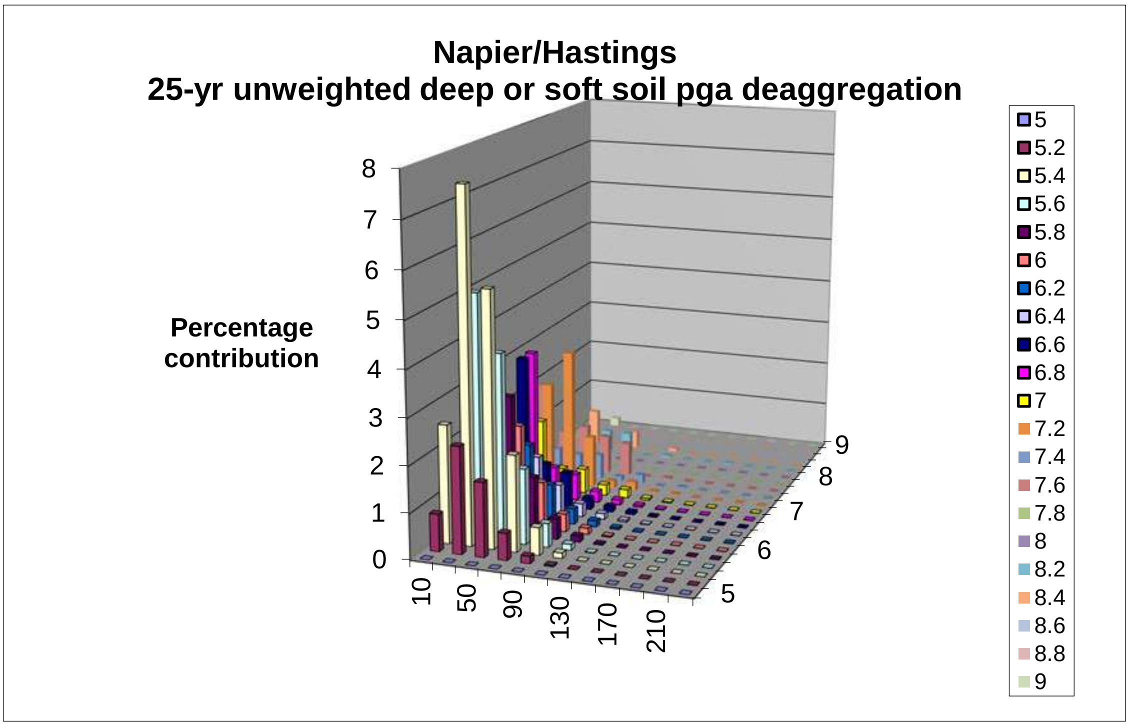

Figure 5.1 PGA disaggregation plot for the 25-year return period earthquake on the Heretaunga Plains. The plot shows the percentage contribution for various magnitude earthquakes at various distances from the epicentre (on the horizontal axis).

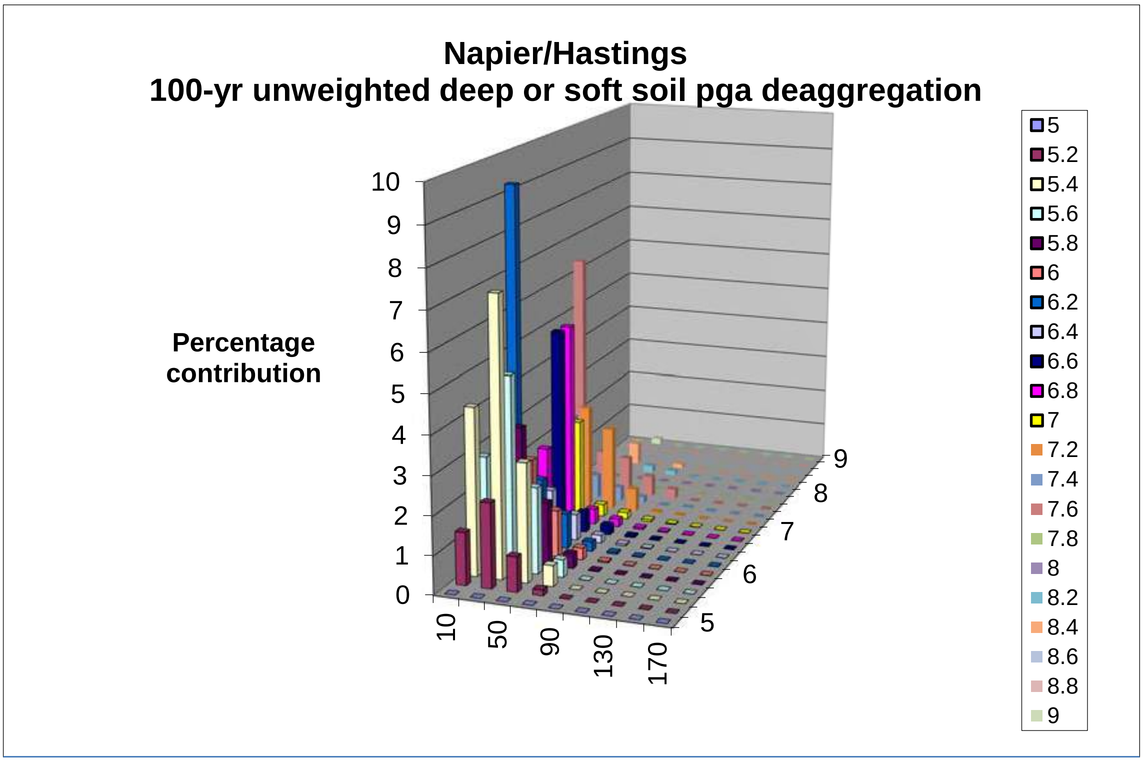

Figure 5.2 PGA disaggregation plot for the 100-year return period earthquake on the Heretaunga Plains. The plot shows the percentage contribution for various magnitude earthquakes at various distances from the epicentre (on the horizontal axis).

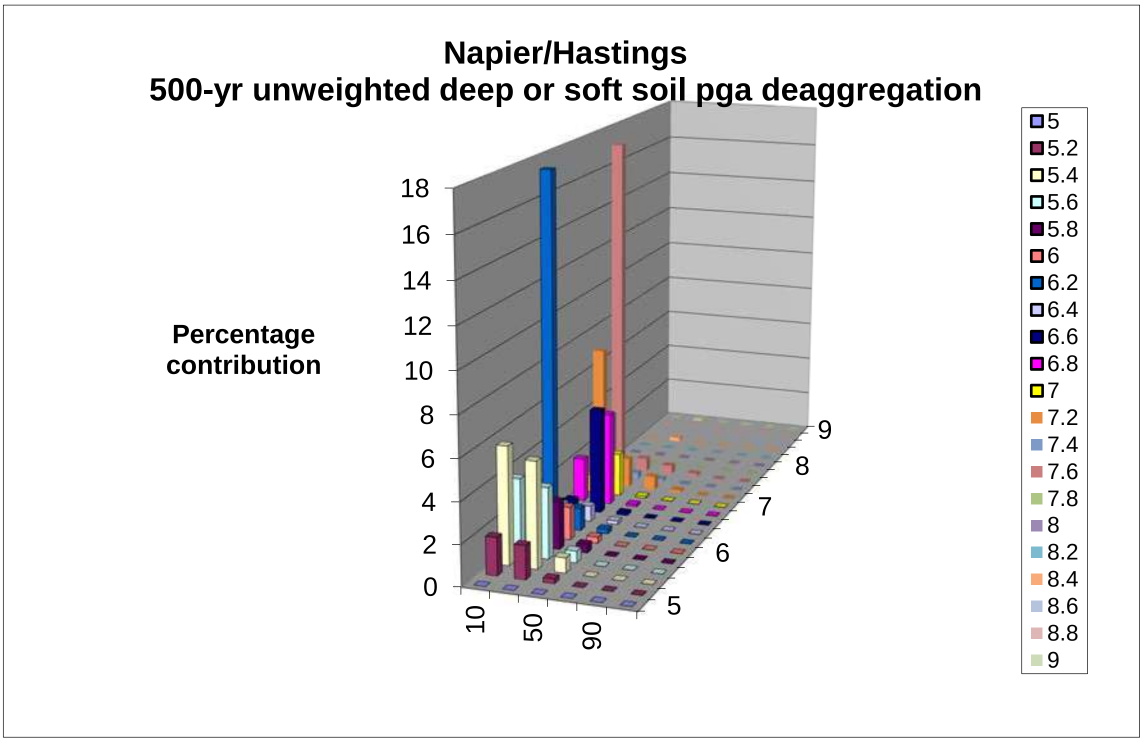

Figure 5.3 PGA disaggregation plot for the 500-year return period earthquake on the Heretaunga Plains. The plot shows the percentage contribution for various magnitude earthquakes at various distances from the epicentre (on the horizontal axis).

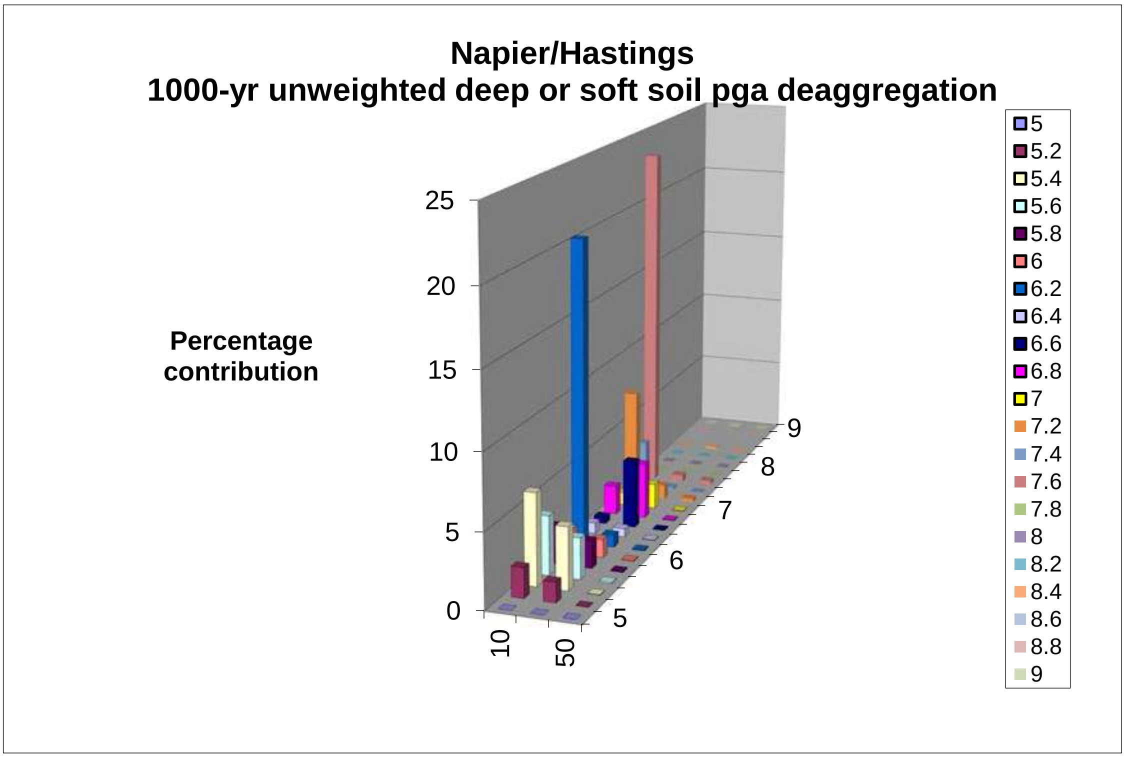

Figure 5.4 PGA disaggregation plot for the 1000-year return period earthquake on the Heretaunga Plains. The plot shows the percentage contribution for various magnitude earthquakes at various distances from the epicentre (on the horizontal axis).

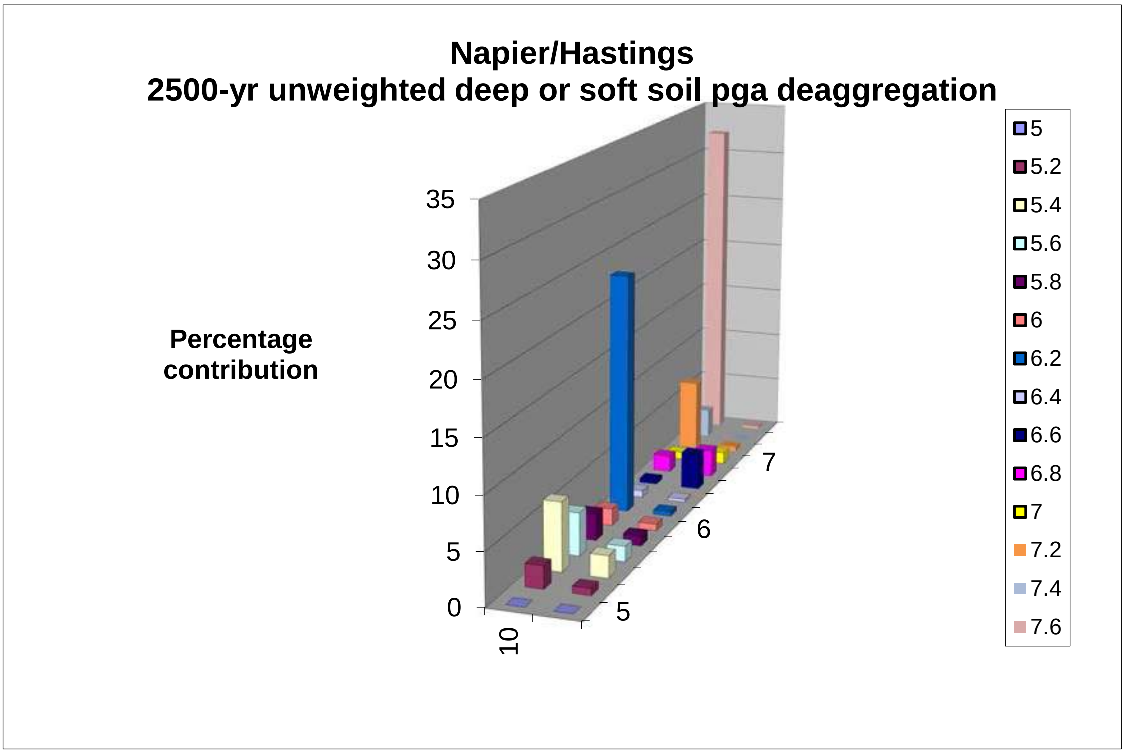

Figure 5.5 PGA disaggregation plot for the 2500-year return period earthquake on the Heretaunga Plains. The plot shows the percentage contribution for various magnitude earthquakes at various distances from the epicentre (on the horizontal axis).

6.0 LIQUEFACTION HAZARD MAPPING METHODOLOGY

6.1 HERETAUNGA PLAINS

6.1.1 Geomorphic Zoning

The first requirement in the analysis of the geology of the Heretaunga Plains was to map the surface geomorphology (Figure 3.6). An enlargement of the surface geomorphology of the Heretaunga Plains is shown in Figure 6.1. The geomorphology map shows the variation in surface processes that are present across an area. It maps the sedimentary origin (and relative age) of the near-surface sediments (1–5 m depth).

Most geomorphic units (similar age and origin) are comprised of multiple polygons reflecting the complexity of the processes forming the ground surface. For example, variations in the alluvial geomorphology are demonstrated by the multiple polygons mapped between Hastings and the coast (Figure 3.6 and Figure 6.1). Similarly, human modified ground (Figure 3.6 and Figure 6.1) includes drains across much of the former (pre-1931) Ahuriri Lagoon resulting in multiple polygons defining the extent of the former lagoon.

This representation of large geomorphic units as composites of several smaller polygons allows further refinement of the liquefaction hazard as additional datasets are added to the analysis.

The basic spatial differentiation is provided by the geomorphic map (Figure 3.6 and Figure 6.1). The next dataset to be examined in relation to the geomorphic base map was the subsurface borehole dataset. Analysis of the borehole database established several constraints on the sedimentary basin.

The first was the presence of a gravel/sand-silt boundary where the Tukituki and Ngaruroro Rivers gradient changes on entering the Heretaunga Basin (Figure 3.5). This is important because gravels are generally not prone to liquefaction.

In addition, two gravel bodies were identified at either end of the Clifton-Napier beach barrier. The gravel beneath Napier City's central business district (CBD) is consistent with the lack of reported or visible (in contemporary photographs) liquefaction damage in the Napier CBD during the 1931 Hawke's Bay earthquake.

The second constraint was on the margins of the Heretaunga Plains where the surface of rock units forming the hills could be projected down to a depth of 20 m, with some areas having rock at quite shallow depths some distance from the margin of the basin. This is important because it is the total thickness of the liquefiable materials that largely determines the liquefaction response, albeit with the shallower portion of the sedimentary column being more important to the liquefaction response at a site than are deeper layers.

The third constraint was in the inability to find discrete differences in the top twenty metres of fine grained (estuarine) sediments in the Heretaunga Plains using borehole data. The borehole data showed a mix of sands, silty sands, sandy silts and silts with individual beds showing little continuity across the plains. This lack of discernible heterogeneity in the top 20 m of estuarine sediments in the Heretaunga Plains is attributed to the complex tectonic and sedimentary history of the area, with much of the area of fine-grained sedimentation representing a mix of fluvial and estuarine conditions.

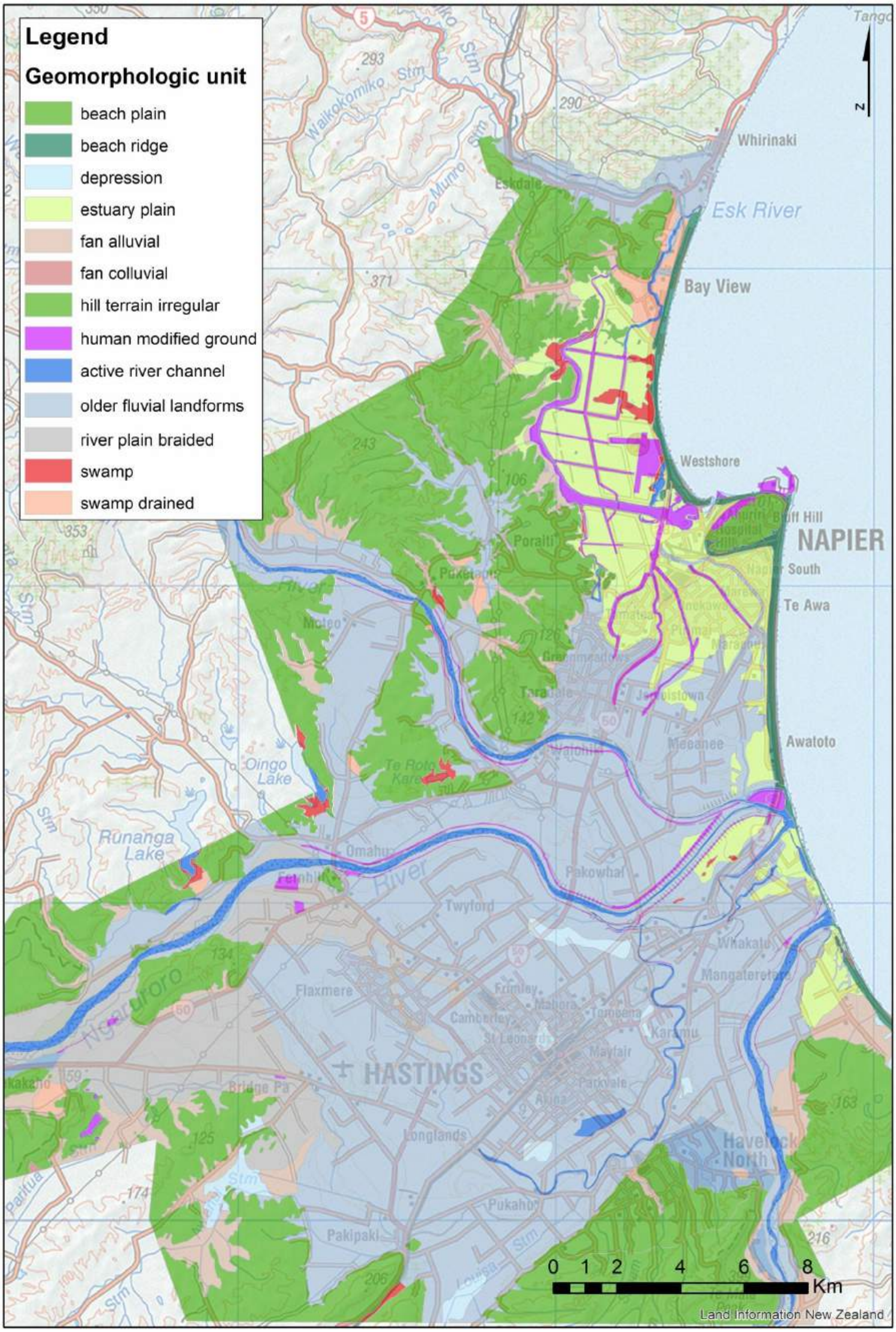

Figure 6.1 Geomorphology map of the Heretaunga Plains.

6.1.2 Liquefaction Susceptibility

As discussed in Section 2.3.2 the soil behaviour index (I_c) as determined from Cone Penetration Test (CPT) testing is a simple method to identify soils that are likely to be susceptible to liquefaction. An I_c of 2.6 or greater is typically indicative of soils that are not susceptible to liquefaction (Robertson & Wride, 1998) and is commonly referred to as the I_c 'cut-off'. Also, as discussed in Section 2.3.2, it is possible to calibrate the I_c cut-off value using laboratory test data from adjacent borehole samples. This method was not used for this study because no laboratory test data is available and adopting a default parameter of 2.6 is considered appropriate for the assessment of liquefaction vulnerability at a regional scale.

For this study, CPTs were qualitatively analysed to assess the liquefaction susceptibility of the soil layers. By grouping the CPT by their geomorphic zone and considering the spatial variation in the q_c and I_c plotted against depth, it was possible to identify areas with similar ground conditions and determine whether or not the underlying soil is likely to be susceptible to liquefaction. An example of the plot of q_c and I_c vs depth is presented in Figure 6.2 for Area A, and Figure 6.3 for Area B (refer to Figure 6.4 for area extents). In Figure 6.2 q_c vs. depth is plotted on the right-hand side of the figure and I_c vs. depth is presented on the left-hand side of the figure. The I_c cut-off of 2.6 is shown as a dashed orange line.

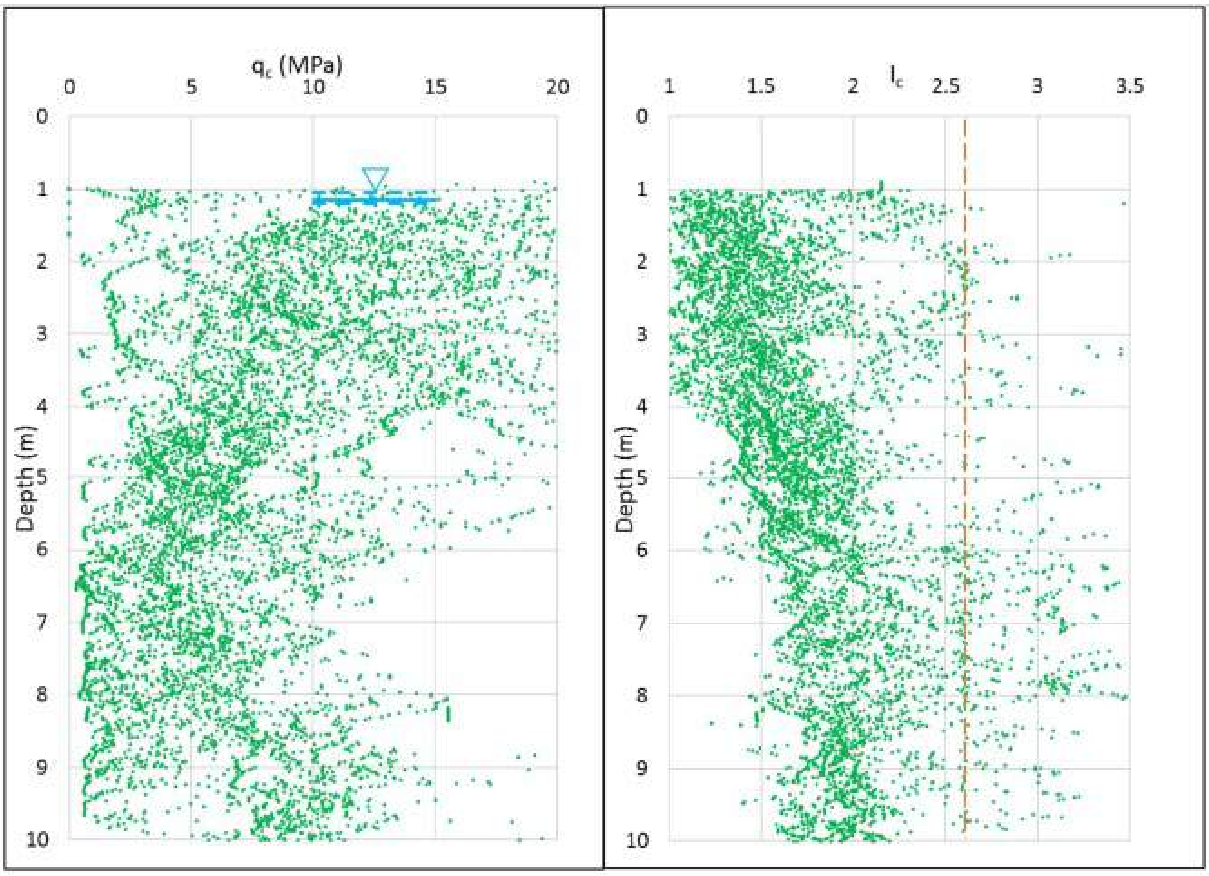

Figure 6.2 Example plot of q_c and I_c vs depth for Area A, Napier. Assumed depth to groundwater is shown by the dashed blue line, and the I_c cut-off of 2.6 by the dashed orange line.

Interpretation of the q_c plot in Figure 6.2 indicates that the top 5m of the soil in area A is of variable density ranging from approximately 2 MPa to more than 20 MPa. Below 5m the soil density is less variable and of relatively low density with q_c generally plotting between 1 and 15 MPa. Interpretation of the I_c plot indicates the top 5m of the soil in area A is also of variable soil type typically ranging from gravelly sand to silty sand/sandy silts. Below 5m the soil conditions become less variable with the predominant soil type being sand and silty sand although there appear to be some clay like lenses. In general, most of the soil profile I_c values in Figure 6.1 plots below the I_c cut-off value of 2.6 indicating that the soils in area A are likely to be susceptible to liquefaction.

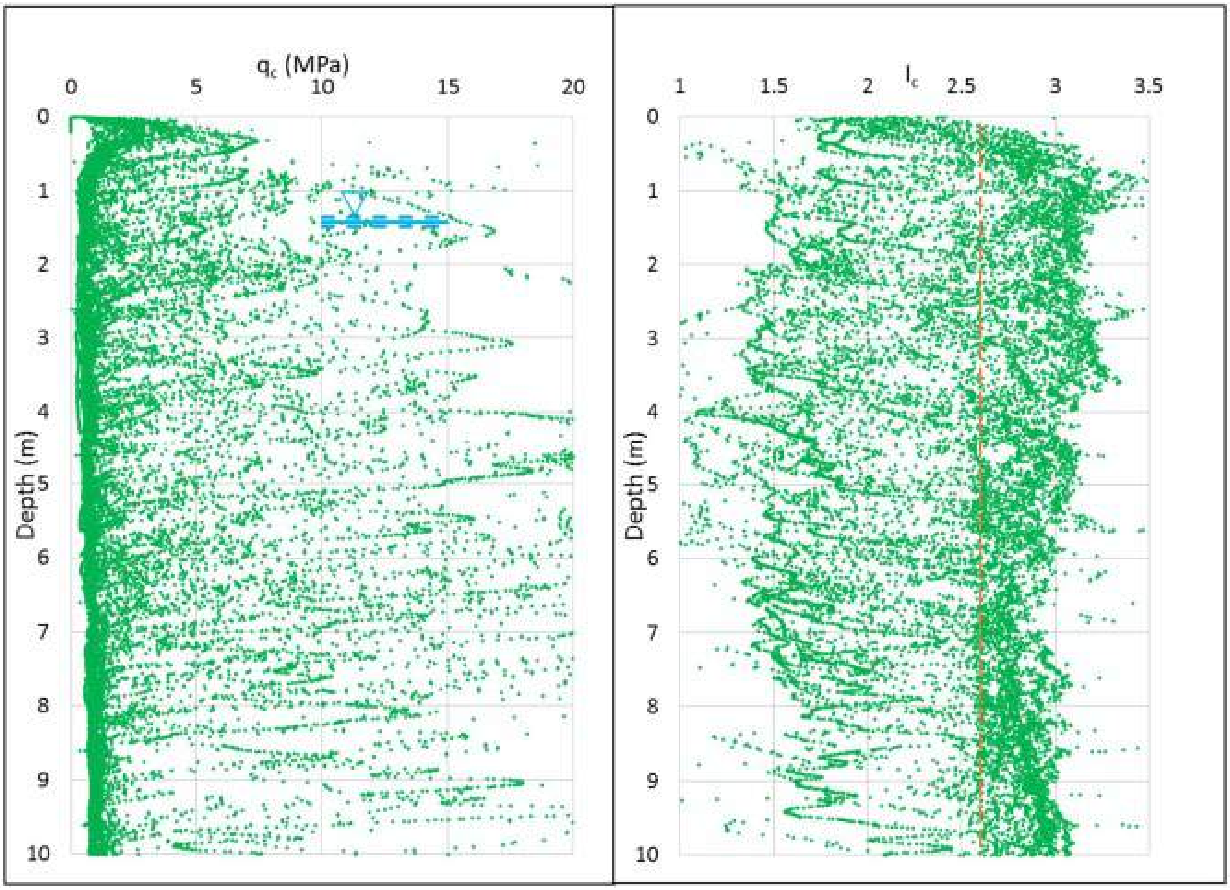

Figure 6.3 Example plot of qc and Ic vs depth for Area B, Napier. Assumed depth to groundwater is shown by the dashed blue line, and the I_c cut-off of 2.6 by the dashed orange line.

Interpretation of the q_c plot in Figure 6.3 indicates that the soil in area B is of reasonably consistent density of approximately 0 to 2 MPa. In general, most of the soil profile I_c values in Figure 6.3 plot above the I_c cut-off value of 2.6 indicating that the soils in area B are much less likely to be susceptible to liquefaction. In area B2 the soils comprise thinly interbedded sands, silts and clays with a high proportion of soil layers in the top 10m too clay like in behaviour to liquefy.

By interpretation of the q_c and I_c vs. depth plots in the manner described above, a first pass of liquefaction susceptibility of the different geomorphic groupings was undertaken (Figure 6.4). However, as discussed in Section 3.5 and shown in Figure 3.7, the CPT data on the Heretaunga plains are largely clustered in the Hastings area, the industrial areas of Napier City and Havelock North but elsewhere they are sparsely distributed. Figure 6.5 shows the level of confidence provided by the CPT data across the Heretaunga Plains. The variation in the quality of the CPT data across the Heretaunga Plains means it was not possible to use CPT's to determine liquefaction susceptibility across the entire Heretaunga plains and alternate methods were used.

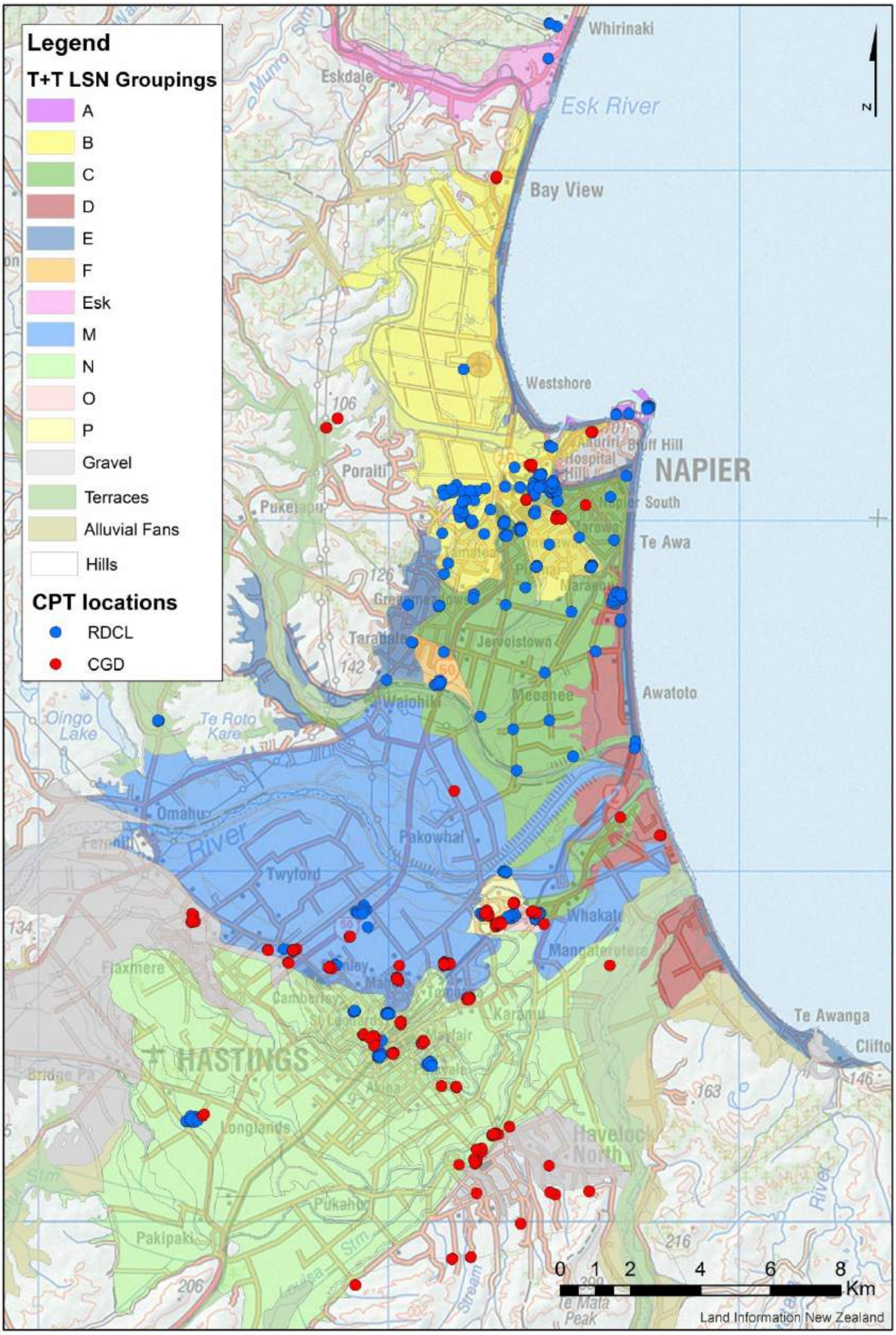

Figure 6.4 Areas of similar expected liquefaction response extrapolated to the wider area of susceptible sediments using the available data on the geotechnical properties of the underlying sediments and the geomorphic processes that formed the current ground surface. The areas identified as hills, gravels and alluvial fans are assessed as not susceptible to liquefaction based on the available data (CPTs, boreholes, comparison with the behaviour in similar geomorphic settings elsewhere and absence of historical records describing liquefaction in these areas).

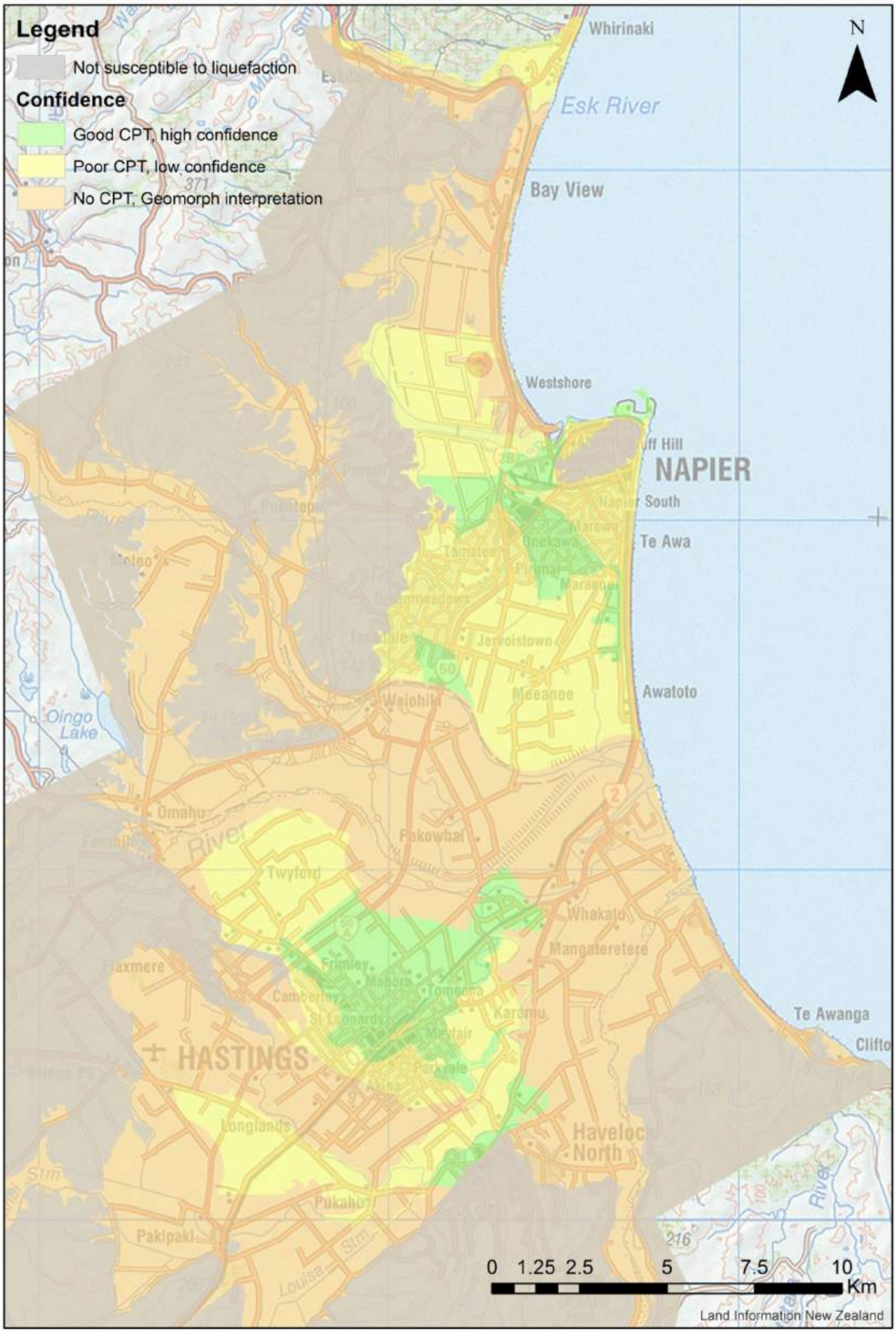

Figure 6.5 CPT spatial density as a means of providing an assessment of the reliability of the liquefaction vulnerability to be assessed for each geomorphic polygon. There is greater confidence in the liquefaction response in areas with many CPT, and lower confidence in areas with few CPT. In areas with no CPT, and the liquefaction response was based on geomorphic interpretation, the confidence was the lowest.

Two alternative methods for assessing liquefaction susceptibility were also undertaken. The first alternate method involved analysing the borehole log data from the HBRC borehole database in the project area. For each soil layer identified on the borehole logs, descriptions were given a ‘liquefiable tag’ (predominantly sands and silts) or a ‘non-liquefiable tag’ (predominantly clays, gravels and peat) to classify each soil layer as susceptible to liquefaction or not susceptible to liquefaction. Figures 6.6 and 6.7 show the thickness of soil layers susceptible to liquefaction between the top of the groundwater table and depths of 5m and 10m below the ground surface respectively based on the available borehole descriptions.

This qualitative assessment of liquefaction susceptibility from borehole data is consistent with best practice in the assessment of liquefaction vulnerability. When geotechnical borehole logs are available, soils that are considered not susceptible to liquefaction should be screened out and excluded from the assessment of liquefaction triggering (refer to Section 2.3.1). However, the borehole data that Figures 6.6 and 6.7 are developed from is of variable quality (e.g. well borehole logs and geotechnical borehole logs). These figures are included here to provide a resource that can be further refined in future updates to the liquefaction hazard maps to eliminate areas in the Heretaunga Plains where the soils are not considered susceptible to liquefaction.

The second alternate method involved qualitative assessment of liquefaction susceptibility by considering the geology, geomorphology and historic observations of liquefaction within each of the zones with a low density or no CPT or borehole data. It also included comparison of the geotechnical properties with the areas with relatively dense CPT data where an interpretation of q_c and I_c plots was feasible and similar soil conditions to the area under consideration with low density or no CPT. Figure 6.4 shows the results of the liquefaction susceptibility mapping for the Heretaunga plains.

The assessment of liquefaction triggering and liquefaction vulnerability described in Sections 6.1.3 and 6.1.4 is limited to the areas in Figure 6.4 considered to be ’Susceptible to Liquefaction.’

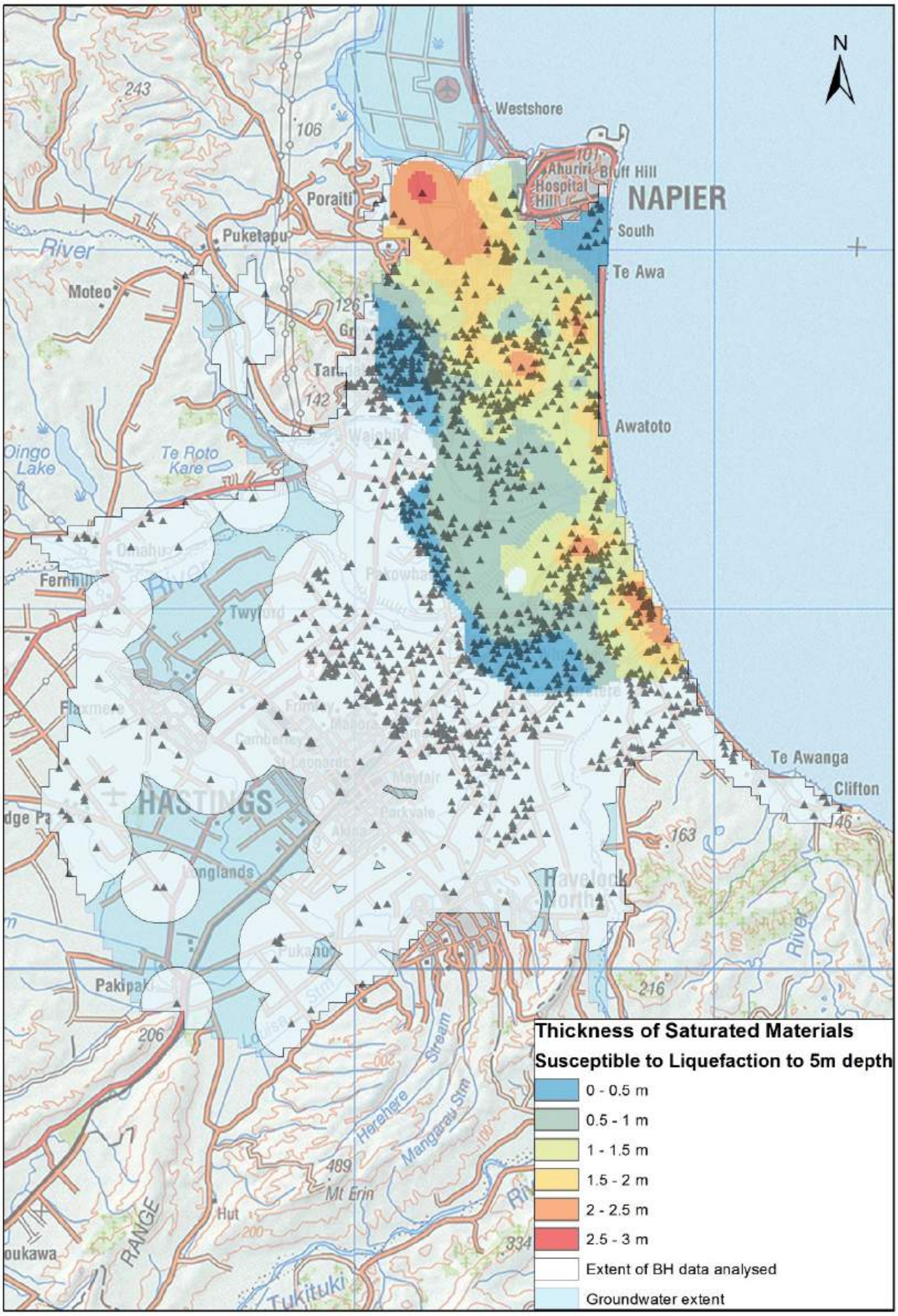

Figure 6.6 Analysis of the HBRC borehole database on the Heretaunga Plains to determine the thickness of sediments susceptible to liquefaction between the top of the groundwater table (Figure 4.2) and a depth of 5 m. Triangles are individual boreholes contributing to the analysis. The area shown as the extent of borehole data analysed indicates areas where there are no sediments susceptible to liquefaction within 5 m of the ground surface.

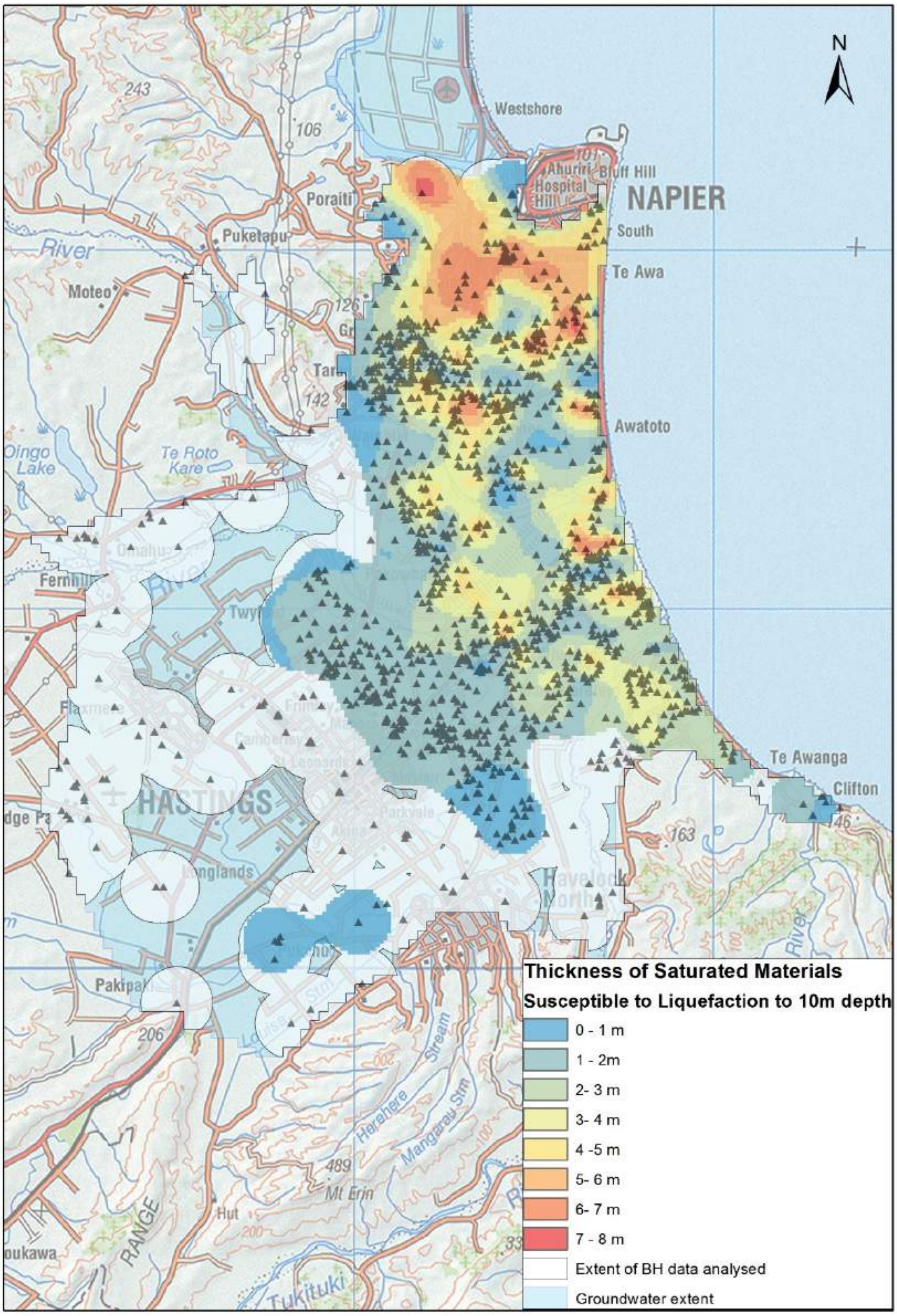

Figure 6.7 Analysis of the HBRC borehole database on the Heretaunga Plains to determine the thickness of sediments susceptible to liquefaction between the top of the groundwater table (Figure 4.2) and a depth of 10 m. Triangles are individual boreholes contributing to the analysis. The area shown as the extent of borehole data analysed indicates areas where there are no sediments susceptible to liquefaction within 10 m of the ground surface.

6.1.3 Liquefaction Triggering

As described in Section 2.3.2, liquefaction is triggered in a susceptible soil if it is saturated (i.e. below the ground water table) and the level of shaking (usually due to an earthquake) is sufficiently large enough to overcome the soil's resistance to liquefaction. The calculation of liquefaction triggering is a key input into the analysis of liquefaction vulnerability. There are several different CPT-based methods available for the assessment of liquefaction triggering including:

- *Robertson and Wride (1998);*
- *Moss and Seed (2006);*
- *Idriss and Boulanger (2008); and*
- *Boulanger and Idriss (2014).*

For this study, the Boulanger and Idriss (2014) triggering method was adopted because, of the methods listed above, van Ballegooy et. al. (2015b) found it provided the best fit to the mapped liquefaction induced damage for the regional predication of liquefaction triggering for Christchurch soils. Christchurch ground conditions are considered to be a reasonable proxy for the ground conditions found in the Heretaunga plains.

In order to assess liquefaction triggering using the Boulanger and Idriss (2014) methodology values for the input parameters must be adopted. As the method applied in this case is a regional assessment it was not feasible to vary these input parameters based on the soil conditions encountered at the individual CPT locations. Therefore, default input parameters were adopted for this study and these are listed in Table 6.1.

Table 6.1 Default input parameters adopted for the assessment of liquefaction triggering.

Input Parameter	Default value	Comments
Soil unit weight	18 kN/m^3	Liquefaction triggering assessments are typically not sensitive to changes in soil unit weight.
FC-I_c Correlation	C_{FC} = 0.0	As per recommendations of Boulanger & Idriss (2014).
I_c cut-off	I_c cut-off = 2.6	As per recommendations of Robertson & Wride (1998).
Level of earthquake shaking - Magnitude (M_W)	5, 6, 7 and 8	Varying values adopted to explore sensitivity.
Level of earthquake shaking - Peak Ground Acceleration (PGA)	0.1, 0.15, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0g	Varying values adopted to explore sensitivity.
Probability of liquefaction (P_L)	15%	Conservative estimate based on engineering practice
Depth to Groundwater (GWD)	GNS model for Zone 2	Key assumptions with GWD are that the groundwater profile is hydrostatic below the groundwater surface and the soils are fully saturated below the groundwater surface.

The reasoning behind the adoption of each of the default parameters listed in Table 6.1 is discussed in further detail below.

6.1.3.1 Soil Unit Weight

Tonkin + Taylor (2013) demonstrated that the Idriss and Boulanger (2008) liquefaction triggering methodology is not sensitive to variations in soil density in Christchurch soils and adopting a uniform default parameter is appropriate. The Boulanger and Idriss (2014) methodology accounts for soil density in the same manner as the Idriss and Boulanger (2008) methodology. Therefore, adopting a uniform default soil unit weight of 18 kN/m^3 is considered appropriate for the purposes of this study.

6.1.3.2 Fines Content correlations with I_c

When using Boulanger and Idriss (2014), the relationship between Fines Content (FC) and I_c can be derived empirically based on the equation below.

$$FC = 80(I_c + C_{FC}) - 137$$

Where C_{FC} is a fitting parameter used to calibrate the basic equation to site specific conditions. At an individual site scale, C_{FC} can be determined for different geological units using a targeted laboratory testing regime. Given that no laboratory test data is available for this regional study, it was deemed appropriate to adopt the Boulanger and Idriss (2014) default C_{FC} value of 0.0. It is noted that Lees et al. (2015) demonstrated that this was a conservative value for the Christchurch soils resulting in under-estimating the actual FC of the soil and therefore over-estimating the liquefaction potential.

6.1.3.3 Soil behaviour type index (I_c) cut-off

As discussed in Section 2.3.1 the I_c cut-off is used for the assessment of liquefaction susceptibility. Accordingly, it is one of the key input parameters for the assessment of liquefaction triggering. As discussed in Section 6.1.2, an I_c cut-off of 2.6 has been adopted for the regional assessment of liquefaction susceptibility in this study. Therefore, it has also been adopted for the CPT-based assessment of liquefaction triggering.

6.1.3.4 Level of earthquake shaking (M_W and PGA)

As discussed in Section 5, the Boulanger and Idriss (2014) liquefaction triggering methodology requires an earthquake M_W - PGA pair, in order to calculate the liquefaction triggering for an individual CPT. Rather than specifying a unique M_W – PGA pair for the assessment of liquefaction triggering, the range of M_W and PGA values shown in Table 6.1 were adopted. Adopting a range of values was the preferred approach be it enables consideration of the sensitivity calculation to M_W and PGA.

6.1.3.5 Probability of Liquefaction (P_L)

The Boulanger and Idriss (2014) liquefaction triggering methodology incorporates a probability of liquefaction parameter (P_L) for selecting the liquefaction resistance equations. The P_L = 50% liquefaction resistance equation provides a best fit to the data with a 50% chance that the liquefaction triggering is under-predicted and a 50% chance that it is over-predicted. The P_L = 15% liquefaction resistance equation provides a conservative fit to the data with a 15% chance that the liquefaction triggering is under-predicted and an 85% chance that it is over-predicted.

It is standard engineering practice to adopt the P_L = 15% liquefaction resistance equation when undertaking deterministic design based calculations. Therefore, for the purposes of this regional assessment, the P_L = 15% liquefaction resistance equation has been adopted.

6.1.3.6 Depth to Groundwater (GWD)

Adopting an appropriate depth to groundwater is a critical assumption in the assessment of liquefaction triggering because liquefaction can only occur if the soil is saturated. The groundwater depth adopted for the assessment of liquefaction triggering at each CPT location is that provided by the model described in Sections 3.2 and 4.

There is potential for significant uncertainty in the groundwater data used in this assessment. This uncertainty has two aspects. The first relates to the variation in spatial density of the groundwater records (see Appendix 6). The second relates to the lack of time-series data for the groundwater observations to quantify the seasonal variation in groundwater levels. This uncertainty could be significant if there are large seasonal fluctuations in the groundwater level. This could potentially result in the liquefaction triggering being underestimated using the currently available groundwater data.

Key assumptions associated with adopting a groundwater surface for liquefaction triggering are:

- ***The soils above the groundwater surface are not saturated*** *- It is standard engineering practice to assume that the soil layers above the groundwater surface are not saturated and hence are not evaluated for liquefaction triggering. This assumption has also been adopted for this study;*
- ***The soils below the groundwater surface are fully saturated*** *– Chaney (1978) and Yoshimi et al. (1989) amongst others have studied the effects of partial saturation on liquefaction triggering and found that a reduction in the saturation ratio resulted in an increase in the resistance of soils to liquefaction (i.e. partially saturated soils require an increased level of shaking to trigger liquefaction). However, because the degree of saturation below the groundwater surface is not well understood and is potentially seasonably variable, it is most appropriate to conservatively assume full saturation below the groundwater surface level.*
- ***The pressure profile below the groundwater surface is hydrostatic*** *– In liquefaction triggering assessments it is typical to assume a hydrostatic groundwater profile. However, in some soils this is not the case. Groundwater can be partially perched resulting in a groundwater pressure profile which is less than hydrostatic. In other areas, there are upward pressure gradients resulting in a groundwater pressure profile which is greater than hydrostatic. In either case it is not practical to evaluate these highly localised groundwater conditions at a regional level. Therefore, it is practical to assume a simple hydrostatic groundwater pressure profile.*

6.1.4 Liquefaction Vulnerability

In order to further understand liquefaction vulnerability on the Heretaunga Plains, LSN indices were calculated for each of the CPT available for the Magnitude and PGA pairs listed in Table 6.1. For each magnitude level (i.e. 5, 6, 7 & 8) and geomorphic zone (refer to Section 3.3 and Figure 6.4) plots of LSN vs. PGA were produced and are shown in Figure 6.8 and Figure 6.9, where each line represents the LSN vs. PGA response for a single CPT. The median, 15^{th} and 85^{th} percentile LSN vs. PGA lines for the grouping of CPT in each geomorphic zone were then calculated and overlaid on the plots of the individual CPT.

Figure 6.8 and 6.9 show the LSN vs. PGA plots for Napier and Hastings respectively for a magnitude 6 earthquake. Similar curves were produced for magnitude 5, 7 and 8 earthquakes. Table 6.2 shows the 15th, 50th and 85th percentile LSN values for each area in Napier and Hastings, at PGA = 0.14g, 0.25g and 0.42g with corresponding MW values of 6.2, 6.3 and 6.5 (corresponding with the 25, 100 and 500-year return period level of earthquake shaking (refer to Section 5)). The LSN values presented in Table 6.2 have been developed from linear interpolation between the LSN values from the LSN vs. PGA curves presented in Figures 6.8 and 6.9. That is, the LSN values have not been calculated specifically for the MW and PGA pairs presented in Table 6.2, but they represent a very close approximation. Note Table 2.1 provides a summary of the indicative land performance for different LSN values.

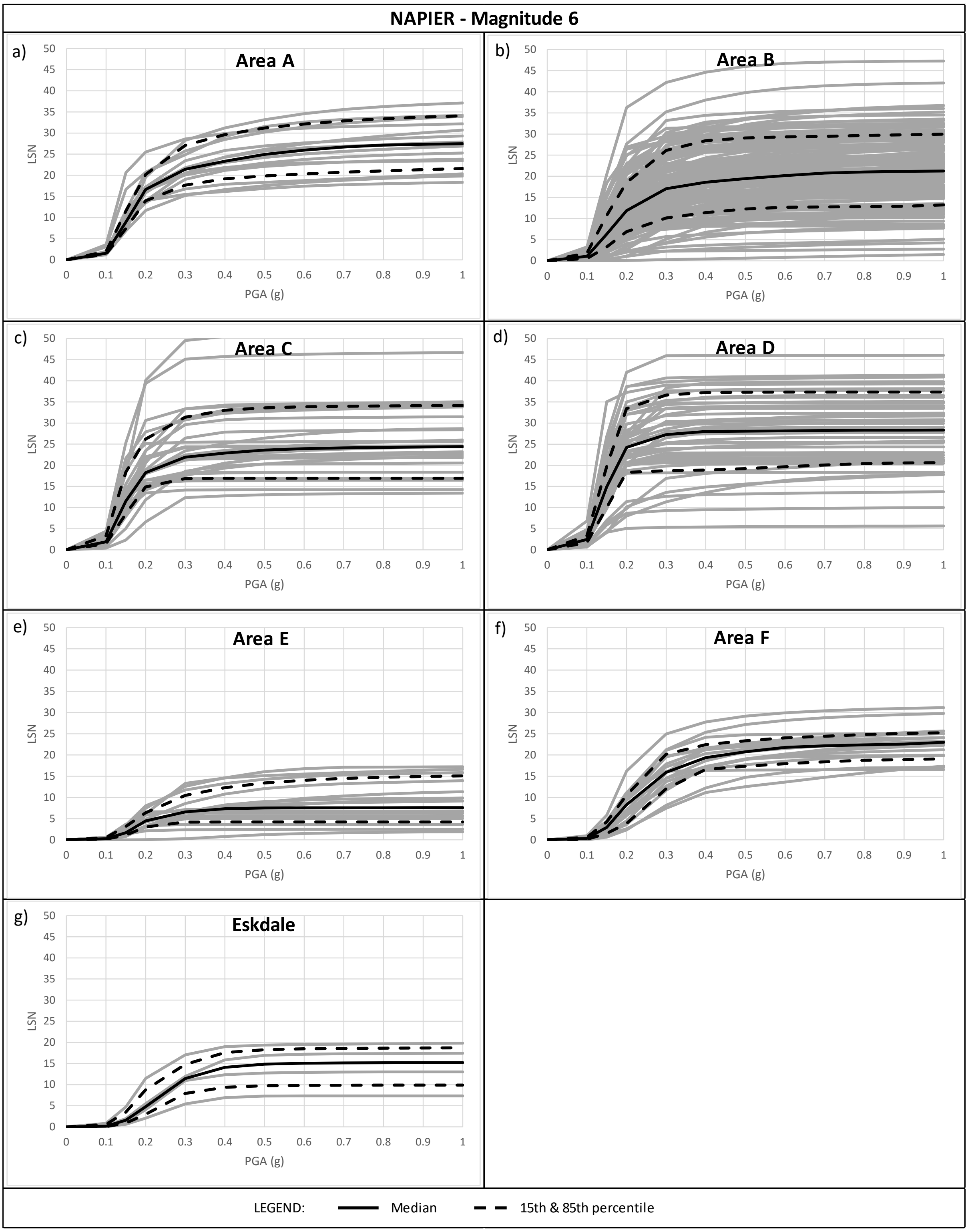

Figure 6.8 LSN vs PGA plot for Napier for a Magnitude 6 earthquake. The spatial variability of the LSN values (15th and 85th percentiles) are shown as dashed lines. See Figure 6.4 for the location of the areas.

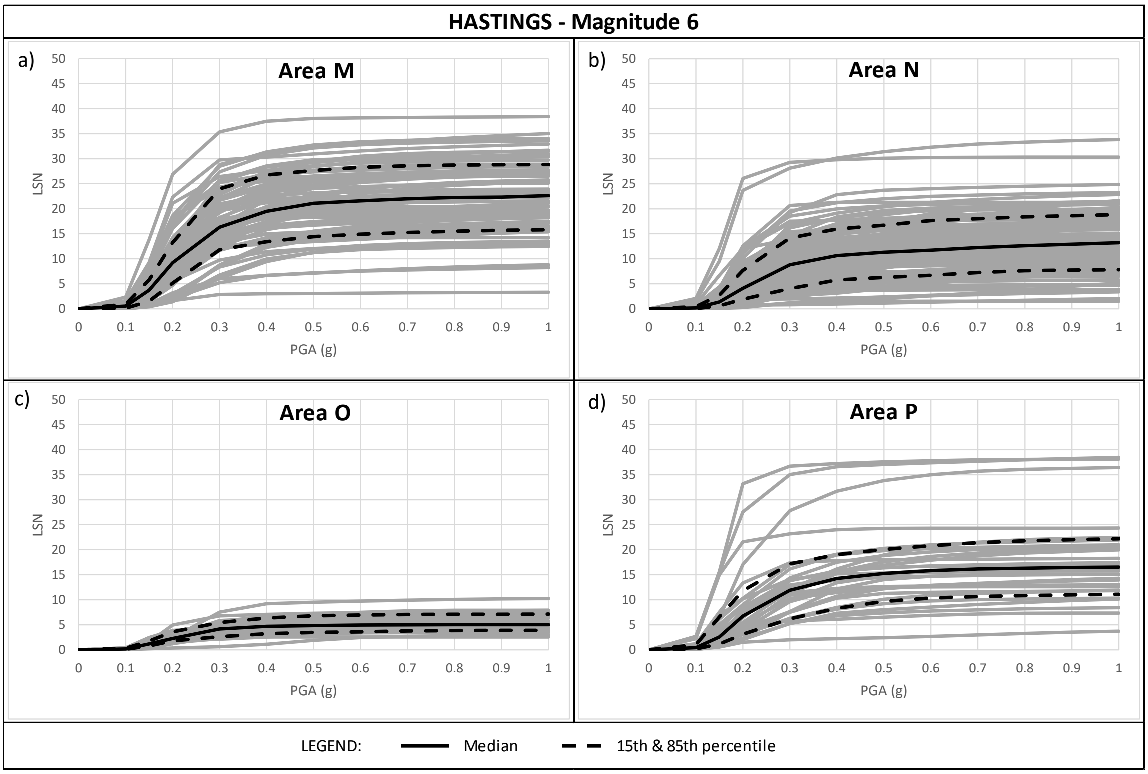

Figure 6.9 LSN vs PGA plot for Hastings for a Magnitude 6 earthquake. The spatial variability of the LSN values (15th and 85th percentiles) are shown as dashed lines.

Table 6.2 15th, 50th and 85th percentile LSN values for each area in Napier and Hastings, at PGA = 0.14g, 0.25g and 0.42g for M_W 6.2, 6.3 and 6.5 earthquakes respectively (corresponding with the 25, 100 and 500-year return period levels of earthquake shaking). The number of CPTs (n) used for the calculation is also shown. See Figure 6.4 for the location of areas.

Area	n	0.14g M_W 6.2			0.25g M_W 6.3			0.42g M_W 6.5		
		15th %ile	50th %ile	85th %ile	15th %ile	50th %ile	85th %ile	15th %ile	50th %ile	85th %ile
A	17	4	7	10	15	20	24	19	25	31
B	150	3	5	9	9	16	23	12	19	27
C	28	6	10	17	14	27	33	17	29	34
D	43	7	13	16	19	27	36	19	28	36
E	17	1	2	3	6	9	13	8	12	21
F	19	1	2	3	9	14	18	17	21	23
M	4	1	3	6	10	15	24	14	22	29
N	76	1	1	2	4	8	14	7	12	18
O	132	1	1	1	2	4	5	3	6	7
P	32	1	2	6	5	12	31	10	16	35
Total CPTs	549									

Inspection of Figure 6.8 and Figure 6.9 provides an indication of the level of spatial variability of expected performance for each of the geomorphic zones. For example, if the lines on the LSN vs. PGA plots are that are tightly grouped and the 15th and 85th percentile LSN vs. PGA lines are close together (e.g. Areas A, E and F in Figure 6.8 and Area O in Figure 6.9), indicates a relatively uniform predicted land performance for the entire geomorphic area. Whereas, if the individual LSN vs. PGA lines are widely spaced and the 15th and 85th percentile LSN vs. PGA lines are far apart (e.g. Areas B & D in Figure 6.8), this indicates a relatively spatially variable predicted land performance ranging from none to minor predicted liquefaction in some parts of the geomorphic zone to very high predicted liquefaction in some parts of the geomorphic zone. It is noted that for the geomorphic zones where significant spatial variability is predicted, it is not possible to distinguish which parts will have none to minor predicted liquefaction and which parts have very high predicted liquefaction.

The results of the CPT analysis were then extended to cover the area identified as susceptible to liquefaction (Figure 6.4) by assigning areas with no CPT data to the same liquefaction response as units with CPT data and the same geomorphic origin.

The geomorphic groupings after considering the CPT derived LSN response included the following:

- Reclaimed land on the north side of Bluff Hill (area A on Figure 6.4);
- The pre-1931 Ahuriri Lagoon sea-floor, including inter-tidal areas (area B on Figure 6.4);
- Areas underlain by a deep thickness of estuarine silt in the deltaic-inter-tidal area of the pre-1931 Ahuriri Lagoon (area C on Figure 6.4)
- Areas underlain by sand dominated estuarine sediments immediately behind the barrier beach between Napier and Clive (area D on Figure 6.4)
- An area marginal to the eastern hills of Taradale where the Holocene sediments are relatively thin over the underlying bedrock (areas E and F on Figure 6.4)
- The alluvial sediments of the Esk River (area 'Esk' on Figure 6.4)
- Areas underlain by mixed gravel and estuarine sediments (sandy silts and silts) but probably dominated by estuarine sediments (area M on Figure 6.4)
- Areas underlain by mixed gravel and estuarine sediments (sandy silts and silts) but probably dominated by gravels, especially near the surface (area N on Figure 6.4)
- Small areas where the CPT derived LSN analysis is distinctly different than the surrounding areas (areas O and P on Figure 6.4)
- Gravel alluvium where the unconfined shallow groundwater surface is more than three metres deep ('Gravel' on Figure 6.4)
- Alluvial terraces of the Tukituki (gravels) and Tutaekuri (sandy gravels and silty sands) Rivers ('Terraces' on Figure 6.4)
- Alluvial fans marginal to hill slopes ('Alluvial fans' on Figure 6.4)

The last three areas do not contain any CPT tests and so the liquefaction response is based on historical performance in this area and in similar geomorphic settings elsewhere.

The liquefaction hazard maps for the three return periods being considered are presented in Section 7.1 (Figure 7.1 to Figure 7.3), based on the results presented in Table 6.2. The progression in the extent and severity of the liquefaction as the earthquake shaking levels increase is plainly visible in these maps. The range of LSN values calculated for the Hawke's

Bay area ranged from 5 to about 35, based on the distribution of available CPT dataset for the region. The areas of greatest liquefaction damage in Christchurch had LSN values in the range of 30 to 40. Therefore, there are some parts of the Hawkes Bay where the liquefaction is predicted to be as severe as the worst parts of Christchurch.

The predicted liquefaction extent and severity, at levels of earthquake shaking comparable to the 1931 earthquake, is significantly greater that the extent and severity of liquefaction observed from the 1931 earthquake (Dellow et al, 1999; El Kortbawi, 2017). Research is currently being undertaken to better understand the reasons for the inconsistency between the predicted and observed liquefaction. This means that the liquefaction maps presented in this report will need to be updated in the future as scientific knowledge of predicting the liquefaction hazard improves.

The CPT profiles for geomorphic Areas B, C and D in Napier and areas M and N in Hastings comprise finely interbedded sand, silt and clay stratigraphy. Based on case histories of sites with finely interbedded sand, silt and clay stratigraphy from Whakatane following the 1987 Edgecumbe earthquake, Christchurch following the 2010-2011 CES earthquakes and Blenheim following the 2016 Kaikoura earthquake, the common liquefaction evaluation procedures have been found to have a tendency to over-predict liquefaction in these interbedded profiles. The potential for common liquefaction evaluation procedures to over-predict liquefaction effects in finely interbedded sand, silt and clay deposits stems from several contributing factors associated with: (1) limitations in site characterization tools and procedures, (2) limitations in liquefaction triggering or consequence correlations, and (3) limitations from analysis approaches and neglected mechanisms. The factors are summarised in Table 6.3. The first three factors listed under site characterization tools in Table 6.3 are described in relation to the CPT, but analogous issues exist with all in situ testing methods.

However, it is also appropriate for the hazard maps presented here to reflect some conservatism because of the lack of data (few or no CPT profiles in some areas), the possibly incomplete observations in the historical record and the lack of data on the seasonal, or other, fluctuations in groundwater levels.

Table 6.3 Factors affecting prediction of liquefaction effects in interbedded soil deposits (reproduced from Boulanger et al., 2016).

Factor	Role
Limitations in site characterization tools and procedures	
Interface transitions	Penetration resistance (e.g., q_t) in sandy soils reduced near interfaces with clays or silts. I_c values increase in the sandy soils and decrease in the clays/silts near the interface.
Thin layer effects	Penetration resistance (e.g., q_t) in sand reduced if the sand layer is less than about 1 m thick (with clays/silts on either side of the layer).
Fining sequences	In-situ tests may not distinguish between distinct interfaces and fining sequences. Transition and thin layer effects in fining sequences are not well understood.
Continuity of lenses	Large horizontal spacing of explorations may not enable quantifying the lateral continuity of weak or liquefiable layers.
Saturation	Presumption of 100% saturation below the groundwater table may underestimate cyclic strengths for partially saturated zones.
Limitations in correlations for liquefaction triggering or consequences	
Triggering correlations	Triggering correlations are not well constrained for intermediate soils with certain FC and PI combinations. CRR likely underestimated if soils are treated as sand-like, and overestimated if treated as clay-like.
Strain correlations	Correlations for estimating shear and volumetric strains have been developed primarily from data for sands or clays; the extension of these correlations to intermediate soils has not been systematically examined.
Limitations from analysis approaches and neglected mechanisms	
Spatial variability	The assumption that liquefiable layers are laterally continuous can contribute to over-estimation of potential liquefaction effects. Composite strength from nonliquefied and liquefied zones may limit deformations.
Thick crust layers	Thick crust layers can reduce surface manifestations of liquefaction at depth in areas without lateral spreading.
Dynamic response	Liquefaction of loose layers in one depth interval may reduce seismic demand on soils in other depth intervals.
Geometry & scale	The 2D or 3D scale of a deformation mechanism affects the dynamic response and role of spatial variability.
Diffusion	Seepage driven by excess pore pressures may increase or decrease ground deformations depending on stratigraphy, permeability contrasts, geometry, seismic loading, and other factors.

The final step in the consideration of liquefaction vulnerability for the Heretaunga Plains is to consider the impact of lateral spreading. For lateral spreading to occur, generally, a free face (e.g. river, stream or drain bank) is required to allow lateral movement of the ground toward the watercourse. This can be accommodated by placing a buffer around watercourses. The types of soil stratigraphy that produced large scale lateral spreading in Christchurch do not appear to be present in the Heretaunga Plains (pers. comm. Sjoerd Van Ballegooy). Therefore, the width of the buffer on both sides of the watercourses is assumed to be 40 times the difference in height between the top of the bank / flood plain and the bottom of the water-course for this study area. The width of the buffer is in proportion to the depth of the watercourse. For example, for streams and drains where the height difference between the bottom of the channel and the top of the bank is 2 m a buffer of 80 m on both sides of the centreline of the channel would be used. This would increase to a buffer width of 200 m for rivers which have a height difference of 5 m between the bottom of the river channel and the top of the river bank. The absence of accurate information about the height difference between the bottom of channels and the tops of banks for watercourses has precluded the consistent presentation of buffer zones on the maps. In areas identified as susceptible to liquefaction, lateral spreading adjacent to rivers, streams and drains needs to be considered in the assessment of liquefaction vulnerability.

It is important to note that liquefaction induced lateral spreading is a complex phenomenon and that this buffering process is a simplified approach. The method does not account for variable ground conditions encountered around watercourses, free faces that are not associated with watercourses (e.g. road cuttings) or lateral spreading that may occur on sloping ground in the absence of a free face. Liquefaction can also be a cause of overall ground surface subsidence, along with broader scale tectonic subsidence. In low lying areas near watercourses ground surface subsidence can result in houses becoming more flood prone.

6.2 WAIROA

A liquefaction susceptibility map was compiled for Wairoa from the following data: Qmap Hawke's Bay; Qmap Raukumara; LiDAR data; the historical earthquake record and CPT data in Wairoa. The map scale used to identify liquefiable areas for this work is 1:250,000. More detailed mapping (at 1:25,000 or greater) would be required to establish boundaries suitable for use at the scale of a District Plan.

6.2.1 Geomorphic Zoning

QMAP geology (Figure 6.10) was used to spatially differentiate the area into liquefiable and non-liquefiable units. The identified liquefiable units were then checked against the LiDAR data (Figure 6.11). All geological units, labelled as older than Holocene (more than 10,000 years old) were eliminated, on the basis:

1. All pre-Quaternary (older than 2.5 million years) geological units will not experience liquefaction as their densities are too great.
2. Quaternary geological units (gravel dominated river alluvium) whose surfaces were mantled with loess were assessed as being deposited prior to the Holocene (last 10,000 years) and assessed as too old (dense) to experience liquefaction:
    a. Pre-Holocene river alluvium and mixed pre-Holocene alluvial and estuarine deposits (both with loess cap) include: lQal; lQal; lQae.
    b. Pre-Holocene alluvial fans (gravel dominated with a loess cap) include: uQaf.

This left five geological units that met the age criteria (i.e. Holocene, less than 10,000 years old).

Q1b are beach sediments of sand and gravel of the modern (active) shoreline and includes minor marginal dunes. These sands are exposed to open coastal processes including wave action and are probably dense enough to preclude liquefaction occurring (c.f. New Brighton in Christchurch, http://cera.govt.nz/sites/default/files/common/tonkin-and-taylor-land-damage-presentation-ccc-area-23-june-2011.pdf; accessed 26 August 2016). These sediments are assessed as non-liquefiable.

The Q1as is peat dominated accumulations of fine-grained sediment in swamp deposits. The presence of peat reduces the likely severity of any liquefaction (van Ballegooy, pers. comm.), although these sediments are likely to meet the criteria necessary for liquefaction to occur – they are young (Holocene, less than 10,000 years old), fine grained, probably non-cohesive and a shallow water table (less than 2 m below the ground surface) is likely present.

Q1al (and Q1at) are alluvial sediments of the Wairoa River valley and along the coastal fringe between the hills and the estuarine sediments between Wairoa and Nuhaka. On the Hawke's Bay 1:250,000 geological map (Lee et al, 2011) the sediments of the Waiau River (a tributary of the Wairoa River) are mapped as Taupo pumice alluvium (Q1at) but this map assignation does not continue across the map boundary into the earlier Qmap Raukumara (Mazengarb and Speden, 2000). In hand-auger and borehole logs presented in Ota et al (1989) a thin layer of Taupo pumice is identified in most of the logs. These same bore-logs indicate fine-grained sediments are present to depths ranging from 4 m to 45 m. These fine-grained sediments are recorded as sandy silts, silts and clays. The presence of clays indicates some areas of cohesive sediments that are unlikely to liquefy. Conversely the non-cohesive sandy silts and silts indicate non-cohesive sediments that will liquefy in the right conditions.

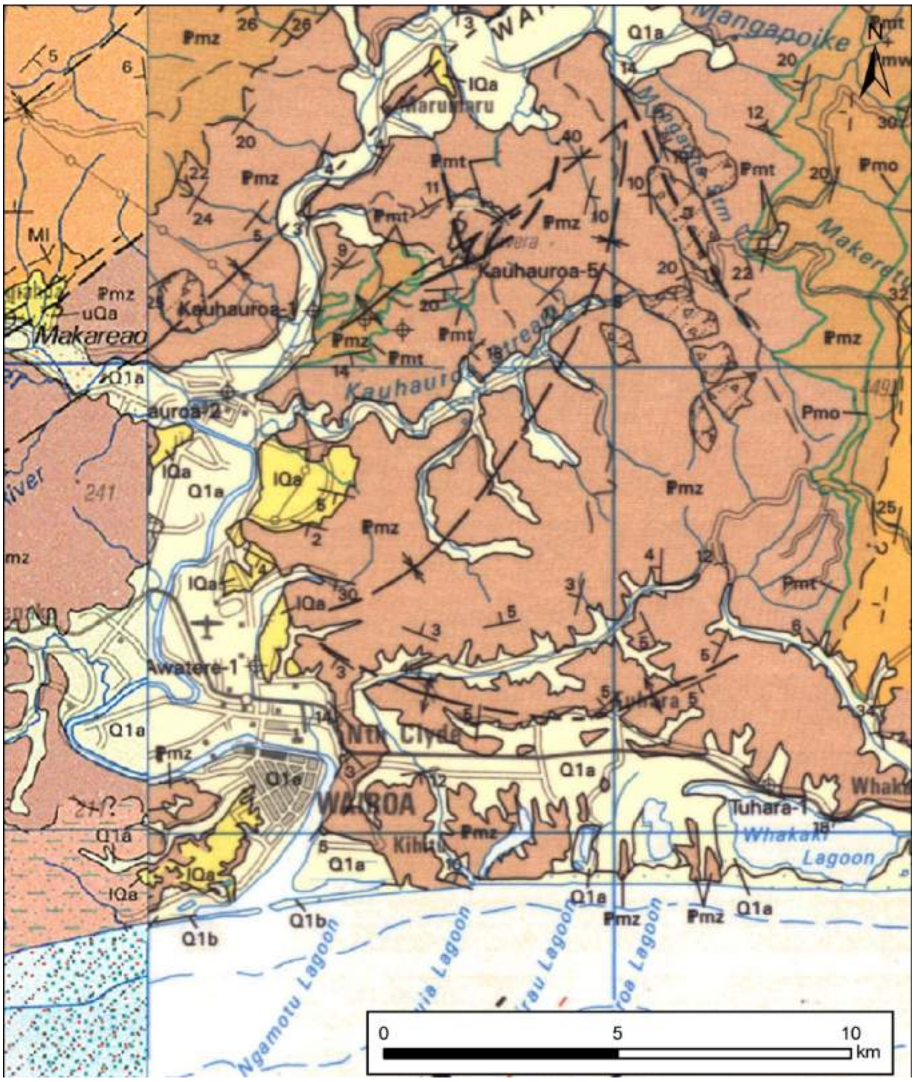

Figure 6.10 1:250,000 geological map (Lee et al, 2011; Mazengarb and Speden, 2000) for the main urban areas (Wairoa and Frasertown) of the Wairoa District.

Q1ae are estuarine sediments mapped between the marginal marine beach sediments and the alluvial river terraces formed by rivers and streams. The estuarine deposits are described as poorly consolidated peat, mud, sand and minor gravel (Mazengarb and Speden, 2000). This is consistent with the borehole and auger logs described in Ota et al (1989). The presence of peat reduces the likely severity of any liquefaction (van Ballegooy, pers. comm.). The presence of clay (cohesive and therefore non-liquefiable) also reduces the likely severity and extent of liquefaction in the Holocene sediments of the Wairoa area.

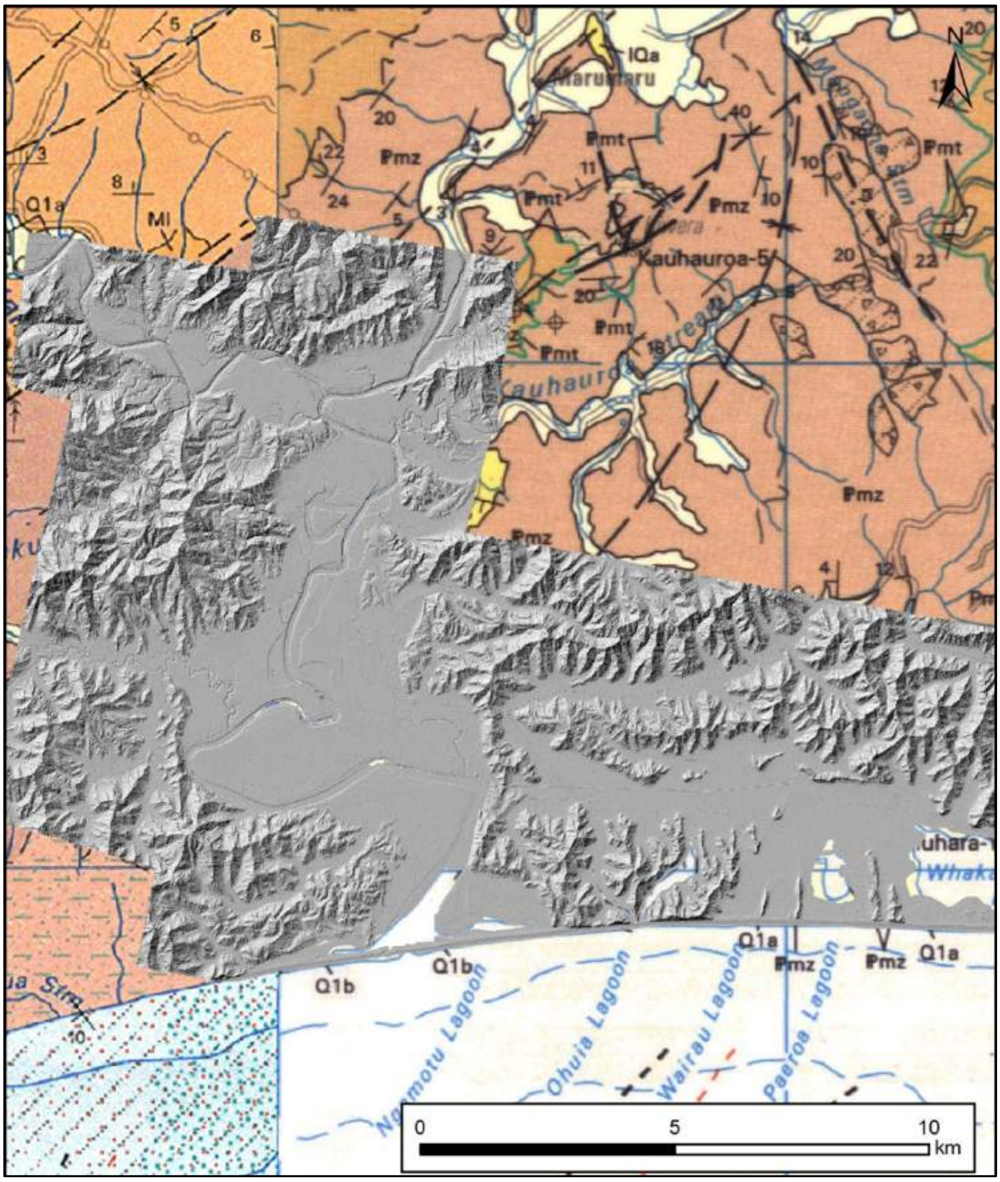

Figure 6.11 Available LiDAR topographic data for the main urban centres of the Wairoa District.

The combination of geology (QMAP), LiDAR topography, shallow subsurface geology, cone penetrometer tests records and shallow unconfined groundwater surface model (Appendix 6; Figure 6.4) all combine to indicate that liquefaction is possible in areas of Holocene alluvial and estuarine sediments in the Wairoa-Mahia area. This is supported by reports of liquefaction features after historical earthquakes. These reports include lateral spreading and sand boils.

Based on the available data, a liquefaction hazard requiring mitigation is present in the Wairoa District (Figure 6.12; Table 6.4 and Table 6.5). However, both the environmental data and the historical data indicate a high degree of variability within the Holocene sediments that are potentially susceptible to liquefaction. In particular, the presence of cohesive clays in several of the subsurface records would likely reduce consequential liquefaction occurring in some areas.

Table 6.4 Peak ground acceleration values from the New Zealand National Seismic Hazard Model for Wairoa (highlighted in green).

Hawke's Bay Sites un-weighted Site Class D PGA values (g)					
Location	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Wairoa	0.14	0.24	0.40	0.47	0.59
Waipukarau	0.17	0.29	0.47	0.57	0.71
Napier/Hastings	0.14	0.25	0.42	0.51	0.64

Table 6.5 The average magnitude of an earthquake contributing to PGA at different return periods (Wairoa highlighted in green).

Hawke's Bay Sites un-weighted Site Class D Average Magnitude Contributions to PGA					
Location	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Wairoa	5.9	5.9	6.0	6.0	6.1
Waipukarau	6.0	6.1	6.3	6.4	6.4
Napier/Hastings	6.2	6.3	6.5	6.6	6.7

If the shallow, unconfined groundwater surface is set at 0.5 m below the ground surface (as per Figure 6.4 in Appendix 6) this gives an LSN range of 12 to 35 at one standard deviation, with a median of 19 at a PGA of 0.3 g for a magnitude 6.0 earthquake (Figure 6.12).

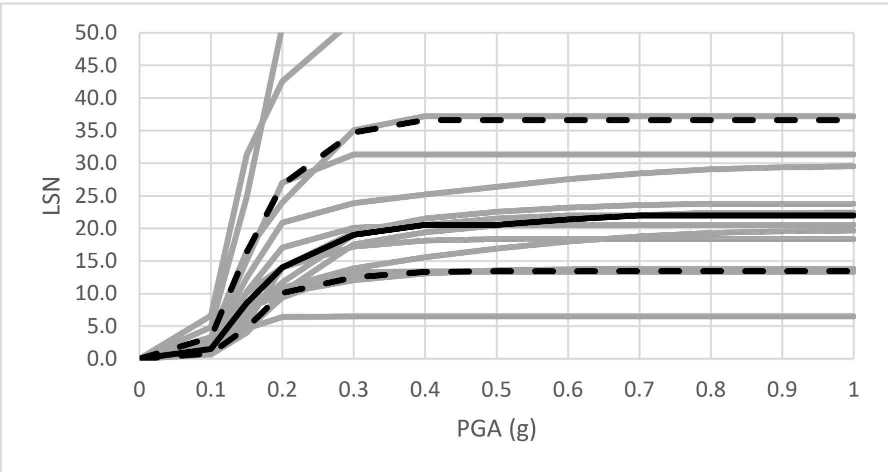

Figure 6.12 CPT curves for Wairoa for a shallow, unconfined groundwater surface 0.5 metres below the ground surface (as per Figure 6.4 in Appendix 6) for a magnitude 6 earthquake.

Based on the location of the CPT curves in the Wairoa township it would be expected that sand boils and other ejecta would have been observed and reported after historical earthquakes. The lack of contemporary accounts of ejected material in Wairoa is not easily dismissed as these features were commonly reported by observers during and after earthquakes (c.f. reports from Mahia c.1932). However, in the subsurface borehole and auger data pumiceous materials are present at depths of up to two metres. As was observed in Whakatane, pumiceous material may result in over-prediction of LSN values (Van Ballegooy pers. comm.).

The other feature that may be contributing to this is the high uncertainty on the shallow, unconfined groundwater surface (Appendix 6; Figure 6.9). A shallow, unconfined groundwater surface one metre below the ground surface yields a different set of curves (Figure 6.13) - an LSN range of 9 to 21 at one standard deviation, with a median of 10 at a PGA of 0.3 g for a magnitude 6.0 earthquake. These curves are a better representation of the observed liquefaction ground damage after historical earthquakes.

Putting the data together for Wairoa town strongly suggests that the expression of liquefaction is most sensitive to the shallow, unconfined groundwater surface. The CPT data is consistent with the borehole and auger data with the most susceptible sediments – pumiceous sands present at depths of less than two metres. The CPT data also indicates that the estuarine sediments are much less susceptible to liquefaction than the overlying sands.

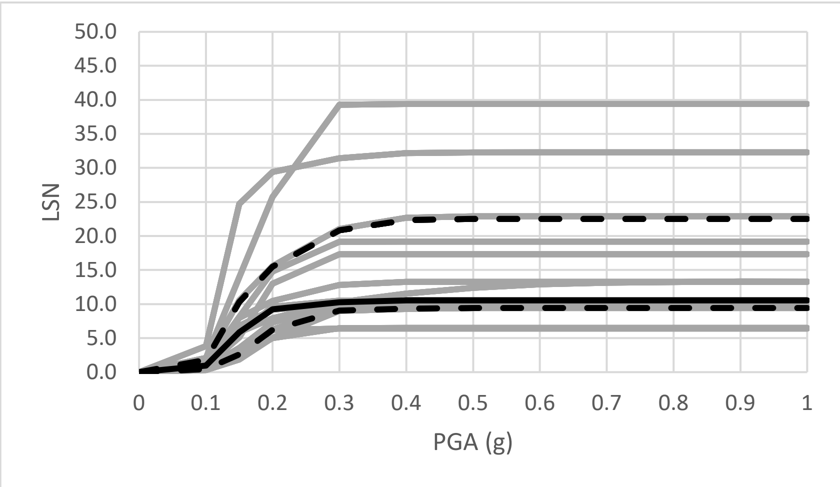

Figure 6.13 CPT curves for Wairoa for a shallow, unconfined groundwater surface 1.0 metre below the ground surface for a magnitude 6 earthquake.

Based on the available data the sediments potentially susceptible to liquefaction are Holocene age estuarine, alluvial and swamp sediments in the Wairoa District. This potentially affects the urban areas of Wairoa, Frasertown, Nuhaka, Opoutama and Mahia Beach (Figure 6.14). However, historical reports of liquefaction after the 1931 Hawke's Bay and 1932 Wairoa earthquakes indicate that liquefaction damage in these urban areas was limited to specific areas and was not widespread. If the areas of Holocene sediment are not liquefiable the geological sub-surface data indicates they are probably going to be Class E ground in terms NZS 1170.5 (very soft ground that strongly amplifies earthquake shaking).

In the areas identified as susceptible to liquefaction (Figure 6.14) Wairoa would benefit from getting a long-term record of the shallow, unconfined groundwater surface in areas where urban development is planned. In addition, it is recommended that a detailed geomorphic map of the Holocene sediments of the Wairoa area from Frasertown to Mahia Beach, at a scale of 1:25,000 or better, be prepared as a basis for refining the liquefaction assessment to include triggering and vulnerability assessments.

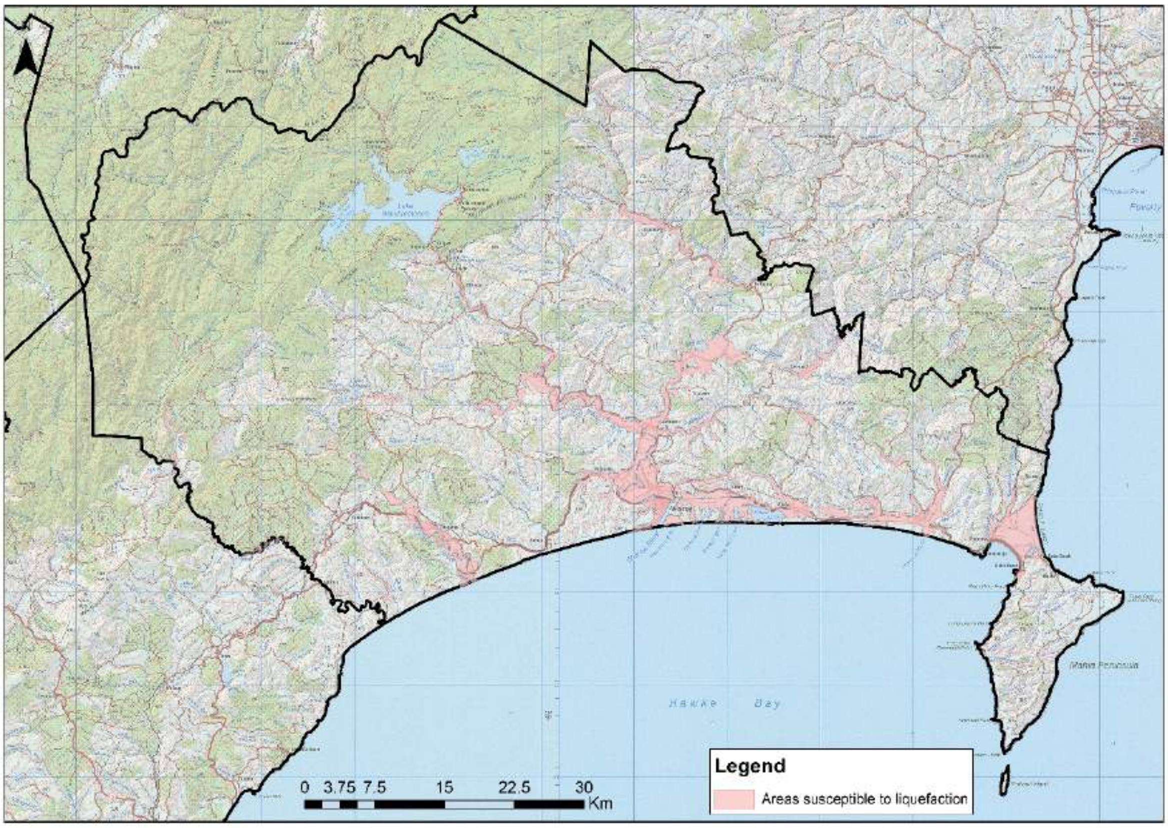

Figure 6.14 Liquefaction susceptibility map for the Wairoa District based on geological maps, historical reports, borehole and CPT data.

6.3 CENTRAL HAWKE'S BAY

A liquefaction susceptibility map was compiled for the main urban areas of Central Hawke's Bay using QMAP Hawke's Bay (1:250,000 geological map), LiDAR data and analysis and interpretation of the historical earthquake record. The map scale used to identify liquefiable areas for this work is 1:250,000. More detailed mapping (at 1:25,000 or greater) would be required to establish boundaries suitable for use at the scale of a District Plan.

6.3.1 Geomorphic Zoning

The QMAP geology polygons were used to spatially differentiate the area (Figure 6.15). The identified liquefiable units were then checked against the LiDAR data. All geological units, labelled as older than Holocene (more than 10,000 years old) were eliminated, on this basis:

1. All pre-Quaternary (older than 2.5 million years) geological units will not experience liquefaction as their densities are too great.
2. Quaternary geological units (gravel dominated river alluvium) whose surfaces were mantled with loess were assessed as being deposited prior to the Holocene (last 10,000 years) and assessed as too old (dense) and too coarse (gravel) to experience liquefaction:
    a. Pre-Holocene river alluvium (gravel dominated with loess cap) include: mQal; lQal; uQal; Q4al; Q3al; Q2al.
    b. Pre-Holocene alluvial fans (gravel dominated with a loess cap) include: lQaf; uQaf; Q2af.

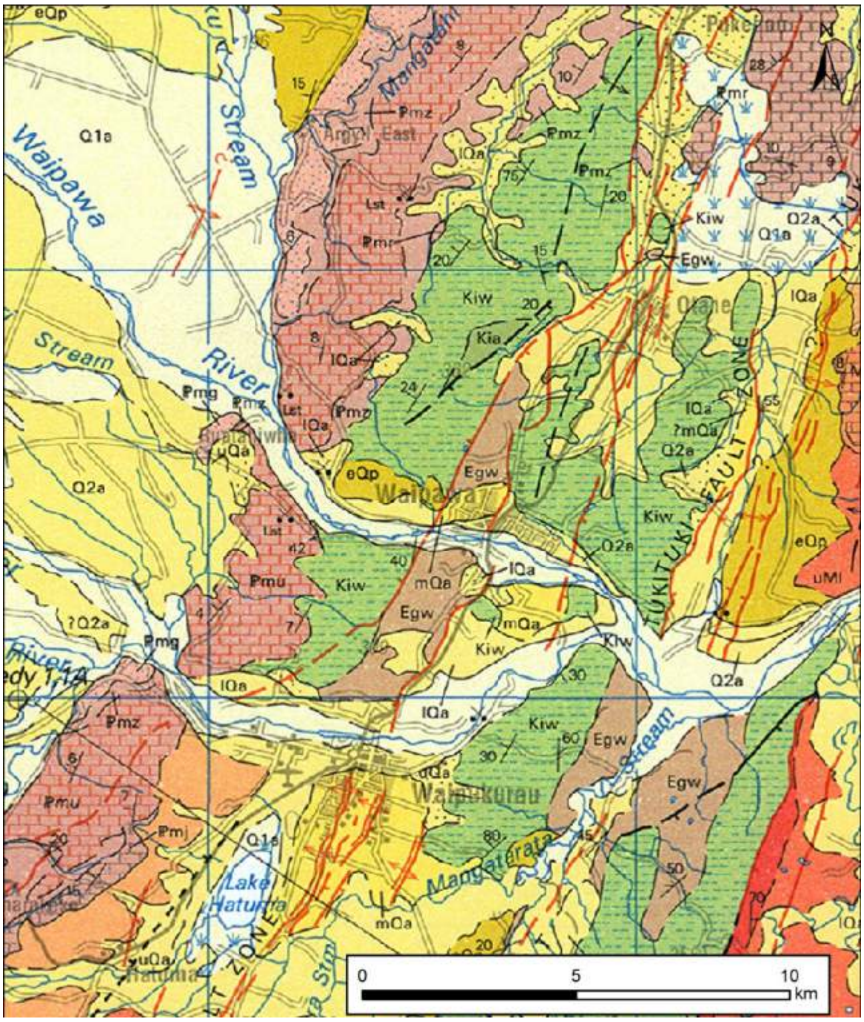

Figure 6.15 1:250,000 geological map (Lee et al, 2011) for the main urban areas of the Central Hawke's Bay District.

This left two geological units that met the age criteria (i.e. Holocene, less than 10,000 years old). The Q1al is gravel dominated river alluvium of the active river channels. The coarse-grained sediment (gravel) indicates that liquefaction, if it does occur, will be limited to small isolated pockets.

The Q1as is peat dominated accumulations of fine-grained sediment in swamp deposits. The presence of peat reduces the likely severity of any liquefaction (van Ballegooy, pers. comm.), although these sediments are likely to meet the criteria necessary for liquefaction to occur – they are young (Holocene, less than 10,000 years old), fine grained, probably non-cohesive and a shallow water table (less than 2 metres below the ground surface) is likely present.

There are no CPT data available for the Central Hawke's Bay urban centres – this is entirely consistent with the mapped geology and geomorphology as CPT is seldom a viable investigation tool in gravel sediments.

Ground damage from liquefaction has been recorded in Central Hawke's Bay during historical earthquakes (1904, 1931), but is limited to the bed of the old Waipawa River and the Q1as (swamp) north and east of Otane. This is consistent with the Holocene sedimentary environments of the Central Hawke's Bay District. At sites where fine-grained sedimentary deposition dominated, such as the northern end of the old bed of the Waipawa River and the swamp to the north of this, liquefaction has been reported after historical earthquakes producing strong ground shaking in the area (MM7 or greater). In contrast, liquefaction has not been reported from the gravel dominated braided river systems (Hancox et al, 2002). These areas are seldom sites of liquefaction, and if liquefaction does occur it is confined to small isolated areas.

One area assigned lQal has been reassigned to Q1al based on evidence of historical liquefaction and the construction of an engineering structure (earth bund) to divert the course of the Waipawa River. This is the area of the ‘old’ Waipawa River bed. This is consistent with the LiDAR data (Figure 6.16). A bund can be seen blocking the entrance to the ‘old’ Waipawa River bed and on this basis if the area were to be mapped at a larger scale, then the ‘old’ Waipawa River bed would be able to be identified and mapped as Q1al.

At Porangahau, the township is located on Q1al river sediments that, given the source rock, are likely to be fine-grained, and are therefore potentially liquefiable. During the 1904 earthquake, there were reports of sand boils near the township (nearby creek?) and cracks in the ground parallel to the river channel 50 m long. The beach settlement is built on sand dunes. This is consistent with observations from dune areas elsewhere in New Zealand affected by strong earthquake shaking, where liquefaction has not been observed.

The groundwater modelling carried out for the Central Hawke’s Bay District (Appendix 6) covers the main urban areas and several minor ones and shows the shallow unconfined groundwater surface is generally shallow (-1 to -4 m below the ground surface; Figure 6.7 to Figure 6.8 in Appendix 6). None of the areas where groundwater modelling is available are in areas that have been identified as susceptible to liquefaction.

Based on the available data a liquefaction hazard requiring mitigation is unlikely to be present in the main urban areas of Central Hawke’s Bay (Figure 6.17; Table 6.6 and Table 6.7).

The Q1as swamps, the old bed of the Waipawa River and the Q1al fine-grained river alluvium near Porangahau (Porangahau town) are sites where liquefaction has been reported during historical earthquakes. These sites could be targeted for mitigation strategies to limit liquefaction damage if these areas are being proposed as sites for future urban development. Given their locations they are also likely to be at risk from flooding.

There is insufficient data to carry out an analysis of liquefaction triggering and vulnerability in Central Hawke’s Bay. On the basis of historical observations of liquefaction (Section 2.4 and Appendix 3) and the performance of similar geological units elsewhere, the sediments potentially susceptible to liquefaction are shown in Figure 6.17.

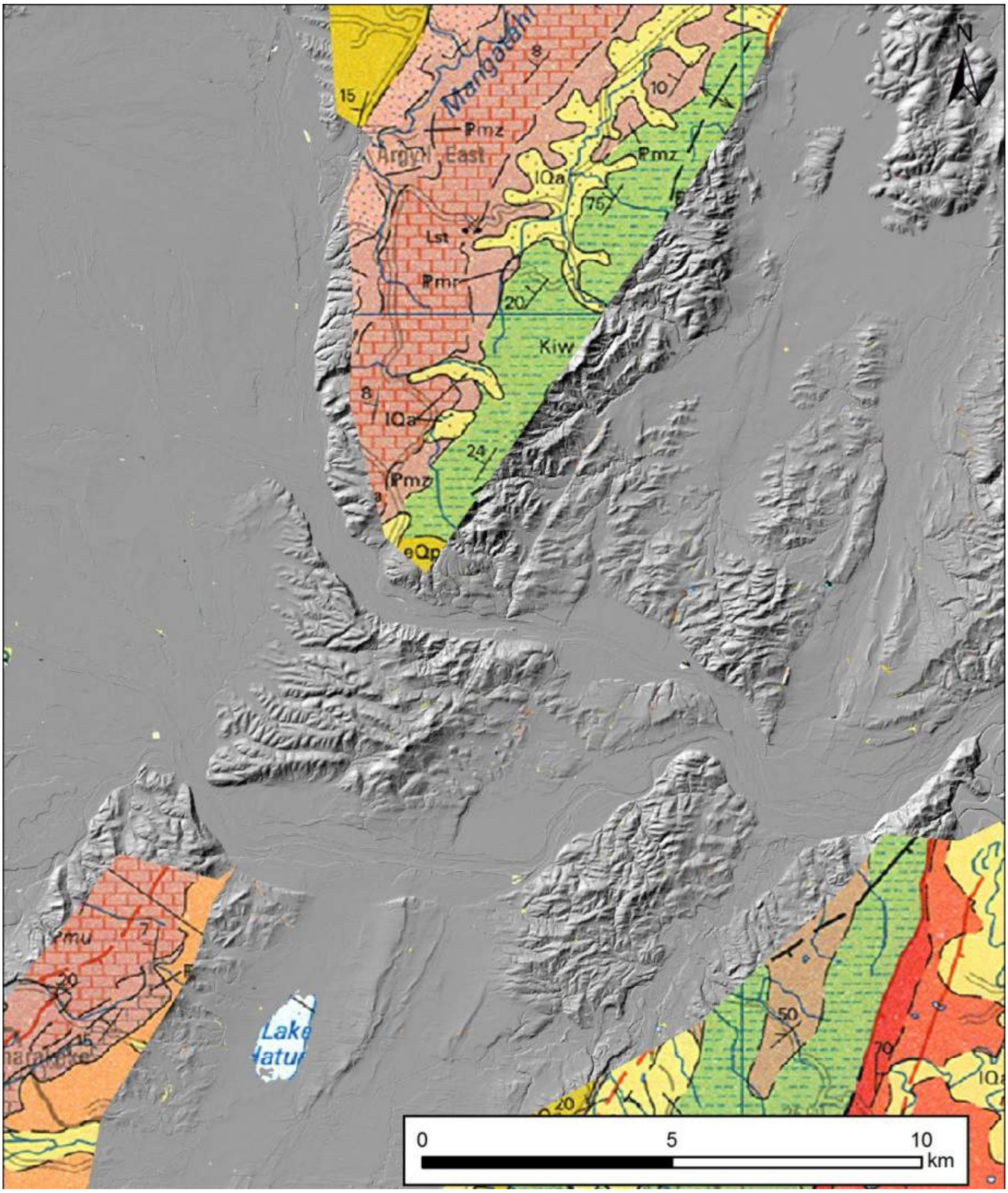

Figure 6.16 Available LiDAR topographic data for the main urban centres of the Central Hawke's Bay District.

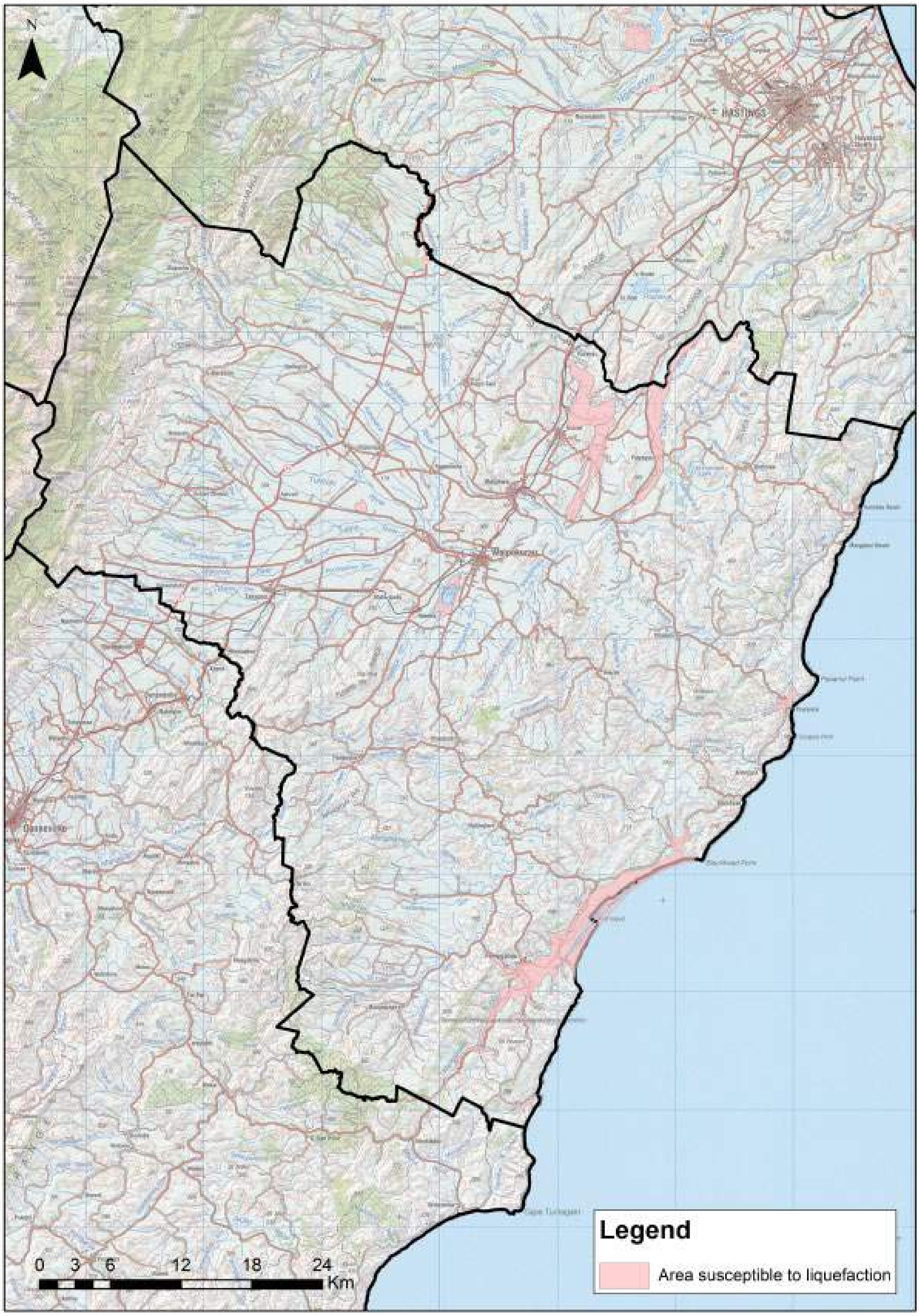

Figure 6.17 Liquefaction susceptibility map for the Central Hawke's Bay District, based on geological maps and historical reports.

Table 6.6 Peak ground acceleration values from the New Zealand National Seismic Hazard Model for Central Hawke's Bay (highlighted in green).

Hawke's Bay Sites un-weighted Site Class D PGA values (g)					
Location	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Wairoa	0.14	0.24	0.40	0.47	0.59
Waipukarau	0.17	0.29	0.47	0.57	0.71
Napier/Hastings	0.14	0.25	0.42	0.51	0.64

Table 6.7 The average magnitude of an earthquake contributing to PGA at different return periods (Central Hawke's Bay highlighted in green).

Hawke's Bay Sites un-weighted Site Class D Average Magnitude Contributions to PGA					
Location	**Return Period (years)**				
	25	**100**	**500**	**1000**	**2500**
Wairoa	5.9	5.9	6.0	6.0	6.1
Waipukarau	6.0	6.1	6.3	6.4	6.4
Napier/Hastings	6.2	6.3	6.5	6.6	6.7

6.4 Hastings District

A liquefaction susceptibility map was compiled for Hastings District using QMAP Hawke's Bay (1:250,000 geological map) and analysis and interpretation of the historical earthquake record. The map scale used to identify liquefiable areas for this work is 1:250,000. More detailed mapping (at 1:25,000 or greater) would be required to establish boundaries suitable for use at the scale of a District Plan.

The Qmap geology polygons were used to spatially differentiate the area (Lee et al, 2011). All geological units, labelled as older than Holocene (more than 10,000 years old) were eliminated, on this basis:

1. All pre-Quaternary (older than 2.5 million years) geological units will not experience liquefaction as their densities are too great.
2. Quaternary geological units (gravel dominated river alluvium) whose surfaces were mantled with loess were assessed as being deposited prior to the Holocene (last 10,000 years) and assessed as too old (dense) and too coarse (gravel) to experience liquefaction:
    a) Pre-Holocene river alluvium (gravel dominated with loess cap) include: mQal; lQal; uQal; Q4al; Q3al; Q2al.
    b) Pre-Holocene alluvial fans (gravel dominated with a loess cap) include: lQaf; uQaf; Q2af.

This left two geological units that met the age criteria (i.e. Holocene, less than 10,000 years old). The Q1al is gravel dominated river alluvium of the active river channels. The coarse-grained sediment (gravel) indicates that liquefaction, if it does occur, will be limited to small isolated pockets.

The Q1as is peat dominated accumulations of fine-grained sediment in swamp deposits. The presence of peat reduces the likely severity of any liquefaction (van Ballegooy, pers. comm.), although these sediments are likely to meet the criteria necessary for liquefaction to occur – they are young (Holocene, less than 10,000 years old), fine grained, probably non-cohesive and a shallow water table (less than 2 m below the ground surface) is likely present.

Ground damage from liquefaction has not been recorded in Hastings District beyond the Heretaunga Plains during historical earthquakes (1904, 1931). This is consistent with the Holocene sedimentary environments of Hastings District beyond the Heretaunga Plains.

The groundwater modelling carried out for Heretaunga Plains does not extend to the wider area of Hastings District. Based on the available data a liquefaction hazard requiring mitigation is unlikely to be present except in small isolated areas in the wider Hastings District beyond the Heretaunga Plains (Figure 6.18).

There is insufficient data to carry out an analysis of liquefaction triggering and vulnerability in the wider Hastings District. Based on the performance of similar geological units elsewhere the sediments potentially susceptible to liquefaction in the wider Hastings District are shown in Figure 6.18.

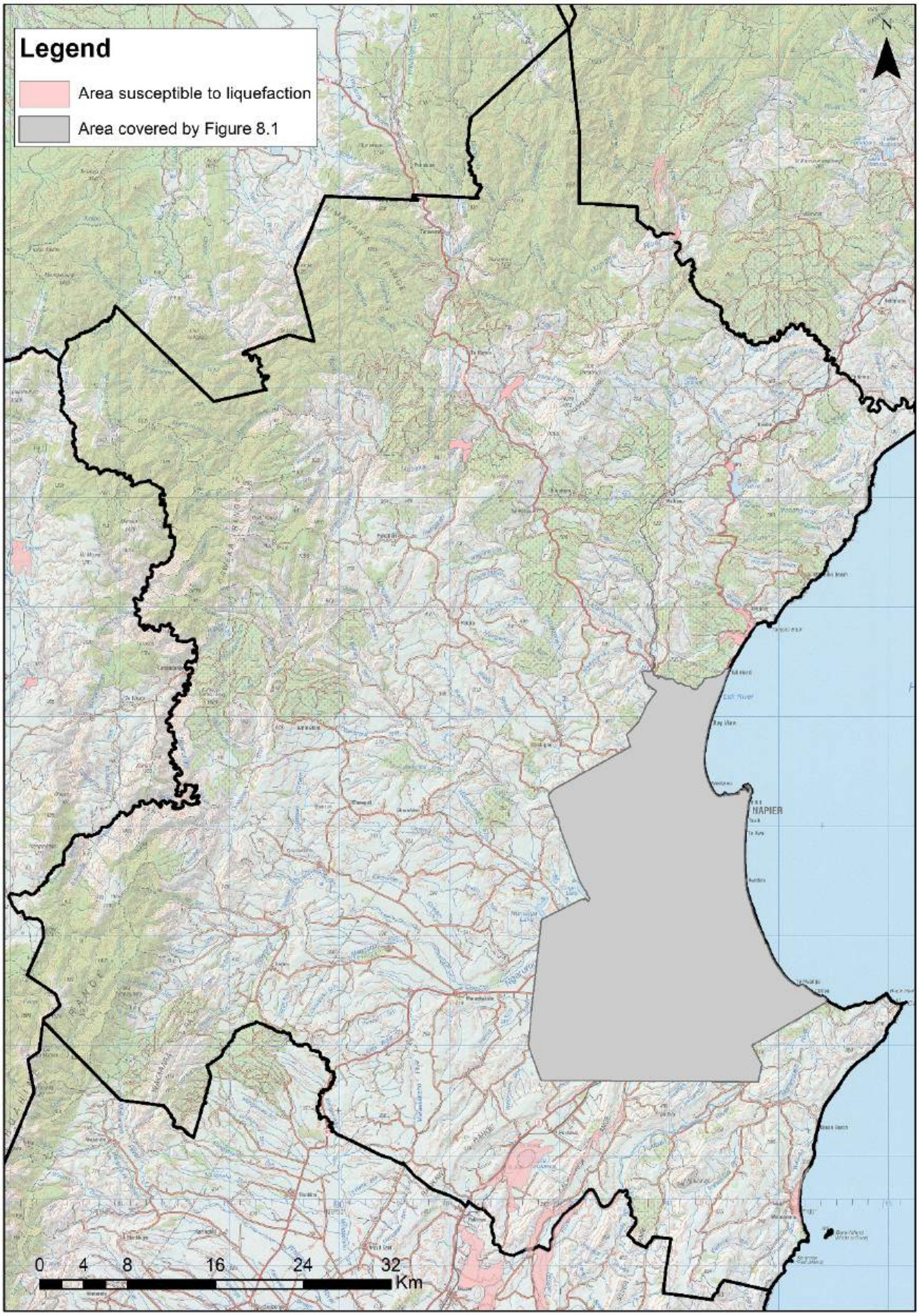

Figure 6.18 Liquefaction susceptibility map for the wider Hastings District (excluding the Heretaunga Plains), based on geological maps and the performance of similar geological units elsewhere.

7.0 LIQUEFACTION HAZARD MAPPING RESULTS

7.1 HERETAUNGA PLAINS

This section presents the results of the liquefaction hazard mapping for the Heretaunga Plains which have been developed using the methodology described in Section 6.1.

The LSN values used to determine the severity of the liquefaction hazard at different shaking return periods have, where possible, been derived from CPT results using a combination of the average LSN at the 50th percentile (and the 85th percentile value) as set out below (these have been selected based on LSN values from Table 6.2 and thresholds from Table 2.1):

- No liquefaction expected – LSN = 0
- Insignificant liquefaction – LSN < 5 (85th <10)
- Up to minor liquefaction – LSN < 10 (85th < 15)
- Up to moderate liquefaction – LSN 10 - 20 (85th 15 – 25)
- Up to very high liquefaction – LSN > 20 (85th > 25)

In most cases the 50th and 85th percentile values are consistent and deliver the same liquefaction severity. In the cases where they differ the liquefaction severity as determined by the 85th percentile LSN value is used.

In the four geomorphic units that do not have any CPT data to use to determine LSN values, the historical performance and performance of similar geomorphic units in other areas has been used as a guide. No liquefaction is expected in the hill, gravel and alluvial fan units (Figure 6.4). The geomorphic unit labelled ‘Terraces’ (Figure 6.4) has been conservatively assessed as having an up to minor, up to moderate and up to very high liquefaction response at the 25, 100 and 500 year shaking return periods respectively.

Figure 7.1 shows the liquefaction hazard for 25-year return period levels of earthquake shaking (M_W = 6.2, PGA = 0.14g). At this level of earthquake shaking it is anticipated that up to moderate liquefaction related land damage could occur in the southern suburbs of Napier (e.g. Napier South, Marewa, Maraenui, Jervoistown, Meeanee and Whakatu). Up to minor liquefaction related land damage could occur in the northern suburbs of Napier (e.g. Bayview, Westshore, Tamatea and Onekawa) and the suburbs to the west of Napier and north of Hastings (e.g. Pakowhai and Twyford). Insignificant liquefaction land damage could occur in around the mouth of the Esk River and in large parts of Hastings and Havelock North. The remaining area is classified as not susceptible to liquefaction and no liquefaction related land damage is expected, based on the susceptibility mapping described in Sections 6.1.1 and 6.1.2.

Figure 7.2 shows the liquefaction hazard for 100-year return period levels of earthquake shaking (M_W = 6.3, PGA = 0.25g). At this level of earthquake shaking it is anticipated that up to very high liquefaction related land damage could occur in the southern suburbs of Napier (e.g. Napier South, Marewa, Maraenui, Jervoistown, Meeanee and Whakatu). Up to moderate liquefaction related land damage could occur in the northern suburbs of Napier (e.g. Bayview, Westshore, Tamatea and Onekawa) and the suburbs to the west of Napier, in and around Hastings the Esk River and parts of Havelock North. Insignificant liquefaction land damage is limited to a small pocket of land northeast of Hastings where there are numerous CPT records. The remaining area is classified as not susceptible to liquefaction and no liquefaction related land damage is expected, based on the susceptibility mapping described in Sections 6.1.1 and 6.1.2.

Figure 7.3 shows the liquefaction hazard for 500-year return period levels of earthquake shaking (M_W = 6.5, PGA = 0.42g). At this level of earthquake shaking it is anticipated that up to very high liquefaction related land damage could occur in the southern suburbs of Napier, in the former Ahuriri Lagoon north of Napier and on the plains north of Hastings including the Tutaekuri River valley. Up to moderate liquefaction related land damage could occur in the in the Esk River valley, parts of Taradale and within and south of the Hastings urban area. Insignificant liquefaction land damage is limited to a small pocket of land northeast of Hastings where there are good CPT records. The remaining area is classified as not susceptible to liquefaction and no liquefaction related land damage is expected, based on the susceptibility mapping described in Sections 6.1.1 and 6.1.2.

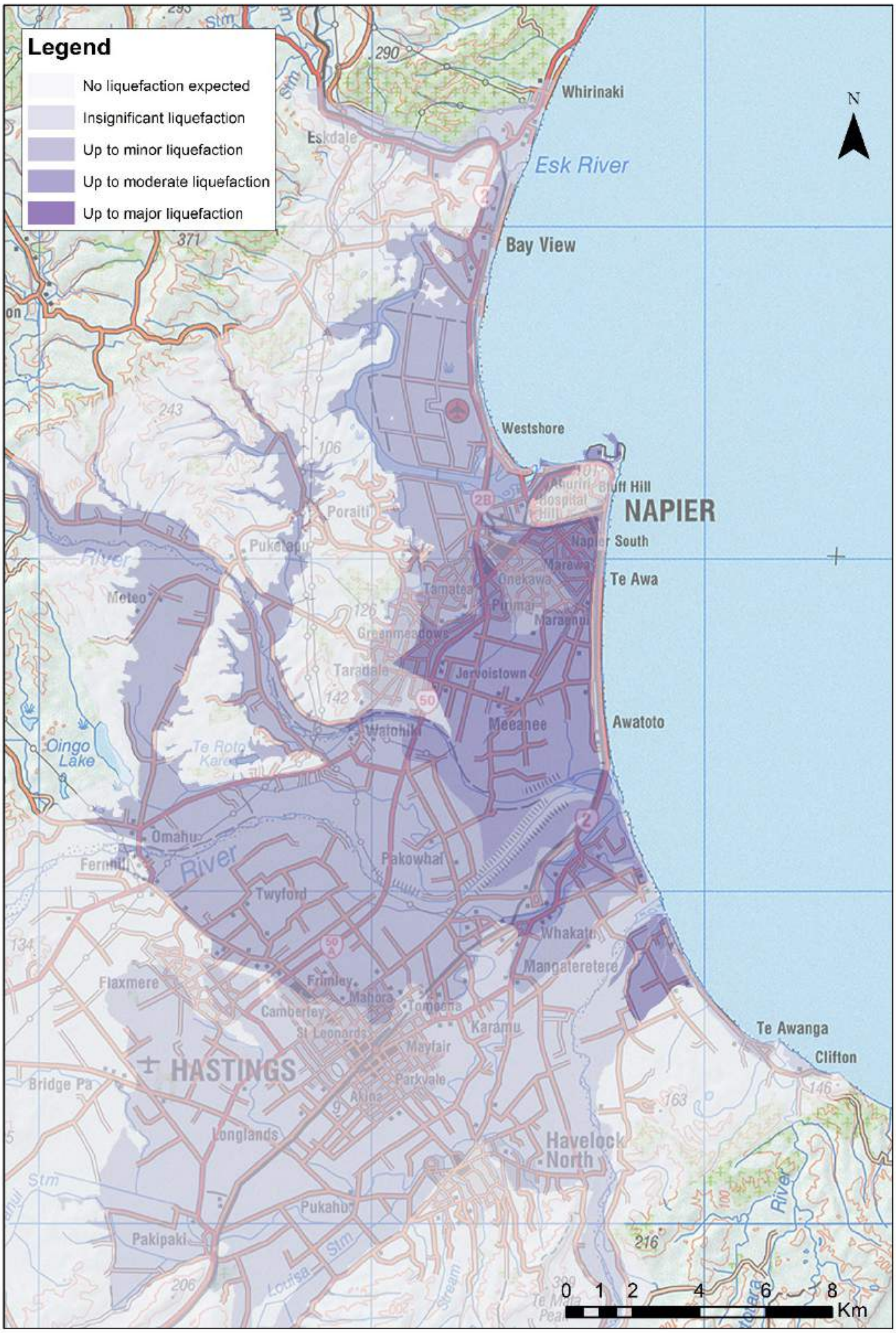

Figure 7.1 The liquefaction severity expected at the 25-year return period shaking at a magnitude of 6.2 (Table 6.2) and a PGA of 0.14 g (Table 5.1).

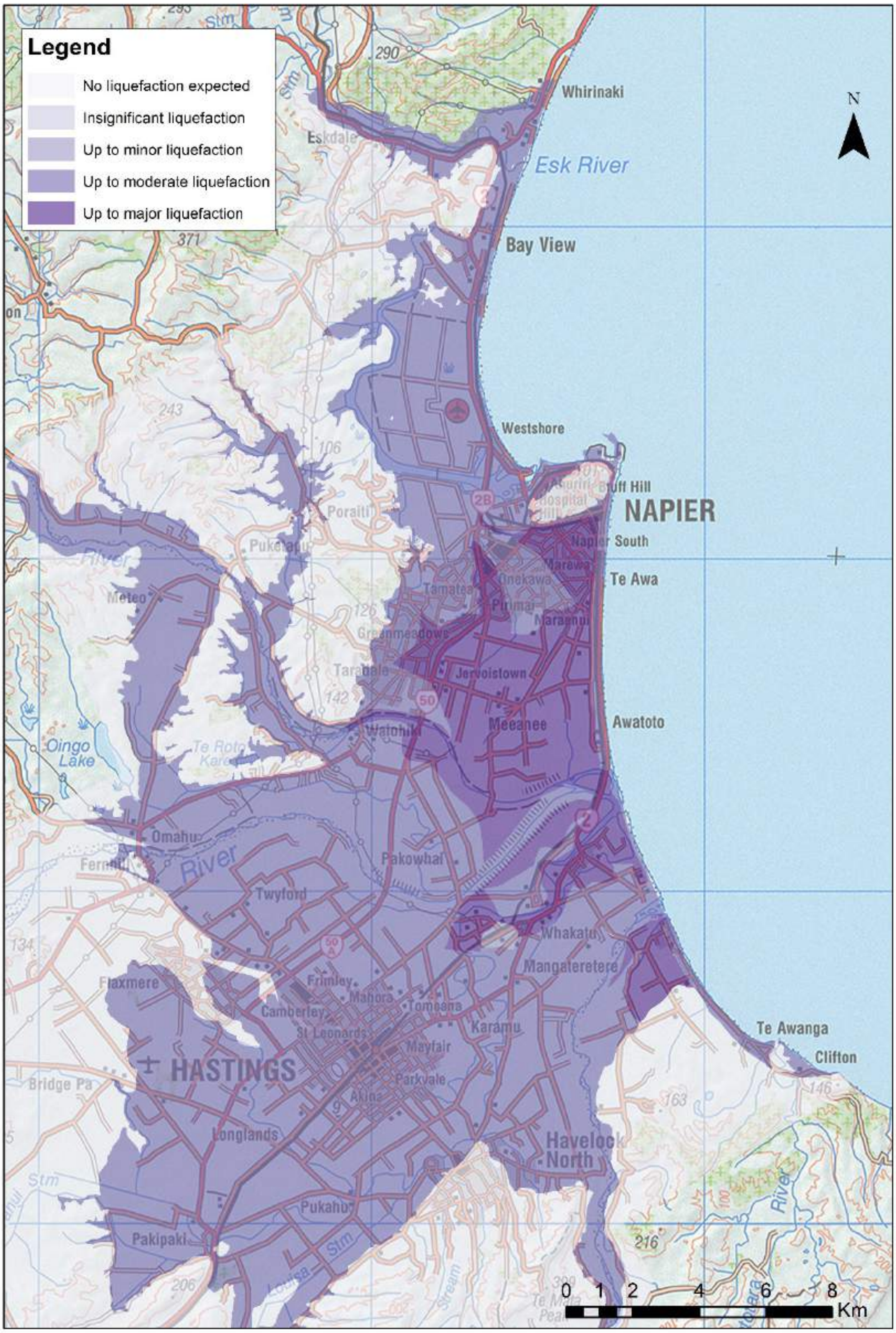

Figure 7.2 The liquefaction severity expected at the 100-year return period shaking at a magnitude of 6.3 (Table 6.2) and a PGA of 0.25 g (Table 5.1).

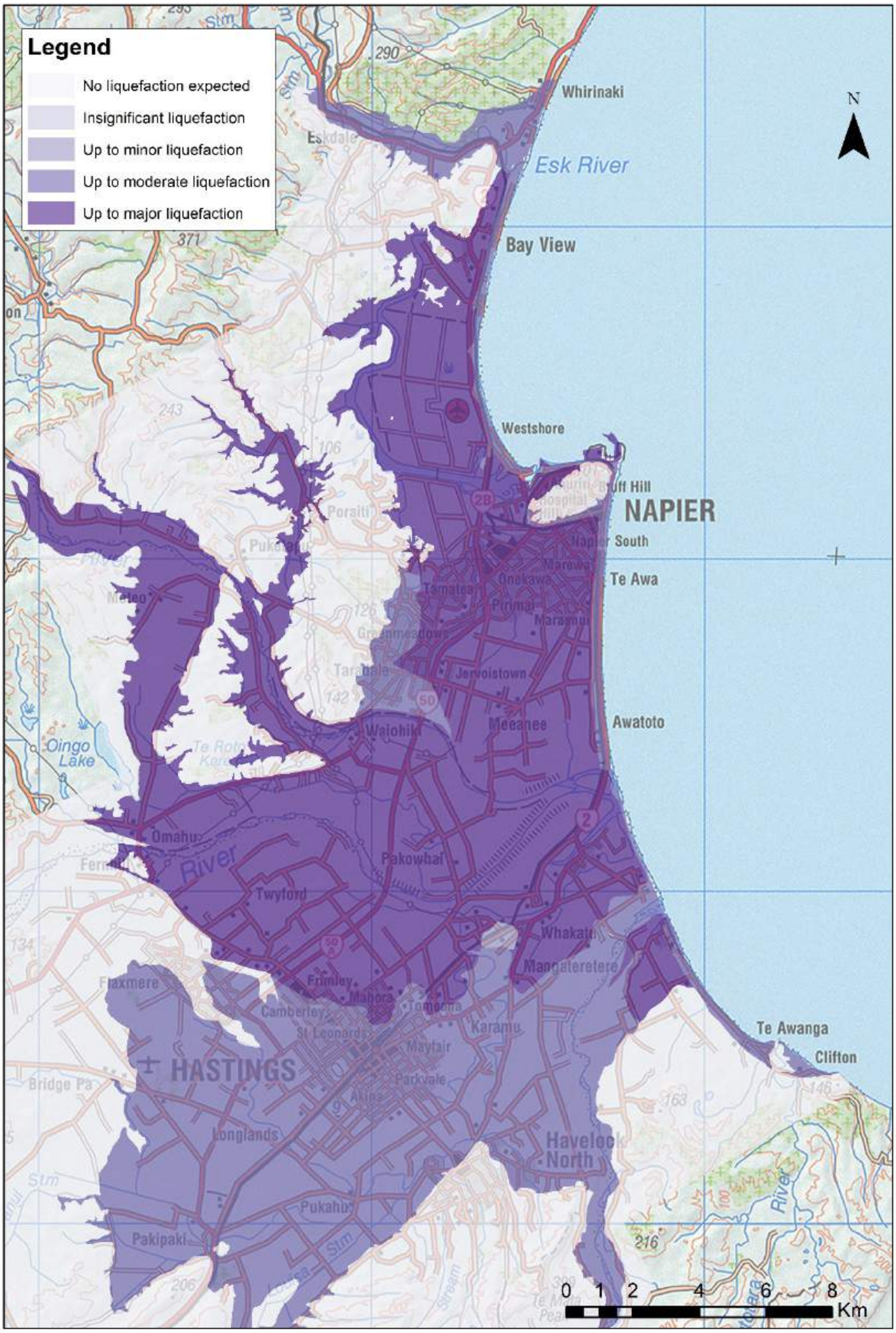

Figure 7.3 The liquefaction severity expected at the 500-year return period shaking at a magnitude of 6.5 (Table 6.2) and a PGA of 0.42 g (Table 5.1).

8.0 LIQUEFACTION HAZARD PLANNING MAPS

8.1 HERETAUNGA PLAINS

The final step in the preparation of a liquefaction hazard map, in terms of a liquefaction land vulnerability map, for the Heretaunga Plains is to combine the three hazard maps at the various return period levels of earthquake shaking into a single map for the purpose of managing the liquefaction hazard for residential development purposes. The rationale behind the presentation of a single liquefaction hazard map is to provide a simplified basis for management of the risks from liquefaction in terms of requirements for investigation, detailed assessment and mitigation (if required) that might be required under the Resource Management Act and Building Act with respect to planning purposes.

The three hazard maps (discussed in Section 7) above were combined to create three zones by applying the following conditions:

Liquefaction unlikely – very low to low liquefaction vulnerability:

- $LSN_{100} < 5$ *and* $LSN_{500} < 10$
- For areas where liquefaction hazard is not present or is not significant – use current policies, procedures and rules (e.g. foundation types as per NZS 3604).

Liquefaction possible – medium liquefaction vulnerability:

- $LSN_{25} < 10$ *and* $LSN_{500} < 25$
- Areas where the liquefaction vulnerability is likely to be medium – could specify use of foundations types such that repair is easily facilitated post-earthquake or carry out geotechnical investigations to determine the actual liquefaction hazard at the site and use or design foundations appropriate to support the house for the site conditions.

Liquefaction possible - high liquefaction vulnerability:

- $LSN_{25} > 10$ *or* $LSN_{500} > 25$
- Areas where the liquefaction vulnerability is likely to be high – could require geotechnical investigations to determine the actual liquefaction hazard at the site and use or design foundations appropriate to support the house for the site conditions.

Note that the LSN subscripts above denote the return period level of earthquake shaking for which the LSN is calculated.

This map (Figure 8.1) shows the potential vulnerability of the land to liquefaction only and other potential geotechnical issues and natural hazards will need to be considered for any development.

Widespread liquefaction-induced settlement, especially if accompanied by tectonic subsidence as occurred in parts of Christchurch, can result in an increase in flooding potential. Increasing the floor level height requirements for residential properties in areas shown to be potentially subject to widespread liquefaction-induced settlement could be considered as a way to mitigate against any post-earthquake increase in flooding potential.

Details of appropriate geotechnical investigations for the identification, assessment, and mitigation of liquefaction hazards can be found in New Zealand Geotechnical Society (2016).

In areas where the liquefaction land vulnerability is expected to be no more than medium the specified use of strengthened foundation types similar to those developed for mitigating moderate liquefaction hazards in Christchurch would be an advantage. The Christchurch experience is that strengthened or enhanced foundations are no more expensive than standard foundation types (Nick Traylen, pers. comm.)

The map showing the three zones is shown in Figure 8.1. It is noted that the liquefaction hazard for other asset types such as commercial buildings, underground pipe networks, pump stations and bridges will also need appropriate management strategies to be developed. This is beyond the scope of this report, because Figure 8.1 is for residential building development purposes only.

This analysis is based on the data available as of July 2016. As more data becomes available and the science of predicting liquefaction vulnerability improves (as discussed in Section 6.1.4) the areas identified as subject to a medium or high liquefaction land vulnerability may be revised.

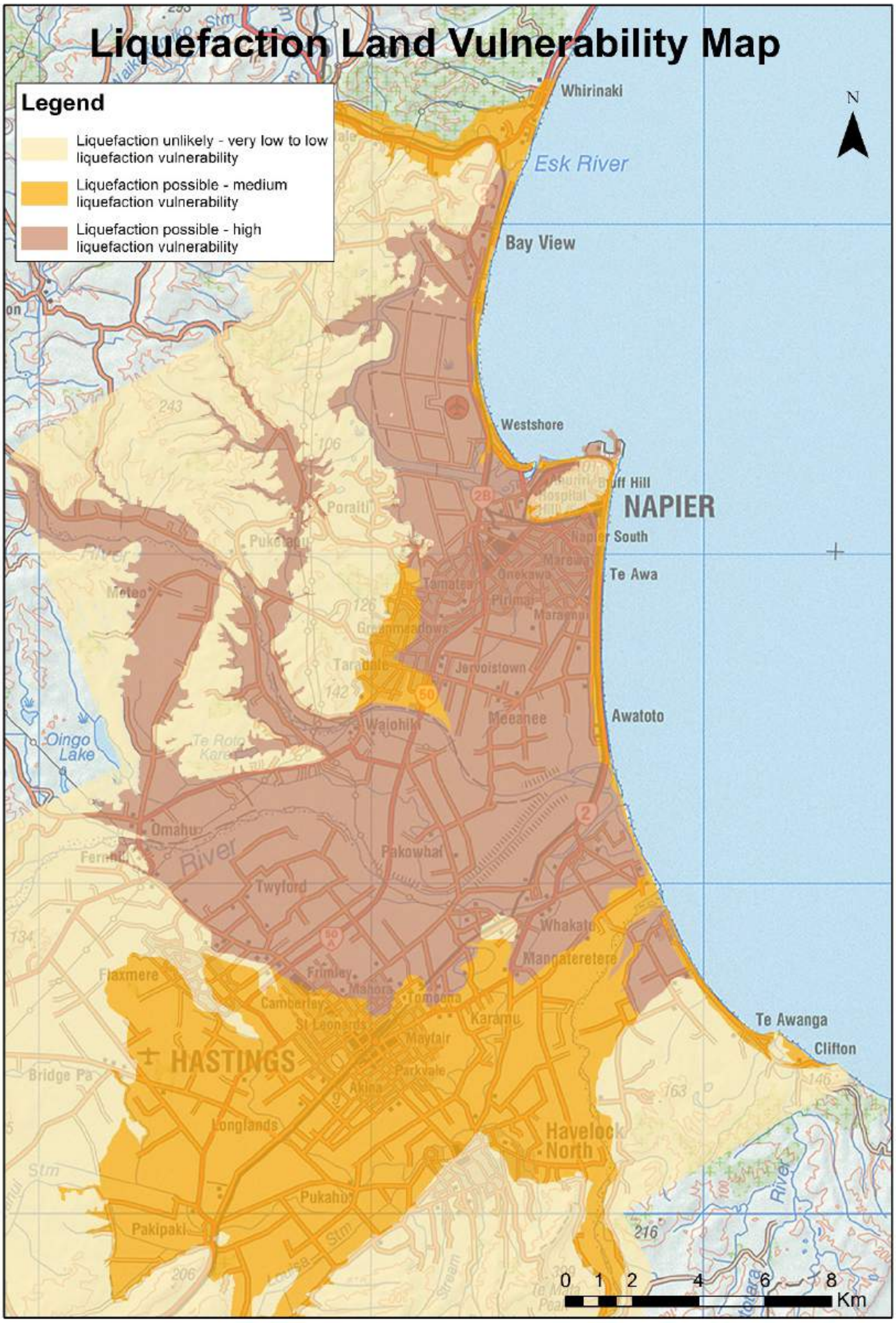

Figure 8.1 The liquefaction land vulnerability map for the Heretaunga Plains.

8.2 WAIROA

This section presents a liquefaction planning map for Wairoa using the same map units developed for the Heretaunga Plains (Figure 8.1). The data and method used to derive a liquefaction susceptibility map (Figure 6.14) for Wairoa is set out in Section 6.2 above. The lack of suitable data precludes undertaking a liquefaction triggering and vulnerability analysis as carried out for the Heretaunga Plains (Section 6.1). This map meets the requirements for a Level A liquefaction assessment as set out in Table 3.1 of the draft liquefaction guidance released by the Ministry for the Environment and Ministry of Business, Innovation and Employment (2017).

Although some CPT data is available for the Wairoa area, the range of values available for the depth of the water table (Appendix 6, Figure 6.4) and the high level of uncertainty (both spatially and temporally) associated with this data (Appendix 6, Figure 6.9) and the concentration of CPT records within Wairoa township limit their utility. As a result, the data used to assess liquefaction across the district includes boreholes available from published work (e.g. Ota et al, 1989), geological maps and historical records. Figure 8.2 shows a liquefaction planning map for Wairoa District prepared using the same map units as Figure 8.1, developed for the Heretaunga Plains.

The liquefaction planning map for Wairoa (Figure 8.2), although presented using the same map units as Figure 8.1 for the Heretaunga Plains, is based on less robust data and because of this there is a greater level of uncertainty in the map assignation. For all the sediments susceptible to liquefaction in Wairoa District, the most rigorous liquefaction assessment requirements have been applied. Based on Figure 8.2 the planning implications would be that ground investigation and assessment of the liquefaction hazard is currently necessary in the areas identified as susceptible to liquefaction (Figure 6.14) in Wairoa District.

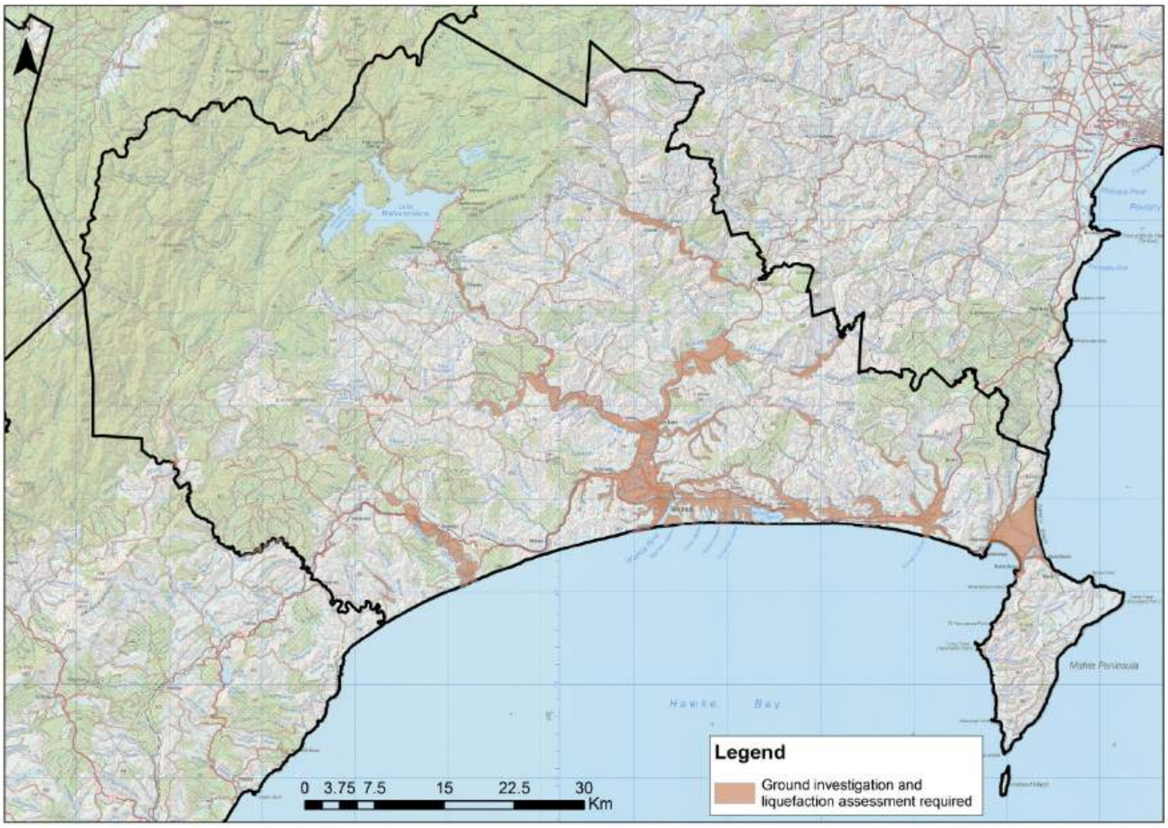

Figure 8.2 The liquefaction planning map for Wairoa based on the liquefaction susceptibility map for Wairoa presented in Figure 6.14.

8.3 CENTRAL HAWKE'S BAY

This section presents a liquefaction planning map for Central Hawke's Bay using the same map units developed for the Heretaunga Plains (Figure 8.1). The data and method used to derive a liquefaction susceptibility map (Figure 6.17) for Central Hawke's Bay is set out in Section 6.3 above. The lack of suitable data precludes undertaking a liquefaction triggering and vulnerability analysis as carried out for the Heretaunga Plains (Section 6.1). This map meets the requirements for a Level A liquefaction assessment as set out in Table 3.1 of the draft liquefaction guidance released by the Ministry for the Environment and Ministry of Business, Innovation and Employment (2017).

No CPT or borehole data was available for the Central Hawke's Bay area. The data available for the assessment of liquefaction hazard was limited to geological maps and historical records. Figure 8.3 shows a liquefaction planning map for Central Hawke's Bay District prepared using the same map units as Figure 8.1, developed for the Heretaunga Plains.

The liquefaction planning map for Central Hawke's Bay (Figure 8.3), although presented using the same map units as Figure 8.1 for the Heretaunga Plains, is based on less robust data and because of this there is a greater level of uncertainty in the map assignation. For all the sediments susceptible to liquefaction in Central Hawke's Bay District the most rigorous liquefaction assessment requirements have been applied. Based on Figure 8.3 the planning implications would be that ground investigation and assessment of the liquefaction hazard is currently necessary in the areas identified as susceptible to liquefaction (Figure 6.17) in the Central Hawke's Bay District.

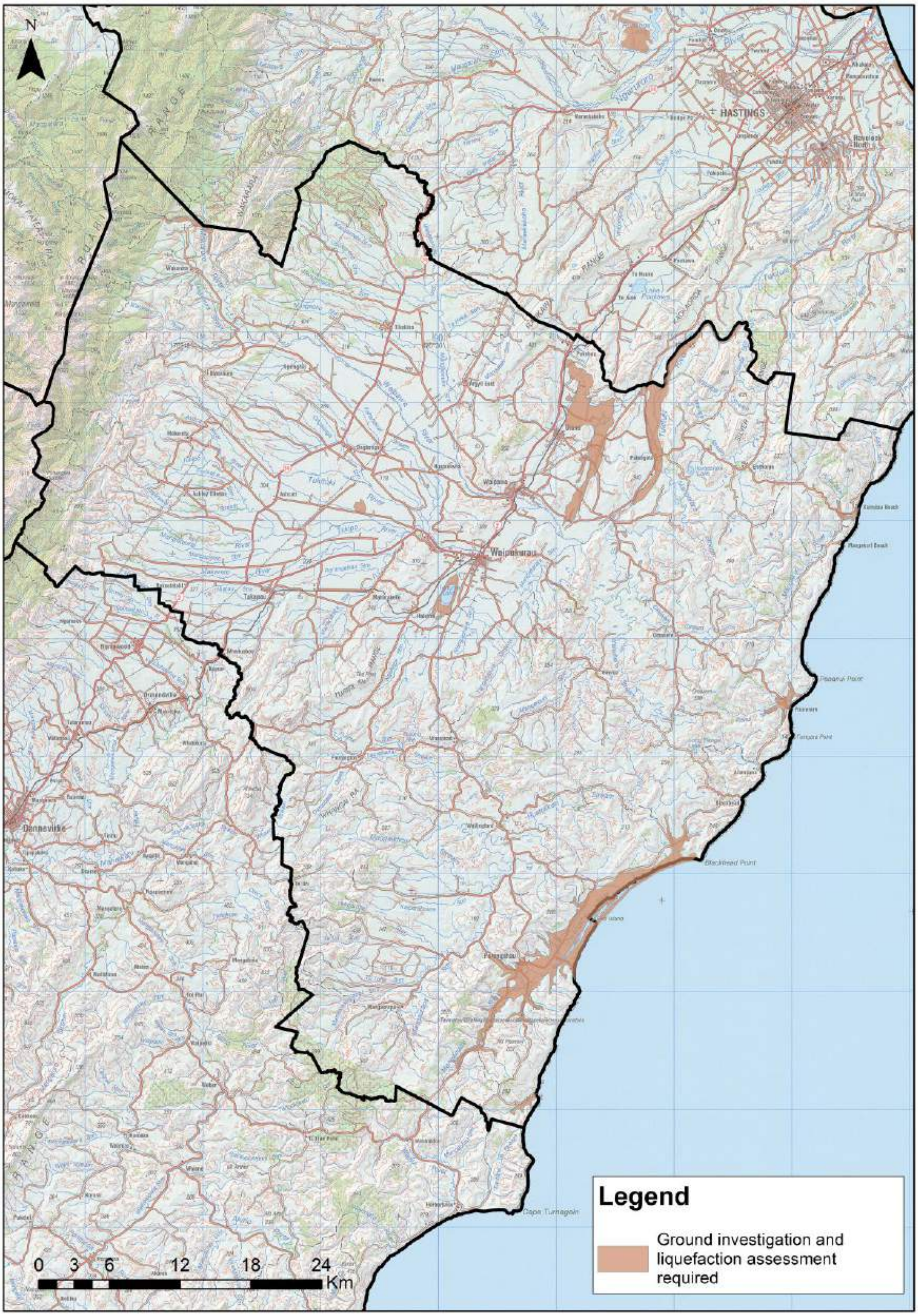

Figure 8.3 The liquefaction planning map for Central Hawke's Bay based on the liquefaction susceptibility map for Central Hawke's Bay presented in Figure 6.17.

8.4 HASTINGS DISTRICT

This section presents a liquefaction planning map for Hastings District beyond the Heretaunga Plains using the same map units developed for the Heretaunga Plains (Figure 8.1). The data and method used to derive a liquefaction susceptibility map (Figure 6.18) for Hastings District beyond the Heretaunga Plains is set out in Section 6.4 above. The lack of suitable data precludes undertaking a liquefaction triggering and vulnerability analysis as carried out for the Heretaunga Plains (Section 6.1). This map meets the requirements for a Level A liquefaction assessment as set out in Table 3.1 of the draft liquefaction guidance released by the Ministry for the Environment and Ministry of Business, Innovation and Employment (2017).

No CPT or borehole data was available for Hastings District beyond the Heretaunga Plains. The data available for the assessment of liquefaction hazard was limited to geological maps and historical records. Figure 8.4 shows a liquefaction planning map for Hastings District beyond the Heretaunga Plains prepared using the same map units as Figure 8.1, developed for the Heretaunga Plains.

The liquefaction planning map for Hastings District beyond the Heretaunga Plains (Figure 8.4), although presented using the same map units as Figure 8.1 for the Heretaunga Plains, is based on less robust data and because of this there is a greater level of uncertainty in the map assignation. For all the sediments susceptible to liquefaction in Hastings District beyond the Heretaunga Plains the most rigorous liquefaction assessment requirements have been applied. Based on Figure 8.4 the planning implications would be that ground investigation and assessment of the liquefaction hazard is currently necessary in the areas identified as susceptible to liquefaction (Figure 6.17) in the Hastings District beyond the Heretaunga Plains (Figure 8.4).

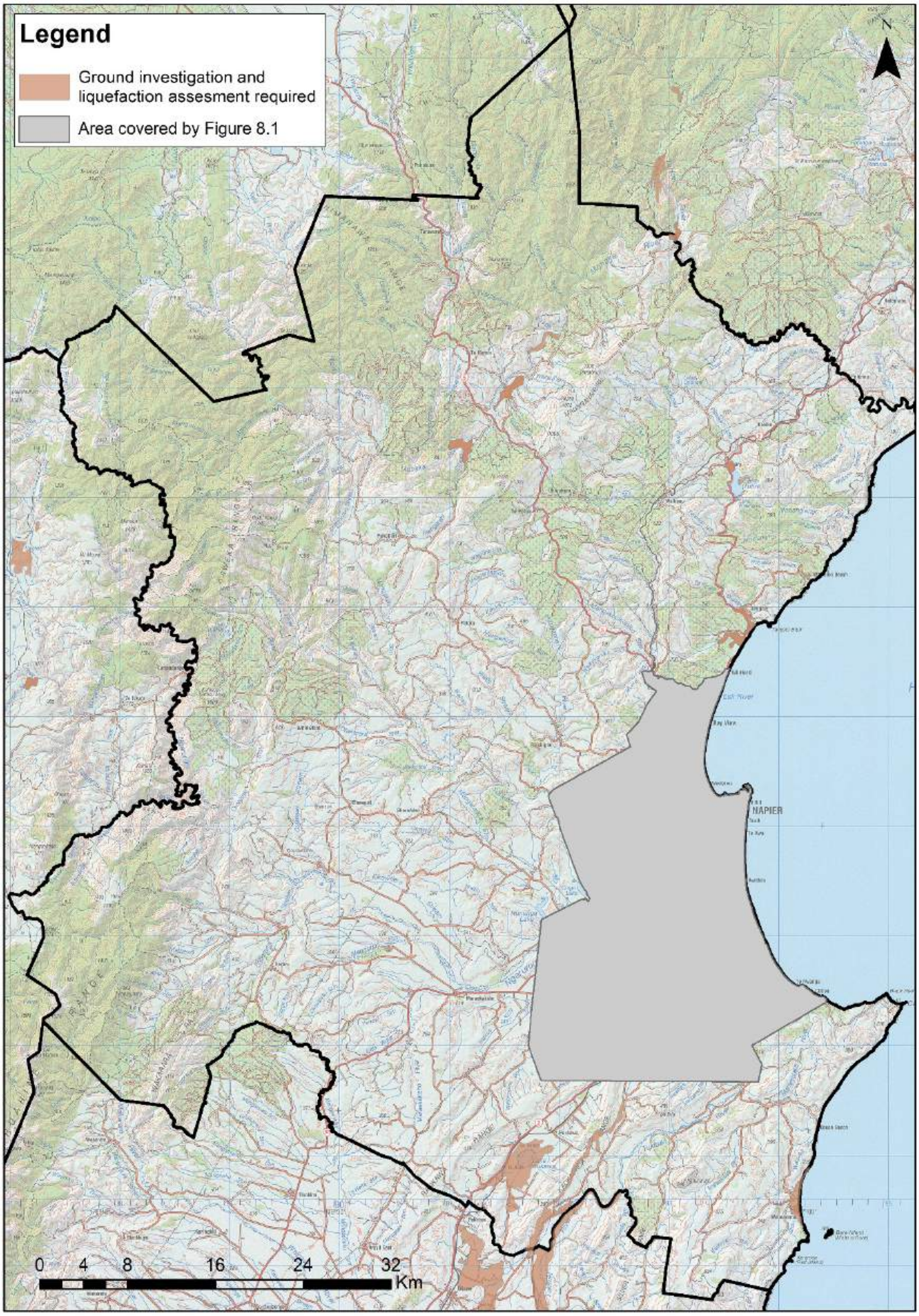

Figure 8.4 The liquefaction planning map for Hastings District beyond the Heretaunga Plains based on the liquefaction susceptibility map for Central Hawke's Bay presented in Figure 6.18.

9.0 DIFFERENCES COMPARED TO THE 1999 MAP

The liquefaction susceptibility map produced for the 1999 Hawke's Bay Liquefaction study (Dellow et al, 1999, 2003) (Figure 2.10) is similar to the comparable map from this study (Figure 8.1). However, the maps are not directly comparable because they have been produced using different datasets and different methodologies.

The maps themselves also present the liquefaction hazard in different ways. The work of Dellow et al (1999, 2003) presents a liquefaction hazard map in terms of severity of the hazard, whereas this work presents the liquefaction hazard map in terms of an appropriate management strategy taking into consideration the relevant current legislation (Building Act, Resource Management Act).

However, considering the different origins of the two maps, there are some broad similarities. The first is that most areas identified as most vulnerable to liquefaction (high and very high liquefaction susceptibility of Dellow et al (1999, 2003) and areas requiring site specific geotechnical investigation (Figure 8.1) are underlain by fine-grained estuarine sediments. This applies both on the Heretaunga Plains and at Wairoa. The areas identified as having a moderate liquefaction susceptibility in Dellow (1999, 2003) are generally where strengthened or enhanced foundations are the minimum recommended requirement for managing the liquefaction hazard. The areas identified as having a very low to low liquefaction susceptibility in Dellow et al (1999, 2003) are generally mapped as areas where existing foundation design requirements could be used (Figure 8.1) for single storey, timber framed homes. However, strengthened or enhanced foundations as recommended in areas with a minor to moderate liquefaction hazard could potentially manage any residual liquefaction hazard in these areas as they are reported (Nick Traylen, pers. comm.) to be no more expensive to build than standard foundations.

9.1 HERETAUNGA PLAINS

The differences between the earlier liquefaction hazard mapping (Dellow et al, 1999, 2003) and the current mapping on the Heretaunga Plains (Figure 8.1) are primarily driven by the different datasets used to derive the maps. The relative liquefaction hazard for the major urban areas remains similar.

Napier City surrounding Bluff Hill still has the highest liquefaction hazard which will require investigation to determine appropriate mitigation. The wedge of beach gravels underneath the Napier City central business district (Figure 3.5) may reduce the liquefaction hazard in this area, but uncertainties around its shape and boundary relationships make mandatory investigation of liquefaction in this area a prudent step.

Parts of Taradale are the only urban areas that have seen a change, in this case a reduction in the mapped liquefaction hazard from the earlier work. This is due to the greater detail available from the new datasets. The subsurface geology indicates a relatively shallow thickness of estuarine sediments overlying non-liquefiable Tertiary-age mudstone adjacent to the hills. In combination with the CPT data (Area E, Figure 6.2) this reduces the liquefaction hazard in this area. A lower liquefaction hazard may also exist around the margins of the former Ahuriri Lagoon to the north but CPT data in this area is currently lacking to establish this definitively. As a consequence, the areas of former lagoon adjacent to the hills to the north of

Taradale are mapped as areas requiring mandatory investigation of the liquefaction hazard. CPT data acquired in the future work may change this.

Hastings City, in both the earlier and the current work, is mapped with an intermediate liquefaction hazard. In the context of the current report this requires either investigation or use of a pre-approved mitigation technique for the assets under consideration.

The liquefaction hazard in Havelock North remains consistent with the very low to low liquefaction susceptibility mapped in Dellow et al (1999, 2003). Existing foundation design requirements could be used (Figure 8.1) for single storey, timber framed homes in Havelock North. However, strengthened or enhanced foundations as recommended in areas with a minor to moderate liquefaction hazard could potentially manage any residual liquefaction hazard in these areas as they are reported (Nick Traylen, pers. comm.) to be no more expensive to build than standard foundations.

9.2 WAIROA DISTRICT

The liquefaction hazard in the Wairoa District has changed little between the two maps. A moderate to very high liquefaction susceptibility was recognised in Dellow et al (1999, 2003) (Figure 2.10) and is still recognised in this report (Figure 8.3). The liquefaction observations during historical earthquakes describe moderate liquefaction effects and curiously a lot of fissuring but no ejecta, with two exceptions, one near the Wairoa River mouth and the other near Mahia on the isthmus linking the Mahia Peninsula to the mainland.

The new datasets (geotechnical, groundwater) and updated datasets (geology) have changed little with respect to the severity of the liquefaction hazard except for recognising the Holocene sediments of the coastal platform between Wairoa and Nuhaka, some of which were identified as having low liquefaction susceptibility, is now mapped as having a liquefaction hazard requiring further investigation. Whether the liquefaction hazard requires investigation or the use of prescribed mitigation techniques requires better data (geomorphology (at 1:25,000 or better), unconfined groundwater surface, CPTs). Uncertainties around the severity and extent of the liquefaction hazard in this area, indicate mandatory investigation of liquefaction in this area a prudent step.

9.3 CENTRAL HAWKE'S BAY DISTRICT

The area where the liquefaction hazard has changed significantly between the earlier work (Dellow et al, 1999, 2003; Figure 2.9) and the current work (Figure 8.2) is in the Central Hawkes Bay District. In the earlier work, the Poukawa and Otane Basins and the Tukituki River Valley downstream of the Waipawa River forks were mapped as having very high liquefaction susceptibility. Careful investigation of the reported liquefaction during historical earthquakes and an updated and more detailed geological map of the area (Lee et al, 2011) has resulted in a large reduction in the area mapped with a liquefaction hazard requiring investigation and/or mitigation.

The areas now mapped with a liquefaction susceptibility in the Central Hawke's Bay District are small, are associated with swamps and are prone to flooding (Figure 8.2). Development in these areas is limited to pastoral farming and is zoned 'Rural' (Central Hawke's Bay District Plan, 2003). The only town where liquefaction hazards warrant further investigation and/or mitigation is Porangahau. This is based primarily on reports of historical liquefaction. The other urban areas in the Central Hawke's Bay District and the rest of the rural areas are either hill country or gravel dominated braided river systems where existing foundation design requirements can continue to be used (Figure 8.2) for single storey, timber framed homes.

9.4 HASTINGS DISTRICT (BEYOND THE HERETAUNGA PLAINS)

The liquefaction hazard in the wider Hastings District (beyond the Heretaunga Plains) remains consistent with the very low to low liquefaction susceptibility mapped in Dellow et al (1999, 2003). Existing foundation design requirements could be used (Figure 8.4) for single storey, timber framed homes in the wider Hastings District.

10.0 CONSTRAINTS ON USING THE LIQUEFACTION PLANNING MAPS

The information presented in this report is not suitable for use to assess the liquefaction hazard and/or risk at a site-specific level. At the site-specific level, site-specific data is required to determine the consequences of liquefaction. At the very least this should include CPT and water depth data and analysis of this data used to inform the design of appropriate mitigation measures.

A range of uncertainties are present within the work presented in this report. These are addressed in the recommendations below. However, one crucial uncertainty not addressed in the recommendations is map boundaries. The data used to constrain boundaries on the geomorphic map is not directly related to quantified liquefaction effects, primarily due to the uneven distribution of CPT test sites. The map boundaries are based on the best available data and could change as more data becomes available. Another uncertainty is the variation in groundwater levels over time. The geotechnical analysis method used in this report is highly sensitive to changes in the groundwater level.

The mean magnitude approach used in this report allows a single hazard map for key return periods to be presented. The return periods of interest agreed to for this study ranged from 25 years (10% probability of occurrence in 2.5 years) to 2500 years (10% probability of occurrence in 250 years). This range spans often-used return periods for expected damage – 25 years for the serviceability level (no damage expected) to 2500 years which is reserved for damage assessment of critical facilities (buildings such as hospitals and emergency services). The liquefaction analysis method used gives the same severity of liquefaction at a site for the 500, 1000, and 2500-year return periods. Hence, only the 500 year-return period map is presented as the 1000-year and 2500-year liquefaction hazard maps are identical to the 500-year liquefaction hazard map (Figure 7.3).

The peak ground acceleration deaggregation plots for the Heretaunga Plains (Figure 5.1 to Figure 5.5) show a bi-modal hazard distribution, particularly at the longer return periods. The mean magnitude approach, while convenient, does not represent the most likely earthquake events. The bimodal distribution shows that a local earthquake with a smaller magnitude than the mean will make a significant contribution to the seismic hazard for Hawke's Bay (e.g. the 1990 magnitude 6.4 Weber earthquake) as will a larger magnitude regional earthquake (e.g. the magnitude 7.8 Hawke's Bay earthquake of 1931). The implications of this are that the extent of liquefaction is likely to be either less extensive or more extensive than for an earthquake scenario based on the mean magnitude event.

This work does not consider changes, particularly in the shallow unconfined groundwater surface, that might occur in relation to sea-level rise due to climate change or on-going tectonic deformation of the Heretaunga Plains. Conclusions and Recommendations

11.0 CONCLUSIONS

There is a liquefaction hazard present in several areas of Hawke's Bay. The areas with a liquefaction hazard are mostly low-lying areas near the coastline. Liquefaction causes ground deformation that has the potential to damage buildings and infrastructure, but it is not expected to result in building collapse or to heighten life-safety risk levels for single-story timber framed residential houses.

This report can be used to understand the variation, spatially and temporally of liquefaction hazards in Hawke's Bay. There is no unique solution as to the liquefaction hazard of any site since the liquefaction potential is driven by many variables some of which are seasonal (groundwater depth), some that are site specific (density and composition of the near-surface soil conditions) and some that are event dependent (the shaking intensity at any specific site, the magnitude of the triggering event and the source to site distance). Thus, apart from being able to identify specific site conditions where liquefaction is unlikely to occur (gravels and hilly terrain), all other sites can be expected to experience liquefaction to a greater or lesser extent when shaken severely enough and for long enough. The greatest uncertainty with respect to the liquefaction analysis undertaken for this report is in the groundwater data. Better data showing the seasonal fluctuations of the groundwater surface could result in changes (increase or decrease) the liquefaction planning maps presented in this report.

This report can, in conjunction with the draft liquefaction planning guidelines (Ministry for the Environment and Ministry of Business, Innovation and Employment, 2017), be used as a guide to policy and planning decisions. This report allows for liquefaction hazards to be considered and planned for prior to future residential development. The consideration of liquefaction, and mitigation of its effects, will improve the resilience of Hawke's Bay communities.

The liquefaction land vulnerability map (Figure 8.1) is suitable for use in conjunction with the district plans for Napier City and Hastings District. The liquefaction hazard planning map can be used to delineate, at the property level on the district plan, the appropriate means to identify, investigate and/or mitigate the liquefaction hazard that may or may not be present at the property.

The liquefaction planning maps for Wairoa District, Central Hawke's Bay District and Hastings District (beyond the Heretaunga Plains) (Figure 8.2, Figure 8.3 and Figure 8.4) are not suitable for use in conjunction with their respective district plans because of the scale difference between the underpinning geological maps (1:250,000) used to delineate the liquefaction susceptibility and most district plan maps (1:1500 to 1:25,000) and the limited datasets used to compile the maps. The liquefaction planning maps for Wairoa District, Central Hawke's Bay District and Hastings District (beyond the Heretaunga Plains) meet the requirements for a Level A liquefaction assessment, a basic desktop assessment as set out in Table 3.1 of the liquefaction planning guidelines (Ministry for the Environment and Ministry of Business, Innovation and Employment, 2017).

The Hawke's Bay region is seismically more active than is the Canterbury region and must expect to experience shaking strong enough to initiate liquefaction more often, but perhaps with less severity than was observed in Canterbury in 2010-2011.

11.1 RECOMMENDATIONS

The recommendations that follow-on from this part of the study are about improving the quality and quantity of the data used as inputs into the processes required to deliver a liquefaction hazard management strategy for territorial local authorities, particularly for single-story, timber-framed residential houses. This volume focuses on delivering a tool, the liquefaction hazard planning map (Figures 8.1 through to Figure 8.4) to allow territorial local authorities to initiate the planning for and management of the liquefaction hazard to single-story, timber-framed residential houses in areas under their jurisdiction using existing systems such as the District Plan, the Building Act and the Resource Management Act.

This report should be used in conjunction with the draft planning and engineering guidance for potentially liquefaction-prone land (Ministry for the Environment and Ministry of Business, Innovation and Employment. 2017). This document provides further information on the data required for the different levels of liquefaction assessment used to manage the liquefaction hazard.

It is also recommended that CPT data acquired for the purpose of issuing consents under the Building Act is required to be uploaded into the NZ National Geotechnical Database.

11.1.1 Data Quality and Quantity (all areas)

- Acquire better coverage of the geotechnical site characteristics across the region – this to include both additional CPT test results and laboratory testing. The laboratory testing of the Holocene sediments (< 10,000 years old) is needed in order to calibrate CPT-based liquefaction triggering methodology, particularly the influence of pumice and fines in the soil profile and their ability to influence both the onset and the severity of liquefaction effects.
- Ensure that the geotechnical data acquired is captured into the recently available National Geotechnical Database.
- Identify gaps in data and data with large uncertainties (e.g. unconfined shallow groundwater surface) and initiate activities to improve these in critical areas (e.g. new urban development). These data could be used to provide statistics around the recorded fluctuations for input into the liquefaction triggering and vulnerability calculations.

11.1.2 Heretaunga Plains

The two improvements in data quality and quantity that will have the greatest impact on improving the liquefaction risk results are:

- Acquire a better understanding of the near-surface groundwater depth across the district both spatially (increased density of observations) and temporally (increased length of observational record to quantify the seasonal variation).
- Acquire better coverage of the geotechnical site characteristics across the region – this to include both additional CPT test results but also laboratory testing of the Holocene sediments (< 10,000 years old), particularly the influence of pumice in the soil profile and its ability to influence both the onset and the severity of liquefaction effects. Ensure that the geotechnical data acquired is captured into the recently available National Geotechnical Database.

11.1.3 Central Hawke's Bay District

- Identify areas with a greater risk to liquefaction consequences from the District Plan (e.g. areas zoned town centre, industrial, residential, settlement, schools) as priority areas for undertaking the work outlined below.
- Acquire a better understanding of the near-surface groundwater depth across the district both spatially (increased density of observations) and temporally (increased length of observational record to quantify the seasonal variation).
- Undertake geomorphic mapping of at a scale of 1:25,000 (or greater detail) to provide a basis for delineating areas susceptible to liquefaction using newly acquired geotechnical and groundwater data.
- Prepare a liquefaction planning map at a scale of 1:25,000 (or better) to be incorporated into the next revision of the District Plan.

11.1.4 Wairoa District

- Identify areas with a greater risk to liquefaction consequences from the District Plan (e.g. areas zoned town centre, industrial, residential, settlement, schools) as priority areas for undertaking the work outlined below.
- Acquire a better understanding of the near-surface groundwater depth across the district both spatially (increased density of observations) and temporally (increased length of observational record to quantify the seasonal variation).
- Undertake geomorphic mapping of at a scale of 1:25,000 (or greater detail) to provide a basis for delineating areas susceptible to liquefaction using newly acquired geotechnical and groundwater data.
- Prepare a liquefaction planning map at a scale of 1:25,000 (or better) to be incorporated into the next revision of the District Plan.

11.1.5 Hastings District (beyond the Heretaunga Plains)

- Identify areas with a greater risk to liquefaction consequences from the District Plan (e.g. areas zoned town centre, industrial, residential, settlement, schools) as priority areas for undertaking the work outlined below.
- Acquire a better understanding of the near-surface groundwater depth across the district both spatially (increased density of observations) and temporally (increased length of observational record to quantify the seasonal variation).
- Undertake geomorphic mapping of at a scale of 1:25,000 (or greater detail) to provide a basis for delineating areas susceptible to liquefaction using newly acquired geotechnical and groundwater data.
- Prepare a liquefaction planning map at a scale of 1:25,000 (or better) to be incorporated into the next revision of the District Plan.

12.0 ACKNOWLEDGEMENTS

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13.0 GLOSSARY

Term – Definition

100-year event, 1 in 100 AEP – Shorthand for the earthquake with a 1 in 100 (1%) annual exceedance probability (AEP).

Borehole (BH) – A small diameter vertical soil core mechanically drilled for geotechnical investigation purposes. This includes examination and recording of soil characteristics of the core by an engineering geologist or geotechnical engineer, in-situ testing of the soil to characterise its strength and stiffness properties and collection of soil samples for laboratory testing.

Building Damage Ratio (BDR) – The ratio between the cost to repair earthquake related damage to a residential building and the greater of the replacement value or valuation of that building.

Box and Whisker Plot – A graphical representation of the median, upper quartile, lower quartile, maximum and minimum values of a dataset. The median value is represented by the middle line bisecting the box. The upper quartile and lower quartile values are represented by the right side and left sides of the box. The maximum and minimum values are represented by the right and left most ends of the whiskers.

Calculated parameter – An indicator of liquefaction vulnerability. Typically calculated based on CPT results for different scenarios. An example of a calculated parameter is the cumulative thickness of liquefied material in a specific earthquake using a specific liquefaction triggering method.

Canterbury Earthquake Recovery Authority (CERA) – Agency established by the Government to lead and coordinate the ongoing recovery effort following the Canterbury Earthquake Sequence. As of 1 February 2015, it is a Department Agency within the Department of the Prime Minister and Cabinet.

Canterbury Earthquake Sequence (CES) – The sequence of earthquakes and aftershocks in the Canterbury area from 4 September 2010 to the end of 2011. This included four main earthquakes on 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011.

Canterbury Geotechnical Database (CGD) – An online database established by CERA and now managed by MBIE. The CGD was set up to promote sharing of existing and new geotechnical and Christchurch recovery related information between professional engineers, EQC, insurers and local territorial authorities.

Central Hawke's Bay District Council (CHB DC) – The local council for the Central Hawke's Bay area.

Cone Penetration Test (CPT) – A geotechnical in-situ ground investigation test which involves pushing an instrumented steel cone into the ground at a controlled rate measuring the cone tip resistance, sleeve friction and pore water pressure.

CPT triggering (simplified method) – Method used to assess the likelihood of a given soil layer liquefying under seismic loading. Compares the cyclic resistance ratio (CRR) to the cyclic stress ratio (CSR) and calculates a factor of safety against liquefaction for a given situation.

CPT Tip Resistance (qc) – A measure of the force required to push the tip of a CPT probe through a given soil layer.

Cyclic Resistance Ratio (CRR) – A representation of the ability of the ground to resist liquefaction.

Cyclic Stress Ratio (CSR) – A representation of the liquefaction demand imposed on the ground by seismic shaking.

Crust Thickness (CT) – The thickness of the uppermost layer of non-liquefying material.

Cumulative Thickness of Liquefaction (CTL) – An estimate of the total thickness of soil layers that are predicted to liquefy at a given level of earthquake shaking. It is typically estimated from CPT soundings.

Damage attributes – Measured damage indicators, typically comprising residential land damage, liquefaction induced dwelling foundation damage and liquefaction induced elevation change. The measured damage attributes are compared with the calculated parameters to determine the best fit.

Department of Building and Housing (DBH) – Previously the government agency of the New Zealand government responsible for developing and implementing building legislation in New Zealand. In March 2012, the DBH was integrated into MBIE.

Digital Elevation Model (DEM) – A model of the ground surface elevation derived from a LiDAR survey that consists of a regular grid of equal size cells (i.e. 1m x 1m, 5m x 5m, 25m x 25m, etc.). The elevation at the centre of each cell is derived by taking the median elevation of all of the LiDAR ground classified point elevations within that cell.

Differential Settlement – Uneven subsidence of the foundation or columns supporting a structure.

Dwelling damage or dwelling foundation damage – The damage caused to a dwelling foundation by liquefaction, comprising stretching, hogging, dishing, racking/twisting, tilting, discontinuous foundation or global settlement.

Earthquake Commission (EQC) – A government owned entity responsible for carrying out the statutory functions set out in the Earthquake Commission Act 1993. This includes natural disaster insurance for residential property, administration of the natural disaster fund and funding research and education into natural disasters and ways of reducing their impact.

EQC Act – The Act of parliament that details the provisions of a home owners entitlements for EQC insurance cover.

Fines content – The proportion of fine grained material present in the soil. Typically defined as silt and clay sized particles passing the 63-micron sieve.

Factor of safety against liquefaction (FoS) – The ratio of CRR/CSR. FoS of 1.0 or more indicates no liquefaction (i.e. capacity exceeds demand). FoS less than 1.0 indicates liquefaction is likely (i.e. demand exceeds capacity).

GeoNet – The network of seismometers in New Zealand operated by GNS.

GNS – GNS Science (formerly Institute of Geological and Nuclear Sciences) is a crown research institute in New Zealand and operate the seismic recording stations (GeoNet) and carry out seismicity modelling.

Groundwater – Water present beneath the ground surface in soil pore spaces and in the fractures of rock formations.

Groundwater depth – The depth from the ground surface to the water table. For the purposes of this report, this is estimated by calculating the difference between the DEM and the median groundwater surface.

Groundwater Surface Elevation – The height of the groundwater surface above sea level. For the purposes of this report, this is estimated using groundwater surface models derived from groundwater monitoring well data.

H1, H2 – Ishihara's (1985) notation for the thickness of a non-liquefying crust (H1) and the thickness of the liquefied layer beneath this (H2).

Hawke's Bay Regional Council (HBRC) – The local council for the Hawke's Bay region.

Idriss & Boulanger (I&B or IB) – Method for assessing CPT triggering CRR and CSR.

Soil behaviour type index (Ic) – A single value calculated from the CPT data for each soil layer that represents the normalised cone parameters (i.e. whether the soil behaves as a coarse grained or fine-grained soil).

Ic Cut-off – An estimate of the threshold above which soils are not considered to be susceptible to liquefaction.

Laboratory Tests – Laboratory based tests undertaken on either disturbed or undisturbed samples obtained from the field to characterise various soil properties. For the purposes of this report this term is used to refer to Fines Content (FC), Particle Size Distribution (PSD) and Atterberg Limits tests.

Land Damage Assessment Team (LDAT) – The engineering team that carried out site by site inspections of residential dwelling foundations around Canterbury following the Canterbury earthquakes to provide information for the dataset of dwelling foundation damage. At the end of December 2011, approximately 75,000 inspections have been undertaken on 60,000 properties. Around 15,000 properties had inspections repeated after earthquake events followed the original inspection.

Land Information New Zealand (LINZ) – A government organisation responsible for managing land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, managing Crown property and supporting government decision making around foreign ownership.

Lateral Spread – A consequence of liquefaction where horizontal movement of upper soil layers occurs relative to soil layers at greater depth. It is measured as the global horizontal movement of a block of land.

Levels of earthquake Shaking – The PGA and MW of an earthquake event.

Light Detection and Ranging (LiDAR) – A method used to survey large areas using laser range-finding technology. LiDAR can be undertaken from an aeroplane (an aerial survey) or on the ground. Used here to measure ground surface elevation from a plane (an aerial survey).

LiDAR Survey Point Cloud – The complete set of data supplied for a LiDAR survey. Specifically, the x, y, z location that each laser impulse which was captured during the survey. The points are also classified to indicate the type of surface that they were reflected from, with the most LiDAR returns classified as either ground or non-ground classified points.

Liquefaction – The process by which earthquake shaking increases the water pressure in the ground in sandy and silty soil layers resulting in temporary loss of soil strength. Liquefaction can give rise to significant land and building damage, for example through the ejection of sediment to the ground surface, differential settlement of the ground due to volume loss in liquefied soil and lateral movement of the ground.

Liquefaction Consequence – The effects of liquefaction e.g. liquefaction ejecta, ground surface subsidence, differential settlement, lateral spread, buoyancy of underground structures and ground cracking.

Liquefaction Ejecta – Where water and liquefied soil material is ejected to the ground surface. Commonly observed as cone shaped piles of soil on the ground surface.

Liquefaction related elevation change – The LiDAR measured liquefaction related elevation change damage attribute which has had the tectonic component removed.

Liquefaction Potential Index (LPI) – A liquefaction vulnerability parameter developed by Iwasaki et al. (1978; 1982).

Liquefaction Severity Number (LSN) – A new parameter to indicate the liquefaction related vulnerability of residential dwellings developed by Tonkin + Taylor Ltd.

Liquefaction Susceptibility – The susceptibility of a soil to liquefaction, which is dependent on its compositional characteristics. Soils that are cohesive in nature such as clays with high plasticity are not susceptible to liquefaction.

Liquefaction Triggering – The initiation of liquefaction from shaking, commonly caused by earthquakes. Shaking must be sufficiently intense to trigger or initiate liquefaction. The shaking level that triggers liquefaction varies for different soils.

Liquefaction Vulnerability – The exposure of the land to damage at the ground surface from soil layers liquefying.

Liquefaction Vulnerability Parameters – Calculated parameters which can be used to estimate Liquefaction Vulnerability – e.g. CTL, LPI, LPIISH, SV1D and LSN.

Liquefiable – Soil that can liquefy (i.e. is susceptible to liquefaction).

Liquefying – Soil that is subjected to the seismic demand necessary to trigger liquefaction.

Liquid Limit (LL) – The water content at which the behaviour of a soil changes from plastic to liquid.

Magnitude (MW) – A measure of earthquake energy. For the purposes of this report it is estimated using the Richter magnitude scale.

Magnitude Scaling Factor (MSF) – A factor applied in the Boulanger and Idriss (2014) liquefaction triggering methodology used to account for earthquake duration effects on the triggering of liquefaction.

Ministry of Building Innovation and Employment (MBIE) – The government department that administers the Building Act. It includes what was previously the Department of Building and Housing (DBH).

Median groundwater – The median depth to the groundwater table. This represents the median groundwater level considering both summer and winter conditions.

Napier City Council (NCC) – The local council for the Napier City area.

Non-liquefiable – Soil that are not able to liquefy (i.e. are not susceptible to liquefaction).

Non-liquefying – Soil that can liquefy but has not been subjected to the seismic demand necessary to trigger liquefaction.

Non-liquefying Crust – The non-liquefying soil layers from the ground surface to the first liquefied soil layer.

New Zealand Geotechnical Society (NZGS) – The affiliated organization in New Zealand of the International Societies representing practitioners in Soil mechanics, Rock mechanics and Engineering geology.

One Dimensional Volumetric Consolidation Settlement (SV1D) – A calculated settlement liquefaction vulnerability parameter recommended by MBIE using a method proposed by Zhang et al. (2002).

Particle Size Distribution (PSD) – An index indicating what sizes of soil particles are present as a percentage by weight in a given soil sample.

Peak Ground Acceleration (PGA) – The maximum acceleration of the ground during an earthquake.

Potential – Whether the soil has the geotechnical characteristics such that it could theoretically liquefy if subjected to sufficient seismic loading. Potential has not changed in Canterbury because of the earthquake series as the soil characteristics have not substantially changed.

Quotable Value Property Identification (QPID) – A unique number that identifies a residential property

R&W or RW Robertson & Wride – Used here to refer to the calculation of apparent fines content based on CPT results.

Return Period – The estimated average period between natural hazard events (in this case earthquake shaking levels) of the same size or intensity.

Serviceability limit state (SLS) – The 25-year return period design earthquake loading for residential structures. Structures are expected to be designed to experience little to no damage under SLS conditions. This is modelled as a 0.13g, M7.5 earthquake load.

Seismic – Relating to earthquakes or other vibrations of the earth and its crust.

Seismic Demand –The level of earthquake shaking (PGA and MW) required to trigger liquefaction.

Seismicity – The occurrence or frequency of earthquakes in a region.

Sleeve Friction (fs) – A measure of the friction between the sleeve of a CPT probe and a given soil layer.

Soil Behaviour Type Index (Ic) – A CPT-based soil behaviour classification method developed by Robertson and Wride (1998).

Soil Density – The ratio of the mass to the total volume of a soil.

Standard Penetration Test (SPT) – A geotechnical in-situ ground investigation test which involves driving a standard steel probe into the ground measuring the number of blows to drive the probe a certain distance into the ground.

Tectonic movement – Regional change in ground elevation induced by earthquake displacements in the underlying bedrock.

Tonkin + Taylor (T+T) – Consulting firm specialising in liquefaction assessment and modelling.

Ultimate limit state (ULS) – The 500-year return period design earthquake loading for residential structures. The structure is expected not to collapse under ULS conditions. This is modelled as a 0.35g, M7.5 earthquake.

Volumetric Strain (εv) – The calculated unit change in volume due to granular soils being shaken into a more compact arrangement. Does not include loss of material due to surface expression of liquefaction.

Vulnerability – The consequence of triggered liquefaction at the ground surface on residential land in Canterbury. Vulnerability has changed because of ground surface subsidence, as the ground surface moves towards the groundwater table and consequently the depth to potentially liquefiable materials decreases (i.e. the crust thickness reduces). The closer the potentially liquefiable deposits are to the ground surface, the more vulnerable the property is to the liquefaction hazard.

Wairoa District Council (WDC) – The local council for the Wairoa area.

Water Content (wc) – A laboratory test used to estimate the percentage by mass of water in a soil.

Zhang Robertson & Brachman (ZRB) – A method for calculating volumetric densification.

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