REPORT

Liquefaction Desktop Study

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Hamilton City Council
Prepared by
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LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-induced Ground Damage to Inform Planning Processes' published by the Ministry of Business, Innovation and Employment in 2017. https://www.building.govt.nz/building-code-compliance/geotechnical-education	
Client	Hamilton City Council
Assessment undertaken by	Tonkin & Taylor Ltd
Report date	26 February 2019
Extent of the study area	• Hamilton City Council (HCC) Boundary • Refer to Figure 1.1
Intended RMA planning and consenting purposes	• To provide HCC with a high level screening tool for assessment of land use and subdivision consents.
Other intended purposes	• To combine hazard data with infrastructure criticality to identify and understand the risk areas of the city. • To provide HCC with information about liquefaction hazard for insurance purposes. • To provide Civil Defence with a high-level understanding of liquefaction hazard areas in Hamilton for use in a Civil Defence Emergency.
Level of detail	• Level B (Calibrated desktop assessment)
Notes regarding base information	• This assessment includes all CPT investigations available that were within the study extent along with CPT adjacent to the study extent on the NZ Geotechnical Database as at 21 August 2018. Refer to maps in Appendix A for investigation location details. • No groundwater model is available for Hamilton City. Assessment has been carried out at groundwater depths of 0.1, 1.0, 2.0, 3.0 and 4.0m to show sensitivity to groundwater levels within each geomorphological zone
Other notes	• The assessment is high-level in nature, and is not suitable for other purposes (e.g. for appending to Land Information Memorandum reports or detailed design).

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1 Introduction

The study area is defined by the Boundary of the City of Hamilton, Waikato. The City covers approximately 13,000 hectares and consists of residential, commercial, industrial, recreational and rural areas.

Tonkin & Taylor Ltd (T+T) has been engaged by Hamilton City Council (HCC) to provide information on the liquefaction vulnerability of all areas of the city, primarily as a high-level screening tool for the assessment of land use and subdivision consent applications.

The two primary objectives of this assessment are the identification of the likely spatial distribution of the liquefaction vulnerability of the land and recommendations for stakeholders to further refine the assessment of liquefaction vulnerability at their site.

This report includes:

- The ground conditions within the study extent.
- The groundwater assumptions for the purpose of the liquefaction assessment.
- The seismic shaking hazard adopted for the assessment of liquefaction for the study extent.
- An assessment of the likelihood of liquefaction-induced land damage within the study extent.
- Information about lateral spreading.
- Suggested information required to complete a liquefaction assessment.

The high-level assessment is not suitable for alternate purposes (e.g. for appending to Land Information Memorandum reports or detailed design). This is because the recommendations and opinions in this report are based on data from CPT and borehole locations (often widely-spaced) and the nature and continuity of subsoil away from these locations are inferred and it must be appreciated that actual conditions could vary from the assumed model.

Further, understanding the location of groundwater levels is a key component in the assessment of liquefaction vulnerability, however currently neither long term groundwater monitoring records nor a groundwater model is not available in the study area.

Finally, the soil maps sourced from Moon (2012) were the primary information source for defining the geomorphic zones. This soil map was prepared based on data originally mapped at 1:250,000 to 1:50,000 scales. The mapping precision is such that it should not be interpreted to individual property levels. It is also likely that there are small areas of recent deposits that are not resolved at the scale of the mapping undertaken; zones in particular of colluvium or peat at the base of hills or other steep slopes in the City.

1.1 Scope of work

The scope of works comprises a calibrated desktop assessment of liquefaction vulnerability of the soils of Hamilton City in general accordance with a Level B assessment as described in Planning and Engineering Guidance for Potentially Liquefaction-Prone Land (MBIE/MfE/EQC, 2017). The key information required to undertake a liquefaction assessment at a given site include a good understanding of the subsurface ground conditions, groundwater levels and seismic shaking hazard. The scope of this project can be summarised as:

- Collation and review of available data that is relevant to this study including:
  - Geological and geomorphological maps.
  - Ground surface elevation levels for the extent of the study area.
  - Geotechnical investigations and laboratory tests that are currently available on the New Zealand Geotechnical Database (NZGD).
  - Groundwater level information for the study extent.
- Assessment of the liquefaction and lateral spreading hazard of the study extent at 25, 100, 500, and 1,000 year Average Recurrence Interval (ARI) levels of earthquake shaking for differing groundwater scenarios.
- Production of statistical plots of Liquefaction Severity Number for the identified geomorphological zones for the different earthquake/groundwater scenarios.
- Development of suggested site specific additional information requirements for liquefaction assessments within the City.
- A desktop study report summarising the methodology and results of this study.

The study extents are shown in Figure 1.1 below.

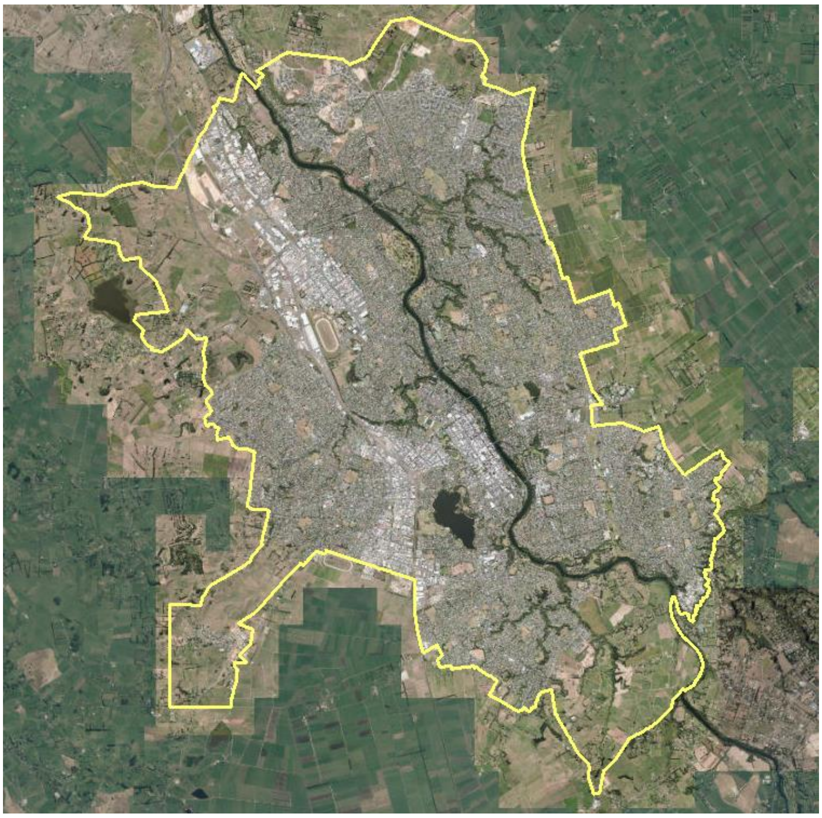

Figure 1.1: Aerial image showing the study extents.

2 Ground conditions

2.1 Geology

Hamilton City is situated within the Hamilton lowlands or basin (Figure 2.1), a graben that has been progressively infilled with a complex sequence of volcanogenic alluvium and various ignimbrites and tephra since c. 2 million years ago (McCraw, 2011).

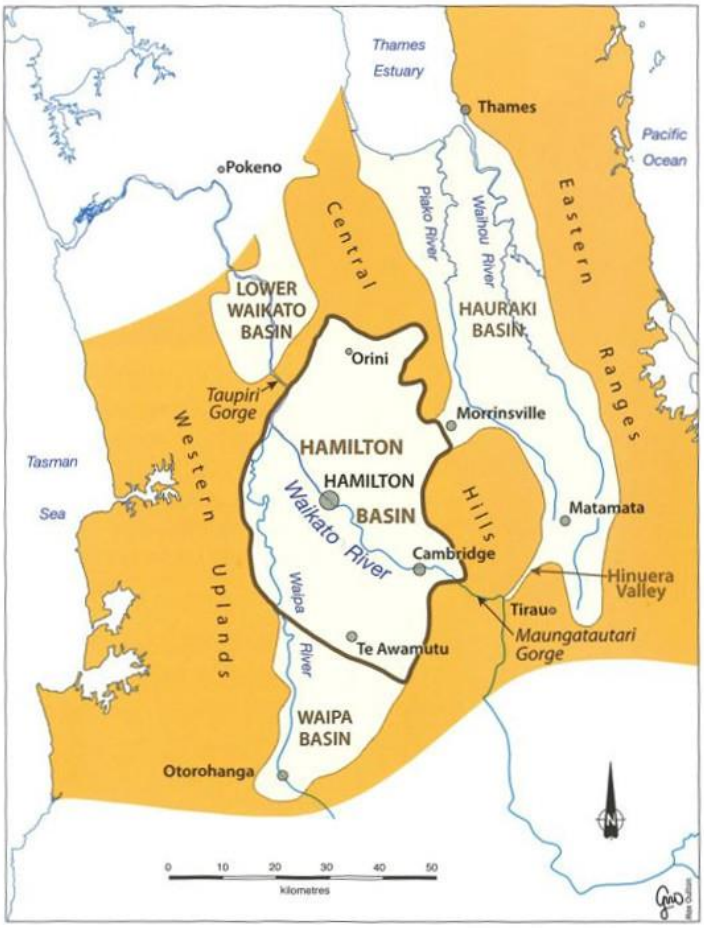

Figure 2.1: The Hamilton lowlands or Basin in the upper central North Island is bounded to the west and east by ranges and bisected by the Waikato River (McCraw, 2011).

Two distinct periods of deposition can be characterised in the Hamilton lowlands and are observed in the present day landscape as older materials (Walton Subgroup) forming the broad hills and younger materials (Primarily the Hinuera Formation of the Piako Subgroup) forming extensive plains. The Walton Subgroup and Piako Subgroup are part of the Tauranga Group. Younger Holocene sediments are also present in the Hamilton Basin within gullies, peat bogs and along river terraces. The adopted geological units within the project area are illustrated in conceptual form in Figure 2.2 and described in greater detail below. See Figure A1.3 in Appendix A for soil map.

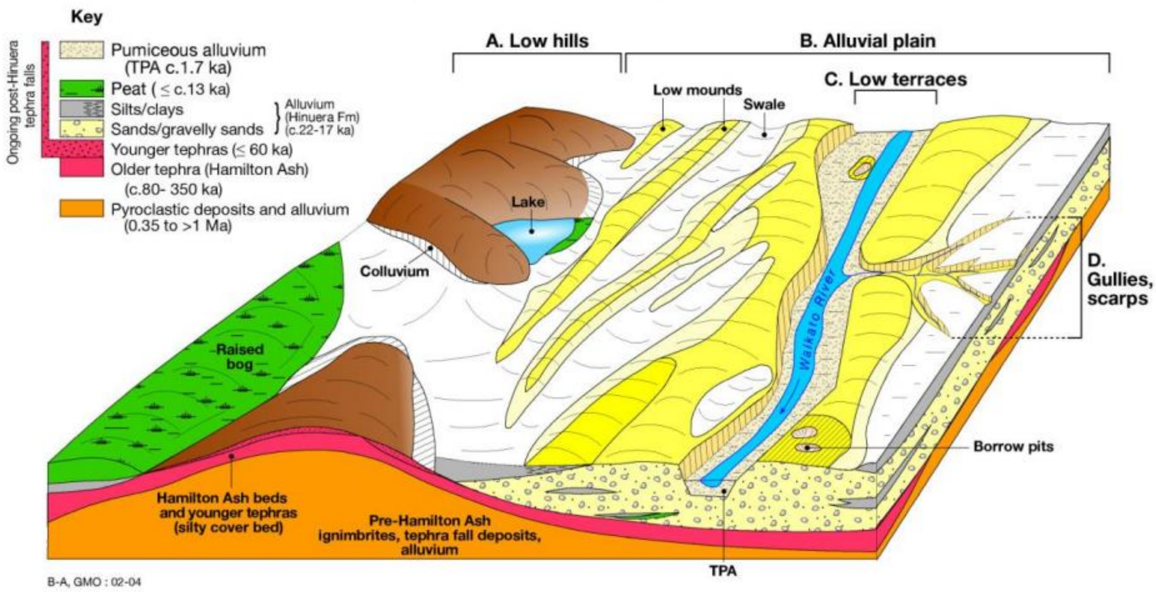

Figure 2.2: Main landscape units and geological materials, Hamilton Basin (Lowe, 2010).

<u>Walton Subgroup</u>

The Walton Subgroup, forming the present day broad hills, comprises a sequence of ignimbrites and tephra from several sources and fine grained volcanoclastic alluvium (Edbrooke, 2005). The deposition of the Walton Subgroup beds occurred between 2 million years ago to 27,000 years ago in the Pleistocene Epoch. During later stages these materials eroded forming hills and valleys. The Walton Subgroup deposition ended upon the Oruanui Eruption (27,000 years ago).

<u>The Hinuera Formation</u>

Following the Oruanui eruption, the existing topography was infilled by the Piako Subgroup, specifically the Hinuera Formation, which formed the extensive plains observed in Hamilton lowlands. The Hinuera Formation comprises interbedded coarse alluvium, pumice gravels, peat and silts deposited by braided river systems of the ancestral Waikato and Waipa Rivers. These rivers continued to deposit vast amounts of sediment into the Hamilton lowlands until climatic conditions changed c. 17,000 and the river systems entrenched into present day positions (Molloy, 1998).

Due to the nature of the depositional environment, the Hinuera Formation is highly variable both laterally and vertically. Loose sands and gravels are found in the higher energy environments and levees and finer grained sediments such as silt represent the low energy environments such as embayed channels and on the inside of river bends.

<u>Peat</u>

The nature of the depositional environment of the Hinuera Formation also led to the impeding of many of the braided channels which subsequently would go on to form lakes and swamps leading to the development of vast peat deposits on the Hinuera Formation or at the slope margins of the Walton Subgroup. Some of these are visible at the surface today as raised bogs although peat layers and lenses are common throughout the Hinuera Formation. Singleton (1991) also attributes the peat bogs visible within Hamilton Basin to a warming of the climate and the river carrying less sediment therefore changing from a being a braided system to the entrenchment into more discrete channels.

Recent Holocene Sediments

Subsequent to the deposition of the Hinuera Formation to form the "Hinuera Surface", a network of gullies have formed within the Hamilton basin. The floors of these narrow gullies are filled with young Holocene (<12,000 years old) colluvium and alluvium deposits consisting of reworked sands, silts and gravels of the Hinuera Formation and Walton Subgroup.

The most recent volcanic activity of the Taupo eruption, c. 2000, resulted in large volumes of pumiceous material entering the Waikato River. The river flooded the Hamilton basin leaving the lower terraces and some channels covered in the pumiceous silts, sands and gravels comprising the Taupo Pumice Alluvium (Manville & Colin, 2004); (Edbrooke, 2005). The Waikato River then entrenched again through the Taupo Pumice Alluvium.

2.2 Faulting

The GNS New Zealand Active Fault Database identifies the Kerepehi fault as the closest active fault to the site at approximately 42km to the east. Other faults affecting the Hamilton basin include the inferred non-active Waipa fault and the Taupiri fault to the north proposed by (Kirk, 1991). Recent studies by the University of Waikato (Spinardi, et al., 2017) propose the presence of faulting within the Hamilton Basin. Whilst the evidence does suggest that these faults may exist at depth, to date no definitive evidence of activity within the last 350,000 years has been identified. Figure 2.3 shows the location of the non-active faults in the vicinity of the Study area.

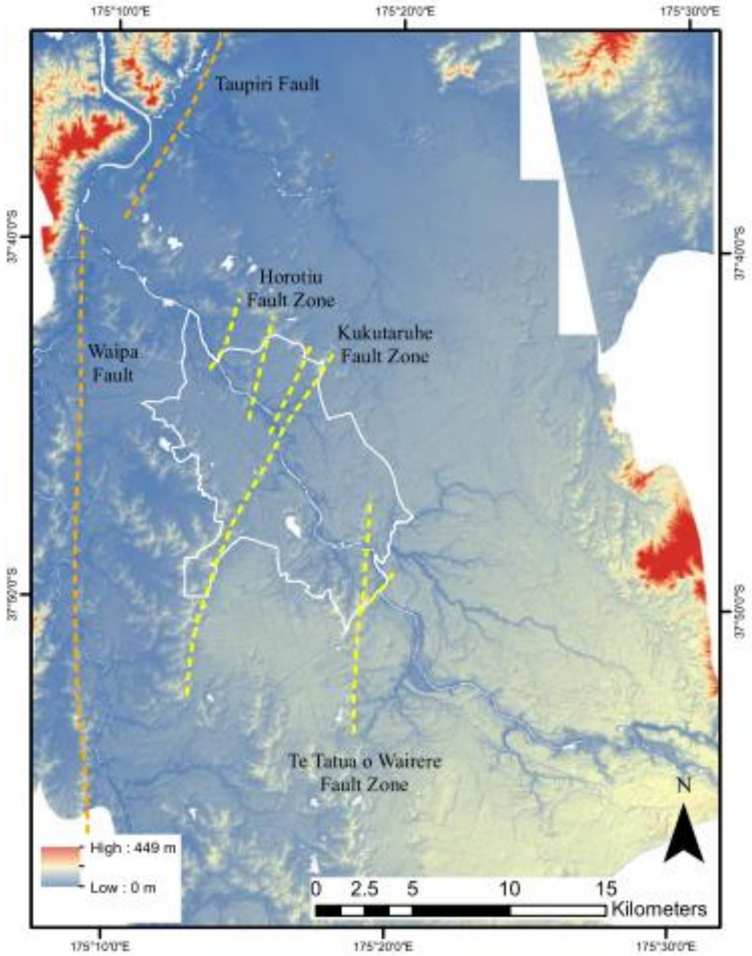

Figure 2.3: Map of inferred fault zones recognised from surface exposures and geological mapping of the Waikato River, (Spinardi, et al., 2017).

2.3 Geotechnical investigations

Existing geotechnical investigations from the publicly available NZGD and from T+T's own records have been considered for this study, including 1141 Cone Penetration Tests (CPT). The locations of the investigations are presented in Figures A1.1 in Appendix A. For the most part, investigations were located within the study area. Additional data points located just outside of the project extents were also included in order to characterise the geological units with greater certainty.

Some of the data within T+T's own records remains confidential. The data has been considered in the assessment of liquefaction vulnerability but the location of the data has not been disclosed at the request of the client and owner of the data. In some cases CPT traces on the NZGD were not available in digital format, a process of digitisation was undertaken in order to bring this data into the liquefaction assessment. Table 2.1 provides a breakdown of the number of CPT based on the source and format. The spatial distribution of the CPT which T+T have permission to disclose the location of is shown in Figure B1.1 in Appendix B.

As one might expect, the distribution of CPT across the region is not a uniform spacing in a grid pattern. CPT are grouped together in linear features representing recent infrastructure projects such as the Hamilton Section of the Waikato Expressway, the Te Rapa bypass and parts of Wairere Drive Upgrade. Other groups of CPT are found across the city associated with both large and small scale residential and industrial development sites.

Many other CPT are known to exist within the city, HCC may wish to request that all CPT undertaken on their behalf are uploaded to the NZGD as part of their terms of engagement with consultants. The spacing and density of the CPT information is discussed further in section 2.6.

Table 2.1: Source and format of CPT data used for this assessment

Source	Format	CPT No.
NZ Geotechnical Database	Electronic	440
	Digitised	142
T+T Geotechnical Database	Electronic	332
	Total	**914**

2.4 Site geomorphology

For the purposes of this study, the site has been divided into four geomorphic zones based largely on the microzones described in previous work by (Hodder & Moon, 2007) and (Moon, 2012). These zones are presented in Figure B1.1 in Appendix B and described in Table 2.2. The basis of the zones are the geological mapping (Bruce, 1979) & (Kear & Schofield, 1965), a Digital Elevation Model (DEM) derived from LiDAR data (shown in Figure A1.2 in Appendix A) and comparison of the available CPT and BH data.

Table 2.2: Description of geomorphic zones adopted for the study area

Geomorphic zone	Typical geology	Description
Low hills	Walton Subgroup	The “Hamilton Hills” making up the relatively higher ground of the city consists of low rounded hills representing the remnants of a previous ground surface. A typical sequence through this zone may consist of: Post Hamilton Ash Tephra – silt Hamilton Ash weather tephra – clay Karapiro Formation – Alluvial gravelly clay Puketoka Formation – ignimbrites
Alluvial plains	Hinuera Formation	Highly variable both vertically and laterally as the ancestral Waipa and Waikato Rivers deposited material eroded from the volcanic catchments of the central North Island. The deposits filled the low lying ground and channels and depressions within the eroded surface of the Walton Subgroup. The “Hinuera Surface” today consists of a series of low ridges, swales and flat plains sloping gently to the north. Soils comprise cross-bedded silts, sands, gravels with peat lenses also common. Sequences may exhibit a general fining upwards sequence, (McKay, Lowe, & Moon, 2017).
Peat	Peat	Large raised bogs that developed on originally low lying areas on top of the Hinuera formation or at the slope margins of the Walton Subgroup. Peat consistency and thickness is variable. It is likely that the liquefaction potential is linked to the geological unit underlying the peat.
Gullies/river terraces	Recent Holocene Deposits and Taupo Pumice Alluvium	Gullies are formed in the Hinuera Surface forming moderately steep slopes and terraces. Material within the gullies is recent alluvium derived from the parent materials in the basin. Uncontrolled filling is also often encountered in these zones. The River Terraces are characterised by steep low, flat terraces of younger pumiceous silts, sands and gravels.

2.5 Groundwater

In the absence of long term widespread groundwater monitoring data we have undertaken a review of groundwater information for Hamilton City.

Waikato Regional Council (WRC) undertake regular shallow groundwater monitoring at Percival Road at the Eastern edge of the City. In this location the median groundwater level is approximately 2 m below ground level (bgl) with a seasonal fluctuation of ±0.25 to 0.50 m. This location is within the alluvial plains geomorphic zone and may be representative of depth to groundwater within this zone when located away from the river or gully systems. The river and gully systems typically have the effect of lowering groundwater levels on the elevated areas of the plains. Crowcroft (1992) found that water levels monitored in shallow wells within the region ranged from 1.0 to 3.0 m bgl.

Due to the lateral and vertical variability within the Hamilton basin soils, the presence of low permeability layers often results in perched water tables. These are often visible as seepages within slopes above the regional groundwater table that is influenced by the Waikato River and its tributaries.

From experience in working within the Hamilton basin it is possible to draw some conclusions about the groundwater within the identified geomorphic zones (Table 2.3). However, it is not possible to assign groundwater levels in an area to the level of certainty required to refine this liquefaction assessment without long term groundwater monitoring records of sufficient density to build a reliable groundwater model.

Table 2.3: General groundwater observations for the geomorphological zones within the study area.

Geomorphic Zone	Groundwater observations
Low hills	Higher ground and often lower permeability soils leading to deeper groundwater levels relative to other geomorphic zones.
River/Gullies	Deposits in gully bases normally at or close to the median water table. River terraces generally coincident with river level. Presence of perched water normally results in the development of gullies and instability.
Peat	Characterised by shallow groundwater leading to swamp-like conditions. Often drained by swales, water level coincident with depth of swale.
Alluvial plain	Relatively shallow groundwater when not controlled by localised drainage associated with river terraces, gullies and deep swales. Phreatic surfaces can be steep at slope margins depending on the underlying conditions.

For the purposes of the study we have carried out the liquefaction assessments across a range of groundwater depths, at 0.1, 1.0, 2.0, 3.0 and 4.0 m below ground level.

It is understood that Waikato Regional Council (WRC) are currently planning an extensive groundwater monitoring project for the City. Liaison with WRC is recommended to ensure that the data is collected with the objectives of a specific liquefaction assessment in mind. HCC may also consider requesting developers/consultants upload groundwater data to the New Zealand Geotechnical Database.

2.6 CPT characterisation of geomorphic zones

Where possible the CPT data used in this study were sourced from within the project extent. However, to provide a better characterisation of each zone, CPT from nearby areas with the same geomorphology were also incorporated. For each geomorphic zone described in Table 2.2, the CPT tip resistance (q_C) and Soil Behaviour Type (I_C) has been plotted against depth. These plots are referred to hereafter as “CPT traces.” An example of these CPT traces from the low hills geomorphic zone is shown in Figure 2.4 and the complete set of CPT traces for each geomorphic zone is shown in Appendix B2.

The CPT traces shown in Figure 2.4 and Appendix B2 are cut off at 10 m depth because liquefaction of soil layers more than 10 m below the ground surface provides a negligible contribution to liquefaction damage of the land at the ground surface (Tonkin + Taylor, 2015). The dashed purple and red lines on the I_C vs. depth plot shown in Figure 2.4 are values of I_C that represent the transition from clean sand to silty sand like behaviour (purple dashed line) and sandy silt to silty clay like behaviour (red dashed line).

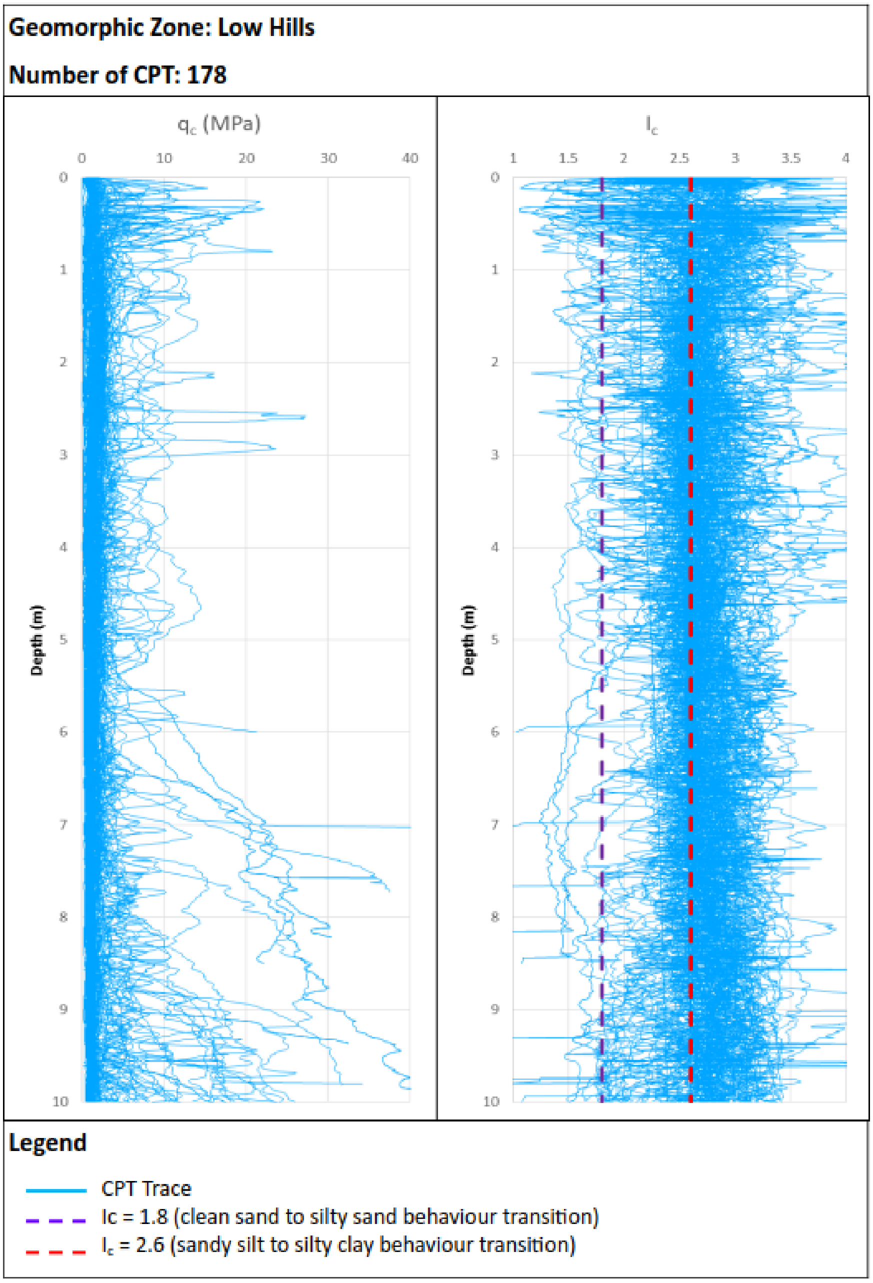

Figure 2.4: Example of CPT traces from the Low Hills geomorphic zone

T+T attempted to refine these geomorphic zones into smaller sub areas by regrouping the CPT traces into smaller groups. However, inspection of these smaller groups of CPT did not show any better characterisation of the soil conditions beyond the general trends captured within the four broad geomorphic zones.

In general CPT traces indicate there is a high degree of variability in the nature and thickness of the soils in the study area. In particular this is apparent in the areas mapped as Alluvial Plains and Peat which both exhibit a high degree of variability. The CPT traces in these zones indicate the presence of loose/soft soils exhibiting clay like behaviour to denser sands and gravels across the full ten meter length of CPT analysed.

The Recent Gullies/River Terraces and Low Hills indicate less variability than the other two groups. In general the Recent Gullies/River Terraces CPT traces indicate a moderately dense material with sand to silt like behaviour, whereas the Low Hills CPT traces indicate a loose/soft material exhibiting clay like behaviour.

Table 2.4 provides the total number of CPT and the typical characteristics of the soil profile as inferred from CPT traces for each geomorphic zone. The distance to closest CPT statistics are a measure of the distance to the closest CPT from any point within the study area, this is provided as a useful metric to illustrate CPT coverage. Due to data clustering, quoting the average density of CPT within the study area is potentially misleading as it does not convey the areas that are further from clustered data points. The closest CPT statistic shown below compare favourably with the indicative average investigation densities suggested in the MBIE (2017) guidelines which correspond to distances of 160 to 1000 m to the nearest investigation point for a level B liquefaction assessment.

From these values it can be seen that The Alluvial Plains appear to be better characterised than the other groups. The reasons for there being a lower density of CPT in the other areas is likely to be that there has been less development within the more challenging zones (Peat and Gullies) and the Low Hills mostly having been developed already and also requiring fewer deep investigations CPT to assess ground conditions for residential development.

Table 2.4: CPT characteristic by geomorphic zone

Geomorphic zone	Total CPT No.	Distance to closest CPT	Characteristic soil profile inferred from CPT traces
Low hills	178	Lower Q: 350 m Median: 760 m Upper Q: 1660 m	Generally consistent q_C of approx. 1 to 3 MPa throughout the top 10 m depth although some traces did see an increase with depth. I_C indicates sandy silt to silty clay behaviour although with a high degree of scatter for the full depth of influence. The top 4-5 m shows a higher number of traces indicating clay-like behaviour.
Alluvial plains	523	Lower Q: 240 m Median: 480 m Upper Q: 780 m	Split into 3 geographic sub-zones to demonstrate CPT trace patterns (NE of Waikato River, south east of Waikato River and west of Waikato River). General linear increase in q_C of approx. 1 to 10 MPa from GL to 10 m bgl albeit with a degree of scatter. Range of I_C indicates clean sand to silty clay-like behaviour. Each set of traces exhibits similar behaviour in terms of qc and I_C indicating that the same degree of soil behaviour variation can be expected within different areas of the city.
Peat	96	Lower Q: 340 m Median: 630 m Upper Q: 950 m	General linear increase in q_C of approx. 1 to 8MPa from GL to 10 m bgl albeit with a degree of scatter. Range of I_C indicates clean sand to silty clay-like behaviour. Organic soil-like behaviour more common in the 0 to 6 m range. Variable CPT traces linked to the nature of peat along with the thickness present and the underlying geological unit.
Gullies/river terraces	117	Lower Q: 340 m Median: 700 m Upper Q: 1260 m	q_c range of approx. 0 to 10MPa for top 3 m. q_c range of approx. 0 to 15-20MPa from 3 to 10 m. I_C indicates silty sand to silty sand-like behaviour from 0 to 10m. Upper 1 to 2 m indicates greater range of behaviour from Gravel to Organic soil-like behaviour.

3 Seismic hazard

3.1 Seismic site subsoil class

The seismic subsoil class in accordance with NZS 1170.5:2004 (Section 3.1.3) for the study area is considered to be 'Class D – Deep or Soft Soil Sites' due to the large depth to bedrock at the site. The Te Rapa borehole undertaken for the oil exploration of the Hamilton Basin indicated that bedrock was in excess of 100 m.

Further investigations and assessment of subsoil class (e.g. deep borehole or microtremor testing) are unlikely to modify the conclusion of Class D.

3.2 Ground shaking hazard

The seismic hazard in terms of Peak Ground Acceleration (PGA) for the area has been assessed based on the NZTA Bridge Manual in accordance with the approach recommended in NZGS Module 1 (NZGS/MBIE, 2016). Table 3.1 presents the Average Recurrence Intervals (ARI) for earthquakes with various 'unweighted' PGAs with corresponding earthquake magnitudes.

The seismic hazard for the study area was assessed at 4.0%, 1.0%, 0.2%, 0.1% and 0.04% Annual Exceedance Probability (AEP), which correspond to 25, 100, 500 and 1,000 year ARI earthquake events.

Table 3.1: Ground seismic hazard

AEP (%)	ARI (years)	PGA (g)	Magnitude (M_{eff})
4.0	25	0.05	5.9
1.0	100	0.11	5.9
0.2	500	0.22	5.9
0.1	1,000	0.28	5.9

Note:

PGA and M_{eff} has been assessed based on the Bridge Manual SP/M/022 Third Edition for the following:

Return period factor, Ru	0.25 for 25yr; 0.5 for 100yr; 1.0 for 500yr; 1.3 for 1000yr return period (NZS 1170.5:2004, Table 3.5)
Subsoil class	D (Deep soil) – refer Section 3.1
Return period PGA coefficient, $C_{0,1000}$	0.28 (Bridge Manual Figure 6.1(b))
Site subsoil class factor, f	1.0 (Bridge Manual Section 6.2)
PGA	$C_{0,1000}$ x Ru/1.3 x f x g (Bridge Manual Section 6.2)
Effective Magnitude, M_{eff}	5.9 (Bridge Manual Table 6.2(d))

3.3 Average Recurrence Intervals considered in hazard assessment

The design ARI's considered for this study are 25, 100, 500, 1,000 year. The 25 and 500 year ARI correspond to Serviceability Limit State (SLS) and Ultimate Limit State (ULS) design events for importance level two structures respectively specified by the Building Code. The 100 and 1,000 year ARI are useful events for considering the sensitivity of the soils to varying levels of PGA and to assess relative liquefaction risk for the different areas of land that compromise the study area.

4 Liquefaction susceptibility, triggering, vulnerability and consequence

4.1 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, can 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 two 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 a number of 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. The ground rarely subsides uniformly resulting in differential settlement of buildings and foundations. Figure 4.1 summarises the process of liquefaction with a schematic representation.

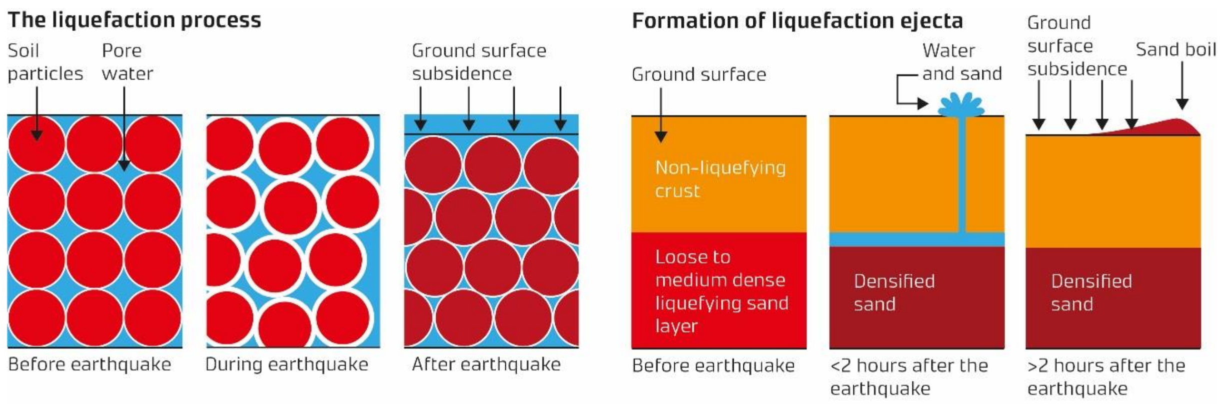

Figure 4.1: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta.

4.2 Liquefaction susceptibility and triggering

Liquefaction only occurs in some soil types. These are typically soils which are saturated, non-cohesive, and low to moderate permeability. Soil types which are susceptible to liquefaction include:

- Sands and low plasticity/non-plastic silts. (Bray & et al, 2014).
- Fine grained low to non-plastic soils with a high moisture content. (Bray & Sancio, 2006), (Boulanger & Idriss, 2006).
- Young, typically Holocene-aged (≤12,000 years old) deposits.

- Gravels can liquefy if they have a low permeability or are confined by less permeable layers.

Susceptible soils require a certain level of earthquake shaking in order to trigger liquefaction. Denser soils require more intense and/or longer duration of shaking than those that are less dense.

The trigger level of earthquake shaking (in terms of PGA and magnitude (M_W)) for each soil layer identified as being susceptible to liquefaction has been assessed by the method proposed by Boulanger and Idriss (Boulanger & Idriss, 2014). This method is based on the empirical relationship between the CPT tip resistance (q_c) and soil fines content derived from the soil behaviour type index (I_C).

The input parameters that have been adopted for the Boulanger and Idriss (2014) liquefaction triggering assessment for this study are listed in Table 4.1.

Table 4.1: Input Parameters for Boulanger and Idriss (2014)[10]

Input parameter	Default value adopted	Comments
Soil Density	18 kN/m^3	Not sensitive to the typical variability in soil density in the study area
FC - I_c correlation	C_{FC} = 0.0	Appropriate default value for soils in the study area
I_c - cut off	I_c cut off = 2.6	Appropriate default value for soils in study area
Magnitude of earthquake shaking	M_w = 5.9	Calculated effective magnitude as discussed in Section 3.2
Peak Ground Acceleration (g)	0.05, 0.11, 0.22, 0.28	Range of values considered to investigate sensitivity to PGA
Probability of Liquefaction, P_L (%)	P_L = 15%	Based on standard engineering design practice and discussed further below
Depth to Groundwater, GWD (m)	0.1, 1.0, 2.0, 3.0, 4.0	Range of values considered to investigate sensitivity to GWD

The method of Boulanger and Idriss (2014) uses a probability analysis to assess liquefaction triggering for each CPT data point at three probability levels: P_L 15%, P_L 50% and P_L 85%. These levels represent the uncertainty in the scientific ability to characterise the seismic resistance of the soil using CPT data. Because every soil deposit has its own unique characteristics, it is not possible to perfectly predict the intensity of shaking required to trigger liquefaction. Essentially a P_L of 15% means that there is a 15% possibility that the actual factor of safety against liquefaction triggering for a particular soil deposit will be less than the calculated value. Similarly for the P_L values of 50% and 85% there is 50% and 85% possibility respectively that the actual factor of safety against liquefaction triggering is less than the calculated value.

For the purposes of engineering design (e.g. for new buildings) a probability level of 15% is typically adopted to provide a degree of conservatism in the design. Further, this approach is recommended by Module 3 of the MBIE guidance document *Earthquake Geotechnical Engineering* (NZGS/MBIE, 2016).

4.3 Liquefaction consequence

Table 4.2 presents the characteristics of liquefaction related land damage, and a summary of the likely consequences of liquefaction related damage for each category of land damage. This table has been reproduced from (MBIE/MfE/EQC, 2017). Appendix A of the MBIE Guidance includes photos of liquefaction-induced land damage for each of these categories. These provide a useful reference for understanding the magnitude of land damage that can be expected within each category.

Table 4.2: Degrees of liquefaction-induced land damage (MBIE/MfE/EQC, 2017)

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

Notes:

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

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

The main potential consequences of liquefaction are discussed in MBIE Planning and Engineering Guidance for Potentially Liquefaction-Prone Land. Table 2.1 from these guidelines is reproduced in Table 4.3 of this report.

Table 4.3: Consequences of liquefaction, as published in Planning and engineering guidance for potentially liquefaction-prone land

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

While the immediate effects of liquefaction relate primarily to land, building and infrastructure damage, liquefaction can also have a significant social, economic and environmental impact, refer to Section 2.4 of Planning and Engineering Guidance for Potentially Liquefaction-Prone Land (MBIE/MfE/EQC, 2017).

4.4 Liquefaction vulnerability indicators

"Vulnerability" of the land relates to the consequence of liquefaction and/or lateral spreading at the ground surface. It is dependent on the depth to groundwater (i.e. crust thickness), the thickness of liquefiable soils, the level of earthquake shaking, the slope of the ground surface and the proximity to nearby free faces. The closer the liquefiable soils are to the ground surface, the more vulnerable the land is to damage due to liquefaction (all else being equal). Also, the more sloping the land and the nearer to a river edge or other free face the more vulnerable the land is to damage due to lateral spreading.

The indicators which have been evaluated to assess the vulnerability of land as a result of liquefaction at the study area are summarised in Table 4.4.

Table 4.4: Liquefaction and lateral spreading vulnerability indicators

Land Vulnerability Indicator	Comments and observations from past events
Depth to groundwater	Observations from Christchurch and Japan indicate that the greater the thickness of the non-liquefying crust the less damage is likely to be reflected at the ground surface. Examples of sand boils and damaging differential settlement are very few for sites with a crust thickness greater than 3 m (Ishihara, 1985).
CPT Traces	Reviewing the q_C and I_C vs. depth plots grouped by geomorphic zone provides insight into the likely liquefaction-induced land damage under earthquake loading. Looser soils are more likely to liquefy than denser soils and cohesionless soils are more likely to liquefy than cohesive soils. An experienced geotechnical engineer is also able to interpret these CPT traces to understand how the soil profile will influence liquefaction-induced land damage which is useful when reviewing the liquefaction indices. In particular liquefaction indices derived from soil profiles with interbedded silt and sand layers tend to over predict liquefaction vulnerability of the land.
Liquefaction Severity Number (LSN) (van Ballegooy & et al, 2014)	LSN is a parameter which characterises the vulnerability of land to damage due to liquefaction for a given level of shaking and a given groundwater level. This parameter has been correlated with evidence of surface ground damage in Christchurch (Tonkin + Taylor, 2015). A higher LSN value indicates a greater likelihood of surface ground damage.

The depth to groundwater and Liquefaction Severity Number (LSN) are the indicators that have been used to assess liquefaction vulnerability of the land for this study. Other indicators such as the Liquefaction Potential Index Ishihara (Maurer & et al, 2015), the Cumulative Thickness of liquefaction and the lateral Displacement Index (Zhang, Robertson, & Brachman, 2004) have not been considered in this high-level regional assessment. However, these tools may be useful additional liquefaction vulnerability indicators for an individual area or site.

As outlined in the MBIE (2017) guidelines, when assigning liquefaction vulnerability categories for an area-wide hazard assessment it is important to account for the uncertainties within the assessment, and the potential consequences of over-estimating or under-estimating the liquefaction vulnerability. Accordingly, Table 4.4 and Appendix J of the MBIE (2017) guidelines sets out a philosophy for evaluating performance based on the level of certainty in the estimated liquefaction-induced ground damage. Taking this philosophy into account, for the purposes of the current high-level hazard study we have adopted approximate characteristic LSN ranges for each degree of liquefaction-induced damage as shown in Table 4.5. These are used to assist with interpretation of the maps and summary statistics shown in Appendix C.

These characteristic LSN ranges are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design) where more detailed information is available, there is less uncertainty, and there are different consequences for under-predicting or over-predicting liquefaction vulnerability.

Table 4.5: Characteristic LSN adopted for purposes of the study

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

Lateral spreading has not been included in these characteristics of liquefaction related land damage because LSN is not intended for lateral spreading assessment.

To understand the potential liquefaction vulnerability of the study area, the LSN value was calculated at each CPT location for the each of the combinations of earthquake shaking and depth to groundwater shown in Table 4.1. The relationship between LSN and each geomorphic zone was investigated in two ways; first by overlaying the calculated LSN value at each CPT location and second by producing combinations of summary statistics of the LSN values grouped by geomorphic zone, earthquake shaking and depth to groundwater.

Maps showing the geospatial distribution of the calculated LSN value overlaid on the geomorphic zone for the Average Recurrence Intervals (ARI) and depth to groundwater combinations shown in Table 4.6 are included in Appendix C1.

Table 4.6: Mapped combinations of ARI Earthquake and GWD shown in Appendix C1

	ARI Earthquake		
GWD	**100 year**	**500 year**	**1,000 year**
1	Figure C1.1	Figure C1.2	Figure C1.6
2	N/A	Figure C1.3	N/A
3	N/A	Figure C1.4	N/A
4	N/A	Figure C1.5	N/A

The summary statistics generated were histograms and box and whisker plots of LSN. These were compiled onto a single page to enable comparison between each geomorphic zone for the ARI and GWD shown in Table 4.7. These summary statistics are included in Appendix C2 and an example of the 500 year ARI for 1 m GWD is provided in Figure 4.2.

Table 4.7: Summary statistic combinations of ARI and GWD shown in Appendix C2

	ARI Earthquake			
GWD (m)	**25 year**	**100 year**	**500 year**	**1,000 year**
0.1	Figure C2.1	Figure C2.2	Figure C2.3	Figure C2.4
1	Figure C2.5	Figure C2.6	Figure C2.7	Figure C2.8
2	N/A	N/A	Figure C2.9	Figure C2.10
3	N/A	N/A	Figure C2.11	Figure C2.12
4	N/A	N/A	Figure C2.13	Figure C2.14

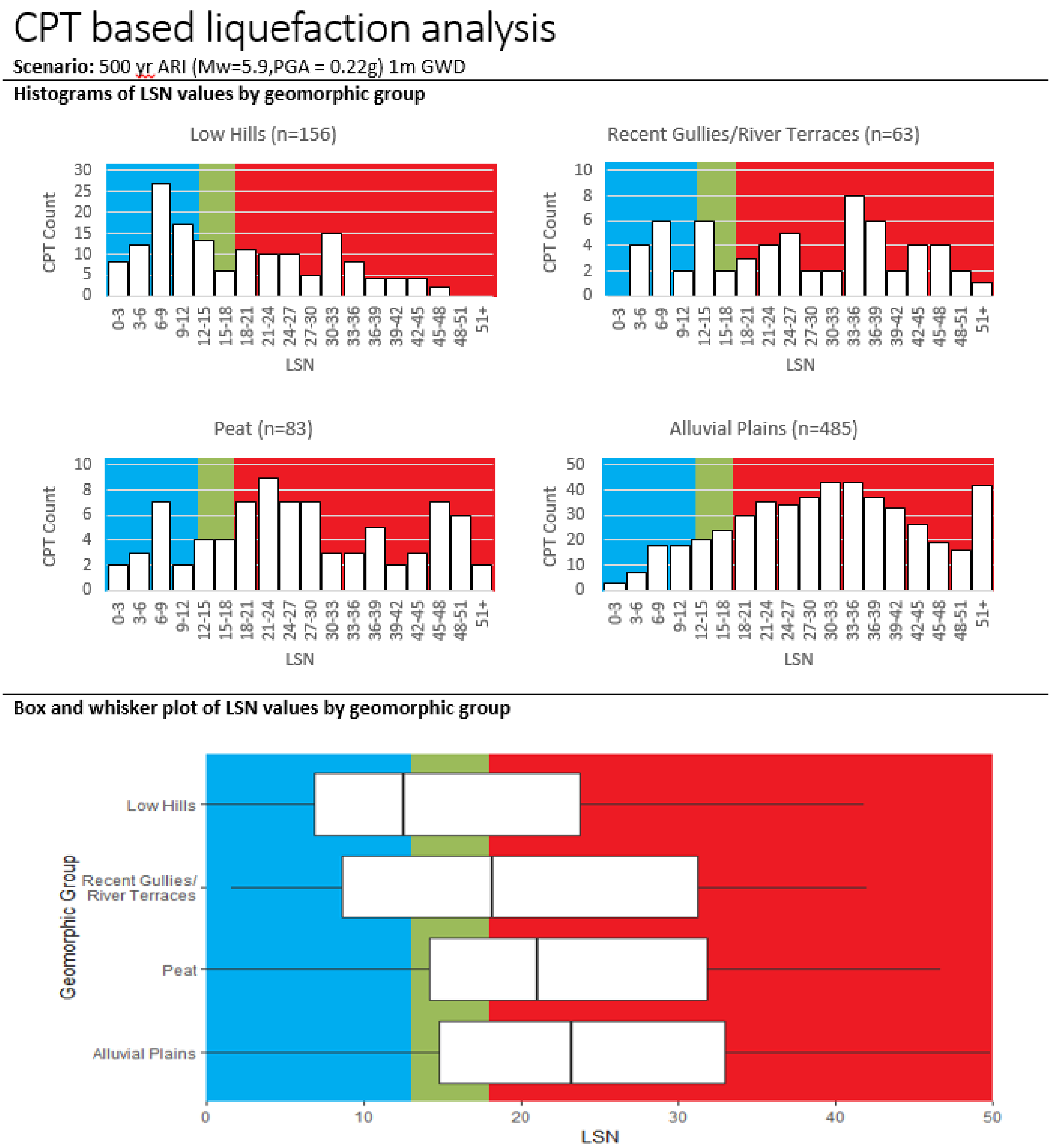

Figure 4.2: Example LSN summary statistics for the 500 year ARI and 1m GWD. The "box" represents the lower and upper quartiles with the vertical line showing the median. The horizontal "whiskers" are the maximum and minimum extents of the data excluding any points which are classed as outliers (shown as individual dots).

This same information was also recompiled onto a single page to enable comparison between various GWD for the 500 year ARI for each geomorphic zone as shown in Table 4.8. These summary statistics are included in Appendix C3 and an example of the Low Hills for 500 year ARI is provided in Figure 4.3 below.

Table 4.8: Summary statistics for 500 year ARI earthquake for each geomorphic zone shown in Appendix C3

Geomorphic Zone	Figure No.
Low Hills	Figure C3.1
Recent Gullies/River Terraces	Figure C3.2
Peat	Figure C3.3
Alluvial Plains	Figure C3.4

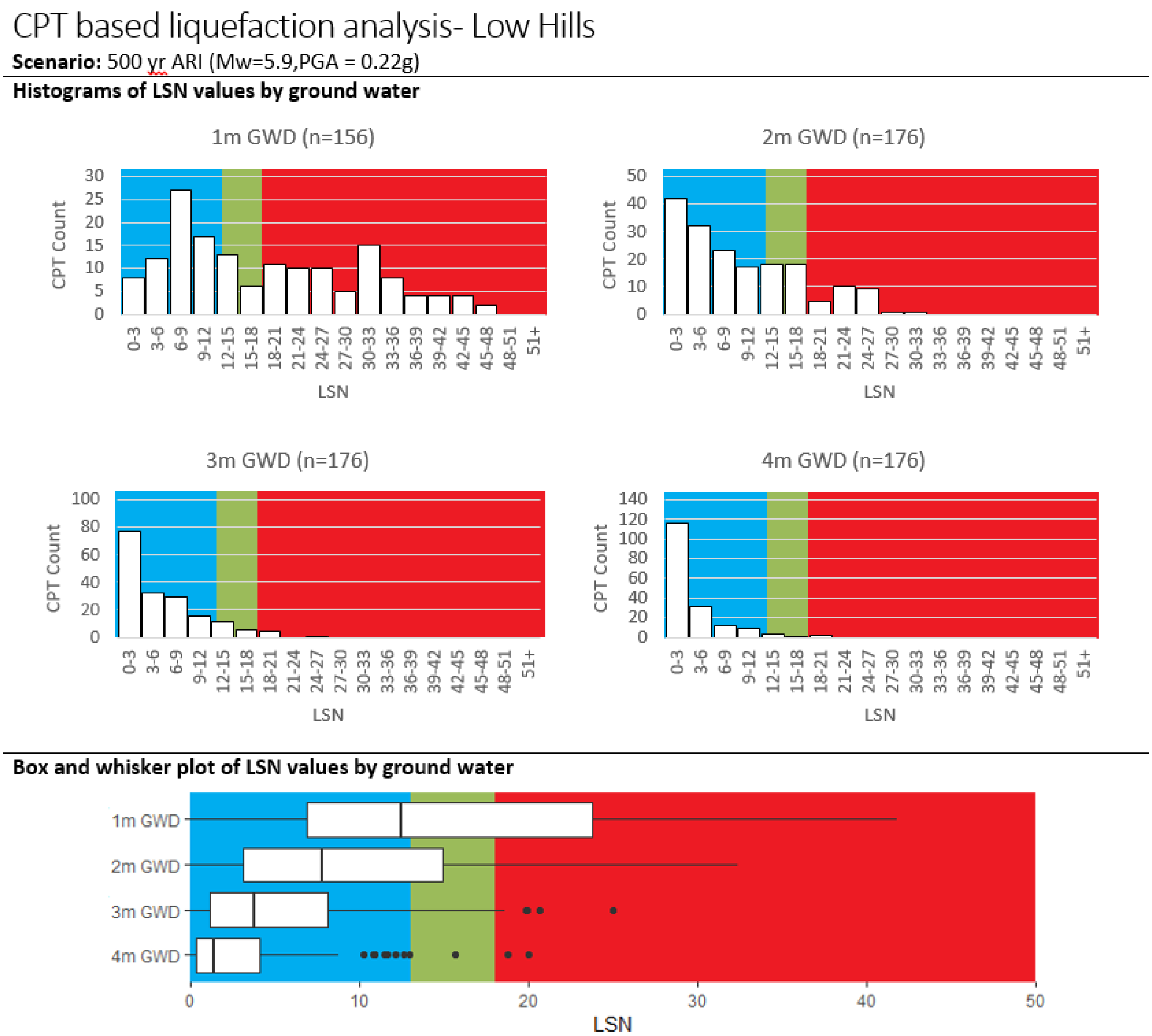

Figure 4.3: Example LSN summary statistics for the low hills geomorphic group and 500 year ARI. The "box" represents the lower and upper quartiles with the vertical line showing the median. The horizontal "whiskers" are the maximum and minimum extents of the data excluding any points which are classed as outliers (shown as individual dots).

In order to safely clear underground services, some locations where CPT were undertaken were predrilled with a hand auger. This means that the predrilled portion of the CPT trace is not representative of the true undisturbed ground conditions. The depth of the predrilled portion of the CPT varies depending on the specific requirements of each site however 1.5 m is typical.

While the portion of CPT that is predrilled is cannot be reliably interpreted, it is still useful to consider the available CPT data for depths below the predrill depth as this provides important information about the underlying soil conditions. For the maps shown in Appendix C1, if the predrilled portion of the CPT is affecting the calculation of LSN, this is shown as a grey dot. For the summary statistics, if the predrilled portion of the CPT was affecting the calculation of LSN the CPT was not included in the analysis.

4.5 Pumiceous soils and aging factors

Recent research has suggested that the use of CPT (and other large strain tests) in pumiceous soils may lead to an underestimate of the soil strength due to the particles having a low crushing resistance. This underestimate in turn may lead to an underestimate of the liquefaction resistance of that soil (Wesley, Meyer, & Pender, 1998). The proportion and particle size of the pumice present within the soils in the study area is highly variable and therefore the effect of low crushing resistance at the scale of this study cannot be quantified. Alternative geotechnical testing methods for assessing liquefaction resistance of pumiceous soils, such as shear wave velocity testing, are currently used by geotechnical practices for detailed assessment. However, their use is currently not widespread, the results require careful interpretation and application, and only a small number of these types of investigations are available in the HCC area.

Early work on liquefaction by Youd and Perkins (1978) suggested that liquefaction resistance increases markedly with geologic age, attributable mainly to cementation and secondary consolidation of the deposits. While the CPT values increase as a soil age increases, they increase at a slower rate than the cyclic resistance to liquefaction therefore it may be argued that an aging factor should be applied to the CPT data. There is no international consensus on what the correction factors should be, and as a result recommended practice is not to make aging corrections unless the corrections are based on shear wave velocity results since shear wave velocity testing can be demonstrated to be more responsive to aging (i.e. as the soil ages the shear wave velocity increases at the same rate as the cyclic resistance to liquefaction. Clayton & Johnson (2013) propose that the potential aging effects within Hinuera Formation and Walton Subgroup may be a more significant issue for Hamilton than the issue of low crushing resistance in pumice. They suggest the method of (Andrus, Hayati, & Mohanan, 2009) could be adopted to develop an age related liquefaction resistance factor (KDR).

The liquefaction analyses presented in this study have not been modified to make allowances for either pumiceous soils or aged soils. This is considered appropriate for the broad range of conditions assessed and the relatively high level nature of the assessment. However, the potential influence of these types of soils should be considered for site specific liquefaction assessments.

5 Liquefaction vulnerability assessment

One of the primary outputs of this study is a map categorising the land within the study extent into one of the liquefaction vulnerability categories listed in Table 4.1 of the Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017). This map is presented in Appendix D.

To accompany these maps, this section also presents:

- A summary of the methodology applied to assess the liquefaction hazard for the study extent.
- A discussion of the results of the assessment.

5.1 Methodology

This liquefaction vulnerability assessment has been undertaken general accordance with a Level B assessment as described in Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017). In that document a Level B assessment is described as a *Calibrated Desktop Assessment* which means a high-level assessment of geological/geomorphic maps calibrated by subsurface investigations. In this instance we have primarily used CPT data to calibrate the assessment with confirmation of the CPT results using inspection of some available borehole data.

The methodology described in the Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017) recommends categorisation of the liquefaction vulnerability of the land based on the performance criteria described in Figure 5.1 below.

<table>
<tr><td colspan="4">LIQUEFACTION CATEGORY IS UNDETERMINED
A liquefaction vulnerability category has not been assigned at this stage, either because a liquefaction assessment has not been undertaken for this area, or there is not enough information to determine the appropriate category with the required level of confidence.</td></tr>
<tr><td colspan="2">LIQUEFACTION DAMAGE IS UNLIKELY
There is a probability of more than 85 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.
At this stage there is not enough information to distinguish between Very Low and Low. More detailed assessment would be required to assign a more specific liquefaction category.</td><td colspan="2">LIQUEFACTION DAMAGE IS POSSIBLE
There is a probability of more than 15 percent that liquefaction-induced ground damage will be Minor to Moderate (or more) for 500-year shaking.
At this stage there is not enough information to distinguish between Medium and High. More detailed assessment would be required to assign a more specific liquefaction category.</td></tr>
<tr><td>Very Low Liquefaction Vulnerability
There is a probability of more than 99 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.</td><td>Low Liquefaction Vulnerability
There is a probability of more than 85 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking.</td><td>Medium Liquefaction Vulnerability
There is a probability of more than 50 percent that liquefaction-induced ground damage will be:
Minor to Moderate (or less) for 500-year shaking; and
None to Minor for 100-year shaking.</td><td>High Liquefaction Vulnerability
There is a probability of more than 50 percent that liquefaction-induced ground damage will be:
Moderate to Severe for 500-year shaking; and/or
Minor to Moderate (or more) for 100-year shaking.</td></tr>
</table>

Figure 5.1: Performance criteria for determining the liquefaction vulnerability category - reproduced from Table 4.4 of MBIE/MfE/EQC (2017)

The performance criteria listed in Figure 5.1 relate the liquefaction vulnerability category to the expected liquefaction-induced land damage at a given ARI level of earthquake shaking. The assessment requires the assessor to consider the probability that a particular level of liquefaction-induced land damage will occur for a given level of shaking. In undertaking this assessment it is important to understand the following note attached to the table in the guidance document:

"The probabilities listed in this table are intended to provide a general indication of the level of confidence required to assign a particular category, rather than to be a specific numerical criteria for calculation. Conceptually, these probabilities relate to the total effect of all uncertainties in the assessment…"

That is, the guidance recommends the assessor consider the combined effect of all the uncertainties associated with the available information in the determination of the land damage category.

The general methodology applied to determine the liquefaction vulnerability category for the study area is as follows:

1 Evaluate the uncertainties associated with the mapping of each geomorphic zone. This includes consideration of the resolution of mapping and the variability of soil conditions within each geomorphic zone interpreted from geotechnical investigations.

2 Evaluate the uncertainties associated with the groundwater level within each geomorphic zone. Due to the limited amount of information about groundwater within the study area this is primarily dependent on field experience and engineering judgement and is one of the most significant sources of uncertainty in this assessment.

3 Evaluate the uncertainties associated with the determination of the seismic hazard for the study extent. Whilst current scientific understanding suggests that the Hamilton area is expected to have a relatively low level of seismic hazard compared to other regions across New Zealand, there remains considerable uncertainty regarding the likelihood and intensity of earthquake shaking that could occur. This uncertainty is especially relevant where liquefaction-susceptible soils are present but estimated design shaking intensities (e.g. PGA for 100 year ARI design event) are unlikely to be strong enough to trigger liquefaction. This means that if earthquake shaking intensity is slightly greater than assumed for design (or if design PGA values increase in future due to improved understanding of the hazard), then a step-change worsening in performance could occur. For this reason, where liquefaction-susceptible soils are present it is generally not preferable to rely exclusively on low design PGA values to assign a liquefaction vulnerability category of *Liquefaction Damage Is Unlikely, Very Low* or *Low*.

4 Evaluate the uncertainties associated with the evaluation of liquefaction vulnerability from the CPT analysis. This includes consideration of the inherent uncertainties in the calculation of LSN from CPT, the possible range of liquefaction-induced land damage that could occur for a given LSN value. It also includes consideration of how well that particular unit is characterised by CPT and how well the likely performance of the land can be inferred from these CPT. This is a source of significant uncertainty in the assessment of liquefaction vulnerability because the analyses carried out represent probabilistic analyses of empirical liquefaction databases under various earthquakes. Earthquakes are unique and impose different levels of shaking in different directions on different sites.

5 Based on the consideration of all of these uncertainties, assign one of the liquefaction vulnerability categories defined in Figure 5.1 to the land within the project extent.

5.2 Results

Review of the overall trends shown in the liquefaction hazard maps and summary statistics presented in Appendix C reveals results that are consistent with current understanding of liquefaction science. In particular the following observations can be made:

- Given sufficient levels of earthquake shaking, there is the potential for liquefaction to occur across the majority of the study extent. This is attributable to the presence of soil layers that are susceptible to liquefaction within the majority of the CPT included in the assessment.
- For a constant level of earthquake shaking, a decrease in the depth to groundwater results in an increase in the expected liquefaction related land damage.
- For a constant depth to groundwater, an increase in the level of earthquake shaking results in an increase in the expected liquefaction related land damage.
- Simultaneously decreasing the depth to groundwater and increasing the level of shaking produces the worst expected liquefaction related land damage for the scenarios considered.

With more detailed review of the information presented in Appendix C the following are observed:

- Relatively low levels of liquefaction related land damage (none to minor) are anticipated at levels of earthquake shaking less than and equal to 25 year ARI across all groundwater conditions. This is because at a PGA of 0.05 g liquefaction is only triggered in soils most vulnerable to liquefaction. Similar observations can be made for levels of earthquake shaking less than and equal to the 100 year ARI however with high groundwater levels (i.e. 0.1 m) relatively high LSN values are calculated for some CPT and a greater degree of liquefaction-induced damage is predicted. While some of this may be the result of over prediction, which is inherent in the way in which LSN is calculated, the potential for damaging liquefaction should still be considered when very shallow groundwater levels are encountered.
- Although low levels of liquefaction induced damage is expected at events less than or equal to the 100 year ARI due to a low PGA, the uncertainties around the seismic hazard may mean that damage could occur at intermediate events if the intensity of ground shaking was slightly higher than currently estimated.
- It is possible that minor-to-moderate or moderate-to-severe liquefaction related land damage will occur within some portion of the project extent across the groundwater levels considered for 500 year ARI levels of earthquake shaking and greater. This is attributable to the soils within the project extent predominantly being susceptible to liquefaction and the potential for a relatively (i.e. less than 4 m) shallow depth to groundwater across the area.

Using the methodology outlined above T+T has developed the liquefaction vulnerability map presented in Figure D1.1 in Appendix D. Inspection of this map shows that the Low Hills has been categorised as *Liquefaction Category Is Undetermined* and that the Alluvial Plains, Peat, River Terraces/Gullies are categorised as *Liquefaction Damage Is Possible*. A summary of the results of the liquefaction hazard assessment for each geomorphic zone is provided in Table 5.1.

The following additional observations are made about the results of this assessment:

- With additional investigation and analysis it is possible that significant areas of the Low Hills geomorphology could be categorised as *Liquefaction Damage Is Unlikely*. This is due to the relatively large proportion of soils that exhibit clay like behaviour (i.e. not susceptible to liquefaction) and that it is more likely that relatively deep (i.e. deeper than 4 m) groundwater would be encountered in this area.
- The current categorisation of *Liquefaction Damage Is Possible* for the other geomorphic zones does not preclude the later categorisation of these areas into *the Liquefaction Damage Is Unlikely* category (or *Low* or *Very Low* categories) if appropriate based on additional local investigation and analysis.

Table 5.1: Summary of the results of the liquefaction hazard assessment for each geomorphic zone

Geomorphic zone	Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required to refine the liquefaction assessment
Low hills	The low hills generally represent areas of the Walton Subgroup. The liquefaction assessment of this zone indicates that this zone typically has lower liquefaction vulnerability than the other zones in the study area, with the LSN values for almost all CPTs plotting in the "*None to Minor*" land damage category for the scenario with groundwater at 4m depth. However, because specific groundwater depths across the area are unknown, the range of LSN values calculated for shallower groundwater depths means that it is not possible to assign a category of "*Liquefaction Is Unlikely*". A large proportion of the units within the Walton Subgroup exhibit clay-like behaviour, so site-specific confirmation of the presence of clay-like soil may lead to assigning a category of "*Liquefaction Is Unlikely*". The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present and whether or not they are susceptible to liquefaction should be the first component of the assessment of liquefaction vulnerability in this area. Groundwater likely to be deeper within this zone.	*Liquefaction Category Is Undetermined*	• Presence and thickness of soils exhibiting clay-like behaviour • Groundwater levels • Thickness and distribution of liquefiable layers • Proportion of pumiceous particles	• Confirm geological unit, i.e. Walton Subgroup • Confirm clay-like soils present. • Confirm whether groundwater is present within top 4m • Determine soil type to sufficient depth depending on the geological formation (top 4m if Walton Subgroup or Hinuera Formation are confirmed, deeper for more vulnerable units) • Assess soil relative density if non-plastic
River Terraces/Gullies	This geomorphic zone shows a range of LSN and may also show two populations that could correspond to some of the gullies or river terraces being composed of denser material that has a greater resistance to liquefaction. Development within this zone may also be within the previously mapped gully hazard zone and as such will require engineering assessment due to the presence of unstable slopes. The gully bottoms are likely to contain looser, younger material and may often have high groundwater, meaning that higher LSN values would be common in this zone. The presence of uncontrolled fill in these areas will also exacerbate the risk. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. Deposits in gully bases are normally at or close to the median water table. River terraces are generally coincident with river level. Presence of perched water normally results in the development of gullies and instability.	*Liquefaction Damage Is Possible*	• Groundwater levels at slope margins • Geological unit • Perched water • Thickness and distribution of liquefiable layers • Proportion of pumiceous particles	• Confirm whether groundwater is present within top 4m • Determine geological unit • Determine soil type • Confirm whether uncontrolled fill is present • Assess soil relative density

Geomorphic zone	Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required to refine the liquefaction assessment
Peat	The peat areas of Hamilton are shown to have a wide range of LSN for the groundwater depths analysed. It is likely that groundwater in these areas will be high but other factors may determine the liquefaction vulnerability here. Peat itself has been shown to have a degree of liquefaction resistance, however this does depend on the fibrous nature of the peat. The underlying geology is an important factor and this should be determined. It is likely that any development within the peat areas will have further constraints such as static settlement from consolidation. This factor means careful engineering assessment is required when considering liquefaction vulnerability and other geotechnical constraints. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. This zone is typically characterised by shallow groundwater leading to swamp-like conditions. Often drained by swales, where water level is coincident with the depth of the swale.	*Liquefaction Damage Is Possible*	• Groundwater levels • Amount of organic material • Thickness of Peat • Underlying geology • Depth of foundations required to manage other geotechnical constraints	• Confirm geological unit • Confirm whether groundwater is present within top 4 m • Determine peat thickness • Determine underlying geological unit • Consider proximity to slopes including swales • Other engineering factors will influence the liquefaction in peat
Alluvial plains	The alluvial plains are highly variable in geology both laterally and vertically. This is reflected in the wide range of LSN, especially at shallow groundwater depths. Land damage of *"None to Minor"* through to *"Moderate to Severe"* are all possible within the alluvial plains, therefore it is important to have a good understanding of the underlying geology. The site may be underlain by a great thickness of liquefiable soils or may only have thin, intermittent layers of liquefiable soils interbedded with medium dense to dense gravels. It has been suggested that the interfluve areas within the Hinuera Formation have increased liquefaction potential compared to channels or low ridges (McKay, Lowe, & Moon, 2017). Determining soil class by considering the landform present may be an indication of the liquefaction potential of the site. A site with a high water table and the presence of non-plastic soils may require CPT investigations to determine the land damage category applicable. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. Groundwater is typically relatively shallow when not controlled by localised drainage associated with river terraces, gullies and deep swales. Phreatic surfaces can be steep at slope margins depending on the underlying conditions.	*Liquefaction Damage Is Possible*	• Groundwater levels • Thickness and distribution of liquefiable layers • Proportion of pumiceous particles • Soil family (pedological soil class) • Geomorphology	• Confirm geological unit • Confirm whether groundwater is present within top 4 m • Determine soil type to sufficient depth depending on the geological formation (top 4m if Hinuera Formation is confirmed, deeper for more vulnerable units) • Consider proximity to slopes including swales • Determine pedological soil class • Determine what landforms are present • Assess soil relative density

6 Lateral spreading vulnerability

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

When considering the potential for lateral spreading adjacent to a free-face, the Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017) notes that *"It is less likely (but not impossible) for lateral spreading to occur if there is no liquefied soil within a depth of 2H of the ground surface (where H is the height of the free-face)."* Zhang, Robertson, & Brachman (2004) define H as the difference in height from the toe of the embankment (frequently the invert of a river or other water surface body) to the top of the embankment for which lateral spreading is being assessed (see Figure 6.1).

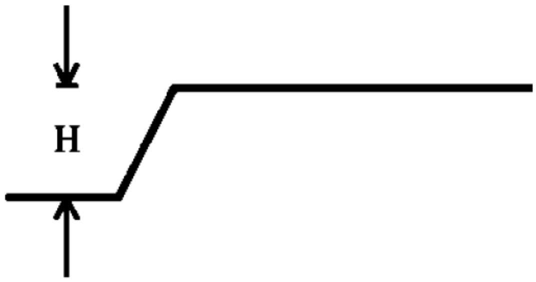

Figure 6.1: Free face height (H) as defined by Zhang et al. (2004)

However, with the information available for this study it is difficult to accurately define the free face height (H). This is primarily because it is difficult to confirm whether or not Digital Elevation Models (DEM) derived from LiDAR data are accurately estimating the elevation of the invert due to it frequently being obscured by water or vegetation.

The Planning and engineering guidance for potentially liquefaction-prone land (MBIE/MfE/EQC, 2017) recommends that particular attention should be given to land that is susceptible to liquefaction within 100 m of a free face less than 2 m high; or within 200 m of a free face greater than 2 m high.

Also, particular attention should be given to the potential for lateral spreading to occur on land within the River Terraces/Gullies geomorphic zone. This is because of a combination of the land being categorised as *Liquefaction Damage Is Possible*, the potential for relatively shallow groundwater and there being a significant number of free faces associated with rivers and streams in this zone. It is noted that generally this zone will fall within the HCC gully hazard area which already has provisions for hazard assessment within the Operative District Plan.

7 Potential options to manage liquefaction-related risk

There are various potential options available to manage liquefaction-related risk, as summarised in Section 6 of MBIE (2017).

One potential solution is to avoid exposure to the hazard by not constructing within liquefaction-prone land. However as noted in Section 5.2, whilst it can be demonstrated that for the 25 year ARI (i.e. SLS) widespread liquefaction-induced ground damage is not expected, in the 500 year ARI (i.e. ULS) case it is recognised that soil conditions are such that liquefaction damage is possible in large parts of the project extent and so avoiding the hazard may not be a feasible option.

Another potential solution is to reduce or mitigate liquefaction-related risk by reducing the likelihood of liquefaction occurring and/or reducing the consequences if liquefaction occurs. Potential foundation design and ground improvement options to mitigate the damaging effects of liquefaction are discussed in the series of guidance documents produced by MBIE for repairing and rebuilding houses affected by the Canterbury earthquakes (MBIE, 2012). Generally, the type of damage experienced may result in differential settlements, global settlements and ingress of liquefaction ejecta that could damage infrastructure and buildings. The risk of damage such as this is normally treated in one or a combination of the following ways:

- Undertake **ground improvement** so that a higher level of earthquake shaking is required to trigger liquefaction. In some cases it may be possible to change the fundamental behaviour of the ground (e.g. by physically removing or cementing susceptible soil) so that liquefaction will not occur even under the highest levels of earthquake shaking expected.
- Specify **robust foundation systems** that are able to tolerate liquefaction related land damage, such as thick reinforced foundations or stiff platforms. The importance level of the structure and the specific ground conditions at the site would inform the performance standard required for these foundation systems.
- Specify **readily repairable foundation systems** that are able to be reinstated relatively easily following liquefaction induced land damage.
- Specify the use of **lightweight building materials** for construction of buildings. Adopting lightweight cladding and roofing materials reduces the required bearing strength of the underlying soils and the severity of structural shaking imposed on the foundations. As such, lightweight building materials reduce the potential for liquefaction-induced foundation and building damage to occur.

There are various potential opportunities for HCC to take an active role in managing liquefaction-related risk, while also facilitating development by simplifying site-specific ground investigation and foundation design requirements where appropriate. We would be happy to work with HCC to explore how these could be implemented. Possible examples include:

- Defining succinct geotechnical information requirements for resource and building consent applications, which focus on resolving the key uncertainties in the liquefaction assessment relevant for each geomorphic zone.
- Identifying standard foundation solutions which can be applied “off the shelf” once the liquefaction vulnerability category has been confirmed with sufficient certainty.
- Undertaking a widely-spaced grid of ground investigations and/or groundwater monitoring across parts of the region where there is substantial new greenfield development or intensification of existing urban areas. This would provide greater certainty in the assessment of liquefaction vulnerability, and could allow some types of development to proceed relying only on the existing information without the need for site-specific investigations (where appropriate, and subject to a requirement for robust foundations).

8 Conclusions

T+T has undertaken a calibrated desktop assessment of liquefaction vulnerability for Hamilton City in general accordance with a Level B assessment as described in the Planning and Engineering Guidance for Potentially Liquefaction-Prone Land (MBIE/MfE/EQC, 2017). The results of this assessment are considered suitable to aid HCC in the assessment and management of liquefaction-related risk and provide guidance on further investigation and potential risk treatment options.

The key conclusions of this study are:

- Given sufficient levels of earthquake shaking, there is the potential for liquefaction-induced ground damage to occur across most of the study extent. This is attributable to a combination the majority of the soil being susceptible to liquefaction and the potential for relatively shallow groundwater (i.e. less than 4 m) that is encountered across the study extent.
- Relatively low levels of liquefaction-induced land damage are anticipated at levels of earthquake shaking less than and equal to the 25 year ARI across all groundwater levels considered. This is because at the design PGA value of 0.05 g liquefaction is only triggered in soils most vulnerable to liquefaction.
- It is likely that *Moderate to Severe* liquefaction related land damage will occur within some portion of the project extent across each of the groundwater scenarios considered for 500 year ARI levels of earthquake shaking and greater. This is attributable to the soils within the project extent predominantly being susceptible to liquefaction and the potential for a relatively (i.e. less than 4 m) shallow depth to groundwater.
- Between the 25 year and 500 year ARI scenarios summarised above, a transition is expected in the severity of damage. The current study has not analysed this in any detail, however understanding this transition will be important for refining the liquefaction vulnerability assessment in future (e.g. for site-specific assessments).
- The Low Hills geomorphic zone has been assessed as typically less vulnerable to liquefaction-induced land damage as the other zones. Table 5.1 of this report identifies some key characteristics of this geomorphic zone, which if confirmed for a specific development site may mean that the site can be assessed as *"Liquefaction Damage Is Unlikely"*.
- The Alluvial Plains, Peat and River Terraces/Gullies geomorphic zones are highly variable. There is potential for significant liquefaction-induced ground damage in these geomorphic zones, especially if groundwater is present within the upper 4 m of the soil profile. It is recommended that more detailed investigation and liquefaction assessment be undertaken for development within these geomorphic zones, in line with the MBIE/MfE/EQC (2017) guidelines.
- Particular attention should be given to assess the potential for lateral spreading on land that is susceptible to liquefaction within 100 m of a free face less than 2 m high; or within 200 m of a free face greater than 2 m high.
- Understanding the groundwater is key to developing the liquefaction risk assessment for Hamilton City. It is understood that Waikato Regional Council (WRC) are proposing to undertake a groundwater monitoring programme within the city. Liaison with WRC on this matter will ensure the data is collected to suit the purposes of a liquefaction assessment. HCC may also wish to consider requesting applicants upload groundwater data to the New Zealand Geotechnical Database.
- There are various potential opportunities for HCC to take an active role in managing liquefaction-related risk, while also facilitating development by simplifying site-specific ground investigation and foundation design requirements where appropriate. We would be happy to work with HCC to explore how these could be implemented.

9 References

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10 Applicability

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

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

The analyses carried out represent probabilistic analyses of empirical liquefaction databases under various earthquakes. Earthquakes are unique and impose different levels of shaking in different directions on different sites. The results of the liquefaction susceptibility analyses and the estimates of consequences presented within this document are based on regional seismic demand and published analysis methods, but it is important to understand that the actual performance may vary from that calculated.

Tonkin & Taylor Ltd

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Engineering Geologist	Senior Geotechnical Engineer

Authorised for Tonkin & Taylor Ltd by:

....

Glen Nicholson

Project Director

JJBR
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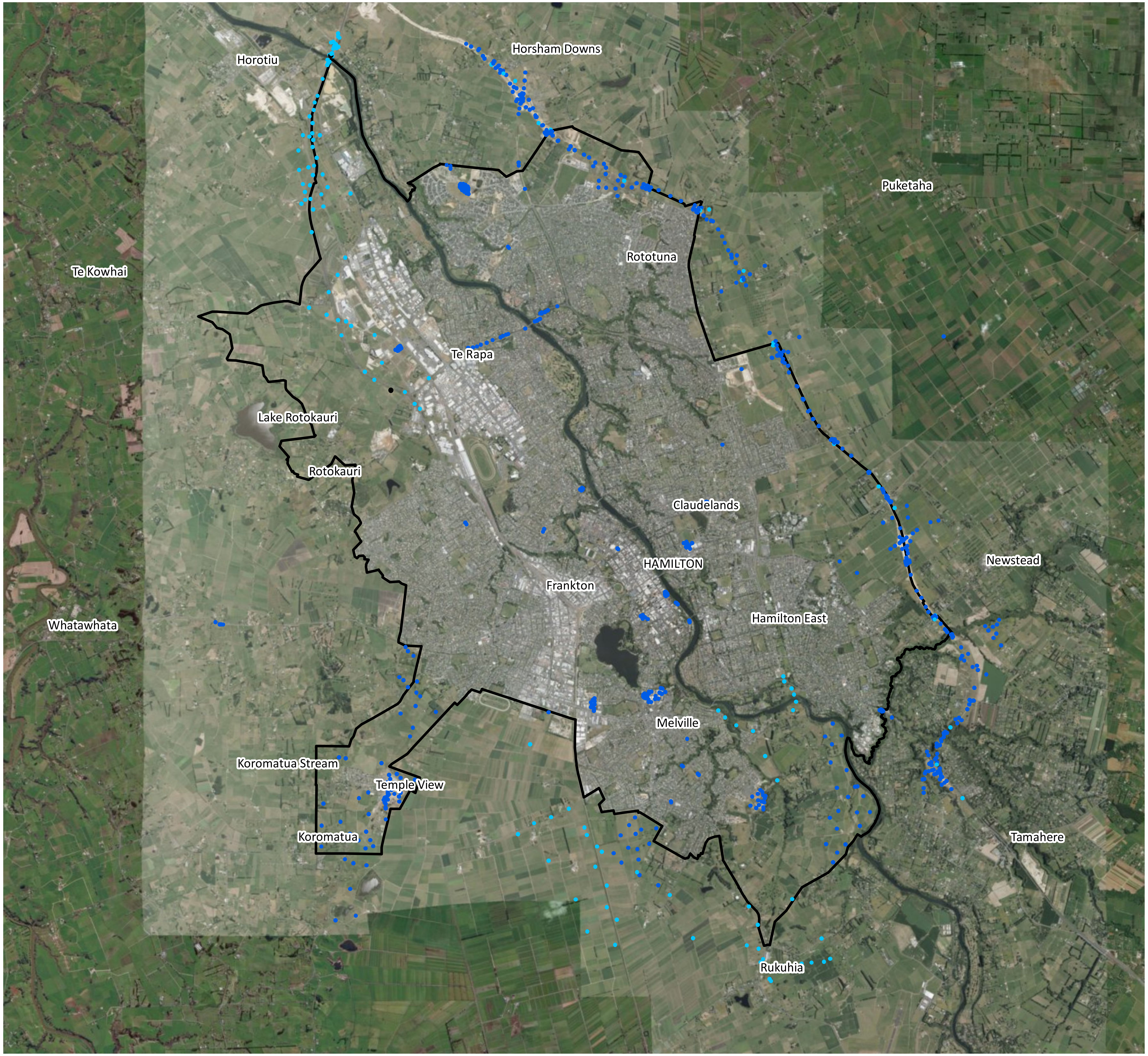
Appendix A: General information

- **Appendix A1 – General maps**



LEGEND

Cone Penetration Test Locations

- Electronic Data
- Digitised Data
- No Data Available

Hamilton City Council Boundary

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

N

Notes:

1.Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.

2. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license

DRAWN	MOLI	Aug.18
CHECKED	JJBR	Sept.18
APPROVED	MEJ	Oct.18

ARCFILE
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SCALE (AT A3 SIZE)
1:70,000

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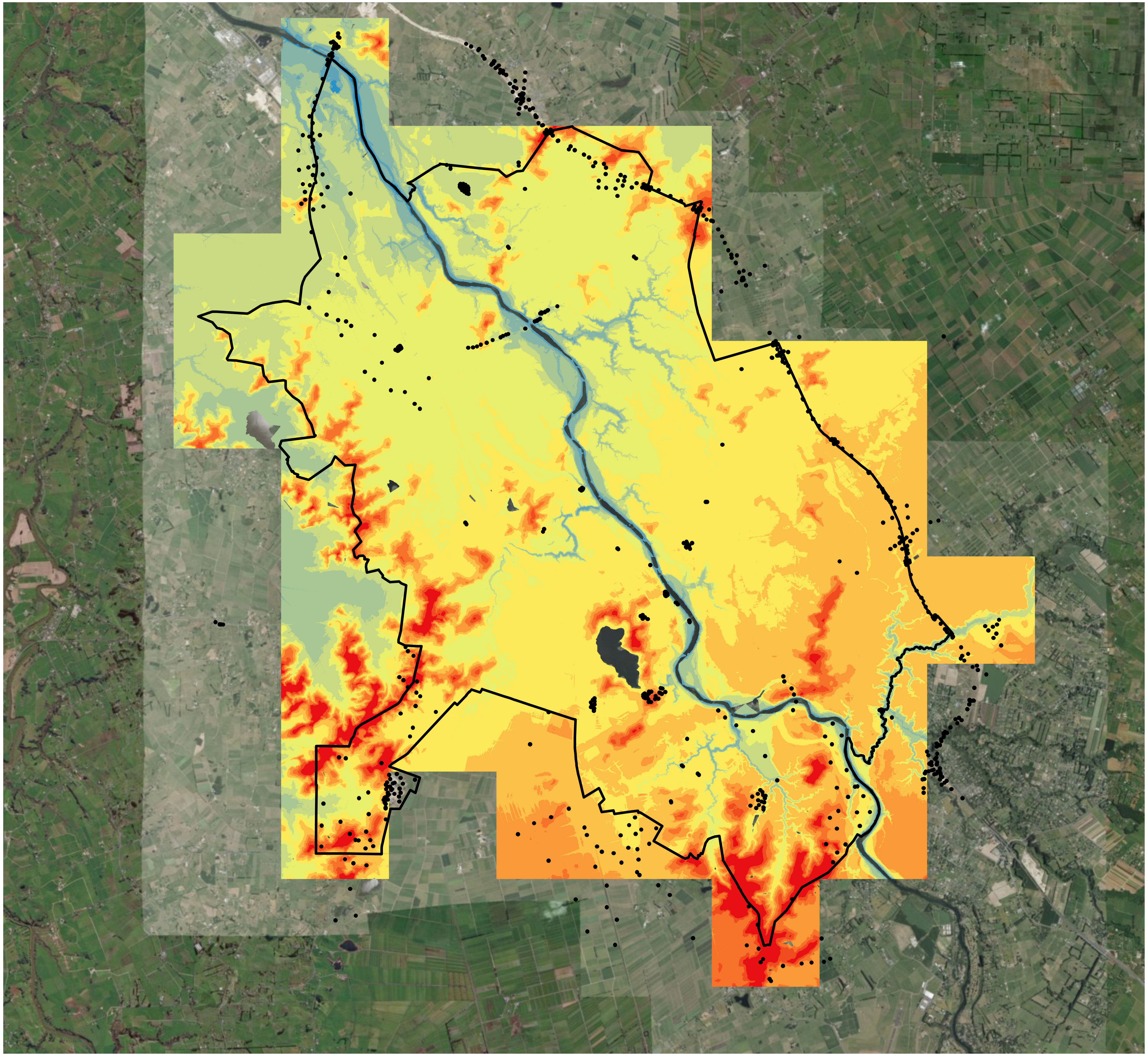
HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
CPT Investigation Locations overlaid on Aerial Imagery

Figure A1.1



LEGEND

- Cone Penetration Test Locations
- Hamilton City Council Boundary

Ground Elevation (m RL)

- 6 - 10
- 10- 15
- 15- 20
- 20- 25
- 25- 30
- 30- 35
- 35- 40
- 40- 45
- 45-50
- 50-55
- 55-60
- > 60

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:

1.Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
2. Ground elevation (2007/2008) sourced from the LINZ Data Service, CC 3.0 New Zealand license
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license

DRAWN	MOLI	Aug.18
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APPROVED	MEJ	Oct.18

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SCALE (AT A3 SIZE) 1:70,000

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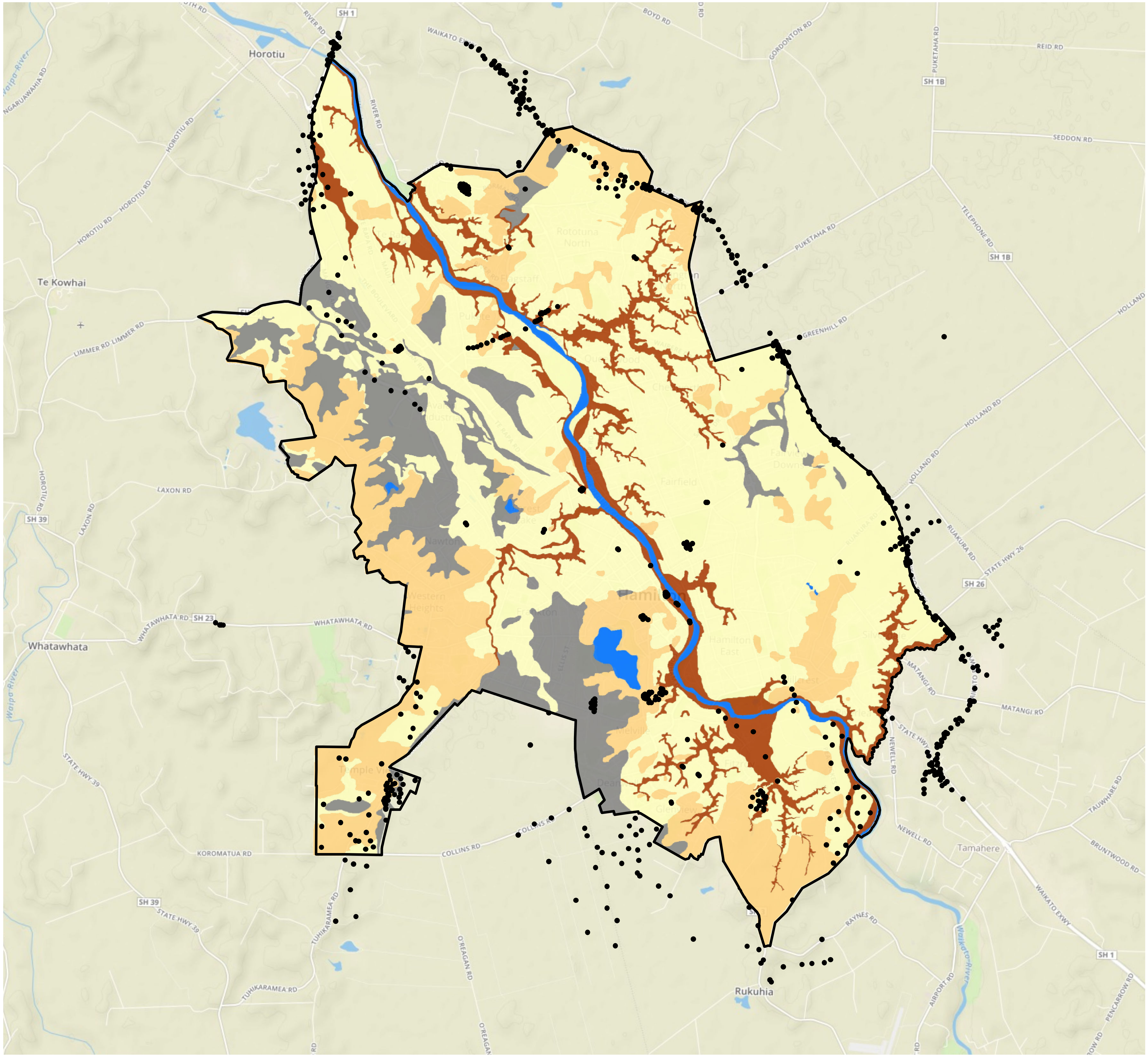
HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
CPT Investigation Locations overlaid on 2007/2008 LiDAR DEM

Figure A1.2



LEGEND

- Cone Penetration Test Locations
- Hamilton City Council Boundary

Soil Type

- Holocene Sediments
- Peat
- Walton Subgroup
- Hinuera Formation

Other

- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:

1. Soil Map based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license

DRAWN	MOLI	Aug.18
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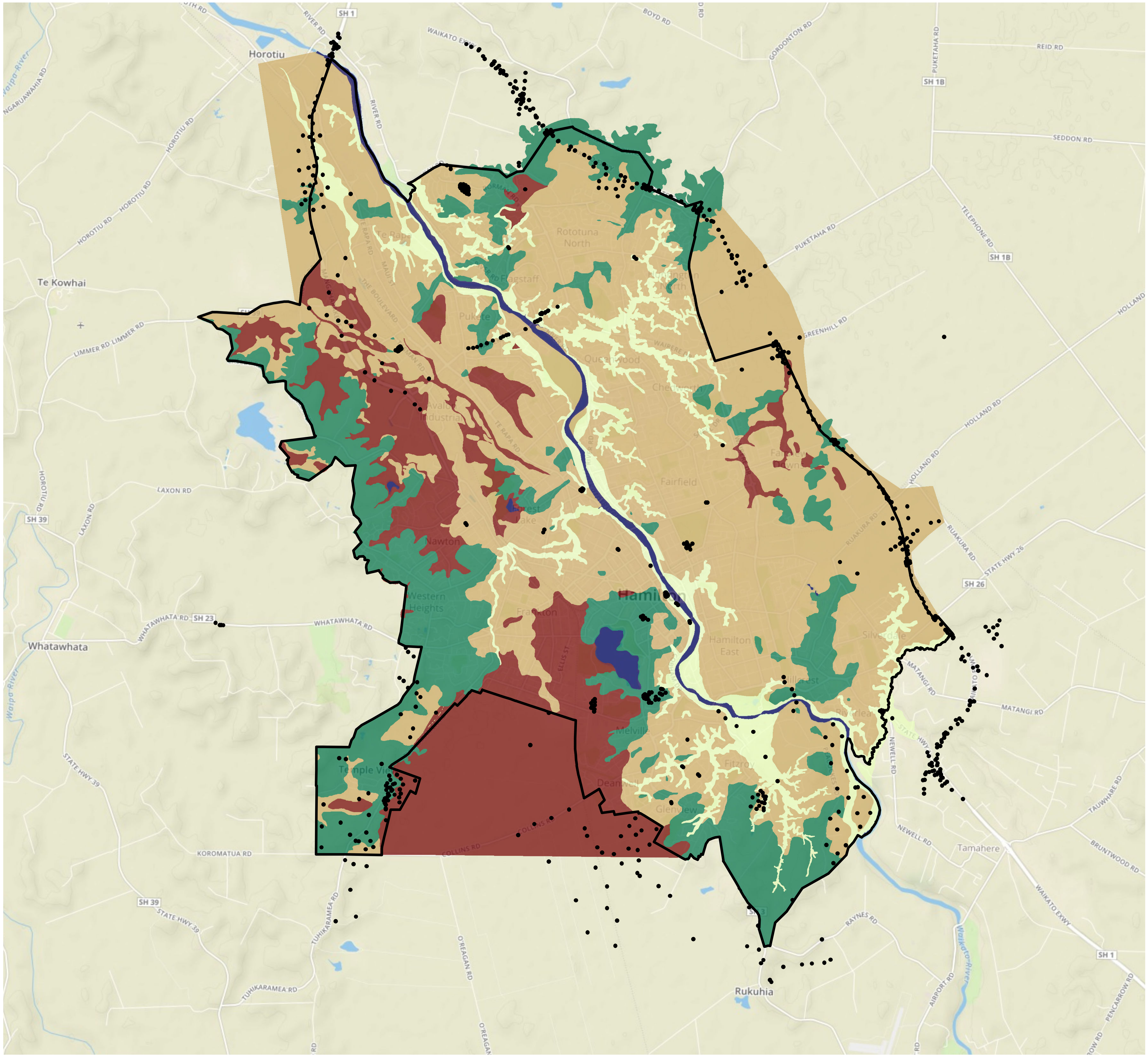
HAMILTON LIQUEFACTION ASSESSMENT

CPT Investigation Locations overlaid on Soil Map (Moon, 2012)

Figure A1.3

Appendix B: Geomorphology

- **Appendix B1 – Geomorphology map**
- **Appendix B2 – q_C and I_C vs. depth plots**



LEGEND

- • Cone Penetration Test Locations
- Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:
1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18

ARCFILE 1007144_FIG004.mxd

SCALE (AT A3 SIZE) 1:70,000

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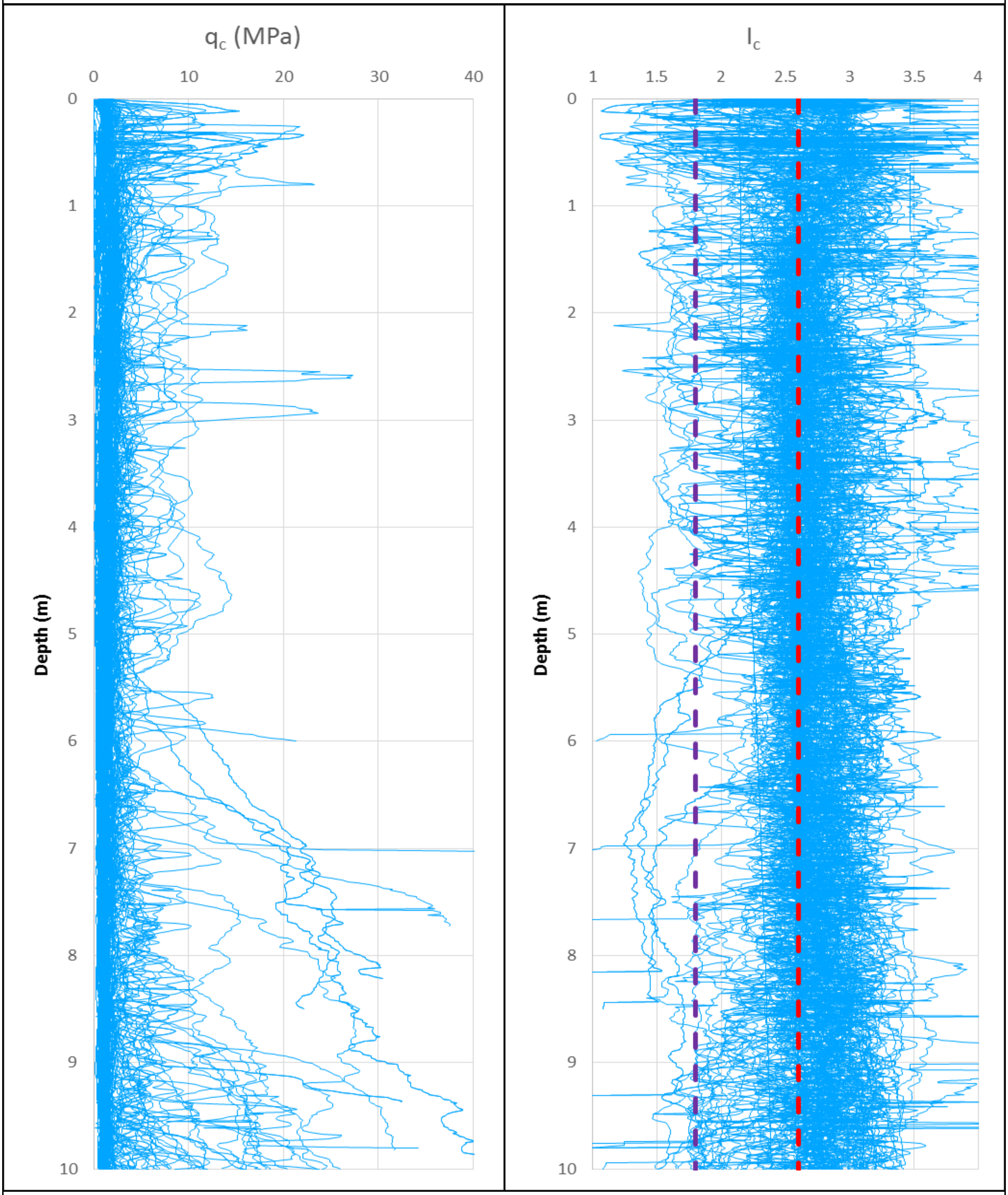
HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
CPT Investigation Locations overlaid on Geomorphic Zones

Figure B1.1

Figure B2.1

Geomorphic Zone: Low Hills

Number of CPT: 178



Legend

CPT Trace

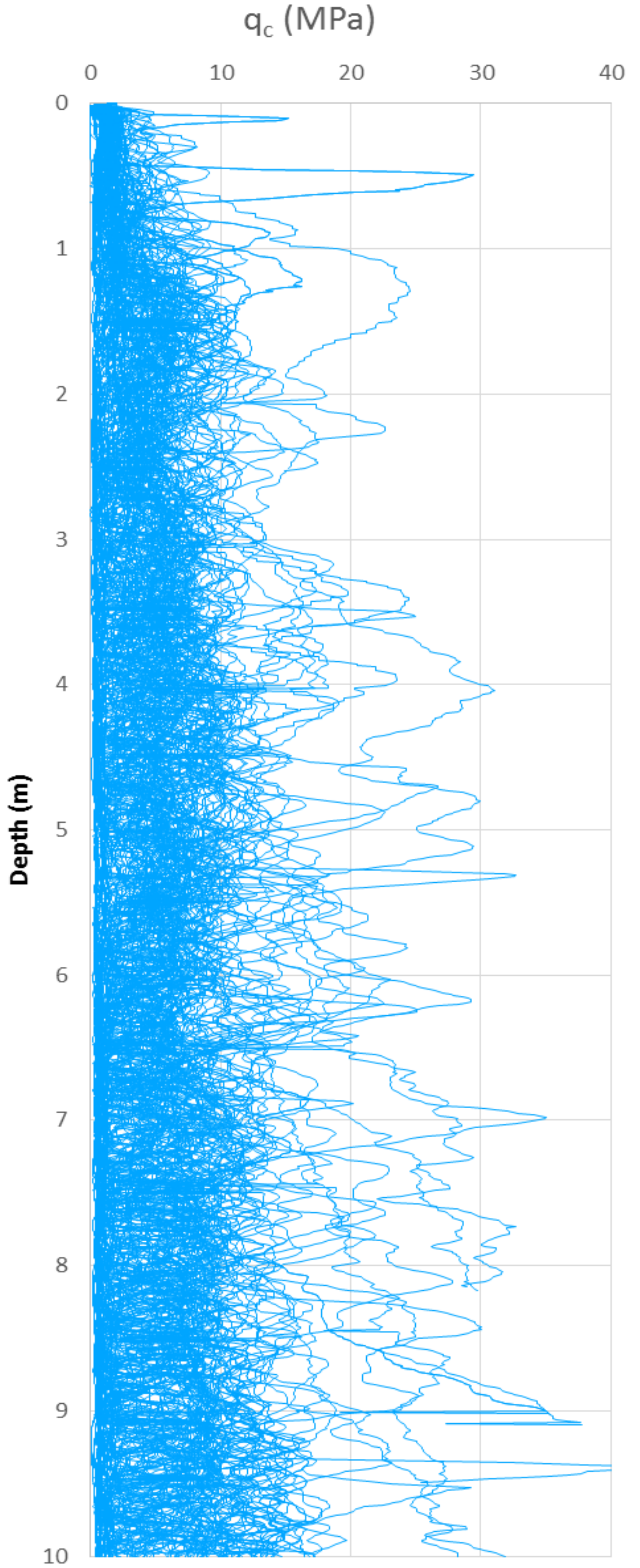
Ic = 1.8 (clean sand to silty sand behaviour transition)

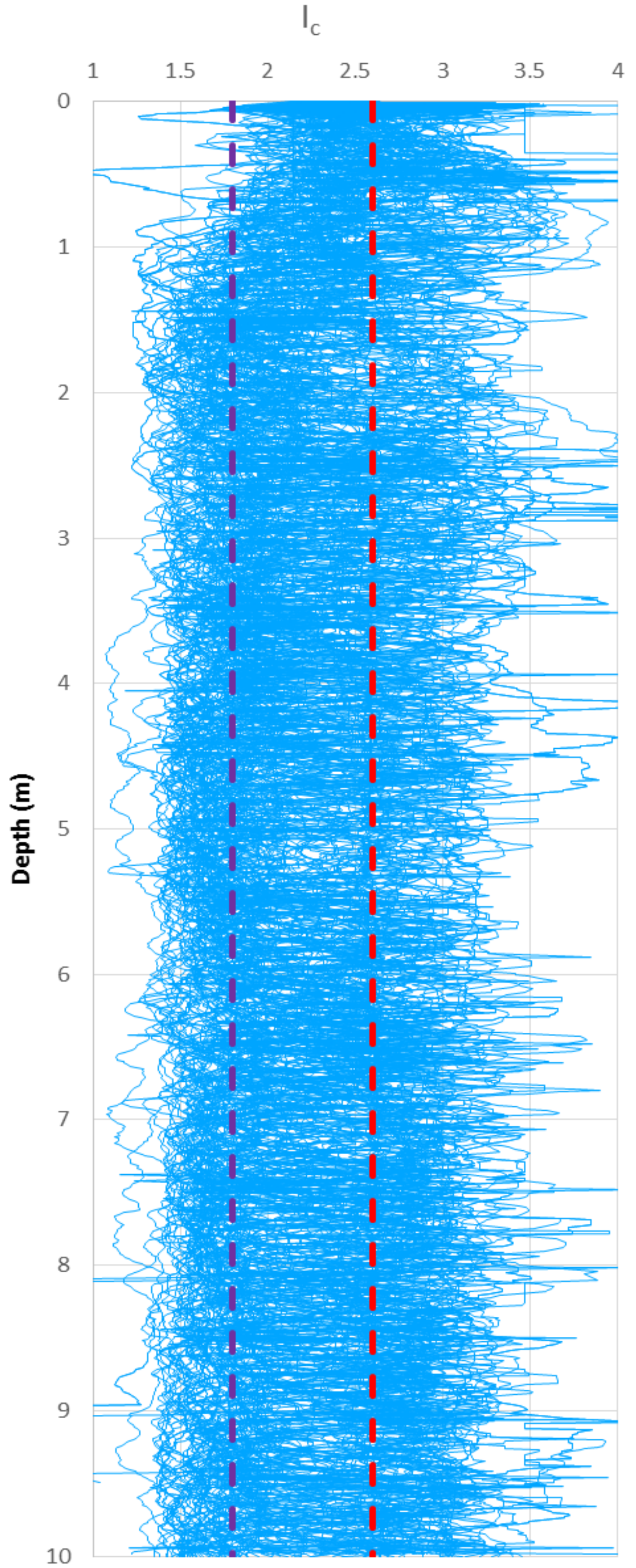
I_c = 2.6 (sandy silt to silty clay behaviour transition)

Figure B2.2

Geomorphic Zone: Alluvial Plains (North East of Waikato River)

Number of CPT: 181





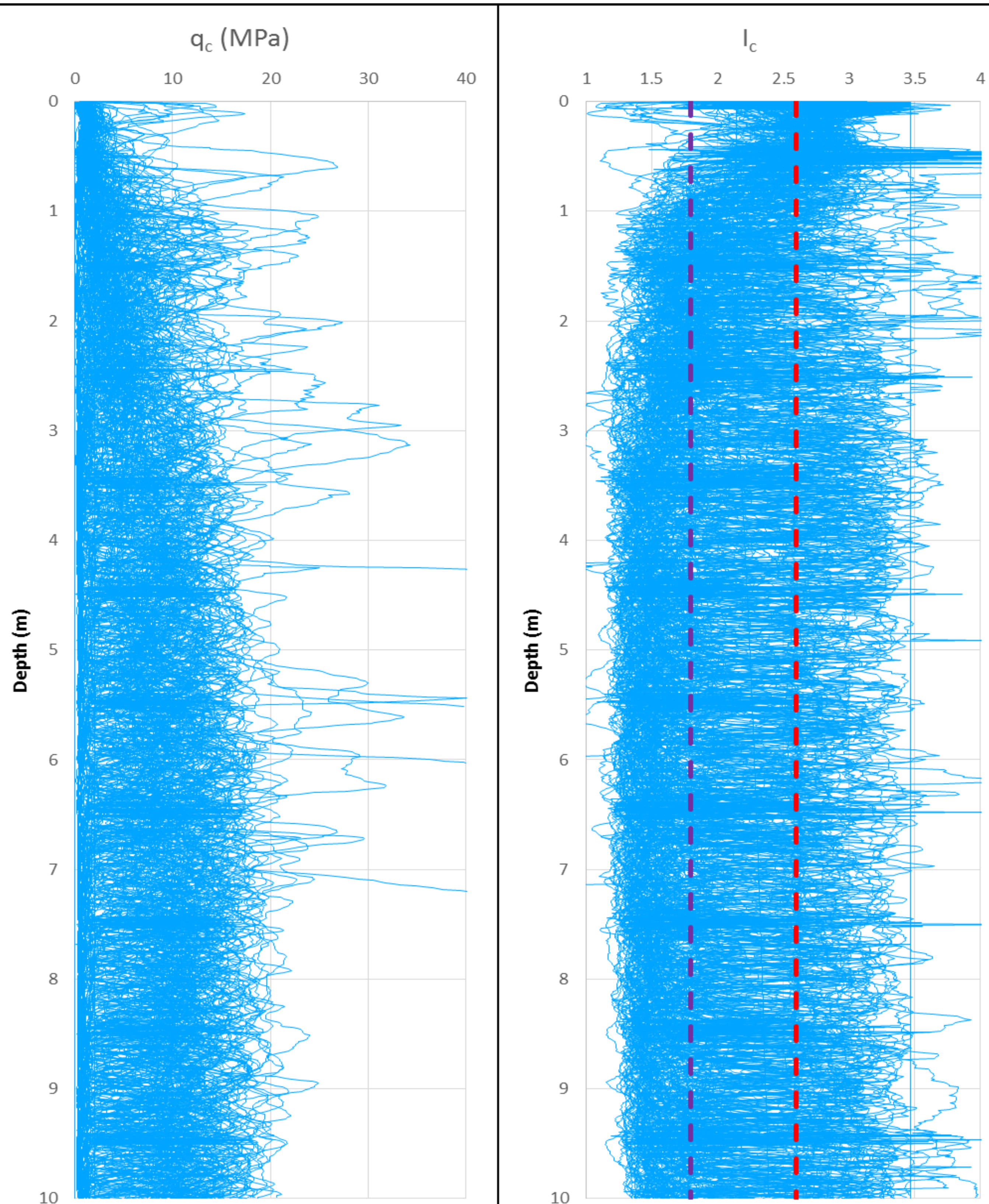
Legend

- CPT Trace
- Ic = 1.8 (clean sand to silty sand behaviour transition)
- I_c = 2.6 (sandy silt to silty clay behaviour transition)

Figure B2.3

Geomorphic Zone: Alluvial Plains (South East of Waikato River)

Number of CPT: 202



Legend

CPT Trace

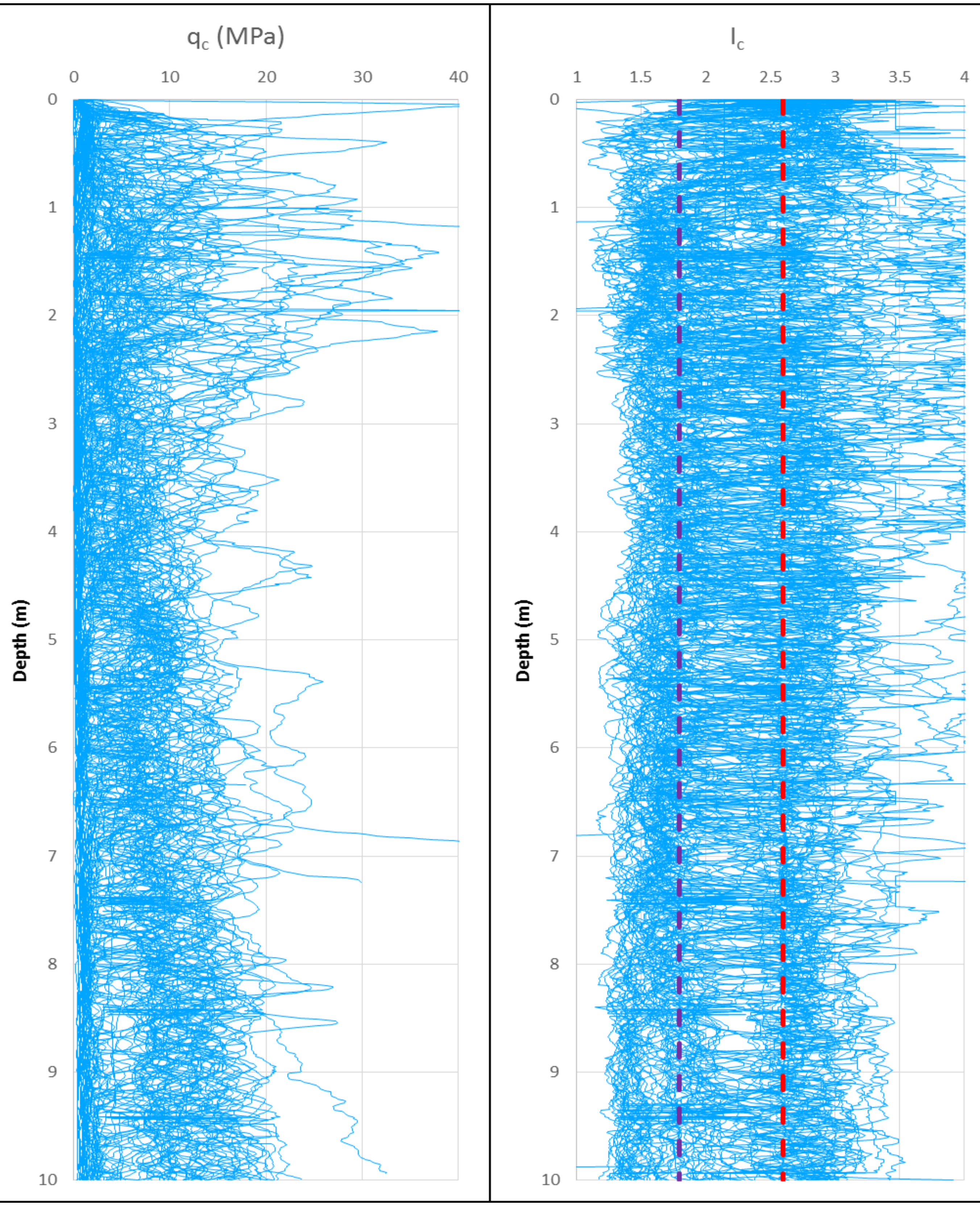
Ic = 1.8 (clean sand to silty sand behaviour transition)

I_c = 2.6 (sandy silt to silty clay behaviour transition)

Figure B2.4

Geomorphic Zone: Alluvial Plains (West of Waikato River)

Number of CPT: 140



Legend

CPT Trace

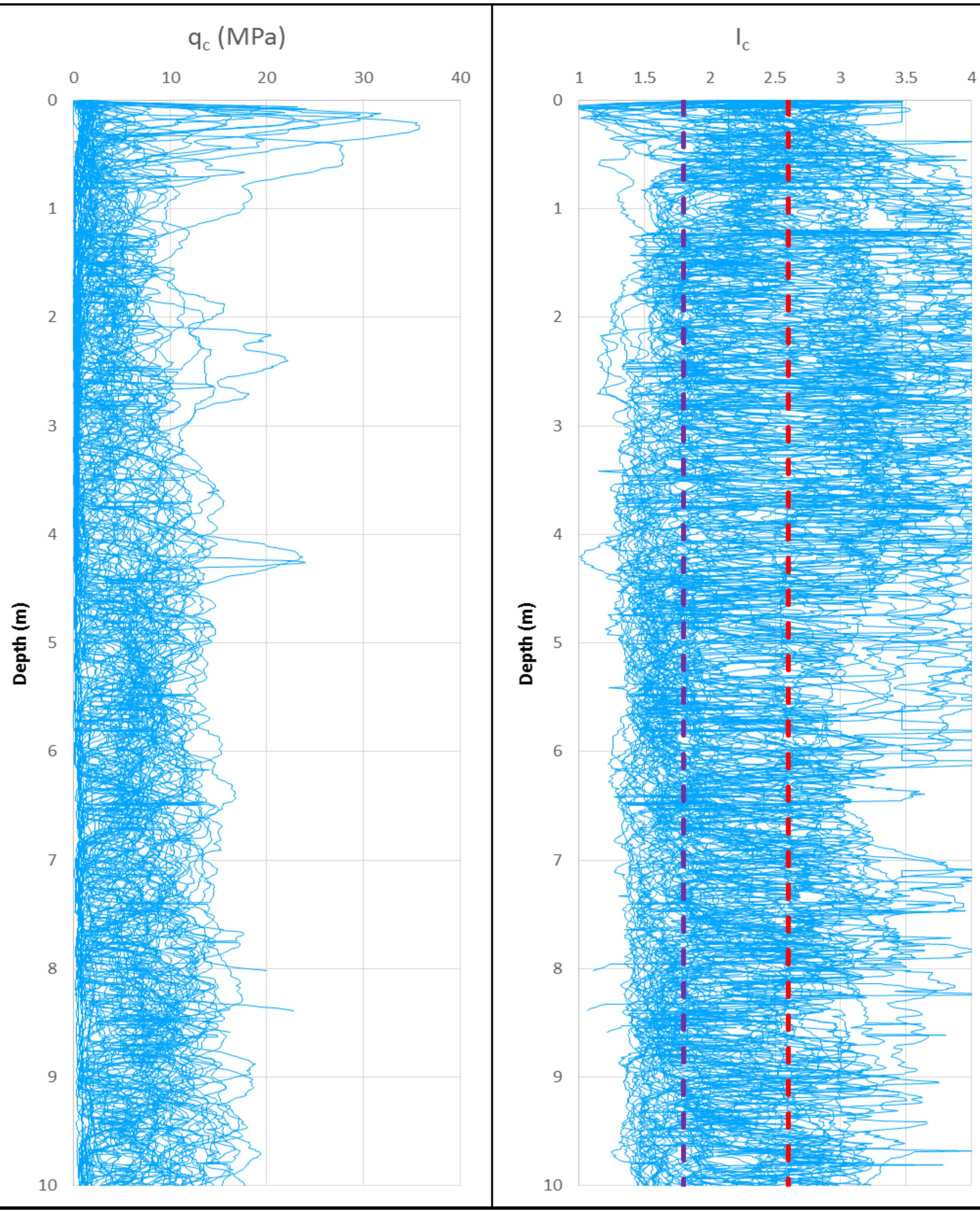
Ic = 1.8 (clean sand to silty sand behaviour transition)

I_c = 2.6 (sandy silt to silty clay behaviour transition)

Figure B2.5

Geomorphic Zone: Peat

Number of CPT: 96



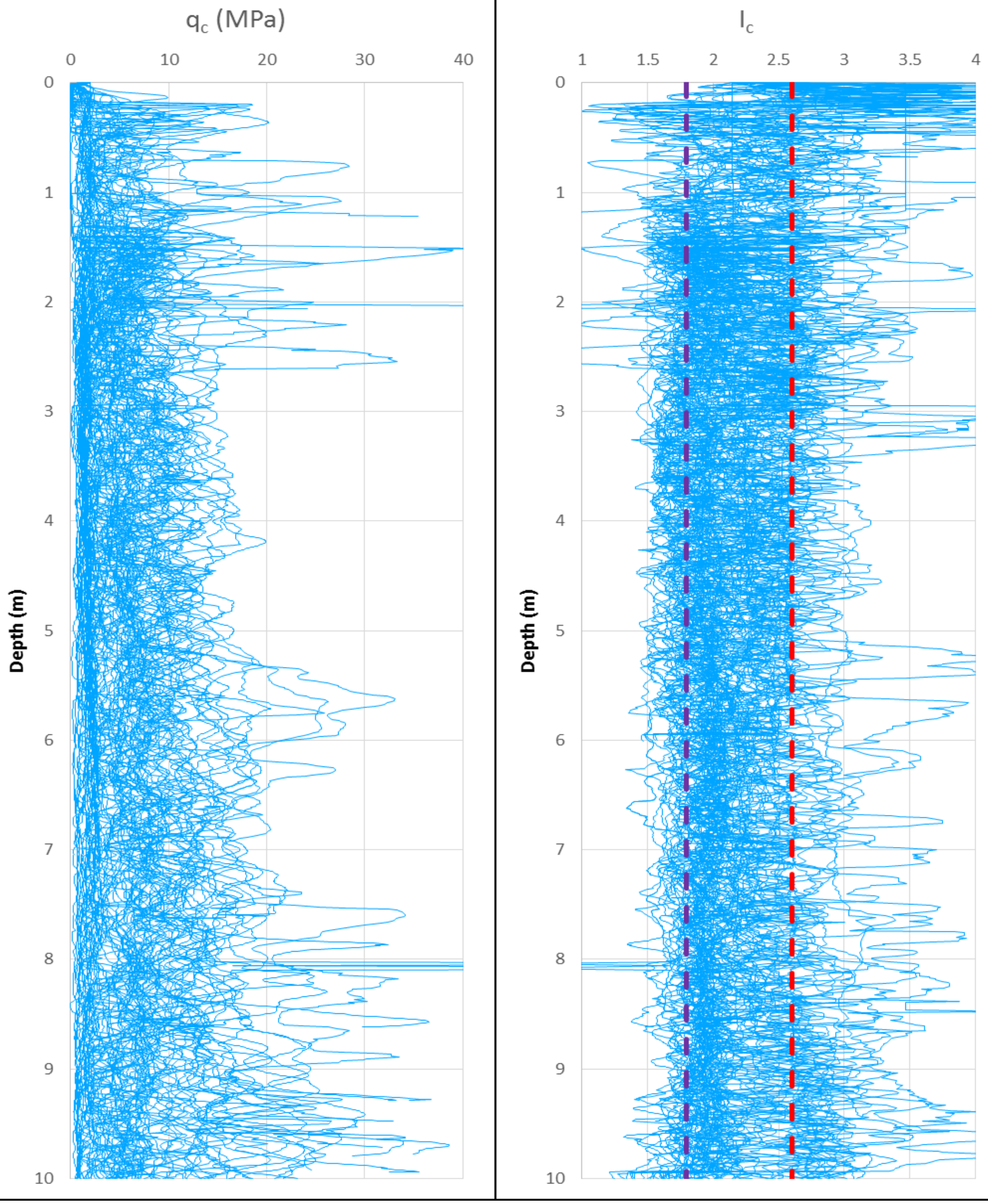
Legend

- CPT Trace
- Ic = 1.8 (clean sand to silty sand behaviour transition)
- I_c = 2.6 (sandy silt to silty clay behaviour transition)

Figure B2.6

Geomorphic Zone: Recent Gullies/River Terraces

Number of CPT: 117

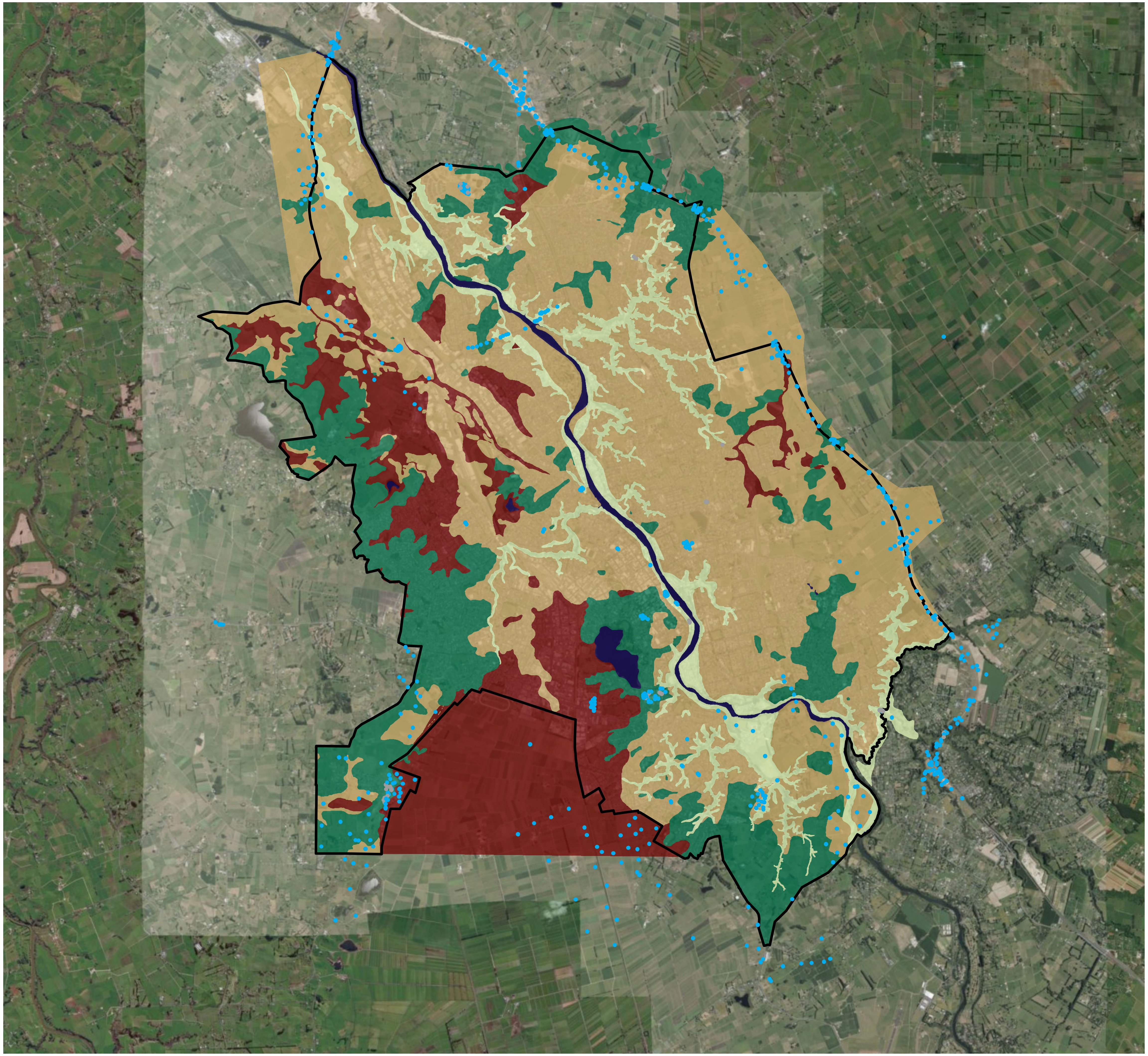


Legend

- CPT Trace
- Ic = 1.8 (clean sand to silty sand behaviour transition)
- I_c = 2.6 (sandy silt to silty clay behaviour transition)

Appendix C: LSN/Groundwater assessment

- **Appendix C1 – CPT analyses overlaid on Geomorphic Zone**
- **Appendix C2 – LSN histogram and box and whisker plots by groundwater depth**
- **Appendix C3 – LSN histogram and box and whisker plots by geomorphic zone**



LEGEND

LSN Values

- < 13
- 13 to 18
- >18
- Affected by Predrill

Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

N

Notes:

1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.29

ARCFILE 1007144_FIG006.mxd

SCALE (AT A3 SIZE) 1:70,000

PROJECT No. 1007144.000

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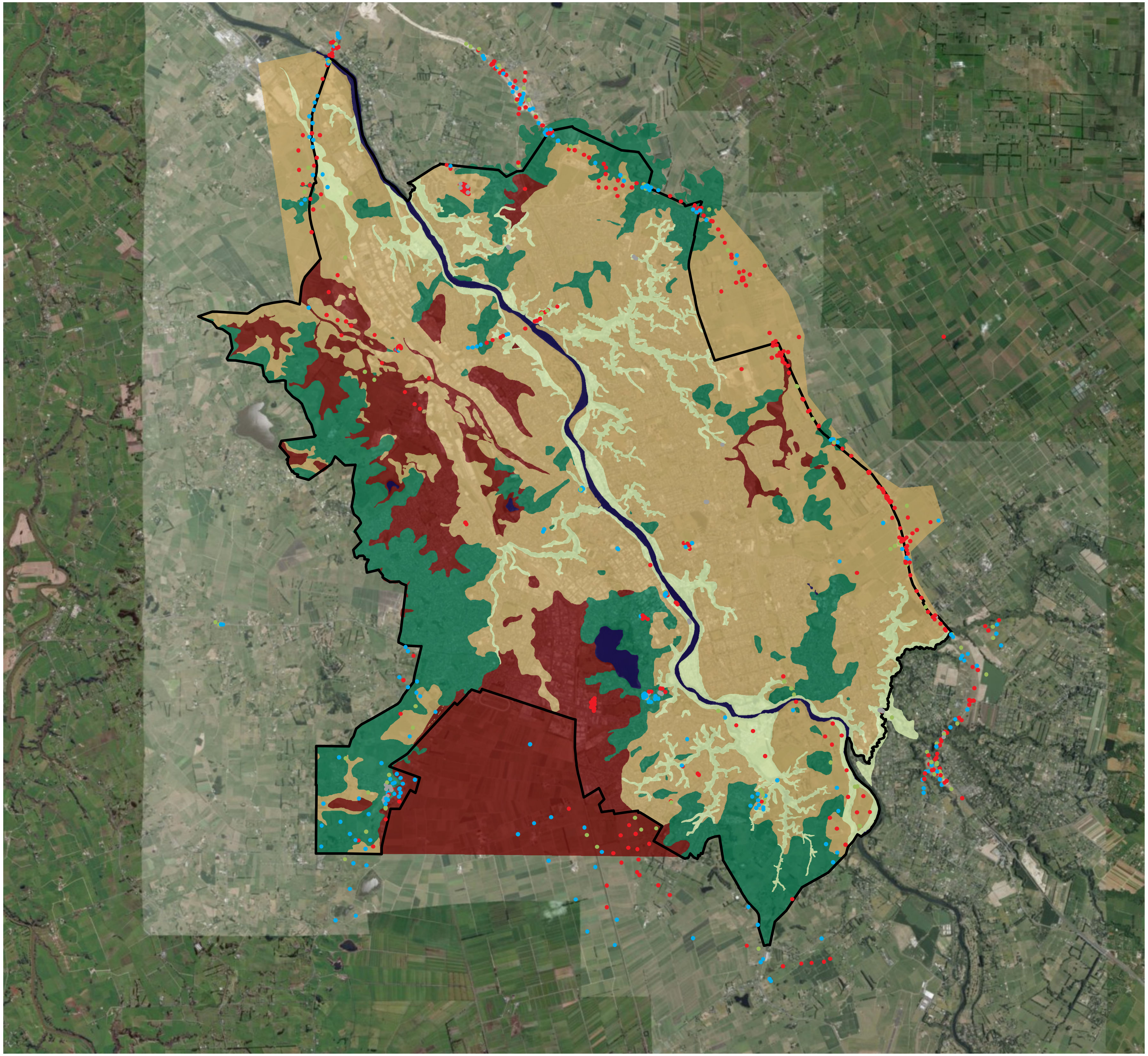
HAMILTON CITY COUNCIL

HAMILTON LIQUEFACTION ASSESSMENT

CPT Analysis overlaid on Geomorphic Zones

100yr ARI (Mw = 5.9, PGA = 0.11g) 1m GWD

Figure C1.1



LEGEND

LSN Values

- < 13
- 13 to 18
- >18
- Affected by Predrill

Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:

1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18

ARCFILE 1007144_FIG007.mxd

SCALE (AT A3 SIZE) 1:70,000

PROJECT No. 1007144.000

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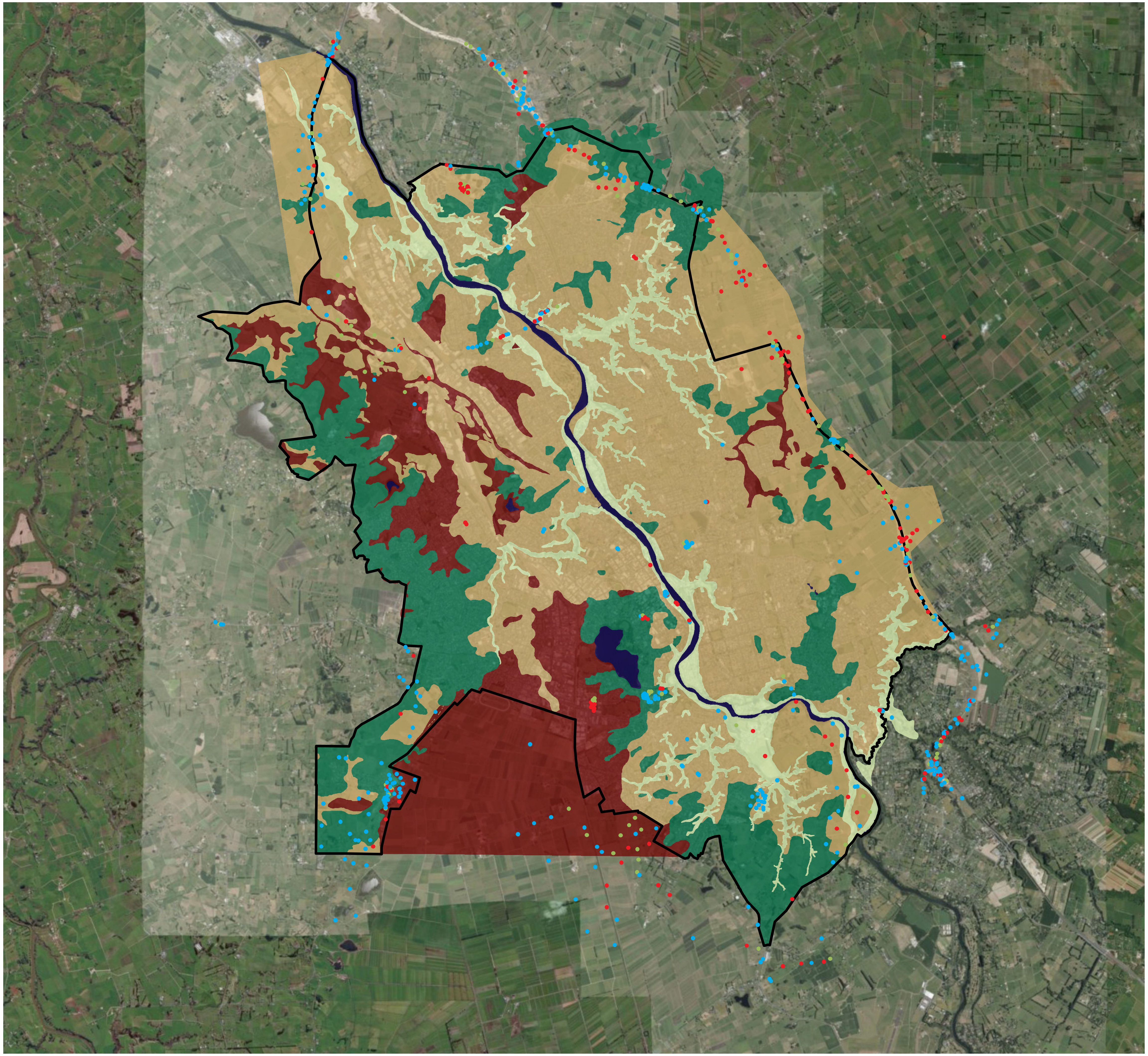
HAMILTON CITY COUNCIL

HAMILTON LIQUEFACTION ASSESSMENT

CPT Analysis overlaid on Geomorphic Zones

500yr ARI (Mw = 5.9, PGA = 0.22g) 1m GWD

Figure C1.2



LEGEND

LSN Values

- < 13
- 13 to 18
- >18
- Affected by Predrill

Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

N

Notes:

1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18
ARCFILE 1007144_FIG008_.mxd		
SCALE (AT A3 SIZE) 1:70,000		
PROJECT No. 1007144.000		

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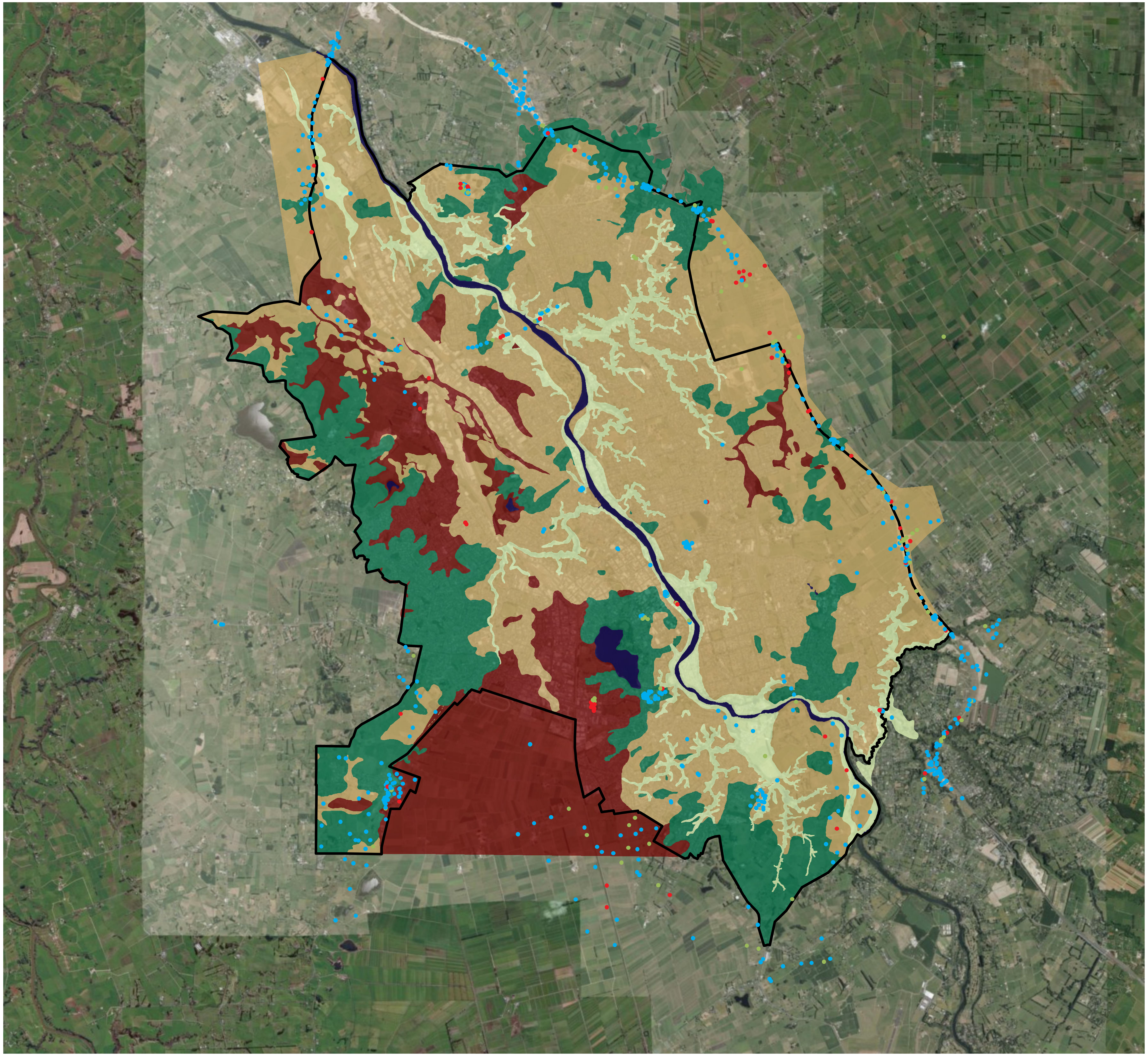
HAMILTON CITY COUNCIL

HAMILTON LIQUEFACTION ASSESSMENT

CPT Analysis overlaid on Geomorphic Zones

500yr ARI (Mw = 5.9, PGA = 0.22g) 2m GWD

Figure C1.3



LEGEND

LSN Values

- < 13
- 13 to 18
- >18
- Affected by Predrill

Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:

1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18

ARCFILE 1007144_FIG009.mxd

SCALE (AT A3 SIZE) 1:70,000

PROJECT No. 1007144.000

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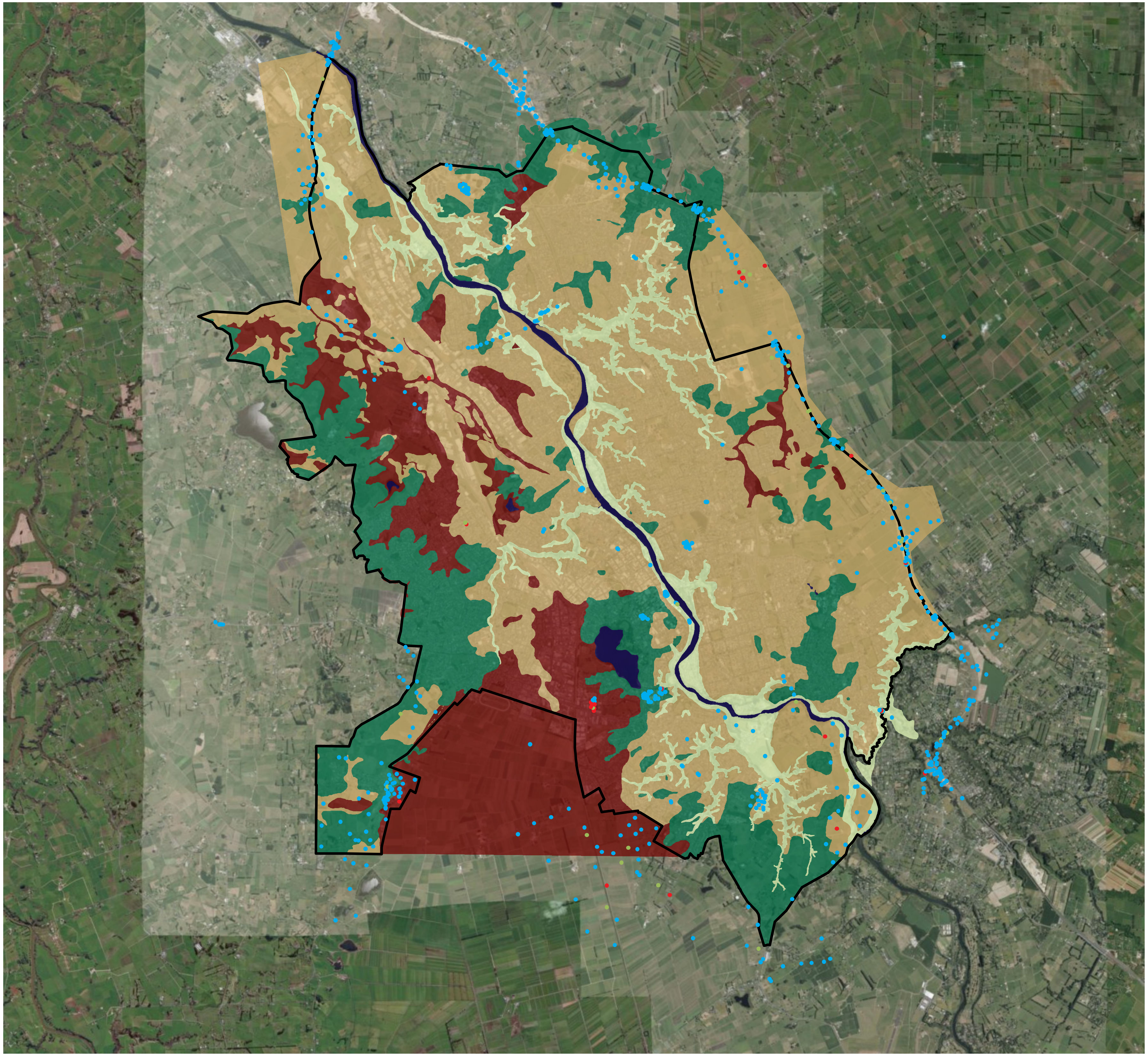
HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
CPT Analysis overlaid on Geomorphic Zones
500yr ARI (Mw = 5.9, PGA = 0.22g) 3m GWD

Figure C1.4



LEGEND

LSN Values

- < 13
- 13 to 18
- >18
- Affected by Predrill

Hamilton City Council Boundary

Geomorphology Zones

- Low Hills
- Alluvial Plain
- Peat
- Recent Gullies/ River Terrace (Taupo Pumice Alluvium)
- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:

1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18
ARCFILE 1007144_FIG010.mxd		
SCALE (AT A3 SIZE) 1:70,000		
PROJECT No. 1007144.000		

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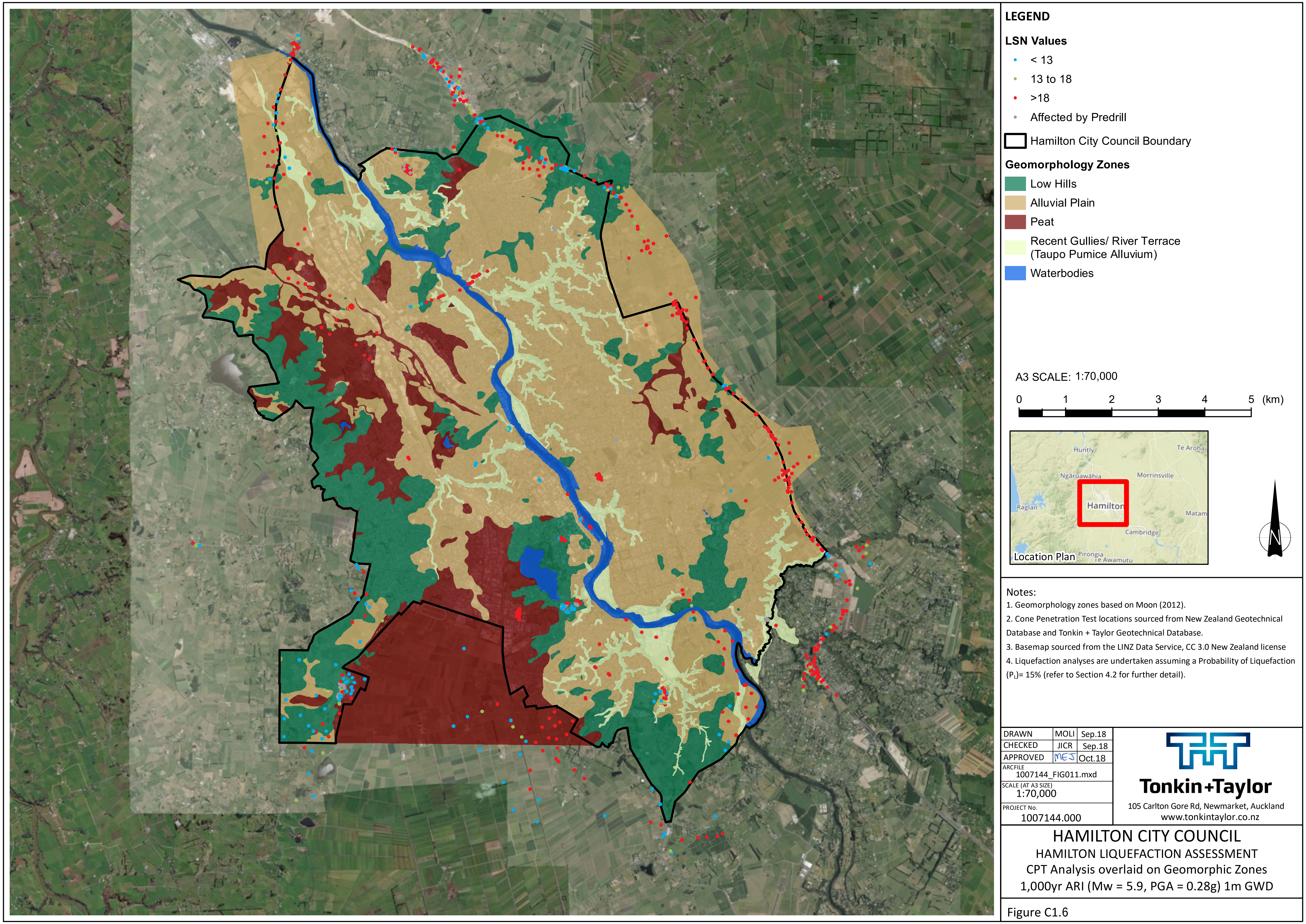
HAMILTON LIQUEFACTION ASSESSMENT
CPT Analysis overlaid on Geomorphic Zones
500yr ARI (Mw = 5.9, PGA = 0.22g) 4m GWD

Figure C1.5



Notes:
1. Geomorphology zones based on Moon (2012).
2. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
3. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license
4. Liquefaction analyses are undertaken assuming a Probability of Liquefaction (P_L)= 15% (refer to Section 4.2 for further detail).

DRAWN	MOLI	Sep.18
CHECKED	JICR	Sep.18
APPROVED	MEJ	Oct.18

ARCFILE 1007144_FIG011.mxd
SCALE (AT A3 SIZE) 1:70,000
PROJECT No. 1007144.000

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HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
CPT Analysis overlaid on Geomorphic Zones
1,000yr ARI (Mw = 5.9, PGA = 0.28g) 1m GWD

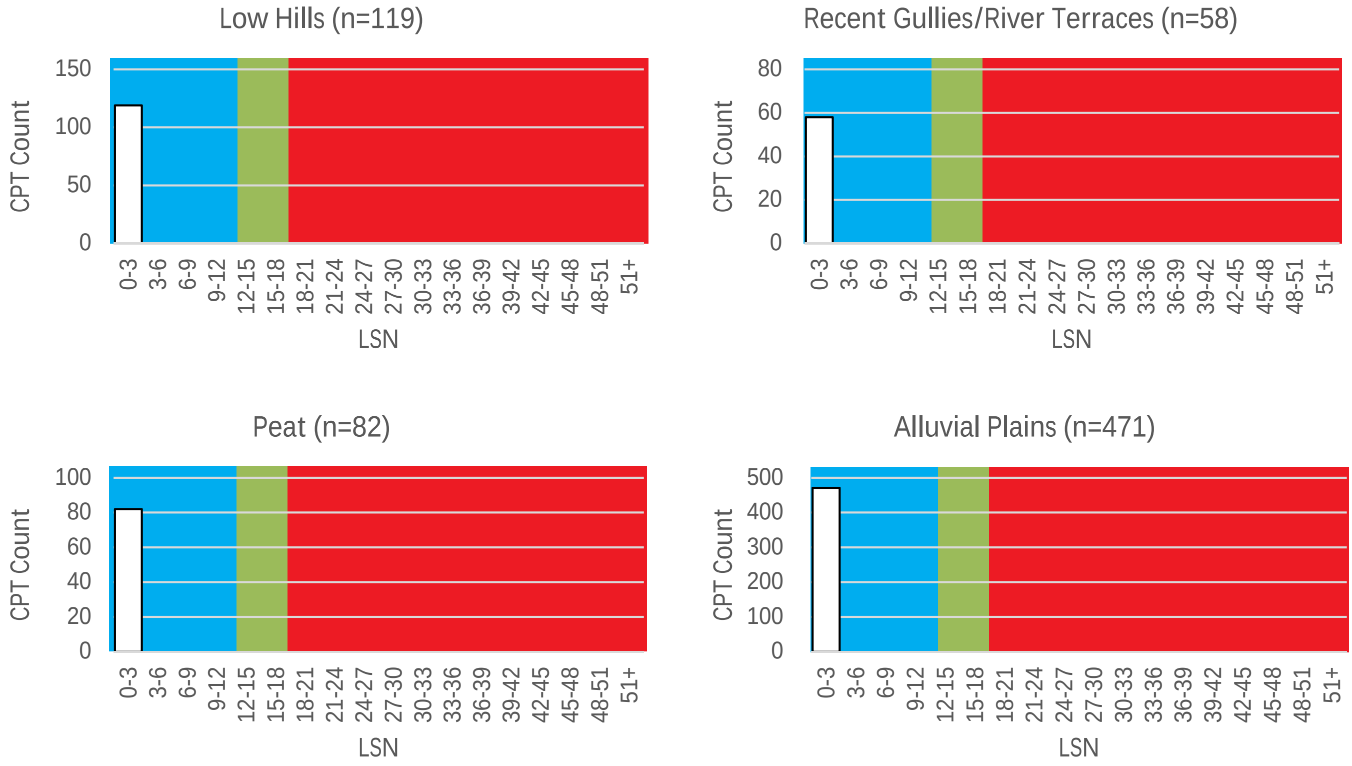
Figure C1.6

Figure C2.1

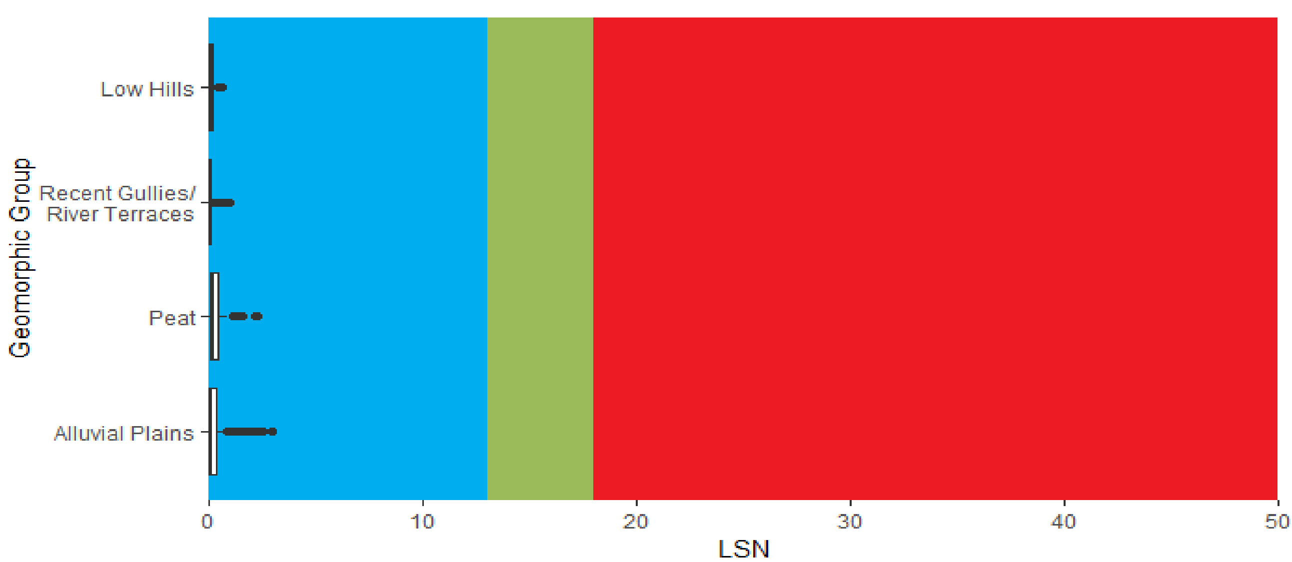
CPT based liquefaction analysis

Scenario: 25 yr ARI (Mw=5.9,PGA = 0.05g) 0.1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

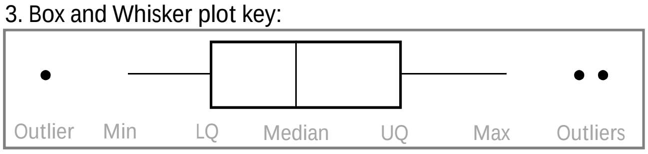
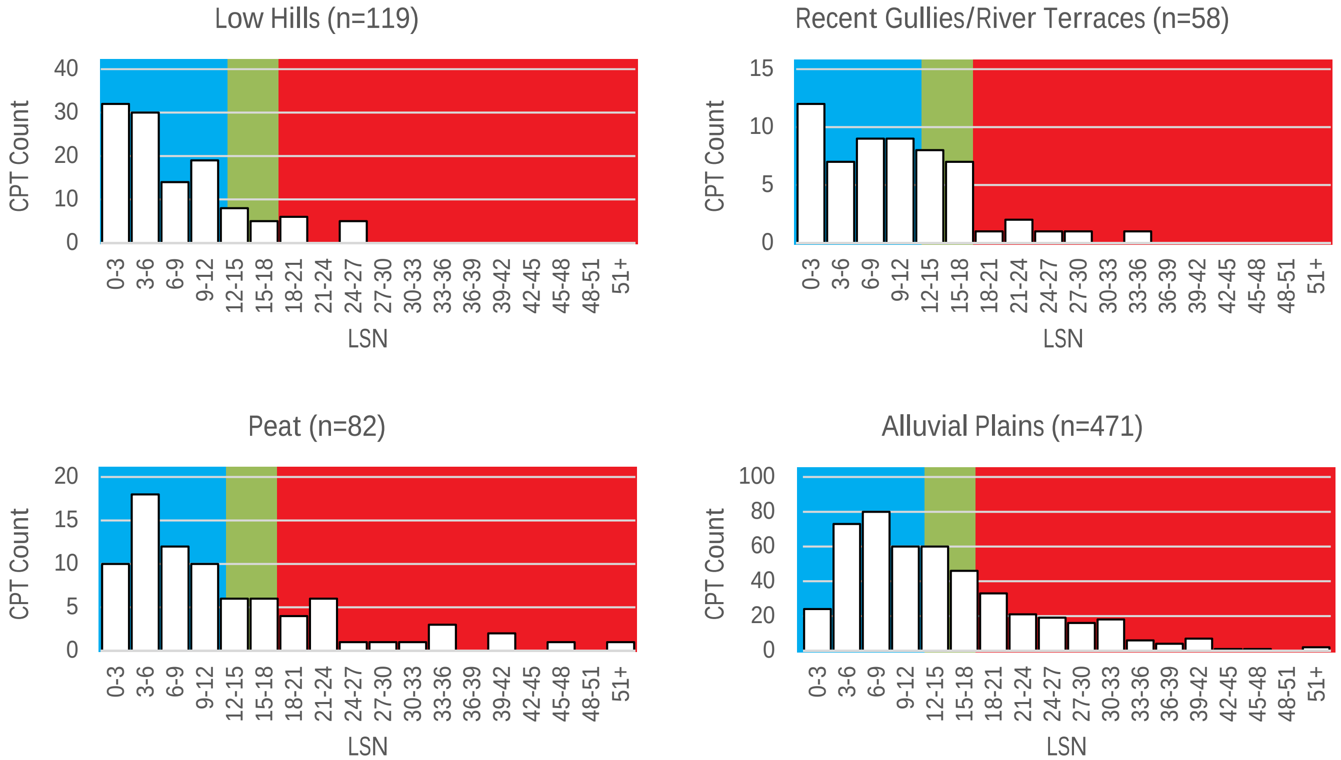


Figure C2.2

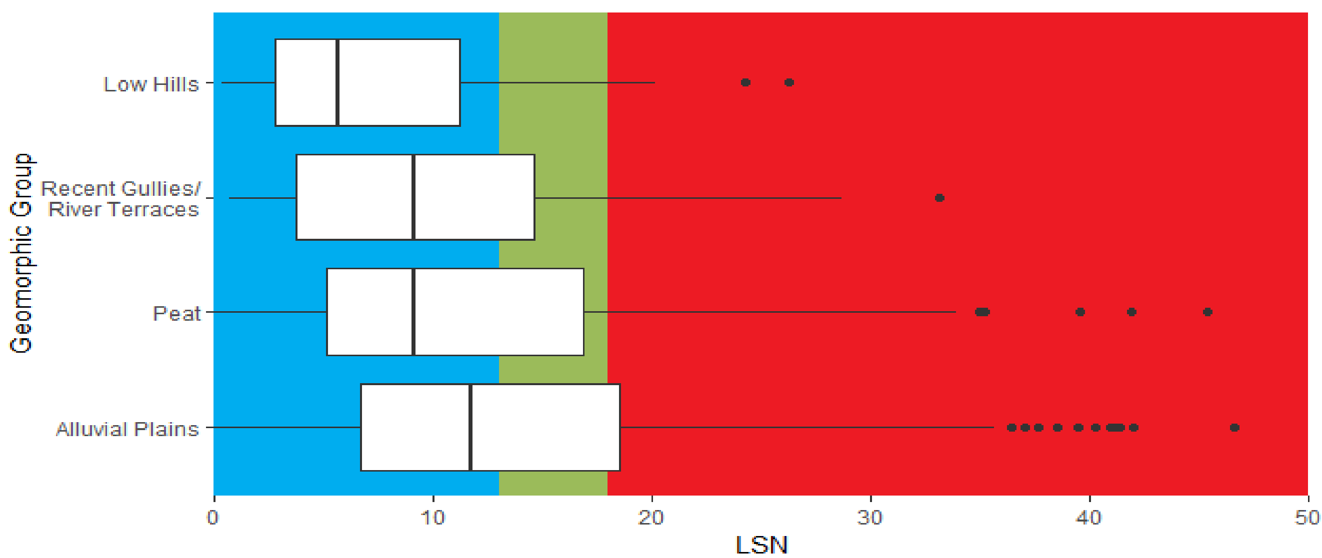
CPT based liquefaction analysis

Scenario: 100 yr ARI (Mw=5.9,PGA = 0.11g) 0.1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

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Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

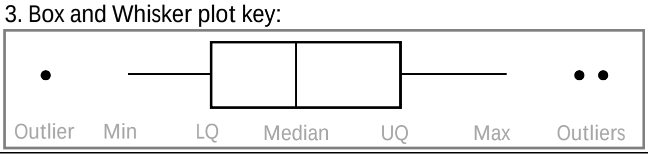
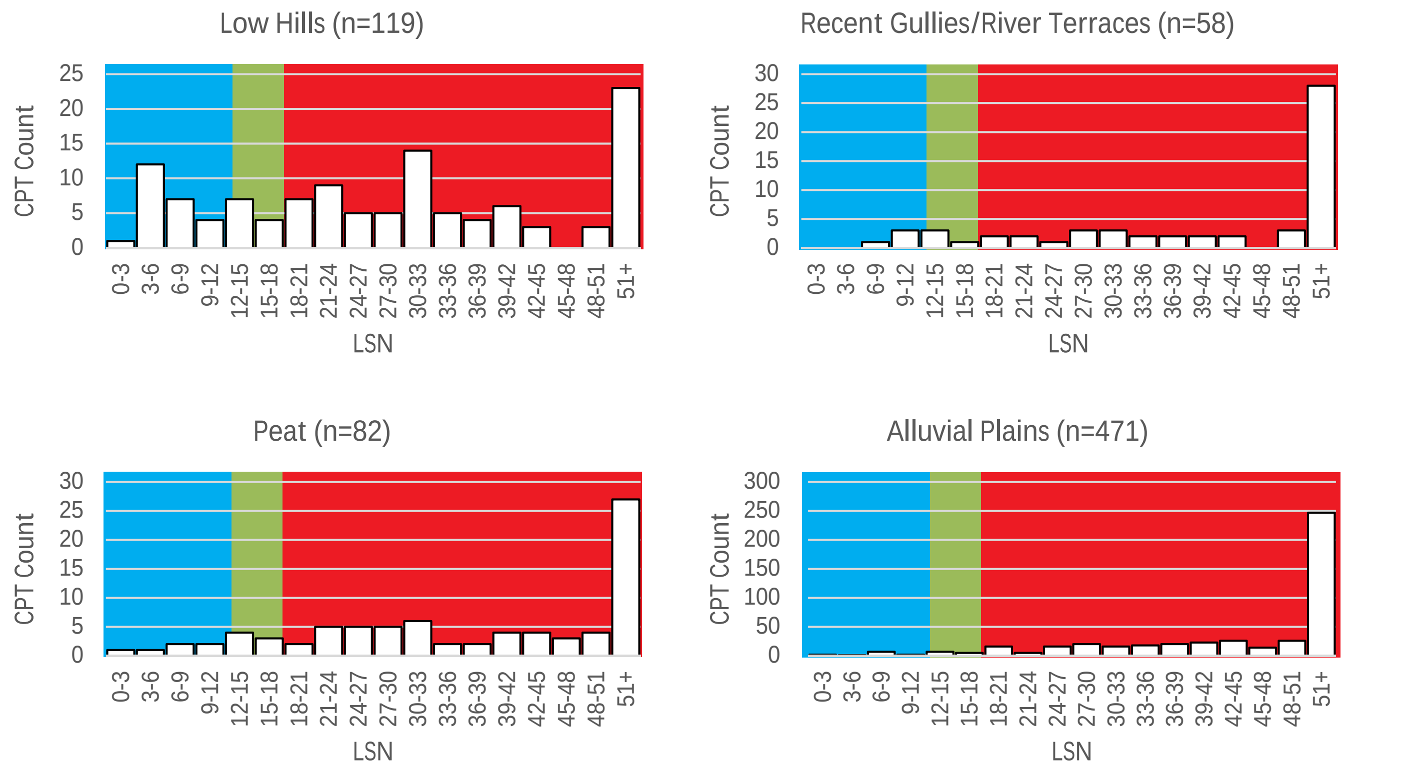


Figure C2.3

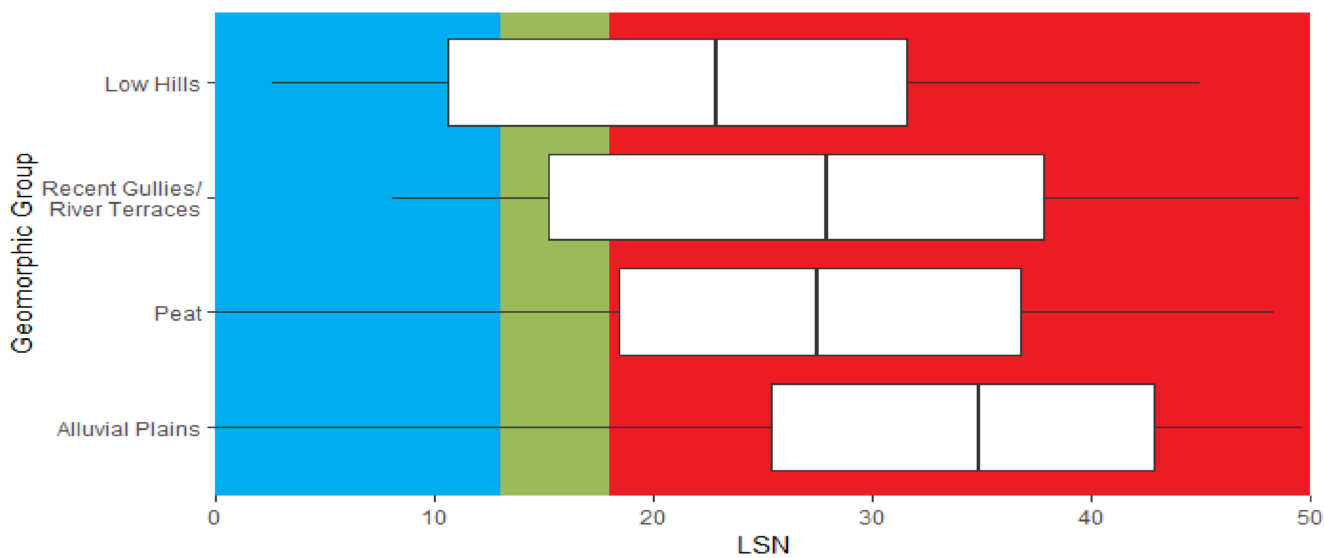
CPT based liquefaction analysis

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g) 0.1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

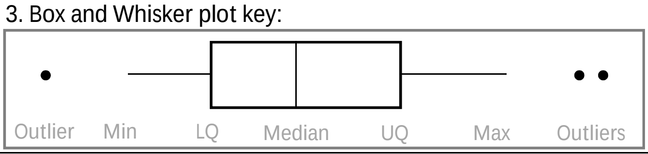
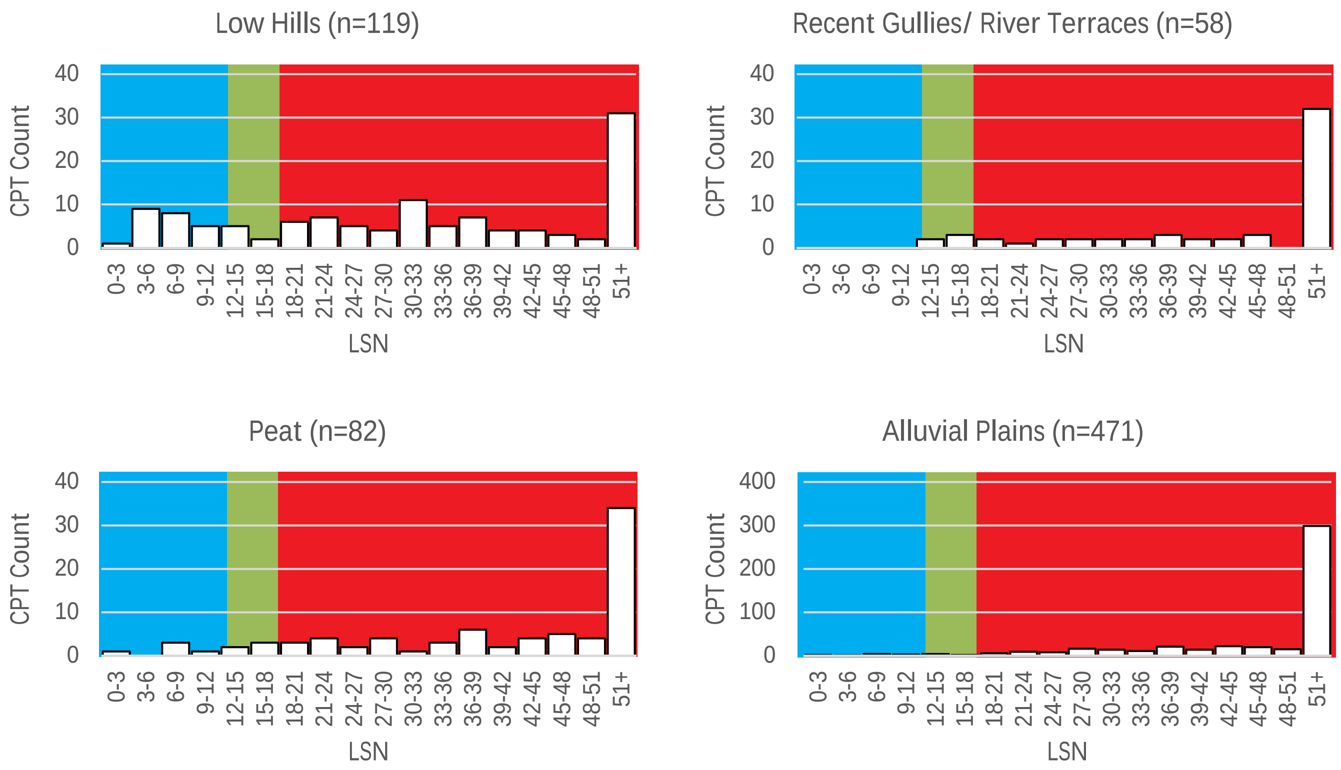


Figure C2.4

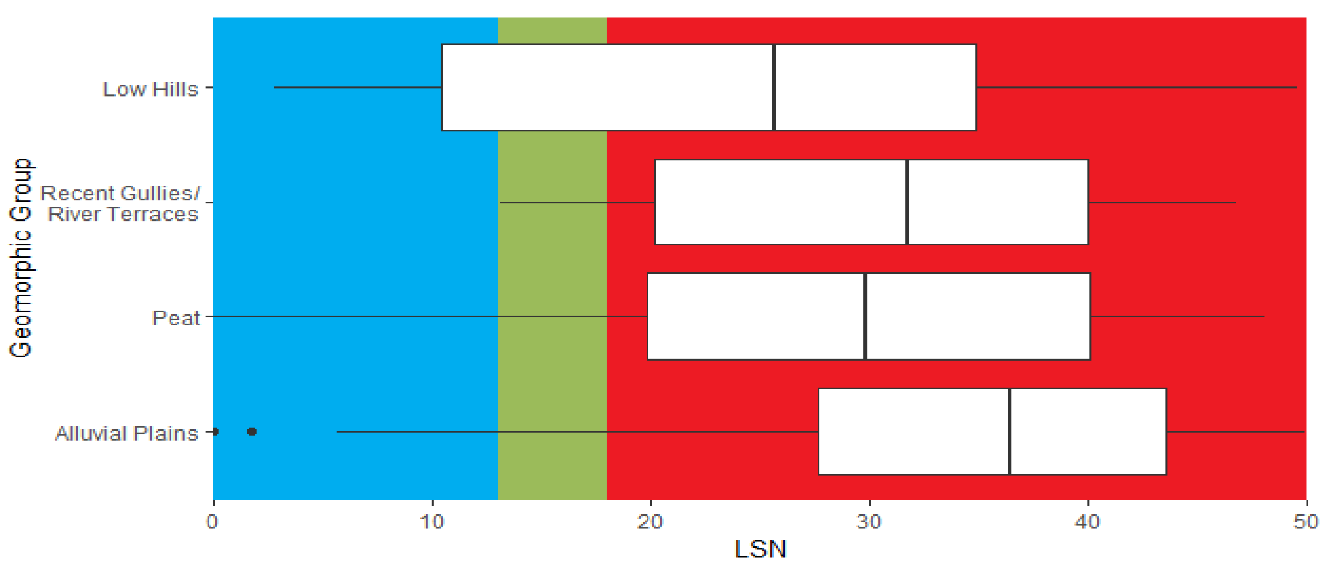
CPT based liquefaction analysis

Scenario: 1000 yr ARI (Mw=5.9,PGA = 0.28g) 0.1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

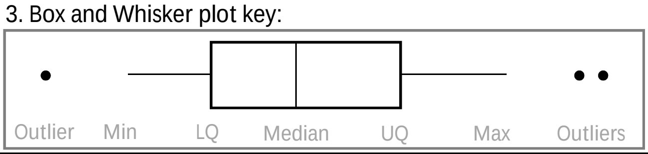
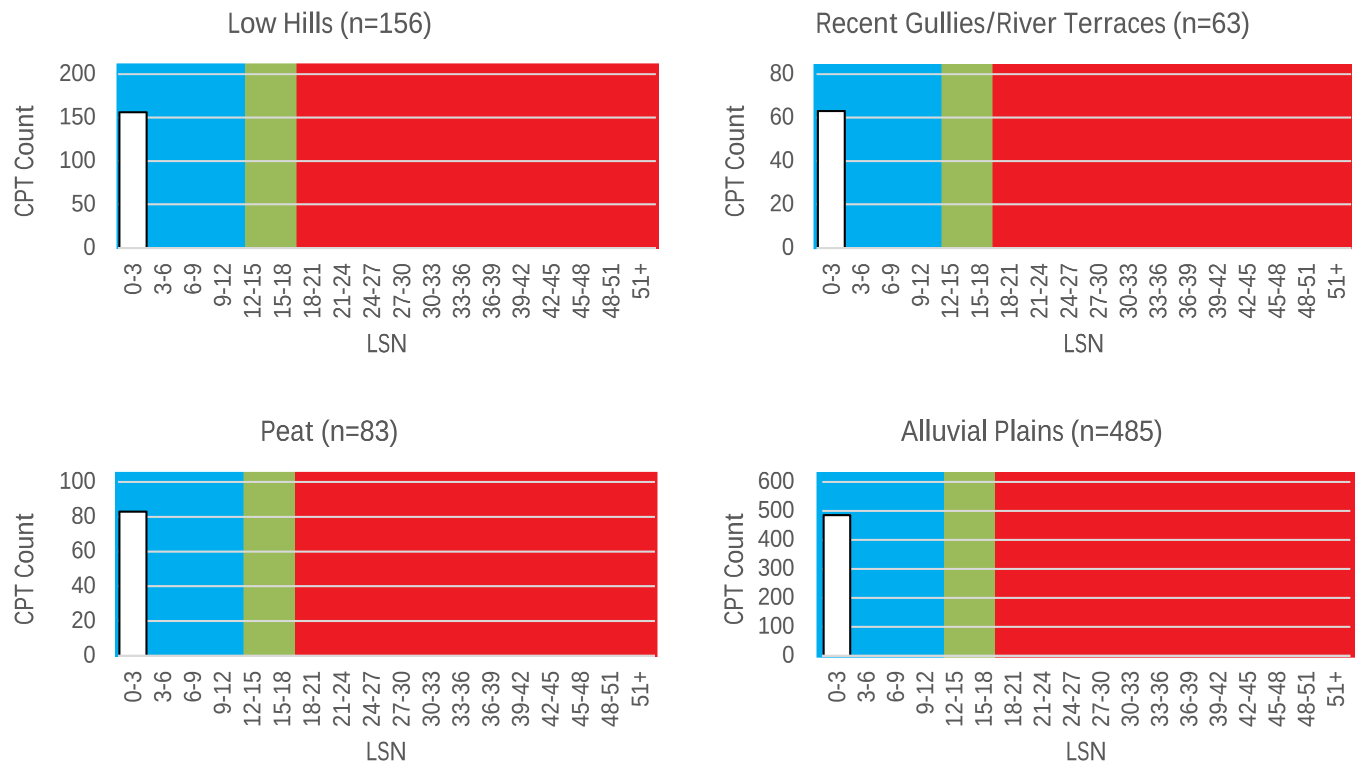


Figure C2.5

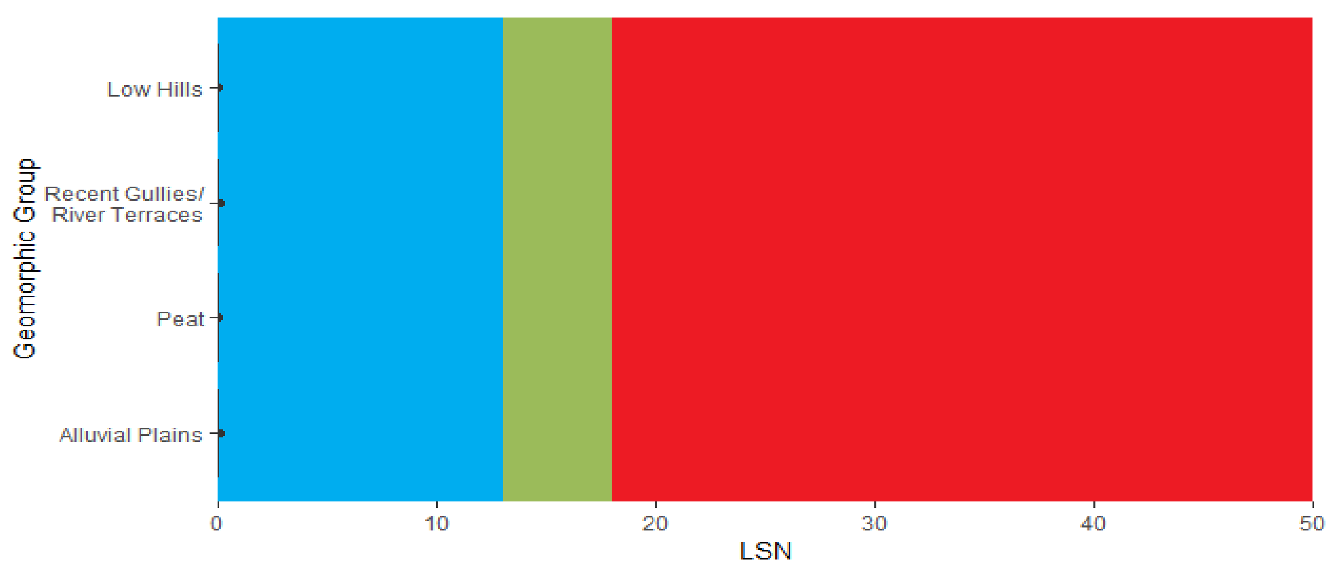
CPT based liquefaction analysis

Scenario: 25 yr ARI (Mw=5.9,PGA = 0.05g) 1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

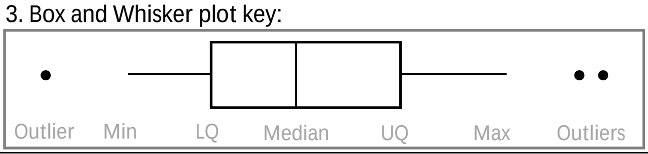
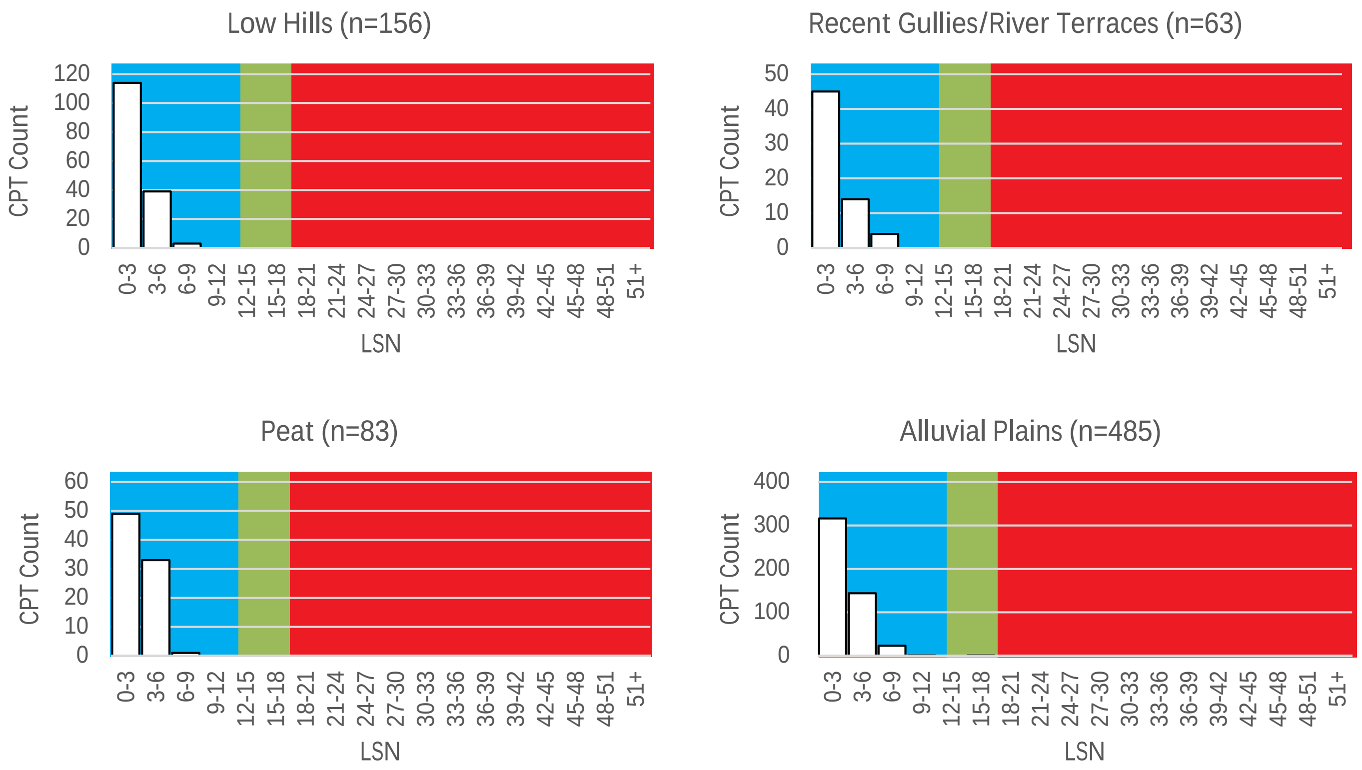


Figure C2.6

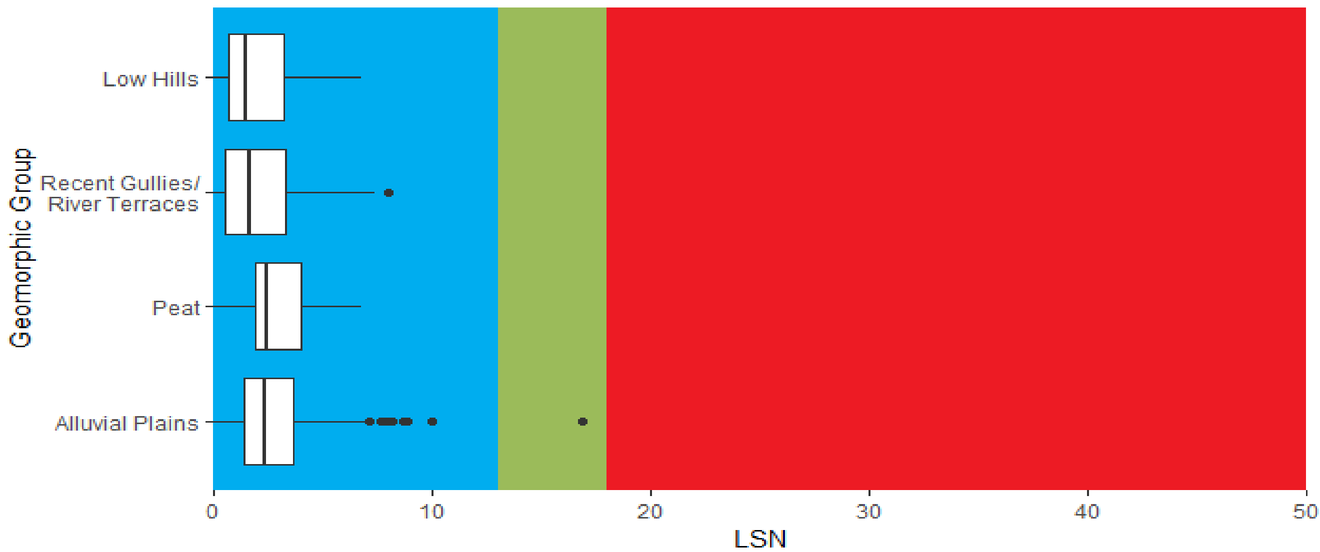
CPT based liquefaction analysis

Scenario: 100 yr ARI (Mw=5.9,PGA = 0.11g) 1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

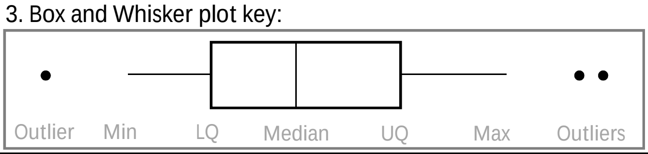
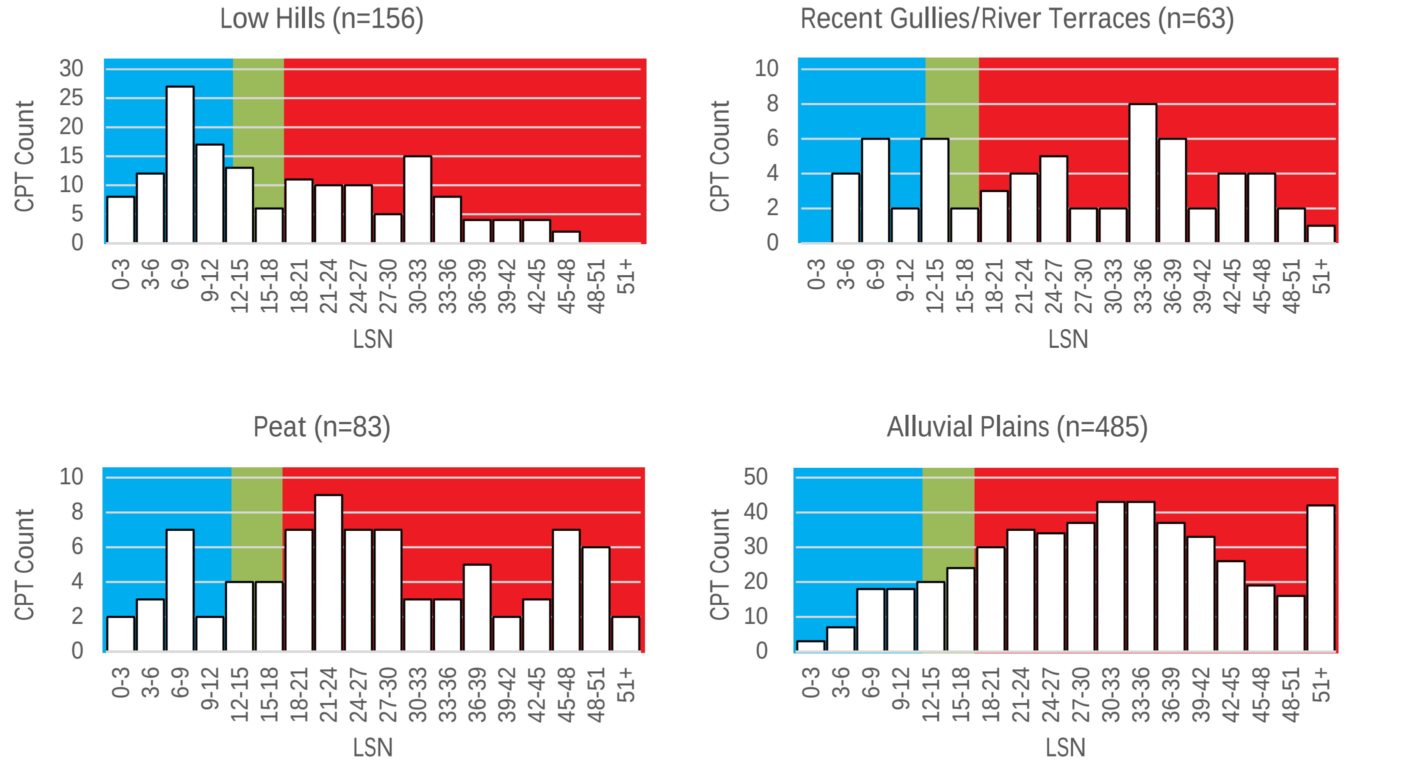


Figure C2.7

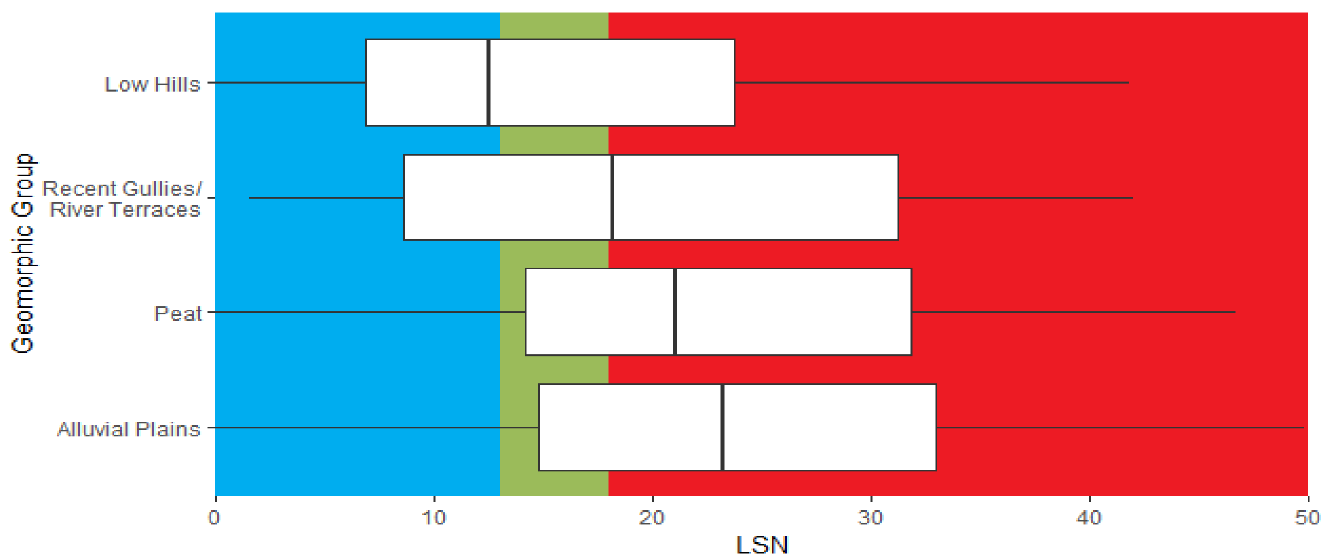
CPT based liquefaction analysis

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g) 1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key

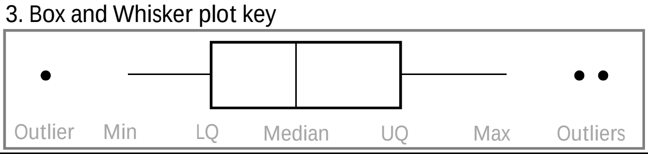
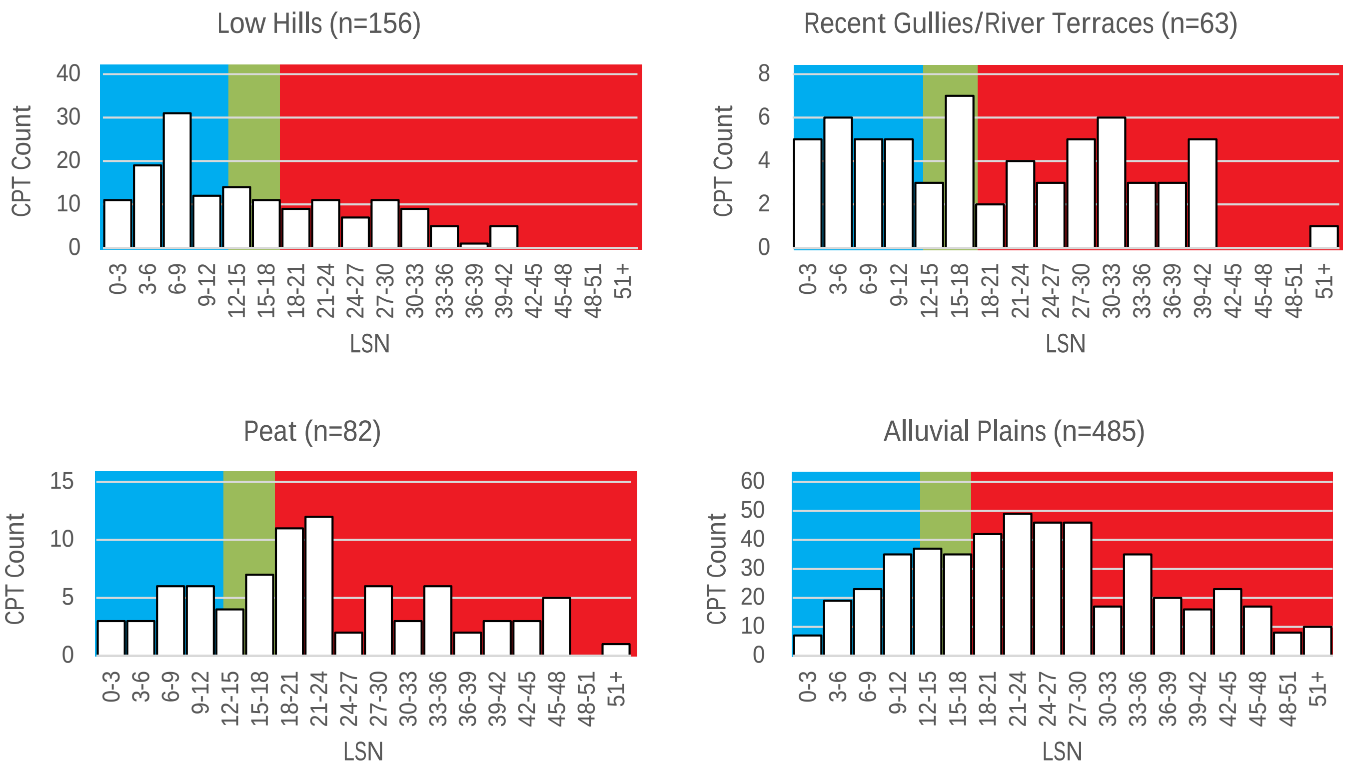


Figure C2.8

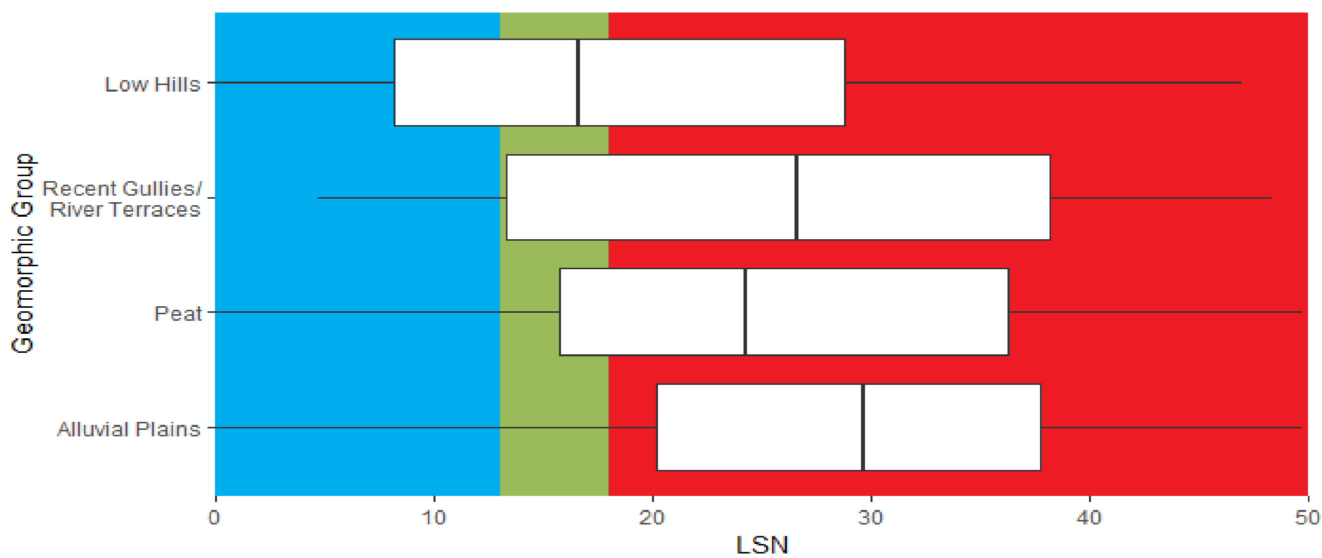
CPT based liquefaction analysis

Scenario: 1000 yr ARI (Mw=5.9,PGA = 0.28g) 1m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key

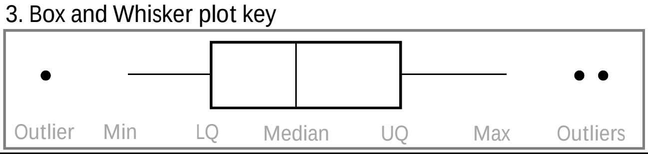
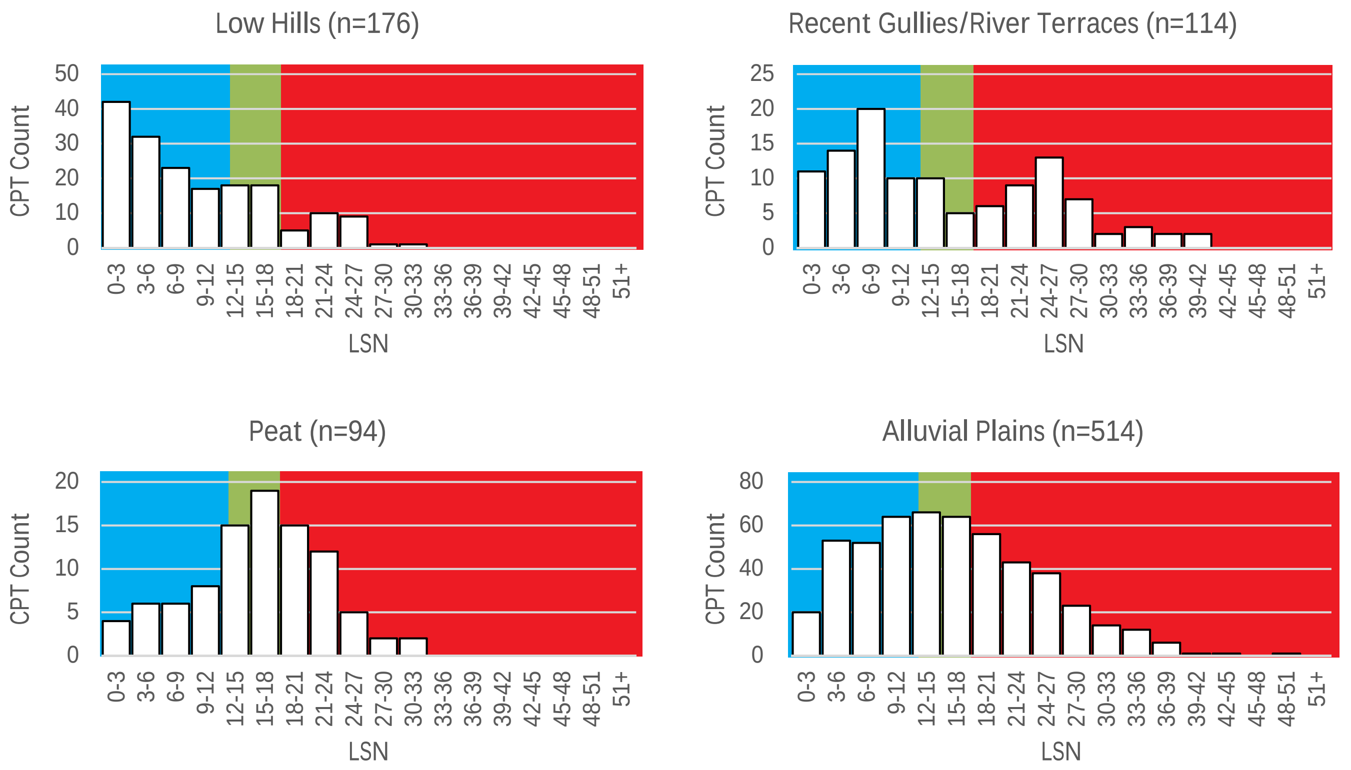


Figure C2.9

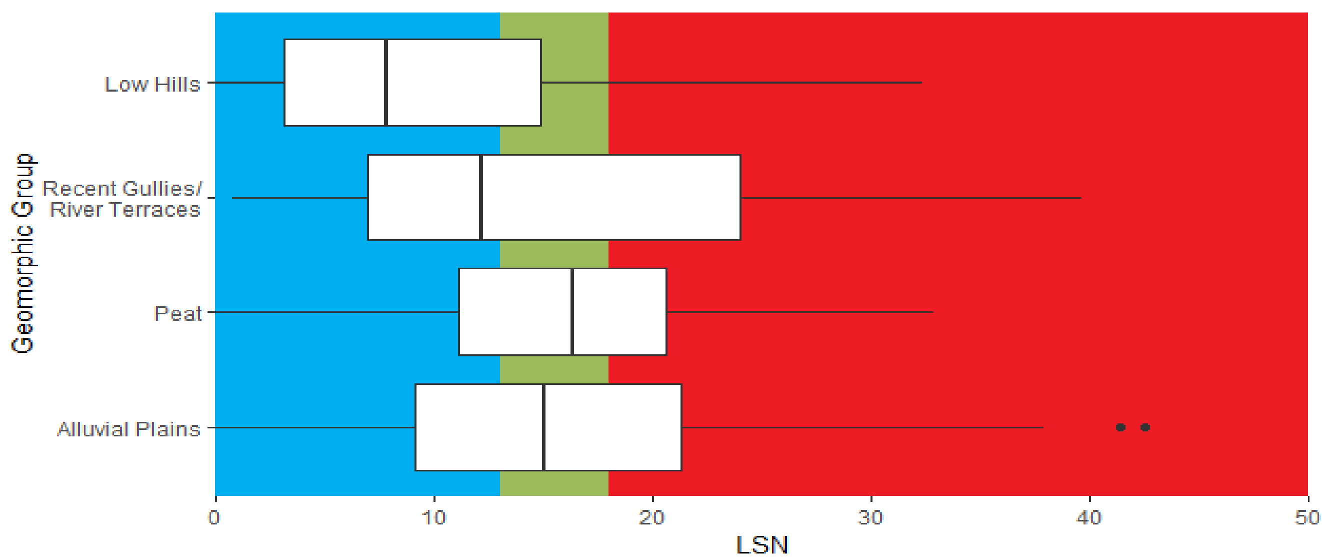
CPT based liquefaction analysis

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g) 2m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

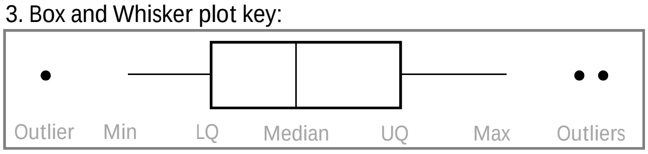
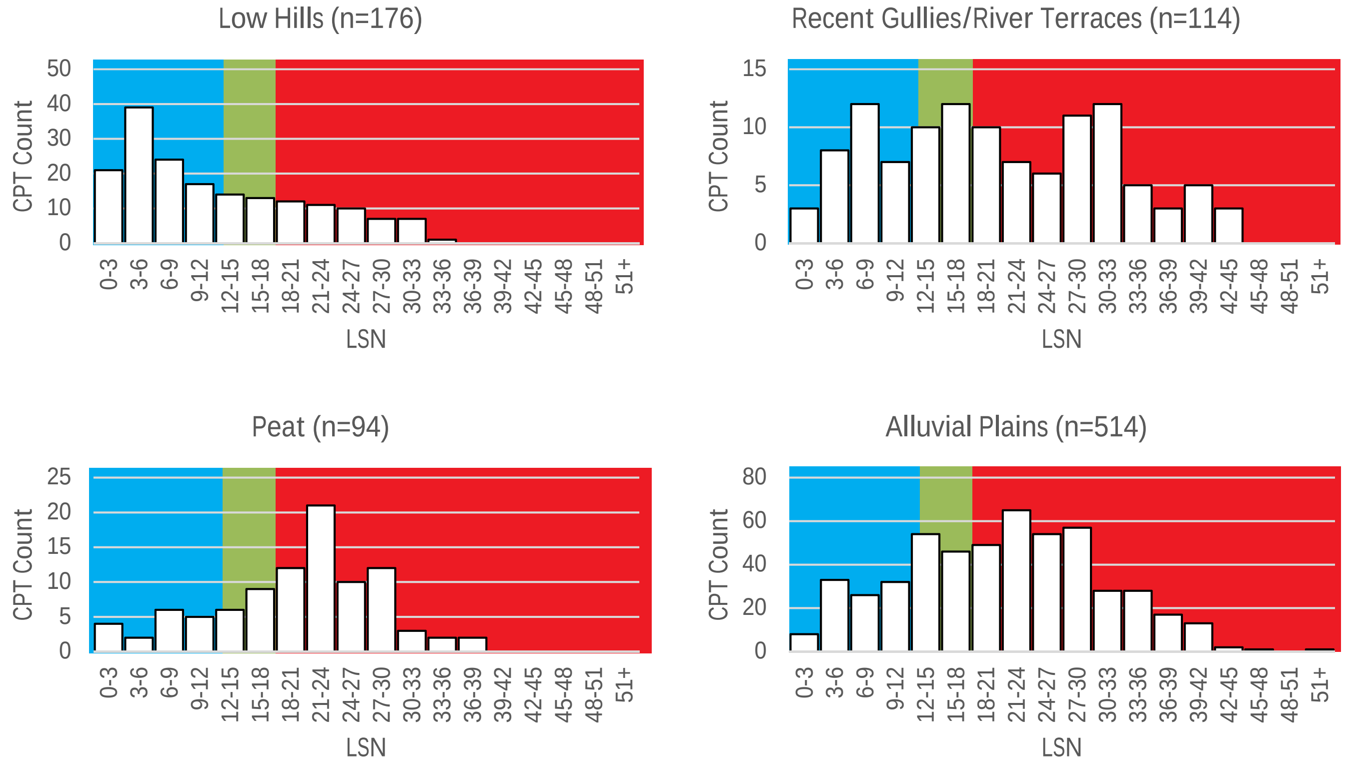


Figure C2.10

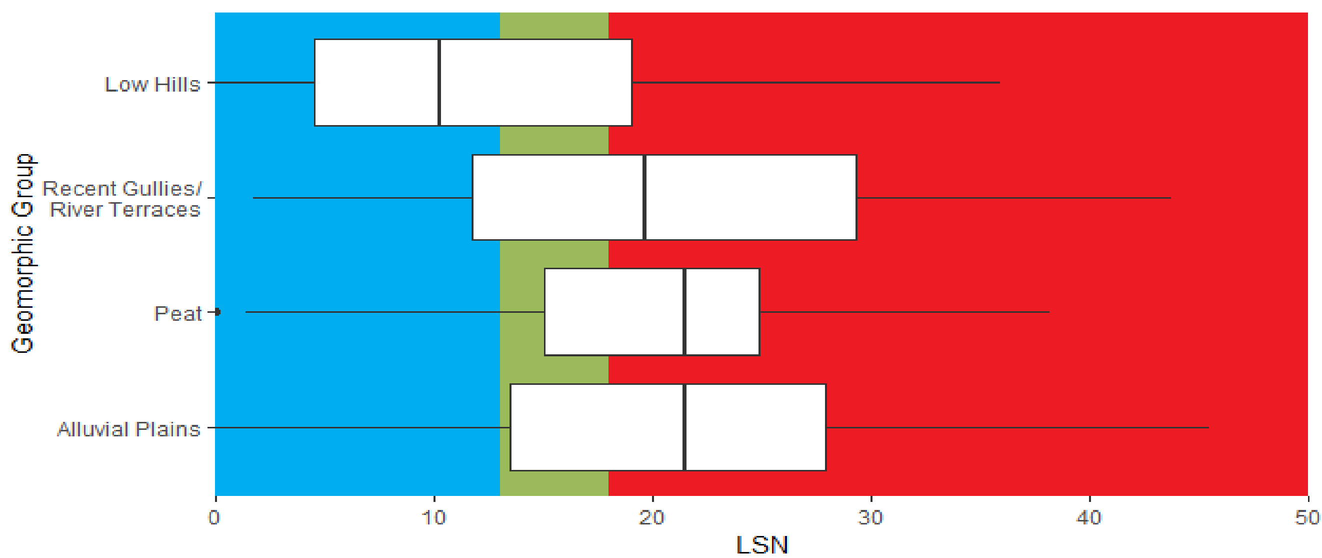
CPT based liquefaction analysis

Scenario: 1000 yr ARI (Mw=5.9,PGA = 0.28g) 2m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

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2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key

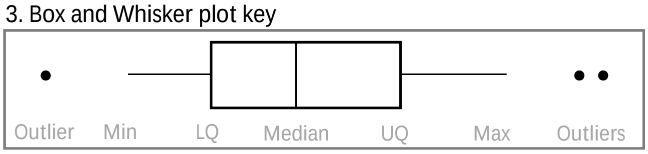
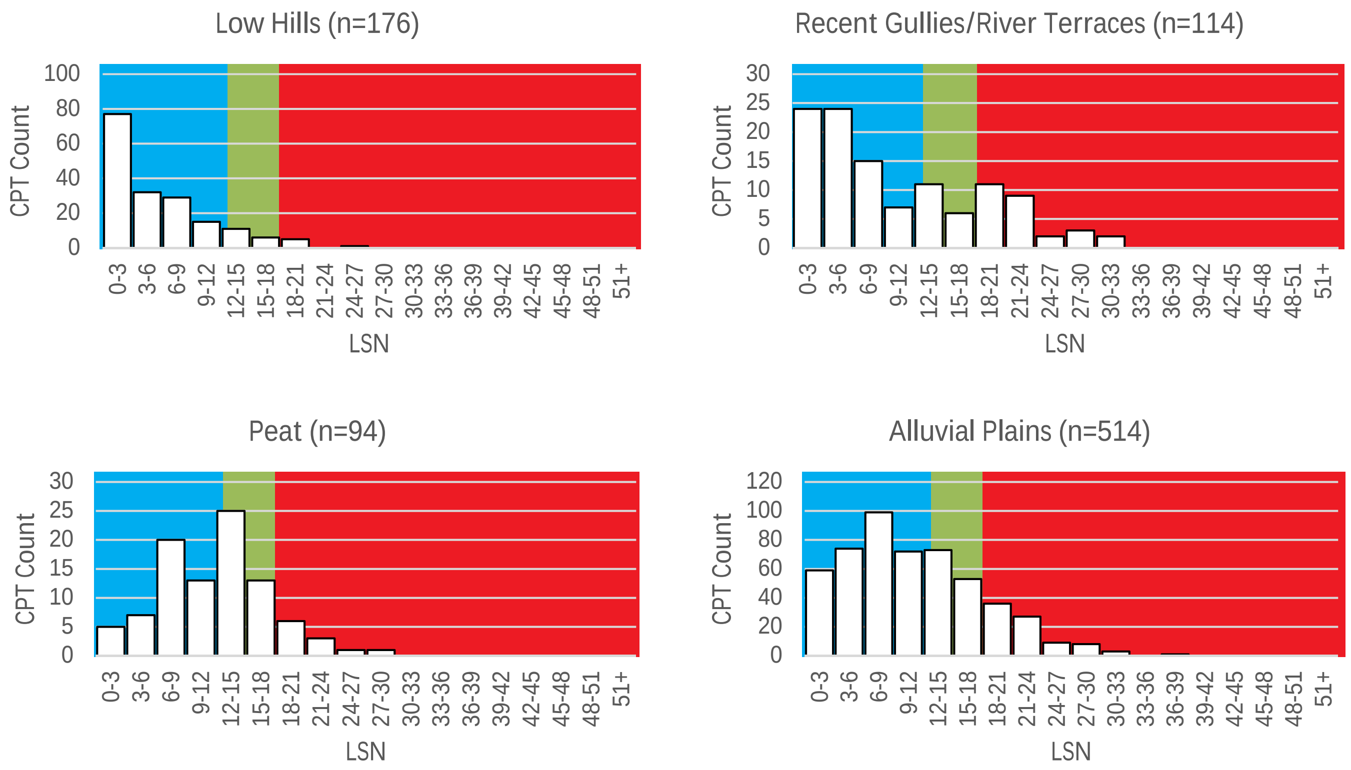


Figure C2.11

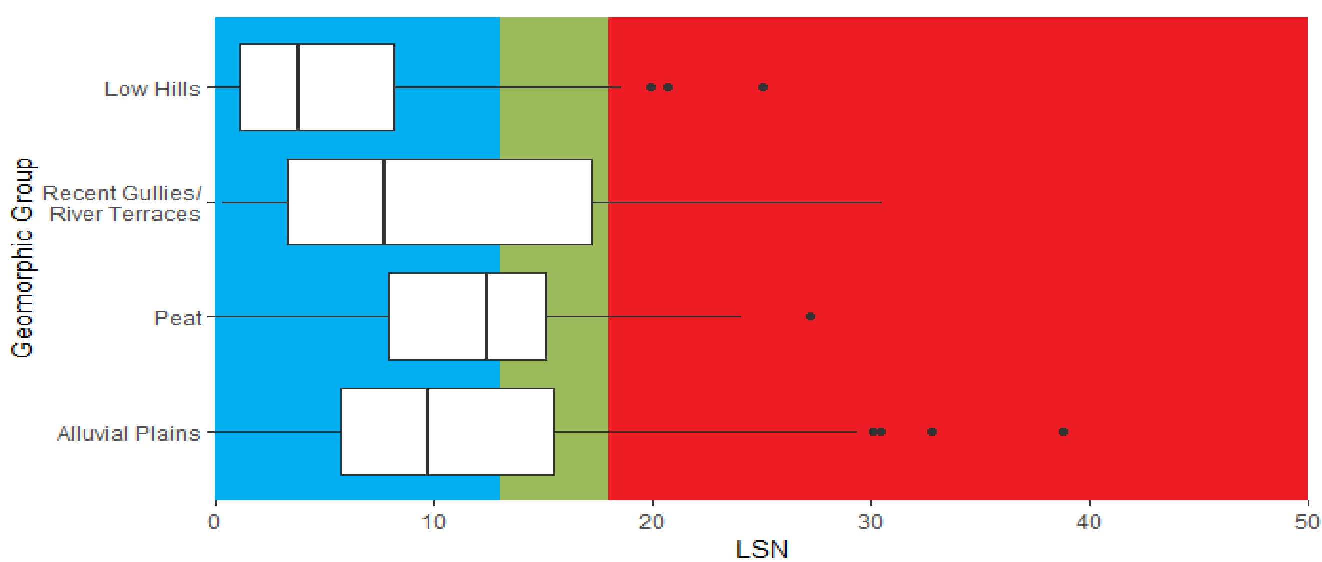
CPT based liquefaction analysis

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g) 3m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

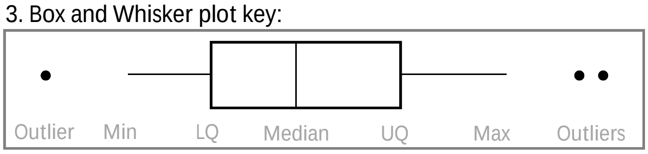
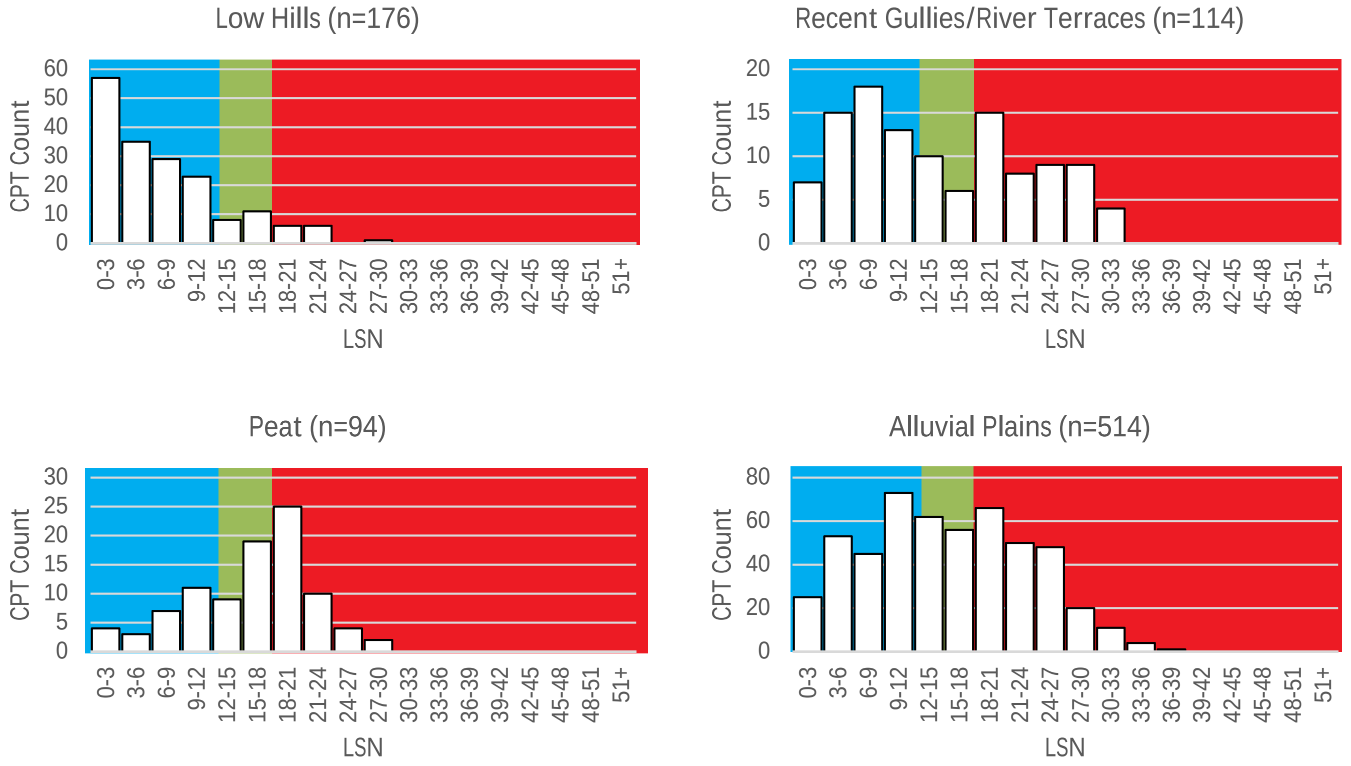


Figure C2.12

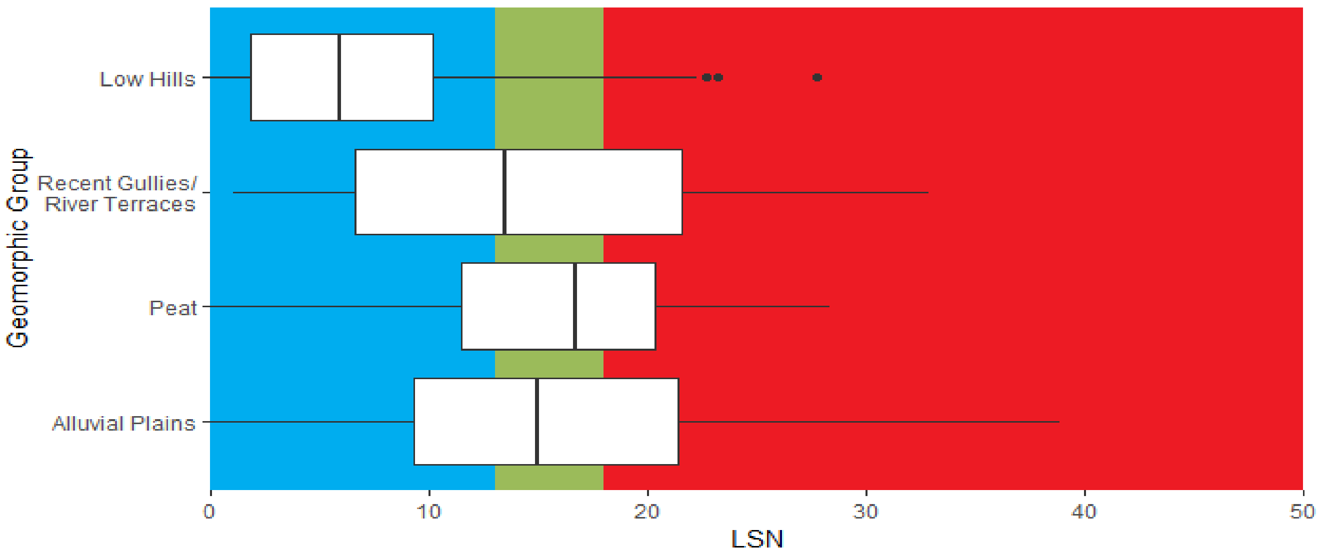
CPT based liquefaction analysis

Scenario: 1000 yr ARI (Mw=5.9,PGA = 0.28m) 3m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

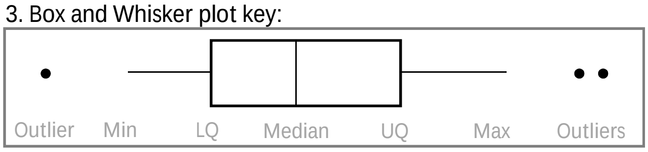
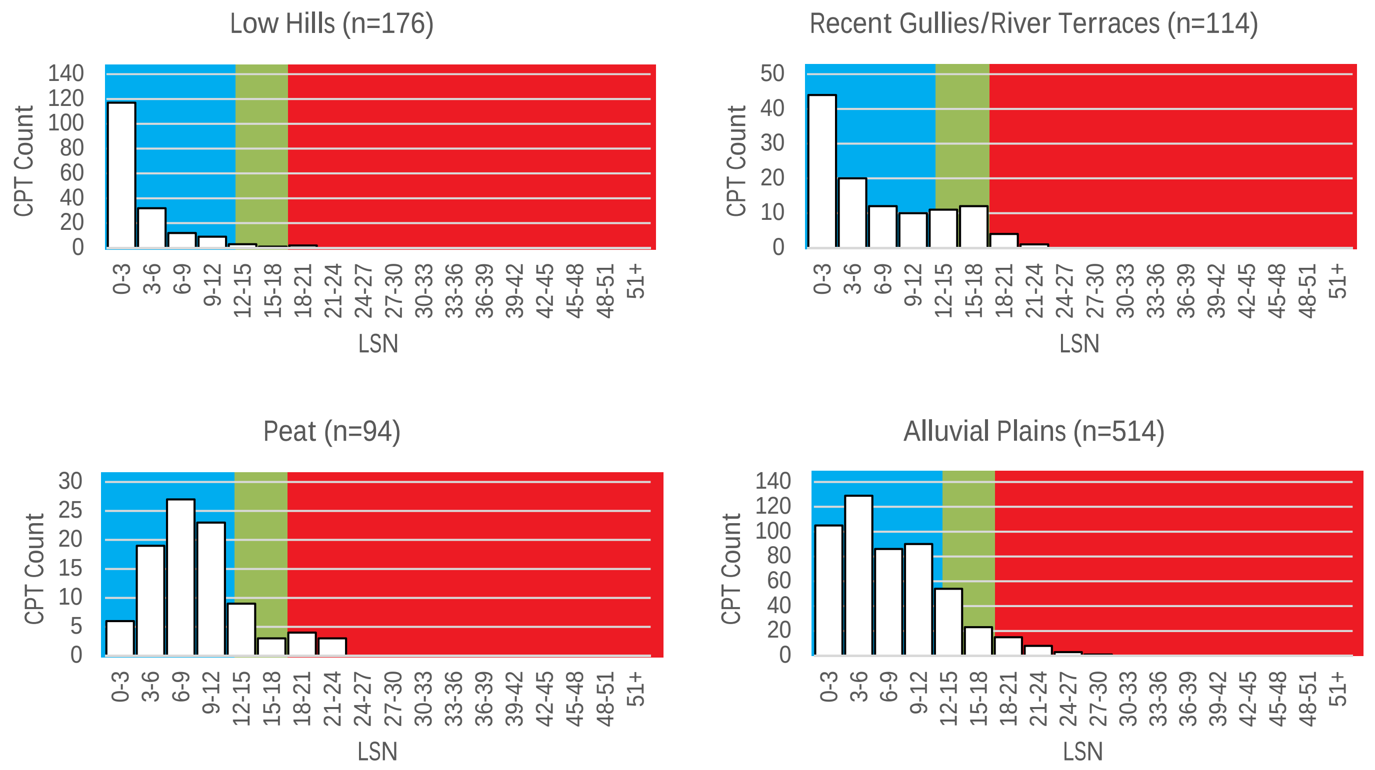


Figure C2.13

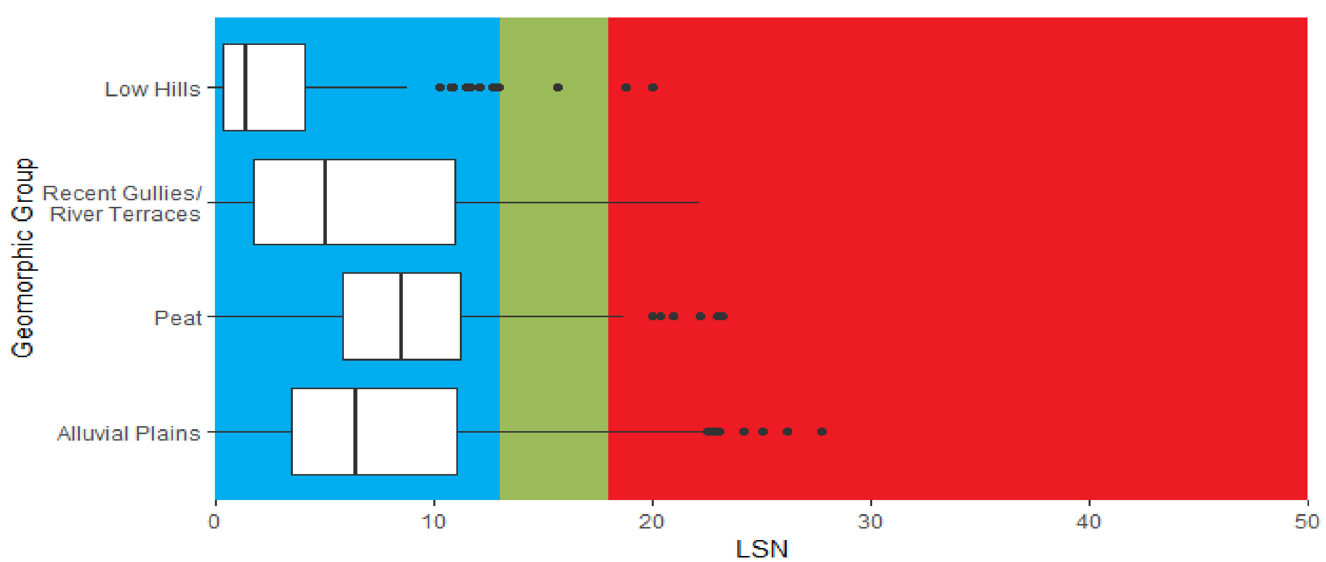
CPT based liquefaction analysis

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g) 4m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

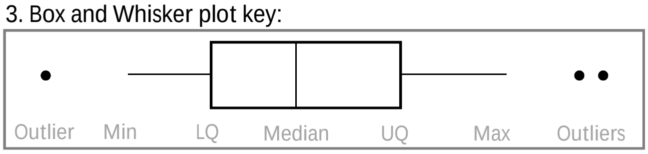
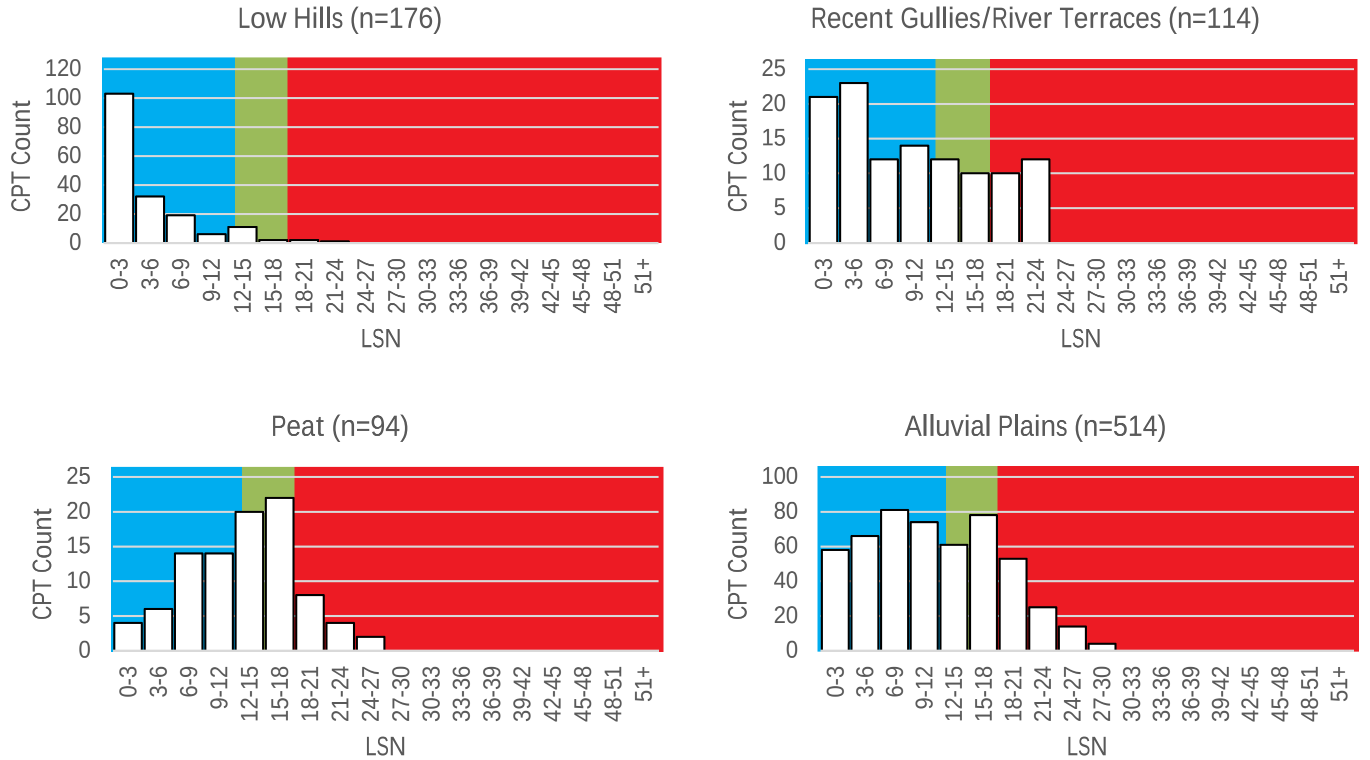


Figure C2.14

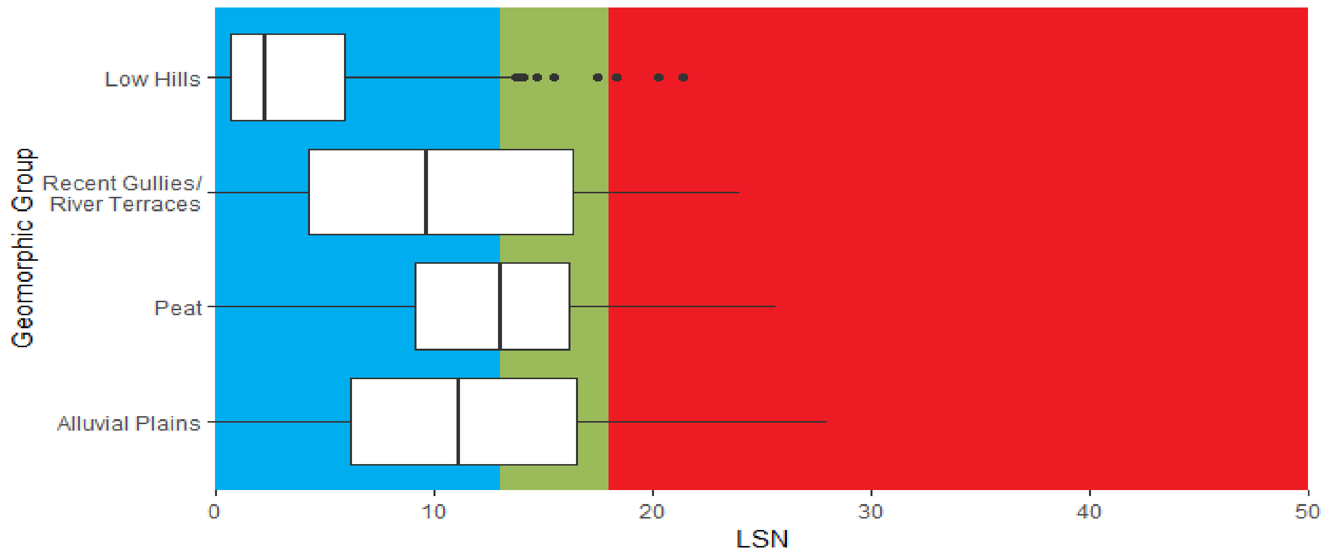
CPT based liquefaction analysis

Scenario: 1000 yr ARI (Mw=5.9,PGA = 0.28g) 4m GWD

Histograms of LSN values by geomorphic group



Box and whisker plot of LSN values by geomorphic group



Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (P_L=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

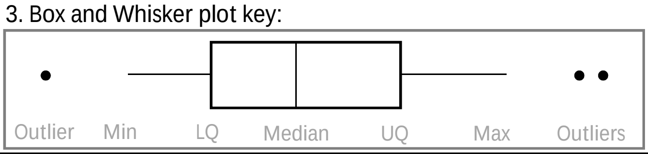
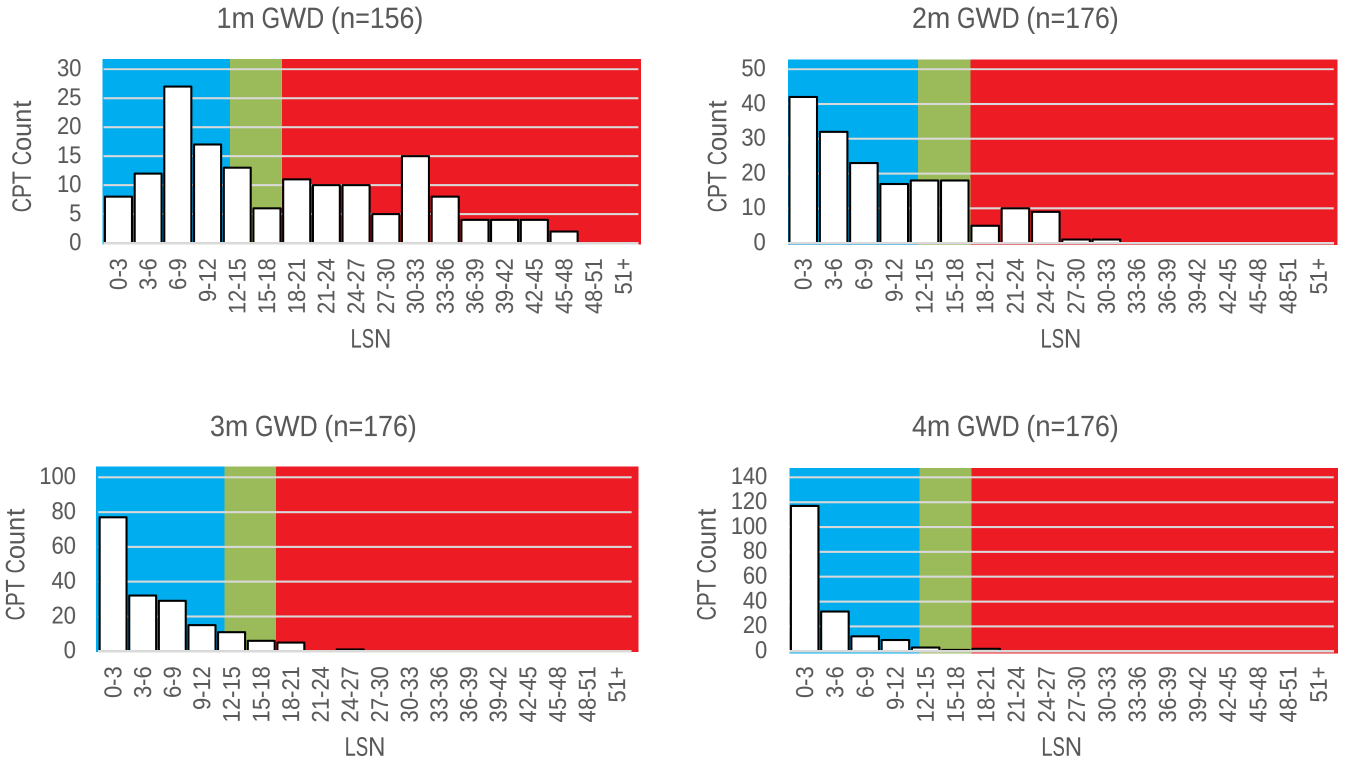


Figure C3.1

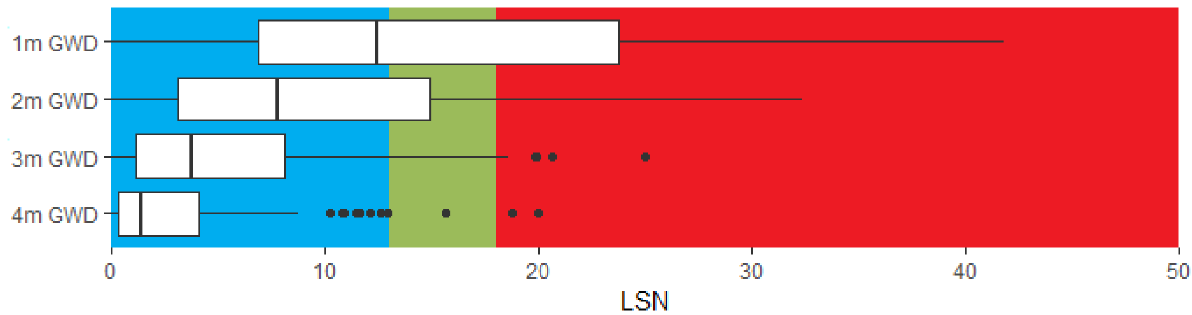
CPT based liquefaction analysis- Low Hills

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g)

Histograms of LSN values by ground water



Box and whisker plot of LSN values by ground water



Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required
The low hills generally represent areas of the Walton Subgroup. The liquefaction assessment of this zone indicates that this zone typically has lower liquefaction vulnerability than the other zones in the study area, with the LSN values for almost all CPTs plotting in the "*None to Minor*" land damage category for the scenario with groundwater at 4m depth. However, because specific groundwater depths across the area are unknown, the range of LSN values calculated for shallower groundwater depths means that it is not possible to assign a category of "*Liquefaction Is Unlikely*". A large proportion of the units within the Walton Subgroup exhibit clay-like behaviour, so site-specific confirmation of the presence of clay-like soil may lead to assigning a category of "*Liquefaction Is Unlikely*". The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present and whether or not they are susceptible to liquefaction should be the first component of the assessment of liquefaction vulnerability in this area. Groundwater likely to be deeper within this zone.	*Liquefaction Category Is Undetermined*	· Presence and thickness of soils exhibiting clay-like behaviour · Groundwater levels · Thickness and distribution of liquefiable layers · Proportion of pumiceous particles	· Confirm geological unit, i.e. Walton Subgroup · Confirm clay-like soils present. · Confirm whether groundwater is present within top 4m · Determine soil type to sufficient depth depending on the geological formation (top 4m if Walton Subgroup or Hinuera Formation are confirmed, deeper for more vulnerable units) · Assess soil relative density if non-plastic

Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (PL=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

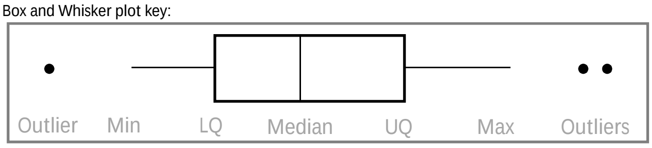
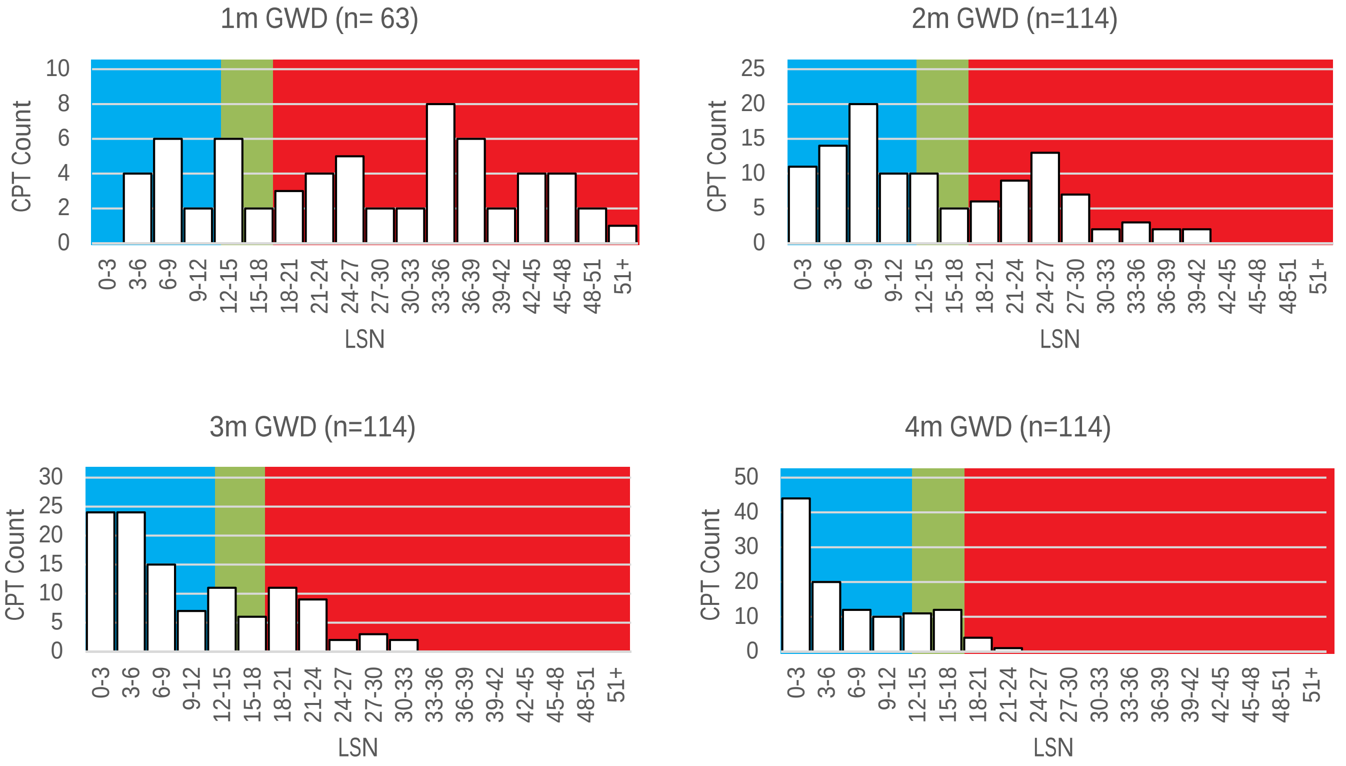


Figure C3.2

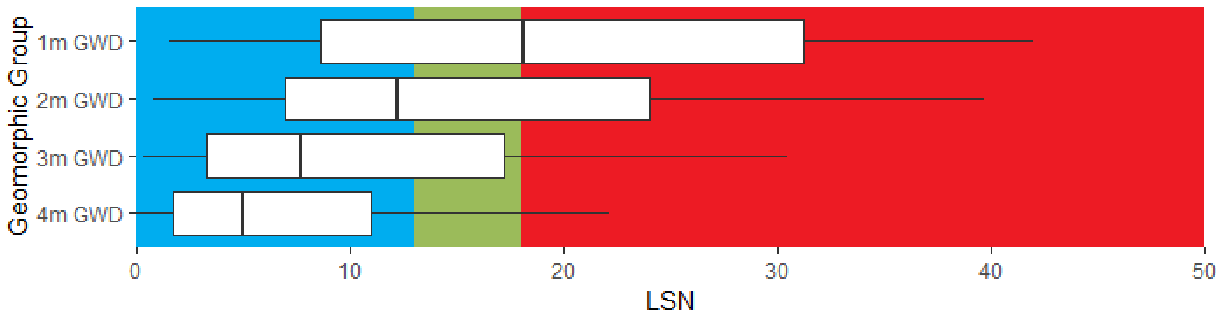
CPT based liquefaction analysis – Recent Gullies/River Terraces

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g)

Histograms of LSN values by ground water



Box and whisker plot of LSN values by ground water



Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required
This geomorphic zone shows a range of LSN and may also show two populations that could correspond to some of the gullies or river terraces being composed of denser material that has a greater resistance to liquefaction. Development within this zone may also be within the previously mapped gully hazard zone and as such will require engineering assessment due to the presence of unstable slopes. The gully bottoms are likely to contain looser, younger material and may often have high groundwater, meaning that higher LSN values would be common in this zone. The presence of uncontrolled fill in these areas will also exacerbate the risk. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. Deposits in gully bases are normally at or close to the median water table. River terraces are generally coincident with river level. Presence of perched water normally results in the development of gullies and instability.	*Liquefaction Damage Is Possible*	· Groundwater levels at slope margins · Geological unit · Perched water · Thickness and distribution of liquefiable layers · Proportion of pumiceous particles	· Confirm whether groundwater is present within top 4m · Determine geological unit · Determine soil type · Confirm whether uncontrolled fill is present Assess soil relative density

Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (PL=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18
These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).	

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

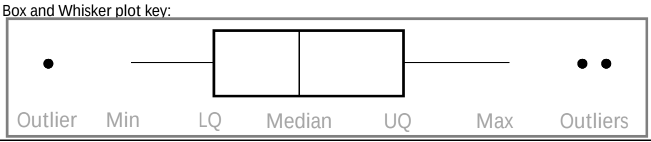


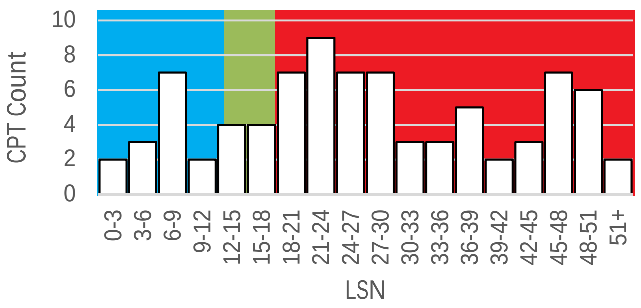
Figure C3.3

CPT based liquefaction analysis – Peat

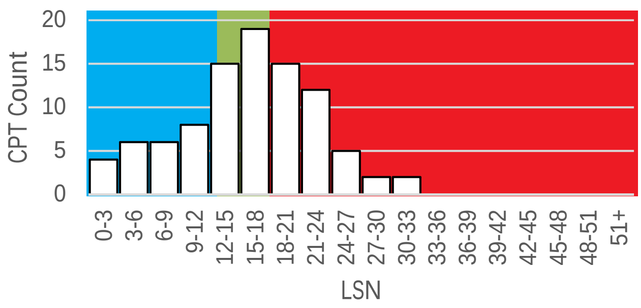
Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g)

Histograms of LSN values by ground water

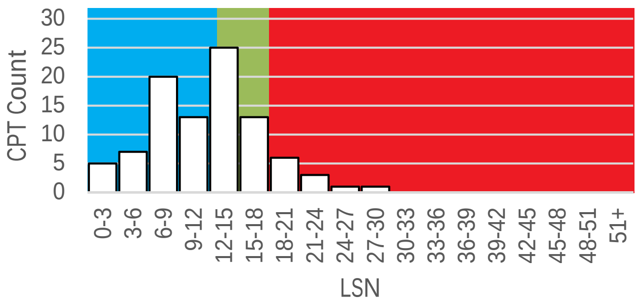
1m GWD (n=83)



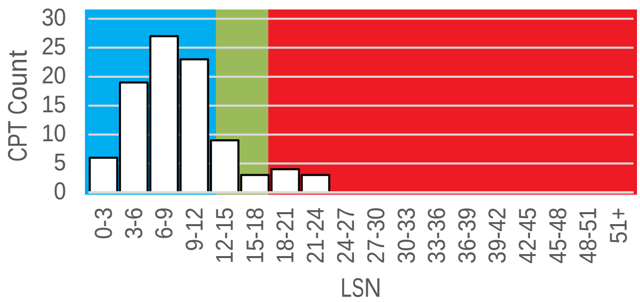
2m GWD (n=94)



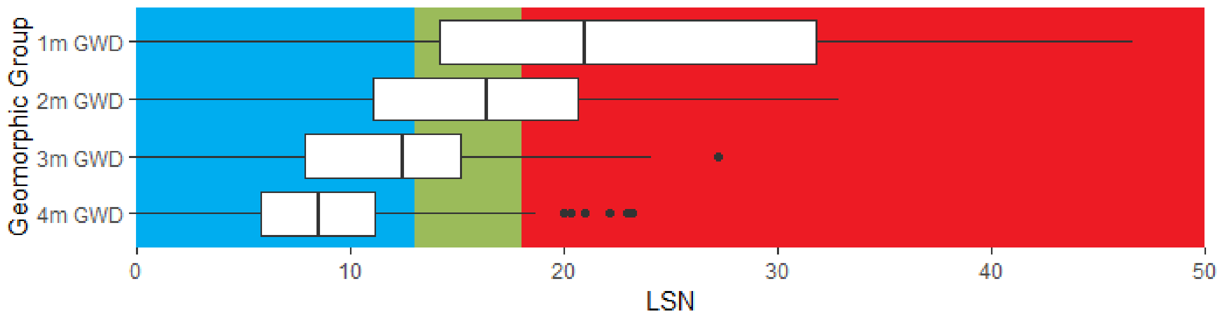
3m GWD (n=94)



4m GWD (n=94)



Box and whisker plot of LSN values by ground water



Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required
The peat areas of Hamilton are shown to have a wide range of LSN for the groundwater depths analysed. It is likely that groundwater in these areas will be high but other factors may determine the liquefaction vulnerability here. Peat itself has been shown to have a degree of liquefaction resistance, however this does depend on the fibrous nature of the peat. The underlying geology is an important factor and this should be determined. It is likely that any development within the peat areas will have further constraints such as static settlement from consolidation. This factor means careful engineering assessment is required when considering liquefaction vulnerability and other geotechnical constraints. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. This zone is typically characterised by shallow groundwater leading to swamp-like conditions. Often drained by swales, where water level is coincident with the depth of the swale.	*Liquefaction Damage Is Possible*	· Groundwater levels · Amount of organic material · Thickness of Peat · Underlying geology · Depth of foundations required to manage other geotechnical constraints	· Confirm geological unit · Confirm whether groundwater is present within top 4m · Determine peat thickness · Determine underlying geological unit · Consider proximity to slopes including swales · Other engineering factors will influence the liquefaction in peat

Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (PL=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18

These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).

Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:

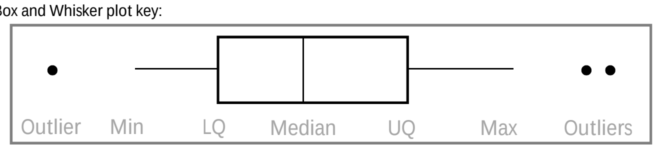
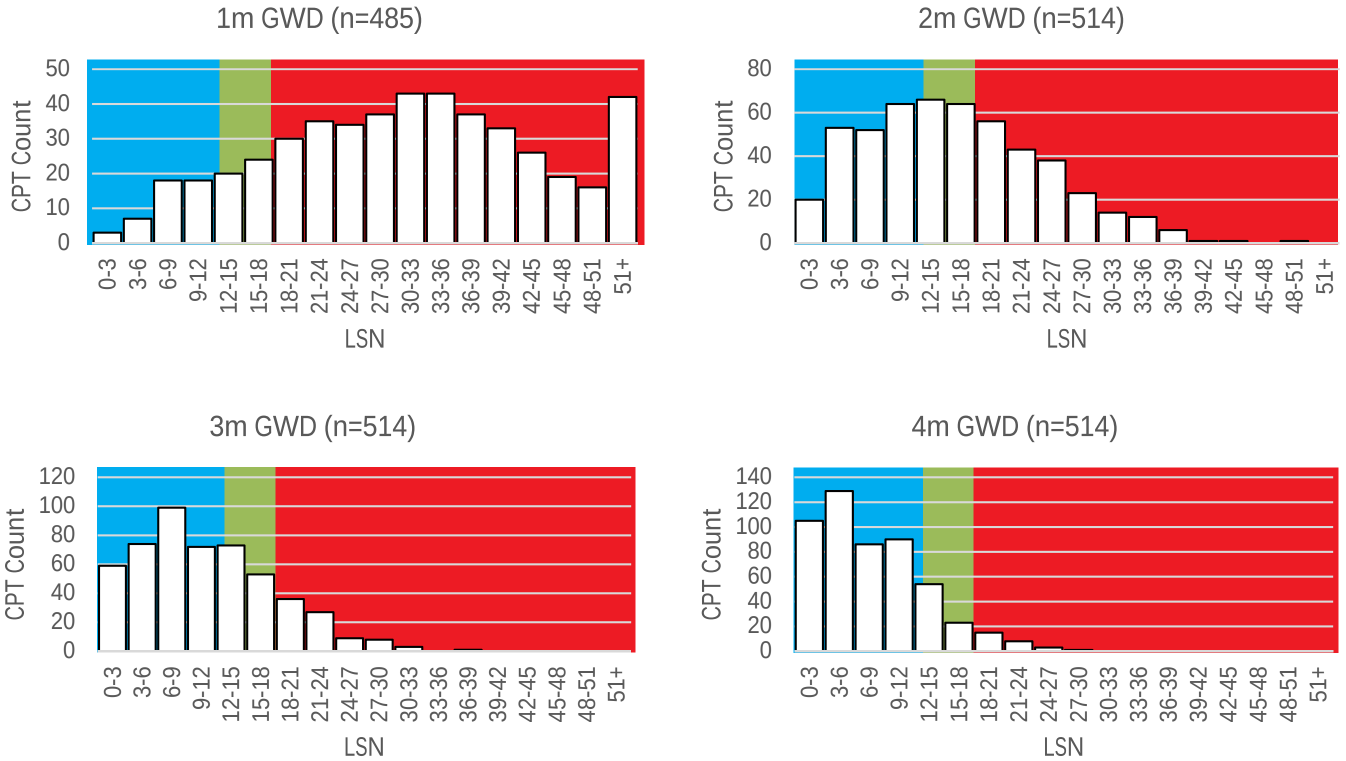


Figure C3.4

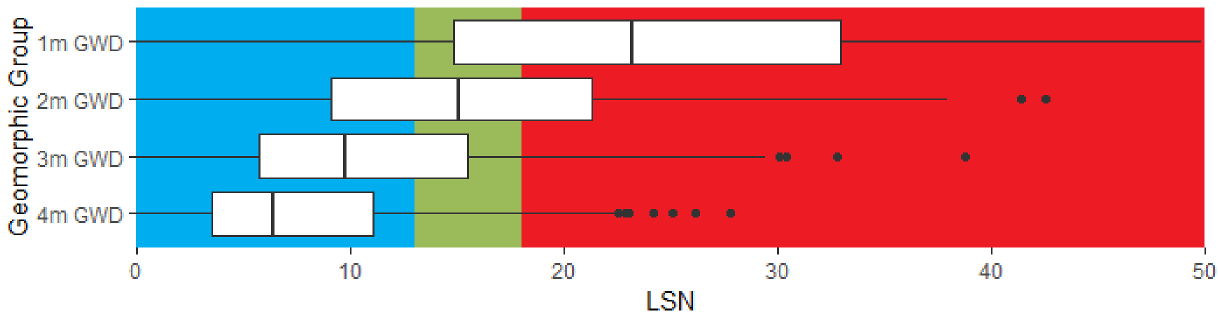
CPT based liquefaction analysis – Alluvial Plains

Scenario: 500 yr ARI (Mw=5.9,PGA = 0.22g)

Histograms of LSN values by ground water



Box and whisker plot of LSN values by ground water



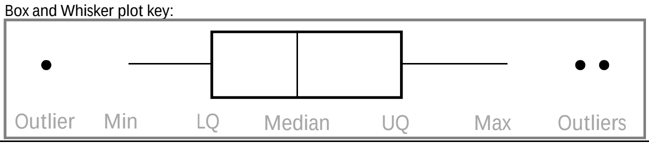
Summary of results	Liquefaction vulnerability category	Key uncertainties	Site specific information required
The alluvial plains are highly variable in geology both laterally and vertically. This is reflected in the wide range of LSN, especially at shallow groundwater depths. Land damage of *"None to Minor"* through to *"Moderate to Severe"* are all possible, as such a good understanding of the underlying geology is required. The site may be underlain a great thickness of liquefiable soil or may only have thin, intermittent liquefiable layers interbedded with medium dense to dense gravels. It has been suggested that the interfluve areas within the Hinuera Formation have increased liquefaction potential compared to channels or low ridges (McKay, Lowe, & Moon, 2017). Determining soil class by considering the landform present may be an indication of the liquefaction potential of the site. A site with a high water table and the presence of non-plastic soils may require CPT investigations to determine the land damage category applicable. The geological mapping has been undertaken at a scale that may lead to some CPTs being assigned to the incorrect geomorphic zone in the statistical analysis undertaken for this study. Confirmation of the geological unit/s present should be the first step in the assessment of liquefaction vulnerability within this area. Groundwater is typically relatively shallow when not controlled by localised drainage associated with river terraces, gullies and deep swales. Phreatic surfaces can be steep at slope margins depending on the underlying conditions.	*Liquefaction Damage Is Possible*	· Groundwater levels · Thickness and distribution of liquefiable layers · Proportion of pumiceous particles · Soil family (pedological soil class) · Geomorphology	· Confirm geological unit · Confirm whether groundwater is present within top 4m · Determine soil type to sufficient depth depending on the geological formation (top 4m if Hinuera Formation is confirmed, deeper for more vulnerable units) · Consider proximity to slopes including swales · Determine pedological soil class · Determine what landforms are present · Assess soil relative density

Legend

Degree of liquefaction induced ground damage	Characteristic LSN values (PL=15%)
None to Minor	0-13
Minor to Moderate	13-18
Moderate to Severe	>18
These values are intended only for use in area-wide hazard assessment using the MBIE (2017) performance criteria. Different values may be more appropriate for other purposes (such as site-specific design).	

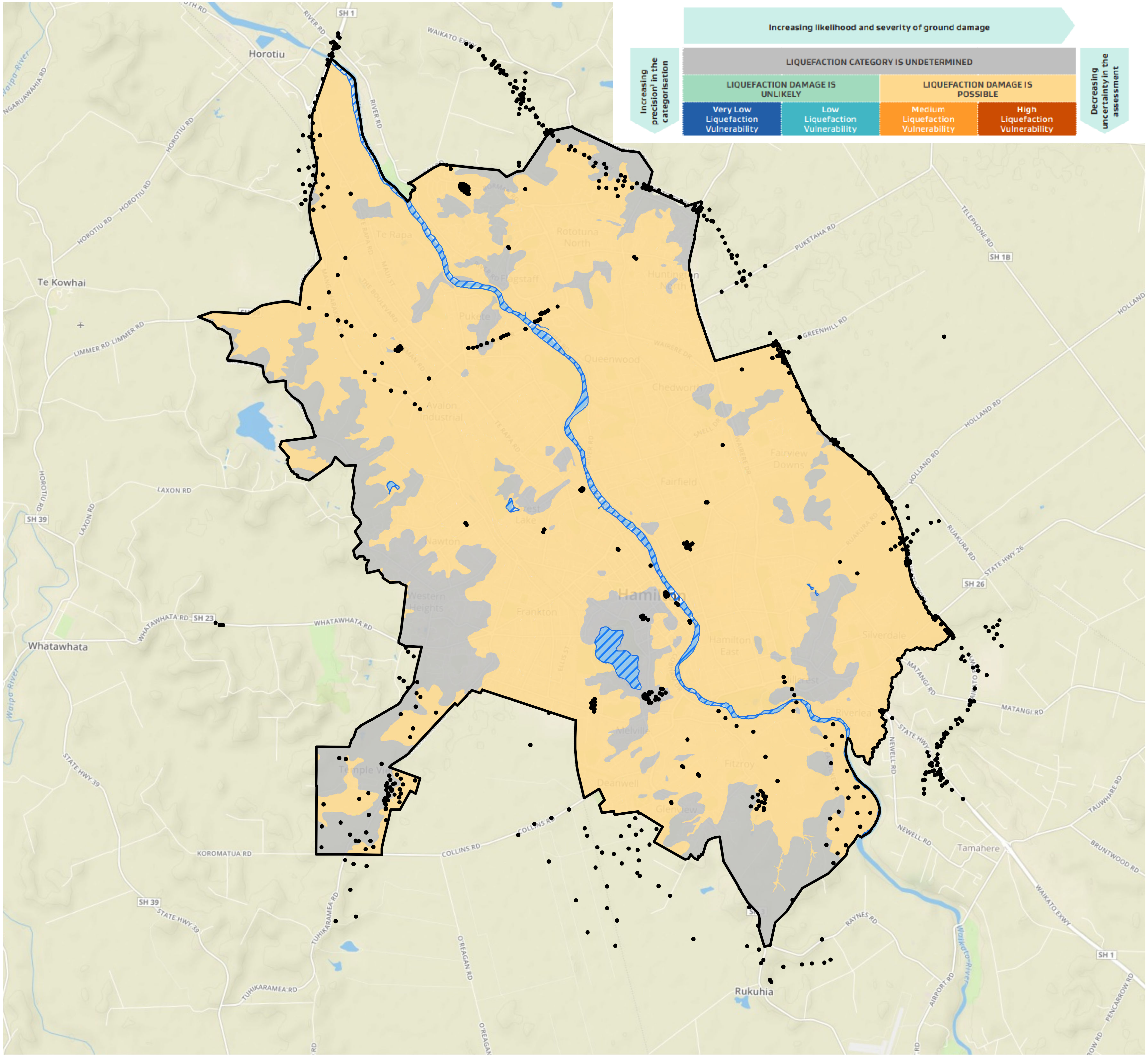
Notes

1. Refer to Table 2.2 and Appendix A of the MBIE liquefaction guidance document for further information about land damage categories.
2. Liquefaction analyses are undertaken assuming a probability of liquefaction (P_L) of 15%. (Refer to section 4.2 for further detail)
3. Box and Whisker plot key:



Appendix D: Liquefaction vulnerability assessment

- **Appendix D1 – Liquefaction vulnerability assessment map**



LEGEND

- Cone Penetration Test Locations
- Hamilton City Council Boundary

Liquefaction Vulnerability Categories

- Liquefaction Category is Undetermined
- Liquefaction Damage is Possible

Liquefaction Vulnerability Categories not used in this map

- Liquefaction Damage is Unlikely
- Very Low Liquefaction Vulnerability
- Low Liquefaction Vulnerability
- Medium Liquefaction Vulnerability
- High Liquefaction Vulnerability

Other

- Waterbodies

A3 SCALE: 1:70,000

0 1 2 3 4 5 (km)

Notes:
1. Cone Penetration Test locations sourced from New Zealand Geotechnical Database and Tonkin + Taylor Geotechnical Database.
2. Basemap sourced from the LINZ Data Service, CC 3.0 New Zealand license.
3.This liquefaction assessment has been undertaken in general accordance with the guidance document 'Assessment of Liquefaction-Induced Ground Damage to Inform Planning Processes' published by the Ministry of Business, Innovation and Employment in 2017.

DRAWN	MOLI	Oct.18
CHECKED	JICR	Oct.18
APPROVED	MEJ	Oct.18

ARCFILE 1007144_FIG005.mxd

SCALE (AT A3 SIZE) 1:70,000

PROJECT No. 1007144.000

Tonkin+Taylor
105 Carlton Gore Rd, Newmarket, Auckland
www.tonkintaylor.co.nz

HAMILTON CITY COUNCIL
HAMILTON LIQUEFACTION ASSESSMENT
Liquefaction Vulnerability Assessment

Figure D1.1

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