REPORT

Tonkin+Taylor

Clutha Delta Liquefaction Vulnerability Study

Prepared for
Otago Regional Council

Prepared by
Tonkin & Taylor Ltd

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LIQUEFACTION ASSESSMENT SUMMARY	
This liquefaction assessment has been undertaken in general accordance with the guidance document 'Planning and engineering guidance for potentially liquefaction-prone land' published by the Ministry for the Environment and the Ministry of Business, Innovation and Employment in 2017. https://www.building.govt.nz/building-code-compliance/b-stability/b1-structure/planning-engineering-liquefaction-land/	
Client	Otago Regional Council (ORC)
Assessment undertaken by	Tonkin & Taylor Ltd, PO Box 13055, Christchurch 8140
Extent of the Study Area	The Study Area aligns with the boundary defined in Figure 1.1.
Intended RMA planning and consenting purposes	To provide ORC with a catchment-wide liquefaction vulnerability assessment to identify areas of land susceptible to liquefaction. The technical report and resulting map outputs will be used to inform land use planning, subdivision consenting, and to identify areas where more detailed, site-specific liquefaction assessments (Level C or D) are likely to be required for building consent applications, in accordance with MBIE/MfE Guidance (2017).
Other intended purposes	To assess the potential impact on infrastructure, particularly the ORC's flood protection and drainage scheme.
Level of detail	Level A/B (basic/calibrated desktop assessment).
Notes regarding base information	The available base information, extended through the course of this project, provides enough information for a Level A (basic desktop assessment) level of detail across the majority of the Study Area. The main factor controlling this level of detail is the spatial extent of the available geotechnical investigations, groundwater information, and high-resolution elevation data. Level B (calibrated desktop assessment) is supported by the base information for the township of Balclutha.
Other notes	This assessment has been made at a broad scale across the entire study area and is intended to approximately describe the typical range of liquefaction vulnerability across neighbourhood-sized areas. It is not intended to precisely describe liquefaction vulnerability at individual property scale. This information is general in nature, and more detailed site-specific liquefaction assessment may be required for some purposes (e.g., for design of building foundations). A key consideration of the liquefaction vulnerability categorisation undertaken in accordance with the MBIE/MfE Guidelines (2017) is the degree of uncertainty in the assessment. Discussion about the key uncertainties in this assessment is provided in Section 3.3 of this report.

1 Introduction

Otago Regional Council (ORC) engaged Tonkin & Taylor Ltd (T+T) to improve the understanding of liquefaction vulnerability across the Clutha Delta. This work builds on previous assessments by incorporating additional geotechnical data collected during this study.

The scope for improving the liquefaction assessment was outlined in T+T (2023a)[1], where a Hybrid Level A/B approach was recommended and subsequently adopted by ORC. This hybrid method applies Level A assessment techniques, supplemented by Level B methods where sufficient data is available.

Existing geotechnical and geological information was previously summarised in T+T (2023b)[2]. Key elements have been reproduced or updated in this report as new data has become available. A primary outcome of the current assessment is a reduction in uncertainty related to ground conditions, which was identified in T+T (2023a) as the main residual uncertainty due to lack of information about the ground conditions.

Figure 1.1 shows the extent of the Study Area, including the townships of Balclutha and Kaitangata.

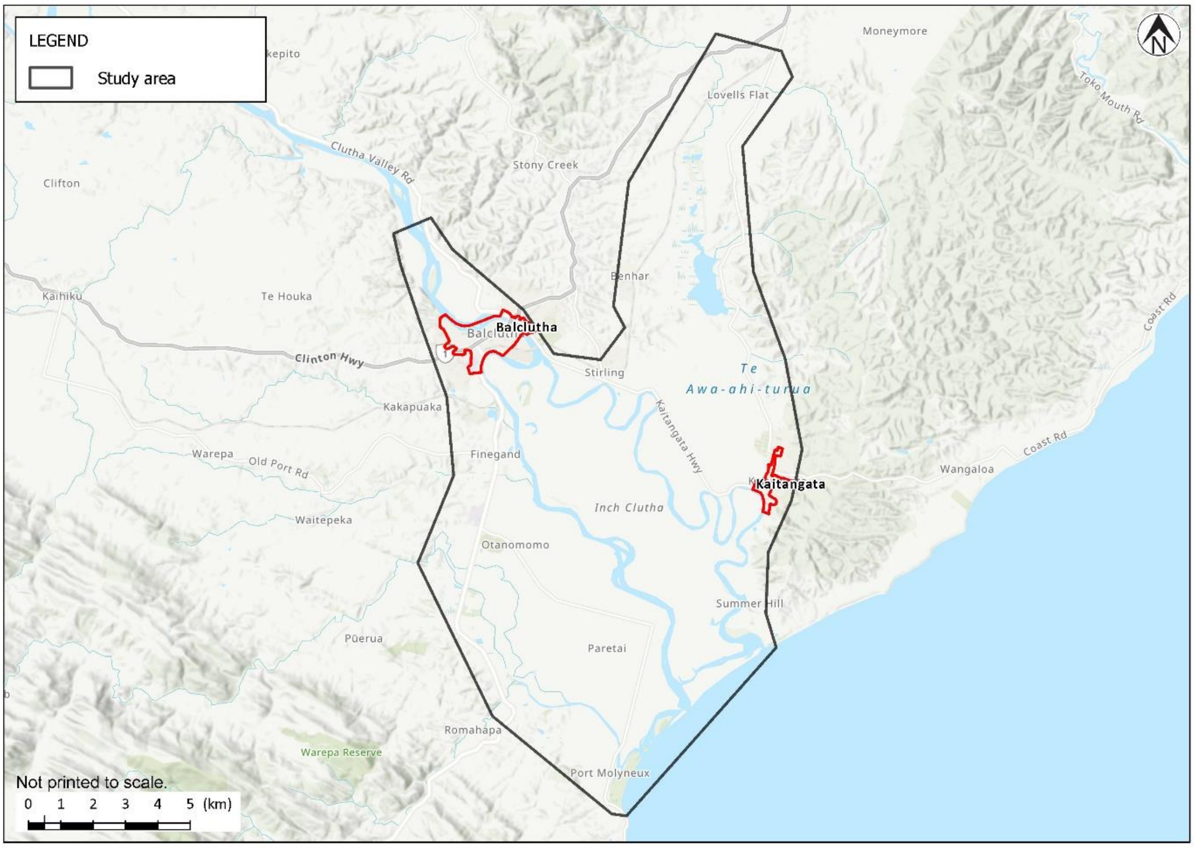

Figure 1.1: Map showing the extent of the Study Area and the townships of Balclutha and Kaitangata.

[1] Tonkin & Taylor Ltd (2023a). Potential scope for the assessment of liquefaction. Job Number: 1090955.0000.

[2] Tonkin & Taylor Ltd (2023b). Evaluation of base information available for the Clutha Delta – Future liquefaction vulnerability assessments. Job Number: 1090955.0000.

This report includes:

- An overview of the project context, the intended use of the findings, and a summary of the compiled liquefaction hazard information (Section 2).
- Liquefaction risk identification (Section 3), including:
  - Discussion regarding appropriate level of detail for the intended purpose (Section 3.1);
  - Summary of relevant base information (Section 3.2); and
  - Assessment of uncertainty in the available data (Section 3.3).
- Liquefaction risk analysis (Section 4), including:
  - Evaluation of groundwater conditions and earthquake scenarios, and sub-area delineation based on expected ground behaviour (Sections 4.1 to 4.3);
  - Assessment of liquefaction vulnerability using MBIE/MfE (2017) guidance (Section 4.4).
- Discussion of the results and key conclusions (Section 5).

The structure of this assessment follows the ISO 31000:2018 risk management process, as shown in Figure 1.2.

It is noted that this report focuses solely on liquefaction hazards. Other natural hazards and geotechnical constraints should also be considered in any future land development or building activity.

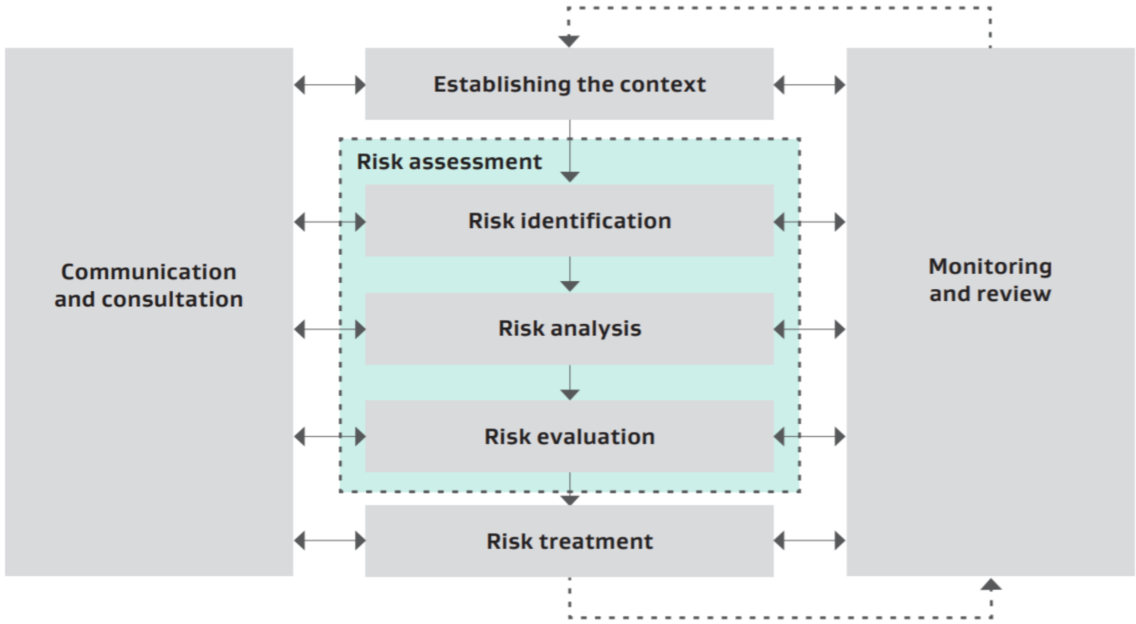

Figure 1.2: Risk management process defined in ISO 31000:2009, which has been used to guide the liquefaction vulnerability assessment and the layout of this report – reproduced from MBIE/MfE Guidance (2017). Note, this figure has been slightly modified in the ISO 31000:2018 standard, however the general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

2 Context

2.1 MBIE/MfE Guidance (2017)

The MBIE/MfE Guidance (2017)[3] sets out a risk-based approach to managing liquefaction-related risk in land use planning and land development decision-making. It was developed in response to the 2010–2011 Canterbury Earthquake Sequence, following recommendations from the Royal Commission of Inquiry into Building Failure caused by the Canterbury Earthquakes.

The guidance aims to support assessments of liquefaction-induced ground damage within the context of the Resource Management Act (RMA) and Building Act. In addition to its role in planning and consenting, liquefaction hazard information may be used in a range of other applications. As outlined in Section 1.2 of the guidance, these include:

- Long-term strategic land use planning
- Development of natural hazard management processes
- Design of land development, buildings, and infrastructure
- Earthquake-prone building assessments
- Enhancing infrastructure and lifelines resilience
- Civil defence and emergency management planning
- Catastrophe loss modelling for insurance and disaster risk reduction

Further detail on the risk-based approach to managing liquefaction hazard is provided in Section 3 of the MBIE/MfE Guidance (2017).

2.2 Background to this project

ORC commissioned this assessment to identify and delineate areas within the Study Area that have the potential for liquefaction-induced ground damage.

The Study Area encompasses a range of landscapes with varying susceptibility to liquefaction hazards. This assessment aims to improve the understanding of liquefaction vulnerability across the area and produce a liquefaction vulnerability map for use by a range of stakeholders.

The study findings are anticipated to be of value to a range of stakeholders and are intended to:

- Inform landowners and residents of the potential risks posed by liquefaction/lateral spreading.
- As an input to the Clutha Delta natural hazards adaptation programme, particularly to inform assessments of seismic risks.
- For the ORC Engineering team, as a high-level assessment of potential liquefaction impacts on scheme infrastructure, and the potential cascading impacts on the performance of the Lower Clutha Drainage and Flood Protection Scheme.
- For Clutha District Council (CDC), to build their awareness of the potential hazard, and to identify areas where this hazard may need to be considered more closely in building consent processes and infrastructure management.
- For Emergency Management Otago, to build their understanding of potential event consequences for a major earthquake.

[3] Ministry of Business, Innovation and Employment (MBIE) and the Ministry for the Environment (MfE) (2017). Planning and engineering guidance for potentially liquefaction-prone land.

2.3 Liquefaction hazard

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

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

1 Loose non-cohesive or weakly cohesive soil (typically sands and silts, sometimes gravels, or fine-grained soils with low plasticity).
2 Saturated or near-saturated soil (e.g. below the groundwater table or in zones influenced by capillary rise).
3 Sufficient ground shaking (a combination of the duration and intensity of shaking).

Figure 2.1 and Figure 2.2 summarises the process of liquefaction through a schematic representation.

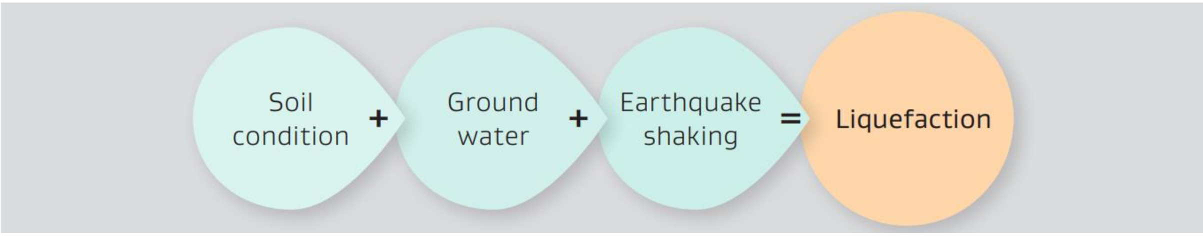

Figure 2.1: Three key elements required for liquefaction to occur - reproduced from MBIE/MfE Guidance (2017).

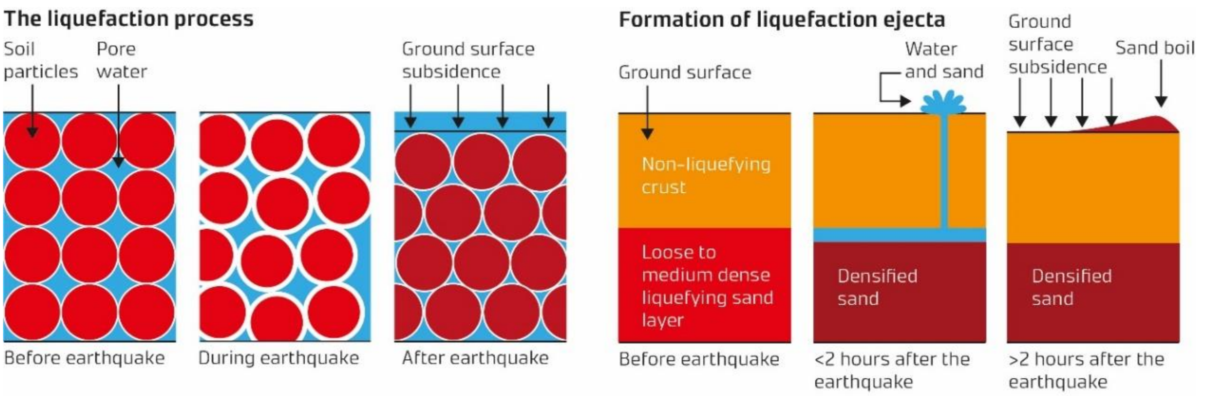

Figure 2.2: Schematic representation of the process of liquefaction and the manifestation of liquefaction ejecta - reproduced from MBIE/MfE Guidance (2017).

Liquefaction can result in significant damage to land and structures. Common manifestations include the ejection of sediment to the ground surface, differential settlement due to volume loss in liquefied soils, and lateral ground movement (lateral spreading). These effects are summarised in Table 2.1.

The consequences of liquefaction can be severe, ranging from land damage to widespread social and economic disruption, as observed during the 2010–2011 Canterbury Earthquake Sequence.

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

Land	• Sand boils, where pressurised liquefied material is ejected to the surface (ejecta). • Ground settlement and undulation, due to consolidation and ejection of liquefied soil. • Ground cracking from lateral spreading, where the ground moves downslope towards an unsupported face (e.g., a river channel or terrace edge).
Environment	• Discharge of sediment into waterways, impacting water quality and habitat. • 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 weather tightness of the building. • Loss of foundation-bearing capacity, resulting in settlement of the structure. • Stretch of the foundation due to lateral spreading, pulling the structure apart. • Damage to piles due to lateral ground movements, and settlement of piles due to downdrag 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 deformations (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 stopbanks, 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 are 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).

The consequences of liquefaction at any location can vary depending on several factors, including:

- **Soil conditions** – Liquefaction is most likely to occur in loose non-cohesive or weakly cohesive soil (typically sands and silts, sometimes gravels, or fine-grained soils with low plasticity). It is unlikely to occur in plastic soils (e.g. clays), dense gravels, or rock. The depositional environment (e.g. river, estuarine, or marine) also influences the soil layering. Thick, continuous layers of liquefiable soil tend to result in more severe consequences than thin, isolated layers interbedded with non-liquefiable material.
- **Depth to groundwater** – Liquefaction occurs in saturated soils. A deeper groundwater table results in a thicker surface crust of non-liquefied material, which can reduce surface manifestation and mitigate overall ground damage.
- **Intensity of earthquake shaking** – More severe shaking can cause a greater thickness of the soil profile to liquefy, increasing the potential for damage.
- **Proximity to free faces or sloping ground** – Lateral spreading typically occurs in liquefiable soils near a free face (e.g. riverbank, channel, or road cut) or sloping terrain. The closer the site is to these features, the more severe the likely consequences.

2.4 Previous liquefaction studies

In 2019, GNS completed a liquefaction hazard assessment for the Queenstown Lakes, Central Otago, Clutha, and Waitaki Districts[4]. The report describes the work as an "office-based evaluation of existing available information", equivalent to a basic desktop assessment as defined in the MBIE/MfE (2017) guidance on liquefaction-prone land.

The GNS study was based on the following information sources:

- Geological, landform, and soil maps
- Topographic data from maps, LiDAR, aerial imagery, and ground photography
- Borehole records and groundwater depth measurements

The assessment differentiated areas underlain by rock or firm sediments, which are unlikely to liquefy, from those underlain by other geologic units that may be susceptible to liquefaction under strong ground shaking.

As part of the assessment, GNS developed a map classifying liquefaction susceptibility using a three-domain system:

- Domain A – Areas predominantly underlain by rock or firm sediments. GNS state that “*it is unlikely that damaging liquefaction could occur*” in these areas.
- Domain B – Areas predominantly underlain by poorly consolidated fluvial sediments with shallow groundwater. GNS consider a “*low to moderate likelihood of liquefaction-susceptible materials being present in some parts*” of this domain. A sub-classification, Domain B1, was applied where geotechnical data indicated the localised presence of susceptible materials.
- Domain C – Areas underlain by poorly consolidated marine or estuarine sediments with shallow groundwater. GNS identify a “*moderate to high likelihood of liquefaction-susceptible material being present in some parts*” of this domain and note that associated ground damage could range from moderate to severe.

[4] Barrell, D. J. A. (2019). Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago Region. Lower Hutt (NZ): GNS Science. Consultancy Report 2018/67. Prepared for Otago Regional Council.

The GNS report links the three domains to liquefaction vulnerability categories from the MBIE/MfE Guidance (2017). Domain A corresponds to ***Liquefaction Damage is Unlikely***, while Domains B, B1, and C correspond to ***Liquefaction Damage is Possible***.

The GNS-derived liquefaction susceptibility domains for the Study Area are shown in Figure 2.3.

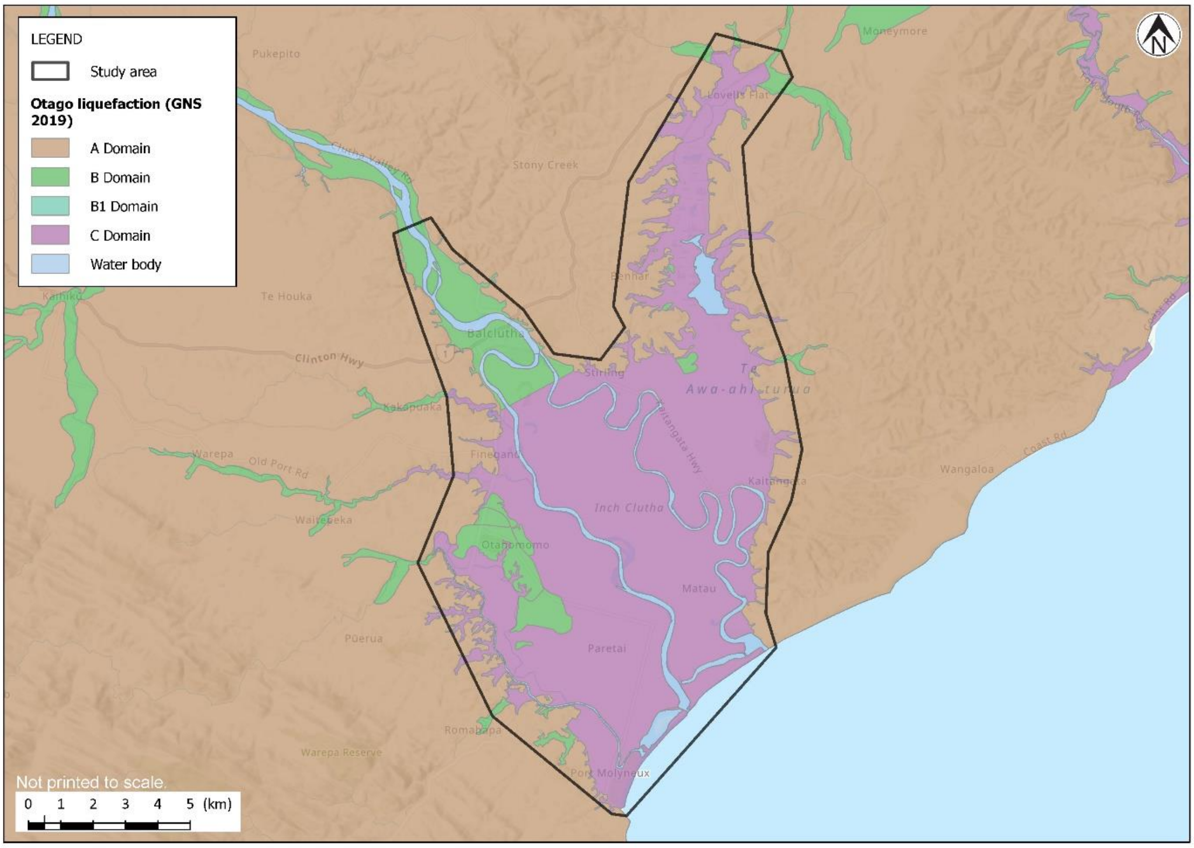

Figure 2.3: GNS liquefaction susceptibility domains within the Study Area (GNS, 2019).

3 Risk identification

3.1 Level of detail

This section outlines the risk identification process undertaken for the liquefaction vulnerability assessment of the Study Area.

The first step was to determine the level of detail required for the intended purpose of the assessment (refer to Section 3.1.2). This involved evaluating the key features associated with each level of detail, as defined in the MBIE/MfE Guidance (2017), and considering ORC's intended applications of the assessment outcomes.

The second step was a review of the base information available for the Study Area (refer to Section 3.2). This included:

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

3.1.1 Level of detail hierarchy

The MBIE/MfE Guidance (2017) outlines four levels of assessment detail, from Level A (least detailed) to Level D (most detailed). Figure 3.1 presents the key features of each level.

A core principle of the level of detail hierarchy is the concept of residual uncertainty—the uncertainty that remains after all available information has been considered. This residual uncertainty is a critical factor in determining whether the assessment is suitable for its intended purpose and helps to guide subsequent risk evaluation and treatment.

Two components inform the determination of the appropriate level of detail:

- The level of detail required for the intended purpose, based on stakeholder consultation and the specific planning and development applications (refer to Section 3.1.2).
- The level of detail supported by the available base information, considering both data quality and the level of uncertainty (refer to Sections 3.2 and 3.3).

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

Increasing level of detail and decreasing degree of uncertainty

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

3.1.2 Level of detail required for intended purposes

Section 3.5 of the MBIE/MfE Guidance (2017) provides recommendations on the appropriate level of detail for liquefaction assessments, based on development intensity, expected ground damage, and the intended use of the outputs.

ORC selected a target level of detail of Level A across the wider district, with Level B applied in areas of higher development focus—specifically Balclutha and Kaitangata.

This decision considered:

- The range of intended uses for the liquefaction vulnerability assessment.
- The minimum level of detail required for those uses.
- The availability, spatial density, and extent of supporting data.
- Whether adopting a higher level of detail than the minimum would improve overall outcomes.

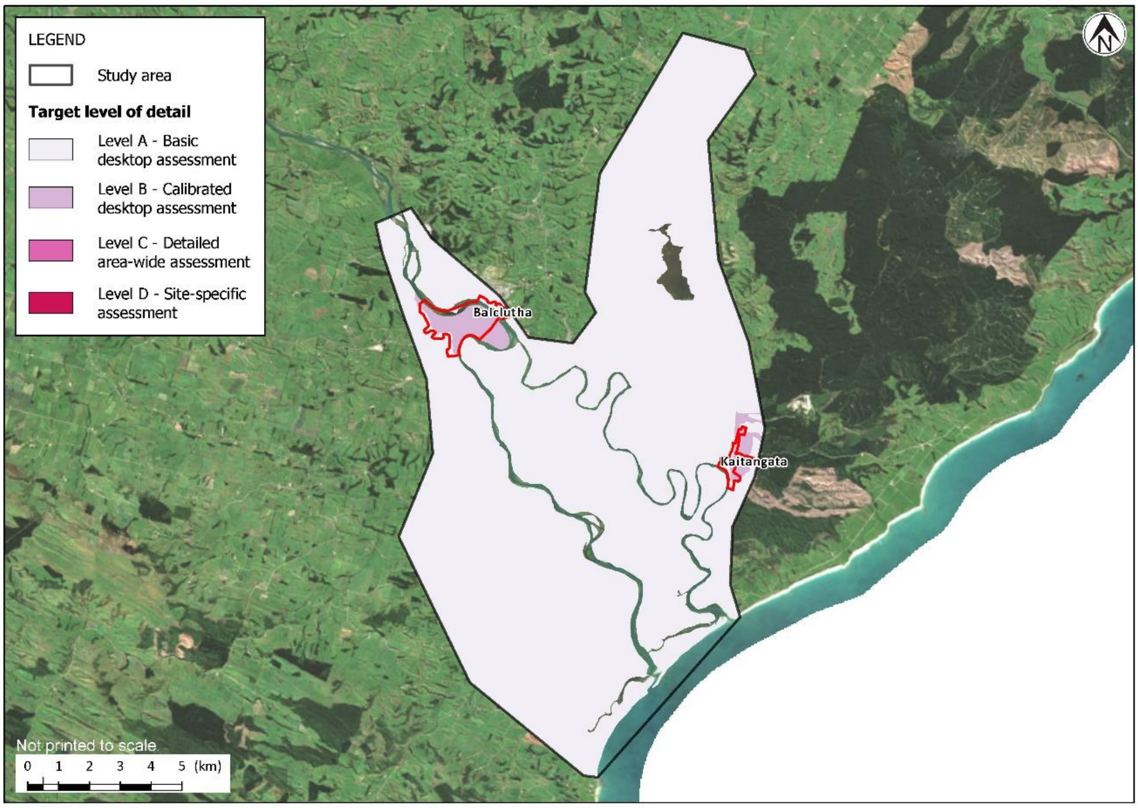

Figure 3.2: Target level of detail for the Study Area – Level A (Basic Desktop Assessment) and Level B (Calibrated Desktop Assessment). Refer to Appendix A for a larger map.

3.2 Base information

This section summarises the base information available for the liquefaction vulnerability assessment and outlines how it has been applied within the risk identification process. The information reviewed includes:

- Ground surface levels
- Geology and geomorphology
- Geotechnical investigations
- Groundwater information
- Seismic hazard
- Historical observations of liquefaction

A high-level assessment of the quality and suitability of each data source has been undertaken to determine its appropriateness for use in this study.

3.2.1 Ground surface levels

The ground surface levels of the entire Study Area are well characterised by LiDAR-derived Digital Elevation Models (DEM). Table 3.1 provides information about the most recent LiDAR data acquisitions.

The extent of coverage and level of resolution of this LiDAR data is considered suitable for the purposes of liquefaction vulnerability assessments.

Table 3.1: Recent LiDAR data acquisitions for the Study Area

Commissioning agency	Year of acquisition	Acquisition by	DEM Resolution (m)	Coverage of Study Area
Otago Regional Council	2024	Landpro	0.25	Balclutha
Otago Regional Council	2021	AAM Ltd	1.0	Otago coastal catchments
Otago Regional Council	2020	Landpro	1.0	Clutha Delta
Otago Regional Council	2016	Aerial Surveys	1.0	Clutha coastal margin

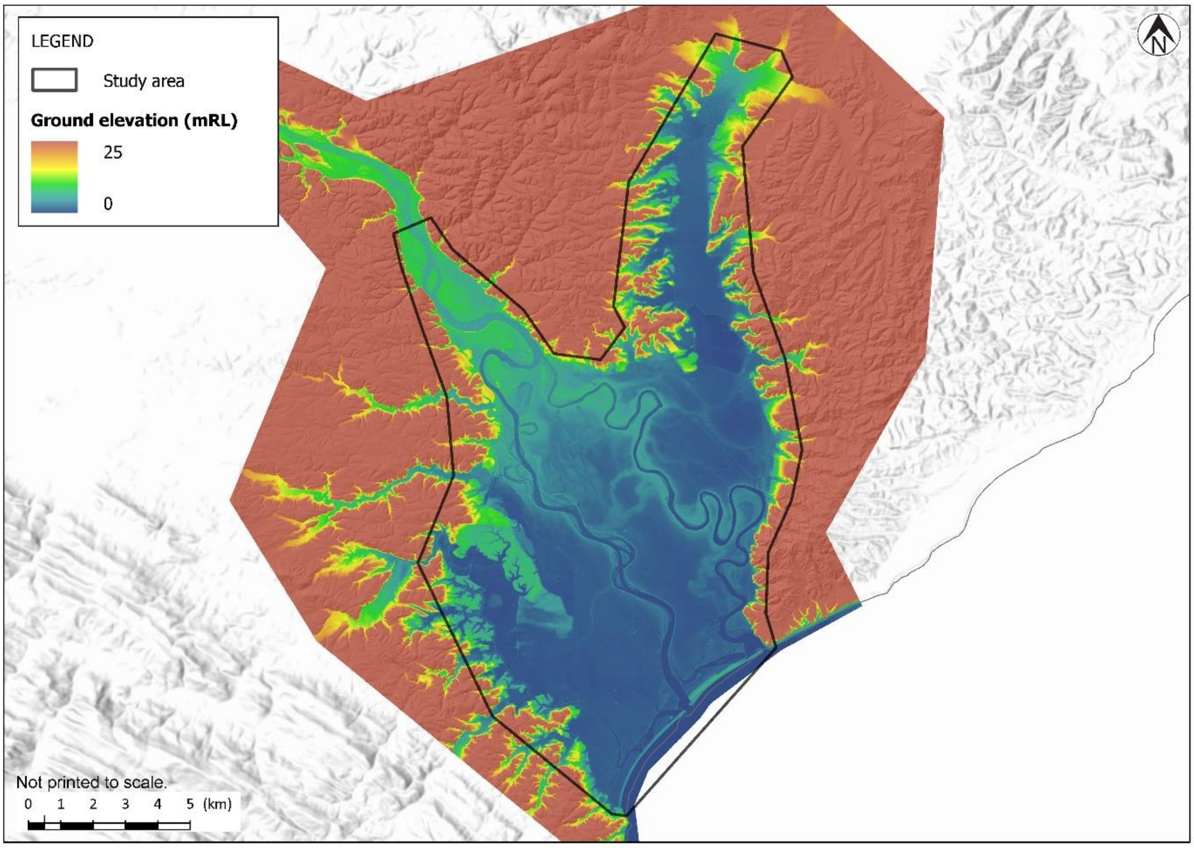

Figure 3.3: Ground surface elevation for the Clutha Delta, 1m LiDAR-derived DEM (2021). Refer to Appendix A for a larger map.

3.2.2 Geology and geomorphology

The Clutha Delta has formed at the mouth of the Clutha River, where the river discharges into the Pacific Ocean near Molyneux Bay. The delta is characterised by extensive alluvial sediments deposited over time by fluvial and coastal processes. These unconsolidated Holocene and Pleistocene sediments are depositional environments like those known to have experienced liquefaction in past New Zealand earthquake events.

The geological and soil information used to inform this study is summarised in Table 3.2.

Table 3.2: Available geological and soil maps in the Study Area

Title	Authors	Published date	Scale	Comments
Geology of the Murihiku area	Turnbull, I.M & Allibone, A.H (Compilers)	2003	1:250,000	Georeferenced
Geology of the Dunedin area	Bishop, D.G & Turnbull, I.M. (Compilers)	1996	1:250,000	Georeferenced
S-MAP Online	Manaaki Whenua Landcare Research	2021	1:20,000 – 1:50,000	Georeferenced

A high-level classification of lithological units across the Study Area has been developed from the QMAP 1:250,000 series. The geology map is shown in Figure 3.4. Table 3.3 summarises the approximate land area associated with each unit, along with an indication of typical liquefaction susceptibility for these types of deposits.

Table 3.3: Description of high-level lithology and the land area within Study Area

Lithology type	Description	Typical liquefaction susceptibility for this type of deposit	Area (km²)	Proportion of study area (%)
Basement and sedimentary rock	Cretaceous to Paleogene-aged bedrock	Less likely to be susceptible	35	22
Pleistocene gravel, sand, silt, clay	River and shoreline deposits	More likely to be susceptible	15	9
Holocene gravel, sand, silt, clay	River, shoreline, swamp, and windblown deposits	Most likely to be susceptible	111	69

Additional geomorphic context is provided in a GNS Science report by Barrell & Crundwell (2022)[5], which includes a geomorphic map of the Clutha Delta. This map categorises the delta into four main terrain types (with expected liquefaction susceptibility):

- **Holocene river plains** – The active, low-lying floodplain of the Clutha River. These areas are expected to be more susceptible to liquefaction due to typical shallow groundwater and prevalence of liquefiable sands and silts.
- **Alluvial fans** – Broad, fan-shaped sediment deposits from tributary streams at the valley margins. While potentially containing some susceptible materials, these are generally expected to have deeper groundwater and less fine grained non-cohesive soils making them less susceptible overall.
- **River terraces** – Deposits from older river systems, generally 2–8 m above the Holocene river plain. Because of their age and deeper groundwater these deposits are considered less susceptible to liquefaction.
- **Marine terraces** – Sediment accumulations overlying wave-cut erosion surfaces, typically elevated above current sea level. Because of their age and deeper groundwater these deposits are considered less susceptible to liquefaction.

For this project, an additional geomorphic terrain—**Hills, ranges and mountains**—has been incorporated to capture terrain outside of these four categories. This unit includes elevated and rolling terrain generally underlain by older, more consolidated geological materials and is considered the least susceptible to liquefaction of all these geomorphic terrains.

The geomorphic map is shown in Figure 3.5. T+T obtained a digital copy of this dataset from GNS under licence solely for use in this assessment.

[5] Barrell, D. J. A. & Crundwell, M. P. (2022). Radiocarbon dating and geological assessment of sediments associated with the Clutha River delta, South Otago. GNS Science Consultancy Report 2022/108.

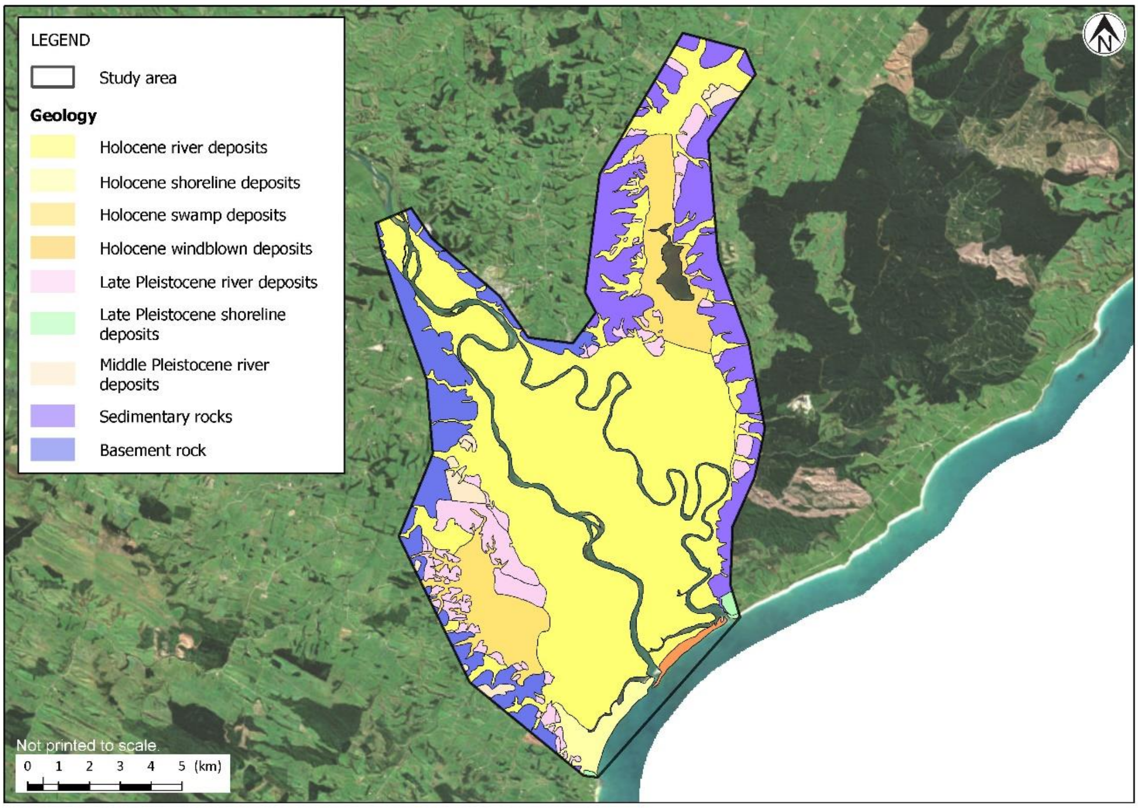

Figure 3.4: Geology of the Clutha Delta (derived from QMAP with boundaries defined in GNS (2022)). Refer to Appendix A for a larger map.

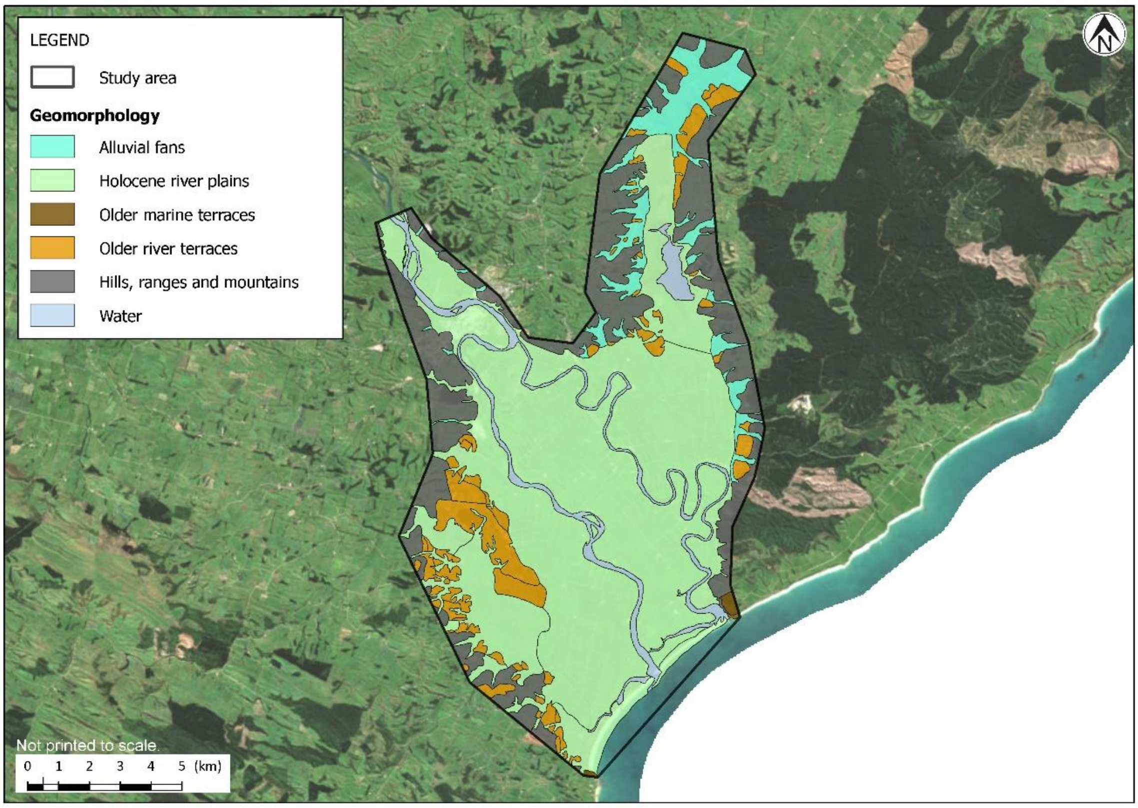

Figure 3.5: Geomorphology of the Clutha Delta (GNS, 2022). Refer to Appendix A for a larger map.

3.2.3 Geotechnical investigations

Geotechnical investigation data from the New Zealand Geotechnical Database (NZGD) were reviewed for this assessment. The available investigations include Cone Penetration Tests (CPTs), machine boreholes, and hand augers.

As part of this project, an additional 29 CPTs were undertaken across the Clutha Delta to increase the availability of ground investigations. These CPTs were carried out by Geotechnics over a three-week period in November 2024. Target investigation depths were 20 m, unless practical refusal was encountered at a shallower depth. Locations were selected to provide broad spatial coverage across the Study Area.

Table 3.4 presents the total number of geotechnical investigations available as of 1 March 2025. Figure 3.6 shows the spatial distribution of all investigations, with the CPTs completed as part of this project highlighted. Figure 3.7 illustrates the spatial density of CPT coverage across the Study Area.

Table 3.4: Summary of geotechnical investigation information within the Study Area as of 1 March 2025

Investigation type	NZGD count (No.)		
	Clutha Delta (including Balclutha and Kaitangata)	Balclutha	Kaitangata
CPT	123	61	3
SCPT	0	0	0
Machine drilled borehole	17	5	0
Hand auger borehole	3	0	0
Machine excavated trial pit	1	0	0

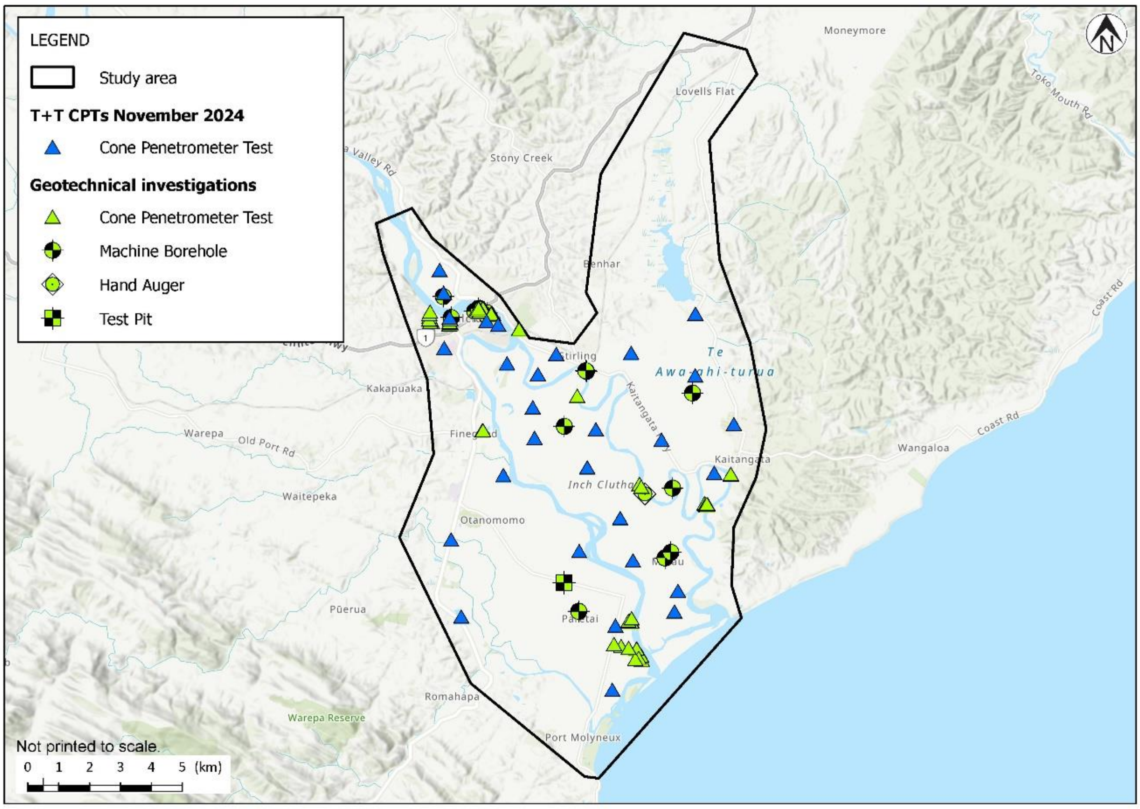

Figure 3.6: Geotechnical investigations in the Clutha Delta available on NZGD as of 1 March 2025, with the new CPTs undertaken as part of this project shown in blue. Refer to Appendix A for a larger map.

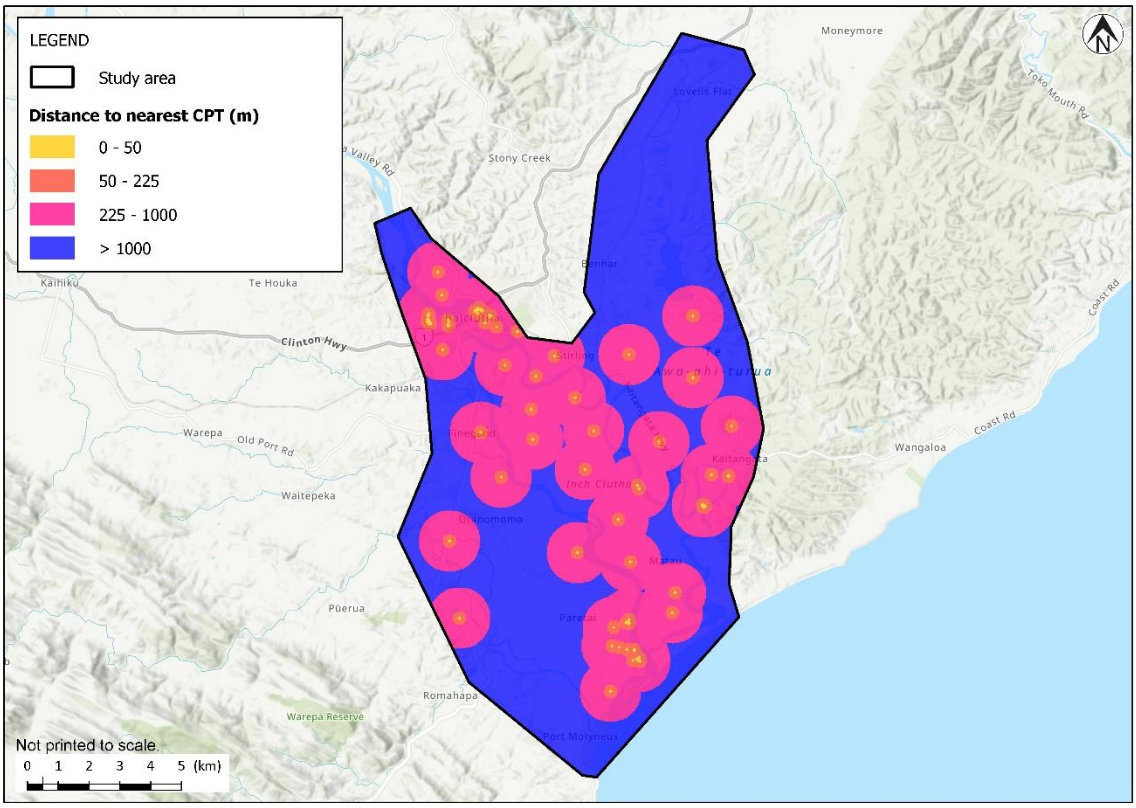

Figure 3.7: Spatial density of CPT investigations. Refer to Appendix A for a larger map.

Table 3.5: Summary of CPTs undertaken for this project

Investigation ID[1]	Easting (m NZTM2000)	Northing (m NZTM2000)	Depth of investigation (m)	Depth of predrill (m)	Depth to groundwater (inferred from CPT trace)
CPT01	1347808	4874233	7.18	0	1.9
CPT02	1349005	4874126	7.16	0	2.2
CPT03	1349383	4874006	20.2	0	2.1
CPT04	1347635	4873253	4.18	0	Null
CPT05	1347618	4875036	20.6	0	2.6
CPT06	1347487	4875777	20.59	0	0.8
CPT07	1351260	4873058	1.5	0	Null
CPT08	1350667	4872403	6.68	0	1.9
CPT09	1349668	4872754	16.3	0.3	1.8
CPT10	1350501	4871331	22.11	0	1.6
CPT11	1352541	4870620	20.6	0	0.4
CPT12	1350557	4870339	23.6	0	0.6
CPT14	1352263	4869385	19.39	0	0.6
CPT15	1353329	4867741	20.1	0	0.6
CPT16	1353743	4866372	20.6	0	0.8
CPT17	1355198	4865388	12.16	0	0.6
CPT18	1355086	4864716	13.2	0	0.9
CPT19	1349549	4869135	5.74	0	1.6
CPT21	1347860	4867048	13.82	0	1.4
CPT22	1352002	4866673	20.58	0	0.4
CPT24	1348186	4864556	1.46	0	Null
CPT26	1353175	4864260	11.94	0	0.7
CPT27	1353075	4862186	10.09	0	0.8
CPT29	1353684	4873093	20.13	0	1
CPT30	1355757	4872360	10.06	0	0.9
CPT31	1356372	4869208	20.24	0.15	1.8
CPT32	1354667	4870276	6.86	0	0.9
CPT33	1357006	4870786	10.66	0	0.8
CPT34	1355764	4874359	7.54	0	1

Notes:

1. Originally 35 investigations were targeted, but 6 were abandoned due to land access constraints.

3.2.4 Groundwater information

Soils must be saturated or nearly fully saturated for liquefaction to occur. In typical liquefaction assessments, the groundwater table is assumed to occur at some depth below the ground surface, below which soils are considered to be fully saturated.

Within the Study Area, ORC operates eight groundwater monitoring wells that provide continuous groundwater level data. These are summarised in Table 3.6.

Table 3.6: Groundwater bores monitored by ORC within the Study Area

Well number	Type	Depth (m)	Screen depth (m)	Data capture start	Recording interval	Location
CF15/0105	Piezometer	6.3	3.3 – 6.3	18/08/2022	1 hour	Centre Road, Inch Clutha
CF15/0106	Piezometer	38	35 – 38	18/08/2022	1 hour	Centre Road, Inch Clutha
CF15/0107	Piezometer	6	3 – 6	18/08/2022	1 hour	Centre Road, Inch Clutha
CF15/0108	Piezometer	6	3 – 6	18/08/2022	1 hour	Lawson Road, Inch Clutha
CF15/0109	Piezometer	39.4	36.4 – 39.4	18/08/2022	1 hour	Lawson Road, Inch Clutha
CF15/0110	Piezometer	6	3 – 6	18/08/2022	1 hour	Kaitangata
CG15/0101	Piezometer	6.3	3 – 6	18/08/2022	1 hour	Settlement Road, Paretai
CG15/0102	Piezometer	35	16.75 – 19.75	18/08/2022	1 hour	Settlement Road, Paretai

Of these eight wells, five are screened to monitor the shallow groundwater table, while the remaining three are screened at depth (which may not reflect the near-surface groundwater aquifers most relevant for liquefaction assessment). The locations of the shallow groundwater wells are shown in Figure 3.8.

In addition to the continuous monitoring network, ORC holds drilling records that include static water level observations made during or shortly after drilling. Of the 59 boreholes reviewed, 56 contain usable water level data.

Further relevant groundwater datasets, which are shown in Figure 3.8, include mapped surface water bodies, flood banks, and drainage networks. Groundwater levels inferred from the geotechnical investigations described in Section 3.2.3 have also been considered in this assessment.

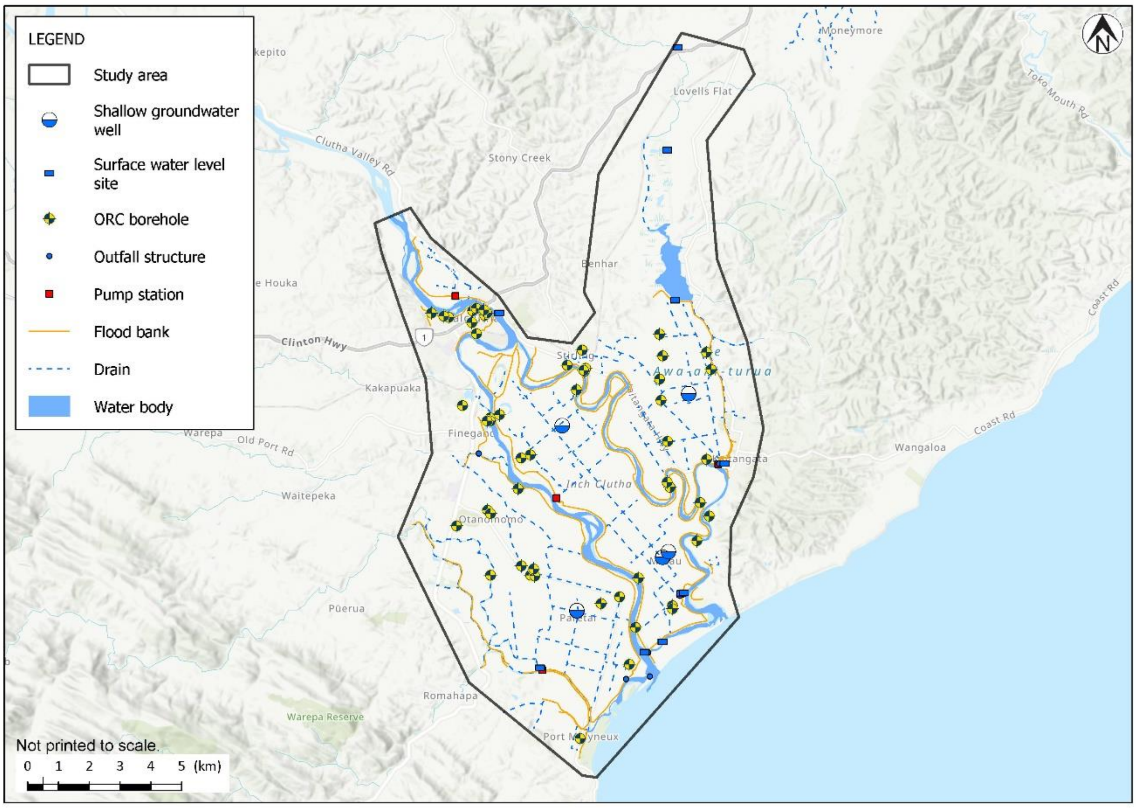

Figure 3.8: Surface groundwater level sites and mapped drains and flood banks in the Clutha Delta. Refer to Appendix A for a larger map.

3.2.5 Seismic hazard

Soils that are susceptible to liquefaction require a sufficient level of ground shaking—both in intensity and duration—to initiate liquefaction. The level of seismic shaking used in a liquefaction assessment is typically selected based on return period events relevant to the performance objectives of the project (e.g. serviceability or ultimate limit states).

Several information sources were reviewed to characterise the seismic hazard for the Study Area:

- New Zealand Transport Agency (2018). Bridge Manual.
- NZGS/MBIE (2021). Earthquake Geotechnical Engineering Practice Series – Module 1: Overview of the Guidelines.
- Barrell, D.J.A. (2021). General Distribution and Characteristics of Active Faults and Folds in the Clutha and Dunedin City Districts, Otago. GNS Science Consultancy Report 2020/88.
- GNS Science (2023). New Zealand Active Faults Database, 1:250,000 scale https://data.gns.cri.nz/af/.
- ORC – Otago Active Faults and Folds, ORC Natural Hazards Earthquakes Otago Active Faults and Folds.
- New Zealand National Seismic Hazard Model (NSHM) – 2022 update (GNS Science).

Ground motion parameters for Balclutha Township, sourced from Module 1 (NZGS/MBIE, 2021), are provided in Table 3.7. These parameters give an indication of expected Peak Ground Accelerations (PGA) and Moment Magnitudes (M) for different return period events and are considered representative for the Study Area. For the broad-scale nature of this Level A/B assessment, the regional variation in seismic hazard across the Clutha Delta is not considered significant enough to warrant distinct hazard parameters for every sub-area. The estimated ground motion parameters generally align with values from the 2022 National Seismic Hazard Model (NSHM) for a NZS 1170.5 Class D (Deep Soil) site classification, which typically corresponds to an average shear wave velocity (Vs30) in the range of 180 to 360 m/s (assumed 200 m/s). The NSHM incorporates updated seismic source modelling and ground motion predictions across New Zealand.

Table 3.7: Ground motion parameters adopted for this study (sourced from MBIE/NZGS 2021 Module 1 for Balclutha), compared to 2022 NSHM estimates (in square brackets)

Return period					
25-year (SLS[1])		100-year		500-year (ULS[2])	
PGA (g)	M	PGA (g)	M	PGA (g)	M
0.06 *[0.05]*[3]	6.0	0.11 *[0.13]*[3]	6.0	0.23 *[0.27]*[3]	6.0

1 SLS: Serviceable limit state event for Importance Level 2 buildings (refer to NZS 1170:2004).
2 ULS: Ultimate limit state event for Importance Level 2 buildings (refer to NZS 1170:2004).
3 2022 NSHM ground motion parameters for centre of the study area assuming Vs30 of 200 m/s.

3.2.6 Historical observations of liquefaction

There are no known historical records of liquefaction occurring within the Study Area. This conclusion is based on a review by Bastin et al. (2021)[6]. No other recent scientific publications were identified that provide evidence of historical liquefaction within the Clutha District. This does not mean that liquefaction has not occurred, simply that there is no historical evidence.

[6] Bastin, S.H., van Ballegooy, S., & Ogden, M. (2021). The past is key to the future: Collating historical cases of liquefaction to supplement liquefaction hazard assessments. In Proceedings of the 21st New Zealand Geotechnical Society Symposium.

While no major earthquake has struck the Clutha Delta in recorded history, the area has experienced strong shaking from distant large events (such as the 2009 Mw 7.8 Fiordland earthquake) and local earthquakes (notably the 1974 Mw 5.0 Dunedin event), with geological evidence indicating that nearby faults, including the Akatore and Settlement faults, have generated powerful prehistoric earthquakes (approximately Mw 7+) capable of significantly impacting the region.

3.3 Uncertainty assessment

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

In accordance with the MBIE/MfE Guidance (2017), uncertainty can be managed by assigning broader or less precise liquefaction vulnerability categories in areas where residual uncertainty remains high. This section also highlights where specific steps have been taken to reduce or manage key sources of uncertainty.

3.3.1 Ground surface levels

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

The 1.0 m resolution LiDAR-derived digital elevation model (DEM) is considered fit for the purposes of this assessment. However, typical limitations of LiDAR surveys should be acknowledged, including:

- Measurement error associated with the LiDAR point cloud collection method.
- Localised error due to interpolation in areas with low point density.
- Limitations in spatial resolution when representing fine-scale elevation variation.

In general, these limitations are expected to have a minor influence on the representation of ground surface features relevant to liquefaction. However, specific applications—such as identifying free-face heights near water bodies—are more sensitive to these limitations. ORC has made available bathymetric data for the section of the Clutha River immediately around Balclutha which enables a more accurate estimate of free-face heights, leading to improved prediction of lateral-spreading severity.

Uncertainty due to temporal changes in ground surface elevation

Ground surfaces are subject to change due to natural processes (e.g. tectonic uplift, erosion, or earthquake-induced deformation) and anthropogenic activity (e.g. land development, earthworks, flood protection infrastructure). These changes introduce temporal uncertainty that cannot be precisely accounted for in a static dataset. Future studies should consider the most current topographic datasets and the proposed finished landform in areas subject to significant change. It is also noted that the current estimated rate of vertical land movement[7] at the coast is small and therefore not likely to introduce additional uncertainty.

3.3.2 Geology and geomorphology

Uncertainty due to mapping precision and terrain boundary accuracy

As discussed in Section 3.2.2, geological and geomorphic boundaries are based on maps with a typical scale of 1:250,000. At this scale, there is inherent uncertainty in the exact position of terrain boundaries. This has been accounted for in the liquefaction vulnerability classification by introducing zones where adjacent landform types differ in susceptibility (e.g. areas classified as ***Liquefaction Category is Undetermined*** between ***Liquefaction Damage is Unlikely*** and ***Liquefaction Damage is Possible***).

Uncertainty due to anthropogenic landform modification

Landform changes due to drainage, river realignment, stopbanks, or development may not be reflected in existing maps. In the Clutha Delta, extensive historical river engineering has altered natural channels and depositional environments. These modifications can affect the current soil

[7] https://www.searise.nz/maps-2

profile and local susceptibility to liquefaction, introducing uncertainty when interpreting historical mapping in these areas.

3.3.3 Geotechnical investigations

Uncertainty due to variability within geomorphic terrains

The Clutha Delta is characterised by complex depositional environments, leading to significant variability in subsurface conditions. This includes interbedded layers and discontinuous lenses of sands, silts, and clays with varying densities and consistencies, even within the same geomorphic terrain.

For a Level A (basic desktop) assessment, this inherent subsurface variability means that broad assumptions about liquefaction susceptibility based on geomorphology carry a high degree of uncertainty. Without very dense subsurface investigations, it is not possible to confidently delineate specific zones or assign more precise liquefaction vulnerability categories (e.g. 'Very Low' or 'Low') beyond ***Liquefaction Damage is Unlikely*** or ***Liquefaction Damage is Possible***.

For a Level B (calibrated desktop) assessment, as undertaken in Balclutha, while additional geotechnical investigations provide calibration points, the spatial density of these investigations is still insufficient to fully capture all localised variations in these heterogeneous soils. This limits the ability to confidently assign more precise vulnerability categories (e.g. Medium or High Liquefaction Vulnerability) or to more accurately delineate smaller areas of distinct liquefaction performance across the entire township.

Uncertainty due to data quality

Geotechnical data quality varies depending on the investigation method, execution, and reporting. Known sources of uncertainty include:

- Interpretation limitations from predrilled CPTs or post-ground improvement testing.
- Logging errors or ambiguous borehole descriptions.
- Missing or partial records (e.g. PDF-only logs without digital data).

A significant portion of this uncertainty has been addressed by selecting a reputable contractor (Geotechnics Ltd) to carry out the additional CPT investigations completed for this project. The contractor’s established methodologies and quality control processes help ensure consistency and reliability in the data collected.

Where legacy data was of uncertain quality or unverifiable, engineering judgement was applied to assess its suitability for use in the liquefaction assessment.

3.3.4 Groundwater

Uncertainty due to spatial data coverage

While several groundwater measurements are available, the data is spatially sparse. The majority of data points are individual observations taken during drilling, with limited continuous monitoring coverage. This makes interpolation of groundwater depth across the Study Area uncertain, particularly in areas distant from known data points.

Uncertainty due to climate change impacts

Long-term changes to the groundwater regime may result from climate change effects. Potential impacts include:

- Altered recharge patterns due to changes in rainfall intensity and distribution.

- Sea level rise, which may lead to higher groundwater tables in low-lying coastal areas.

These changes could increase the depth or duration of soil saturation in the future, potentially influencing liquefaction vulnerability over long planning horizons.

3.3.5 Seismic hazard

Uncertainty due to variability in earthquake shaking scenarios

Liquefaction triggering depends on both the intensity and duration of ground shaking. While this assessment uses representative peak ground accelerations (PGAs) based on standard return periods (as per MBIE/NZGS guidance), the actual shaking experienced at a site during a future earthquake may differ due to:

- Site-specific amplification effects.
- Variability in earthquake source characteristics (e.g. rupture direction, depth, distance).
- Limitations in the resolution of the National Seismic Hazard Model (NSHM) for local-scale applications.

Uncertainty introduced by unmapped or unknown faults

An additional source of uncertainty arises from the presence of unmapped or poorly characterised faults. While the 2022 NSHM includes known active faults and distributed seismicity, it cannot fully capture the hazard posed by faults that have not yet been identified or whose behaviour is not well understood. This residual uncertainty may result in underestimation of localised seismic hazard in some parts of the Study Area.

Uncertainty in selecting representative seismic parameters

The return period ground motions used in this assessment were selected to represent serviceability and ultimate limit state performance levels. These are standard inputs but remain subject to both epistemic (model) and aleatory (random) uncertainties inherent in seismic hazard modelling.

3.3.6 Assess ground damage response against performance criteria

The MBIE/MfE Guidance (2017) provides performance criteria for determining the liquefaction vulnerability category of land, reproduced in Figure 3.9.

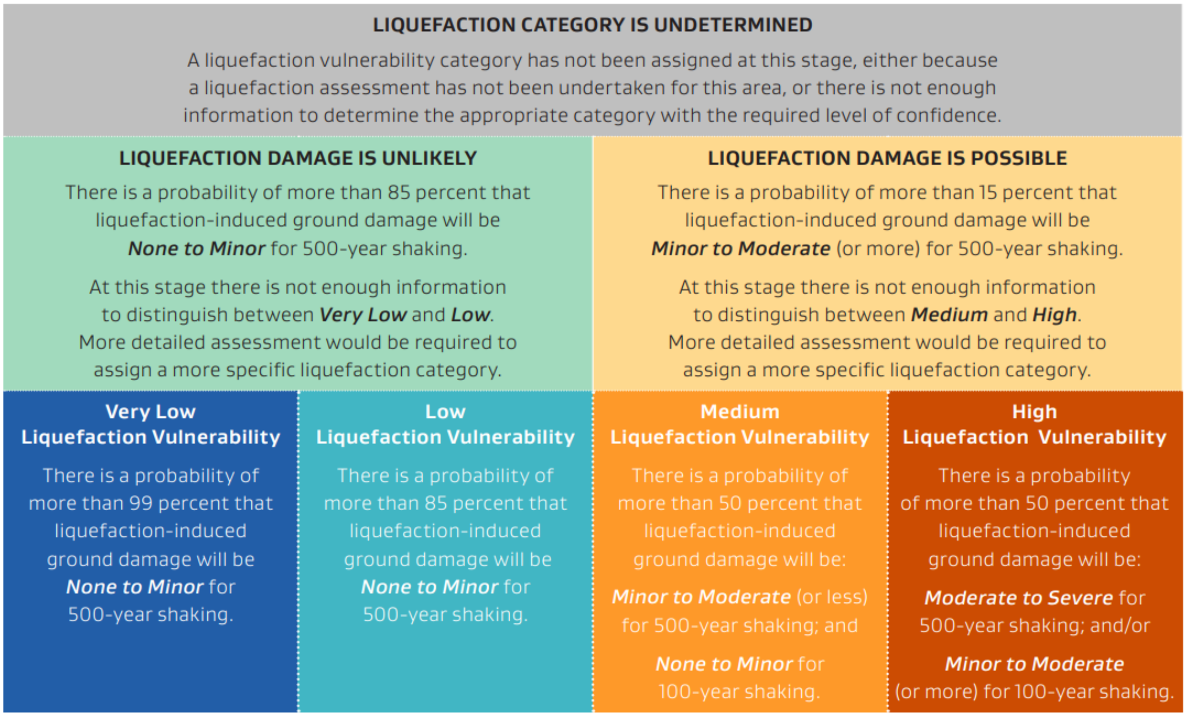

Figure 3.9: Performance criteria for determining the liquefaction vulnerability category – reproduced from MBIE/MfE Guidance (2017).

These criteria are expressed in terms of the expected severity of ground damage during future earthquakes, based on available information about the site's susceptibility to liquefaction. The MBIE/MfE Guidance (2017) includes indicative probabilities of damage occurring at various levels of severity. These probabilities are not intended to serve as fixed numerical thresholds to be calculated, but rather as a qualitative guide to the level of confidence required to assign a given vulnerability category.

It is also important to note that these probabilities relate to the cumulative effect of all uncertainties within the assessment. As a result, direct probabilistic calculation is rarely feasible, and judgement must be applied when assigning categories—particularly in desktop-level assessments such as this one.

In this study, the expected ground performance within each area has been assessed against the MBIE/MfE Guidance (2017) performance criteria using a combination of:

- Geotechnical investigation results (where available)
- Soil type and geomorphic unit
- Groundwater depth
- Proximity to free faces or sloping ground
- Estimated earthquake shaking levels

The level of confidence in assigning each vulnerability category has been evaluated qualitatively, with the indicative probabilities from the guidance used to support this process. As with any assessment, expert judgement is required to weigh the available evidence and determine the most appropriate categorisation for each area.

Where significant uncertainty remains—either due to limited data, conflicting information, or high natural variability—a less precise category has been assigned. In some locations, the ***Liquefaction Damage is Undetermined*** category has been applied to reflect insufficient confidence in the available information to support a more specific classification.

This approach is consistent with MBIE/MfE Guidance (2017) and ensures that the vulnerability assessment remains fit-for-purpose for informing land use planning and development decisions.

3.4 Level of detail achieved in this assessment

As shown in Figure 3.10, a Level A (basic desktop assessment) has been achieved across the majority of the Study Area. This was driven by the spatially sparse geotechnical data across much of the Clutha Delta, as illustrated in Figure 3.7. Extending a calibrated desktop assessment across such a large area would not have sufficiently reduced residual uncertainty to meet the objectives of a Level B assessment as defined in the MBIE/MfE Guidance (2017).

A Level B (calibrated desktop assessment) has been achieved in the township of Balclutha, where additional geotechnical investigations have reduced residual uncertainty to a level consistent with the requirements of the MBIE/MfE Guidance (2017). While the density of investigations in Balclutha approaches the indicative spatial densities that might support a Level C assessment, the scope and intended outcome of this study for Balclutha remained a calibrated desktop assessment. The analysis performed aimed to provide a more confident understanding of the general liquefaction vulnerability of the township at a broad scale, rather than the precise quantitative delineation of damage categories across every property that would be characteristic of a full Level C assessment. This is reflected in the assignment of a broad ***Liquefaction Damage is Possible*** category for the township, as discussed in Section 4.5.6, rather than a finer breakdown into Medium or High vulnerability.

In contrast, although Kaitangata was initially identified as a target area for Level B assessment, the available data was insufficient to meet the criteria for this higher level of detail. As a result, the assessment in Kaitangata has been undertaken at Level A. This achieved level of detail across the Study Area reflects the current availability, spatial density, and quality of base information, as discussed in Section 3.3.

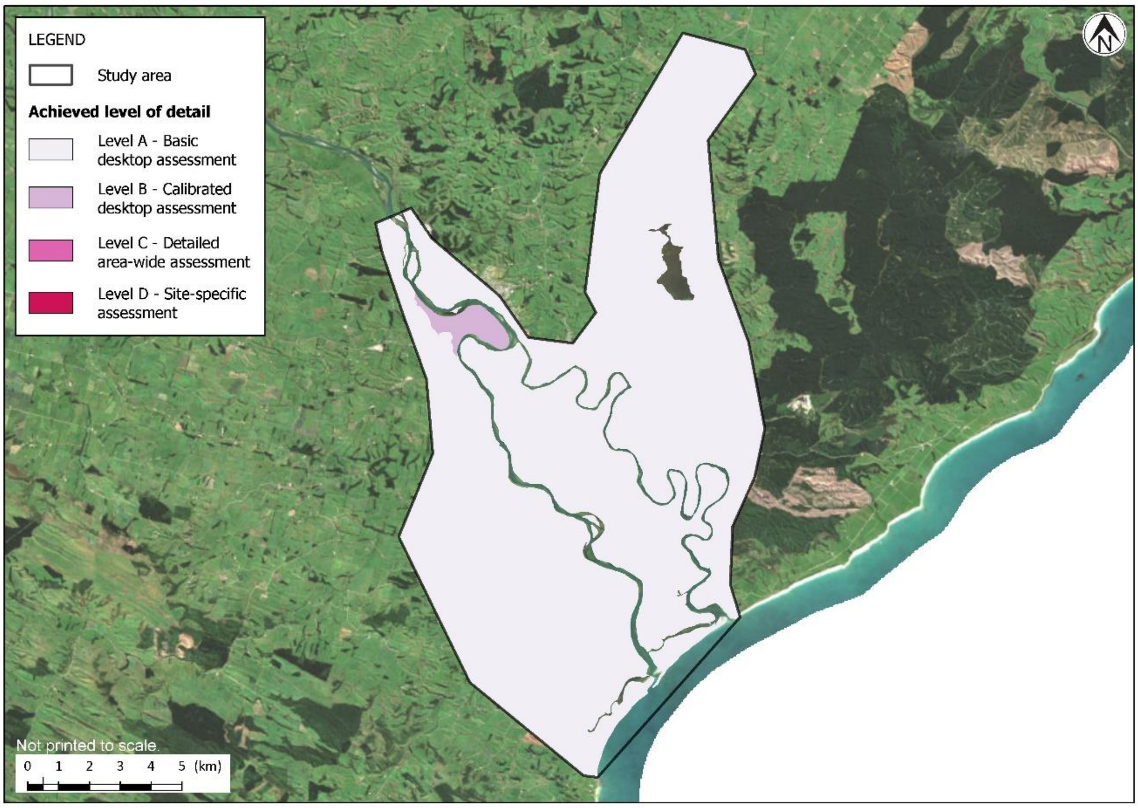

Figure 3.10: Achieved level of detail in this assessment (Level A and Level B).

4 Risk analysis

This section outlines how the base information has been analysed to categorise the liquefaction vulnerability of land within the Study Area. The key tasks in this process include:

- Selecting groundwater levels to support the analysis.
- Selecting earthquake scenarios to support the analysis.
- Delineating sub-areas of similar expected performance.
- Evaluating the expected degree of liquefaction-induced ground damage.
- Assessing liquefaction vulnerability against MBIE/MfE performance criteria.

Each task is discussed in further detail below.

4.1 Groundwater levels for analysis

As described in Section 3.2.4, groundwater data within the Study Area is spatially limited, with most measurements comprising single observations. Due to the limited coverage and the generally flat topography, representative groundwater depths have been assumed for each geomorphic terrain. These assumptions were developed using engineering judgement and are presented in Table 4.1, along with a qualitative assessment of potential climate change effects. It is noted that groundwater levels are highly dependent on rainfall patterns which will also be affected by climate change. These changes are much harder to estimate.

Table 4.1: Assumed groundwater depths and potential influence of climate change

Geomorphic terrain	Elevation summary 5^{th}, 50^{th}, 95^{th} percentile (mRL)	Assumed depth to groundwater (m)	Potential influence of climate change on groundwater
Alluvial fans	0.8, **3.6**, 14.7	0 – 3	Likely to become shallower due to proximity to the coast.
Holocene river plains	0.1, **1.1**, 7.2	0 – 2	Likely to become shallower due to proximity to the coast.
Older river terraces	1.4, **7.0**, 20.6	> 5	Limited influence expected.
Older marine terraces	1.5, **27.6**, 34.4	> 5	Limited influence expected.
Hills, ranges and mountains	5.5, **24.1**, 34.4	> 5	Only lower-elevation valleys may be affected; high ground unaffected.

Notes:
1. Elevation summary calculated from the 2020 LiDAR survey of the Clutha Delta. See Section 3.2.1.

4.2 Earthquake scenarios for analysis

The 500-year return period earthquake scenario is the recommended minimum for Level A and B assessments, as outlined in MBIE/MfE Guidance (2017). For this study, the 500-year scenario was used as the primary basis for evaluating liquefaction vulnerability, as the associated ground motions exceed the threshold required to trigger liquefaction in most susceptible soils.

Additional earthquake scenarios, including 25-year and 100-year events, were also considered to provide a broader understanding of potential liquefaction response across varying levels of seismic shaking.

4.3 Liquefaction vulnerability assessment

A comprehensive suite of liquefaction analyses was undertaken for each CPT profile using a range of groundwater depths (GWD) and peak ground accelerations (PGA). The input ranges used were:

- GWD: 0.1 m increments from 0.1 to 3.0 m
- PGA: 0.05 g increments from 0.0 to 0.6 g, plus discrete return period cases from Table 3.7

The Boulanger and Idriss (2014) simplified method was applied using the following parameters:

- Moment magnitude (Mw): 6 (representative of return period events considered)
- Probability of liquefaction (P_L): 15% (in line with industry practice for geotechnical design)
- Depth of analysis: 10 m (this depth is considered to encompass the most critical layers contributing to liquefaction-induced damage at the ground surface, such as settlement and ejecta, which are of primary concern for typical shallow foundations and infrastructure performance). Adopting this depth cutoff also helps manage differences in termination depth between CPTs (e.g. if a 20 m analysis depth was adopted, then CPTs which were shorter than this would need to be corrected to account for potentially liquefiable soils below the termination depth).

Computed liquefaction parameters included:

- Cumulative Thickness of Liquefaction (CTL)[8]
- One-dimensional Volumetric Settlement (Sv1D)[9]
- Liquefaction Severity Number (LSN)[10]

These parameters were used comparatively to assess spatial patterns and sensitivity across inputs.

For a terrain to be classified as ***Liquefaction Damage is Unlikely*** under the MBIE/MfE Guidance (2017), it is required to meet the performance criteria of 'a probability of more than 85 percent that liquefaction-induced ground damage will be None to Minor for 500-year shaking'. Quantitatively, this has been interpreted for this study to mean that less than 15% of the terrain area exhibits damage exceeding minor – specifically, where calculated Sv1D <15 mm and LSN <5 for 85% of the terrain area. Additionally, this classification can be applied to terrains which have a sufficient groundwater depth, defined as >8 m for Holocene deposits and >4 m for Pleistocene deposits, as specifically outlined in Table 4.3 of the MBIE/MfE Guidance (2017).

In addition, a threshold of 50 mm for Sv1D was considered to assist in identifying areas with the potential for moderate to severe volumetric settlement.

4.4 Sub areas of similar expected performance

Sub-areas of similar expected liquefaction performance were delineated based on the following features:

- **Geomorphology**: Provided the primary basis for delineating expected soil behaviour (Section 3.2.2) – emphasis on the Holocene river plains.
- **Broad delta position**: General position within the Clutha Delta and with respect to the various branches of the Clutha river.

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[8] CTL represents the total thickness of soil layers predicted to liquefy during a seismic event.

[9] Sv1D relates to the vertical settlement resulting from the densification of liquefied soil layers as they reconsolidate post-earthquake.

[10] LSN is an index used to quantify the severity of liquefaction-induced ground damage based on the cumulative effects of excess pore water pressure and soil resistance over a subsoil profile.

The sub areas in this assessment are presented in Figure 4.1 and represent geographically distinct zones where a combination of geology, geomorphic features, and anticipated soil and groundwater conditions lead broadly to comparable seismic response and liquefaction vulnerability.

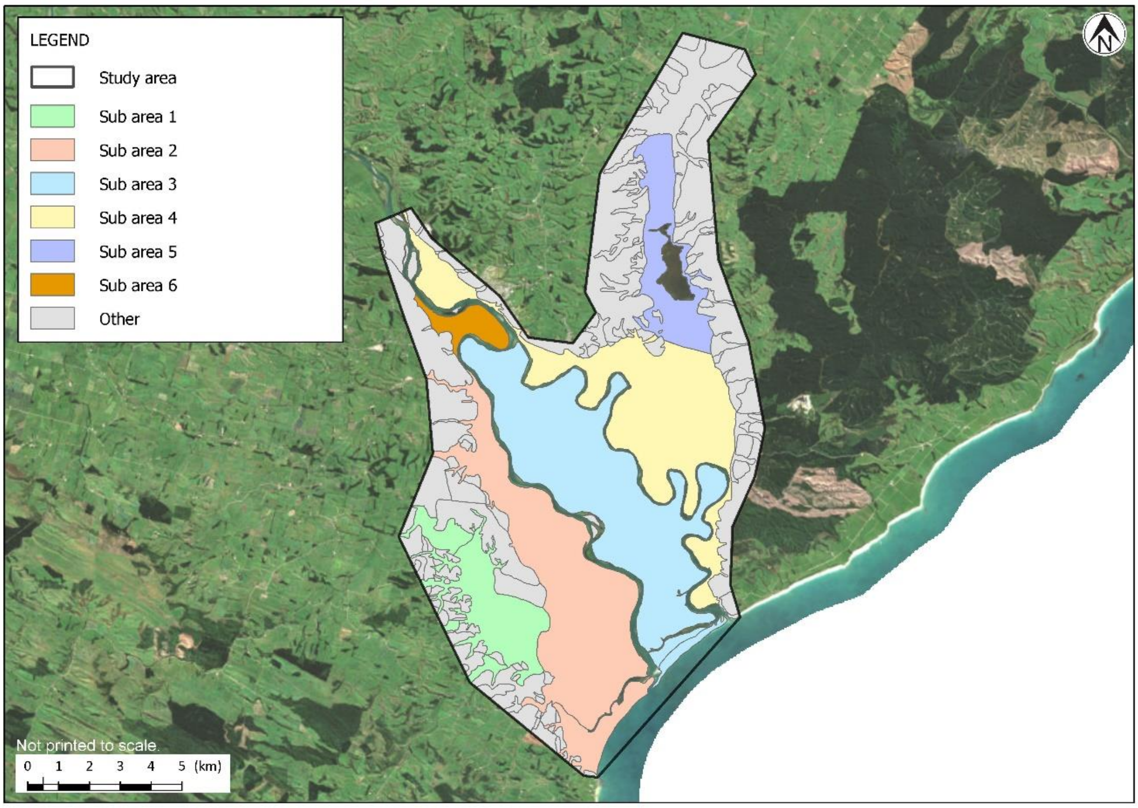

Figure 4.1: Sub-areas of similar expected performance.

4.5 Liquefaction vulnerability assessed against performance criteria

4.5.1 Assigned liquefaction vulnerability categories

Using the available information, the liquefaction vulnerability of each geomorphic terrain has been assessed against the performance criteria. Each terrain is then assigned one of the corresponding liquefaction vulnerability categories shown in Figure 4.2. The resulting liquefaction vulnerability map of the Study Area is shown in Figure 4.3 and Appendix B. Subsequent sections (4.5.2 – 4.5.6) provide discussion on how each of the vulnerability categories were determined.

A polyline categorised as ***Liquefaction Category is Undetermined*** is used between any areas of ***Liquefaction Damage is Unlikely*** and ***Liquefaction Damage is Possible***. This polyline represents the residual uncertainty from the geomorphic mapping and should be interpreted with a width of 50 m.

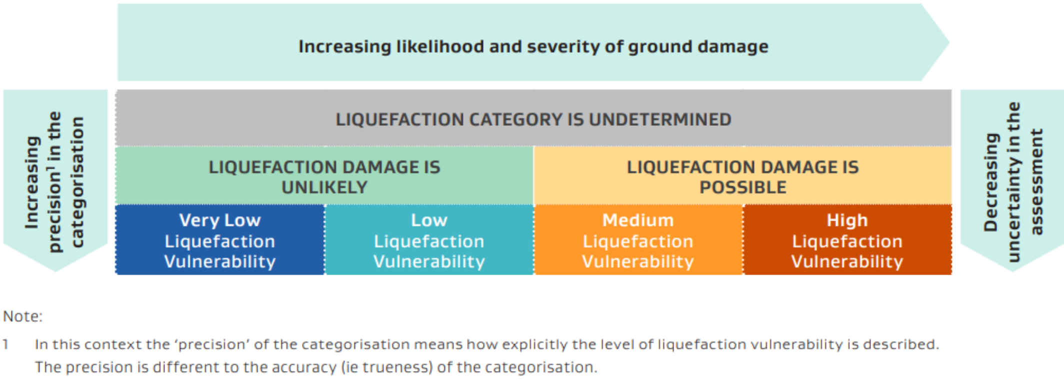

Figure 4.2: Recommended liquefaction vulnerability categories – from MBIE/MfE Guidance (2017).

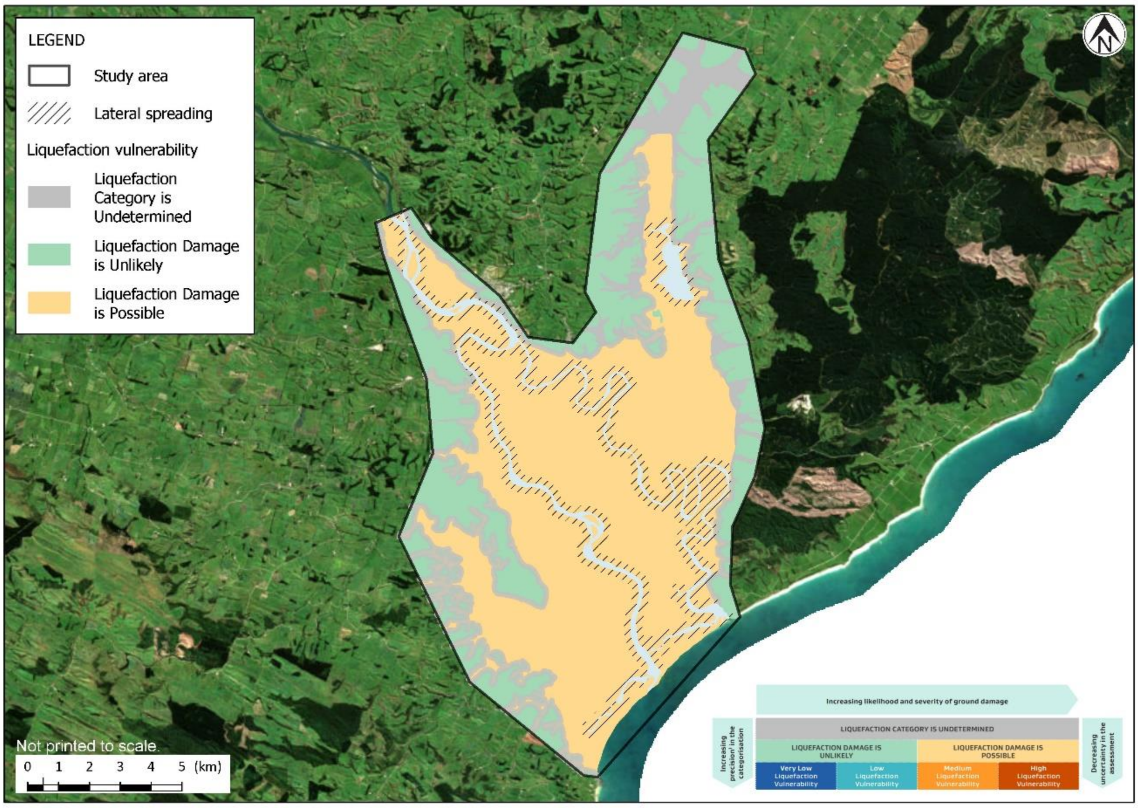

Figure 4.3: Liquefaction vulnerability classification assessed against performance criteria. Refer to Appendix B for a larger map.

4.5.2 Alluvial fans

While the geologic context suggests that alluvial fans are likely to have deeper groundwater and plastic, fine-grained soils that are generally less susceptible to liquefaction, there is limited geotechnical investigation data available to confirm these conditions. Due to this uncertainty, the liquefaction vulnerability of this terrain has been classified as ***Liquefaction Category is Undetermined***.

4.5.3 Older marine and river terraces

The older marine and river terraces typically consist of dense, well-consolidated Pleistocene-aged soils with a groundwater table deeper than 5 m. The combination of soil age, density, and elevation suggests a low likelihood of liquefaction.

In accordance with MBIE/MfE Guidance (2017), specifically Table 4.3, Pleistocene-aged soils can be classified as ***Liquefaction Damage is Unlikely*** if the 500-year PGA is less than 0.3 g (magnitude 7.5 equivalent), or if seasonal higher groundwater levels are deeper than 4 m below ground. For the Study Area, the 500-year PGA of 0.23 g at magnitude 6.0 is equivalent to a PGA of 0.16 g at magnitude 7.5. This satisfies the PGA < 0.3 g criterion by a substantial margin.

While site-specific groundwater measurements are not available for this terrain, the general topographic setting and regional groundwater models indicate that groundwater levels are likely to be deeper than 4m. This criterion is not relied upon to determine the liquefaction vulnerability categorisation, however it provides a degree of reassurance that the categorisation is reasonable.

Based on these characteristics and in accordance with MBIE/MfE Guidance (2017), these terrains have been classified as ***Liquefaction Damage is Unlikely***.

4.5.4 Hills, ranges and mountains

This terrain is characterised by dissected hills, gullies, and elevated ridgelines underlain primarily by Eastern Province basement rock and residual soils. In most locations, the soils are typically not susceptible to liquefaction due to plasticity and consolidation, and the groundwater depth is generally > 5 m.

However, in minor valleys and incised gullies, the presence of younger alluvial deposits and variable groundwater conditions introduces uncertainty (comparable to the alluvial fans discussed in Section 4.5.2).

- Minor valleys: Due to limited data and uncertainty in soil susceptibility and groundwater, these areas are classified as ***Liquefaction Category is Undetermined***.
- Elevated areas: Based on engineering judgement and MBIE/MfE Guidance (2017), these areas are classified as ***Liquefaction Damage is Unlikely***.

4.5.5 Holocene river plains

Holocene river plains are composed of loose, young alluvial sediments, typically deposited in low-energy environments. These soils range from non-plastic sands and silts to plastic clays and are known to include liquefaction-susceptible layers. The depth to groundwater is generally shallow (< 3 m), and the terrain is often adjacent to active or historic river channels/drains.

The analysis of the CPT information to support the liquefaction vulnerability categorisation is summarised in Figure 4.4. The comparison of performance expected across the different sub areas within the Holocene river plains is captured in Figure 4.5. Based on engineering judgement, the analysis of geotechnical information, and the MBIE/MfE Guidance (2017), the Holocene river plains have been classified as ***Liquefaction Damage is Possible.***

Section 4.4.3 of the MBIE/MfE Guidance (2017) recommends that particular attention should be given to the potential for lateral spreading where liquefiable soils are located within 200 m of free faces more than 2 m high (marked with hatched areas in Figure 4.3). The current assessment does not specifically capture all free faces across the study area. Lateral spreading might still be possible outside of the hatched area in Figure 4.3, especially with the free faces which are created by numerous drains across the Clutha Delta. The 200 m buffer has been used as a preliminary screen to identify the most obvious areas where particular attention should be given to the potential for lateral spreading to occur. As part of future development activities or more detailed hazard assessments, site-specific assessment should be undertaken to identify any relevant free faces and assess the lateral spreading hazard.

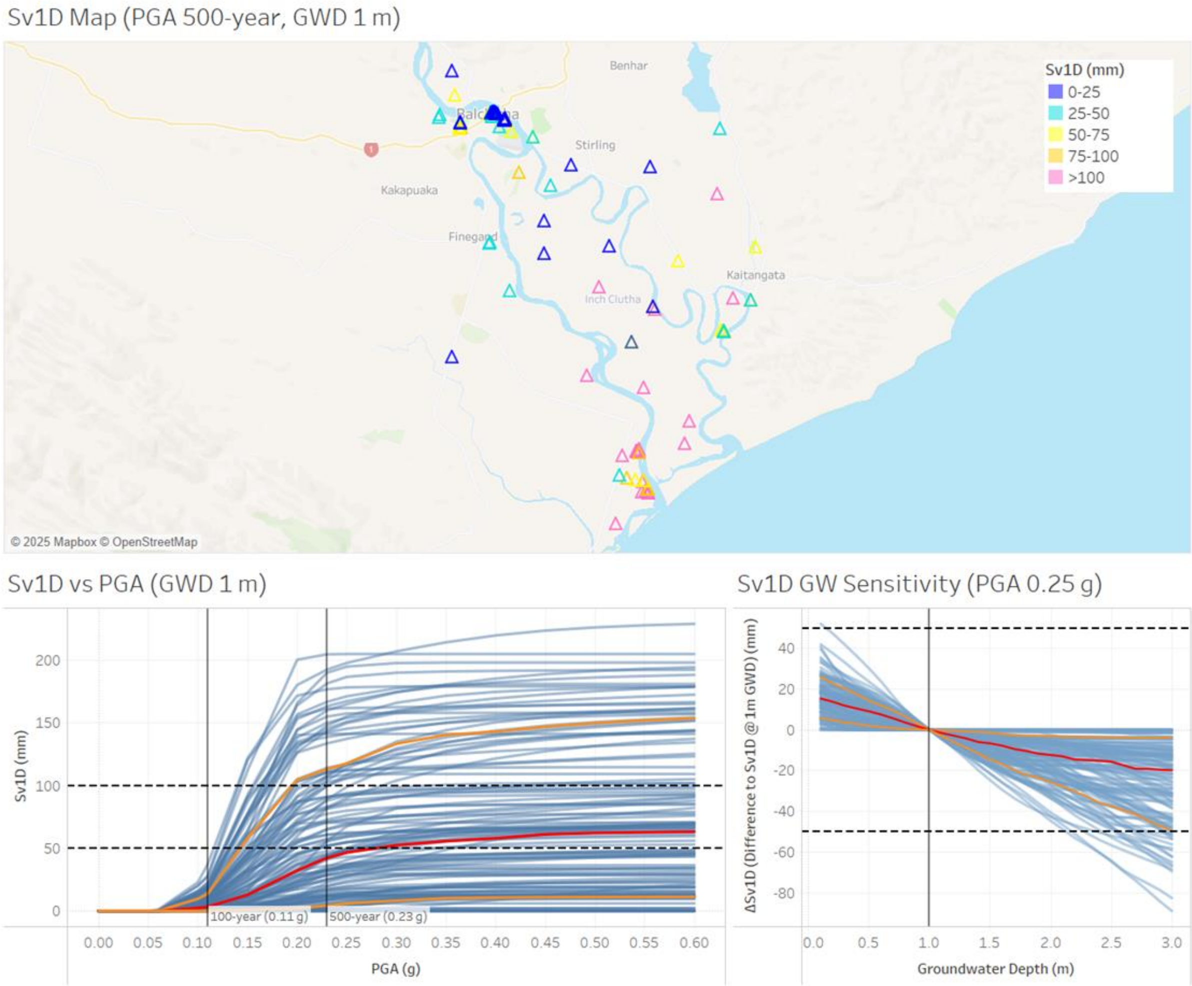

Figure 4.4: Liquefaction vulnerability assessment for Holocene river plains. The figure has 3 components – The top map plots Sv1D (mm) results for a 500-year seismic and 1 m GWD case. The bottom left figure shows the Sv1D (mm) vs PGA response curve for 1 m GWD, with 15th, 50th, and 85th percentile trends identified. The bottom right figure shows the change in Sv1D vs groundwater depth for 0.25 g seismic event, relative to a GWD of 1 m, also with 15th, 50th, and 85th percentile trends identified.

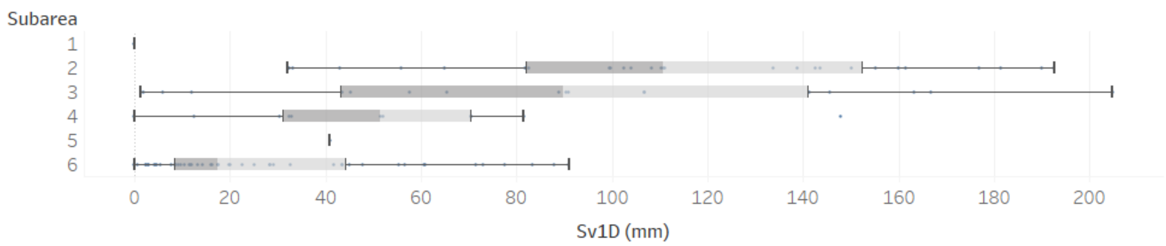

Figure 4.5: Comparison of Sv1D by sub area, for a 500-year seismic and 1 m GWD case. Refer to Figure 4.1 for definition of the sub areas. Note that sub area 1 and 5 only have 1 CPT each and therefore do not support statistical analysis. For the other regions, box and whisker plots show the range of Sv1D (mm) values – the box limits are 25th and 75th percentiles and the boundary between dark and light grey is the 50th percentile.

4.5.6 Balclutha township

A more detailed analysis was undertaken for Balclutha township (subarea 6) given the higher level of detail achieved (as outlined in Section 3.4). Figure 4.6 shows the results of the analysis – there are a significant number of CPTs showing Sv1D > 15 mm at 500-year shaking levels. With no obvious spatial trend that would support further delineation into smaller areas of similar performance, the subarea was categorised as ***Liquefaction Damage is Possible,*** consistent with the other areas of the Holocene river plains.

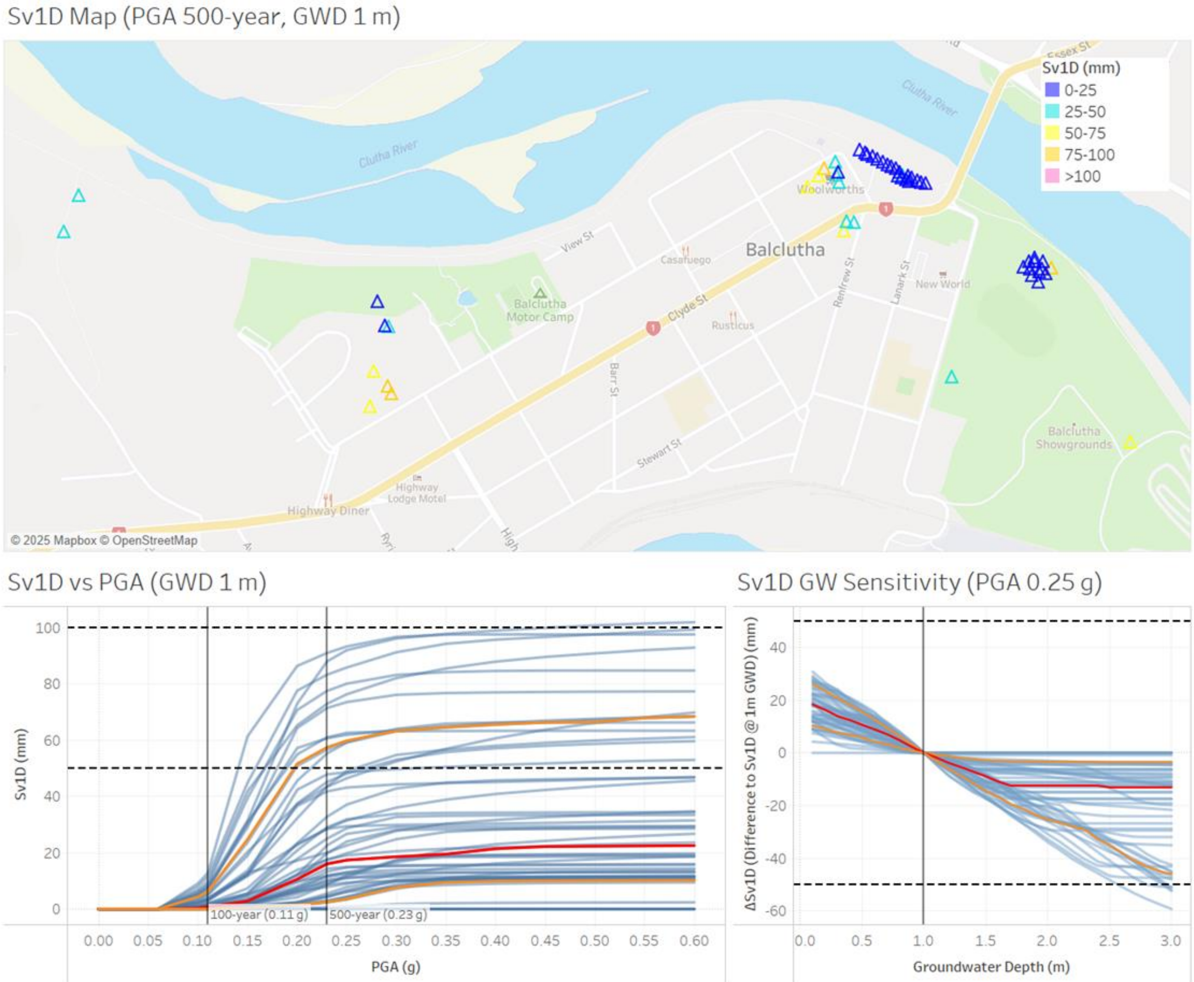

Figure 4.6: Liquefaction vulnerability assessment for Balclutha (subarea 6). The figure has 3 components – The top map plots Sv1D (mm) results for a 500-year seismic and 1 m GWD case. The bottom left figure shows the Sv1D (mm) vs PGA response curve for 1 m GWD, with 15th, 50th, and 85th percentile trends identified. The bottom right figure shows the change in Sv1D vs groundwater depth for 0.25 g seismic event, referenced to a GWD of 1 m, also with 15th, 50th, and 85th percentile trends identified.

5 Discussion and recommendations

Tonkin & Taylor Ltd (T+T) has completed a liquefaction vulnerability assessment of the Clutha Delta in accordance with the MBIE/MfE Guidance (2017). This included a **Level A – Basic Desktop Assessment** across the wider Study Area and a **Level B – Calibrated Desktop Assessment** within the Balclutha township, where additional geotechnical and groundwater information was available to support a higher level of detail.

Based on the results of this assessment, the following conclusions and recommendations are made:

- The land within the Study Area has been classified into one of three liquefaction vulnerability categories:
  - ***Liquefaction Damage is Unlikely***
  - ***Liquefaction Damage is Possible***
  - ***Liquefaction Category is Undetermined***

The classification reflects the spatial variability of ground conditions, groundwater depths, and the degree of uncertainty in each area. The currently available information does not support the use of the more detailed vulnerability categories defined in the MBIE/MfE Guidance (i.e. Very Low, Low, Medium, or High). This is consistent with the expected outcomes of a regional-scale assessment undertaken at Level A or B.

- The liquefaction mapping outputs provide a district-wide base layer that can inform land use planning, infrastructure development, and natural hazard management. These outputs are expected to assist with Resource Consent and Building Consent processes by identifying areas where liquefaction may need to be considered further.
- In most cases, particularly for more sensitive developments or those located in areas classified as ***Liquefaction Damage is Possible*** or ***Liquefaction Category is Undetermined***, additional site-specific investigations will be required to support planning or consenting outcomes. These investigations should be undertaken in accordance with MBIE/MfE Guidance (2017) and the Earthquake Geotechnical Engineering Practice Series, progressing to Level C or D where appropriate.
- The liquefaction classification does not address other geotechnical or natural hazards that may affect land development, such as slope instability, erosion, or flooding. These hazards should be assessed separately as part of future site-specific studies.

5.1 Application to planning and consenting

The liquefaction vulnerability maps produced in this study provide a valuable initial screening tool for land use planning, subdivision, and building consent processes. It is important to reiterate that due to the Level A/B nature of this assessment, the maps are not intended to provide a definitive site-specific assessment of liquefaction hazard for individual properties. Instead, they serve to:

- Inform strategic planning – Guide regional and district councils in long-term strategic land use planning and the development of natural hazard management processes.
- Trigger further investigations – Identify areas where potential liquefaction hazards warrant more detailed, site-specific geotechnical investigations (Level C or Level D assessments). This is particularly critical for proposed building foundations and more sensitive developments within areas classified as ***Liquefaction Damage is Possible*** or ***Liquefaction Category is Undetermined***.
- Streamline consenting – Facilitate the initial stages of Resource Consent and Building Consent applications by clearly indicating the likely requirement for further geotechnical assessment.

This aligns with the hierarchical approach outlined in the MBIE/MfE Guidance (2017) and aims to ensure appropriate consideration of liquefaction risk at all stages of development.

6 Applicability

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

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

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

Tonkin & Taylor Ltd
Environmental and Engineering Consultants

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Project Director

MLO
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Appendix A Risk identification maps

- **Figure A1 – Target level of detail**
- **Figure A2 – Ground surface elevation**
- **Figure A3 – Geology**
- **Figure A4 – Geomorphology**
- **Figure A5 – Geotechnical investigations**
- **Figure A6 – CPT investigation density**
- **Figure A7 – Groundwater information**
- **Figure A8 – Achieved level of detail**

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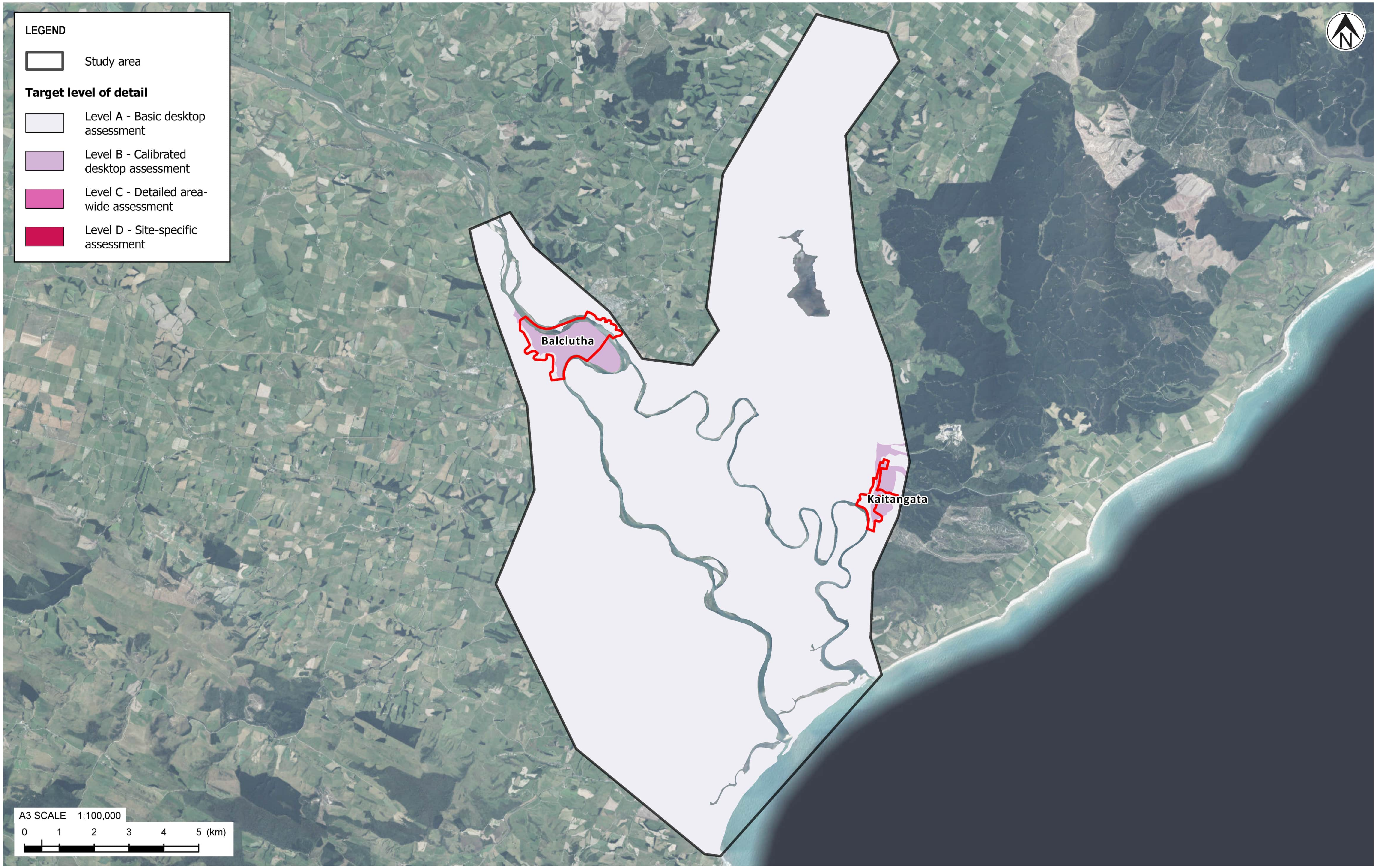
1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx   Layout: Appendix_1093960_FIGA1 Level of detail target



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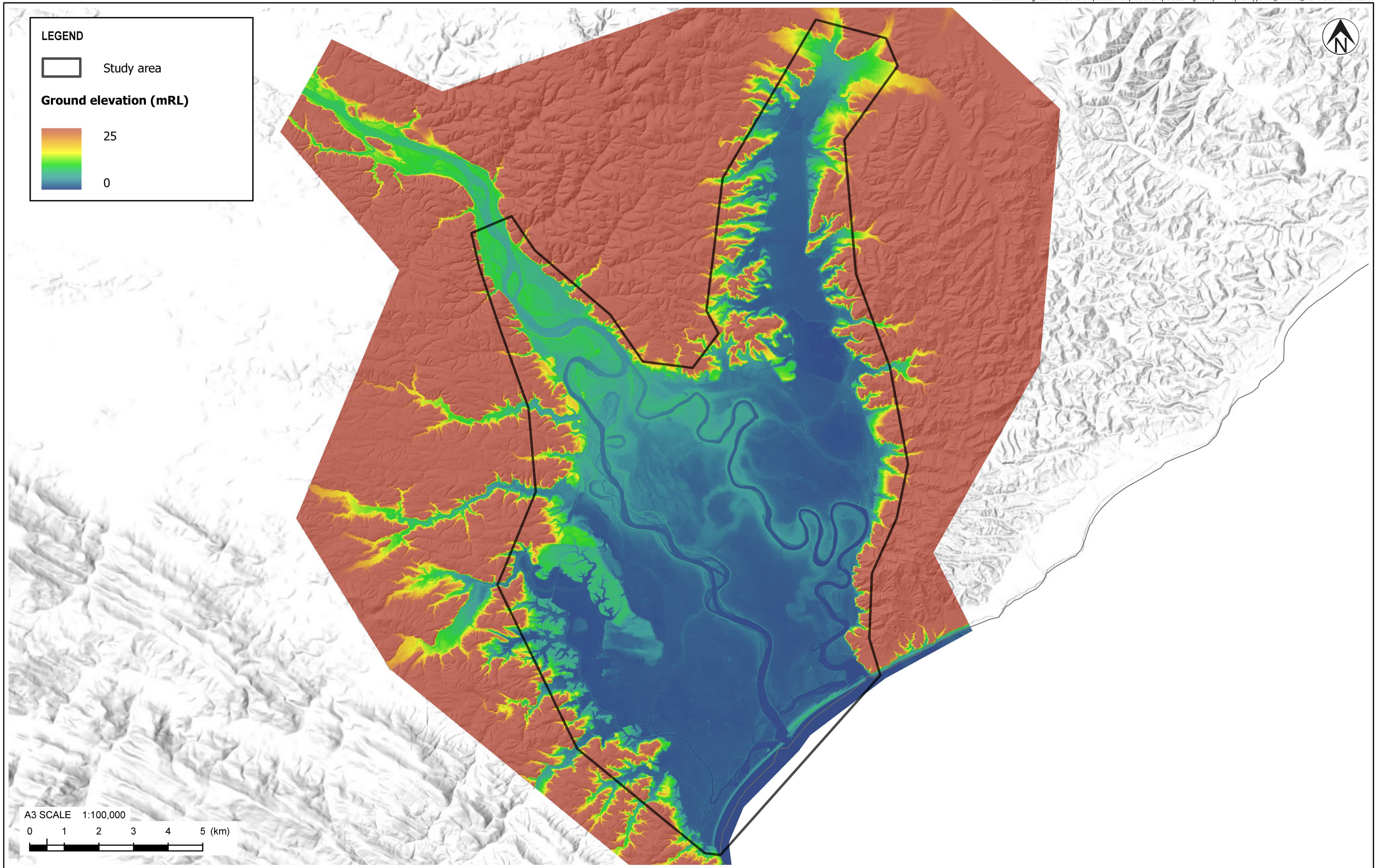
CLIENT **OTAGO REGIONAL COUNCIL**

PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**

TITLE TARGET LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT

SCALE (A3) 1:100,000   FIG No. FIGURE A1   REV 1.0



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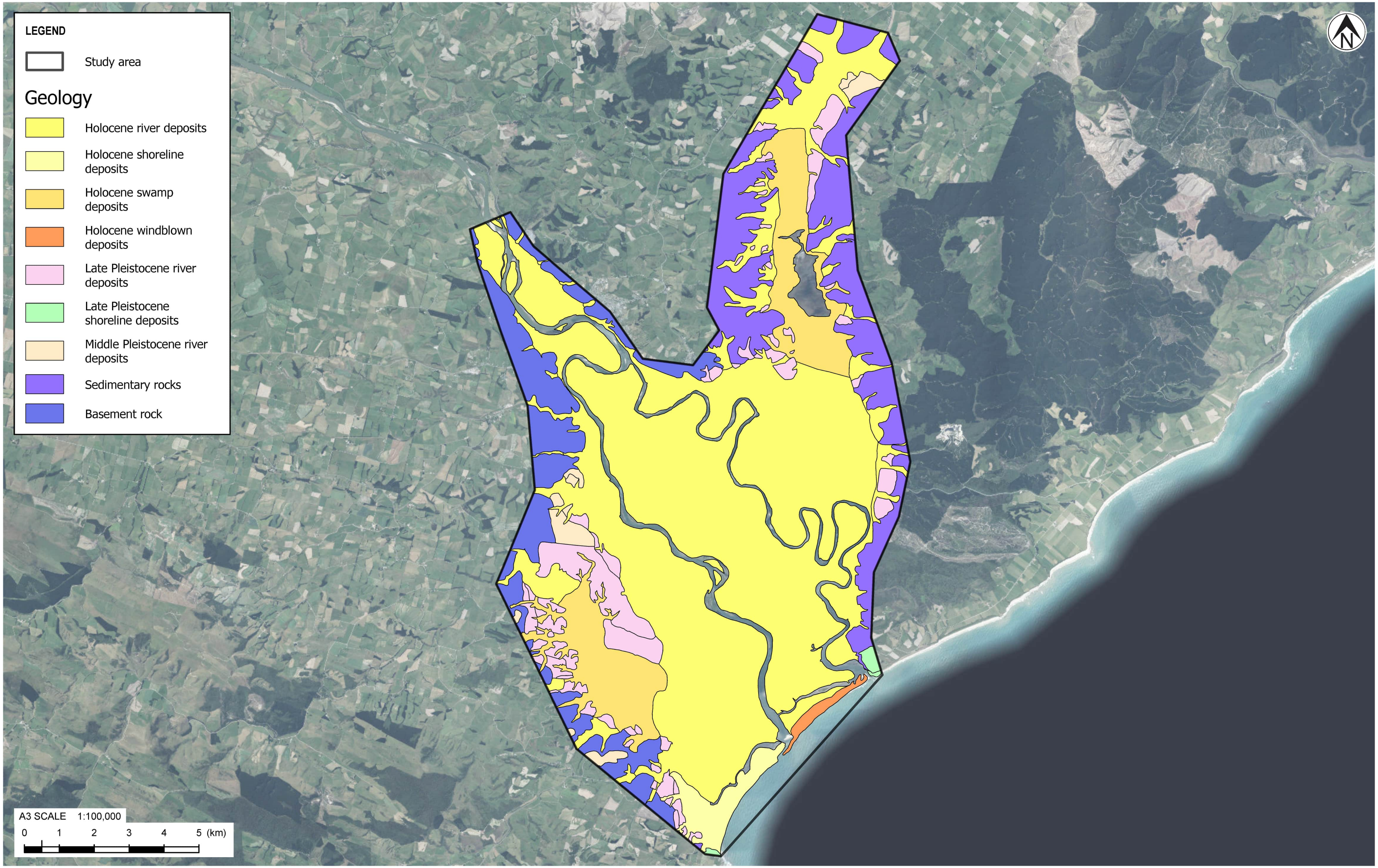
TITLE GROUND SURFACE ELEVATION

SCALE (A3) 1:100,000   FIG No. FIGURE A2   REV 1.0

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGA3 Geology



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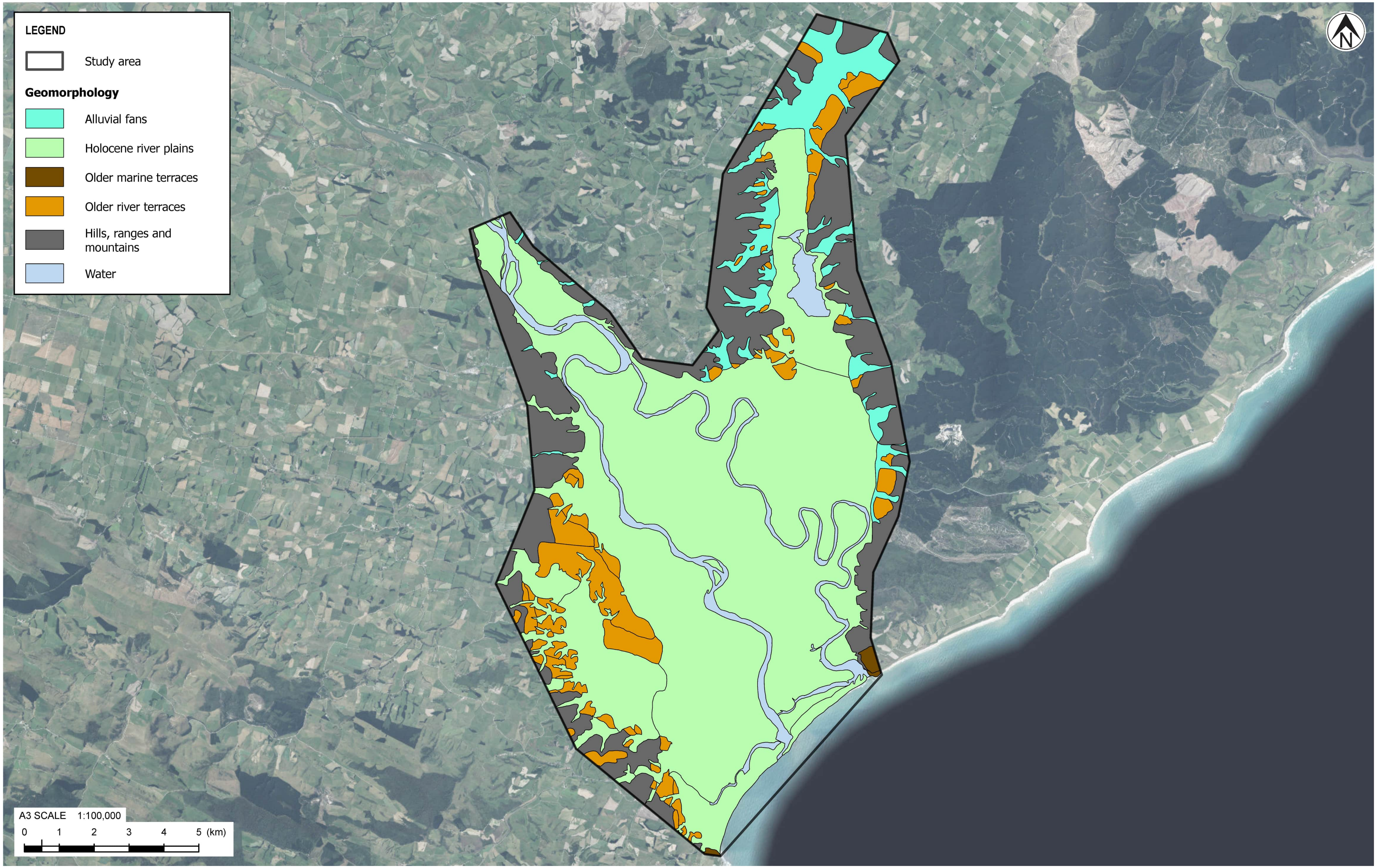
TITLE GEOLOGY

SCALE (A3) 1:100,000 FIG No. FIGURE A3 REV 1.0

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGA4 Geomorphology



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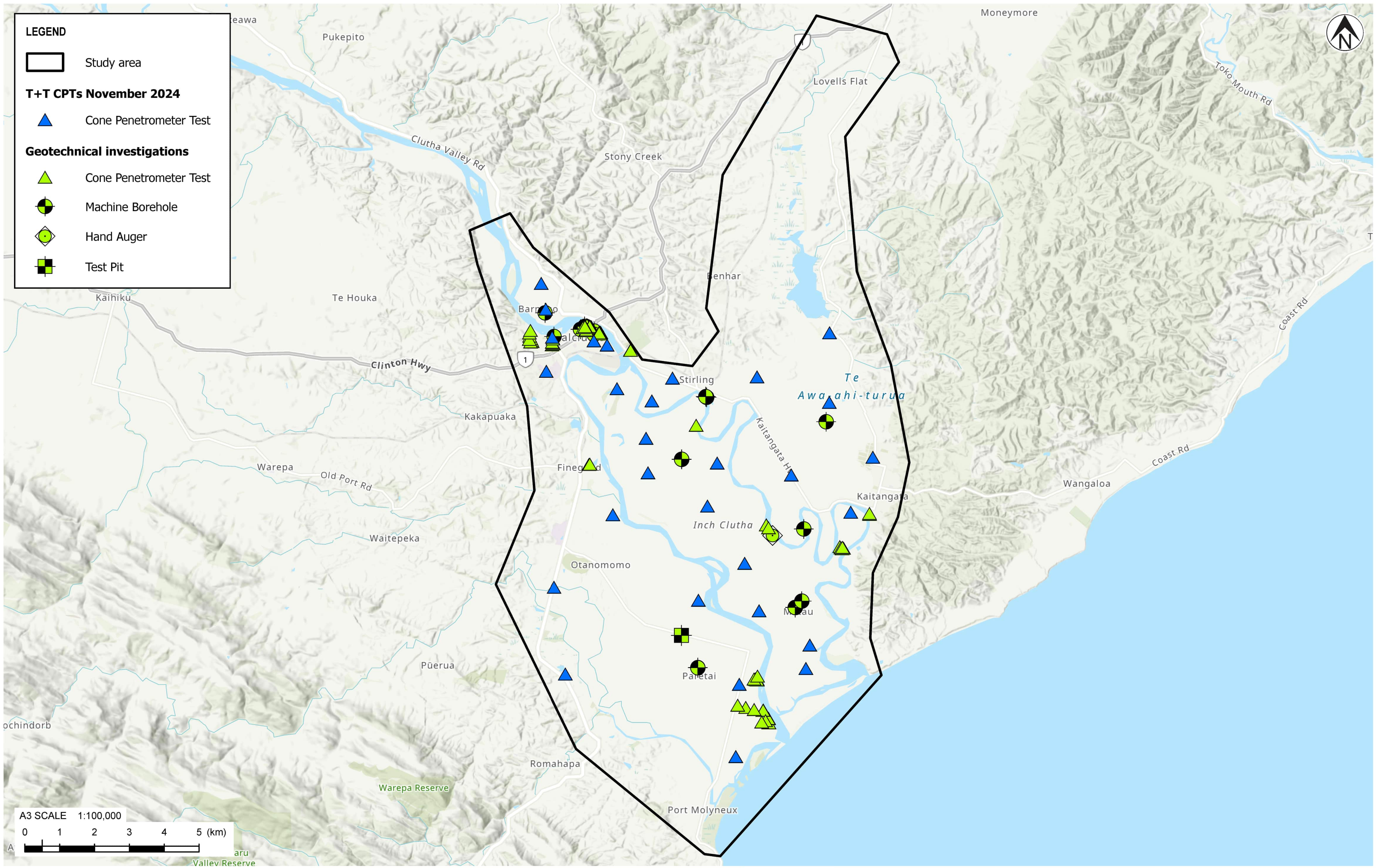
TITLE GEOMORPHOLOGY

SCALE (A3) 1:100,000 FIG No. FIGURE A4 REV 1.0

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGA5 Geotechnical investigations



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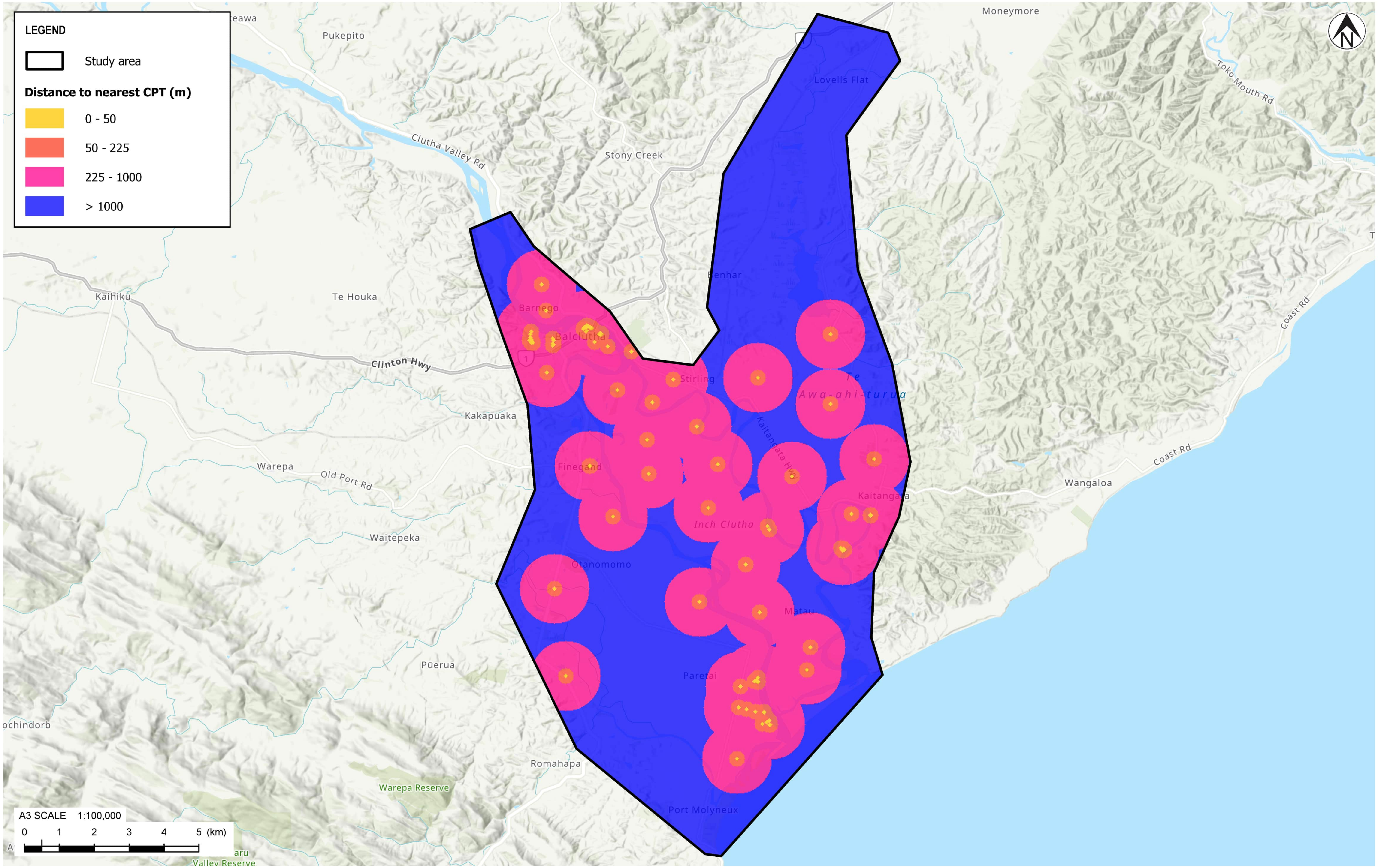
PROJECT: LIQUEFACTION VULNERABILITY ASSESSMENT
TITLE: GEOTECHNICAL INVESTIGATIONS AVAILABLE ON NZGD WITHIN STUDY AREA
SCALE (A3): 1:100,000 FIG No. FIGURE A5 REV 0



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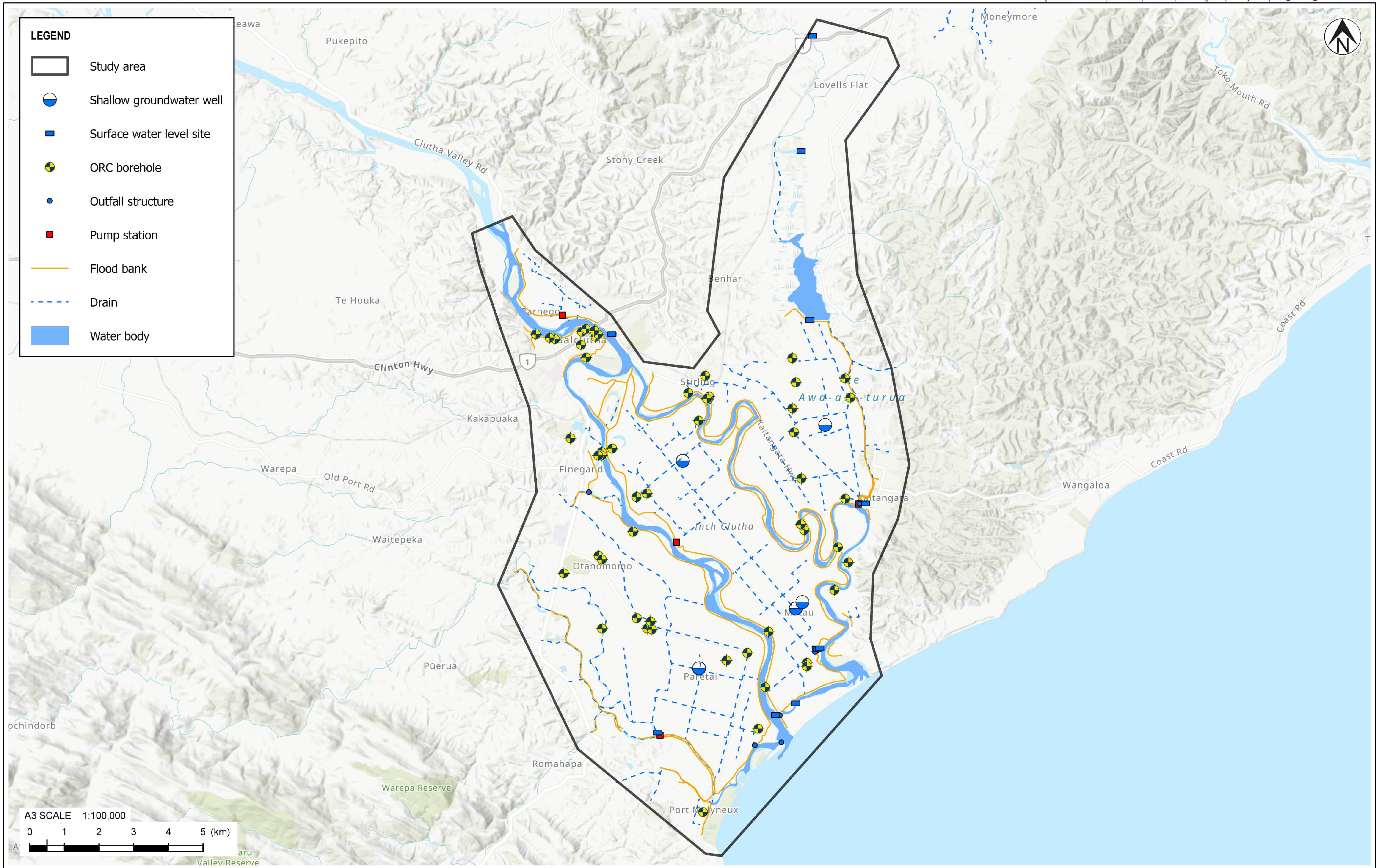
PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**
TITLE CPT INVESTIGATION DENSITY

SCALE (A3) 1:100,000 FIG No. FIGURE A6 REV 0

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGA7 Groundwater



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TITLE GROUNDWATER INFORMATION

SCALE (A3) 1:100,000 FIG No. FIGURE A7 REV 0.1

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGA8 Level of detail achieved

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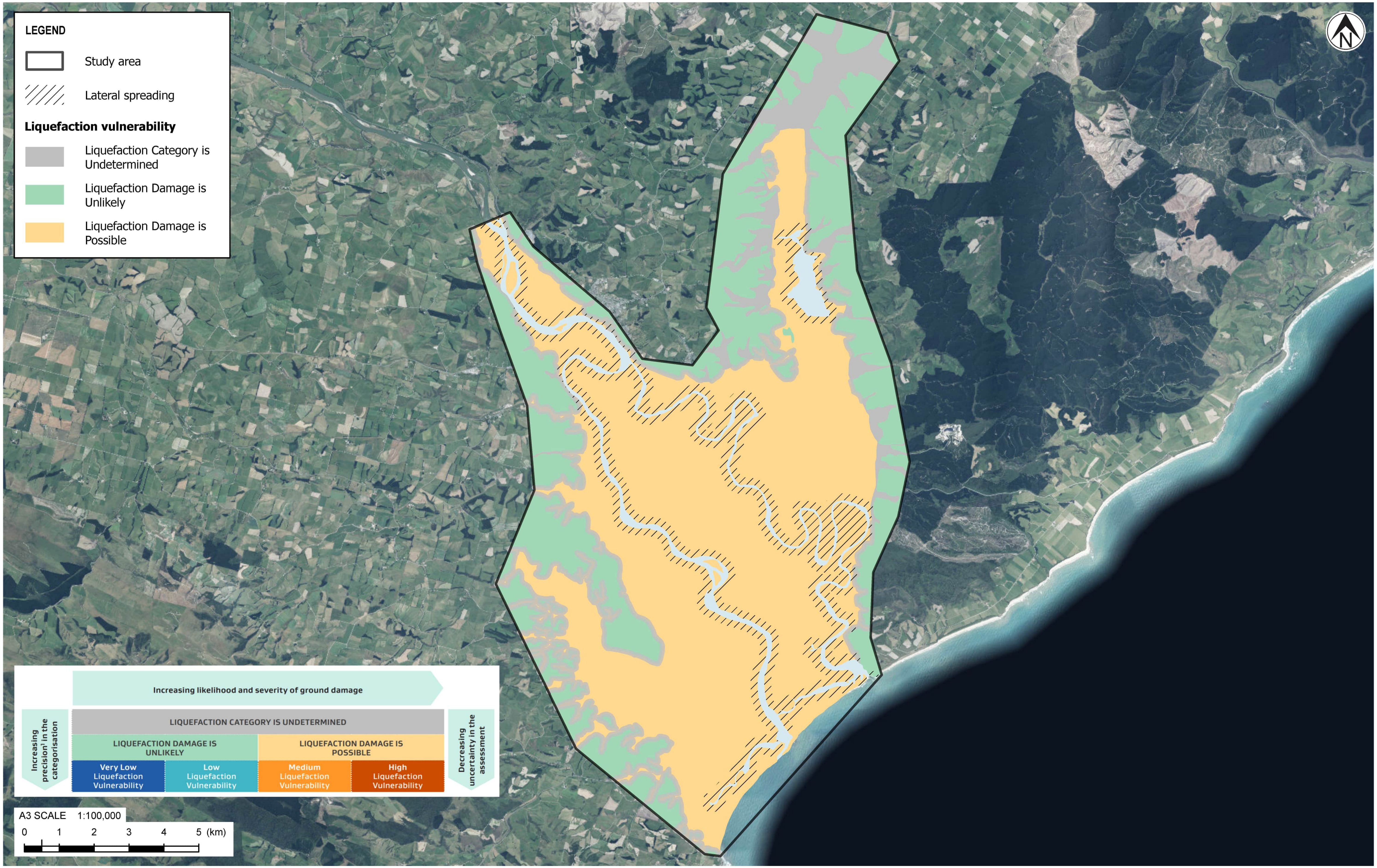
PROJECT LIQUEFACTION VULNERABILITY ASSESSMENT
TITLE ACHIEVED LEVEL OF DETAIL IN THE LIQUEFACTION ASSESSMENT

SCALE (A3) 1:100,000 FIG No. FIGURE A8 REV 1.0

Appendix B Risk analysis maps

- **Figure B1 – Liquefaction vulnerability categories for Study Area**

1093960\WorkingMaterial\GIS\clutha-liquefaction-arcpro\clutha-liquefaction-figures.aprx Layout: Appendix_1093960_FIGB1 Liquefaction vulnerability assessment



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PROJECT **LIQUEFACTION VULNERABILITY ASSESSMENT**
TITLE LIQUEFACTION VULNERABILITY CATEGORIES

SCALE (A3) 1:100,000 FIG No. FIGURE B1 REV 1.0

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