REPORT

Liquefaction Study for Kaikōura District

Submitted to:

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1.0 INTRODUCTION

Environment Canterbury (ECan) engaged Golder Associates (NZ) Limited (Golder) to conduct a review of the liquefaction susceptibility in the Kaikōura District to provide guidance on mitigating future liquefaction hazard in light of the effects of the 2016 Kaikōura earthquake. The M7.8 Kaikōura earthquake of 14 November 2016 resulted in widespread damage in Kaikōura District and other parts of New Zealand. The earthquake triggered secondary hazards including landslides, rockfall, liquefaction, lateral spreading, and a tsunami. The earthquake and secondary hazards damaged buildings and infrastructure throughout the district. This report focuses on liquefaction-induced damage in Kaikōura District and the appropriate geotechnical assessment recommended to address the liquefaction hazard for development or redevelopment. Local government considerations for liquefaction hazard in the development and redevelopment of sites in the district include the Building Act 2004, the Resource Management Act 1991, the Local Government Act 2002, and the Civil Defence and Emergency Management Act 2002. The information is also useful in district planning and resource management by providing insight on the future implications of developing on a site with liquefaction potential.

An earthquake hazard assessment for engineering lifelines in Kaikōura District was undertaken by Geotech Consulting Limited for Environment Canterbury in 2009 (Geotech 2009). As part of this assessment a district-scale liquefaction susceptibility map was produced, which outlined three categories of liquefaction susceptibility, based mainly on the underlying geology. Additional geological information and observations of liquefaction damage, compiled following the 2016 Kaikōura earthquake, have been used to supplement the earlier study (Geotech 2009). Three 'liquefaction assessment zones' have been delineated that describe the liquefaction vulnerability and recommended level of geotechnical assessment required to characterise liquefaction hazard of a site for development or redevelopment.

This report summarises the methodology employed to delineate the liquefaction assessment zones and describes how to use the information during planning and consenting. The uses and considerations for the presented information are then explained. This assessment was prepared using the recommendations outlined in the Ministry of Business, Innovation and Employment (MBIE) guidance titled '*Planning and engineering guidance for potentially liquefaction-prone land'* (MBIE 2017). It is intended that this report be read in conjunction with MBIE (2017).

Your attention is drawn to the document, "Report Limitations", as attached (Appendix A). The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

1.1 Location

Kaikōura District is located in the north east of the South Island and comprises 2,048 km² of mainly sparsely populated rural land including the Seaward Kaikōura Range and Inland Kaikōura Range. The extent of Kaikōura District, which is the project area for this study, is shown in Figure 1.

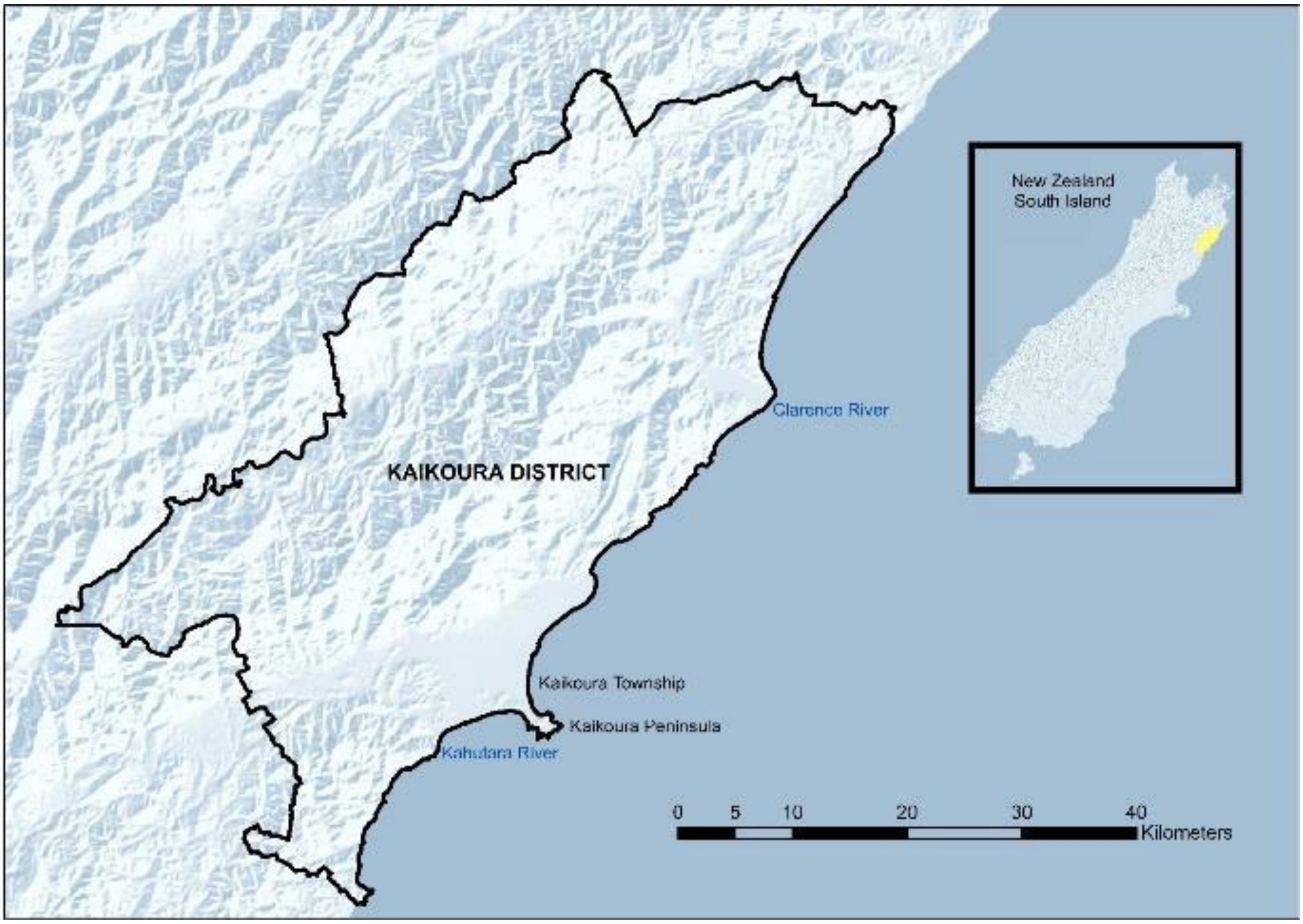

Figure 1: Project area, the Kaikōura District, outlined in black.

1.2 Definition of Liquefaction

In loosely packed soils, earthquake shaking can cause rearrangement of the soil particles. If the soil is saturated, the voids between the soil particles are filled with water and high water pressures (known as pore pressures) can develop during earthquake shaking. Liquefaction is the loss of soil strength and stiffness during earthquake shaking as pore water pressures rise more quickly than the soil can drain. It is a phenomenon most commonly observed in loose, saturated granular deposits (such as alluvium) that are geologically young (i.e., Holocene, meaning younger than 10,000 years).

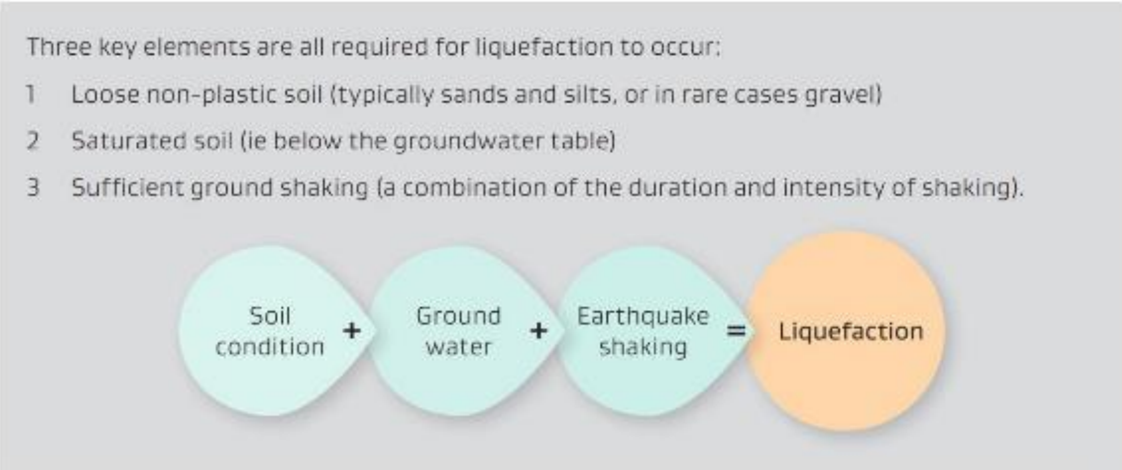

Figure 2: The key elements of liquefaction (figure from MBIE 2017).

Because liquefaction requires specific soil and groundwater conditions to occur (given sufficient earthquake shaking), some types of landforms are more likely to be susceptible than others. These landforms include:

- Along rivers, streams and lakes
- Coastal margins
- Flood plains
- Estuaries and swamps
- Reclamation fills and tailings dams
- Uncontrolled or poorly compacted fill

Liquefaction can have many effects on land and infrastructure including sand boils, lateral spreading, ground settlement, ground cracking and loss of support to building foundations. Figure 3 shows various examples of liquefaction and its effects.

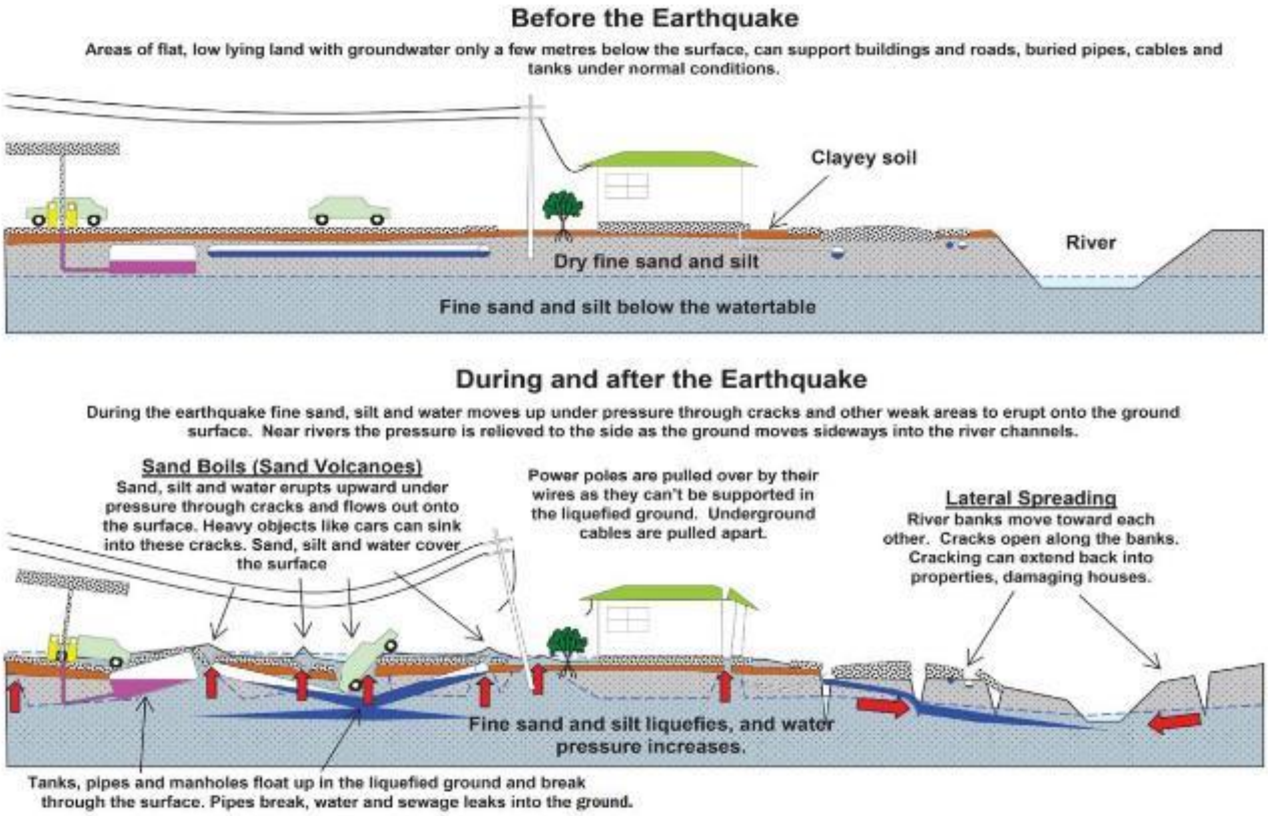

Figure 3: Liquefaction and its effects (Figure from IPENZ 2011).

2.0 LIQUEFACTION HAZARD IN KAIKŌURA DISTRICT

Kaikōura District, especially Kaikōura township, where most of the district's population resides, has many of the landforms described in Section 1.2. For liquefaction to occur, the correct ground conditions, ground water level and earthquake shaking must be present. This section discusses the geological setting of Kaikōura District and the seismic hazard of the region, showing that the elements required for liquefaction to occur are present.

2.1 Geological Setting

The Kaikōura District comprises a number of different landscapes reflecting the underlying geology:

- Hilly and mountainous terrain

  The majority of Kaikōura District is hilly or mountainous and underlain with rock at shallow depth and is not susceptible to liquefaction. This area is also sparsely populated.

- River plains and fans terrain

  Most of the Kaikōura District's flat areas are underlain by alluvial deposits comprising gravel, sand and silt or similar unconsolidated detrital material, deposited during comparatively recent geologic time by streams or other bodies of water. A significant portion of the district's population inhabit this terrain. These areas comprise river beds and alluvial terraces in the main valleys and the alluvial fans around Kaikōura township. In terms of liquefaction susceptibility, these areas can be divided into two zones: areas underlain with older alluvium (Pleistocene deposits, greater than 10,000 years old) and the younger deposits of Holocene age. For the Pleistocene alluvium deposits, both the greater age and the predominantly coarser particle size (e.g., gravel) make widespread liquefaction unlikely. However, there may be rare combinations of loose sand and locally high water table that lead to localised areas of liquefaction hazard. In some areas Pleistocene deposits underlie sloping ground that may have a low liquefaction susceptibility but may be affected by other natural hazards such as slope instability. The remaining Holocene alluvial areas, which are geologically recent, are also dominated by gravelly sediments deposited in relatively steep and high energy environments; and are therefore, unlikely to be liquefiable. Within the recent river deposits there will be areas of sand and minor silt that may be liquefiable.

- Coastal margins

  A large portion of the district's population inhabits the flat area along the coast. In some places the river plains and fans or hilly and mountainous terrains extend all the way to the sea, but others there are coastal plains formed by coastal deposits and swamp deposits. The coastal deposits comprise beach sand and gravel and to a lesser extent dune sand and are often susceptible to liquefaction hazards. Holocene swamp deposits are common in many valleys but are generally small in area. Adjacent to the coast, swamps have developed where drainage has been impeded by dunes and marine sand and gravel. The swamp deposits typically contain silt, peat and sand and are in places susceptible to liquefaction hazards.

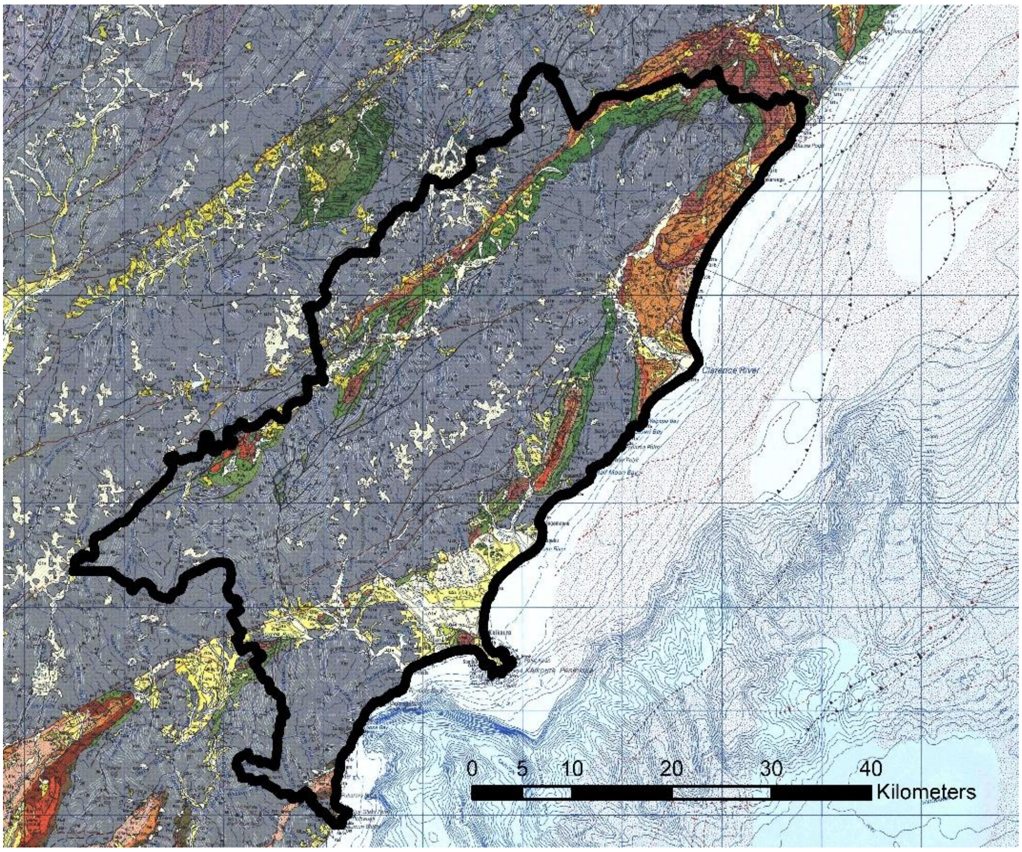

Figure 4: Geology of the Kaikōura area (Rattenbury et al. 2006). Kaikōura District outlined in black. Deposits including alluvial deposits, fan deposits, dune deposits and marine deposits shown in light yellow for Holocene age and yellow for Pleistocene age. Mountainous areas comprising dominantly of sandstone, siltstone mudstone, volcanic rocks and conglomerates all aged older than Pleistocene shown in grey, green and orange. For detailed geological legend, see Rattenbury et al. 2006.

2.2 Seismic Hazard

As described by Rattenbury et al. (2006), Kaikōura District is subject to severe natural hazards, including a high level of seismic activity from the Alpine, Awatere, Clarence, Hope and other active faults. These have potential for generating strong earthquake shaking in Kaikōura District, as well as landslides, liquefaction and fault ground rupture. Several large earthquakes with epicentres within or near Kaikōura District have occurred within the last 160 years. Most recently, the 2016 Kaikōura earthquake has caused widespread damage in the area. Figure 5 shows a map of active faults in the northeast South Island, from Stirling et al. (2017) with the locations of faults that ruptured to the ground surface in the 2016 Kaikōura earthquake. Over the last ten years there has been an increasing awareness of the significant hazard that the Hikurangi Subduction Interface fault has on central New Zealand, including in Kaikōura (e.g., Hayward et al. 2016).

It is important to note that liquefaction is triggered by ground motions and the ground motion caused by the 2016 Kaikōura earthquake varied across the district due to a number of factors, such as distance from the fault rupture. Planning and consenting processes require consideration of different levels of earthquake shaking hazard defined by different annual probability of exceedance. The performance of the ground in the 2016 Kaikōura earthquake should not be considered as the future performance of the ground in earthquakes, but it is indicative of the spatial distribution of the liquefaction susceptibility.

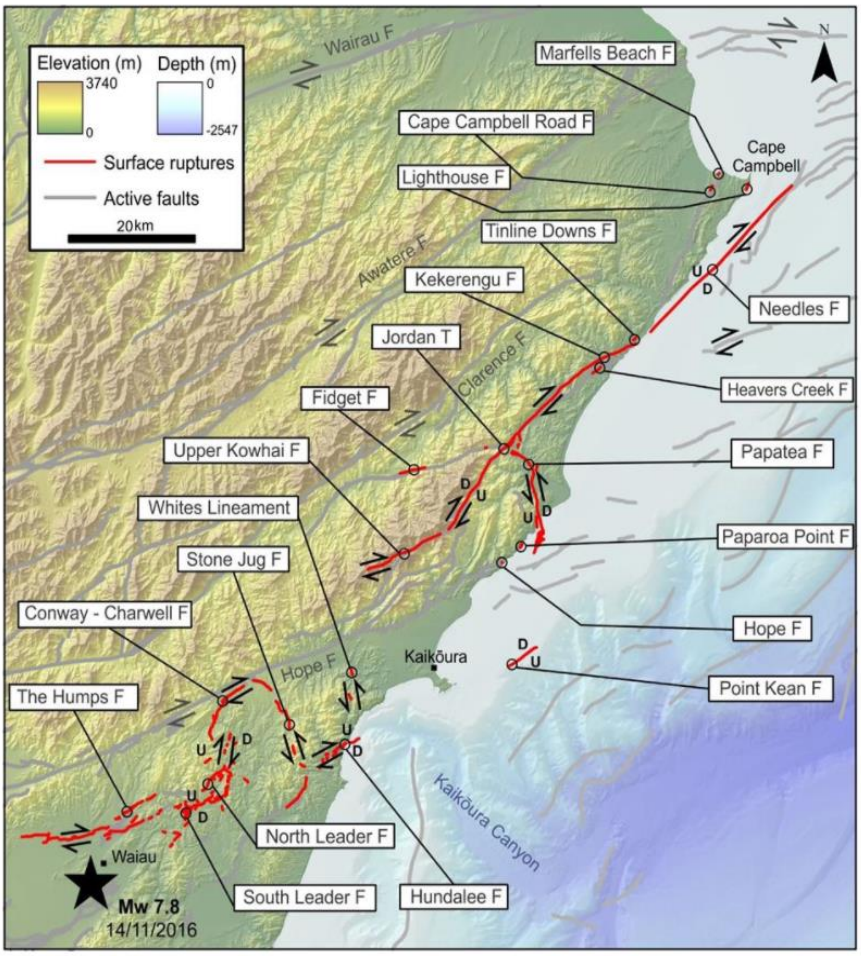

Figure 5: A detailed map of active faults in the northeast South Island, from Stirling et al. (2017) that shows the locations of faults that ruptured to the ground surface during the 2016 Kaikōura earthquake.

3.0 METHODOLOGY

A review and compilation of available datasets relevant to liquefaction hazard within Kaikōura District was undertaken to delineate the liquefaction assessment zones. Using the 2009 liquefaction susceptibility map (Geotech 2009) as a starting point, the zoning was refined using additional information made available following the 2016 Kaikōura earthquake. Available data were compiled in a geographic information system (GIS). The GIS layers were overlain and compared to the 2009 liquefaction susceptibility zones. The liquefaction susceptibility zones were modified to incorporate the knowledge acquired following the 2016 Kaikōura earthquake and renamed as liquefaction assessment zones to reflect the purpose of the current study (i.e., to define different levels of geotechnical assessment required in different areas).

The liquefaction assessment zones are presented in Section 4.0 along with recommendations for geotechnical investigations to adequately characterise the liquefaction potential for development or redevelopment. A summary of the datasets and how they were incorporated into the study is presented in Section 5.0.

4.0 LIQUEFACTION ASSESSMENT ZONES

Three categories of liquefaction assessment zones were outlined for the Kaikōura District and summarised in Table 1. The liquefaction assessment zones mapped throughout Kaikōura District show the initial level of assessment required to characterise liquefaction potential.

Table 1: Summary of Liquefaction Assessment Zones.

	Zone Name	Description	Example Areas
>>>> Increasing level of assessment detail >>>>	Liquefaction damage unlikely - Standard procedure (NZS3604)	Liquefaction damage is unlikely. Standard investigation procedure outlined in New Zealand Standard (NZS) 3604 is likely appropriate.	■ Hilly and mountainous terrain ■ Areas underlain by rock
	Liquefaction damage unlikely - Desktop assessment	Liquefaction damage is possible in some areas but unlikely. Liquefaction potential to be confirmed by a suitably qualified engineer with existing site information and shallow investigation data. Input from a geotechnical engineer is contingent on the results of the desktop assessment.	■ Areas underlain by alluvial deposits older than the Holocene ■ Remote and unpopulated areas with mapped alluvial deposits ■ Remote river plains and fans away from the coastal plains
	Liquefaction damage possible - Detailed liquefaction assessment	Liquefaction damage is possible. Input from a geotechnical engineer is required for ground characterisation regarding liquefaction potential. Deep ground investigations are required, unless otherwise specified by the geotechnical engineer.	■ Areas underlain by Holocene-aged alluvial deposits ■ Areas where liquefaction-induced damage was observed ■ River plains and fans ■ Coastal margins ■ Areas where borehole information confirms that granular soils and high ground water level are present

It should be noted that liquefaction assessments are undertaken at a wide range of scales and detail, ranging from a high-level assessment of an entire region down to site-specific geotechnical investigations and analysis for a specific building. The recommended level of detail in the liquefaction assessment and investigation increases as the likelihood, severity and exposure to liquefaction induced damage increases. A more detailed level of investigation than proposed in the liquefaction assessment zone may be required if the assessment results are inconclusive, liquefaction susceptible soils are identified, and/or the intended scope of works requires a higher level of detail.

It is understood that certain sites in Kaikōura have already had a geotechnical assessment undertaken to determine geotechnical hazards. These assessments may have addressed the liquefaction hazard on site and provided recommendations to mitigate the effects of liquefaction damage; therefore, further geotechnical input may not be required. In cases where previous geotechnical reports are available for the site and are used to assist current proposed developments, the geotechnical reports should be reviewed by the current design engineer or site developer to confirm that the information and recommendations are appropriate for the current proposed works. The performance of the site following the 2016 Kaikōura earthquake should be discussed. If the previous geotechnical works are not considered suitable to adequately mitigate the site from liquefaction damage or if liquefaction damage was observed on site following the 2016 Kaikōura earthquake, a report should be provided which follows the procedure outlined in the liquefaction assessment zones.

Figure 6 shows the distribution of the liquefaction assessment zones in Kaikōura District. More detailed maps are included in Appendix B and GIS files have been provided to Environment Canterbury and Kaikōura District Council. A flowchart providing guidance on how to use the liquefaction assessment zones is provided in Appendix C for the intended use of assessing building consent applications for completeness.

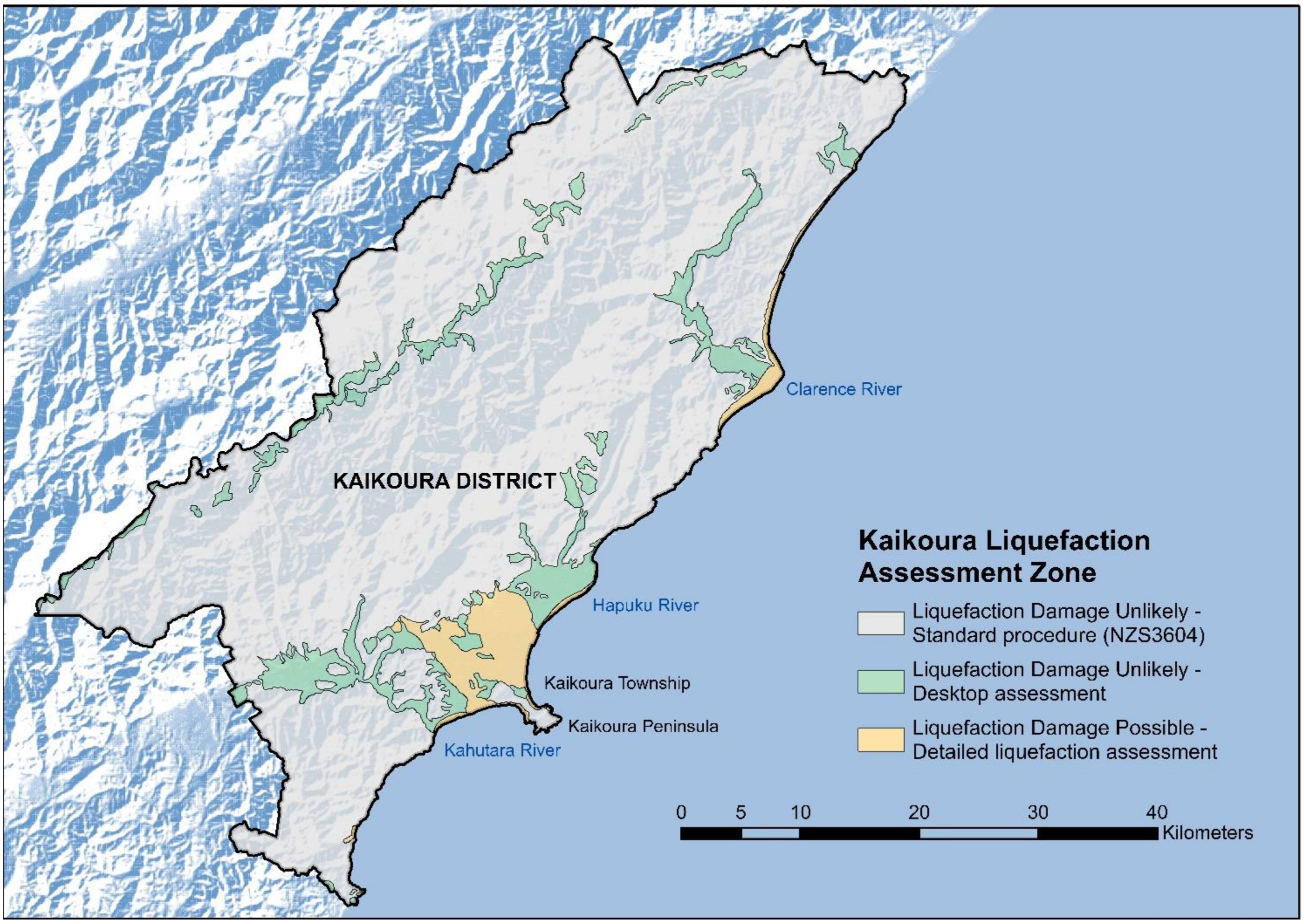

Figure 6: Kaikōura District liquefaction assessment zones.

4.1 Liquefaction Damage Unlikely - Standard Procedure (NZS3604)

In this zone, liquefaction damage is unlikely as defined in MBIE 2017. The zone is dominated by rock or hill sites, where there are little or no liquefaction susceptible soils. Standard investigation procedures outlined in NZS3604 are likely sufficient for planning or consenting purposes. Shallow investigations (see Section 4.1.1) should be undertaken if necessary to confirm that "good ground" is achieved as defined in NZS3604:

> *"Good ground: any soil or rock capable of permanently withstanding an ultimate bearing capacity of 300 kPa (i.e. an allowable bearing pressure of 100 kPa using a factor of safety of 3.0) but excludes:*
>
> *a)Potentially compressible ground such as top soil, soft soils such as clay which can be moulded easily in the fingers and uncompacted loose gravel which contains obvious voids;*
>
> *b)Expansive soils being those that have a liquid limit of more than 50 % when tested in accordance with NZS 4402 Test 2.2, and a linear shrinkage of more than 15 % when tested from the liquid limit in accordance with NZS 4402 Test 2.6; and*
>
> *c)Any ground which could foreseeably experience movement of 25 mm or greater for any reason including one or a combination of land instability, ground creep, subsidence, seasonal swelling and shrinking, frost heave, changing groundwater level, erosion, dissolution of soil in water and effects of tree roots."*

It should be noted that NZS3604 states that there is currently not enough information and evidence-based research to decide if liquefaction should be addressed in the definition of "good ground". For the purposes of the liquefaction assessment zones, if the definition of "good ground" is not met, specifically regarding uncompacted loose gravel, input from a geotechnical engineer or additional investigation/assessment is recommended, at the discretion of the professional conducting the standard NZS3604 assessment.

Additionally, the geological mapping in this zone is broad and often not detailed. Should any significant amount of liquefaction susceptible soils, i.e., soils dominated by silt or sand, be identified during the site specific standard procedure (NZS3604) assessment, liquefaction potential should be considered in more detail by means of a desktop assessment as outlined in Section 4.2.

4.1.1 Shallow Investigations

The primary purpose of a shallow investigation programme is normally to assess the suitability and geotechnical ultimate bearing capacity of the soil. It can also be used to characterise the conditions anticipated for relatively shallow earthworks, and provide a check on the existing fill depths or the presence of organics or topsoil. Shallow subsurface investigations can be carried out by a soils technician or other suitably trained and supervised person. A shallow investigation programme would typically comprise some combination of hand augered holes, dynamic cone penetration (DCP) tests (sometimes called scala penetrometer tests) and/or test pits. The depth of the shallow geotechnical investigations should typically:

- Extend a minimum of 3.0 m below the existing ground surface
- Extend a minimum of 1.0 m into natural ground
- Extend a minimum of 1.0 m below the zone of influence of the proposed foundation system and at least twice the footing width
- Enable visual assessment and confirmation of the soil type and strength/density.

Shallow investigations will not enable characterisation or engineering analysis of liquefaction potential on a site. However, the presence of potentially liquefiable soils near surface (as described in Section 1.2) could be determined during shallow investigations. Geotechnical logs and records should be compiled for the investigation, in accordance with the recommendations outlined in the latest edition of the NZGS field classification and description guideline. Refer to MBIE (2016) document titled *Module 2: Geotechnical Investigations for Earthquake Engineering* for more details on investigation methods.

For concrete slab foundations consideration can be given to enhanced foundations such as 'waffle slabs' (i.e., similar to MBIE 'TC2' type foundations) at the discretion of the designer and contractor as these have been shown to provide superior resilience to earthquake damage compared to standard NZS3604 concrete floor slabs.

4.2 Liquefaction Damage Unlikely - Desktop Assessment

Liquefaction damage is possible (as defined in MBIE 2017) in some areas within this zone but unlikely. This zone is dominated by alluvial deposits older than Holocene age and river plains and fans away from the coastal margins. Liquefaction potential should be discussed/confirmed by a suitably qualified engineer or engineering geologist using results of a desktop study considering available site information or a shallow geotechnical investigation (as described in Section 4.1.1). In other words, the desktop assessment can be used as a starting point to determine if a more detailed liquefaction assessment is required. If the results of the shallow investigation suggest that the liquefaction susceptibility of the site is low (based on ground water level and ground conditions), a detailed liquefaction assessment (Section 4.3) with deep investigations is not required and NZS3604 standard procedures can be followed. The requirement for further input from a geotechnical engineer or engineering geologist and a detailed liquefaction assessment is based on the results of the desktop assessment and is at the discretion of the professional conducting the desktop assessment. Evidence and explanation must be provided to support the assessment of liquefaction susceptibly. Assessment Level A or Level B (depending on the scope of works) is required as per Table 3.2 of MBIE 2017.

Assessment Level A from MBIE 2017 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 (e.g., geological and topographic maps) and local knowledge. It should be possible to confirm if liquefaction hazard is considered an issue on site by citing the available information. If it cannot be concluded that the liquefaction susceptibility is low from the available information, the assessment Level B from MBIE 2017 should be undertaken. If the results of this investigation show that there are potentially liquefiable soils on site, a detailed liquefaction assessment as outlined in Section 4.3 and input from a geotechnical engineer is required.

Assessment Level B from MBIE 2017 is a calibrated desktop assessment which includes 'calibration' of the geological/geomorphic maps using subsurface investigations such as dynamic cone penetration tests (also known as scala penetrometer tests) and hand-augered boreholes. 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. Targeted collection of new information may be useful in areas where existing information is sparse and reducing the uncertainty could have a significant impact on objectives and decision-making. If the results of this investigation show that there are potentially liquefiable soils on site, a detailed liquefaction assessment as outlined in Section 4.3 input from a geotechnical engineer or engineering geologist is required.

Desktop assessments should also consider natural hazards other than liquefaction that could affect the proposed development.

4.3 Liquefaction Damage Possible - Detailed Liquefaction Assessment

Liquefaction damage is possible (as defined in MBIE 2017) in this zone. The geological mapping shows that this zone is dominated by Holocene alluvial deposits including river plains and fans and the coastal margins. Input from a suitably qualified geotechnical engineer or engineering geologist is required for adequate ground characterisation regarding liquefaction potential. Deep investigations (see Section 4.3.1), such as cone penetration testing or borehole drilling with standard penetration tests, are required (as per Section 3.4 of MBIE 2017) unless in specific cases where the geotechnical engineer or engineering geologist can justify that they are not necessary. Specific engineering design recommendations for developing on liquefaction-prone land are required from the geotechnical engineer or engineering geologist with considerations given to the proposed scope of works. Assessment Level C or Level D (depending on the scope of works) is required as per Table 3.2 of MBIE 2017.

Assessment Level C from MBIE 2017 includes a quantitative assessment based on a moderate density of subsurface investigations, with other information (e.g., geomorphology and groundwater) also assessed in finer detail. It may be appropriate to use the results of deep investigations from nearby sites. This level of investigation and assessment will likely require additional ground investigations and more complex engineering analysis.

Assessment Level D from MBIE 2017 is a site-specific assessment drawing on a high density of subsurface investigations (i.e., on site) and considers the specific details of the proposed site development (e.g., location, size and foundation type of building). Liquefaction assessment of the subsurface investigations data is recommended. This level of investigation and assessment should result in a high degree of confidence in the understanding of the site-specific liquefaction hazard.

4.3.1 Deep Investigations

The scope of a deep geotechnical investigation must be determined by a suitably qualified geotechnical engineer or engineering geologist. Common deep investigation methods include the cone penetration test (CPT) and machine-drilled boreholes with standard penetration test (SPT). Other less common deep methods include the heavy dynamic probe (HDP) the Swedish weight sounding (SWS) and the dilatometer test (DMT). The target depth of the investigation depends on the proposed scope of works:

- For shallow foundations supporting lightweight structures, at least two deep investigation points to a depth in the order of 10 to 15 m.
- For heavily loaded or piled foundations, the deep investigation points may need to extend to a depth of 20 m or more.

To the extent practical, a deep geotechnical investigation should not terminate within potentially problematic soils (i.e., liquefiable soils, peat, soft or organic silts and clays), or within a unit which is known to overlie problematic soils. In some cases where CPTs are hampered by gravel layers, a single borehole with SPT testing may be appropriate, augmented by shallower investigations. It should be noted that shallow refusal of a CPT is not necessarily proof that the base of all liquefiable layers has been identified. CPTs can refuse on relatively thin but relatively dense gravel/sandy gravel layers. In alluvial plain deposits (such as those found in parts of Kaikōura District), this is a common occurrence. To overcome the problem of CPT refusal in interlayered but potentially liquefiable deposits, it may be necessary to either pre-drill (in the case of a shallow dense layer for example), or switch over to machine boreholes and SPT sampling. If pre-drilling followed by CPT is utilised, the liquefaction potential of any loose/medium dense soils drilled through should still be assessed utilising SPT

Groundwater measurements following the investigations should be taken. Engineering analysis of the site is required to determine the land performance in future serviceability limit state (SLS) and ultimate limit state (ULS) earthquake events. Refer to MBIE (2016) document titled *Module 2: Geotechnical Investigations for Earthquake Engineering* for more details on investigation methods.

5.0 SOURCE DATA

This section provides a summary of the datasets cited and how they were incorporated into the current study.

5.1 Previous Liquefaction Susceptibility Assessment in Kaikōura District

Based on the available information at the time, Geotech (2009) indicated that there were few deposits judged to be significantly susceptible to liquefaction within Kaikōura District. Geotech (2009) concludes that, while there may be some small areas susceptible to liquefaction with strong earthquake shaking, liquefaction was not regarded as a significant hazard within the district. The district was classified into three categories described in Table 2 and Figure 7.

Table 2: Kaikōura liquefaction susceptibility category descriptions (after Geotech 2009).

Category	Geological Description	Liquefaction Susceptibility
Zone of extremely low to no liquefaction potential	Rock or hill soils	Low to no liquefaction potential
Zone of very low liquefaction potential	Alluvium older than Holocene	Very small possibility of liquefaction in local, isolated areas.
Zone of low liquefaction potential	Holocene alluvium	Possibility of local areas of liquefaction, limited in extent and area.

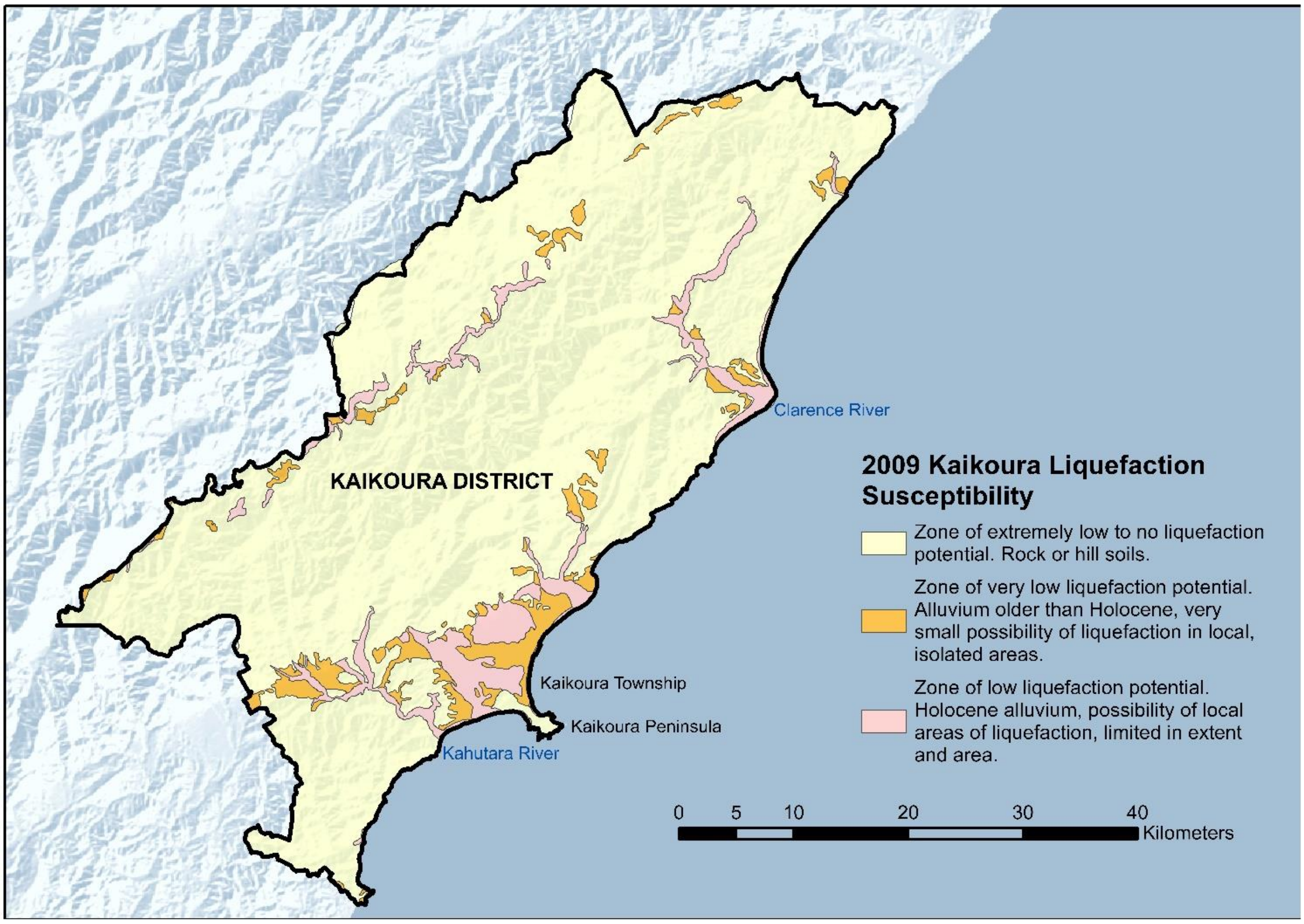

Figure 7: Liquefaction Susceptibility in Kaikōura District (after Geotech 2009).

The zones delineated by Geotech (2009) were used as the starting point for the liquefaction assessment zones presented in this report. Boundaries were modified to suit the liquefaction damage observations and additional information that have been collected since 2009.

The areas zoned pink in 2009 (*zone of low liquefaction potential)* were divided into requiring either a desktop assessment or a detailed liquefaction assessment in the liquefaction assessment zones presented in this report. The coastal areas and the populated areas near Kaikōura township were mapped as requiring a detailed liquefaction assessment as the likelihood of encountering potentially liquefiable soils was considered higher in these areas. The remote areas to the west of the Kaikōura Ranges as well as the areas of the Kahutara River and Clarence River that are away from the coastal plains were classified as requiring a desktop assessment to begin with. Holocene alluvium has been mapped in this area; however, it is likely to be coarser in nature the further it is from the coastal margins. In these remote areas, where limited geotechnical information is currently available, it was not considered practical to start with a deep geotechnical assessment. If the desktop assessment reveals that the site may be susceptible to liquefaction, a detailed assessment will need to be undertaken.

Some areas near Kaikōura township which were mapped orange in 2009 (*zone of very low liquefaction potential*) have been zoned as requiring detailed liquefaction assessment in the liquefaction assessment zones. These are areas where nearby liquefaction damage was observed following the 2016 Kaikōura earthquake.

5.2 Geological Map

The QMAP geological map series covers all of New Zealand at a scale of 1:250 000 and the accompanying texts describe each area's geomorphology, stratigraphy, tectonic history, geological resources, geological hazards and engineering geology in general terms. Rattenbury et al. (2006) compiled the geological map covering Kaikōura District.

From the QMAP data, stratigraphic age, geological formation and rock group information were used to help define the liquefaction assessment zones. The QMAP confirmed that the 2009 liquefaction susceptibility zones (summarised in Section 5.1) followed the geological boundaries to the level of detail required for this project.

5.3 Geomorphological Map

A detailed geomorphological map of the Kaikōura floodplain and neighbouring rivers, streams and fans was prepared by McPherson (1999) at 1:10,000 scale. This map was used to help delineate the liquefaction assessment zones where coastal sea-cut cliffs and alluvial terraces are found in the vicinity of the intersection between Harnetts Road and Beach Road.

5.4 Topographic Data

Digital elevation models developed from aerial light detection and ranging (LiDAR) data were used to outline the hilly areas of the Kaikōura Peninsula around Kaikōura township that are considered unlikely to be susceptible to liquefaction. LiDAR data was sourced from the Land Information New Zealand (LINZ) website, as well as the Kaikōura Earthquake Viewer (KEV). This data includes LiDAR data from the Kaikōura area captured in 2012 for Environment Canterbury by Aerial Surveys Limited. Topographic models from the KEV includes post-2016 Kaikōura earthquake LiDAR elevation data.

5.5 Liquefaction Damage Observations Following the 2016 Kaikōura Earthquake

Following the 2016 Kaikōura earthquake, there was evidence that liquefaction and liquefaction-induced damage had occurred in Kaikōura District. It should be noted that liquefaction observations were primarily made in populated areas. Kaikōura District has remote and unpopulated areas that may have experienced liquefaction-induced ground damage; however, damage may not have been recorded or observed following the 2016 Kaikōura earthquake. Areas where liquefaction-induced damage was observed following the 2016 Kaikōura earthquake were classified to be in the *detailed liquefaction assessment* zone, meaning they require the highest level of liquefaction assessment.

Observations made by Golder in previous work

Golder has worked extensively in Kaikōura District to provide technical advice on liquefaction following the 2016 Kaikōura earthquake. Local knowledge and observations from other studies completed by Golder were locally used to verify the boundaries of the liquefaction assessment zones.

Geotechnical information from Stringer et al. (2017)

Stringer et al. (2017) reported that little liquefaction was observed across the South Island, despite the large magnitude of the 2016 Kaikōura earthquake. The spatial extent and volume of liquefaction ejecta across South Island was significantly less than that observed in Christchurch during the 2010-2011 Canterbury Earthquake Sequence. The impact of the 2016 Kaikōura earthquake on the built environment may have been relatively minor because the severe manifestations occurred away from the areas of intensive development.

In the township of Kaikōura, the majority of the damage to infrastructure caused by liquefaction was concentrated along Lyell Creek, where large lateral displacements were observed within 30 m of the creek resulting in heavy damage to many houses built close to the river, underground services and to one short-span bridge. Other liquefaction related damage in the region included cracking and deformation of the roads, as well as some damage to the liner systems in embankments at the oxidation ponds to the north of the town. Liquefaction ejecta was noted in some areas outside of the main township, though the overall impact of liquefaction was minor in those areas. A map showing the locations of observed damage in Kaikōura township is presented in Figure 8.

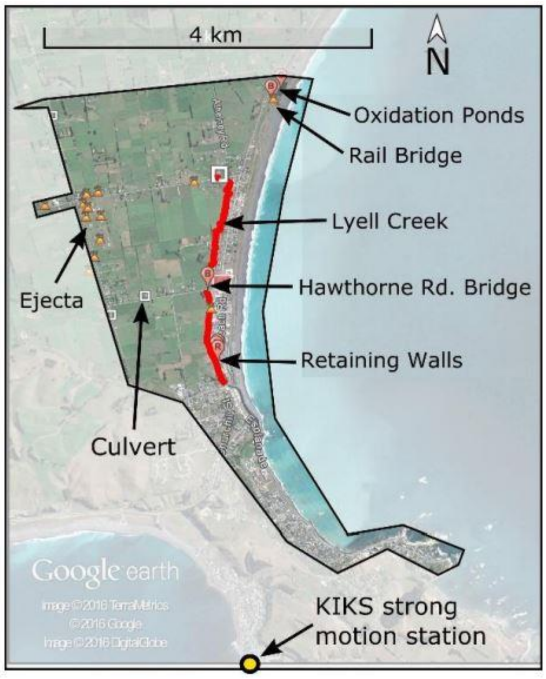

Figure 8: Reconnaissance in Kaikōura by Stringer et al. (2017).

In rural Kaikōura, minor to moderate quantities of liquefaction ejecta were observed in a relatively small number of locations, generally west of the main Kaikōura town. A map showing the locations where liquefaction ejecta was observed is presented in Figure 9. The amount of liquefaction ejecta at each of the recorded locations was reported to be limited and affected only a small area.

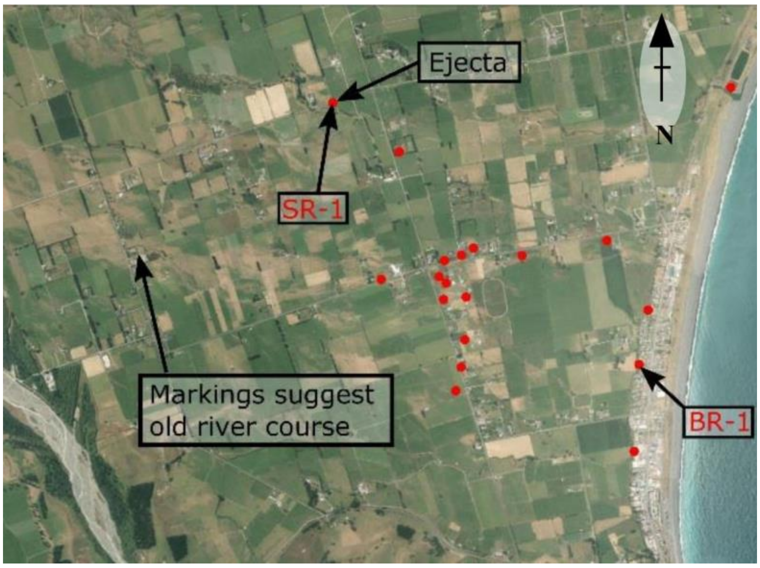

Figure 9: Positions of known liquefaction ejecta in rural Kaikōura observed by Stringer et al. (2017). SR-1 and BR-1 indicate soil sample locations.

For the purposes of defining the liquefaction assessment zones, areas where liquefaction damage was observed, and their vicinity are classified in the *detailed liquefaction assessment* zone. Additionally, we have classified areas where lateral spreading had occurred (such as Lyell Creek) in the *detailed liquefaction assessment* zone despite Stringer et al. (2017) concluding that the driving mechanism was not due to "classic liquefaction-induced lateral spreading". Considering the serious potential structural consequences of lateral spreading to buildings and other infrastructure, input from a geotechnical engineer is required in these areas.

Damage observations from the Kaikōura Earthquake Viewer (KEV)

Photographs taken on the ground during site visits as well as damage observations by University of Auckland, University of Canterbury and Tonkin and Taylor following the 2016 Kaikōura earthquake are available on the KEV.

Wherever liquefaction damage was noted, the area was classified in the *detailed liquefaction assessment* zone. Additionally, geological information and subsurface data near observed liquefaction damage were reviewed to validate the boundaries of the liquefaction assessment zones.

5.6 Post-Earthquake Aerial Photography

High resolution aerial photography of State Highway 1 taken in response to the Kaikōura earthquake (LINZ 2016) was used in this study, as was aerial photography available on the KEV.

Aerial photography was used to outline geological boundaries around the Kaikōura peninsula and the coast of South Bay, specifically to outline the boundary between potentially liquefiable materials and non-liquefiable that were not captured in the geological mapping.

5.7 Environment Canterbury Well and Bore-Logs

Drilling logs for 155 well or bore-logs were available for this report. The logs provide subsurface information including observed lithology and depth to ground water. Where observation information or geological mapping was not specific enough to delineate the liquefaction assessment zones, nearby well/bore logs were evaluated for liquefaction susceptibility by checking the lithology and depth to ground water. A detailed liquefaction analysis of the available subsurface investigation data was not conducted as part of this study.

6.0 USES AND CONSIDERATIONS

There are numerous ways information about the potential for liquefaction-induced ground damage might be used, for example:

- long term strategic land use planning
- developing planning processes to manage risks and the effects of natural hazard events
- design of land development, building and infrastructure works
- informing earthquake-prone building assessments
- improving infrastructure and lifeline resilience
- civil defence and emergency management planning
- catastrophe loss modelling for insurance, disaster risk reduction and recovery planning.

When undertaking liquefaction investigations, it is essential that the intended purpose (or scope of works) of the proposed development is clearly defined to the professional undertaking the liquefaction investigation, as this will govern many aspects of the technical work that needs to be undertaken. If the site is covered by more than one liquefaction assessment zone, the higher level of assessment should be undertaken.

The scientific understanding of liquefaction and seismic hazard is imperfect, so there remains a risk that actual land performance could differ from analysis results even with a high level of site-specific detail in the assessment. Therefore, the professional undertaking the investigations must be suitably qualified to assess the encountered ground conditions. If there is any doubt regarding liquefaction hazard, a peer review should be undertaken. Additionally, peer review should be included where a liquefaction assessment is of particular importance or complexity.

It should be noted that there is a level of uncertainty in the extent of the liquefaction assessment zones due to the lack of data in some areas. However, availability of data was considered when describing the requirements for each of the zones. Ground truthing of the geological boundaries is outside the scope of this report and detailed verification of the datasets was not undertaken.

This report provides guidance on investigations for liquefaction characterisation only. Although the liquefaction assessment zones may suggest that a geotechnical assessment for liquefaction is not required, input from a geotechnical engineer or engineering geologist may be required for other geotechnical hazards. Available information regarding all potential geotechnical hazards (such as slope instability and fault hazard), should be considered during planning or consenting.

7.0 CONCLUSION

Previous liquefaction hazard information and data available following the 2016 Kaikōura earthquake were used to define three liquefaction assessment zones across the Kaikōura District. The liquefaction assessment zones are meant to provide guidance on the level of assessment and investigation required to characterise the liquefaction hazard in a given area during planning and the building consent process. The assessment follows current guidance for planning and engineering for potentially liquefaction prone land (MBIE 2017).

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APPENDIX A

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APPENDIX B

Maps of Liquefaction Assessment Zones

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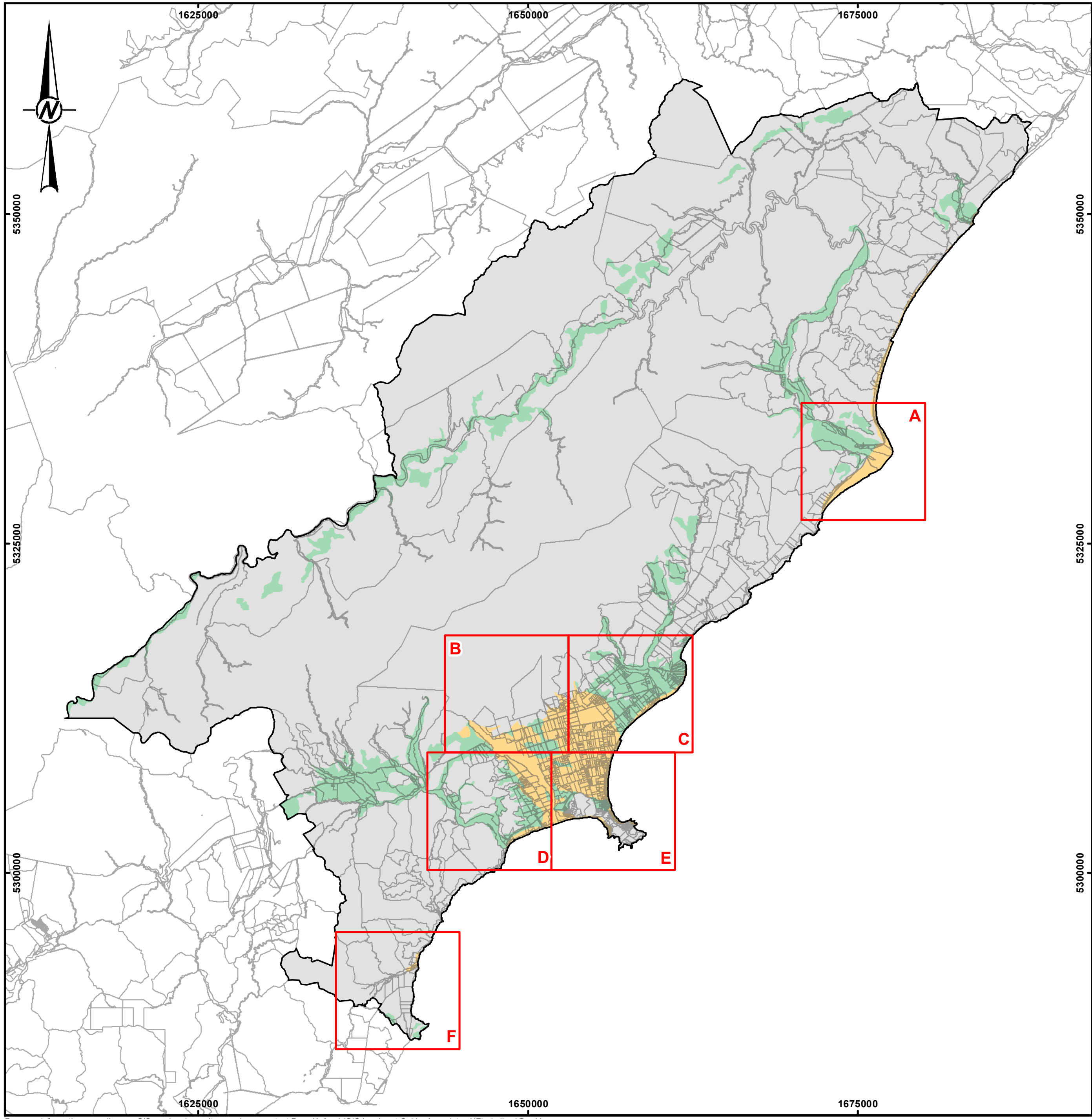

LEGEND

- Kaikoura District boundary
- Property boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment
- Detailed maps A-F

NOTES

1. Aerial: LINZ and Eagle Technology, CC-BY-3.0-NZ.
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KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONES

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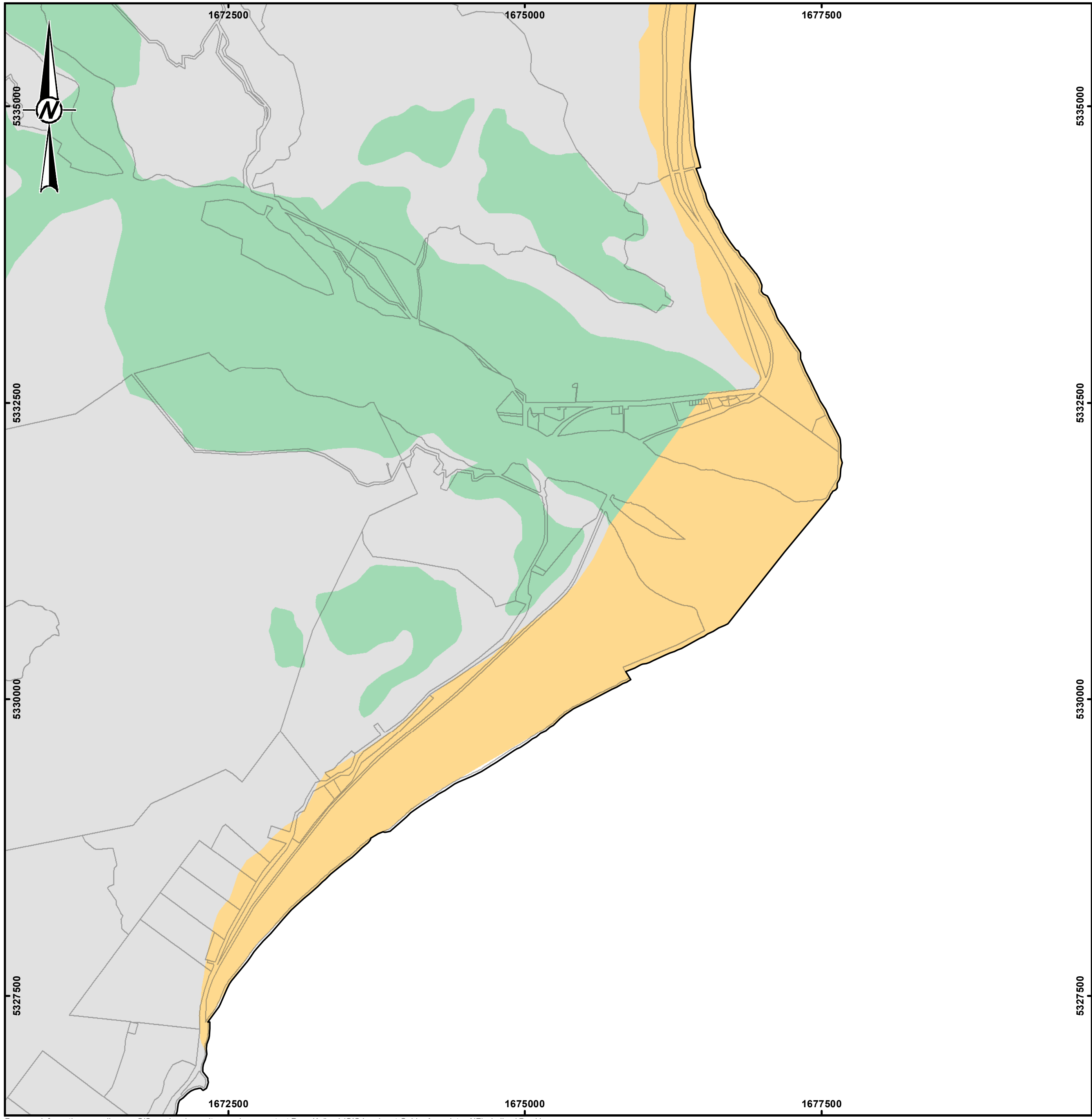

LEGEND

- Kaikoura District boundary
- Property boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
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- Liquefaction Damage Possible - Detailed liquefaction assessment

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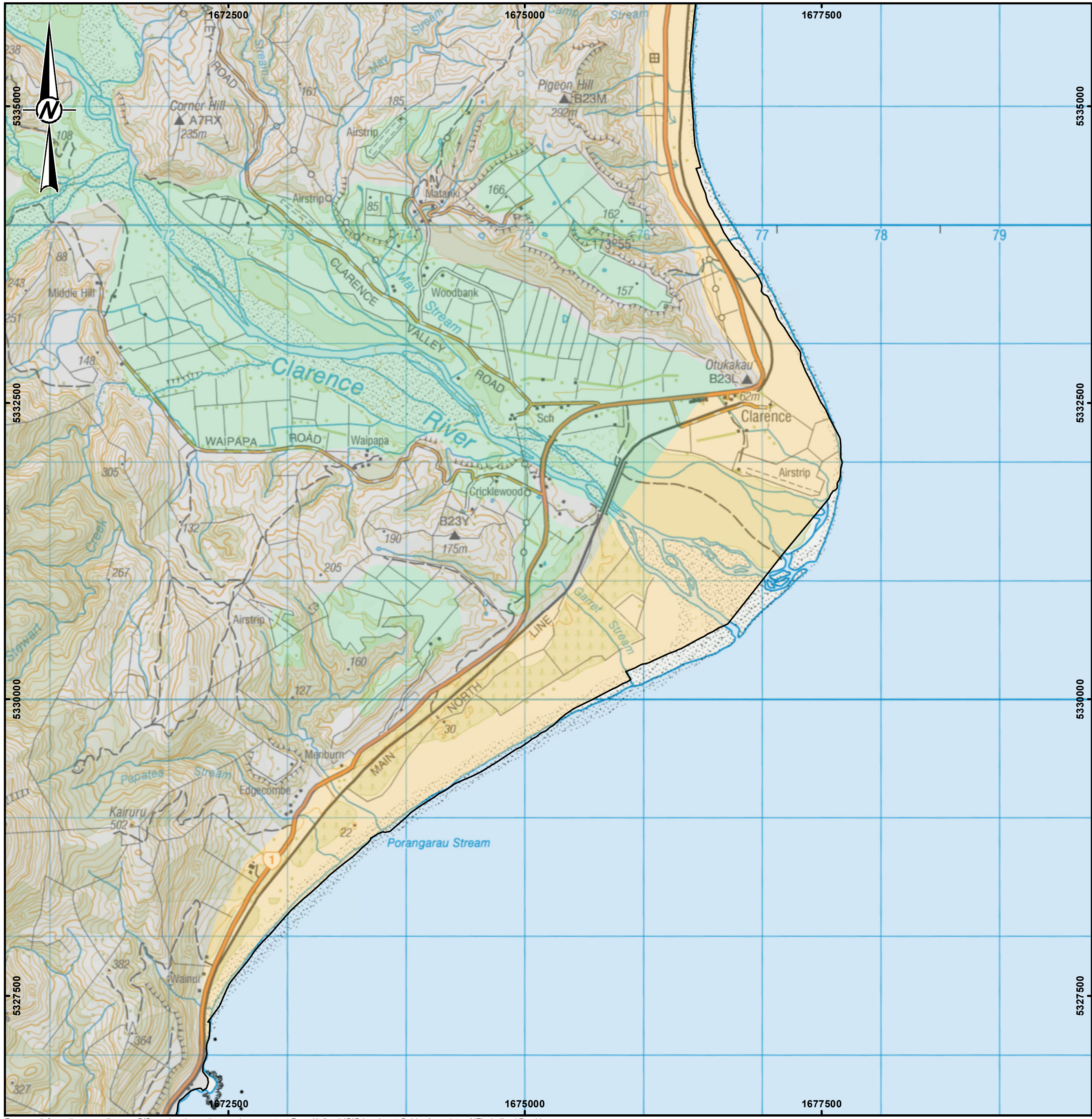

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Kaikoura District boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
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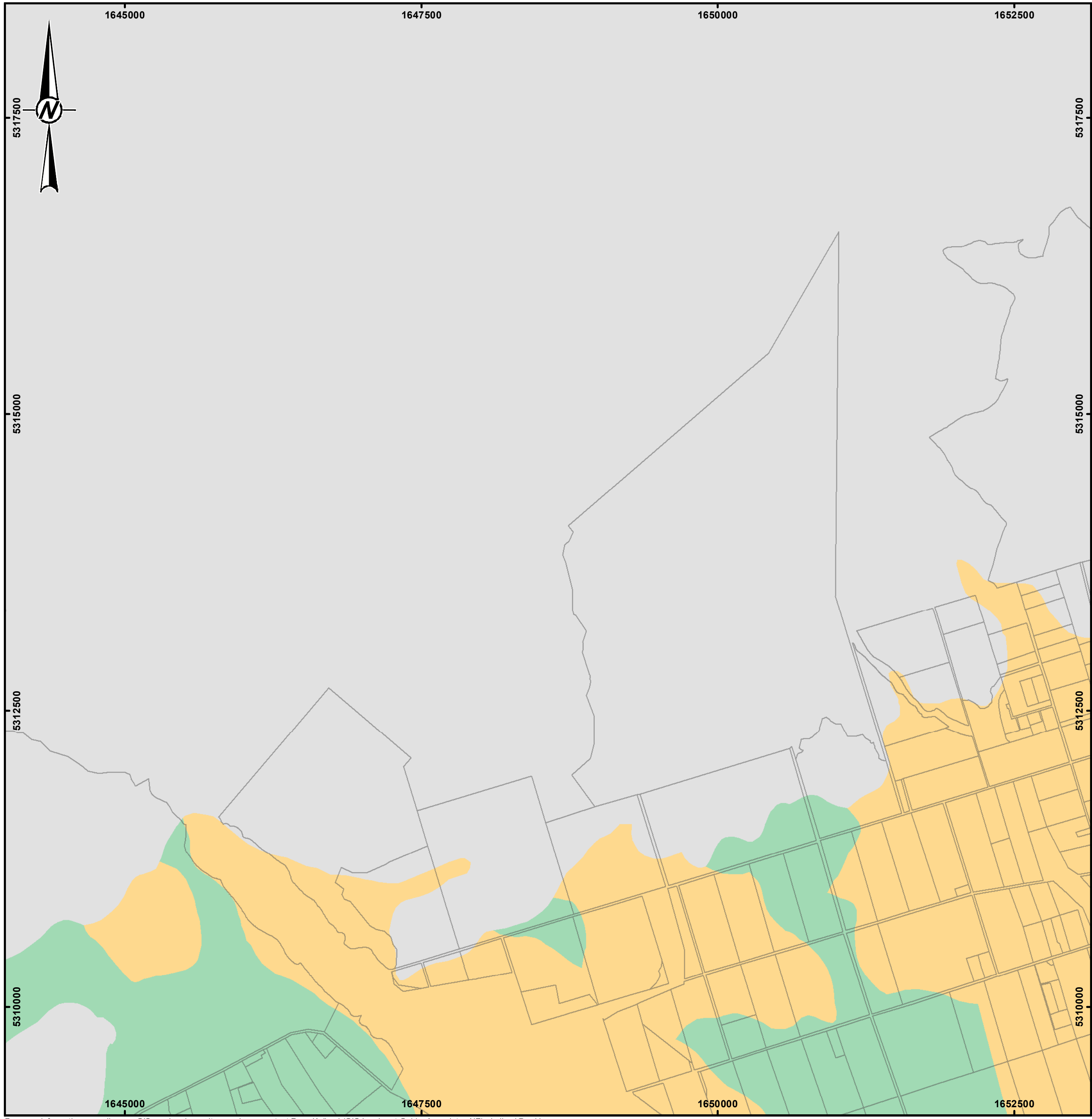

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- Kaikoura District boundary
- Property boundary

Kaikoura Liquefaction Investigation Zones

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LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW B - PROPERTY BOUNDARIES

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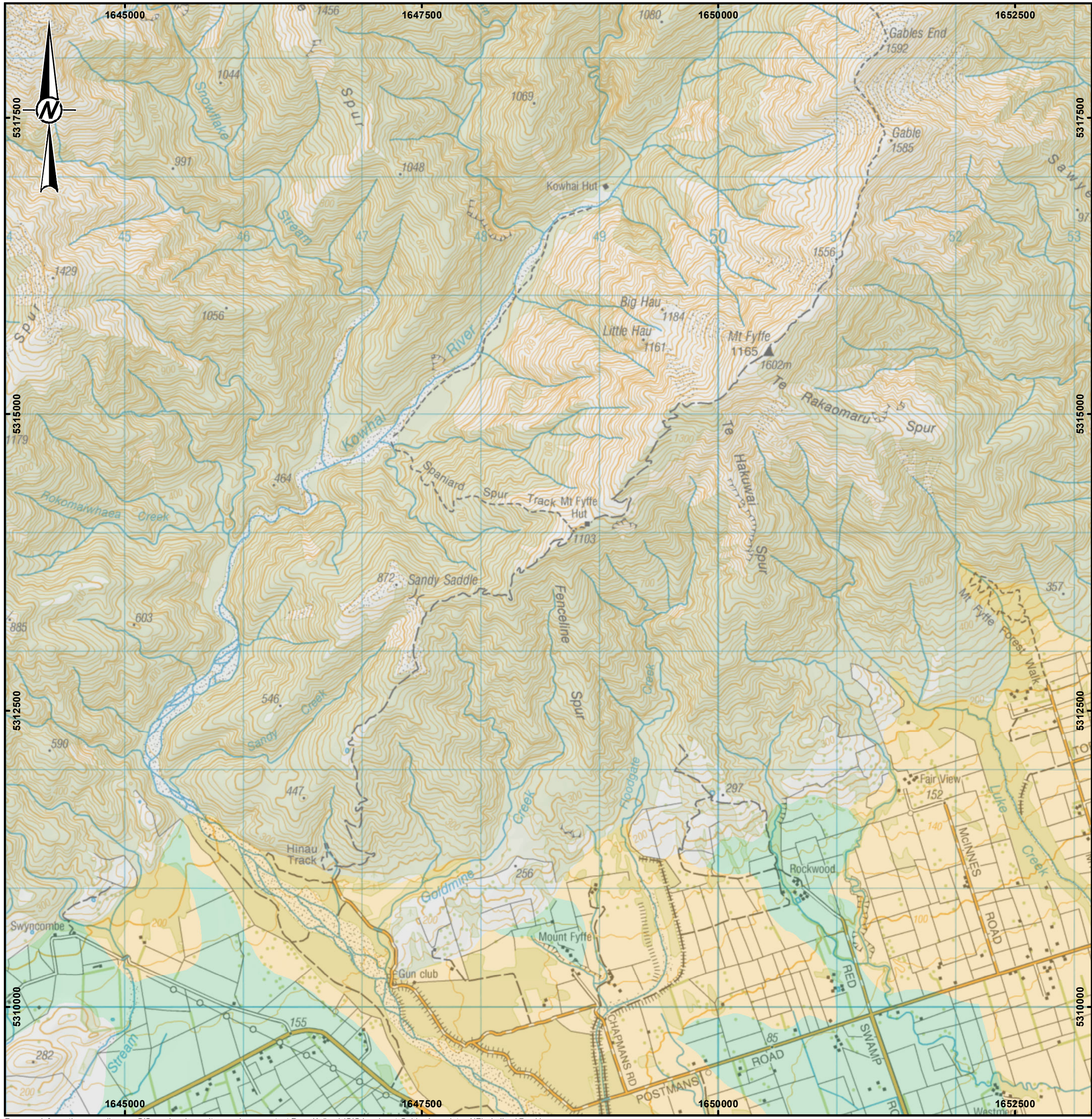

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Kaikoura District boundary

Kaikoura Liquefaction Investigation Zones

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Liquefaction Damage Unlikely - Desktop assessment

Liquefaction Damage Possible - Detailed liquefaction assessment

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LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW B - NZTOPO50 MAP

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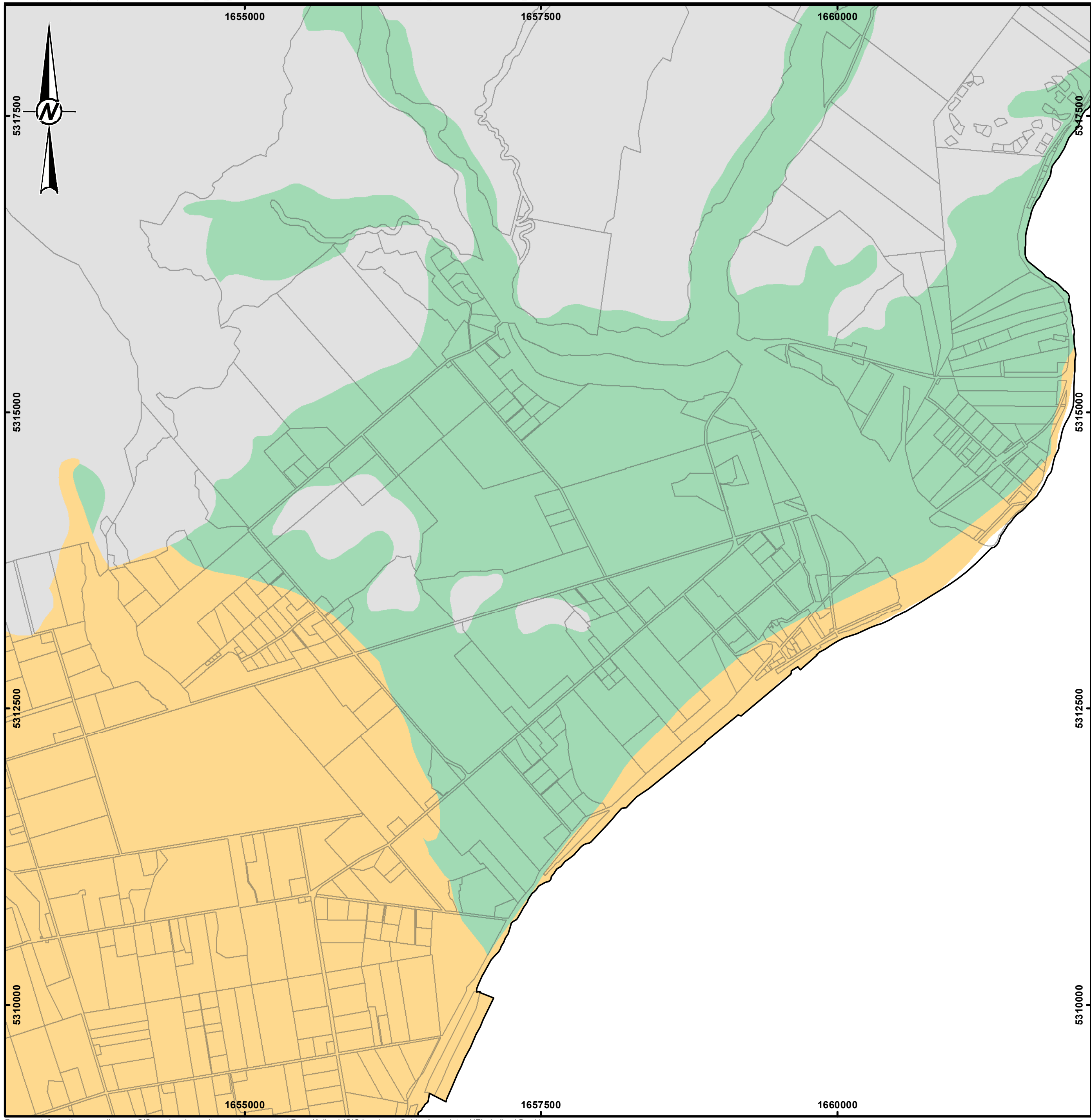

LEGEND

Kaikoura District boundary

Property boundary

Kaikoura Liquefaction Investigation Zones

Liquefaction Damage Unlikely - Standard procedure (NZS3604)

Liquefaction Damage Unlikely - Desktop assessment

Liquefaction Damage Possible - Detailed liquefaction assessment

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TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW C - PROPERTY BOUNDARIES

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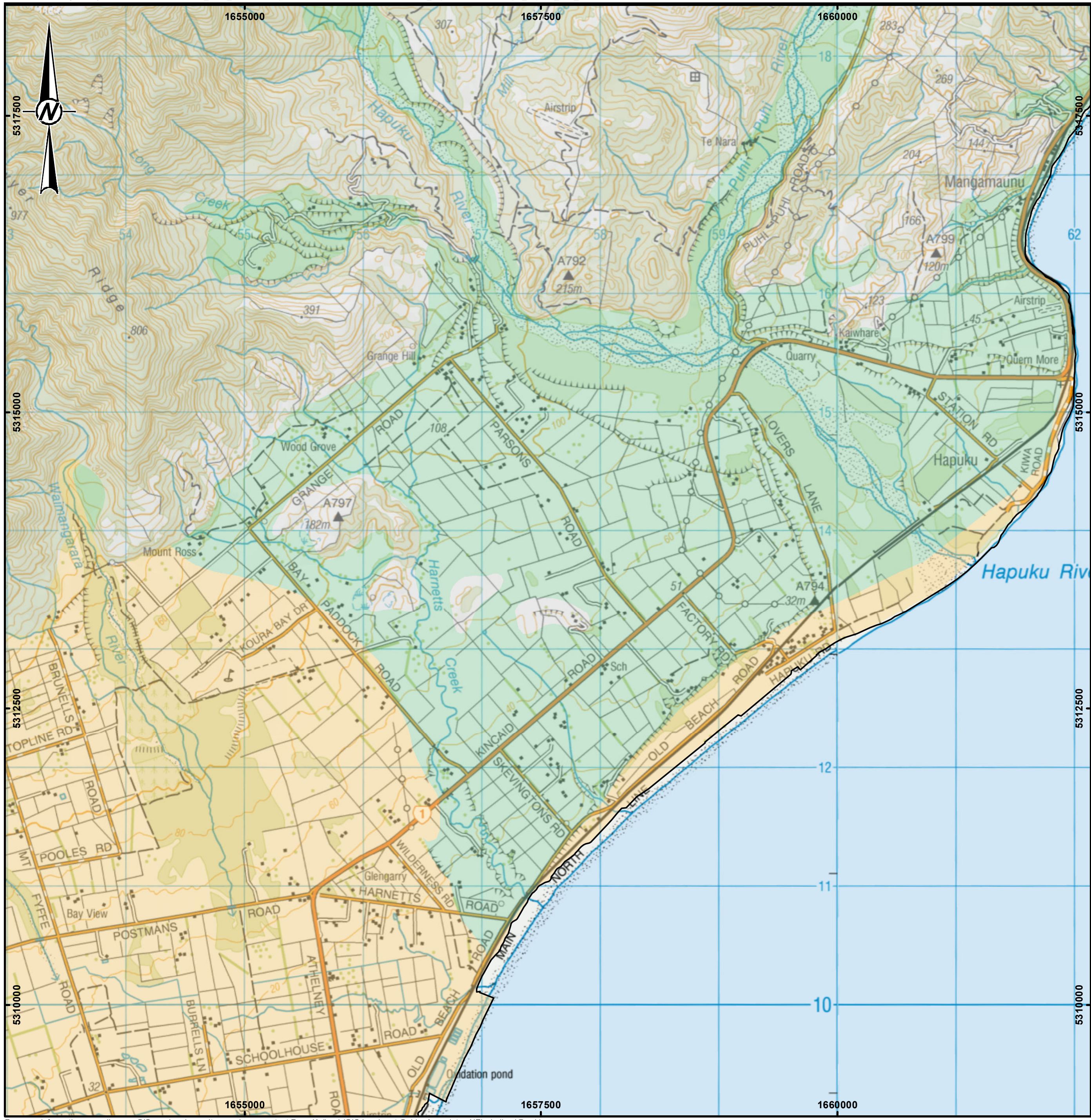

LEGEND

Kaikoura District boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment

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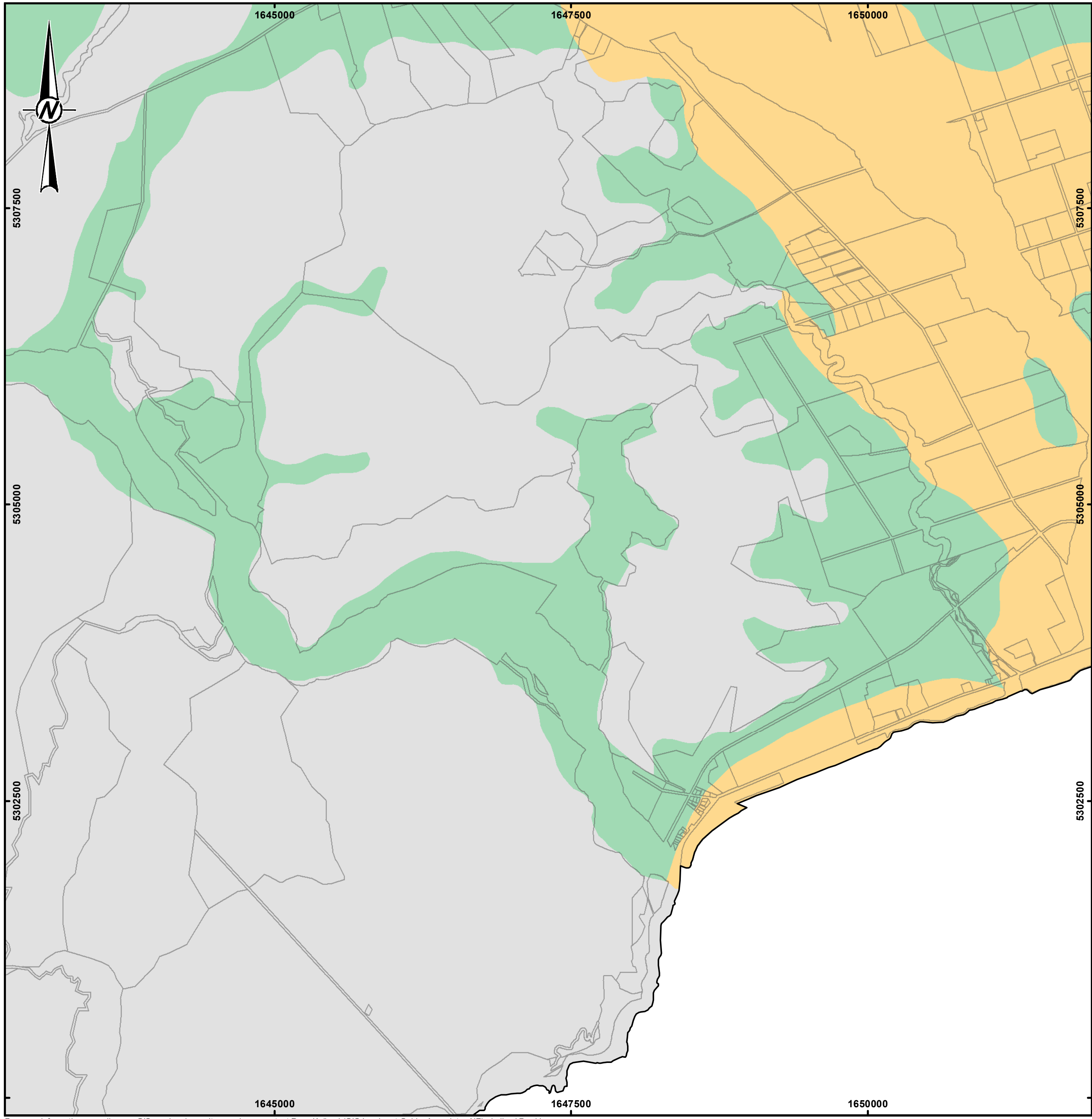

LEGEND

- Kaikoura District boundary
- Property boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

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0 2 4 Kilometers

REFERENCE SCALE: 1:50,000 (at A4)

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

CLIENT

ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT

KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW D - PROPERTY BOUNDARIES

CONSULTANT

GOLDER

YYYY-MM-DD	2019-09-17
PREPARED	LT
REVIEWED	MCH
APPROVED	TJM

PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	B08

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25mm 0

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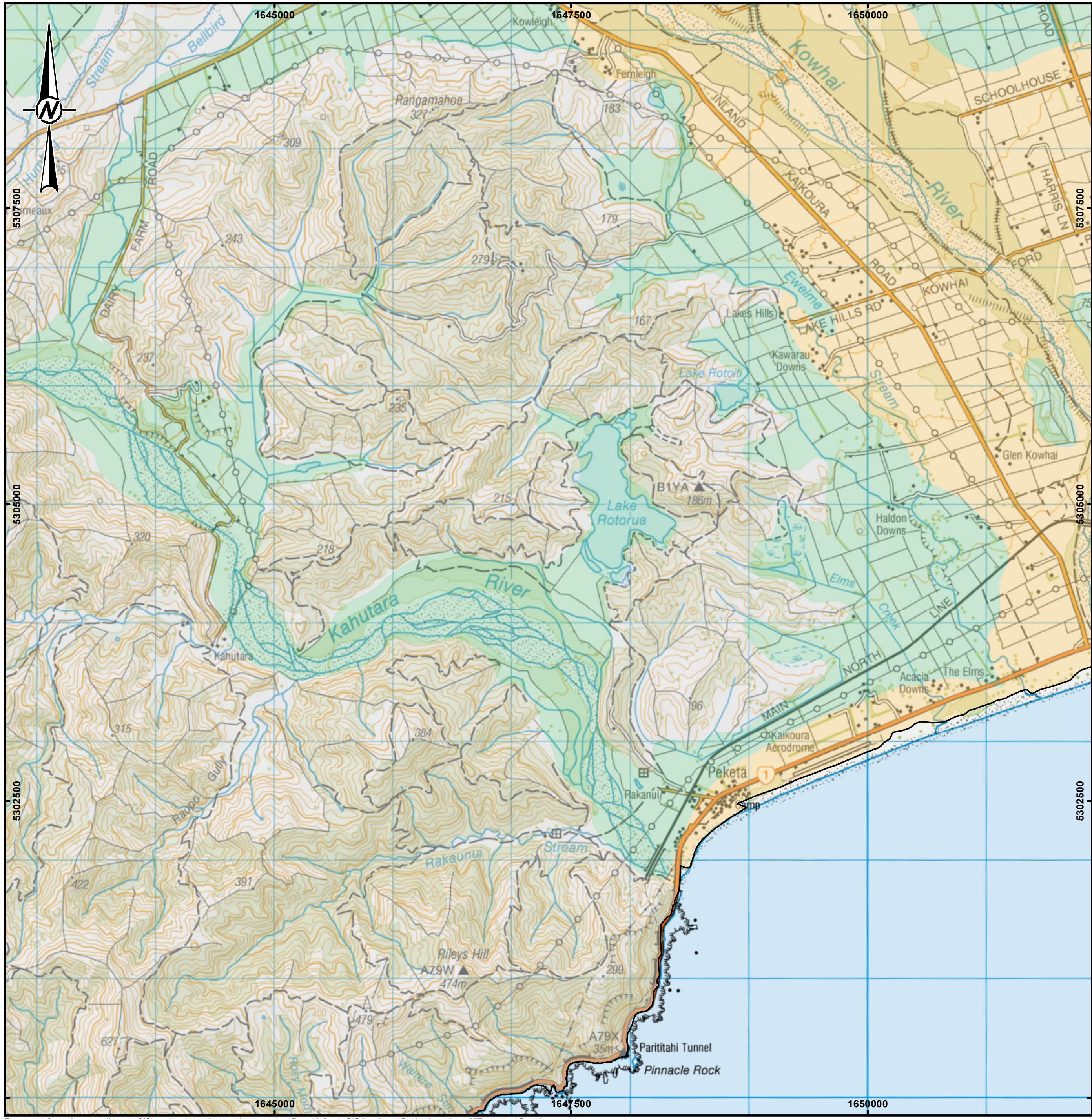

LEGEND

Kaikoura District boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

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0 2 4 Kilometers

REFERENCE SCALE: 1:50,000 (at A4)

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

CLIENT

ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT

KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW D - NZTOPO50 MAP

CONSULTANT

GOLDER

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REVIEWED	MCH
APPROVED	TJM

PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	B09

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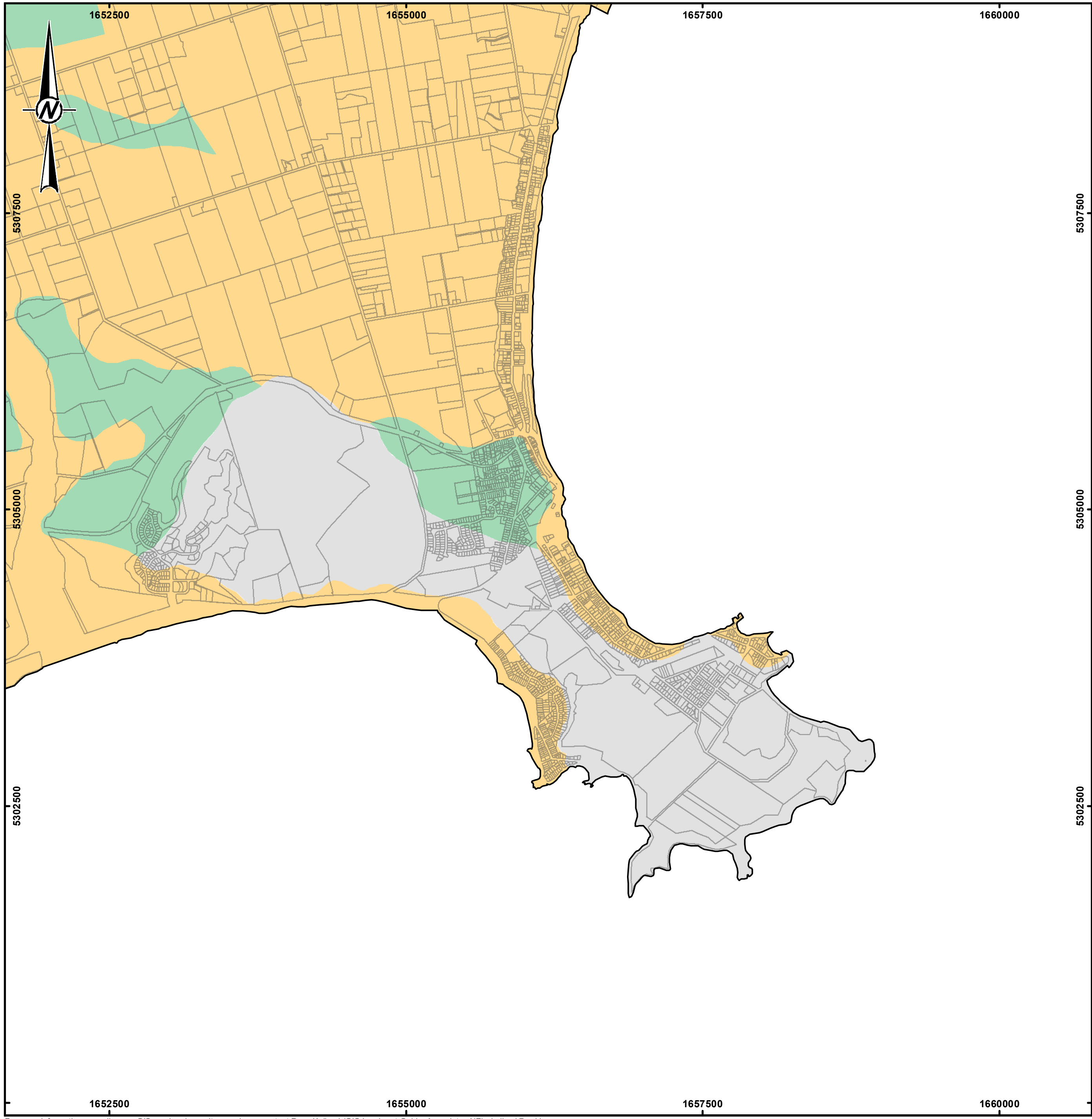

LEGEND

Kaikoura District boundary

Property boundary

Kaikoura Liquefaction Investigation Zones

Liquefaction Damage Unlikely - Standard procedure (NZS3604)

Liquefaction Damage Unlikely - Desktop assessment

Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

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0 2 4
Kilometers

REFERENCE SCALE: 1:50,000 (at A4)
PROJECTION: NZGD 2000 New Zealand Transverse Mercator

CLIENT
ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT
KAIKOURA

TITLE
LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW E - PROPERTY BOUNDARIES

CONSULTANT	YYYY-MM-DD	2019-09-17
GOLDER	PREPARED	LT
	REVIEWED	MCH
	APPROVED	TJM

PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	**B10**

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LEGEND

- Kaikoura District boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

1. Aerial: LINZ and Eagle Technology, CC-BY-3.0-NZ.
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0 2 4 Kilometers

REFERENCE SCALE: 1:50,000 (at A4)

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

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ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT

KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW E - NZTOPO50 MAP

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APPROVED	TJM

PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	B11

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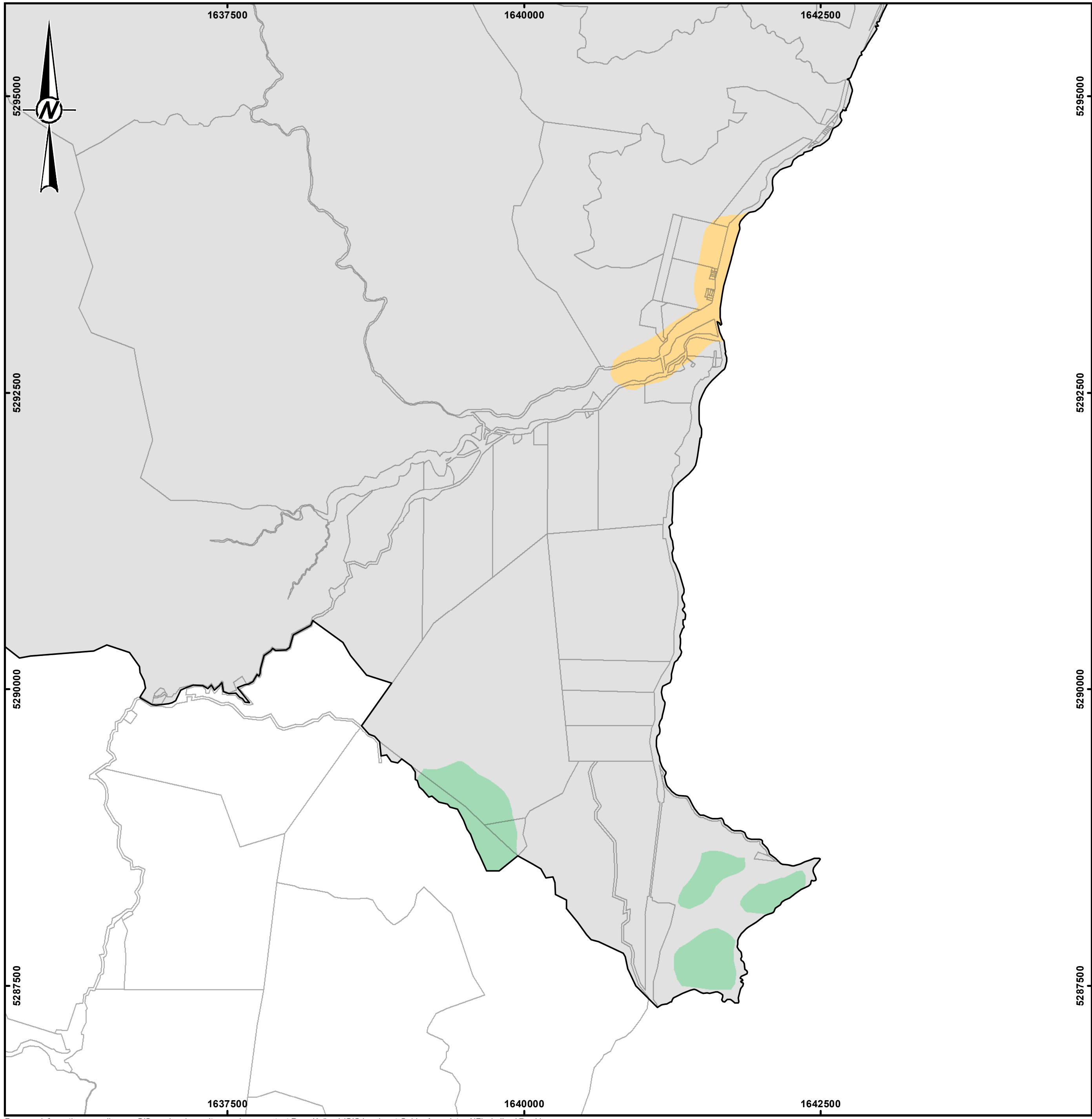

LEGEND

Kaikoura District boundary

Property boundary

Kaikoura Liquefaction Investigation Zones

Liquefaction Damage Unlikely - Standard procedure (NZS3604)

Liquefaction Damage Unlikely - Desktop assessment

Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

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0 2 4

Kilometers

REFERENCE SCALE: 1:50,000 (at A4)

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

CLIENT

ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT

KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW F - PROPERTY BOUNDARIES

CONSULTANT

GOLDER

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PREPARED	LT
REVIEWED	MCH
APPROVED	TJM

PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	B12

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LEGEND

- Kaikoura District boundary
- Property boundary

Kaikoura Liquefaction Investigation Zones

- Liquefaction Damage Unlikely - Standard procedure (NZS3604)
- Liquefaction Damage Unlikely - Desktop assessment
- Liquefaction Damage Possible - Detailed liquefaction assessment

NOTES

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0 2 4
Kilometers

REFERENCE SCALE: 1:50,000 (at A4)

PROJECTION: NZGD 2000 New Zealand Transverse Mercator

CLIENT

ENVIRONMENT CANTERBURY / KAIKOURA DISTRICT COUNCIL

PROJECT

KAIKOURA

TITLE

LIQUEFACTION ASSESSMENT ZONE: DETAILED VIEW F - NZTOPO50 MAP

CONSULTANT	
YYYY-MM-DD	2019-09-17
PREPARED	LT
REVIEWED	MCH
APPROVED	TJM

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PROJECT No.	REPORT	REV.	FIGURE
1894330	003	2	B13

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25mm

APPENDIX C

Liquefaction Assessment Zones Flowchart

LIQUEFACTION ASSESSMENT ZONES FLOWCHART FOR BUILDING CONSENT ASSESSMENT

NOTE: This flowchart should be read in conjunction with the report entitled Liquefaction Hazard for Kaikōura District dated May 2019 (report reference: 1894330-7407-003-R-Rev0).

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