Assessment of liquefaction hazards in the Dunedin City district

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GNS Science Consultancy Report 2014/068

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BIBLIOGRAPHIC REFERENCE

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EXECUTIVE SUMMARY

The susceptibility of land to earthquake-induced liquefaction has been assessed for the Dunedin City territorial authority area (Dunedin district). Liquefaction is a process whereby earthquake shaking causes poorly consolidated, groundwater-saturated, geological materials to lose strength and stiffness, due to increased groundwater pore pressure in the material. Common effects of the liquefaction of near-surface sediments are the expulsion of water, sand and silt from the ground, and associated cracking and subsidence of the ground. Liquefaction can cause severe damage to the built environment, including the breakage of foundations, differential settlement of buildings, fracturing of pipes and the buoyant rise of light buried structures such as tanks. The closely allied phenomenon of lateral spreading involves fissuring and horizontal movement and relaxation of ground close to banks, such as the edge of a stream channel.

Drawing upon methodologies developed for liquefaction hazard evaluation in Canterbury following the 2010–2011 earthquakes, the liquefaction assessment reported here comprised an office-based assessment utilising existing available information. The information sources include geological maps, landform and soil maps, topographic information from maps and lidar surveys, geological information from bore hole records, and measurements of depths to groundwater.

There is insufficient information in the Dunedin district to undertake detailed liquefaction hazard classification analogous to the Technical Category zonation done for parts of the Christchurch urban area following the 2010–2011 Canterbury earthquakes. Instead, the approach used here is to differentiate areas underlain by rock or firm sediments that are too strong to experience liquefaction, from areas underlain by weak geological materials that may be susceptible to liquefaction if strong shaking were to occur. In order to liquefy, the materials need to be poorly consolidated, fine-grained (between coarse silt and fine sand) and water-saturated. Areas within the Dunedin district identified as being potentially susceptible to liquefaction are confined to low-lying places, such as valley floors or coastal plains that are likely, at least in part, to be underlain by soft fine-grained sediments where the groundwater table is less than about 6 m deep.

From the information that is available, a three-fold classification of liquefaction susceptibility has been developed:

- **Domain A**. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring;
- **Domain B**. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B;
- **Domain C**. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

The liquefaction susceptibility map has been compiled in a Geographic Information System (GIS) and the GIS dataset accompanies the report. By area, more than 90% of the district is classified as Domain A. Domains B and C, represent 1.4% and 4.9% of the district respectively, Domains B and C are regarded as ‘liquefaction awareness areas’. They do not represent specific hazard zones, but rather highlight areas where there may potentially be a liquefaction hazard that may need further evaluation, in regard to existing or future infrastructure or development. Areas of land classified as Domain B include parts of the Mosgiel-North Taieri and Strath Taieri areas, while land classified as Domain C includes the southwestern part of the Taieri Plain, low-lying land in South Dunedin and adjacent to Otago Harbour, and low-lying coastal areas. Information in this report is intended to provide a general indication of which areas of the district are potentially subject to liquefaction hazards. A desirable future goal would be to acquire more information on how much potentially liquefiable ground is actually present in areas mapped as Domains B and C.

1.0 INTRODUCTION

1.1 BACKGROUND

Earthquake-induced liquefaction is a potential hazard in some parts of New Zealand. Liquefaction results from the sudden loss of shear stiffness and strength of soils caused by development of excess pore pressure by cyclic shaking during an earthquake. Liquefaction causes ground settlement, lateral spreading, loss of bearing capacity, buoyant rise of buried structures and flow failures. Liquefaction damage occurred to unprecedented levels in Christchurch during the earthquakes of 2010–2011 (Brackley 2012). Media publicity and readily accessible images have resulted in most New Zealanders now having an awareness of the nature and effects of liquefaction.

The Otago Regional Council (ORC) contracted GNS Science to assess liquefaction hazards in the Dunedin City territorial authority area (Dunedin district), and delineate areas that may be susceptible to ground damage as a result of liquefaction, and the closely allied phenomenon of lateral spreading. This report presents the results of that assessment. The information in this report is intended to assist ORC in providing the Dunedin City Council (DCC) with advice on liquefaction and lateral spreading hazards, as part of the formulation of the DCC second generation district plan (2GP), which is expected to be released for public submission during 2014.

1.2 SCOPE OF WORK UNDERTAKEN

The work upon which this report is based included:

1. Collating and reviewing information relevant to liquefaction and lateral spreading in the Dunedin district (Figure 1);
2. Using this information to identify and map areas that may be susceptible to damaging effects of earthquake-induced liquefaction and related phenomena (e.g., lateral spreading) from land where little, if any, liquefaction damage is likely to occur, using methods similar to those applied in eastern Canterbury following the 2010–2011 earthquake sequence (Brackley 2012);
3. Producing maps and an explanatory report documenting the work that was undertaken.

The report presents a geologically-based assessment of information that is intended to create awareness of where in the district liquefaction-related hazards may be present. The mapping was office-based, drawing upon readily available existing information, and no new site investigations were undertaken.

The liquefaction susceptibility domains delineated in this report are intended to highlight areas where liquefaction hazard may warrant further scrutiny for future planning and development activities. The information is, for the most part, based on generalised assessments and broad-scale inferences, rather than detailed investigations, and should not be used in isolation for any purposes that require site-specific information.

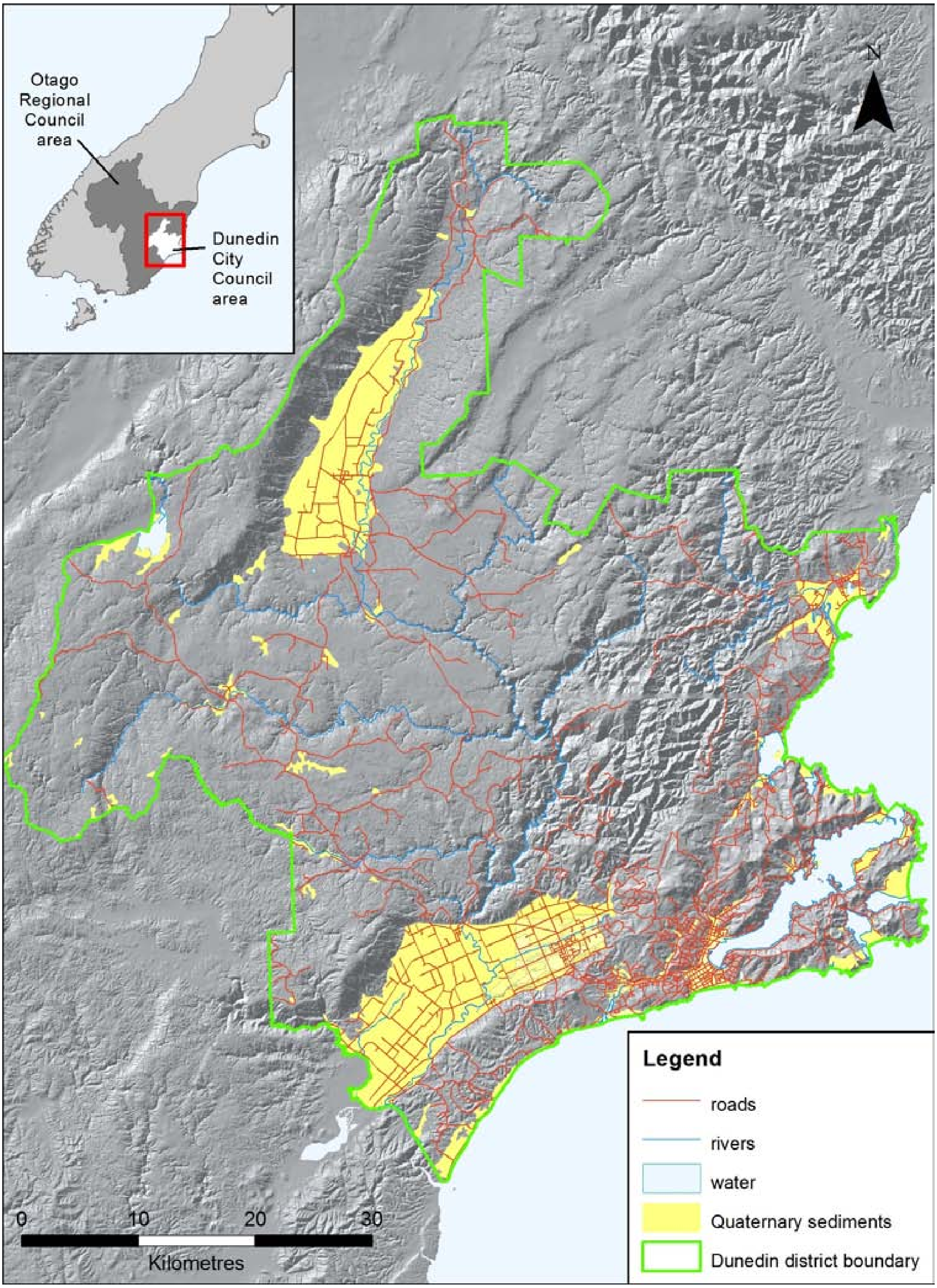

Figure 1 Location of the Dunedin district, and the distribution of Quaternary sediments from 1:250,000-scale geological maps (Bishop & Turnbull 1996; Forsyth 2001). Only those areas underlain by Quaternary sediments have any potential for the occurrence of liquefaction, and then only if the sediments are of a certain type and groundwater is close to the surface.

1.3 DATA COLLATION AND REVIEW

Readily available information relevant to determining areas susceptible to liquefaction and lateral spreading have been collated and reviewed. Such information includes:

- Earthquake hazard in Dunedin (McCahon et al., 1993);
- Review of seismic risk in the Otago region (Murashev & Davey 2005);
- Otago Alluvial Fans Project (Grindley et al., 2009); Otago Alluvial Fans Project: supplementary information (Barrell et al., 2009); Alluvial fan hazards of the North Taieri Plain (Barrell 2014);
- ORC groundwater information for the Taieri Plain, Strath Taieri and South Dunedin, from sources including Irricon & Royds Consulting (1994), Irricon & ESR (1997), Hanson (1997), Irricon & MWH (2004); Irricon (2005), Rekker & Houlbrooke (2010), Rekker (2012) and Fordyce (2013) (Figure 2);
- Soil maps at 1:25,000 scale (growRuralDunedin);
- High-resolution digital elevation models generated from lidar (‘laser radar’) surveys. Lidar data for the Otago coastal zone and the Taieri Plain was supplied by ORC, and the main urban area of Dunedin City was supplied by DCC (Figure 2);
- Bore hole record datasets held by GNS Science and ORC (Figure 3);
- Geological maps at 1:250,000 scale for the Dunedin area (Bishop & Turnbull 1996) and Waitaki area (Forsyth 2001), comprising part of the GNS Science nation-wide ‘QMAP’ geological map series (Quarter-Million-scale mAP). One cm on these maps represents 2.5 km on the ground, and they are therefore highly generalised;
- Geological maps at more detailed scales (Figure 3), including the greater Dunedin area (Benson 1968; 1:50,000), southwest Dunedin urban area (McKellar 1990; 1:25,000), the Palmerston area (McMillan 1999) and the greater Dunedin urban area (GNS Science, unpublished; 1:50 000);
- Geomorphological maps of the coastal Otago area at 1:200,000 scale (Barrell et al., 1998) and the Taieri Plain at 1:100,000 scale (Barrell et al., 1999);
- The eastern Canterbury liquefaction assessment report (Brackley, 2012).

1.4 REPORT LAYOUT

An outline of the geological setting of the Dunedin district is presented in Section 2. Section 3 describes the general nature of liquefaction and factors influencing its occurrence. The approach and methods used for assessing liquefaction susceptibility are set out in Section 4, while Section 5 presents a summary description of the mapped liquefaction awareness areas. Section 6 contains discussion of the findings of the assessment and uses of the information, while conclusions are set out in Section 7. Appendix 1 provides explanation of some of the technical terms used in the report. Selected diagrams from previous reports are collated in Appendix 2. Detailed descriptions of the criteria used for mapping liquefaction susceptibility domains at specific locations in the district, and detailed location maps, are contained in Appendix 3. The GIS dataset of the mapped liquefaction susceptibility domains is described in Appendix 4.

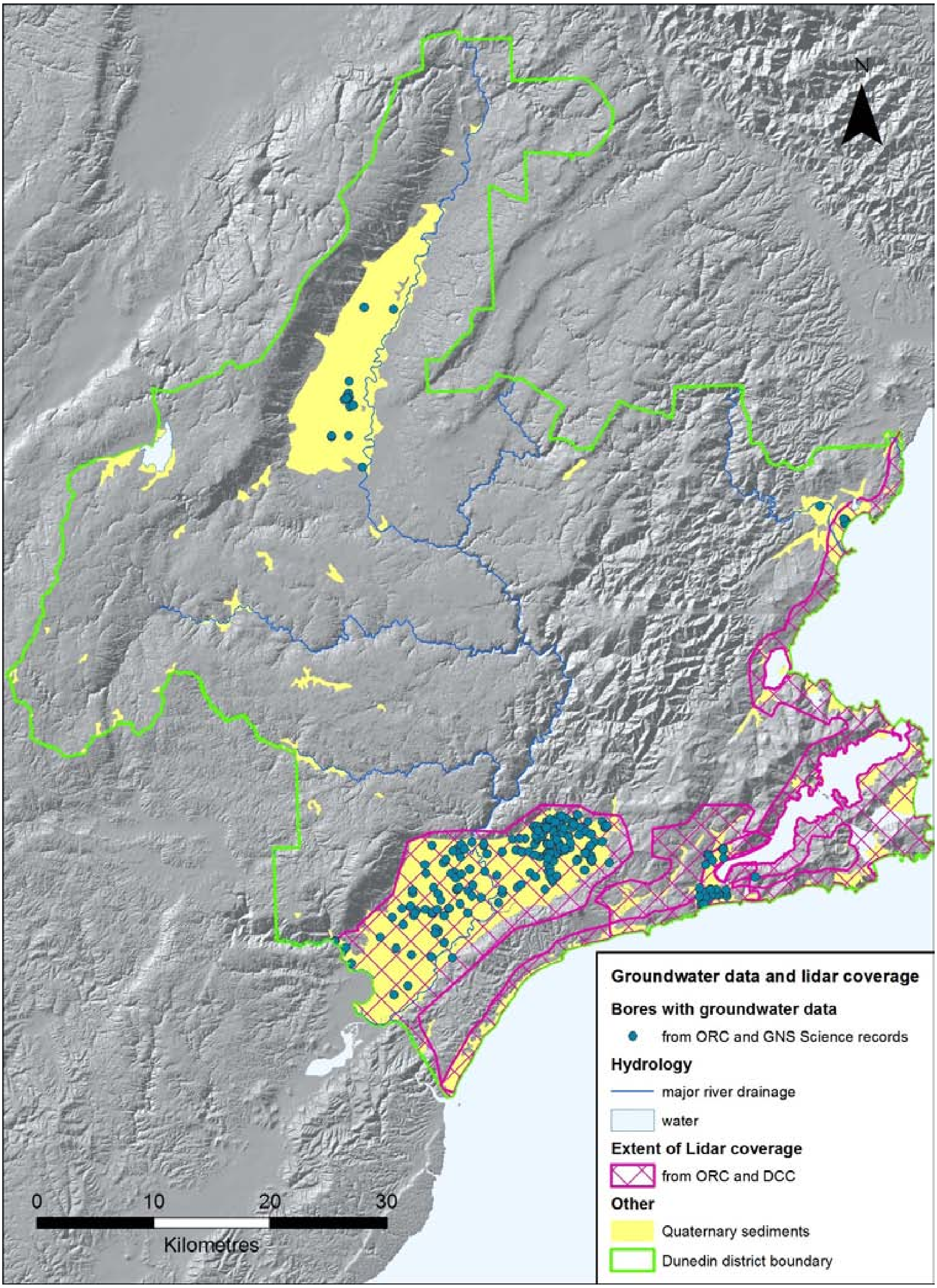

Figure 2 Extent of lidar coverage and the locations of bores for which there is groundwater level information.

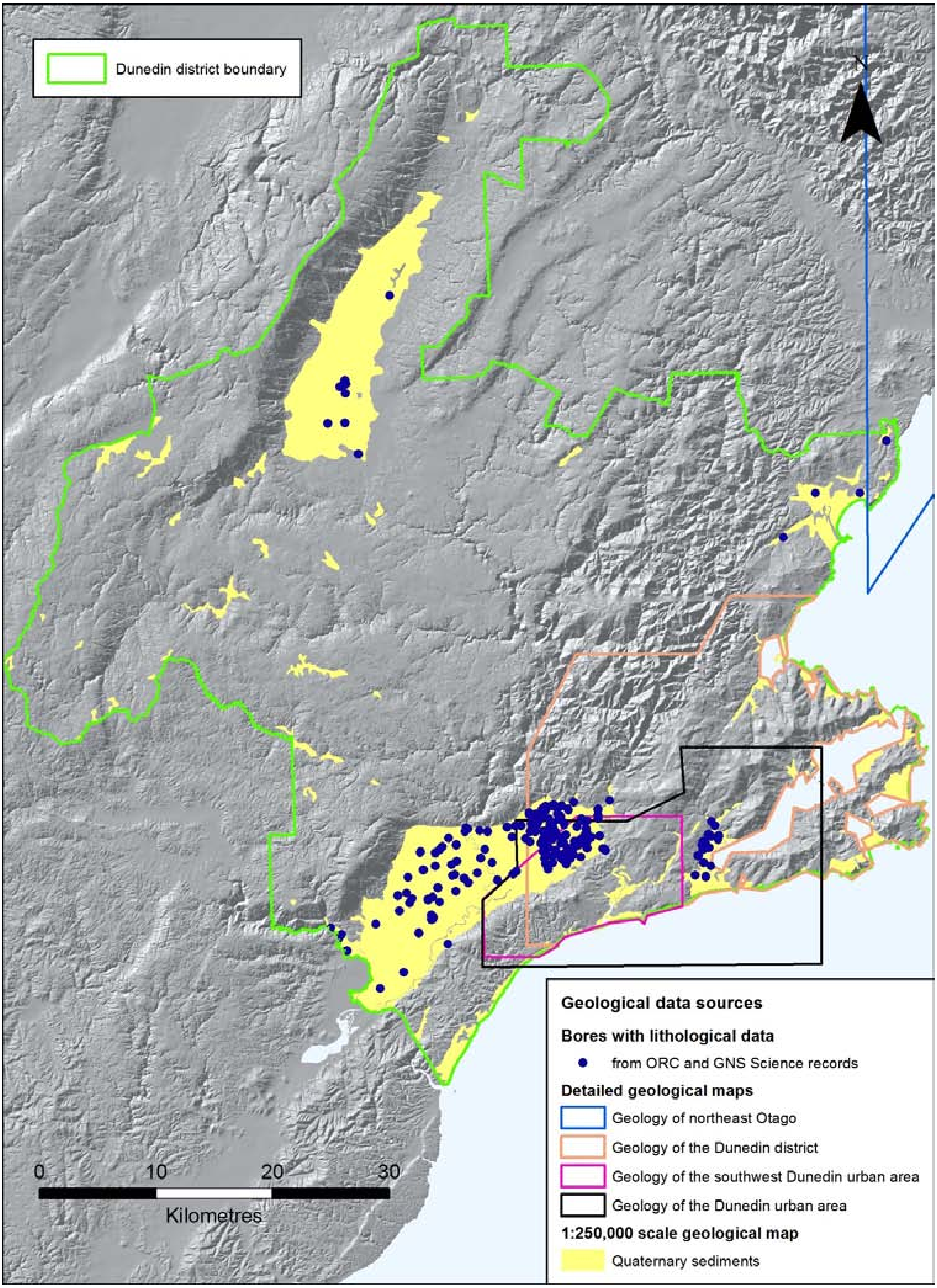

Figure 3 Extent of detailed geological maps and locations of bores for which there is lithological information

2.0 GEOLOGICAL SETTING

2.1 GEOLOGICAL HISTORY

The geological sequence of the Dunedin district comprises, from oldest to youngest, three main categories; basement rock, cover rocks and young poorly consolidated deposits.

The oldest underlying rock (basement rock) consists of schist. The schist is derived from sandstone and mudstone sedimentary rocks of Triassic age (between 250 and 200 million years old) that underwent metamorphism to schist between the Middle Jurassic to Early Cretaceous (between 175 and 100 million years ago).

Following an episode of uplift, faulting and erosion, which resulted in a flattish land surface developing on the schist rock, a blanket of younger sedimentary rocks (cover rocks) was deposited. The cover rock sequence typically has non-marine quartz sandstone and conglomerate in its lower part, overlain by marine mudstones and sandstones, ranging in age from Late Cretaceous to Middle Miocene (between 100 and about 15 million years old). The upper part of the cover rock sequence comprises volcanic rocks, typically of Middle Miocene age. The largest volcanic centre (Dunedin Volcano) was located in the general area that is now the Dunedin urban area, Otago Harbour and Otago Peninsula, but there were numerous other smaller eruptive centres scattered around the district. The volcanic activity took place between about 16 and 10 million years ago (Bishop & Turnbull 1996; Forsyth 2001).

Subsequent uplift and erosion has removed much of the cover rock sequence, and almost all of the original form of the volcanoes. As a result, extensive areas of the underlying schist rock are now exposed across much of the central to western parts of the district. Earth movements involving faulting and folding have helped to produce an array of ranges and basins. The Taieri Plain lies in one such basin, and the Strath Taieri Plain lies in another. The rivers have cut gorges across the up-faulted blocks as the landscape developed, the lower gorge of the Taieri River between Henley and Taieri Mouth being a good example. As a result of these and other processes, poorly consolidated sediments have accumulated in many of the valleys and basins. The general distribution of these sediments, of Quaternary age (less than 2.6 million years old) is shown in Figure 1. These sediments include river sands and gravels, beach and dune sands close to the coast, peats within swamps, as well as sands and muds beneath inlets and estuaries. Some of these sediments, in particular circumstances, are potentially susceptible to liquefaction.

2.2 LANDSCAPE EVOLUTION PROCESSES AND LANDFORMS

A major feature of the Quaternary Period has been a cycle of large-scale natural global shifts in climate, with periods of generally cool conditions (glaciations, or ‘ice ages’) separated by periods of warmer climate (‘interglaciations’), such as that existing today. On average, each cycle is about 100,000 years long. At the latitude of New Zealand during an ice age, ice was not everywhere, but rather the climate cooled enough to allow extensive glaciers to form in high mountain areas. Ice ages have, however, had a major impact on coastal Otago. Sea level is linked to glaciation/interglaciation cycles. During ice ages, so much water became locked up in ice sheets that formed on Europe and North America that the level of the sea dropped. At the peak of the most recent ice age, about 20,000 years ago, sea level was at least 120 m lower than it is now. As Northern Hemisphere ice sheets melted, sea level rose, stabilizing at its present level about 7000 years ago. The last time the sea was as high as it is now was during the last interglacial period, about 125,000 years ago.

At ice age maxima, the Otago coast lay between 30 and 35 km seaward of where it is today, and an extensive plain would have existed on what is now the continental shelf. Today's estuaries, inlets and harbours were river valleys, and Otago Peninsula was a range of hills flanked by valleys and plains. Because the continental shelf off the modern Otago coast is narrower and steeper than in many other parts of New Zealand, coastal Otago's rivers and streams had relatively steep gradients during ice ages. The subsequent rise of sea level during the transition to interglacial conditions drowned the lower parts of the Otago river and stream valleys. That is why the Otago coast is indented by bays and estuaries. The important geological consequence of these processes is that over the past 7000 years or so since present sea level was attained, soft, saturated sands and silts have accumulated in these drowned river and stream valleys, and these sediments are particularly susceptible to liquefaction. The heavy sediment loads of the larger rivers have largely filled in the drowned lower reaches of their valleys, producing low-lying plains at close to sea level. A good example is the Taieri Plain, which 7000 years ago contained an extensive inlet of the sea, almost 30 m deep at Henley, and extending south past Waihola, out to Berwick and Outram, and north towards Mosgiel (Barrell et al., 1999; Litchfield et al., 2002). Lakes Waihola and Waipori are remnants of this inlet and the lower reaches of the Taieri and Waipori rivers remain tidal, with a twice-daily reversal of water flow on the rising tide. The coastal plain of the Waikouaiti River marks an extensively infilled former inlet of the sea, and the river remains tidal upstream to State Highway 1. In contrast, Kaikorai Lagoon is much less filled in, highlighting that Kaikorai Stream carries relatively little sediment compared to the larger rivers. The wide bays and inlets along the coast are enclosed by sand barriers or spits, inside of which extensive sand plains have accumulated. A good example of a barrier is the St Clair-St Kilda dune belt, inside of which an extensive sand/mud flat has accumulated at the head of Otago Harbour, forming the South Dunedin plain. All of these low-lying coastal landforms, as well as the beds of all the bays, estuaries and harbours, are underlain by soft, wet, sediments that may be susceptible to liquefaction.

Farther inland, the floors of most valleys and basins are underlain by river and stream sediments. These can be divided into river alluvium, laid down by the main rivers that occupy the valleys or basins, and fan alluvium, that is deposited, commonly in overlapping aprons, by the tributary streams that drain to the river. The alluvial fans built by the tributary streams tend to have relatively steep gradients, and fan alluvium generally consists of angular gravel in a silty matrix. In contrast, river alluvium generally consists of rounded gravel, with pockets of sand or silt. In particularly low-gradient river systems, such as the coastal reaches of the Waikouaiti and Taieri rivers, the alluvium may consist predominantly of sand or silt. Gravelly sediments are generally not liquefiable, but sand- or silt-dominated sediments are. There is therefore little liquefaction hazard associated with alluvial fans, but there may be potential liquefaction hazard in the valleys of low-gradient rivers.

There will be localised exceptions to these generalisations. Alluvial fan sediments may include sand-filled channels, though these are likely to be narrow and of localised extent. Another consideration is that the alluvial fan sediments reflect the materials in their source catchments. In some instances, where the catchments contain abundant sandy or silty material, the fans will consist of those materials.

2.3 SEISMICITY

Seismicity is an essential consideration, because strong earthquake shaking is necessary for the occurrence of liquefaction. Historically, central to eastern Otago has had a very low level of nearby seismicity, with very few earthquakes centred beneath the area (Stirling et al., 2012). However, there are several known faults in the general area that show evidence for having moved in recent prehistoric times, and woud have generated large earthquakes.

A distinction may be made between 'distant' and 'nearby' seismicity. Distant seismicity relates to large earthquakes that occur on faults located as much as several hundred kilometres away from an observer, but whose shaking is felt over a wide area, with less intensity the farther one is from the fault. Nearby seismicity relates to earthquakes on faults located within a few tens of kilometres of an observer, and it is these earthquakes that, if sufficiently large, are the most damaging.

Recent examples of distant seismicity felt in the Dunedin district are the 2003 Fiordland Earthquake and the 2010 Darfield Earthquake, centred in Canterbury. These earthquakes produced ground shaking that was noticed by many people in the Dunedin area, but caused little if any damage.

The only significantly damaging nearby earthquake recorded in the Dunedin district was the magnitude (M) 4.9 1974 Dunedin Earthquake, which is reviewed in detail by Murashev & Davey (2005). As has been highlighted by the 2010–2011 Canterbury earthquake sequence, damaging earthquakes can occur on faults that lie nearby, but deep underground, and whose existence is not known prior to an earthquake being generated by them. The February 2011 Christchurch Earthquake was an example of this, as was the 1974 Dunedin Earthquake, which although a relatively small earthquake, had a hypocentre (Appendix 1) at shallow depth and epicentre close to the city, and consequently caused notable shaking damage.

There are several faults identified in the Dunedin district that are regarded as active (i.e., have moved within the past 125,000 years or so). These faults have been identified because their past movements have been large enough to break the ground surface, offsetting the near-surface rock layers or deposits. The best known of these faults is the Akatore Fault, southwest of Dunedin, which has generated at least two large, ground surface rupturing eathquakes in recent millennia, one about 3800 years ago, and another about 1100 years ago (Litchfield & Norris 2000). These earthquakes were likely to have been about magnitude 7, and an estimate of their likely shaking effects is presented in Map 13 of Murashev & Davey (2005), which is reproduced in Appendix 2 of this report.

Such an earthquake on the Akatore Fault or other nearby known or unknown faults would produce strong shaking in much of the Dunedin district, and would likely cause significant ground damge in liquefaction-susceptible areas. Moderate earthquakes on known or as yet unknown faults, could also produce sufficient shaking to cause localised liquefaction. Recent estimates of the future probability of different intensities of ground shaking relevant to the Dunedin district, from all earthquake sources, are provided by Murashev & Davey (2005) and Stirling et al. (2012).

3.0 THE OCCURRENCE OF LIQUEFACTION

3.1 THE NATURE OF LIQUEFACTION AND LATERAL SPREADING

The American Society of Civil Engineers (1978) defines liquefaction as “the act or process of transforming cohesionless soils from a solid state to a liquefied state as a result of increased pore pressure and reduced effective stress”. Many people will have generated their own liquefaction when visiting sandy beaches at low tide – by standing on wet sand and wriggling one’s feet, the sand becomes almost liquid and one sinks into it. But if one attempts this on a stony beach, nothing much happens. This illustrates a key requirement for the occurrence of liquefaction; that the material is capable of being liquefied. Generally, three criteria need to be met for sediment to be susceptible to liquefaction:

- Young (e.g., less than 10,000 years) and loose
- Fine-grained (between coarse silt and fine sand) and cohesionless
- Water-saturated.

Strong earthquake shaking is likely to induce liquefaction in susceptible sediments. A typical consequence of liquefaction is the ejection from the ground of liquefied sediment, usually along with copious amounts of groundwater. Moderate amounts of liquefaction may produce sand boils or sand ‘blows’, like little volcanoes (Figure 4). Severe liquefaction may result in the ejection of huge volumes of water and sediment, resulting in the ground surface being buried by vast sheets of sand and silt, sometimes as much as half a metre thick (Figure 5).

The ejection of material commonly results in differential sagging (subsidence) of the ground surface, and because liquefaction significantly reduces the strength of the soil and its supportive ability, it is likely to cause heavy structures to sink into the ground and any light or buoyant structures, particularly buried pipes or tanks, to ‘float’ (Figure 6).

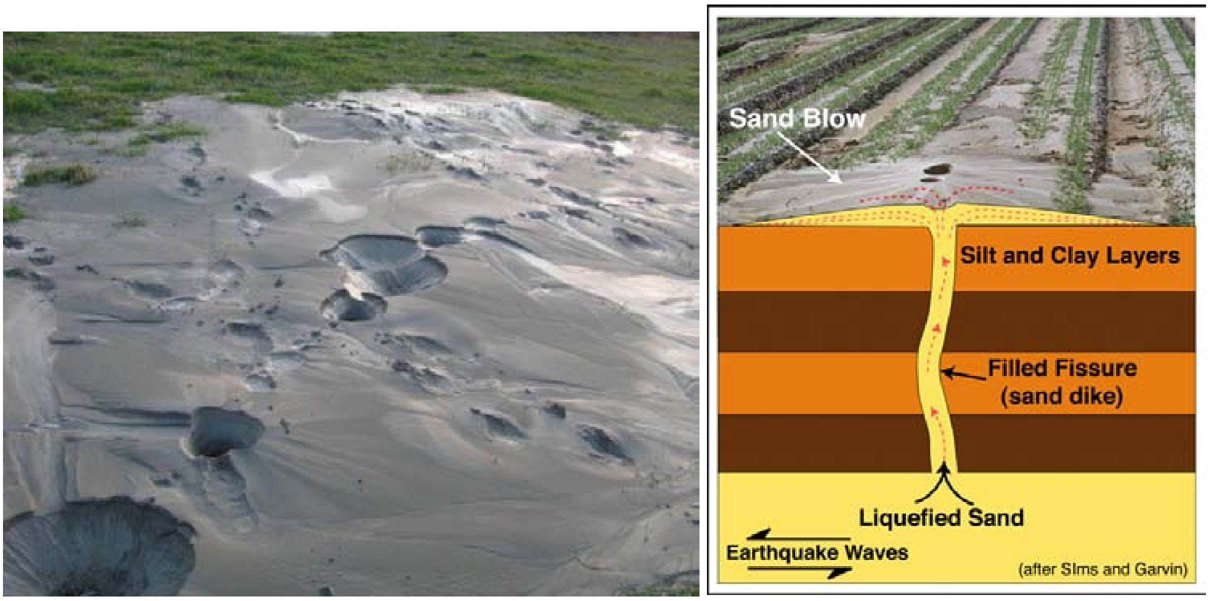

Figure 4 Illustrations of liquefaction processes. (a) Sand boils from the ejection of liquefied sediment following the Christchurch earthquake of 2011. Photo: R.D. Beetham, GNS Science. (b) Schematic illustration of how such liquefied materials may be generated and deposited.

Figure 5 Extensive and severe liquefaction, Christchurch 2011. (a) Significant amounts (0.5 m thick) of sediment were ejected to the surface. (b) The liquefaction process also involved the ejection of large volumes of water which caused flooding. Photos: R.D. Beetham, GNS Science.

Figure 6 Fuel tanks have buoyed up through the ground surface as a result of liquefaction of the enclosing sediment, .Christchurch area, February 2011. Photo: R.D. Beetham, GNS Science.

The 2010–2011 Canterbury earthquake sequence highlighted that places which are underlain by soft, young, sediments deposited across areas that were drowned by the post-glacial rise of sea level are particularly susceptible to liquefaction (Brackley 2012; Orense et al., 2012).

Lateral spreading is a phenomenon also resulting from liquefaction of underlying sediments. Lateral spreading commonly occurs on level or sloping ground close to the edge of a bank, such as the side of a stream channel, but can also affect human-made features such as embankments (Figure 7). Liquefaction-induced loss of strength in the subsurface causes the ground to move almost horizontally toward a free-face (such as a river bank or edge of an embankment). Hence its occurrence is usually associated with coastlines, lakeshores, river channels, and the margins of reclaimed ground or raised embankments (Figure 8).

Ground deformation associated with liquefaction can take various forms and can lead to excessive and non-uniform vertical displacements (settlement) and horizontal displacements (lateral spreading), commonly resulting in large cracks and fissures in the ground (Cubrinovski & McCahon, 2011) and can cause major damage to structures, pavements and buried services (Figure 9). Collectively, liquefaction-induced flooding, differential ground settlement, and the cracking and displacement of ground resulting from lateral spreading, can have severe adverse economic and societal impacts, and may take considerable time and resources to rectify, as illustrated in the 2010–2011 Canterbury earthquake sequence.

Figure 7 Lateral spreading and damage to bridge abutments as a result of liquefaction, Christchurch, February 2011. Photo: R.D. Beetham, GNS Science.

Figure 8 Damage to Hillside Road, Manapouri, Southland, resulting from the 2003 Fiordland earthquake. The road is raised on an embankment. Disaggregation of the embankment fill by ground shaking has caused a lateral spreading failure of the margins of the embankment. The existence of the embankment reflects the soft and saturated nature of the ground here, which probably exacerbated the earthquake shaking and consequential damage to the road. Photo: R Cook.

Figure 9 Damage to underground services as a result of liquefaction, Christchurch 2011.

3.2 THRESHOLDS FOR THE OCCURRENCE OF LIQUEFACTION

Because liquefaction is caused by overpressuring of pore water within a sediment, it can be caused by a variety of factors (e.g., Ishihara 1985; NRC 1985; Youd et al., 2001; Orense 2010), but the most common triggering mechanism is vibrations from strong earthquakes. Figure 10 shows relationships between the distance from the source of an earthquake of a particular magnitude and the occurrence of liquefaction. Although factors other than earthquake magnitude are known to be important, such as the frequency of the earthquake waves and the duration of shaking (Obermeier et al., 2005), magnitude and distance are simple and easily measured parameters. This diagram highlights that susceptible sediments may liquefy in response to a moderate earthquake centred nearby, or a larger earthquake centred farther away.

The Modified Mercalli Scale Intensity (MM) is a measure of the strength of ground shaking at a particular location. It is directly related to the earthquake magnitude, the distance from the hypocentre, and the strength of the ground at that location. An intensity of MM VII or greater is typically necessary in order for liquefaction to occur. Actual conditions at a particular location, including the nature and sensitivity of the sediments to vibrations, and the depth to groundwater, will greatly influence whether liquefaction occurs, and its severity.

Instrumental measurements of ground shaking by seismometers show that liquefaction generally becomes evident at a peak ground acceleration (PGA) of 0.25 g or more (1 g is the acceleration due to the force of gravity). Cubrinovski & McCahon (2011) reported that severe liquefaction occurred in Christchurch at PGA of about 0.5 g or more. A more detailed study by Quigley et al. (2013) found that in areas of highly susceptible materials in eastern Christchurch, slight liquefaction became evident at PGA of 0.057 g and that more extensive liquefaction became apparent at PGA of more than about 0.2 g.

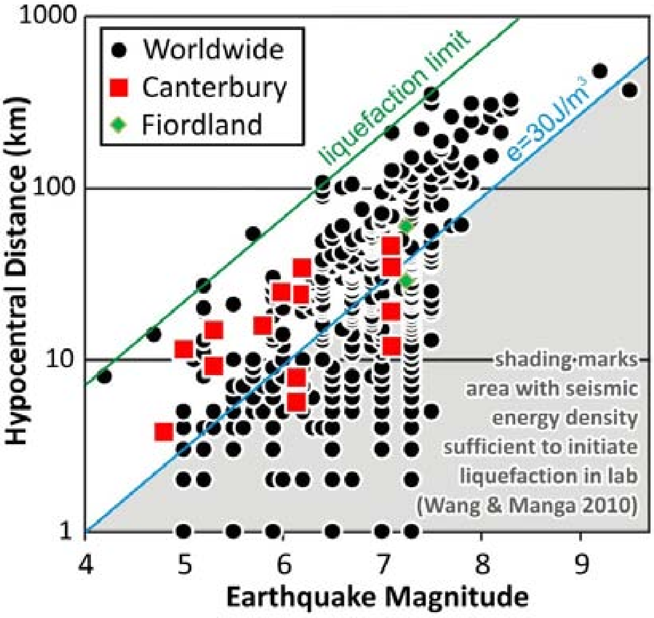

Figure 10 Relationship between the straight-line (hypocentral) distance from the sources of earthquakes of different magnitudes and occurrences of liquefaction. It shows that a M5 earthquake is about the smallest that can generate liquefaction, and only within 10 km or so of the earthquake hypocentre (see Appendix 1). In contrast, a M7 earthquake can generate liquefaction up to as much as 100 km or so from the hypocentre. The plot includes data from the 2010–2011 Canterbury earthquake sequence and the 2003 Fiordland earthquake. Diagram adapted from Wang & Manga (2010).

3.3 LIQUEFACTION IN THE DUNEDIN DISTRICT

There have been no recorded instances of liquefaction in Otago since at least the mid-1800s, when European settlement and written record-keeping began (Murashev & Davey 2005). No liquefaction was reported during the 1974 M 4.9 Dunedin Earthquake (Bishop 1974). That shallow earthquake was centred about 10 km from the city centre, and maximum shaking intensity in South Dunedin was locally as much as MM VII (Murashev & Davey 2005). At that time, there were only two seismometers in Dunedin that could measure ground accelerations. The accelerometer situated at the St Clair telephone exchange recorded a PGA of 0.27 g, while the one at Dunedin Central Post Office recorded 0.12 g (Bishop 1974). The lack of identified liquefaction suggests that the sediments beneath South Dunedin are not as susceptible to liquefaction as those in the most liquefaction-senstive areas of eastern Christchurch. Nonetheless, it is likely that the ground shaking in South Dunedin during the Dunedin Earthquake was close to the threshold for the onset of liquefaction.

3.4 THE IMPORTANCE OF GROUNDWATER

The depth to the groundwater table is fundamentally important in the occurrence of liquefaction, because liquefaction can only occur in water-saturated materials. An upper layer of material that is non-liquefiable, either because it is above the water table, or is a non-liquefiable material such as gravel or clay, has a protective effect. The upper layer (or ‘crust’) can suppress the ejection of liquefied material to the ground surface, or can influence the extent of ground damage. Studies by Ishihara (1985) and Youd & Garris (1995) showed that where a substantial thickness of liquefiable material exists at depth, the presence of a non-liquefying crust extending to between 3 and 8 m depth prevents subsurface liquefied material from being ejected at the ground surface. The depth of that threshold depends on the degree of shaking and total thickness of liquefying layers below. Generally speaking, the likelihood of liquefaction-related damage decreases as the depth to groundwater increases.

There is good knowledge of groundwater levels and their fluctuations in Canterbury on account of a dense network of monitoring wells and hundreds of piezometers installed by the Earthquake Commission (EQC), Environment Canterbury and Christchurch City Council (van Ballegooy et al., 2013). The distribution of liquefaction and/or consequential damage that occurred during the 2010–2011 Canterbury earthquakes has been mapped in detail (Brackley 2012; Tonkin & Taylor 2012). Comparison with depths to groundwater highlights that liquefaction was almost entirely restricted to areas where the unconfined groundwater table was shallower than 5 m, and was most prevalent where depth to groundwater was less than 3 m (Tonkin & Taylor 2012; van Ballegooy et al., 2013).

It has been suggested that the Christchurch situation was exacerbated by the presence and release of artesian groundwater pressure (Cox et al., 2012; Gulley et al., 2013), and this is a topic of ongoing research.

4.0 LIQUEFACTION HAZARD ASSESSMENT

4.1 ASSESSMENT METHODS

There are different approaches to assessing liquefaction hazard. A common goal is to establish the liquefaction susceptibility of the subsurface. Liquefaction susceptibility is a term that relates to the physical state of materials, in regard to whether they have the “ability” (suitable physical characteristics) to liquefy. Assessing liquefaction susceptibility requires information on the nature of the soil materials, and their degree of water saturation.

The extent to which liquefaction susceptibility can be classified depends on whether the assessment is site-specific for a particular structure or is a more generalised assessment that is intended primarily to aid regional-scale land use planning and hazard minimisation. Site-specific assessments generally require geotechnical investigations (see Appendix 1) and collection of subsurface information from test pits, probes or bore holes. General assessments are usually office-based and draw upon existing information from geological maps, soil maps, landform maps, groundwater level measurements, and bore hole records where available.

Where there is a sufficient level of geotechnical and other relevant data, such as the observed effects of damaging previous earthquakes, more quantitative general assessments can be attempted. One example is the delineation of Technical Category areas (TC1, TC2, TC3) that was undertaken for parts of the Christchurch urban area (see Appendix 1). Particularly important for such assessments are sediment strength measurements from Standard Penetration Tests (SPT) or Cone Penetrometer Tests (CPT). A number of specific indices relating to the liquefaction susceptibility of the ground can be calculated from SPT and CPT data, such as Cyclic Resistance Ratio (CRR), Liquefaction Severity Index (LSI), or Effective Stress Analysis (e.g., Seed & Idriss 1971; Iwasaki et al., 1978; Youd & Perkins 1987; Robertson & Wride 1998; Youd et al., 2001). Liquefaction Severity Number (LSN) is a new index developed following the Canterbury earthquakes to assess liquefaction induced vulnerability (Tonkin & Taylor 2012).

The assessment of lateral spreading hazards is generally based on observations of damage from other earthquakes (e.g., Hamada et al., 1986; Youd et al., 2002). The assessment of lateral spreading requires information not only on the ground strength and liquefaction susceptibility, but also on the form, nature and height of nearby ‘free-faces’ (e.g., a river bank). This necessitates complex analytical modelling. One rule of thumb is that lateral spreading can occur at a horizontal distance 20 times the channel depth, or height of the free face. Unfortunately, this is possible only at site-specific scales, and is well beyond the scope of a general assessment, because there are few reliable measurements of channel depths from regional scale data, such as topographic map contours. Furthermore, lateral spreading can occur in association with former channel edges that have been buried by younger sediment and are therefore hidden from view. Areas that are assessed as having liquefaction susceptibility should also be considered to have lateral spreading susceptibility in areas close to free-faces. Where features such as embankments are built on weak ground, failures akin to lateral spreading can occur (see Figure 8). The degree of this hazard is influenced by the cohesiveness of the material forming the embankment. For example, an evaluation of the stability of the floodbanks of the Taieri Plain included some quantification of the materials from which they are constructed (Tonkin & Taylor 2005). This sort of information could be used to aid more detailed assessment of flood bank stability under earthquake shaking.

As far as the authors of this report are aware, there has only been limited geotechnical testing undertaken in the Dunedin district, and no general collation of geotechnical data exists. Instead this project takes a commonly-adopted approach of using subsurface lithological and groundwater information where available, together with geological and geomorphological criteria to provide a regional overview of those areas that may be susceptible to liquefaction.

4.2 ASSESSING LIQUEFACTION HAZARD – THIS PROJECT

4.2.1 Geomorphological-based approach

The form and origin of the ground surface (geomorphology) generally reflects the nature of underlying geological materials, whether solid rock or a variety of poorly consolidated or loose sediments. Although records from the drilling of water bores, geotechnical probes or excavations provide direct information on subsurface materials, each of these points of information may lie a considerable distance apart. Thus, geomorphologic information provides an area-wide, general indication of what lies beneath the near-surface, e.g., within 10 m or so of the ground surface, as well as providing insights into the processes such as erosion and deposition that have shaped the ground surface.

The nature of soils developed on the landforms is an expression of the underlying near-surface geological materials (growRural Dunedin). Furthermore, the maturity of soils is a function of the age of the landform, and the activity of processes that may modify landform surfaces. Soil maps are based on intensive field surveys, and have been an important resource used to aid the geomorphologically-based mapping in this report.

A key aim of the geomorphological approach, in concert with geological information, is to define the extent of areas that were flooded at the culmination of the post-glacial sea level rise (Section 2), and have subsequently been filled in by the accumulation of young marine or estuarine sediments that are commonly susceptible to liquefaction.

4.2.2 Liquefaction hazard assessment methodology

The liquefaction hazard evaluation reported here is a regional-scale susceptibility assessment, using a methodology similar to that applied in eastern Canterbury (Brackley 2012). It differs from a full susceptibility assessment, which would require detailed information on the geotechnical properties of near-surface sediments. Therefore, the focus of this project has been on identifying areas that, from geological and geomorphological considerations, are likely to be underlain, at least in part, by the types of sediments that are liquefaction-susceptible, and where groundwater levels are sufficiently close to the surface to make liquefaction a possibility. For that reason, the areas shown on the maps and contained in the accompanying GIS dataset (Appendix 4) are described as ‘liquefaction susceptibility domains’. The mapping does not identify hazard zones as such, but rather identifies **areas where there may be the possibility of a liquefaction hazard**.

4.2.3 Liquefaction susceptibility domains

The domains identified on the maps accompanying this report are:

- **Domain A**. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring;
- **Domain B**. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B;
- **Domain C**. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

What the domains mean:

Domain A:

- The geological nature of the ground is such that future earthquakes are unlikely to cause land damage from liquefaction;
- Other geohazards are likely to be more dominant, if present at all (see Appendix 1);
- The land in this domain would most likely be classified as TC1 were it to be assessed using the TC methodology (see Appendix 1).

Domains B and C:

- The geological nature of the ground is such that future earthquakes may possibly cause land damage from liquefaction;
- There is no information on the extents of potentially liquefiable ground within these areas. Our assessment is that areas mapped as Domain B have a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the area. Domain C is estimated to have a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the area;
- Collectively, Domains B and C represent what may be termed ‘liquefaction awareness areas’.
- It is likely that within both Domain B and Domain C, some land would be classified as TC1, and some land would be classified as TC2 or TC3, were it to be assessed using the TC methodology (see Appendix 1).
- A salient objective for future planning and hazard minimisation should be to undertake reconnaissance geotechnical testing of the areas mapped as Domain C in particular to establish the presence or otherwise of potentially liquefiable materials, and if present, their general pattern of distribution.

4.2.4 Mapping procedure and limitations

Liquefaction susceptibility domains have been mapped based on the information sources listed in Section 1.3. The weighting of the various components of geological, geomorphological and hydrological information used to map the extent of domains is indicated in Section 5 and Appendix 3.

Lithological and groundwater information from bore holes, where available, was then examined. International historic experience suggests that liquefaction that results in ground surface deformation due to water and sediment ejection, subsidence or lateral spreading, is related to subsurface materials within 10 m or so of the ground surface. In considering bore hole lithological information, the choice was made to focus only on the interval down to 10 m depth.

Groundwater information is quite sparse in the Dunedin district compared, for example, to the Canterbury Plains. Furthermore, the groundwater surveys that have been undertaken in the district tend to have focused on deeper boreholes/water-supply aquifers, rather than the shallow water table (Hanson 1997; Irricon & Royds Consulting 1994; Rekker & Houlbrooke 2010). In the first instance, places where depth to groundwater is known or suspected to be less than 6 m were considered of interest for reviewing liquefaction susceptibility. This threshold of 6 m is conservative given the less than 3 m depth to groundwater predominantly associated with liquefaction occurrence in Christchurch, but allows for possibilities of greater shaking, differences in ground strength, and greater uncertainties in the Dunedin district groundwater data.

Finally, based on all these considerations, the domain boundaries were drawn. In areas of lidar coverage, high-resolution digital elevation models generated from the lidar data were used for precise elevation control to aid in the positioning of the domain boundaries. This is because in many instances, a specific elevation above sea level was used to define the placement of domain boundaries.

The accuracy of the mapping of boundaries between domains needed to be considered in two ways. First, the positioning of a boundary between domains, as described in Appendix 3 for each area, is considered to be accurate to plus or minus 50 m. In other words, even though the boundary line, when viewed in the GIS dataset, is placed at an exact location, that boundary line should be treated as being 100 m wide, centred on the exact location where the line is drawn.

Second, it is important to appreciate that there is considerable uncertainty in the exact nature of the subsurface sediments whose character defines the extent of Domain B and C. The mapped extents of each domain represent best estimates based on the interpretation of geological and gemorphological information, but the uncertainties are difficult to quantify from available data. For this reason, it is important that the GIS map of liquefaction susceptibility domains be seen only as providing general guidance for planning and development. In particular, the dataset should not be used in isolation for any purpose that requires site-specific information.

5.0 DESCRIPTION OF THE AREAS MAPPED

A district-wide overview of the liquefaction susceptibility mapping is provided in Figure 11. Most of the district is underlain by basement schist or cover rocks (see Section 2), which have no possibility of being liquefied. Only areas of Quaternary sediments have any potential for liquefaction. There is no prospect of widespread damaging liquefaction where those sediments are dominated by gravel or groundwater levels are not close to the ground surface. Note, however, that the district-wide geological information is from QMAP (see Section 1.3), and is therefore highly generalised. Considerable localised variability exists within the Quaternary sediments, and there may well be patches of soft sediments within areas mapped as gravel-dominated Quaternary sediments. Those areas mapped as basement or cover rocks may also have localised accumulations of soft sediments, on the floors of stream valleys for example, that were too small to be shown on QMAP. Domain A is therefore characterised as having little or no potential for damaging liquefaction. One cannot, however, rule out the possible existence of localised pockets of liquefaction-susceptible sediments that may warrant consideration in regard to liquefaction at site-specific scales.

Domain C encompasses those areas that were flooded by the sea during the post-glacial sea level rise, and therefore are underlain by young marine or estuarine sediments. These areas typically have shallow groundwater. It is, however, by no means certain that all of the sediments in areas mapped as Domain C may be susceptible to liquefaction. For example, they may include substantial areas underlain by gravelly material that is not liquefiable. Domain C is therefore categorised as having a moderate to high likelihood of containing some areas of liquefaction-susceptible sediments, but the presence and location of such sediments can only be confirmed by specifically designed geotechnical investigations.

Domain B encompasses areas underlain by accumulations of river or stream sediments adjacent to the shoreline at the culmination of the post-glacial sea level rise. Domain B also includes other areas where there may be extensive sandy or silty river sediments with shallow groundwater. Similarly to Domain C, it is uncertain to whether, and to what extent, the sediments in areas mapped as Domain B may be susceptible to liquefaction. Domain B is categorised as having a low to moderate likelihood of saturated, liquefaction-susceptible sediments being present in some parts of each area mapped as Domain B. However, as with Domain C, further investigation would be needed to establish whether or not this is the case at specific localities.

The remainder of this section contains a general description of the liquefaction awareness areas (Domain B or C) that have been mapped in the Dunedin district. Appendix 3 contains detailed description of the criteria used for defining the mapped limits of Domains B and C in each of the areas discussed below.

5.1 DUNEDIN URBAN AREA

Two main areas in the general vicinity of the Dunedin urban area may be susceptible to liquefaction (Figure 12). One is the South Dunedin coastal plain, the other is Kaikorai Lagoon and the lower reaches of the valleys of Abbotts Creek and Kaikorai Stream (Appendix 3).

The area referred to here as the South Dunedin coastal plain includes all low-lying areas up to the edges of the hills, and the lowest reaches of the Water of Leith valley. Included are extensive areas of reclaimed land around the margin of the harbour north to Ravensbourne.

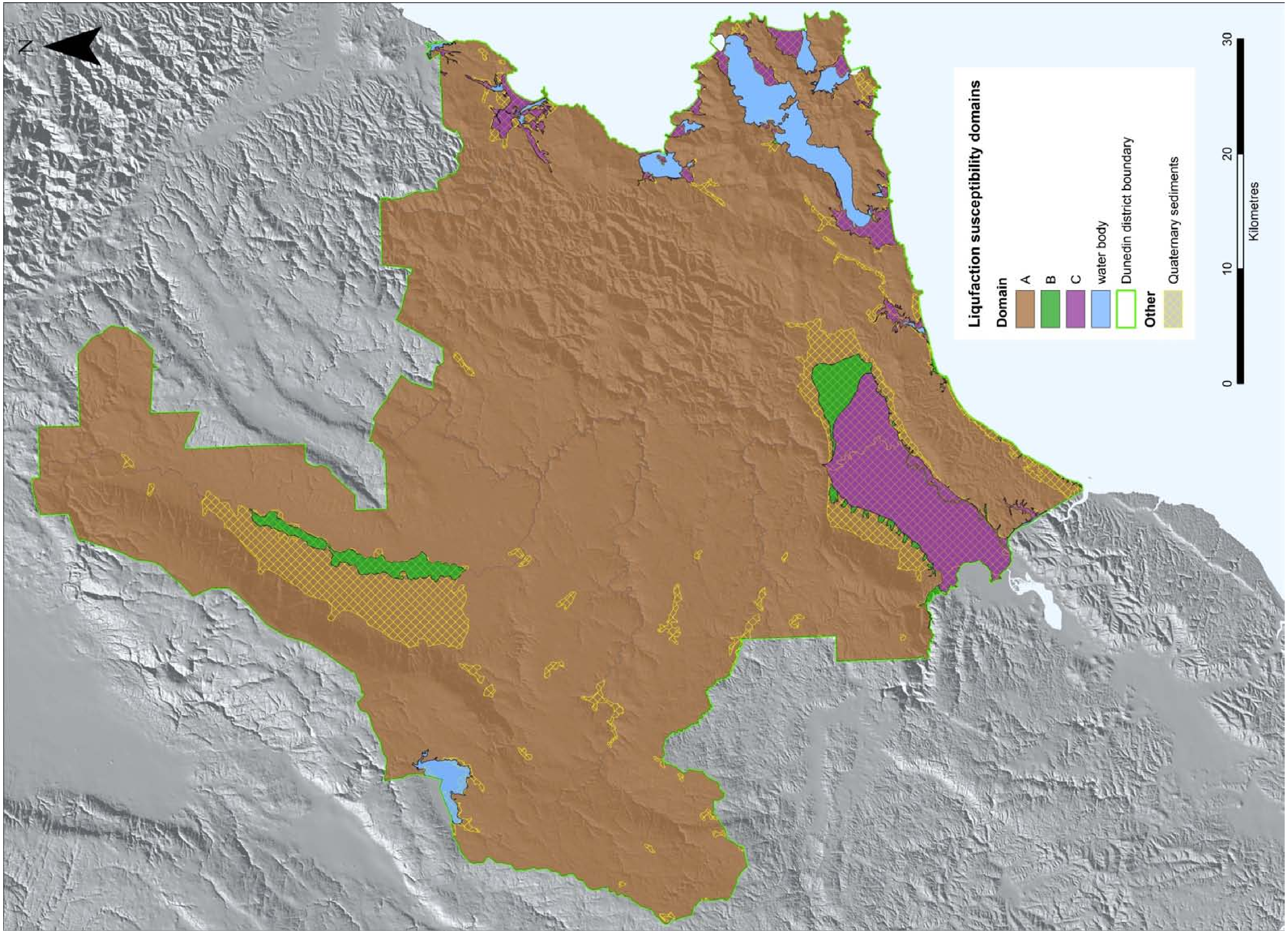

Figure 11 Overview map of liquefaction susceptibility domains for the Dunedin district.

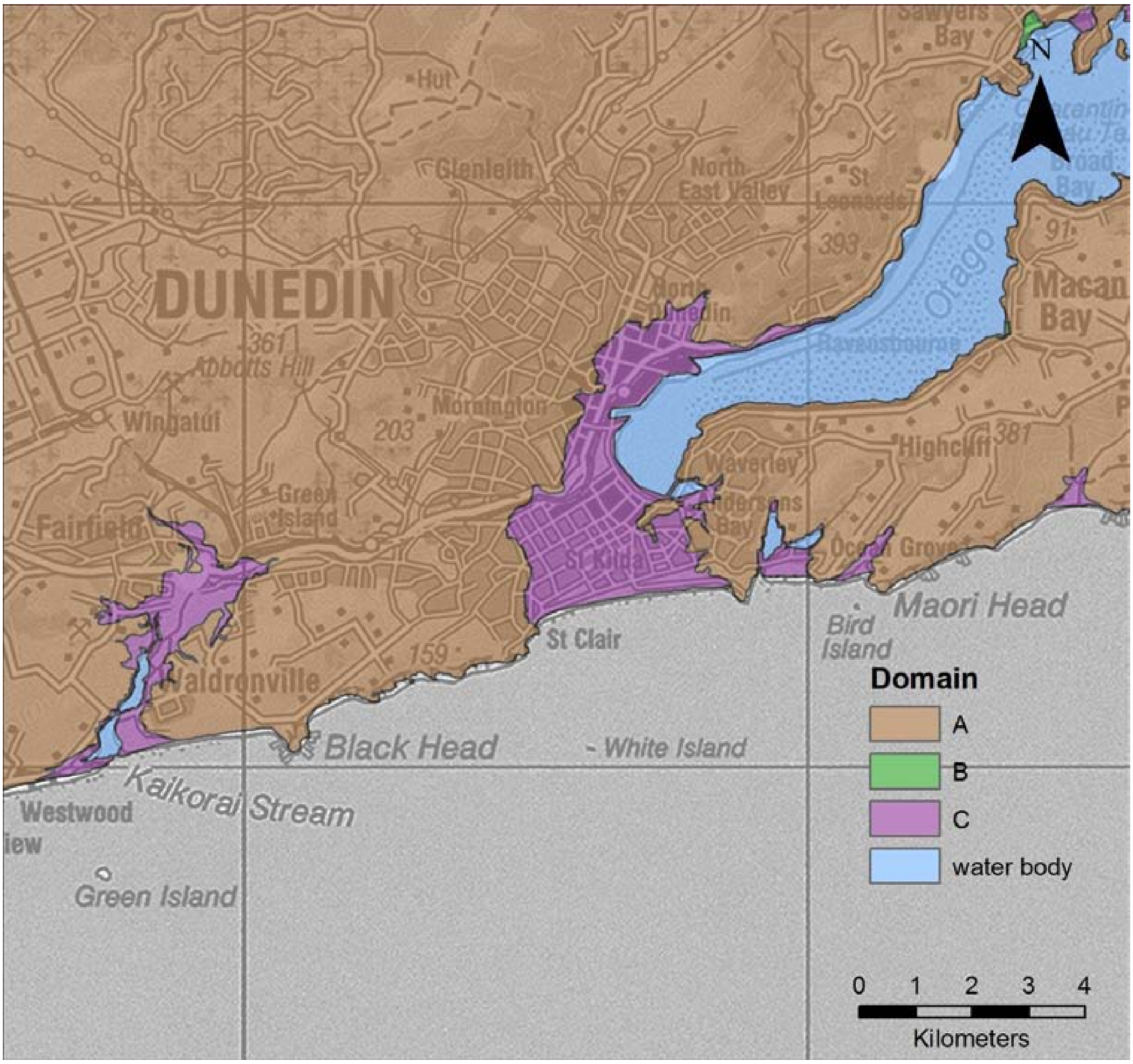

Figure 12 Map of liquefaction susceptibility domains for the Dunedin urban area.

At the culmination of post-glacial sea level rise, the peninsula was an island, separated from the mainland by an ocean passage (now Otago Harbour) that extended from St Clair – St Kilda through to Aramoana. Evidence for this is provided by the relict cliffs cut at the base of the hills at Tainui and Andersons Bay, including the cliffs around the Sunshine hill (Appendix 3). The size and abruptness of these cliffs suggest they were, for some time, subjected to powerful wave action, prior to formation of the St Clair – St Kilda dune barrier. After that barrier formed, fine sediments accumulated in the sheltered water at the head of the harbour, eventually forming the South Dunedin coastal plain. A consequence of the relatively high hills forming the inner margin of the coastal plain from St Clair, through Caversham and around to the Water of Leith is that minor streams and gullies draining from hills have constructed sizeable aprons of alluvial fan sediments out onto the coastal plain.

Extensive fine-grained sediment in combination with a very shallow water table is the reason that this area has been classified as Domain C. It would useful to clarify the extent and degree to which these sediments have material properties, including strength and density, which would make them susceptible to liquefaction. Given the intensive urban and industrial infrastructure in this part of Dunedin, further assessment, including collation of existing geotechnical data, would enable a better appreciation of liquefaction hazards in this area.

5.2 TAIERI PLAIN

The Taieri Plain is a low-lying basin containing extensive development, including the urban settlements of Mosgiel and Outram, and Dunedin International Airport. Much of the basin was flooded as a result of the post-glacial sea level rise, and following its culmination, an extensive marine inlet formed, and has progressively been infilled by sediment, largely carried in by the Taieri River. Much of this sediment is fine-grained, and known as the Waihola silt/sand (Barrell et al., 1999; Litchfield et al., 2002). The area underlain by Waihola silt/sand has been assigned a Domain C classification, and so the approximate extent of this deposit is denoted by the extent of Domain C on the Taieri Plain shown in Figures 11 and 13. In addition, Silver Stream has constructed an alluvial plain that extends southwest over the Waihola silt/sand, and the numerous minor streams that drain into the basin have formed alluvial fans at the margins of the alluvial plain (Barrell et al., 1999; O'Sullivan et al., 2013; Barrell 2014). The lower reaches of the Silver Stream alluvial plain, including the downstream portions of adjacent fans, have been mapped as Domain B (Figures 11 and 13).

5.3 STRATH TAIERI PLAIN

The Strath Taieri Plain lies in a basin on the southeastern side of the Rock and Pillar Range (Figure 14). The Taieri River flows in a broad valley, flanked to the northwest by remnants of old river terraces, underlain by weathered gravel, and an array of alluvium formed by streams draining from the Rock and Pillar Range. Much of the alluvium is gravelly, but the modern valley of the Taieri River has developed a meandering course in places, and these areas of meander channels/bars may potentially include substantial accumulations of sandy or silty sediments, and the groundwater table is likely to be close to the ground surface. Accordingly, Domain B has been mapped in the incised valley of the Taieri River (Figure 14). Specific geotechnical work would be needed to determine the existence, extent, and sensitivity of liquefaction-susceptible sediments, if any, throughout this area.

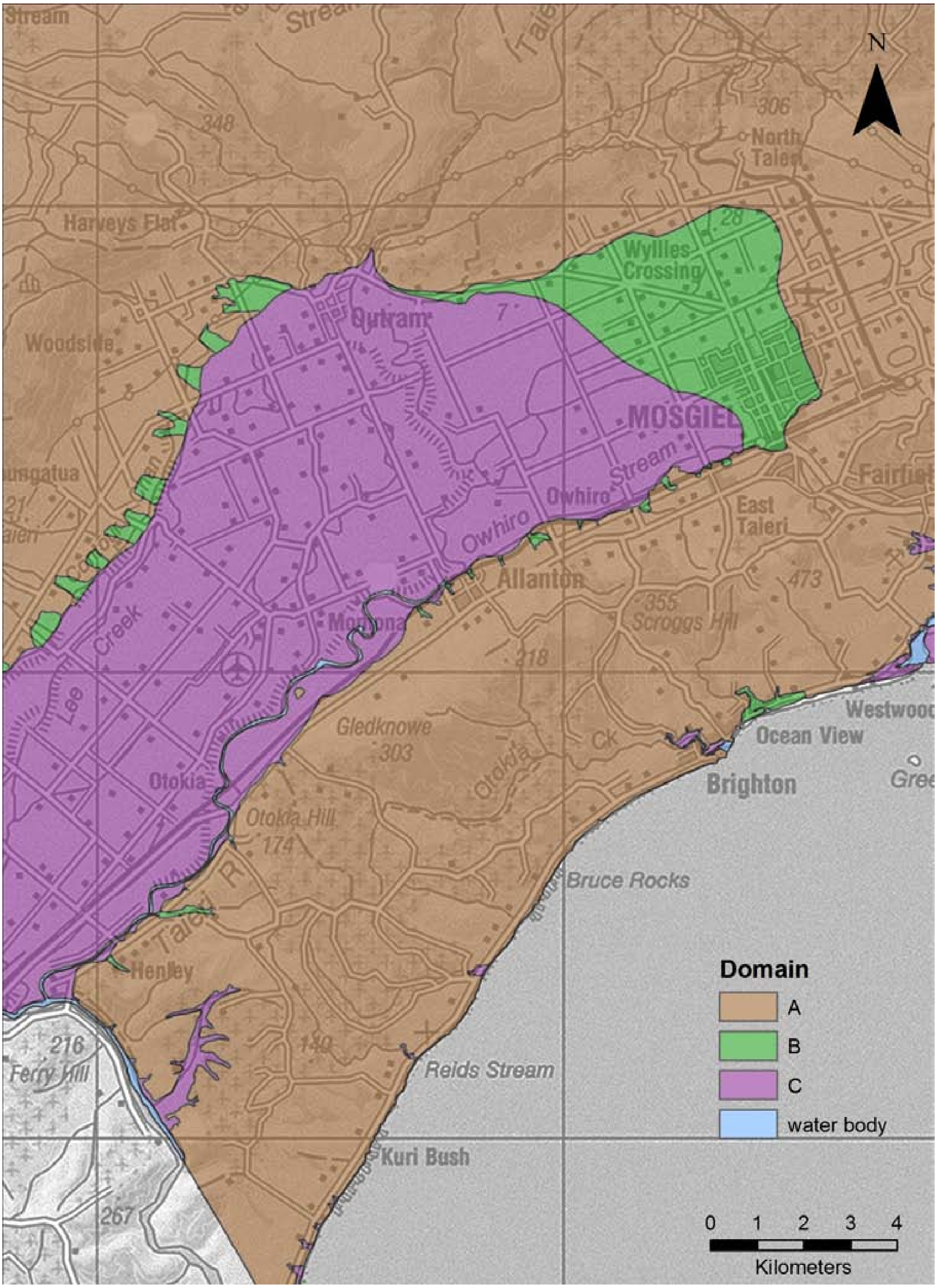

Figure 13 Map of liquefaction susceptibility domains for the northeastern part of the Taieri Plain.

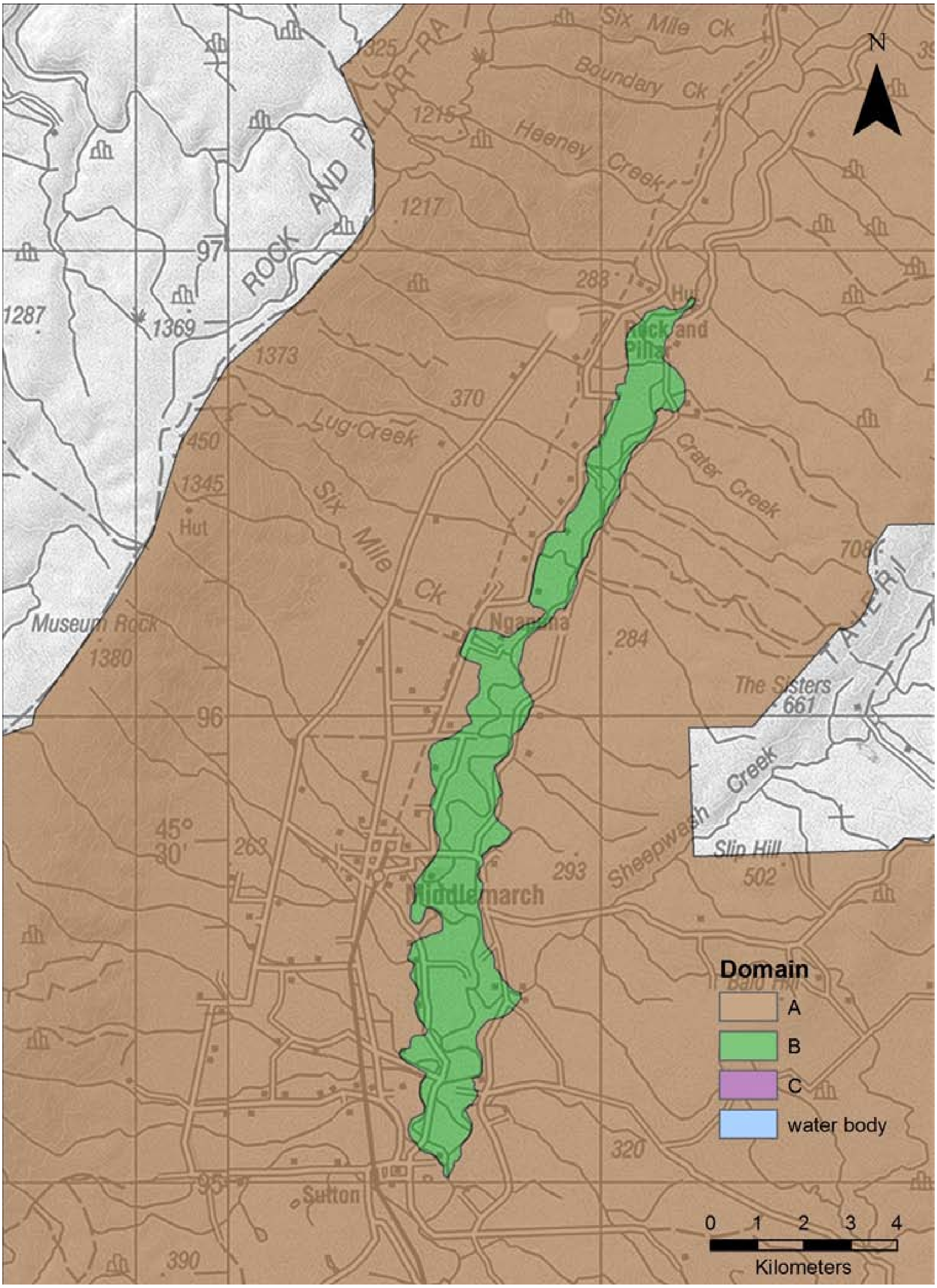

Figure 14 Map of liquefaction susceptibility domains for the Strath Taieri Plain.

5.4 COASTAL AREAS

5.4.1 Taieri Mouth to Waldronville

From Taieri Mouth to Brighton, the coastline is marked by a post-glacial cliff that is cut into the seaward edge of a narrow terrace. That terrace, typically 100 to 200 m wide and standing several metres above sea level, marks an old shore platform cut by wave action during the last interglacial period, about 125,000 years ago. This ‘marine terrace’ is underlain by schist bedrock, with a thin cover of weathered gravel, and silt. The larger streams draining from the coastal hills have cut small valleys where they cross the marine terrace. These valleys were flooded during the post-glacial sea level rise, and are likely to contain saturated, poorly consolidated sediments. In a few places, there are dune barriers enclosing these valleys. Northeast of Brighton, the marine terrace is not evident, and the coastal fringe is largely obscured by dunes. Minor streams have constructed alluvial fans over the marine terrace, but are scarcely, if at all, incised into it. All these areas are included in Domain A. Localised areas of Domains B or C are mapped in the lower reaches of the larger streams (see Figure 13).

5.4.2 Otago Harbour and Otago Peninsula

The western side of Otago Harbour and all of the Otago Peninsula is hill terrain formed on cover rocks, predominantly volcanic. The post-glacial sea level rise drowned the broad stream valleys now occupied by Otago Harbour, plus the broad embayments of Hooper Inlet and Papanui Inlet (Figure 15). All drainage comprises relatively minor streams. The streams draining to the harbour have steep courses, and post-glacial sea level rise caused minimal inundation of their lower reaches. On the eastern side of the peninsula, the stream valleys are gentler, probably because they were graded onto the coastal plain now occupied by the continental shelf. Their lower reaches were more affected by inundation by the sea level rise. For example, the Tomahawk Lagoons are former bays within drowned stream valleys, which became lagoons when the sand dune barrier was formed across their mouths. Sand accumulations are substantial on the eastern side of the peninsula, and near the northeastern end of Otago Harbour. Domain C is mapped on the sand flats and in valleys enclosed by dune barriers, and includes reclaimed land at Port Chalmers. A localised area of Domain B is mapped at Sawyers Bay.

5.4.3 Aramoana to Warrington

In this area, hilly terrain is drained by several broad valleys, whose lower reaches form coastal plains enclosed by dune barriers. Purakaunui Inlet and Blueskin Bay are substantial embayments of the sea that have so far escaped being filled in with sediment. Sand flats, dunefields and the lower reaches of valleys draining to the embayments are mapped as Domain C (Figure 15).

5.4.4 Karitane and Waikouaiti

The lower reaches of the Waikouaiti valley and its tributaries, as well as the lower reaches of Pleasant River, were drowned by post-glacial sea level rise, and as a result there are extensive low-lying areas with groundwater close to the ground surfaces, and a significant likelihood of young marine and estuarine sediments in the subsurface. These areas are mapped as Domain C (Figure 16).

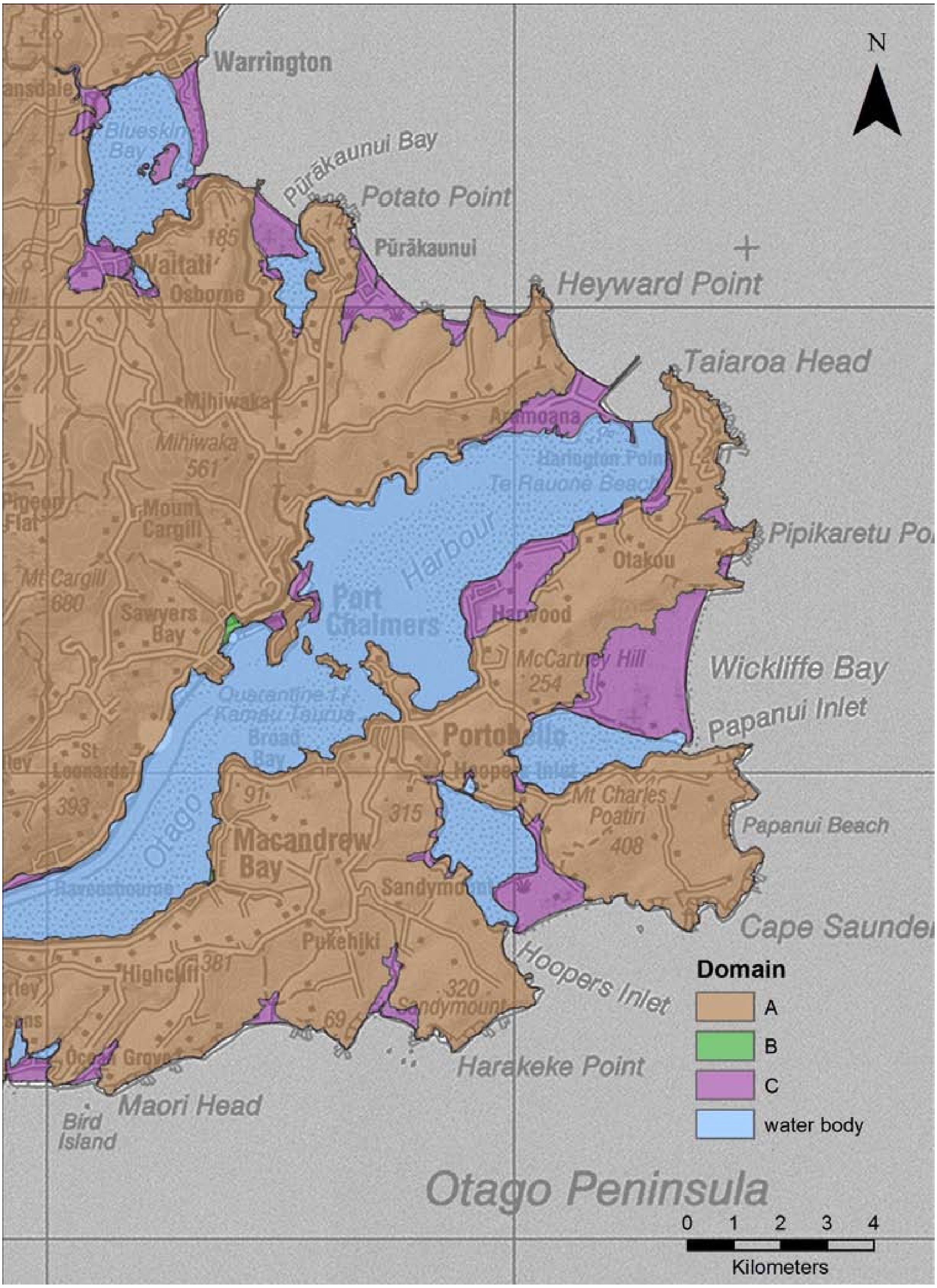

Figure 15 Map of liquefaction susceptibility domains from Otago Peninsula north to Warrington.

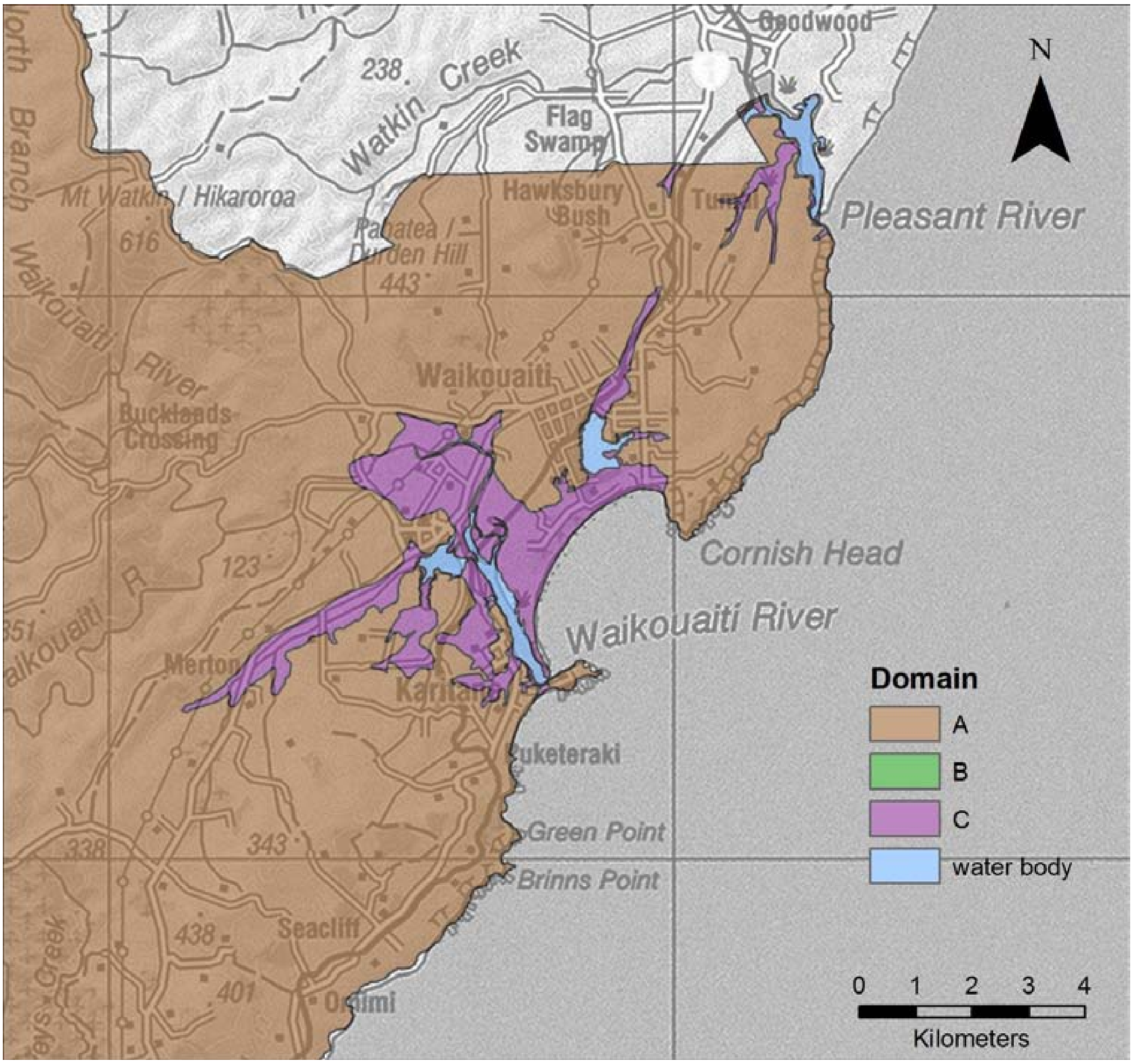

Figure 16 Map of liquefaction susceptibility domains near Karitane and Waikouaiti.

6.0 OVERALL ASSESSMENT

This project has involved an evaluation of information relevant for assessing liquefaction hazards. Being largely office-based, drawing heavily upon regional-scale geological, geomorphological and hydrological information, and not accompanied by subsurface site investigations, the assessment is highly generalised. The information available has been sufficient for the delineation of a three-fold classification of liquefaction susceptibility. These liquefaction susceptibility domains distinguish areas where the geological conditions afford little or no possibility of damaging liquefaction occurring (Domain A), areas with a low to moderate likelihood of being underlain, in part, by liquefiable materials (Domain B), and areas with a moderate to high likelihood of being underlain, in part, by liquefiable materials (Domain C). The uncertainties attending a district-wide evaluation, such as this project, have been highlighted by designating Domain B and C as ‘liquefaction awareness areas’. These are not regarded as hazard zones, because the extent and degree of hazard, if any, is yet to be established. As explained in Appendix 1, there is no easy way to relate the domains mapped in this report with the Technical Category classification of green zone land in eastern Canterbury, because the mapping of Technical Categories is based to a considerable degree on the observed effects of damaging earthquakes in Canterbury. Nevertheless, it is likely that Domain 1 land is equivalent to TC1 land, but the extent to which Domain B and C could be differentiated into TC1, TC2 or TC3 equivalents is unknown.

By way of summary, only 12% of the land area of the Dunedin district is underlain by Quaternary sediments, and only some of which will be susceptible to liquefaction. In regard to the liquefaction susceptibility domains, 91% of the district is mapped as Domain A, 1.4% is Domain B, 4.9% is Domain C, and 2.3% comprises large water bodies, including lakes, Otago Harbour and the main bays and inlets. If one compares the overall susceptibility classification map of the Dunedin district (Figure 11) with the liquefaction susceptibility maps presented by Murashev & Davey (2005) (see Appendix 2 – their Maps 20 and 21), they also present a 3-fold classification. The main difference is that their intermediate zone (‘low susceptibility’) encompasses all areas mapped as Quaternary sediments, whereas Domain B and C of the present report are of much more restricted extent. The reason for this difference is that the Murashev & Davey (2005) ‘low susceptibility’ zone includes extensive areas of predominantly gravelly, and/or older, sediments that in the present study are placed within Domain A. Looking at the Dunedin main urban area, McCahon et al. (1993) presented a map showing the extent of ‘soil types potentially susceptible to liquefaction’ (see Appendix 2 – their Figure 6.1). That area is slightly less extensive than Domain C mapped in the present report, and it is likely that the Domain C mapped here is slightly more conservative. The present assessment has been aided by use of highly detailed lidar topographic information.

Areas within Domain B or C that lie close to ‘free faces’, such as the banks of river or stream channels, may potentially be subject to lateral spreading hazards in the event of an occurrence of liquefaction-inducing earthquake shaking. No attempt has been made to map lateral spreading hazard awareness areas, largely because topographic datasets are too imprecise to undertake a consistent district-wide map of potential lateral spread areas. Another point to consider is that of embankments that are built on potentially liquefiable materials. Although these have not been mapped as part of this project, they do represent a hazard to consider in liquefaction-susceptible areas, especially as many of the embankments relate to important transport routes (road and rail), other infrastructural elements and flood protection (river flood banks).

The designation of Domain B and C as ‘liquefaction awareness areas’ emphasises that the available data sets lack the detail necessary to quantify the natural variability within potentially-liquefiable geological materials. For example, soft liquefiable sediments may occur in former stream channels, either side of which are non-liquefiable gravel bars. But these features may lie beneath younger sediments. Thus, detailed geotechnical investigations are needed for liquefaction hazard zonation, particularly in order to determine liquefaction hazards to a level sufficient for attempting a classification analogous to the Technical Category approach (see Appendix 1).

The domains identified in this report are not envisaged as being suitable for use in a regulatory or restrictive framework. Rather, they highlight areas where there may be an issue requiring consideration, as well as a ‘heads-up’ for existing, and in particular, future development. None of the areas mapped as Domain B or C in this report have hard evidence, so far as the authors of this report are aware, for the existence or exact locations of potentially liquefiable ground. Rather, geological factors indicate some likelihood that liquefaction-susceptible ground may exist in parts of those domains. The placing of restrictions on existing or new developments is not justifiable from the information presented in this report. Instead, this report is seen as providing a road map toward improved knowledge. In areas mapped as Domain B, and especially Domain C, that have major existing infrastructure, or if major new development is proposed, it would be desirable, through the collation of existing geotechnical data or the acquisition of new data, to establish the presence or otherwise of potentially liquefiable materials, and if present, their general pattern of distribution.

7.0 CONCLUSIONS

The susceptibility of land to earthquake-induced liquefaction was assessed for the Dunedin City district in an office-based evaluation of geological criteria relevant to liquefaction hazards, supplemented where possible with available borehole lithology and groundwater data. The mapping identifies areas that, from geological and geomorphological considerations, are likely to be underlain by the types of sediments that are liquefaction-susceptible, and where groundwater is at sufficiently shallow depth.

From the available information, a three-fold classification of liquefaction susceptibility has been developed:

- **Domain A**. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring;
- **Domain B**. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B;
- **Domain C**. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

The domains depicted on maps in this report are provided in greater detail in an accompanying GIS dataset. Areas identified as being potentially susceptible to liquefaction are restricted to low-lying places underlain by Quaternary sediments where the groundwater table is less than about 6 m deep. More than 90% of the land area in the Dunedin district is classified as Domain A – terrain underlain by materials that are non-liquefiable, including schist bedrock or cover sedimentary or volcanic rocks, or by gravelly or relatively consolidated Quaternary sediments. There are significant areas mapped as Domain B in Mosgiel-North Taieri and Strath Taieri, along with indications of shallow groundwater. Land classified as Domain C includes the southwestern part of the Taieri Plain, low-lying land in South Dunedin and adjacent to Otago Harbour, and low-lying coastal areas.

The liquefaction hazard evaluation reported here is a generalised regional-scale susceptibility assessment, using a methodology similar to that applied in eastern Canterbury. It differs from a full susceptibility assessment, which would require detailed geotechnical testing of properties of near-surface sediments. The information in this report is, for the most part, based on generalised assessments and broad-scale inferences, rather than detailed investigations, and should not be used in isolation for any purposes that require site-specific information. The liquefaction susceptibility domains delineated in this report are intended to highlight areas where liquefaction hazard may warrant further scrutiny for future planning and development activities. Domains B and C are regarded as ‘liquefaction awareness areas’, but do not represent hazard zones, as such. The placing of restrictions on existing or new developments is not justifiable from the information presented. Instead, the report provides a road map toward improved knowledge. A desirable future step would be to establish the presence or otherwise of potentially liquefiable materials in areas mapped as Domains B and C, and if present, their general pattern of distribution.

8.0 ACKNOWLEDGEMENTS

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APPENDIX 1: EXPLANATION OF TERMS

Geohazards	Natural ground-related hazards, some examples being: • Landslide or rockfall • liquefaction or lateral spread • strong ground motions from earthquake shaking • earthquake fault ground rupture • soft or compressible ground (e.g., peat) • erosion or sedimentation.
Geotechnical investigations	The process of characterising the ground subsurface conditions at a particular locality. The work must be undertaken or overseen by a ***geotechnical professional***. The work will include examination or measurements of the nature and properties of the ground-forming materials, by means that include: • Examination and documentation of the subsurface materials, exposed in test pits or inspection shafts, or obtained from cored or non-cored bore holes; • Measurements of material properties by means of probes or instruments (e.g., cone penetration tests (CPT) or standard penetration tests (SPT) • Measurements of groundwater conditions, such as standing water levels and piezometric pressures. For house development projects there is a minimum scope of geotechnical assessment work required, as set out in NZS3604:2011 *Timber-framed buildings* http://www.standards.co.nz/default.htm
Geotechnical professional	A suitably qualified or experienced civil engineer, geotechnical engineer, or engineering geologist. Work is expected to be done according to the IPENZ (Institution of Professional Engineers of New Zealand) Code of Ethical Conduct.
Hypocentre	The actual location underground where an earthquake is initiated. The epicentre is the location on the ground surface directly above the hypocentre. The hypocentre is also known as the earthquake focus.
Land zones	Following the Canterbury earthquakes of 2010 and 2011, extensive areas of flat-lying (i.e., not on hills) residential land in the greater Christchurch area have been mapped into land zones. Red zone land is deemed to have been so badly damaged by liquefaction-related phenomena during the Canterbury earthquake sequence that it is uneconomic to repair or rebuild dwellings. Green zone land is generally considered to be suitable for residential dwellings and associated land-use. Green zone land has, in places, been differentiated into Technical Category classes.
Technical categories (TC)	Land in the eastern Canterbury green zone has, in places, been divided into three technical categories – TC1, TC2 and TC3. These categories pertain only to residential land, and boundaries between TC areas are always placed along property boundaries. The mapping of TC areas was based to a considerable degree on the presence or absence of liquefaction occurrence during the Canterbury earthquake sequence, and the severity of the liquefaction effects. Geotechnical investigations involving bore holes, CPTs, and SPTs were also undertaken to assist with the TC mapping.

Technical categories (TC) – continued	The primary objective of the mapping of TC areas is to characterise how the ground is expected to perform in future large earthquakes, and to define foundation design requirements for the repair of existing dwellings or construction of new dwellings. More information can be found at: • http://cera.govt.nz/residential-green-zone-technical-categories#factsheets • http://cera.govt.nz/residential-green-zone-technical-categories Because the observed consequences of strong earthquakes were an integral part of the mapping of TC areas, the TC approach cannot be applied to locations elsewhere in New Zealand that have not experienced large damaging earthquakes historically. For that reason, the liquefaction susceptibility domains mapped in the Dunedin district report do not correlate directly with TC zones. Domain A land is likely to perform similarly to TC1 land as mapped in the Christchurch area, but Domains B and C land are likely to include land that may, from place to place, perform similarly to TC1, TC2 or TC3 land. A considerable body of geotechnical information would need to be obtained from investigations before any attempt could be made to apply a TC methodology to subdividing Domain B or C land into a liquefaction hazard zonation classification.

APPENDIX 2: PREVIOUS HAZARD EVALUATION MAPS

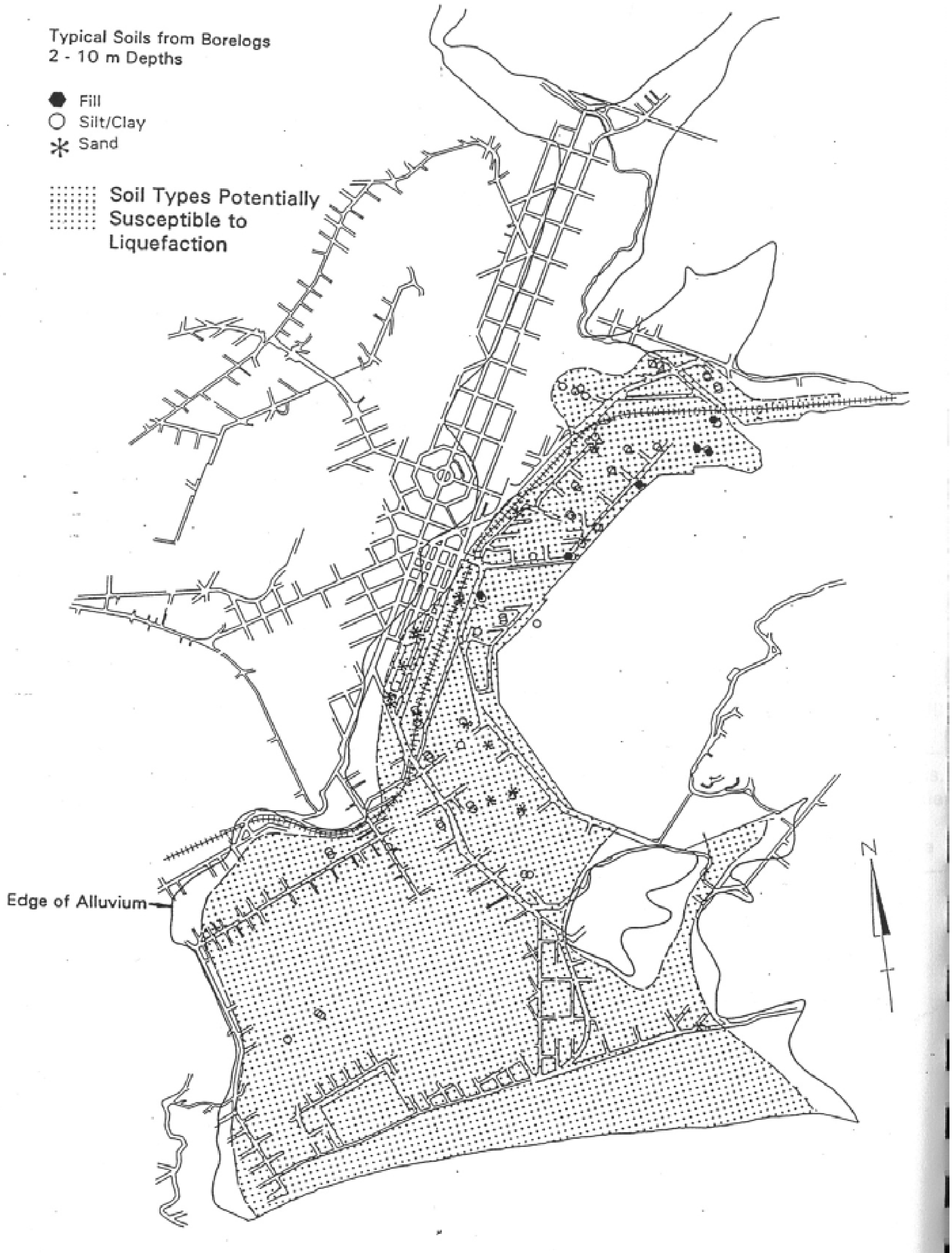

FIGURE 6.1

Map of Dunedin City Showing Areas of Soil Types Susceptible to Liquefactio

Figure A2.1 Liquefaction-susceptible soils, central Dunedin city (McCahon et al., 1993)

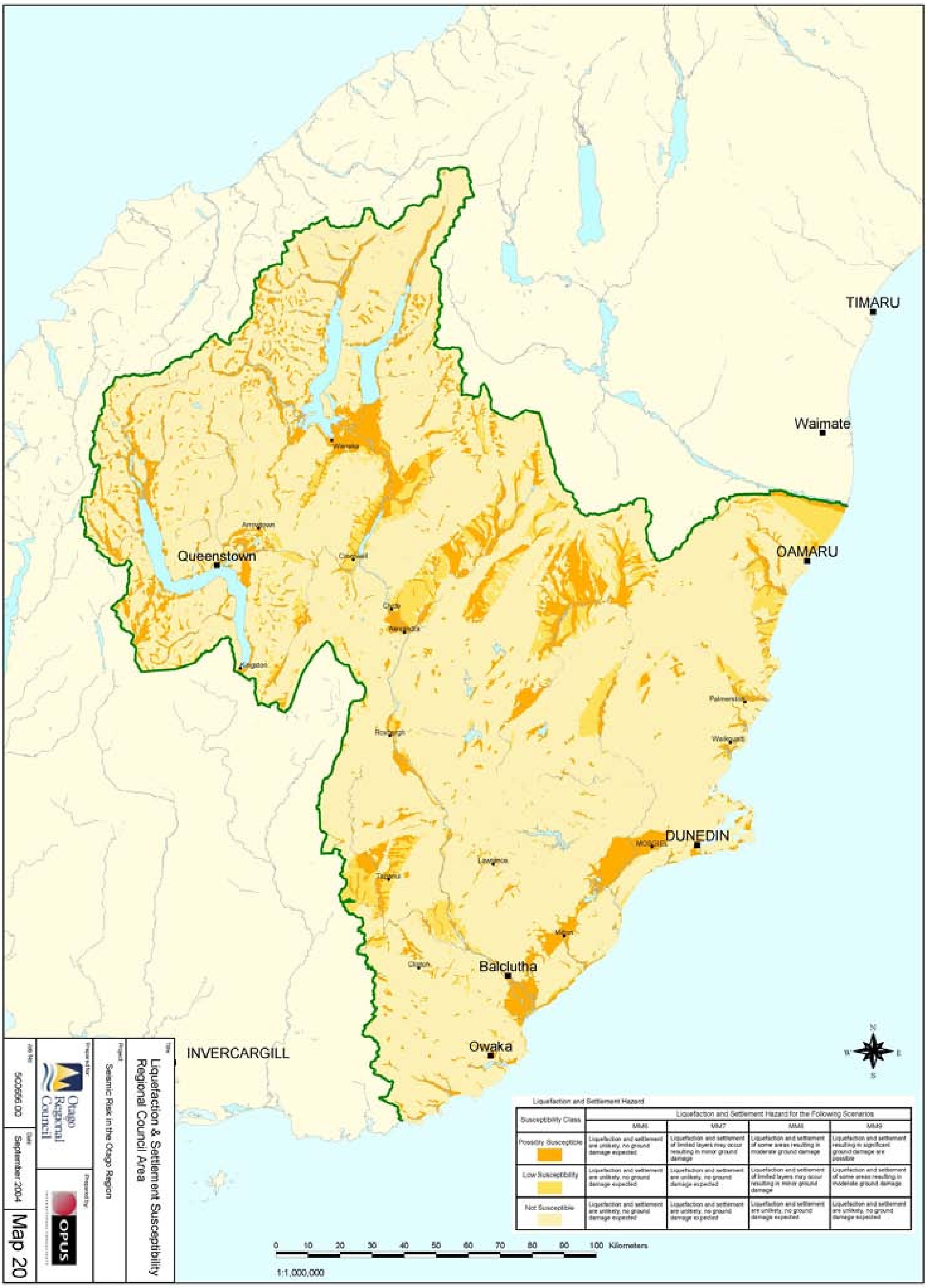

Figure A2.2 Liquefaction and settlement susceptibility, Otago region (Murashev & Davey 2005).

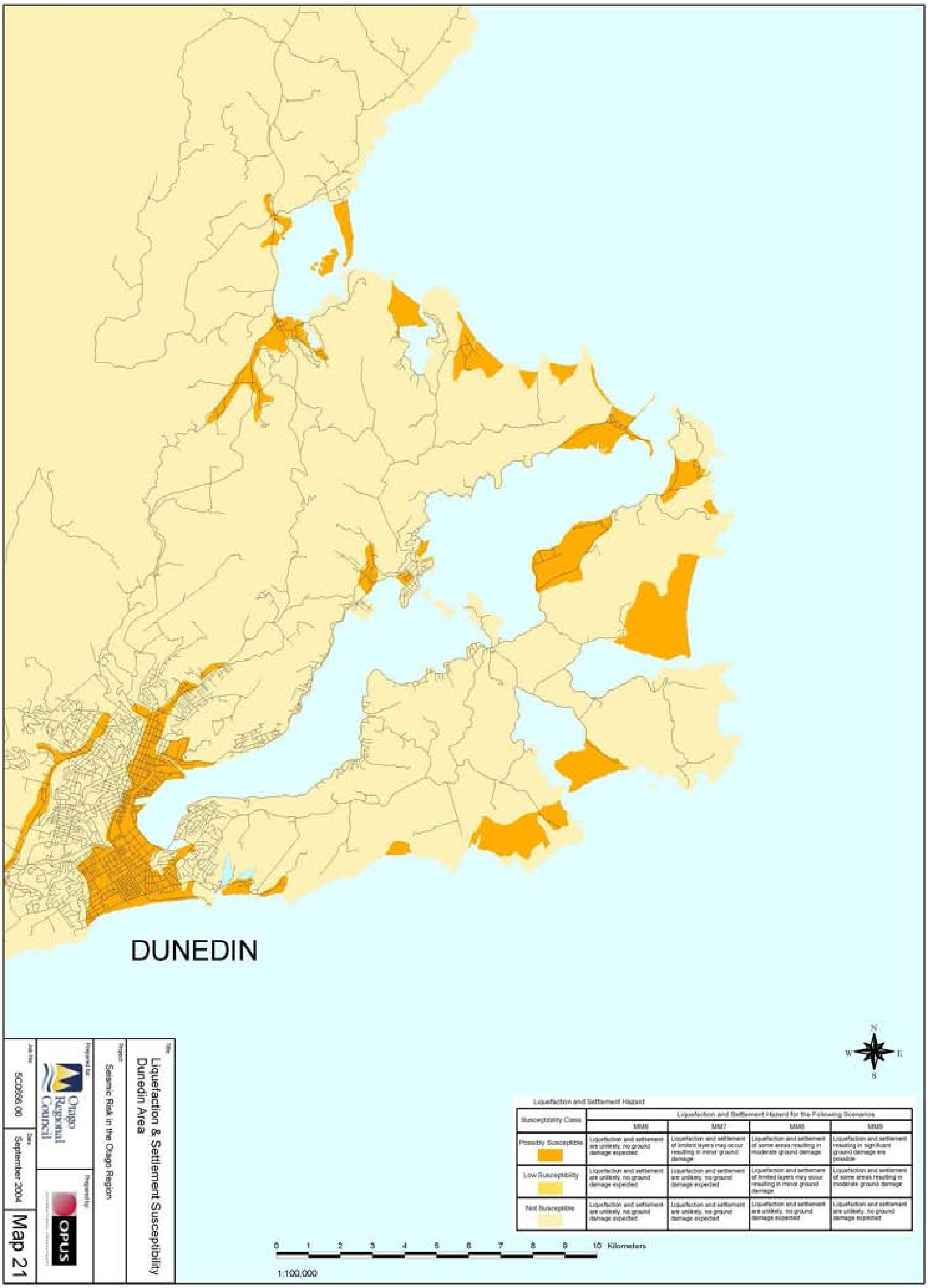

Figure A2.3 Liquefaction and settlement susceptibility, greater Dunedin area (Murashev & Davey 2005).

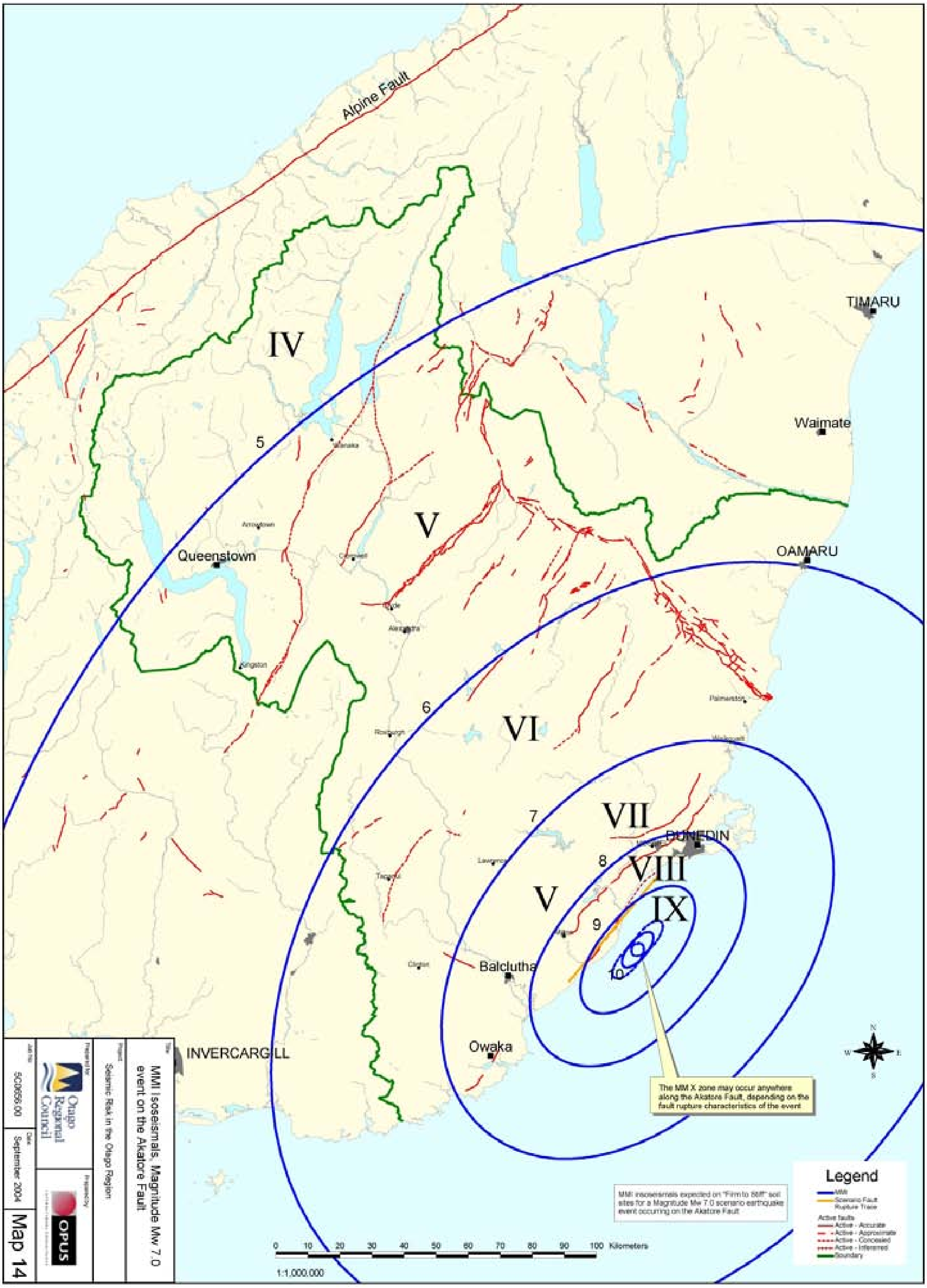

Figure A2.4 Estimated ground shaking, expressed in Modified Mercalli intensity classes, for a magnitude 7 earthquake centred on the Akatore Fault (Murashev & Davey 2005). Intensities of VII and VIII would be expected in coastal sectors of much of the Dunedin district, and would be likely to generate liquefaction in susceptible locations.

APPENDIX 3: DESCRIPTION OF THE MAPPED EXTENTS OF LIQUEFACTION SUSCEPTIBILITY DOMAINS B AND C

A3.1 DUNEDIN URBAN AREA

Mapping was aided by full coverage of lidar data.

Bore records from South Dunedin indicate substantial thicknesses of sand and silt, ranging from about 10 m to as much as 65 m thick (Fordyce 2013). Much of the land surface is within 1 m of mean sea level and is prone to surface flooding after prolonged rainfall. Groundwater is characterised by an unconfined water table that is very shallow, typically 0.3 to 0.9 m below surface, but shallowing in central St Kilda above an extensive area of silt. There may also be local pockets of perched freshwater within coastal dunes (Fordyce 2013). Groundwater is affected by sea level and tides at the ocean and the harbour, and controlled by rainfall-recharge and drainage through the stormwater and wastewater network (Rekker 2012; Fordyce 2013). Shallow groundwater is expected throughout the low-lying land beside the Otago Harbour as far as Logan Park and Ravensbourne. There is a substantial belt of reclaimed land at the margin of the harbour, from Vauxhall around to Ravensbourne.

The basis on which the Domain C/Domain A boundary was positioned is as follows. In order to account for the alluvial fans that grade out onto the coastal plain, and thus likely overlie soft marine sediments, from St Clair around to the Water of Leith, the boundary was placed at 10 m above mean sea level (a.s.l.) as defined by the lidar data (Figure A3.1a). This includes the lowest reaches of the Leith valley and other streams draining to the coastal plain. The 10 m a.s.l. criterion was also applied from Vauxhall around through Andersons Bay and Tainui to Lawyers Head, there accounting for dune sand aprons that probably mantle the base of slopes, along what was a more exposed part of the former embayment. At Lawyers Head, the boundary has been connected to the shore platform rock outcrops. From Logan Park around the reclamation area to Ravensbourne, the boundary was also positioned at 10 m a.s.l.

The Kaikorai Lagoon area is a largely tidal wetland. A major long-standing land-use has been as a landfill area. A sand flat and dunefield at the lagoon mouth was included in the area mapped as Domain C (Figure A3.1b). Lidar coverage runs out at the northwestern edge of the lagoon. The 1:25,000 geological map of McKellar (1990) was used to aid the positioning of the boundary of the Domain C area. The boundary was positioned at 6 m a.s.l., as defined by lidar data, around the lagoon perimeter, and in the valley of Abbotts Creek. It includes all areas of filled and reclaimed land, even though some of those areas stand well above 6 m. The reasoning for a 6 m altitude criterion is that Kaikorai Lagoon has well-defined margins eroded into bedrock terrain, without large catchments draining in. Its intricately multi-branched perimeter suggests that it is a drowned valley with relatively little sediment infill. At Brighton Road, Kaikorai Stream is fast flowing on a gravel bed, suggesting that the sea level rise culminated at about that location. Mapping here was hindered by the extensive embankments associated with the motorway interchange. To be conservative, the boundary of Domain C was extended up the floor of Kaikorai valley to 10 m a.s.l.

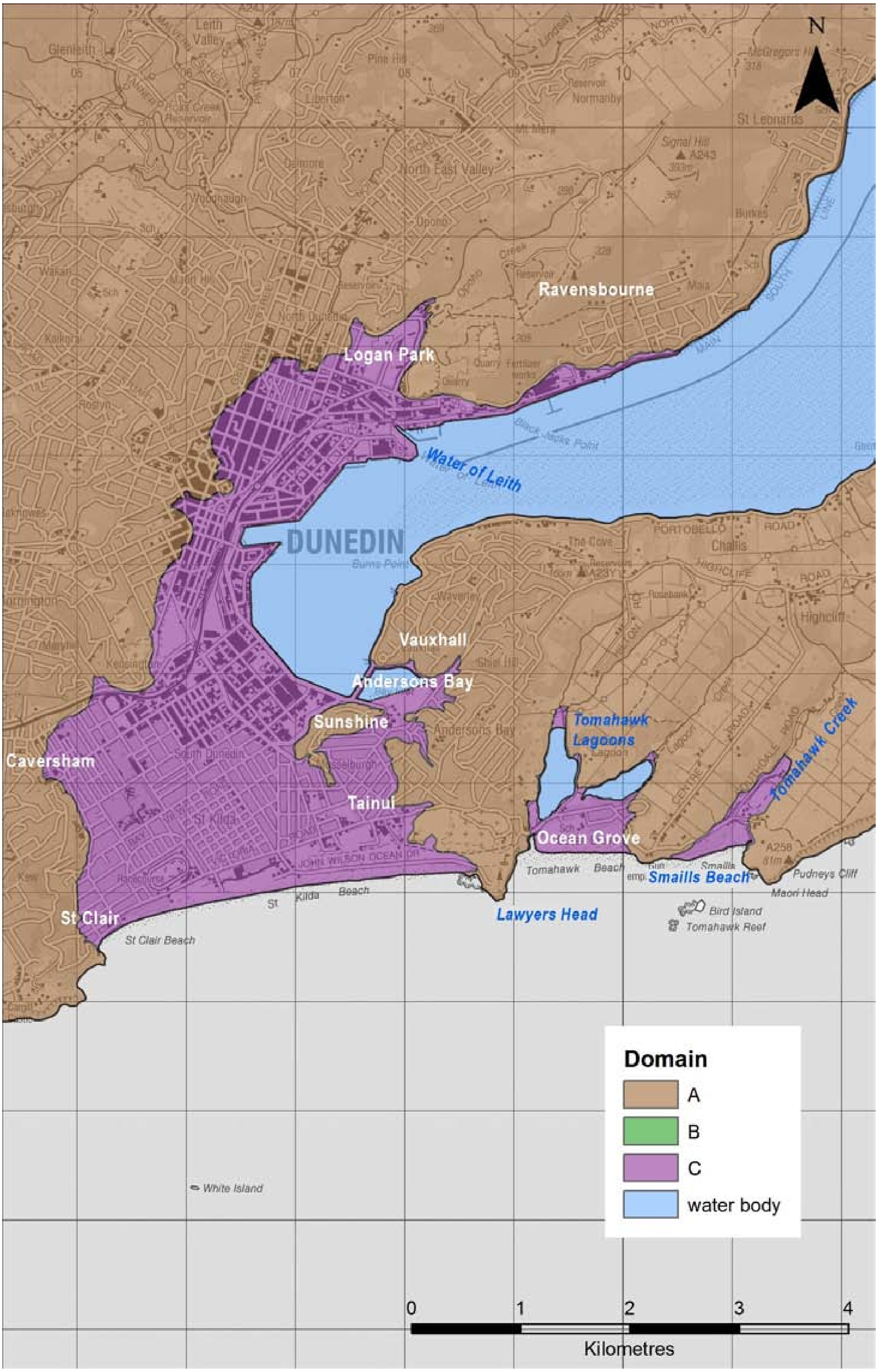

Figure A3.1a Location map for liquefaction susceptibility domains in the Dunedin urban area.

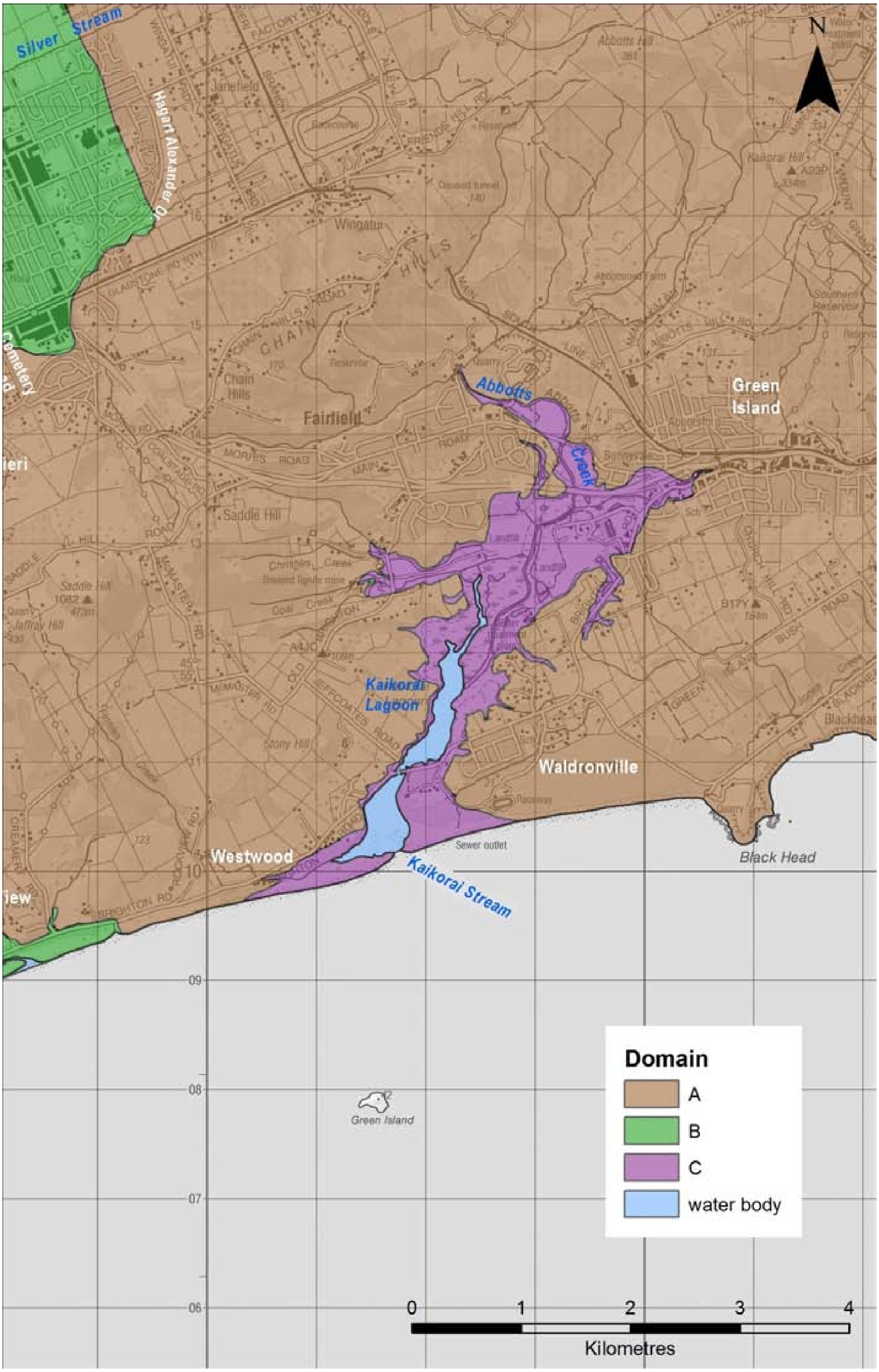

Figure A3.1b Location map for liquefaction susceptibility domains in the Kaikorai Lagoon area.

A3.2 TAIERI PLAIN AND STRATH TAIERI PLAIN

A3.2.1 Taieri Plain

The boundary of Domain C on the Taieri Plain was positioned to coincide with the limit of the Waihola silt/sand. It is most easily defined southwest of Outram and Allanton (Figure A3.2a), because there is a line of wave-cut terrace edges marking the margin of the former inlet, broken by alluvial fans that have built out onto the plain after the inlet became filled in. Between Outram and East Taieri (Figure A3.2b), the mapping of the extent of Waihola silt/sand was derived from information from bores, but there are relatively few bores that have lithological details. Thus the Domain C boundary has less certainty here, but is aligned with the limit of Waihola silt/sand as mapped by Litchfield et al., (2002). In addition, bores indicate the presence of zones of silt or sand in the subsurface, northeast towards the Mosgiel area. However, there is much variability, with sand or silt recorded from some bores, and yet mostly gravel recorded in other bores nearby. Coupled with the observation that groundwater is close to the surface in that area, an area has been mapped as Domain B which includes Mosgiel (Figure A3.2b). The extent and sensitivity of any liquefaction-susceptible materials in this domain will need to be established by specific geotechnical investigation. Similarly, areas of Domain B were mapped in the lower reaches of the infilled valleys of minor streams that have built alluvial fans out over Waihola silt/sand (all areas underlain by Waihola silt/sand are included in Domain C) (see Figures 11 and 13 of main report).

The positioning of the boundaries of these domains was determined as follows. Apart from parts of the lower Taieri Gorge southeast of Henley, there is complete lidar coverage of the Taieri Plain area. In the valley of the Waipori River upstream of Berwick, the Domain C/A boundary was positioned about 1 km northwest of Berwick (Figure A3.2c). The rationale was that the bore holes in the valley upstream of here show predominantly gravel, while those near Berwick encountered mainly fine-grained material. Northeast of Berwick, the Domain B/C boundary was located at the former shoreline, then interpolated beneath fans that post-date the former shoreline. The Domain B/A boundary was positioned across the floor of each minor stream valley at 10 m a.s.l. to allow for the possibility of saturated fine-grained material at depth. On the southeast side of the basin, the Domain B/A boundary was positioned as far up each valley as the valley floor is broad. The reasoning is that, particularly in the area southwest of Allanton, the base of the Waihola silt/sand, which marks the original land surface prior to sea level rise, is as much as 25 m below sea level. The minor valleys were doubtless graded to that old land surface, and it is very likely that the lower reaches of these valleys were also drowned, and subsequently filled with fine sediment. In the lower Taieri Gorge (i.e., between Henley and Taieri Mouth), the boundary was positioned at the margins of the infilled valley, and extended up tributary valleys as far upstream as each valley is broad (Figure A3.2d). The extensive infilled valley on the northern side of the gorge, and into which Knee Stream and Elbow Stream drain, was mapped using the 1:50,000 scale topographic map, because much of this valley is outside the lidar coverage.

More difficult was the placement of the Domain B/A boundary in the vicinity of Wyllies Crossing and Mosgiel (Figure A3.2b). The area mapped as Domain B includes the bores that encountered significant components of fine-grained materials in the top 10 m, and also encompasses most areas where groundwater is shallower than about 5 m. Topographic elevations were used to position the zone boundary, as follows. East from Outram along the northwestern side of the basin, the Domain B/A boundary was positioned at 15 m a.s.l., but shifted to 20 m a.s.l. near Tirohanga Road, and then shifted progressively to 30 m a.s.l.

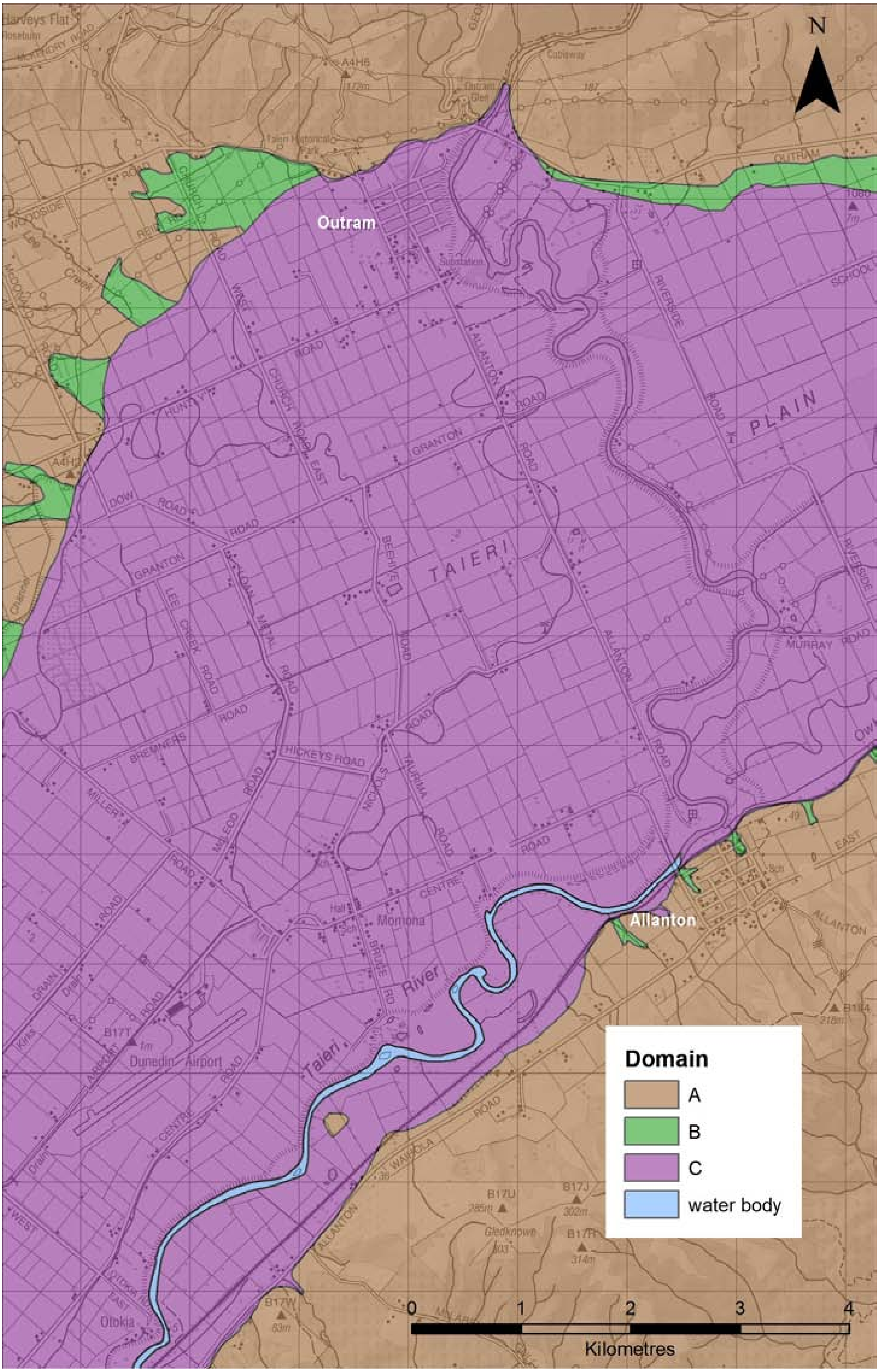

Figure A3.2a Location map for liquefaction susceptibility domains in the central part of the Taieri Plain.

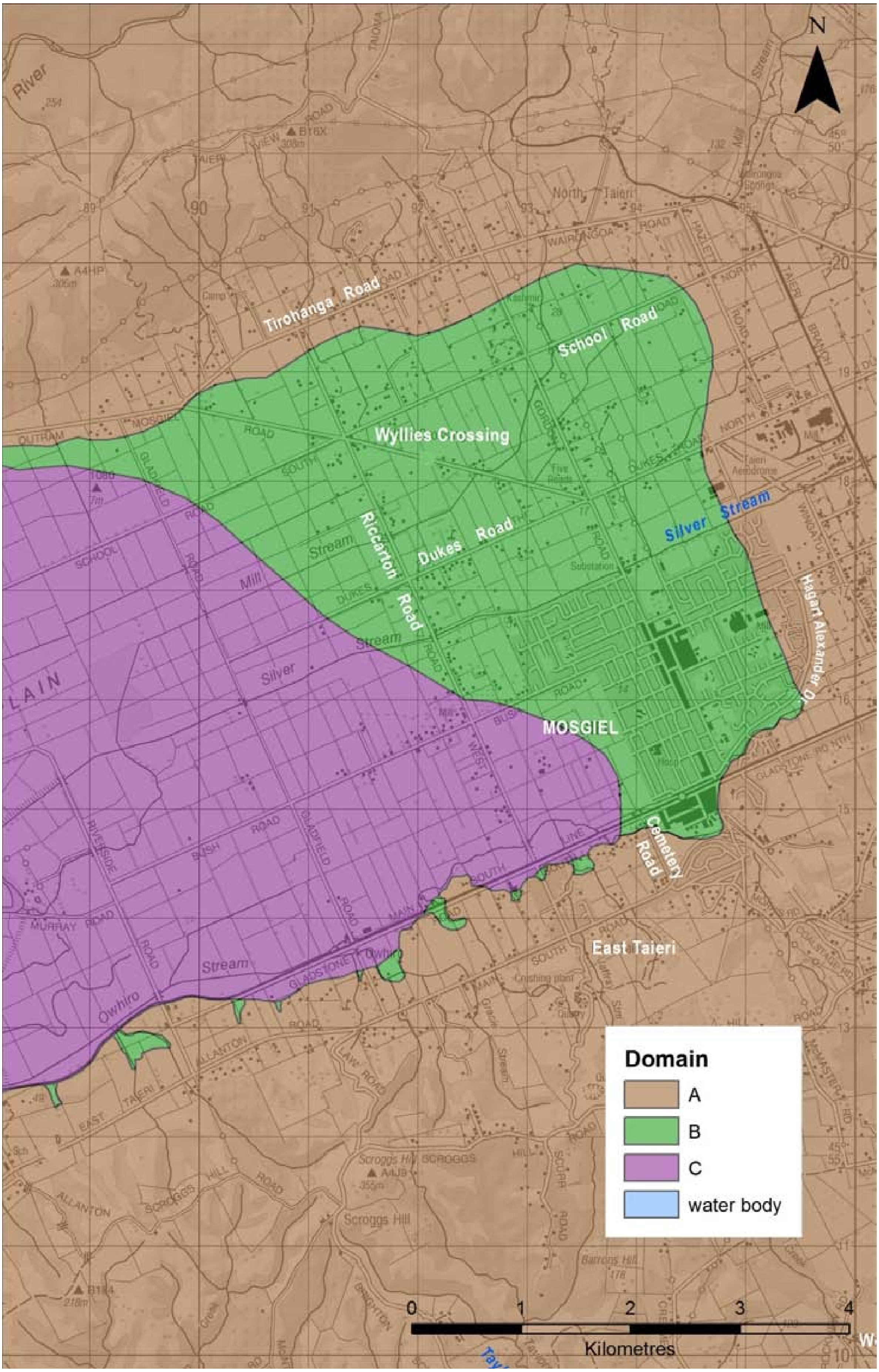

Figure A3.2b Location map for liquefaction susceptibility domains on the northeastern part of the Taieri Plain.

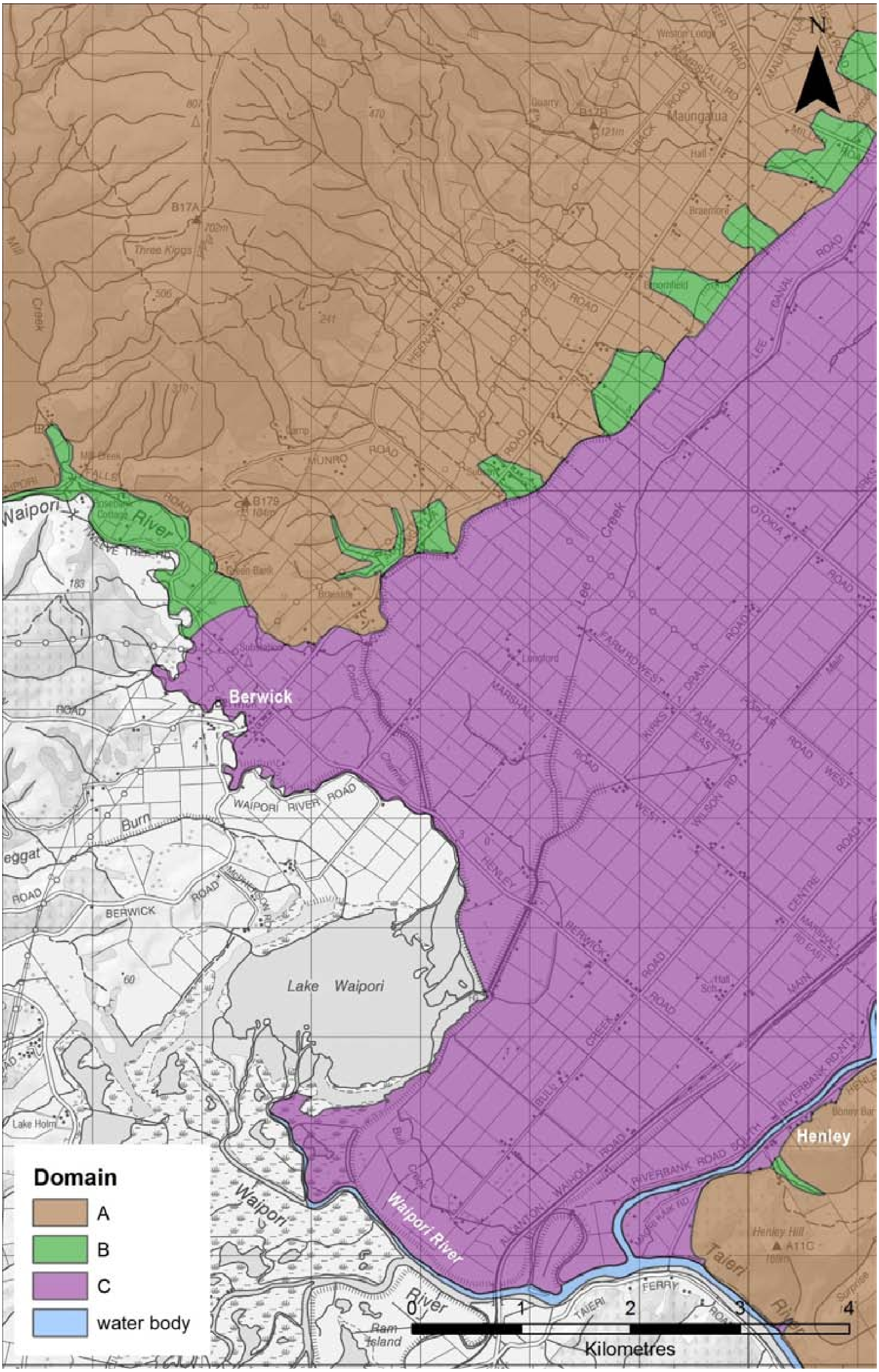

Figure A3.2c Location map for liquefaction susceptibility domains in the southwestern part of the Taieri Plain.

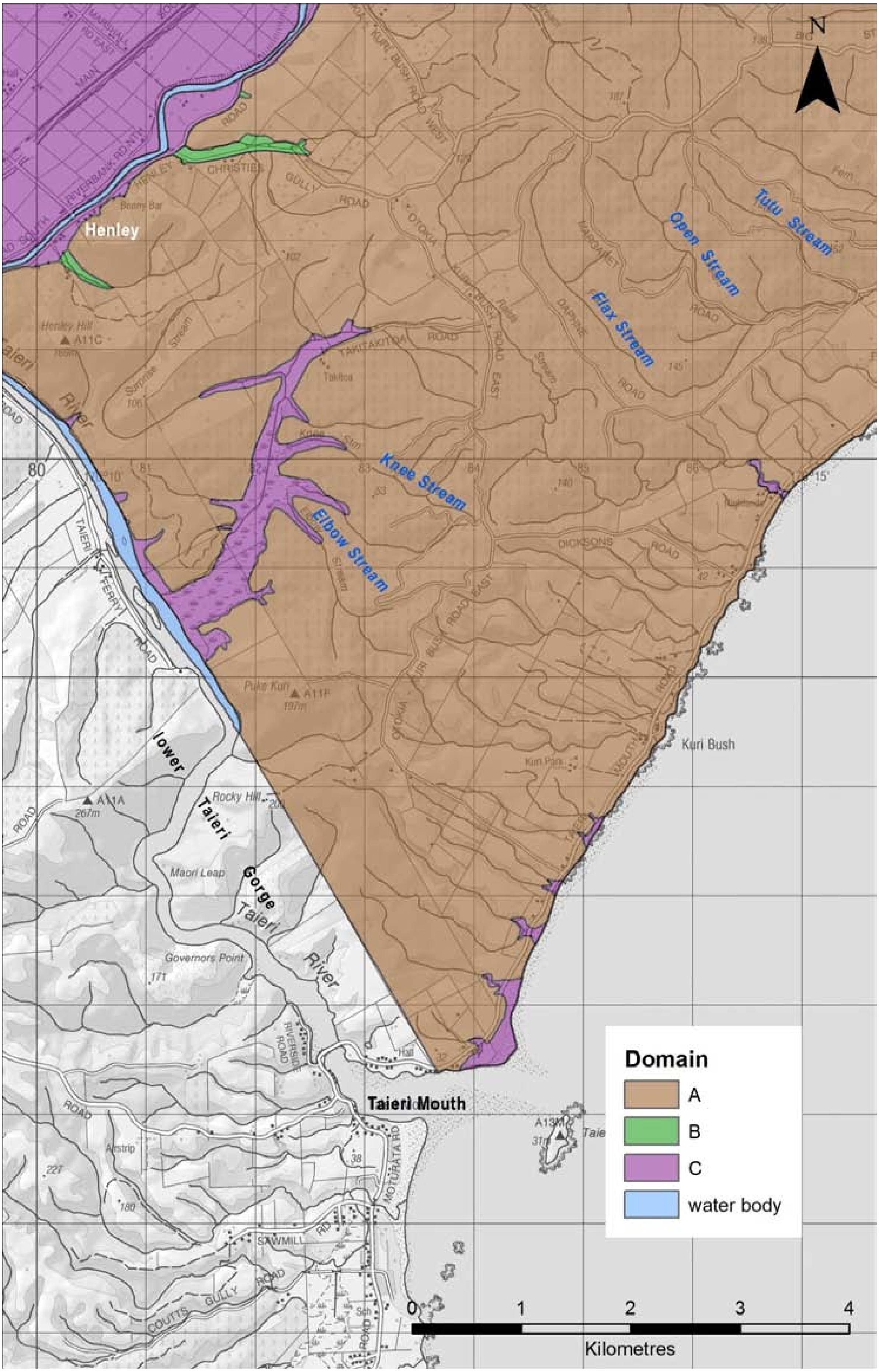

Figure A3.2d Location map for liquefaction susceptibility domains in the lower Taieri Gorge.

Southeast of School Road, its altitude was progressively reduced, reaching 15 m at Dukes Road. It was positioned at 15 m a.s.l. along to Hagart Alexander Drive, continuing southeast to the foot of the alluvial fan complex on the southeast side of the basin. The Domain B/A boundary was placed along the edge of the alluvial fans to just past Cemetery Road, where it terminates at the Domain C boundary.

Groundwater levels are also an important consideration for delineating domain boundaries. A number of groundwater studies have been carried out in the area, summarised in Rekker & Houlbrooke (2010). The most definitive groundwater level contour map available for Taieri Basin was a survey of 52 levelled bores, carried out in mid-May 1994 (Irricon & Royds Consulting 1994), updated with new investigation wells and observations in July 1996 (Irricon & ESR 1997). The Waihola silt/sand exerts an important influence on groundwater beneath the Taieri Plain. Where present, west of Riccarton Road, it separates a near-surface unconfined water table from confined groundwater in aquifers below. East of about Riccarton Road, the sediments include greater quantities of gravel and are characterised by a high degree of lithological variability with rapid lateral transitions in grainsize. Groundwater in that area is mostly unconfined. The potentiometric surface conforms approximately with the elevation of topography, with groundwater at higher elevations in the north, decreasing with distance toward the southwest to approximately mean sea level at Henley. Local departures in the general shape of the surface are caused by: pumping at Mosgiel; discharge at School Swamp; emergence of Taieri River onto the plains at Outram; and the west Taieri drainage scheme (Rekker & Houlbrooke 2010).

Available groundwater information comes mostly from deeper bores, which are typically between 15 and 35 m deep, and screened in productive aquifers. There are relatively few bores less than about 10 m deep, but these shallow bores generally show higher groundwater levels than the deeper bores, indicating downward directed vertical pressure gradients (Irricon & ESR 1997). This is important as deep bores, or derived potentiometric contours, cannot be used as an indicator of the free water table and saturation required for liquefaction assessment. ORC records of shallow bore groundwater levels generally show the water table to be less than about 5 m deep across most of the Taieri Plain. Shallow artesian-flowing groundwater is sometimes present near Wyllies Crossing, but may have been reduced by long-term drawdown caused by land drainage (Rekker & Houlbrooke 2010). The greatest potentiometric depths appear to occur from Mosgiel toward North Taieri, but the position of the shallow water table in this area is not entirely clear. A shallow (6.1 m) bore at Roslyn Woollen Mills (now Mill Park Industrial Estate, Factory Road, central Mosgiel) has a median water level ~2 m below ground, with a long-term record of ±1 m variability closely related to rainfall recharge (Collins 1950; Rekker & Houlbrooke 2010). This suggests that saturation levels are sufficiently shallow for the occurrence of liquefaction if liquefaction-susceptible sediments are present.

A3.2.2 Strath Taieri Plain

The Strath Taieri Plain lies in a basin on the southeastern side of the Rock and Pillar Range (Figure 14 of main report). The Taieri River flows in a broad valley, flanked to the northwest by remnants of old river terraces, underlain by weathered gravel, and an array of alluvium deposited by streams draining from the Rock and Pillar Range. The river and fan sediments are probably 200 m thick at most, and are thought to be underlain by schist basement rock. The maximum confirmed depth of the alluvial deposits is 28 m in well H43/0187 located 2 km south of Middlemarch (Irricon & MWH 2004). The fan sediments are predominantly gravelly.

The Taieri River has developed a meandering course in places, and these areas of meander channels/bars may potentially include sandy or silty sediments.

Groundwater assessments by Hanson (1997) and Irricon & MWH (2004) indicate that there is an unconfined groundwater aquifer within the alluvial sediments, within complex interlayering of gravel, sand, silty sand and silt. Bore logs commonly describe “silty fine gravels”, “claybound gravels” or “very sandy claybound gravels” with low specific yields (Irricon & MWH 2004). A survey of 19 wells on 25 March 1997 indicated that the groundwater table was within 5 m of the ground surface over most of the basin, but at Middlemarch was locally less than 2 m below ground (Hanson 1997). Depth to groundwater is greatest within the alluvial fans on the western side of the valley. About Middlemarch, there are iron pans and minor perched water tables, confined aquifer conditions, and channels of preferred groundwater flow (Hanson 1997). The 1997 groundwater survey was carried out in early autumn, when groundwater conditions are likely to have been low. At times the water table immediately to the west of Middlemarch has risen above the ground surface and caused flooding (Hanson 1997).

To acknowledge the possible existence of fine-grained sediments and a likely high groundwater table, Domain B has been mapped in the incised valley of the Taieri River (Figure 14 of main report). As there is no lidar coverage for the Strath Taieri Plain, the Domain B/A boundary was positioned at the margins of the incised valley, using high-resolution satellite photography accessible via the ArcGIS computer software used for the mapping, and the 1:50,000-scale topographic map.

A3.3 COASTAL AREAS

A3.3.1 Taieri Mouth to Waldronville

There is lidar coverage for this entire coastal stretch, which has aided the mapping of domain boundaries.

The lower reaches of several minor stream valleys south of Kuri Bush are mapped as Domain C (Figure A3.2d). Inland boundaries of Domain C are placed as far up-valley as the valley floor is broad. In places, dunes lie seaward of the post-glacial cliff adjacent to these streams, and are also included in Domain C. North of Kuri Bush, areas of Domain C were mapped in the lower reaches of Reids Stream, which includes a lagoon, and in the combined valley of Flax Stream – Open Stream – Tutu Stream. This combined valley has a broad floor but it may conceivably be an alluvial fan pre-dating the sea level rise, so is not necessarily underlain by young marine sediments. It is tentatively classified as Domain C.

At Brighton, Otokia Creek has a broad estuarine reach, and Domain C was mapped here, encompassing the full width of the valley floor, and adjacent sand dunes at the beachfront near the estuary mouth. The inland boundary is placed as far upstream as the valley is broad (Figure A3.3a).

At Ocean View, a broad low-lying coastal plain is enclosed by the dune barrier. The coastal plain, the dune barrier and the lower reaches of Taylors Creek, as far upstream as the valley floor is broad, are mapped as Domain B (Figure A3.3a). This classification reflects the consideration that substantial parts of this area are on dunes, and likely to be well above groundwater level, which here will approximately coincide with sea level. The Domain B

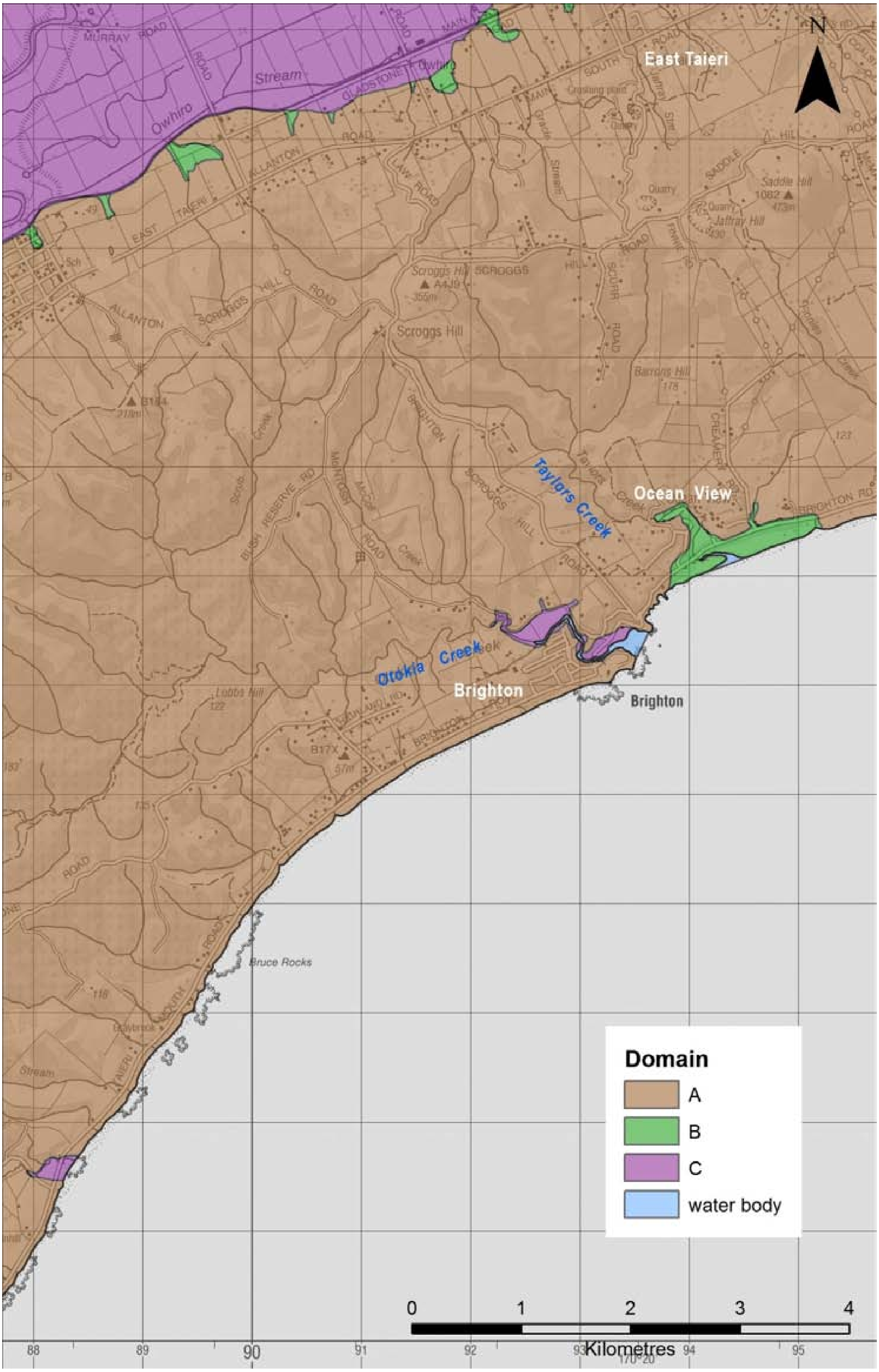

Figure A3.3a Location map for liquefaction susceptibility domains along the coast in the Brighton area.

classification also reflects the possibility that the valley floor may conceivably be an alluvial fan in part pre-dating the sea level rise. To the northeast, the Domain B/A boundary is curved out to meet the coast where the terrain rises up towards Westwood.

From Westwood to Kaikorai Lagoon, low-lying dunes in front of the post-glacial sea cliff are mapped as Domain C, as is the dune/sand plain seaward of the sea cliff on the south side of the lagoon at Waldronville (Figure A3.1b).

A3.3.2 Otago Harbour and Otago Peninsula

There is lidar coverage for most parts of the harbour and peninsula.

Around the margins of both sides of Otago Harbour are extensive road and, on the western side, rail, embankments. These are commonly cut-to-fill constructions. The choice was taken not to map these separately from Domain A, but they may be potentially subject to lateral spreading hazards where the embankments are constructed on top of harbour sediments.

On the western side of the harbour, at Sawyers Bay there is a narrow fringe of low-lying ground, that is probably in part reclaimed land (Figure A3.3b). This was mapped as Domain B, with the Domain B/A boundary positioned at 6 m a.s.l., as defined in the lidar digital elevation model. Reclaimed land at the Port Chalmers port was mapped as Domain C, as was reclamation near Albertson Avenue on the southwest side of Port Chalmers. The inland boundaries of these domains were placed at 4 m a.s.l. Although a Domain C classification was chosen for the port reclamation, because it is built over marine sediments, it is likely that the reclamation has largely been engineered and its foundation on harbour sediment is likely to have been accounted for in the engineering design. At Sawyers Bay, it is unclear to what extent, if any, the area is underlain by soft sediments.

The coastal flat at Waipuna Bay, and the sand flat at Aramoana seaward of the coastal cliff, were both mapped as Domain C (Figure A3.3c). The base of the cliff is sharply defined, and the coastal flats have minimal relief, with negligible accumulation of debris or colluvium at the foot of the cliff, suggesting that the formation of the flats, and cessation of wave action at the base of the cliffs, is relatively recent, perhaps within the last thousand years or so. Due to the sharpness of the base of the cliff, the Domain C/A boundary was placed at 4 m a.s.l., as defined by lidar data. Any sand dunes on the flats that reach above 4 m are included in Domain C.

On the eastern side of the harbour at Macandrew Bay there is a narrow coastal plain, although it is unclear to what extent it is a natural feature, or enhanced by reclamation. It was mapped as Domain B, with the domain boundary positioned at 6 m a.s.l. at the foot of the hill terrain (Figure A3.3b). Farther northeast, there are extensive sand accumulations from Harwood northeast to Harington Point, and these were mapped as Domain C (Figure A3.3c). The mapping was hindered by widespread sand dunes on the costal flats and locally draped against the lower parts of the hill slopes. Generally, the Domain C/A boundary is placed at 6 m a.s.l., as defined by lidar, at the foot of the hill terrain, and interpolated where dunes have accumulated.

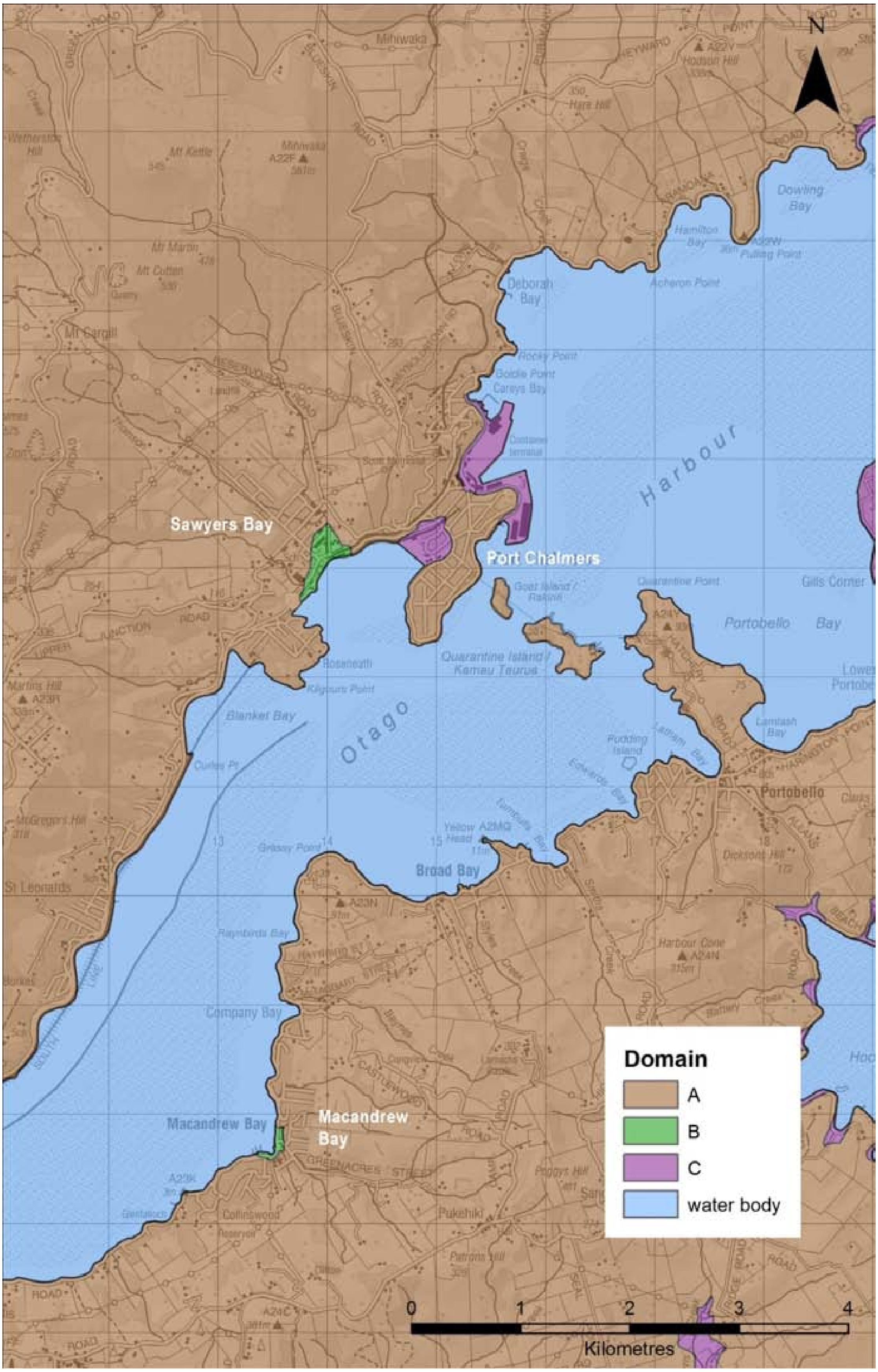

Figure A3.3b Location map for liquefaction susceptibility domains around the middle reaches of Otago Harbour.

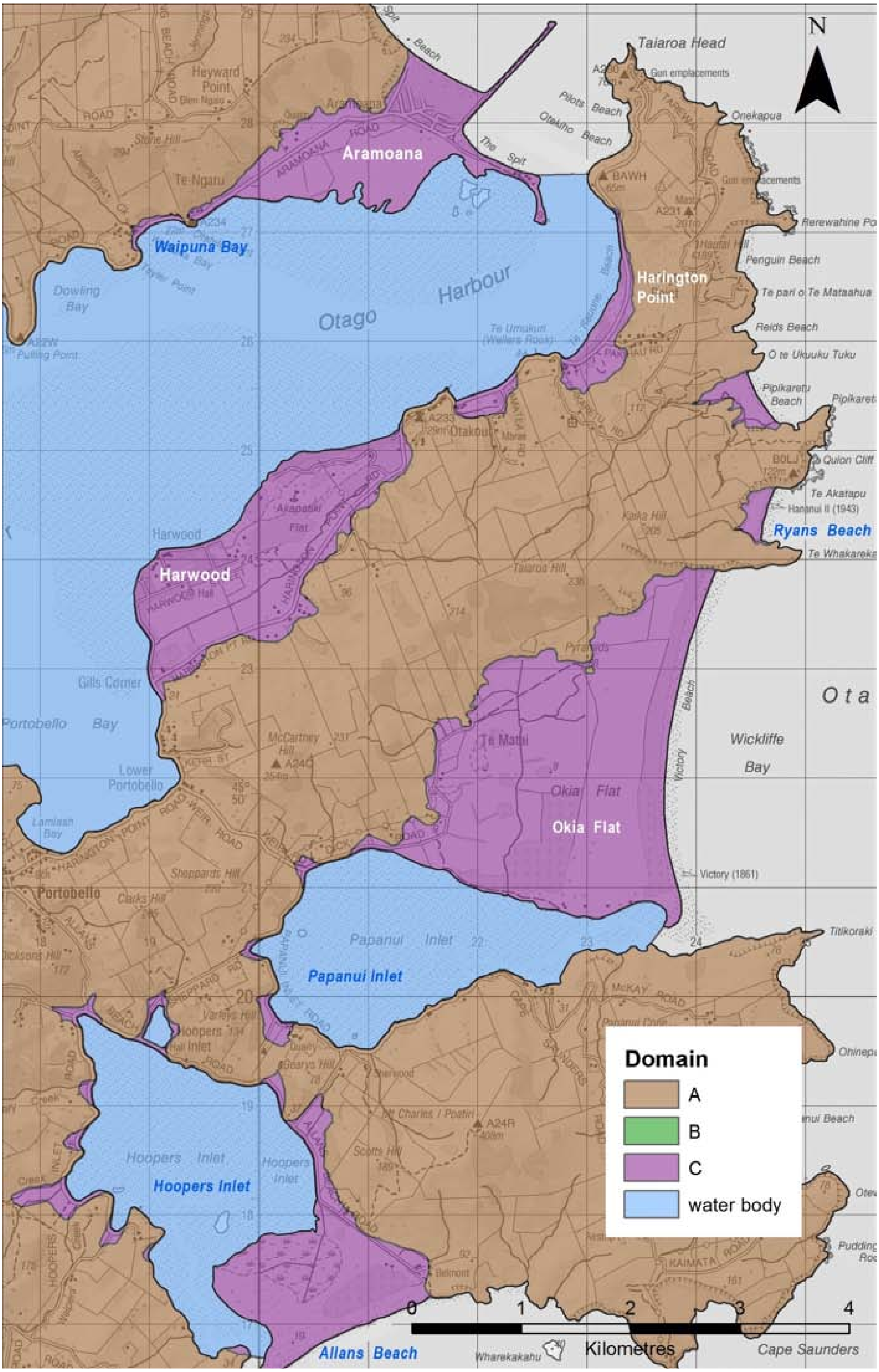

Figure A3.3c Location map for liquefaction susceptibility domains around the northeastern parts of Otago Harbour and Otago Peninsula.

On the eastern side of the peninsula at Ocean Grove, the low-lying margins of the Tomahawk Lagoons, and their enclosing sand dune barrier, were mapped as Domain C (Figure A3.1a). In many places the dunes are more than 10 m high. Where they abut hill slopes either side of the valleys occupied by the lagoons, the Domain C/A boundary was positioned at 15 m a.s.l. Around the perimeter of the lagoons, the boundary was positioned at 6 m a.s.l. The reasoning was that the lagoons have received relatively little sediment infill since culmination of sea level rise, probably reflecting the small size of the catchments that feed them.

At Smaills Beach the broad low-lying valley of Tomahawk Creek, and its enclosing dune barrier, were mapped as Domain C (Figure A3.1a). As this creek has a relatively large catchment, and thus has had a greater sediment accumulation since culmination of the post-glacial sea level rise, the Domain C/A boundary was positioned at 15 m a.s.l., both where the dunes abut the valley sides, and across the valley floor farther upstream.

At Boulder Beach and Sandfly Bay, the bay heads have extensive accumulations of dune sand, and are mapped as Domain C (Figure A3.3d). The inland boundary was placed at 20 m a.s.l., due to the heights to which the dunes mantle the valley sides.

Coastal flats around Hoopers Inlet, and the sand dune spit forming Allans Beach, were mapped as Domain C (Figure A3.3c). Around the inlet flats, the boundary was positioned at 4 m a.s.l., but in the east, the boundary position was raised to 10 m a.s.l. along the northern margin of the Allans Beach dunefield. On the western and southern shore of Hoopers Inlet, south of Battery Creek, lidar coverage is patchy, and mapping of the Domain C/A boundary relied mainly on interpretation of the 1:50,000 scale topographic map, satellite photography, and Google Earth StreetView along Hoopers Inlet Road.

Around Papanui Inlet, there are localised salt marshes that, along with the extensive Okia Flat dunefield, were mapped as Domain C (Figure A3.3c). The Domain C/A margin was placed at 4 m a.s.l. at the back of the salt marshes, but its position was lifted to 10 m a.s.l. where the dunefield abuts the hill slopes.

At Ryans Beach and Pipikaretu Beach, the bayhead was mapped as Domain C (Figure A3.3c). Along the western and northern margins of Ryans Beach, where the dunes are relatively high, the Domain C/A boundary was placed at 20 m a.s.l.

A3.3.3 Aramoana to Purakaunui

Kaikai Beach and Whareakeake (Murdering Beach) have well defined post-glacial sea cliffs, in front of which are dunefields. These dunefields were mapped as Domain C (Figure A3.3e), with the inland boundary positioned at 10 m a.s.l.

Long Beach lies at the seaward edge of a broad infilled valley enclosed by a sand dune barrier (Figure A3.3e). The post-glacial sea cliff is sharply defined close to the present coast, but otherwise the valley slopes merge with the infilled valley floor, suggesting that the dune barrier formed very shortly after culmination of post-glacial sea level rise, isolating the former inlet wave action. The Domain C/A boundary was placed at 6 m a.s.l. around the perimeter of the valley, and was raised to 10 m a.s.l. where sand dunes fringe the foot of the sea cliff.

At Purakaunui, a prominent post-glacial sea cliff is present only near the western end of the inlet, indicating that, like Long Beach, the dune barrier enclosing the inlet formed shortly after culmination of post-glacial sea level rise. There is minimal fan development at the mouths of the streams draining into the inlet, suggesting that it has received minimal post-glacial sediment infill. One localised area of Domain C was mapped at the Bay Road foreshore reserve, and another in the lower reaches of the Purakaunui Creek valley, with its inland boundary positioned at 10 m a.s.l. The sand flats and dunefields north of Osborne were also classed as Domain C, with the domain boundary at 6 m a.s.l., rising to 10 m where dunes abut the former sea cliff (Figure A3.3e).

Figure A3.3d Location map for liquefaction susceptibility domains around the southeastern side of Otago Peninsula.

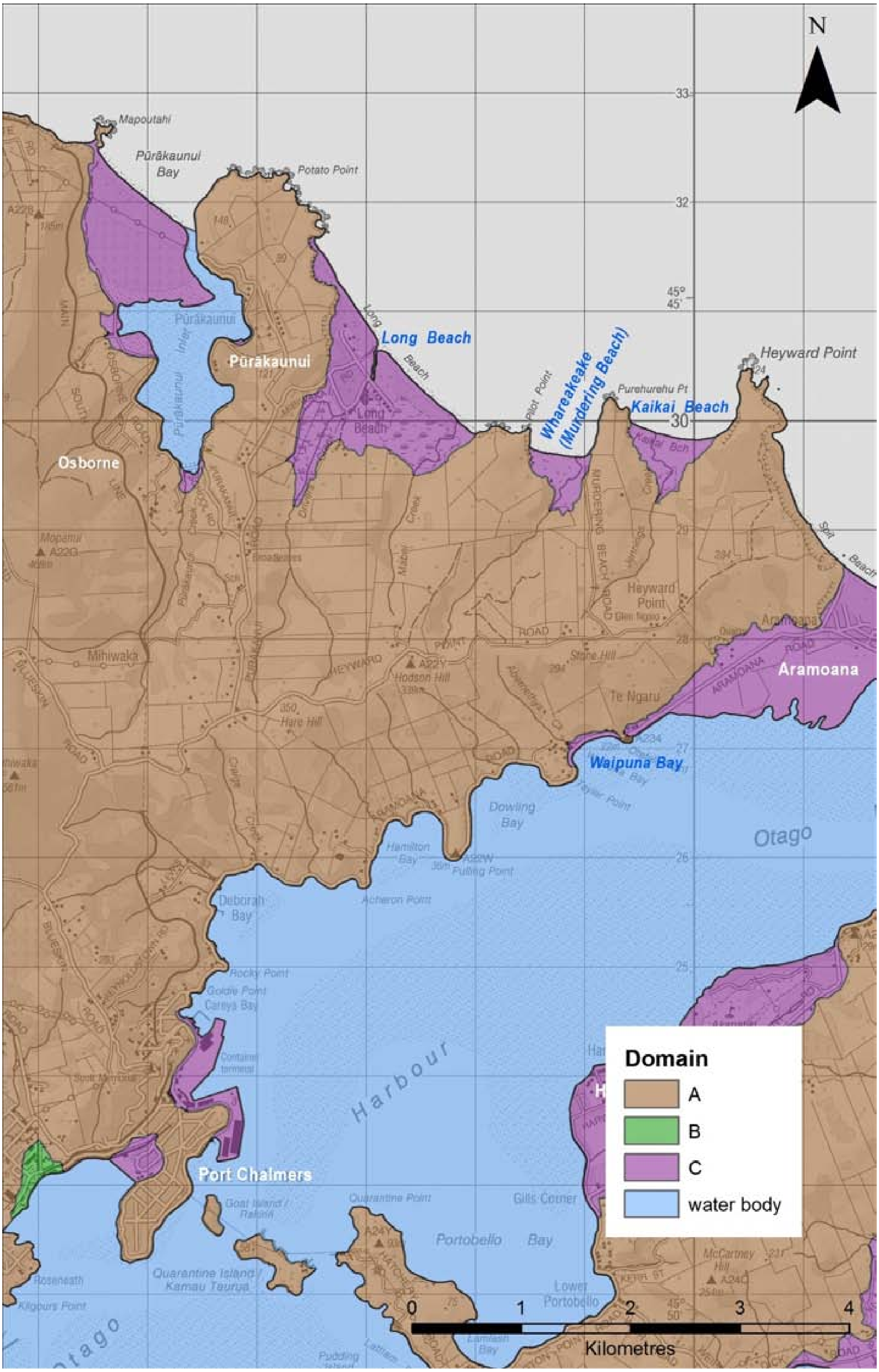

Figure A3.3e Location map for liquefaction susceptibility domains from Aramoana to Purakaunui.

A3.3.4 Blueskin Bay

The Waitati River has built a substantial fan into Blueskin Bay (Figure A3.3f). The river has a gravel bed and flows all the way to the inlet (i.e., it is not tidal). It is likely that this is a post-glacial fan-delta. The fan head is at about 15 m a.s.l., upstream of which the valley is of a uniform width. The broad fan downstream of the fan head was mapped as Domain C, and this domain was extended east around the head of Orokonui inlet, with the inland boundary positioned at 6 m a.s.l. This domain was also extended northeast of Waitati township, along the margin of Blueskin Bay, and includes the road and rail embankments and the lower reaches of minor fans draining to the bay.

At Evansdale, the infilled valley just south of the village appears to be a filled part of the bay, as it does not have a major stream flowing into it. This area and the lower reaches of Careys Creek are mapped as Domain C. The Domain C/A boundary was placed at 6 m a.s.l. rising to 10 m a.s.l. on marginal fans and up the Careys Creek valley.

The Warrington sand spit, and a localised sand flat at Doctors Point, were mapped as Domain C, with the inland boundary positioned at 6 m a.s.l.

A3.3.5 Karitane and Waikouaiti

Karitane and the Waikouaiti beach area have lidar coverage, but elsewhere on the lowland margins of the Waikouaiti River valley, mapping was based on information from soil maps, 1:50,000 scale topographic maps, satellite photography, and Google Earth StreetView.

Extensive remnants of a last interglacial marine terrace (see Section 5.4.1 of the main report) are preserved in the Karitane area. The terrace margins have been dissected by broad low-lying valleys that adjoin the coastal plain fringing the Waikouaiti River estuary. All the low-lying ground was mapped as Domain C (Figure A3.3g), based largely on the extents of Pomahaka, Clutha, Matau, Momona, Berwick and Koau soil groups mapped on the low-lying ground (growRuralDunedin). The area mapped as Domain C includes the swampy unnamed valley that drains the northern side of the Kilmog area (along which SH1 traverses), the Waikouaiti River valley floor upstream to the McGrath Road bridge, the post-glacial beach/dune complex seaward of Waikouaiti township, and low ground fringing the Waikouaiti estuary valley as upstream far as Koau soils are mapped, which includes the racecourse.

At the east-northeastern end of the Dunedin district are several tributary valleys draining to the Pleasant River estuary. The broad floors of these were mapped as Domain C (Figure 16 of main report), guided largely by the presence of the young soils groups mentioned above, as lidar coverage exists only close to the ocean coastline.

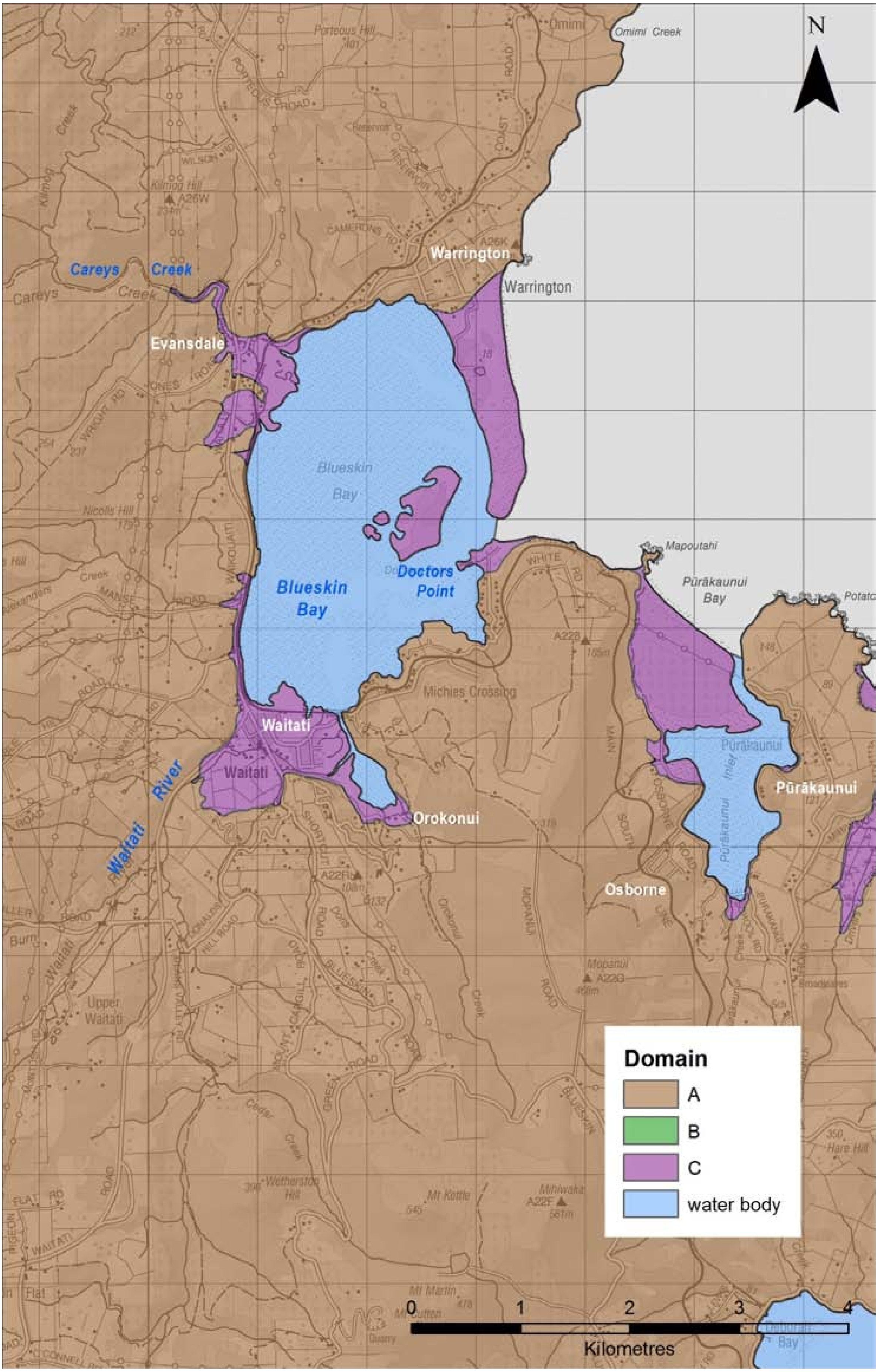

Figure A3.3f Location map for liquefaction susceptibility domains from Purakaunui to Warrington.

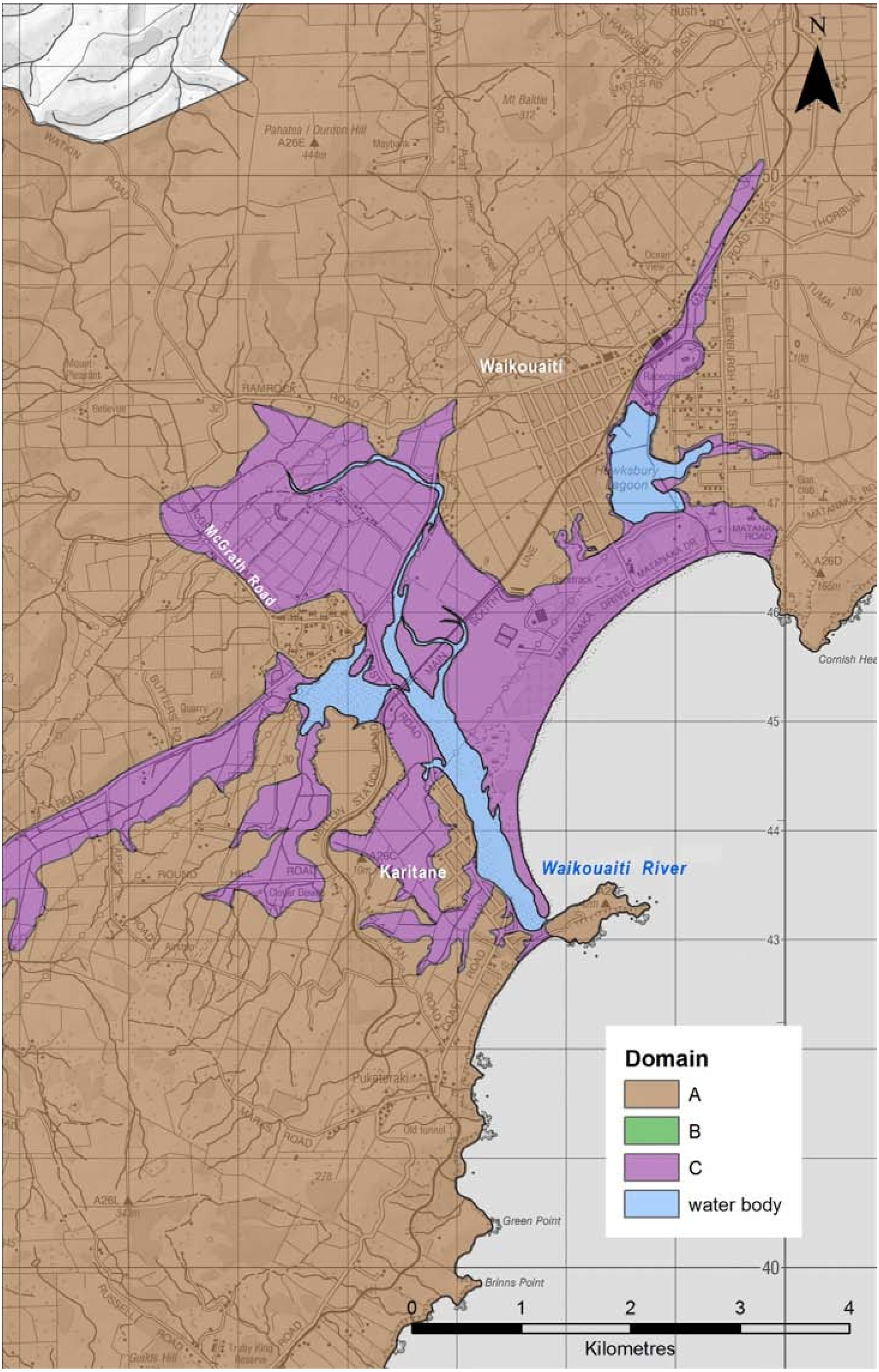

Figure A3.3g Location map for liquefaction susceptibility domains in the Waikouaiti area.

A3.4 APPENDIX 3 REFERENCES

Collins, B.W. 1950. Ground water in the Mosgiel District. Department of Scientific & Industrial Research, New Zealand Geological Survey, Water Resources Division, Hydrological Report No. 36, Christchurch.

All other references cited in Appendix 3 are listed in the reference section of the main report.

APPENDIX 4: DESCRIPTION OF THE GIS DATA SET

The GIS data are provided as an ArcGIS v10.0 file geodatabase:
GNS_Dunedin_liquefaction_study_6May2014

The file geodatabase consists of the polygon feature class: *liquefaction_domain_polygon*

The attribute fields of this feature class are listed below:

Field name	Data type	Field length	Content
Domain	Text	5 characters	A single letter code specifying the liquefaction susceptibility domain assigned to a polygon. Specific list of four values: A, B, C, or W
Description	Text	150 characters	A description of the general geological character of the designated domain. Specific list of three descriptive entries relating to each of domains A, B and C, as defined in Section 4.2.3 of the report. In addition, there is a descriptive entry water body, which is associated with the Domain attribute W.

The Coordinate System for the data is New Zealand Transverse Mercator, based on New Zealand Geodetic Datum 2000.

The boundaries between domain polygons are considered to have a positional accuracy of ± 50 m, related to the generalised topographic and photographic base information upon which the polygons are drawn. In addition, there is considerable geological uncertainty regarding the exact nature and extent of the subsurface sediments whose character defines the extents of Domain B and C. The mapped extents of each domain represent best estimates based on the interpretation of geological and gemorphological information, but the geological uncertainties are difficult to quantify from available data. The GIS map of liquefaction susceptibility domains is intended to provide only general guidance, and should not be used in isolation for any purpose that requires site-specific information.

Also provided is a layer file *liquefaction_domain_polygon.lyr* depicting how the data have been rendered on maps presented in this report.

The file geodatabase and layer file, along with a digital version of the report in PDF format, are provided on a computer disk inside the back cover of the printed report.

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