

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

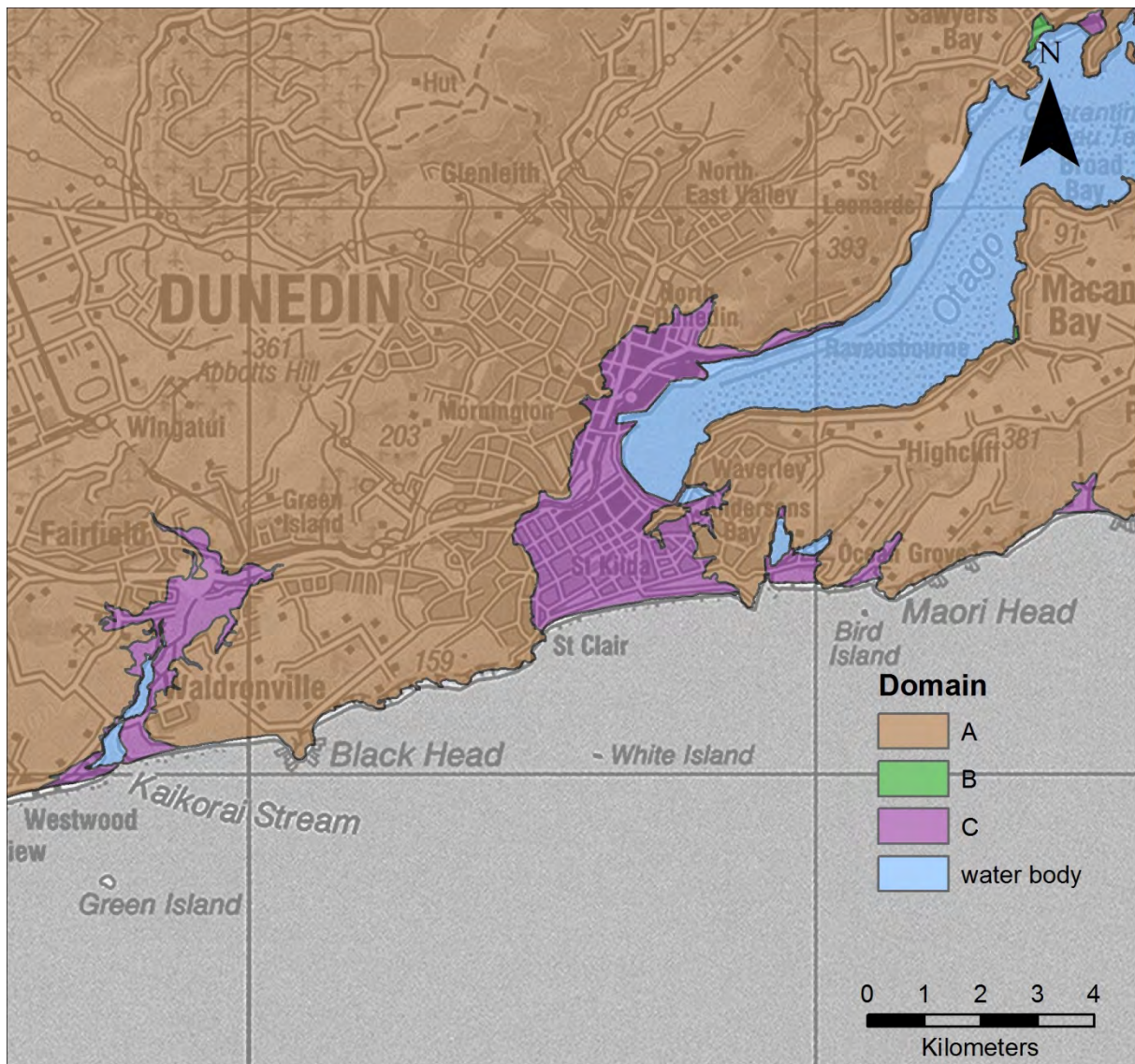


Figure 12 Map of liquefaction susceptibility domains for the Dunedin urban area.

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 be 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.

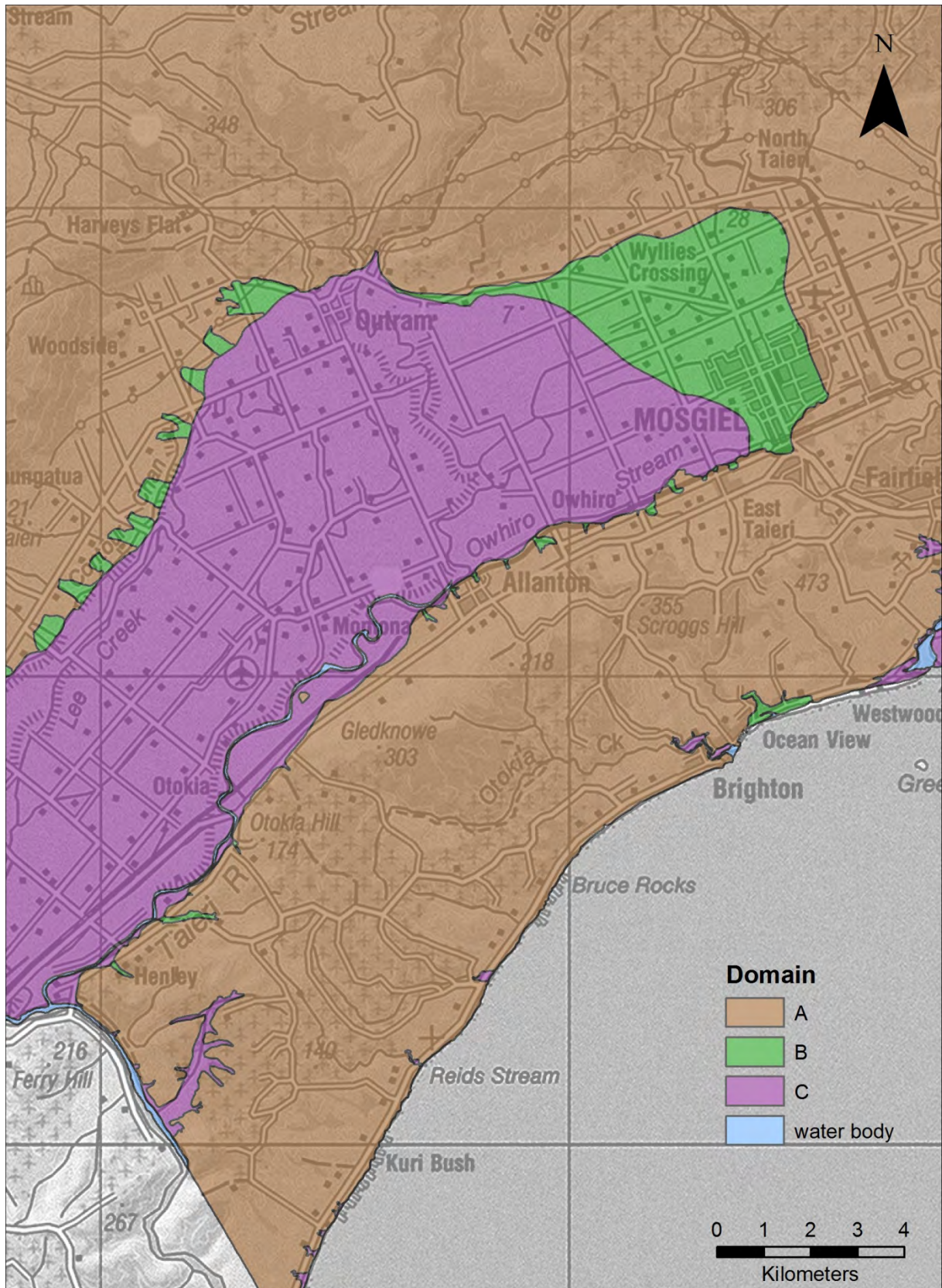


Figure 13 Map of liquefaction susceptibility domains for the northeastern part of the Taieri Plain.

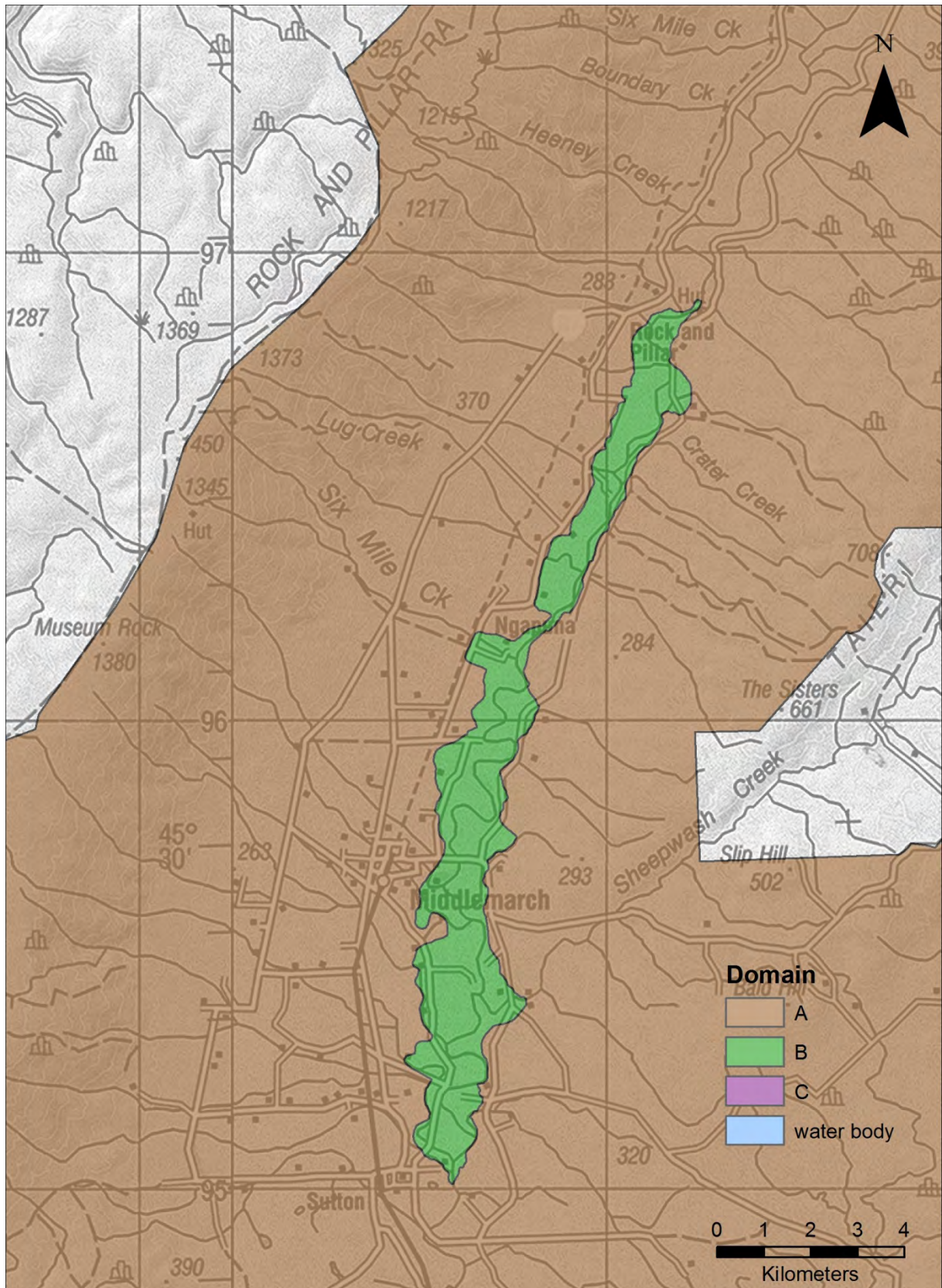


Figure 14 Map of liquefaction susceptibility domains for the Strath Taieri Plain.

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).

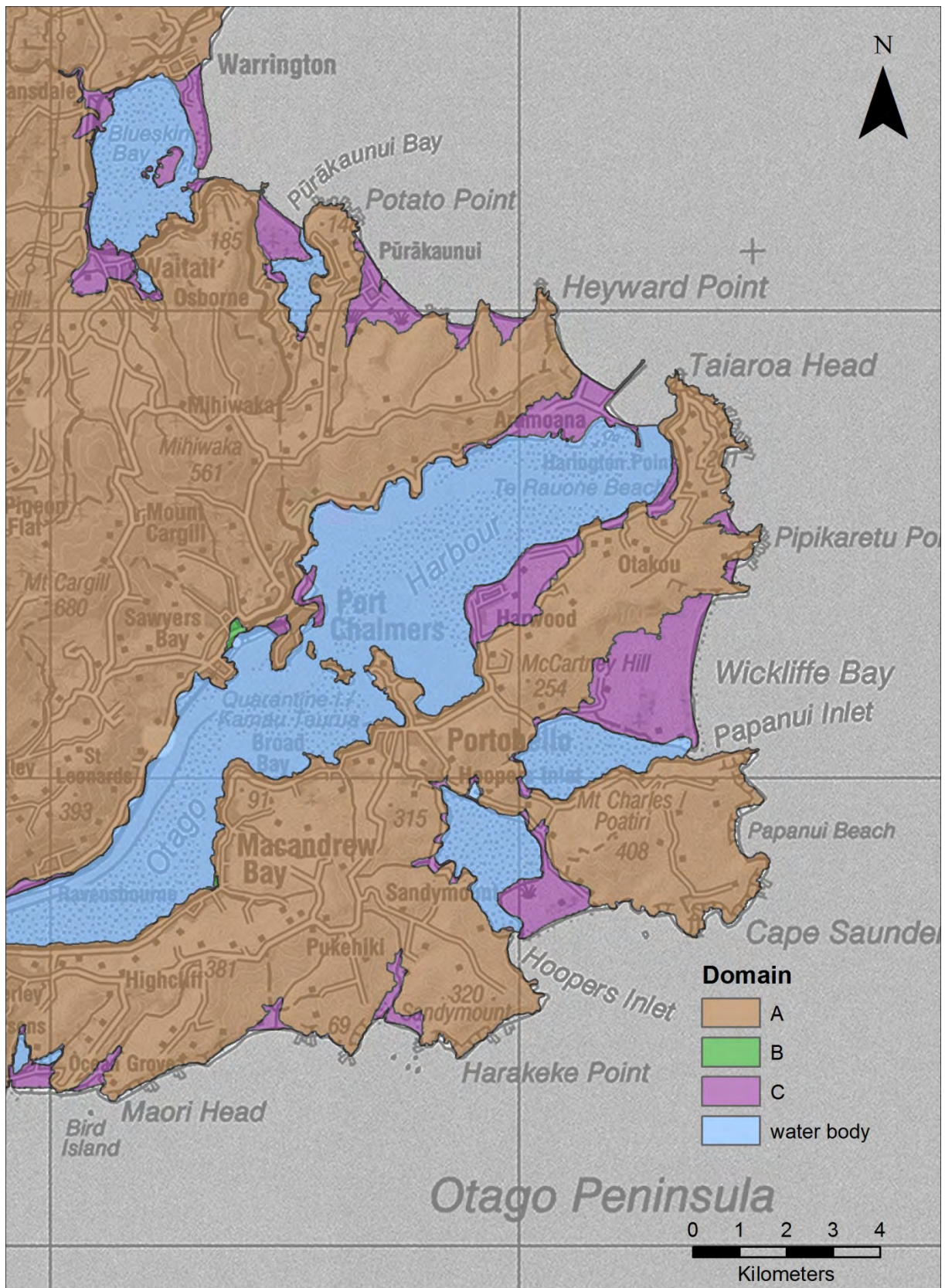


Figure 15 Map of liquefaction susceptibility domains from Otago Peninsula north to Warrington.

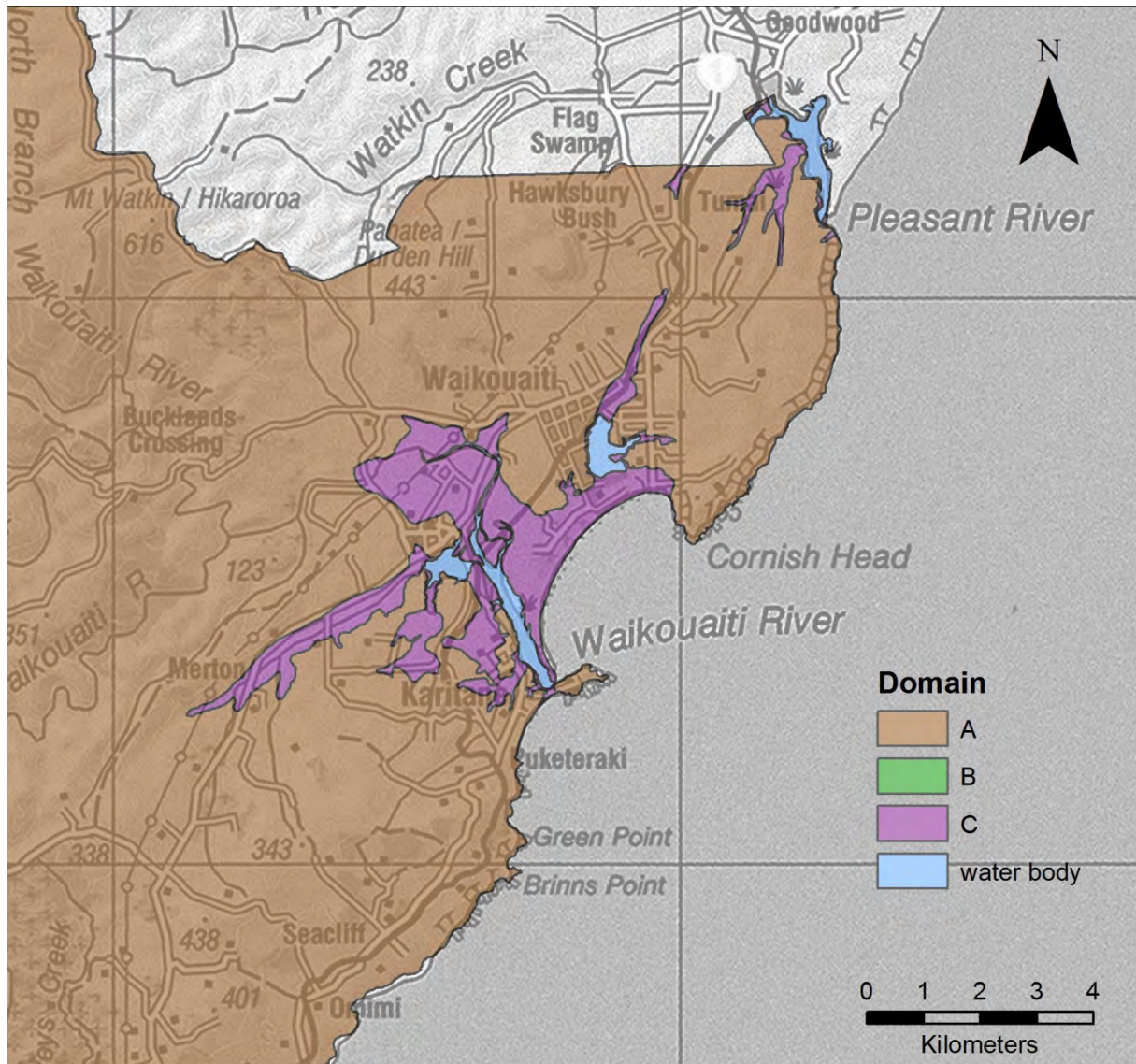


Figure 16 Map of liquefaction susceptibility domains near Karitane and Waikouaiti.

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	<p>Natural ground-related hazards, some examples being:</p> <ul style="list-style-type: none"> • 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	<p>The process of characterising the ground subsurface conditions at a particular locality. The work must be undertaken or overseen by a geotechnical professional.</p> <p>The work will include examination or measurements of the nature and properties of the ground-forming materials, by means that include:</p> <ul style="list-style-type: none"> • 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. <p>For house development projects there is a minimum scope of geotechnical assessment work required, as set out in NZS3604:2011 <i>Timber-framed buildings</i> http://www.standards.co.nz/default.htm</p>
Geotechnical professional	<p>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.</p>
Hypocentre	<p>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.</p>
Land zones	<p>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.</p>
Technical categories (TC)	<p>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.</p>

<p>Technical categories (TC) – continued</p>	<p>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.</p> <p>More information can be found at:</p> <ul style="list-style-type: none"> • http://cera.govt.nz/residential-green-zone-technical-categories#factsheets • http://cera.govt.nz/residential-green-zone-technical-categories <p>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.</p>
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APPENDIX 2: PREVIOUS HAZARD EVALUATION MAPS

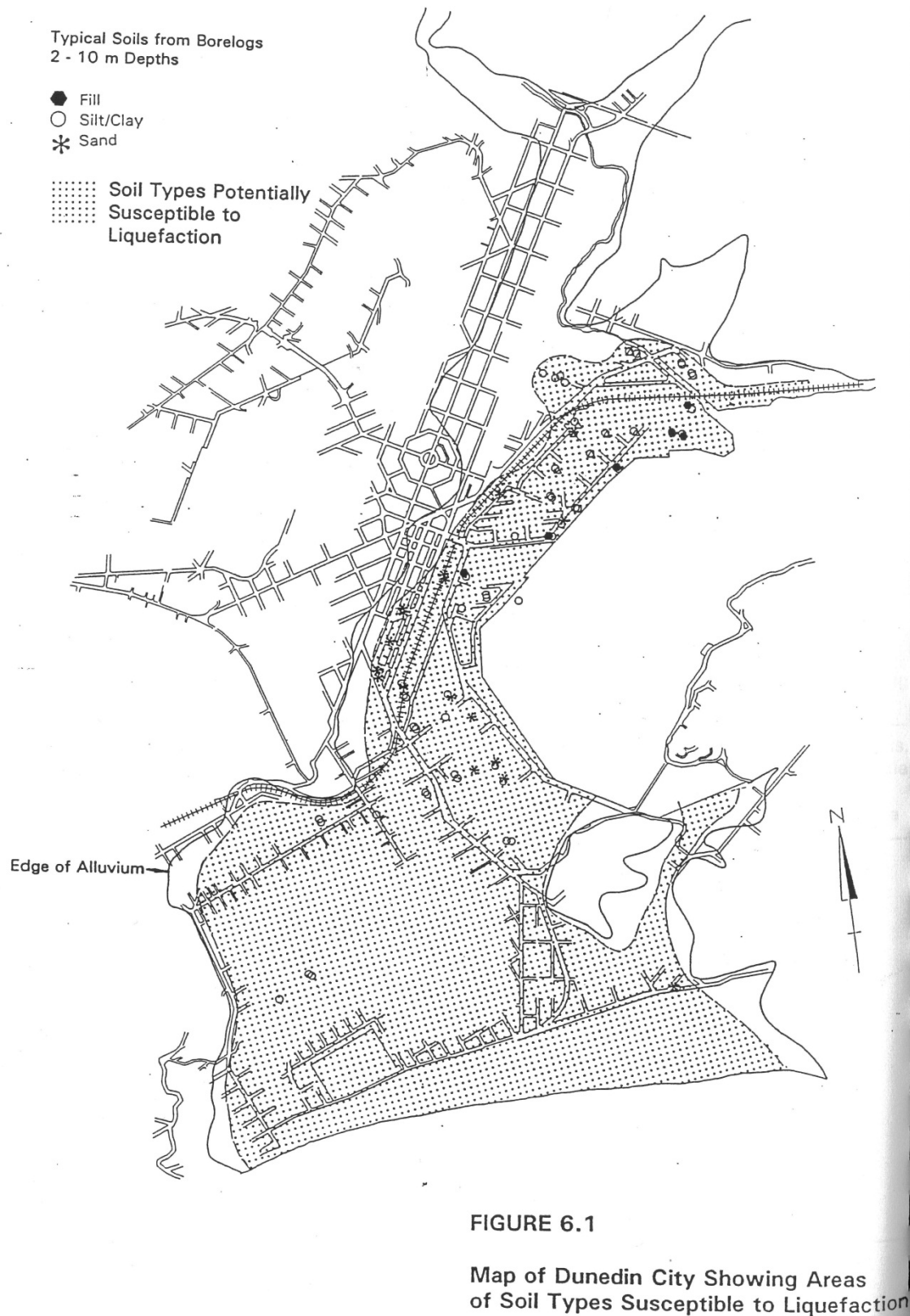


Figure A2.1 Liquefaction-susceptible soils, central Dunedin city (McCahon et al., 1993)

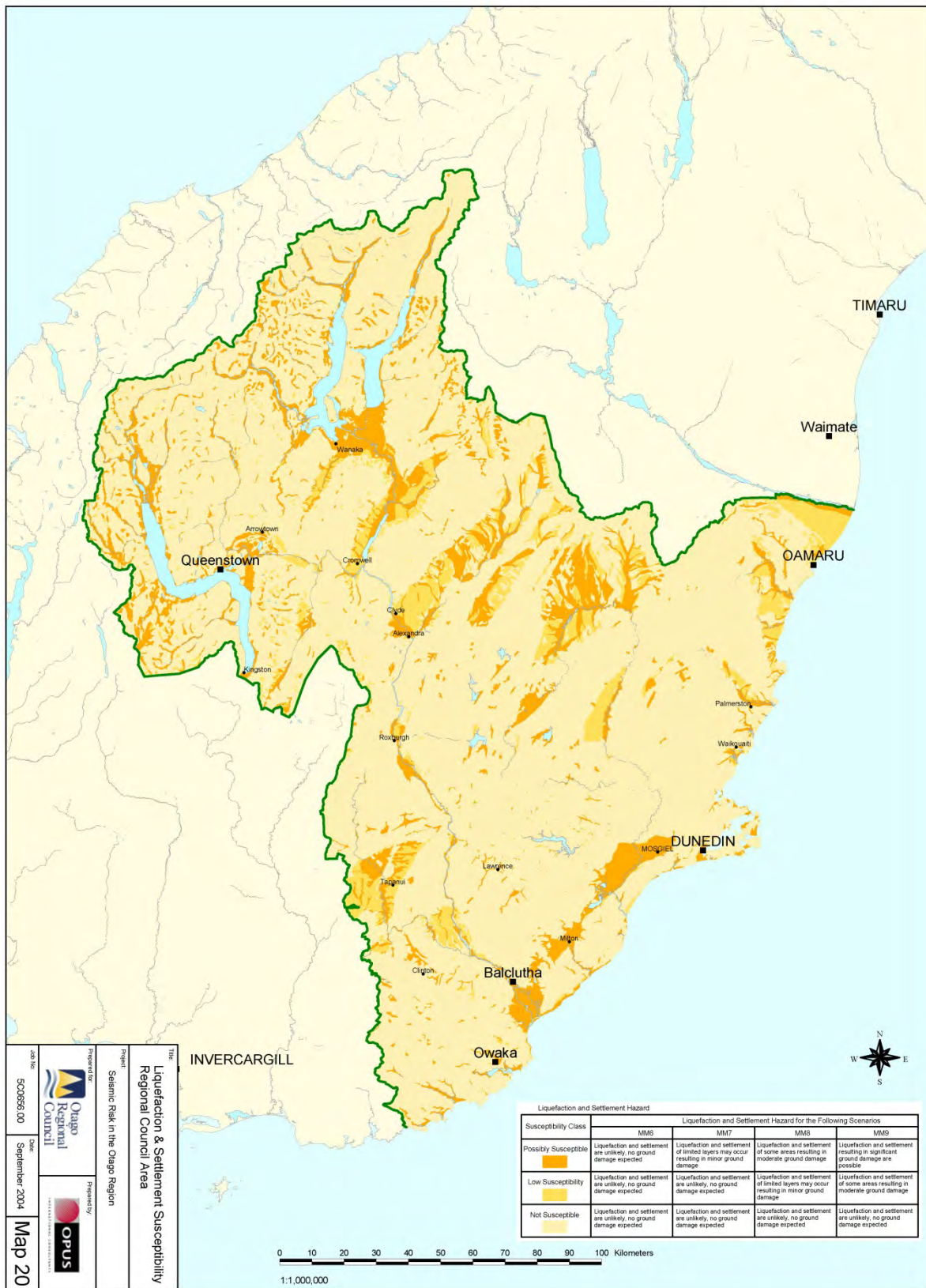


Figure A2.2 Liquefaction and settlement susceptibility, Otago region (Murashev & Davey 2005).

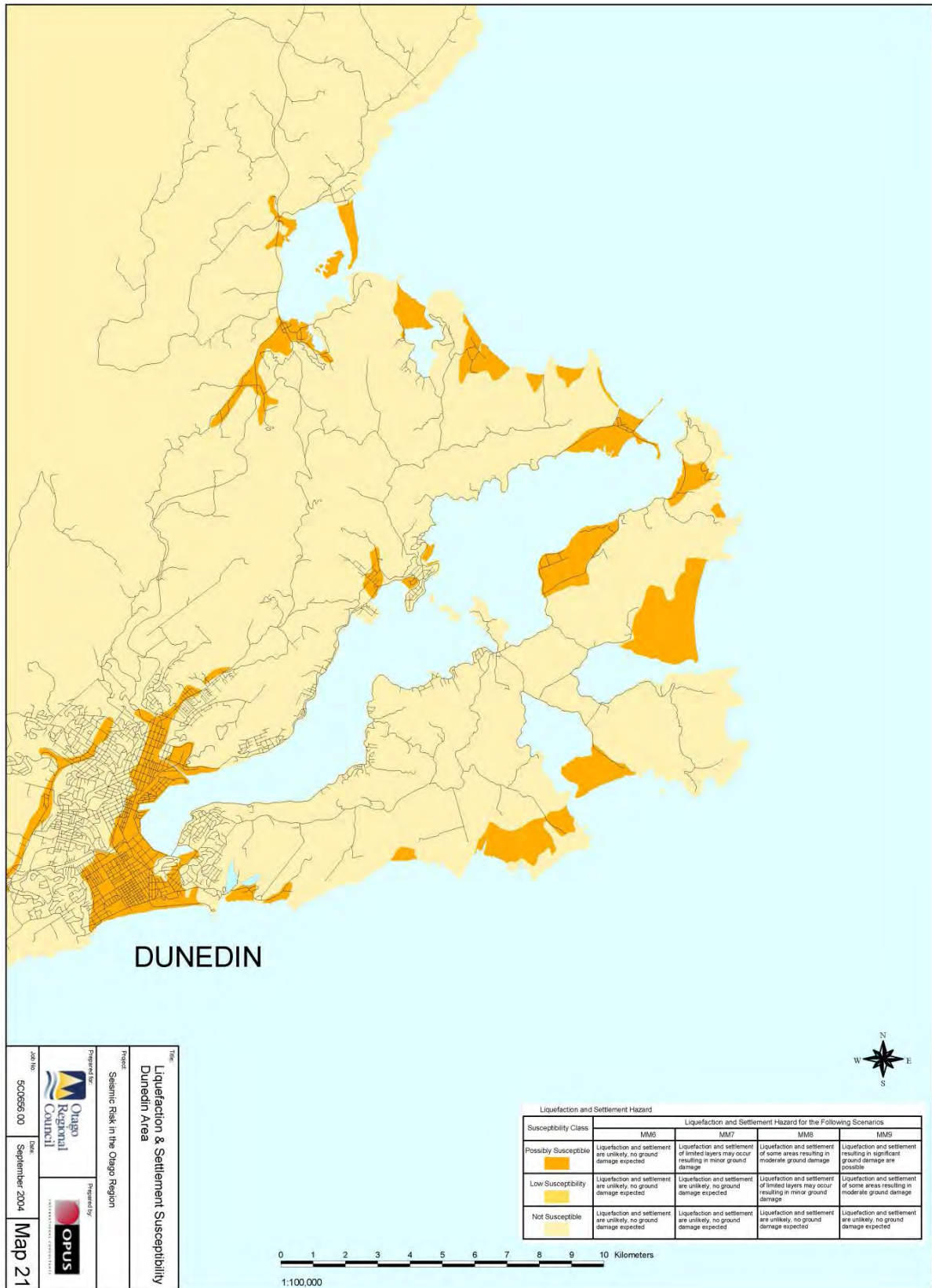


Figure A2.3 Liquefaction and settlement susceptibility, greater Dunedin area (Murashev & Davey 2005).

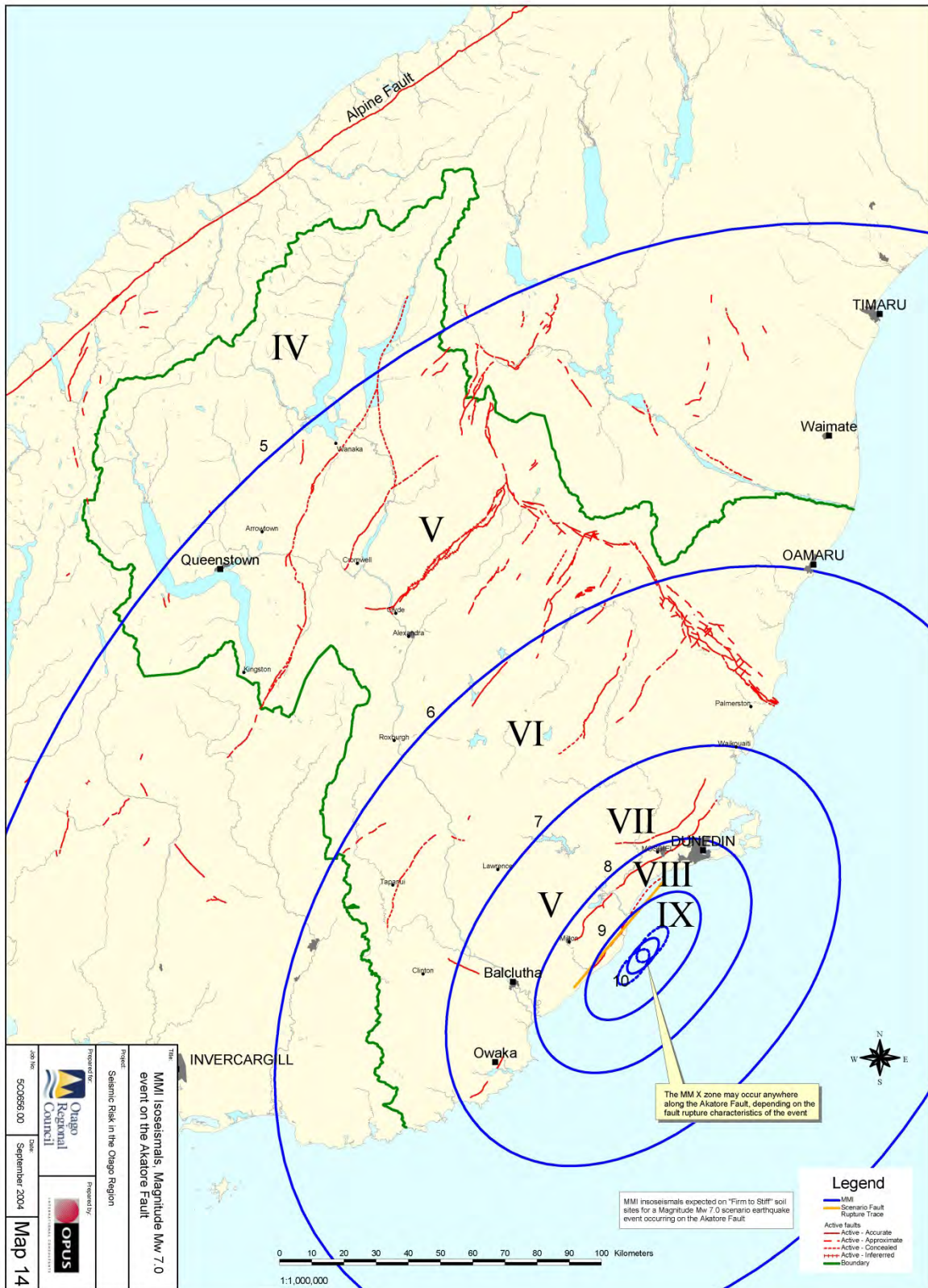


Figure A2.4 Estimated ground shaking, expressed in Modified Mercalli intensity classes, for a magnitude 7 earthquake centred on the Akatore Fault (Murashev & Davey 2005). Intensities of VII and VIII would be expected in coastal sectors of much of the Dunedin district, and would be likely to generate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

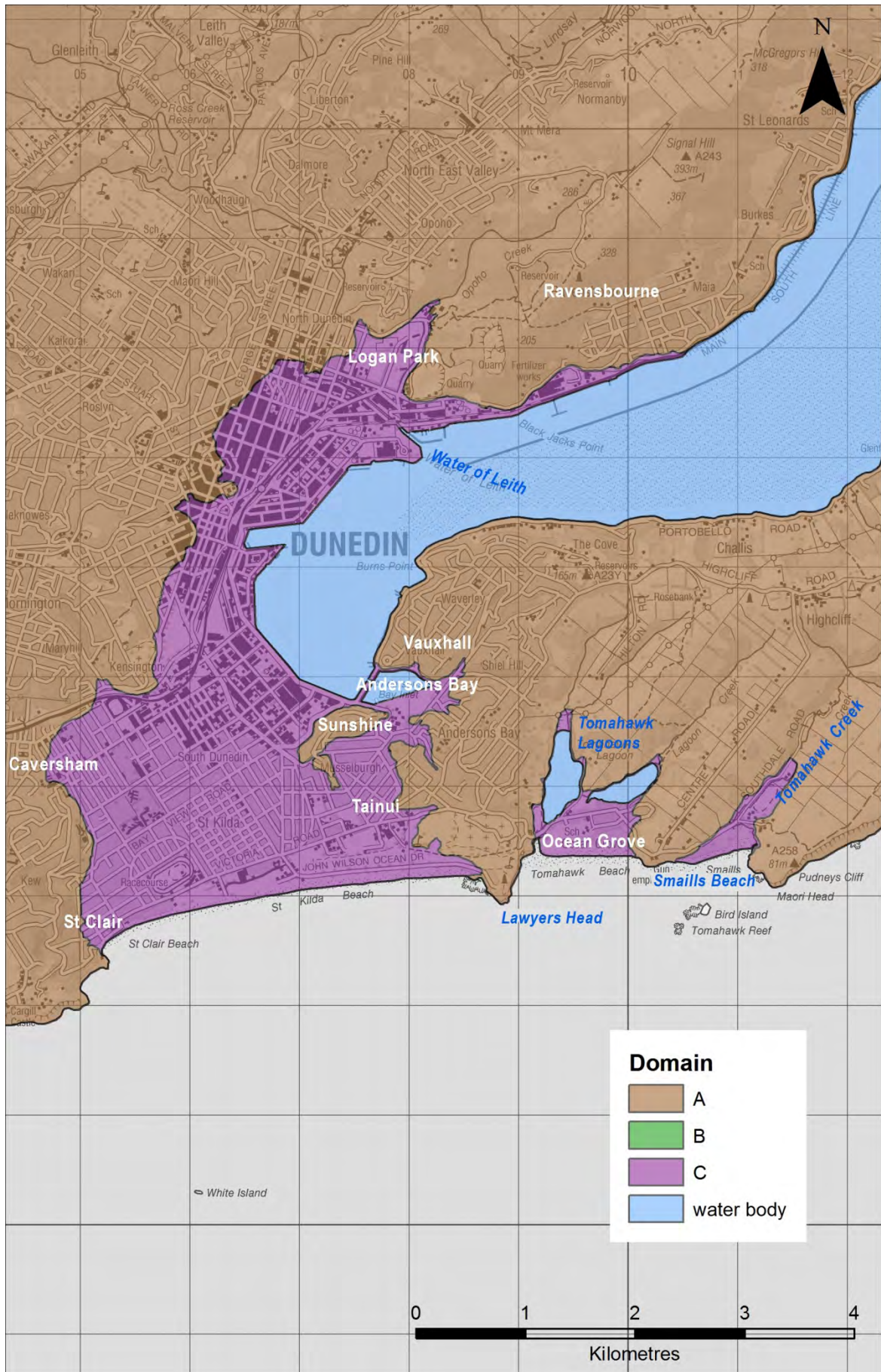


Figure A3.1a Location map for liquefaction susceptibility domains in the Dunedin urban area.

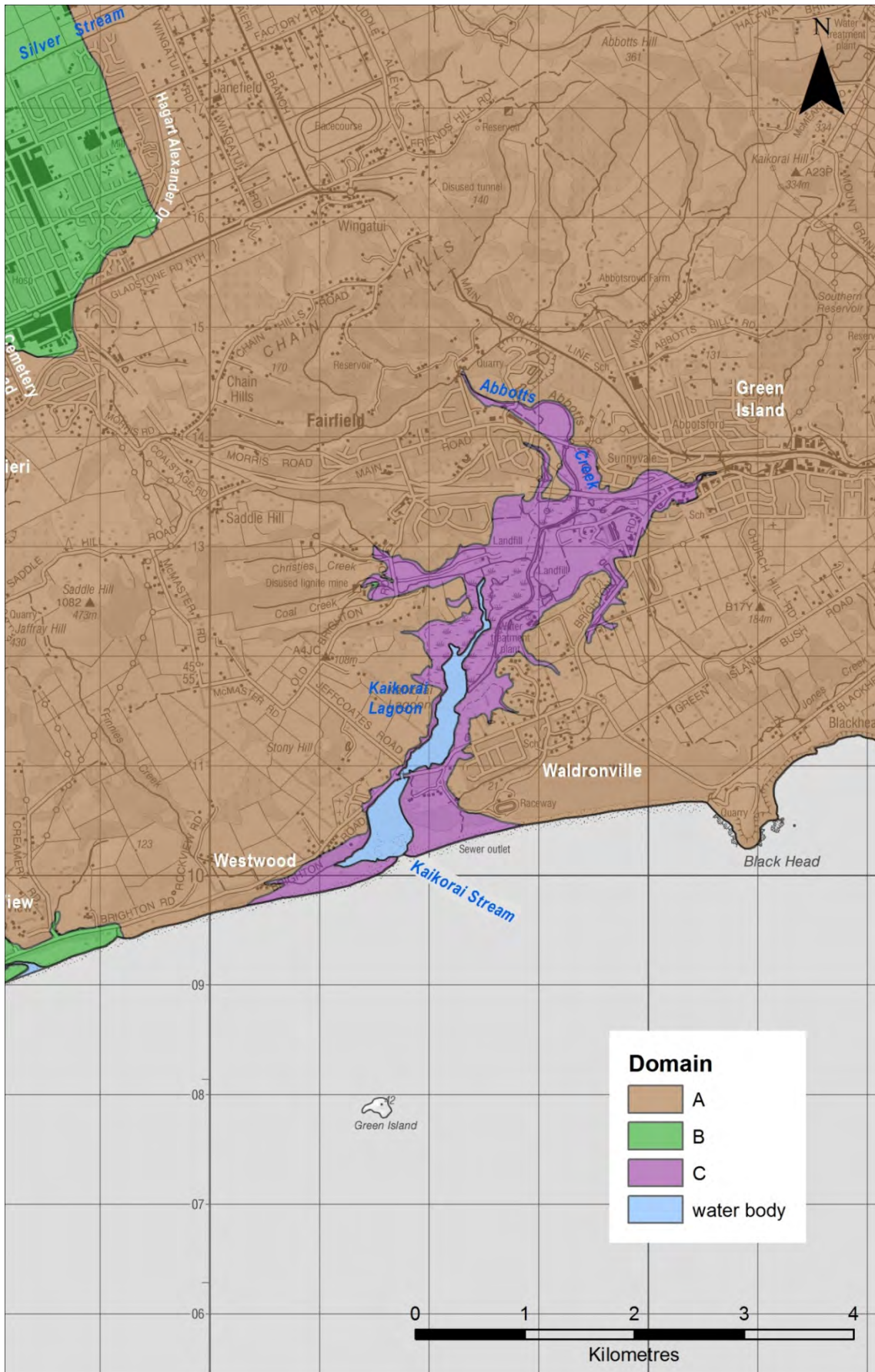


Figure A3.1b Location map for liquefaction susceptibility domains in the Kaikōrai Lagoon area.

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.

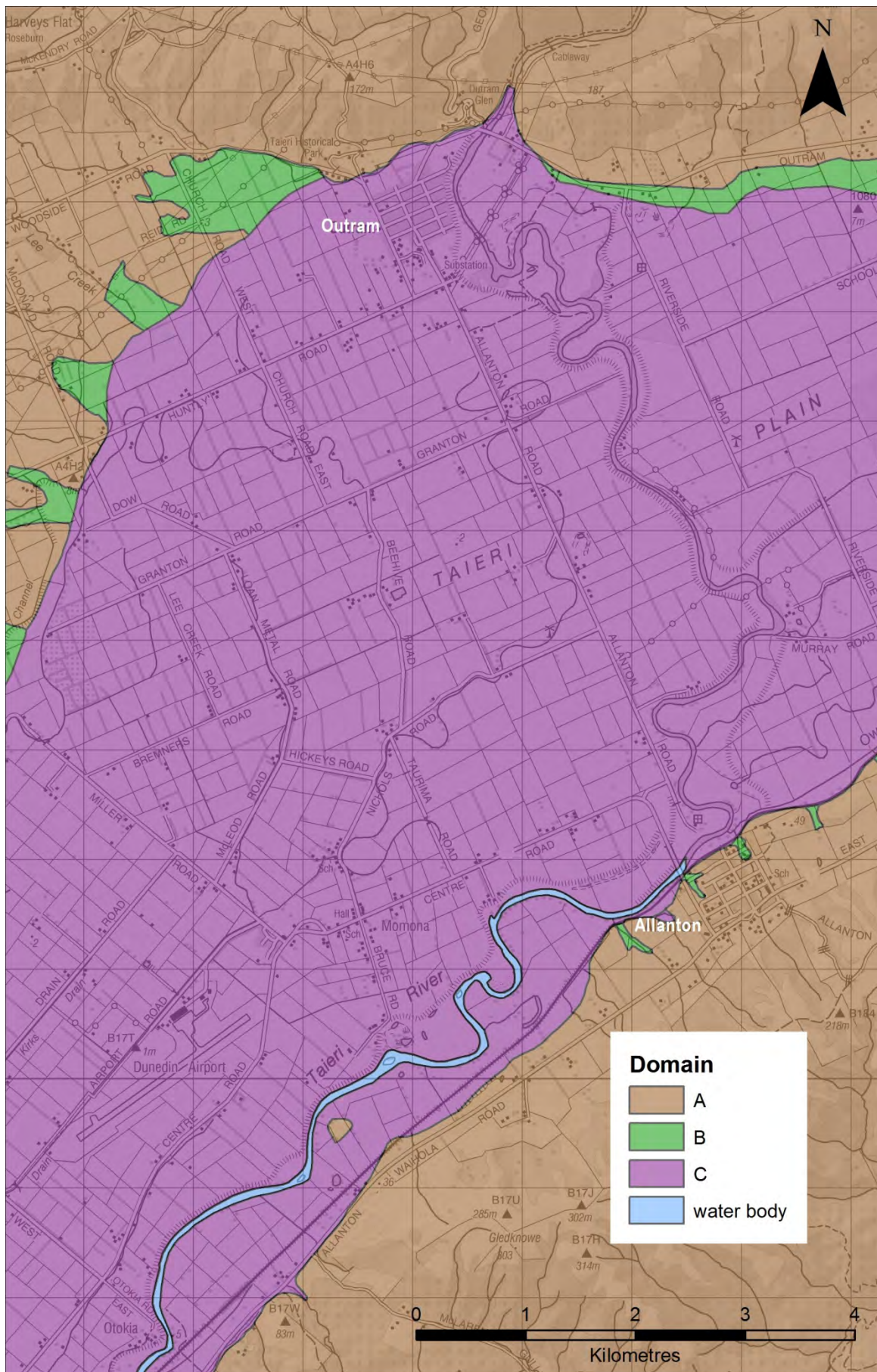


Figure A3.2a Location map for liquefaction susceptibility domains in the central part of the Taieri Plain.

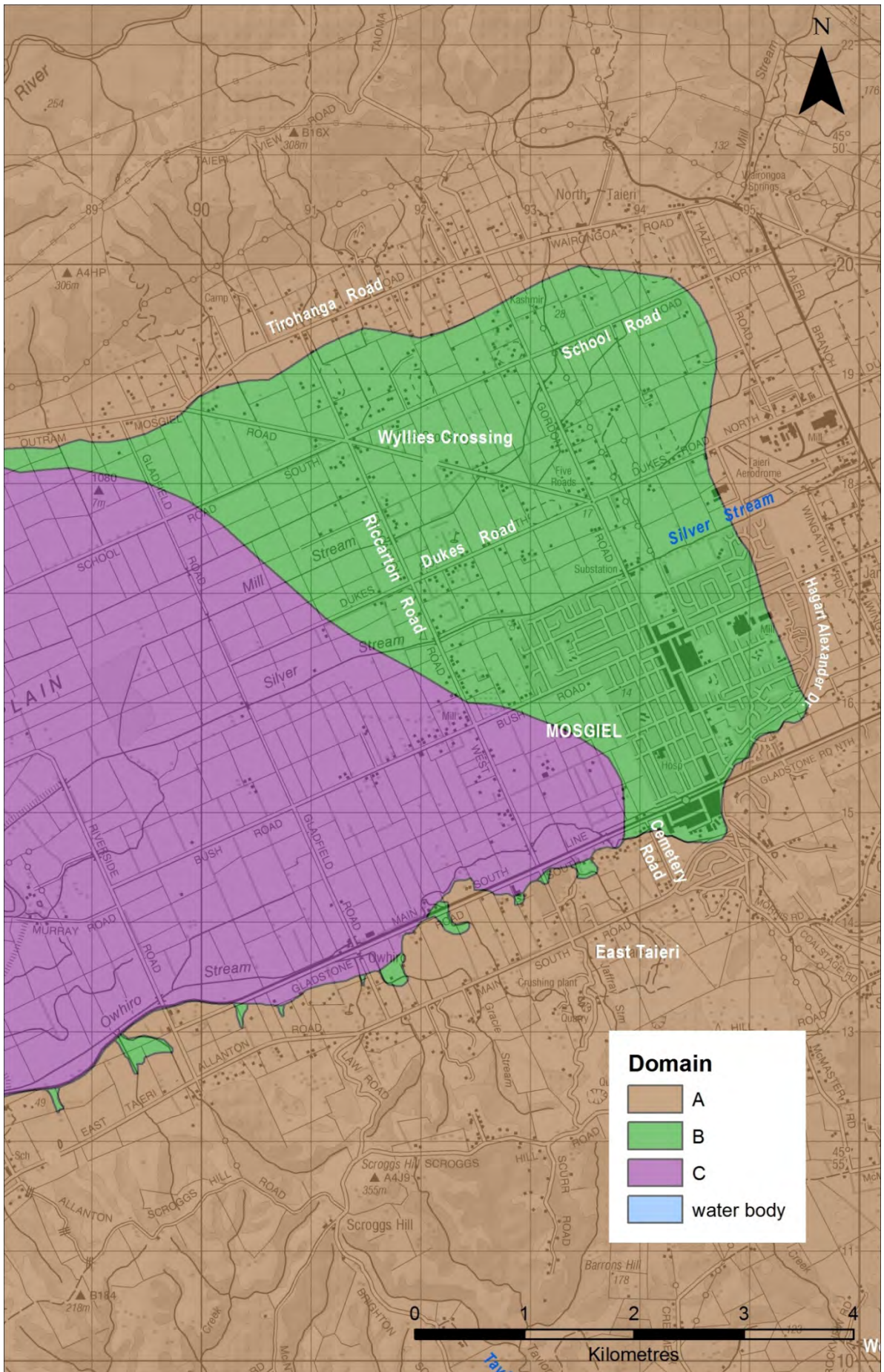


Figure A3.2b Location map for liquefaction susceptibility domains on the northeastern part of the Taieri Plain.

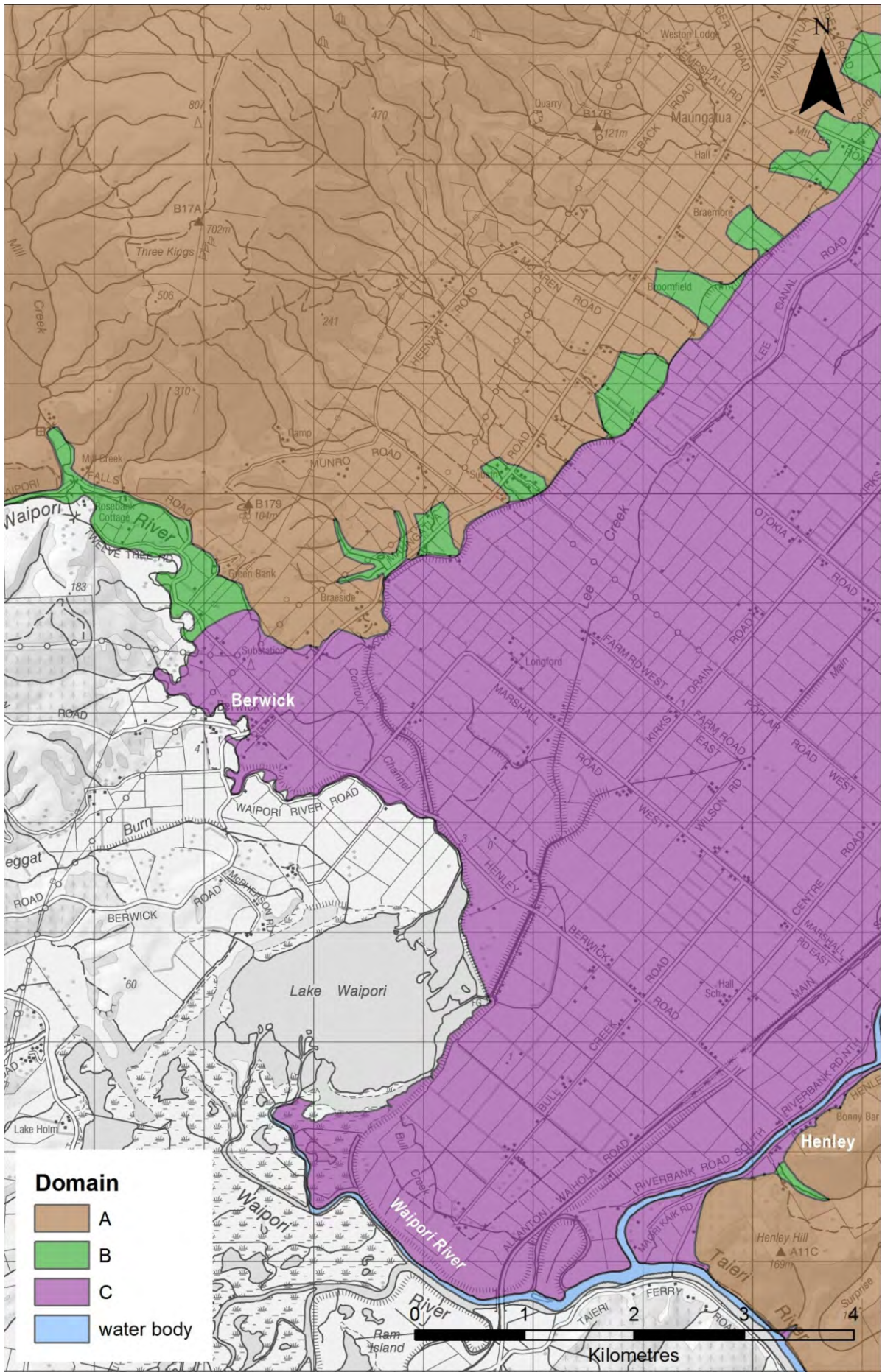


Figure A3.2c Location map for liquefaction susceptibility domains in the southwestern part of the Taieri Plain.

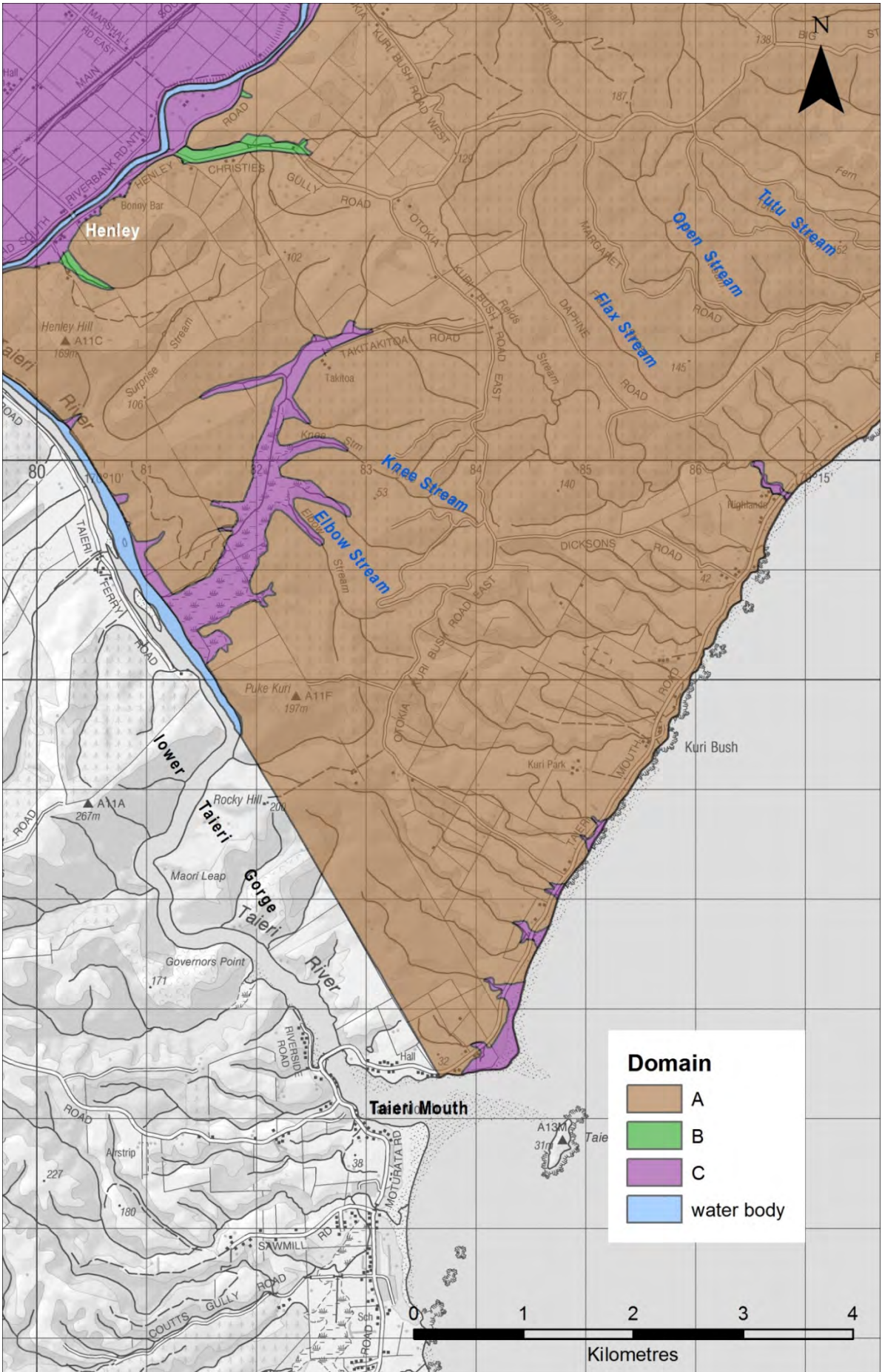


Figure A3.2d Location map for liquefaction susceptibility domains in the lower Taieri Gorge.

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 grain size. 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

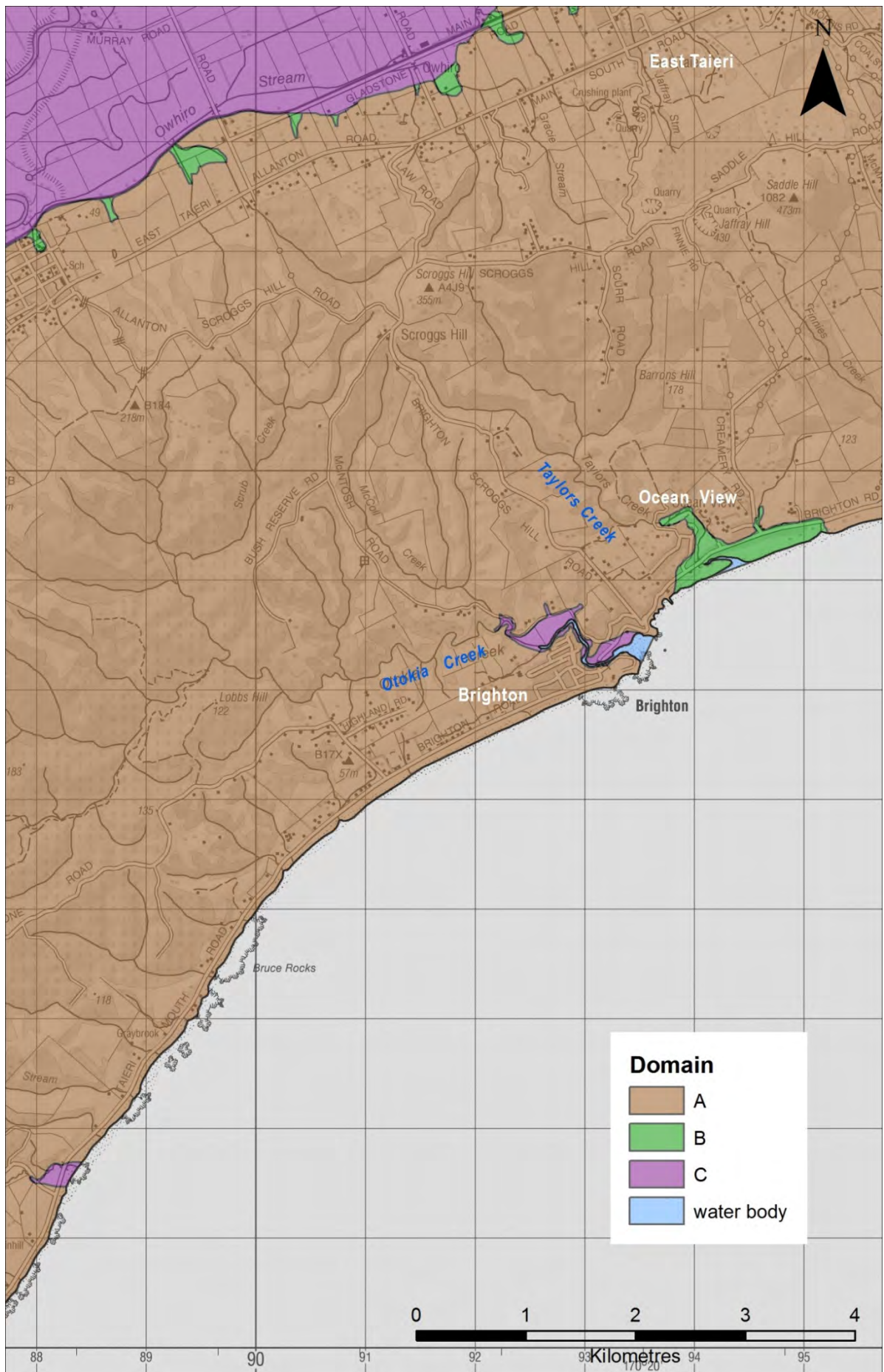


Figure A3.3a Location map for liquefaction susceptibility domains along the coast in the Brighton area.

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 coastal 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.

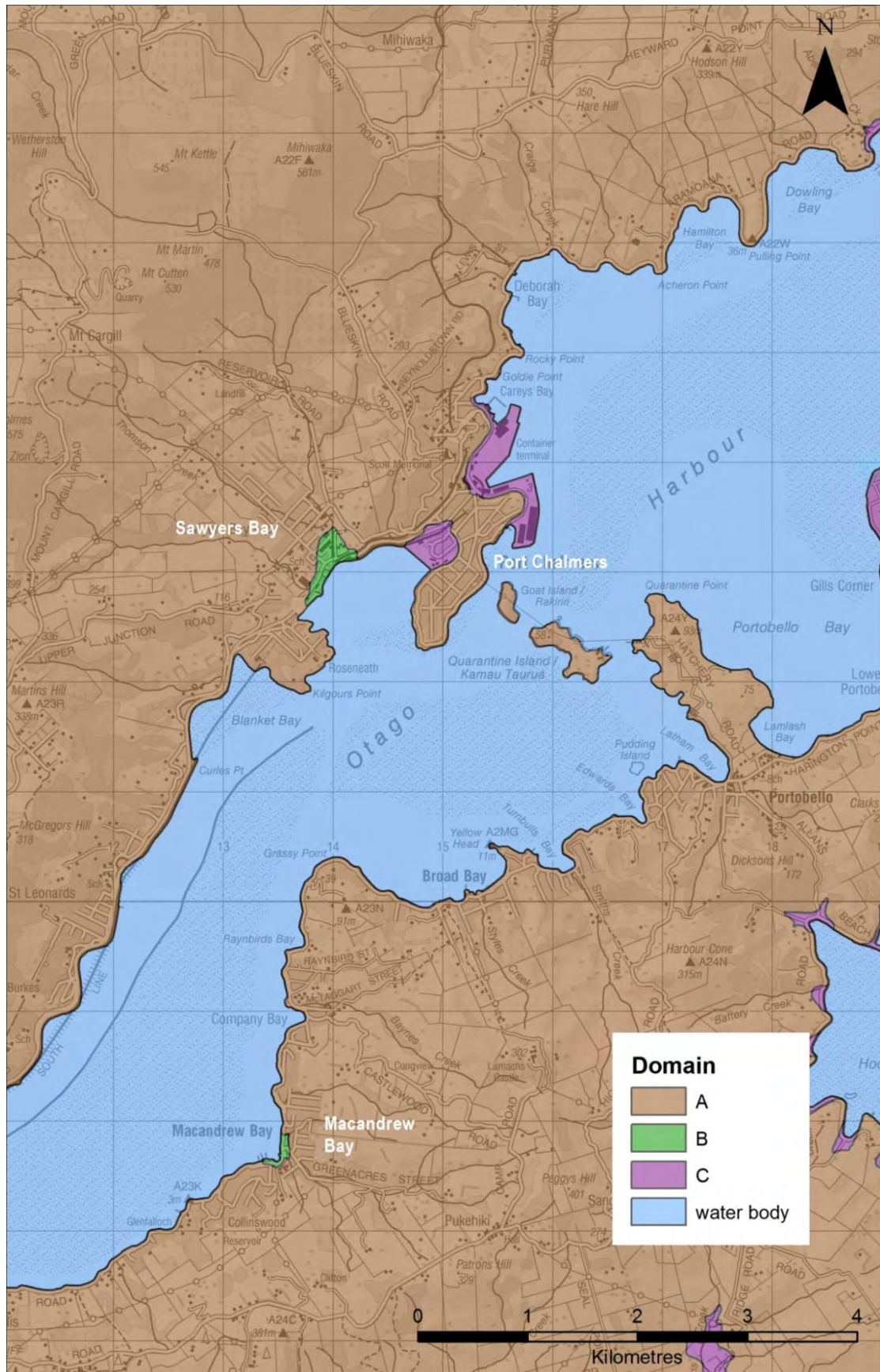


Figure A3.3b Location map for liquefaction susceptibility domains around the middle reaches of Otago Harbour.

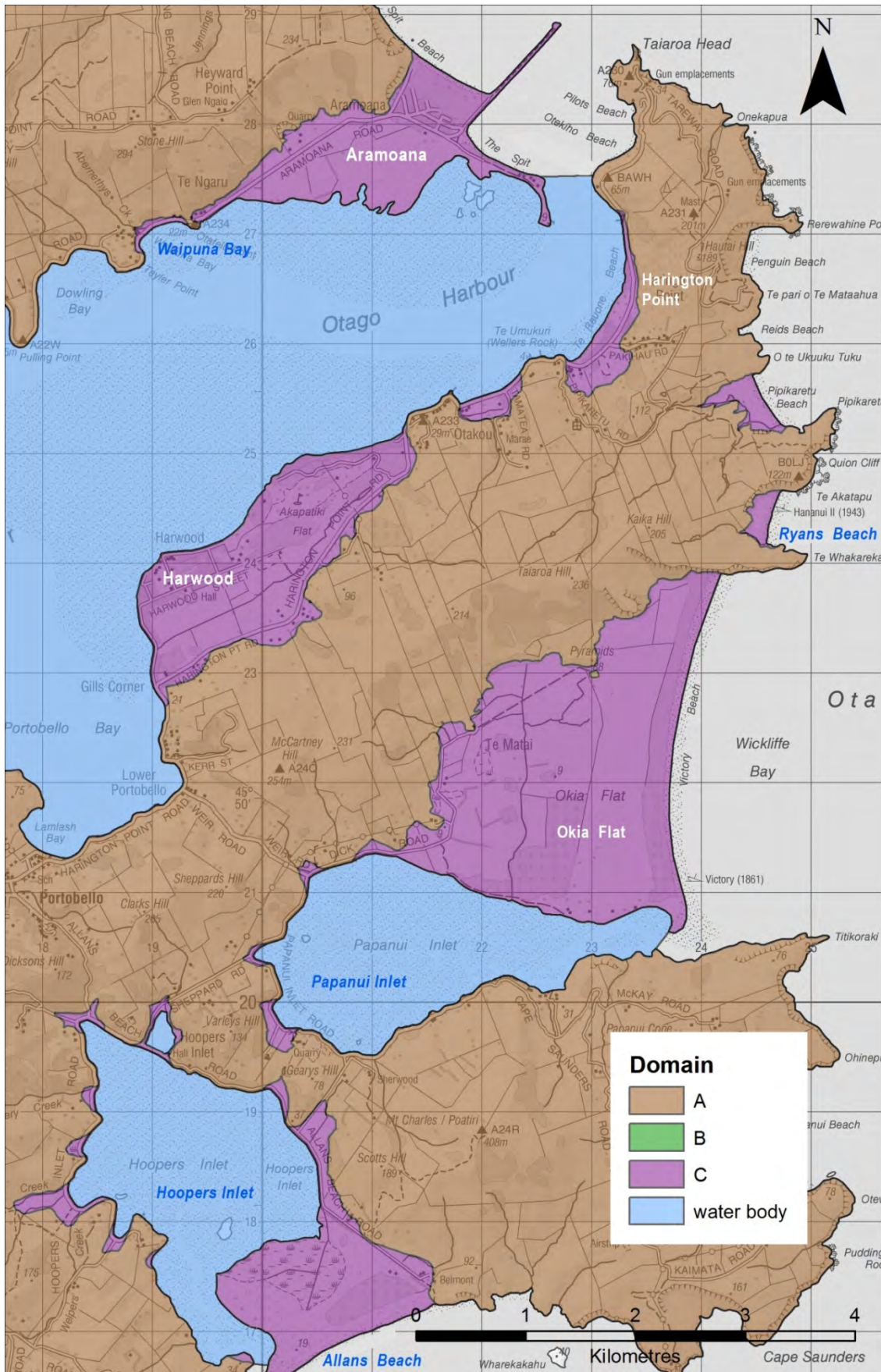


Figure A3.3c Location map for liquefaction susceptibility domains around the northeastern parts of Otago Harbour and Otago Peninsula.

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 Smalls 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).

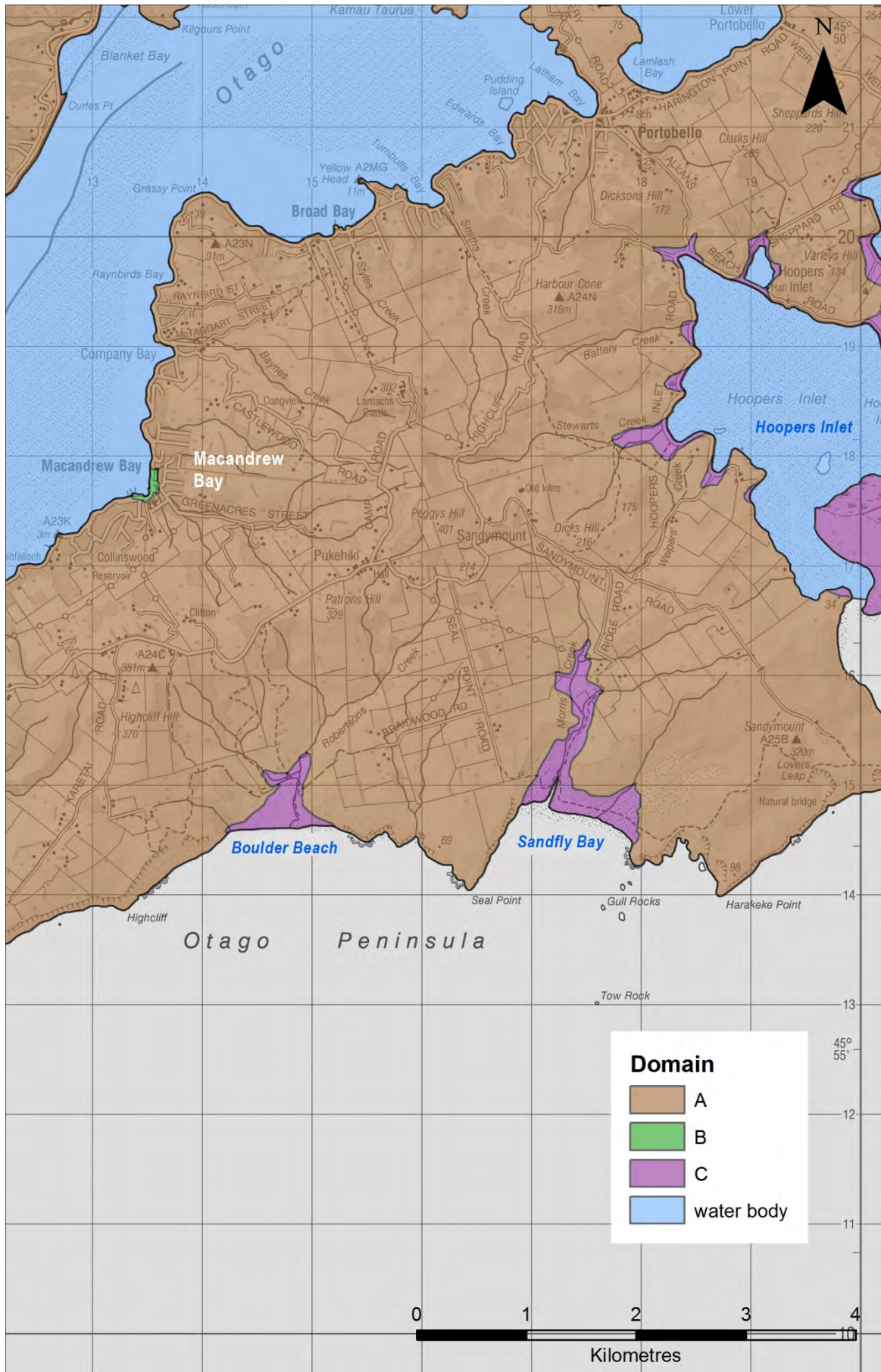


Figure A3.3d Location map for liquefaction susceptibility domains around the southeastern side of Otago Peninsula.

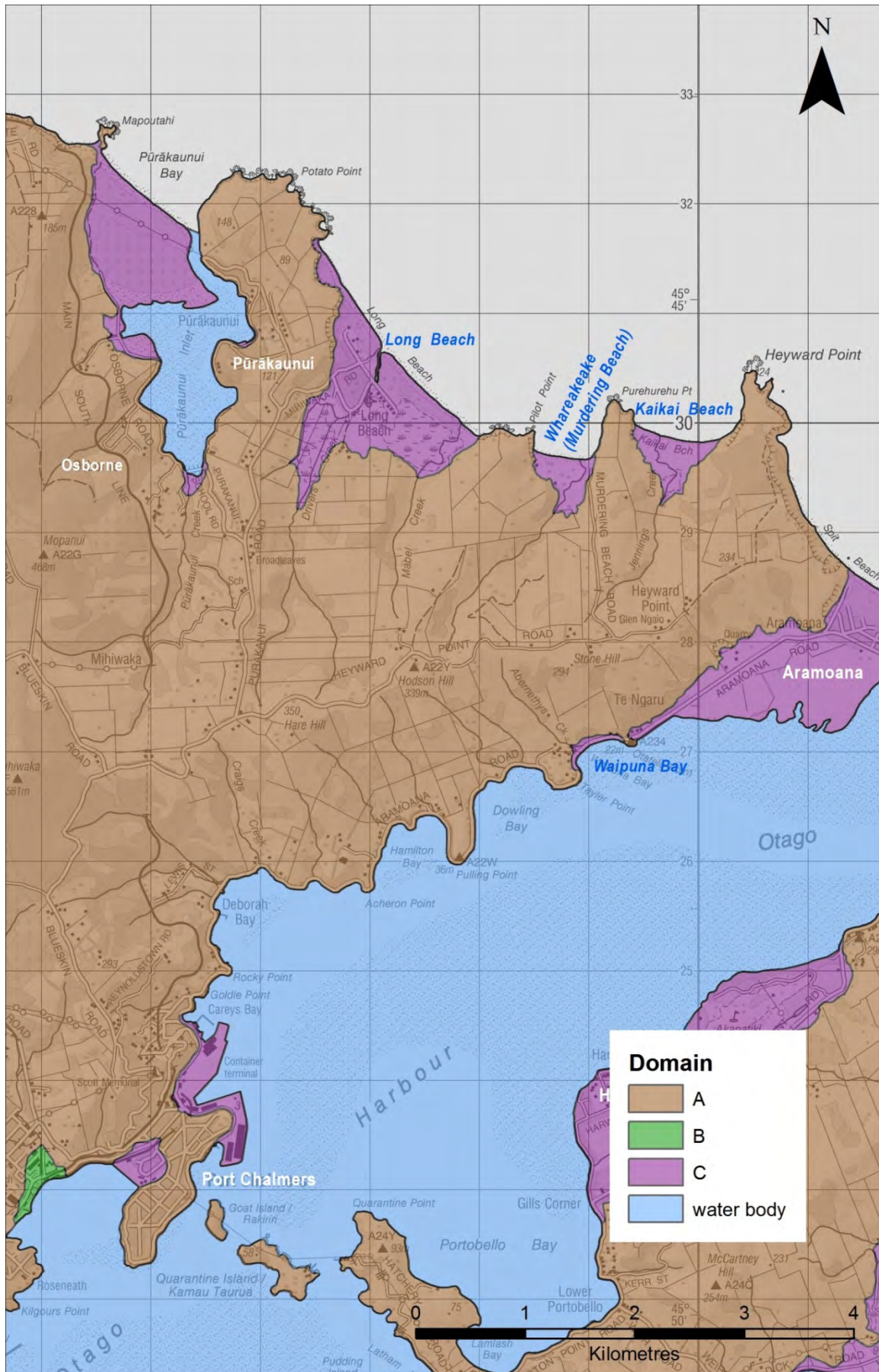


Figure A3.3e Location map for liquefaction susceptibility domains from Aramoana to Purakaunui.

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.

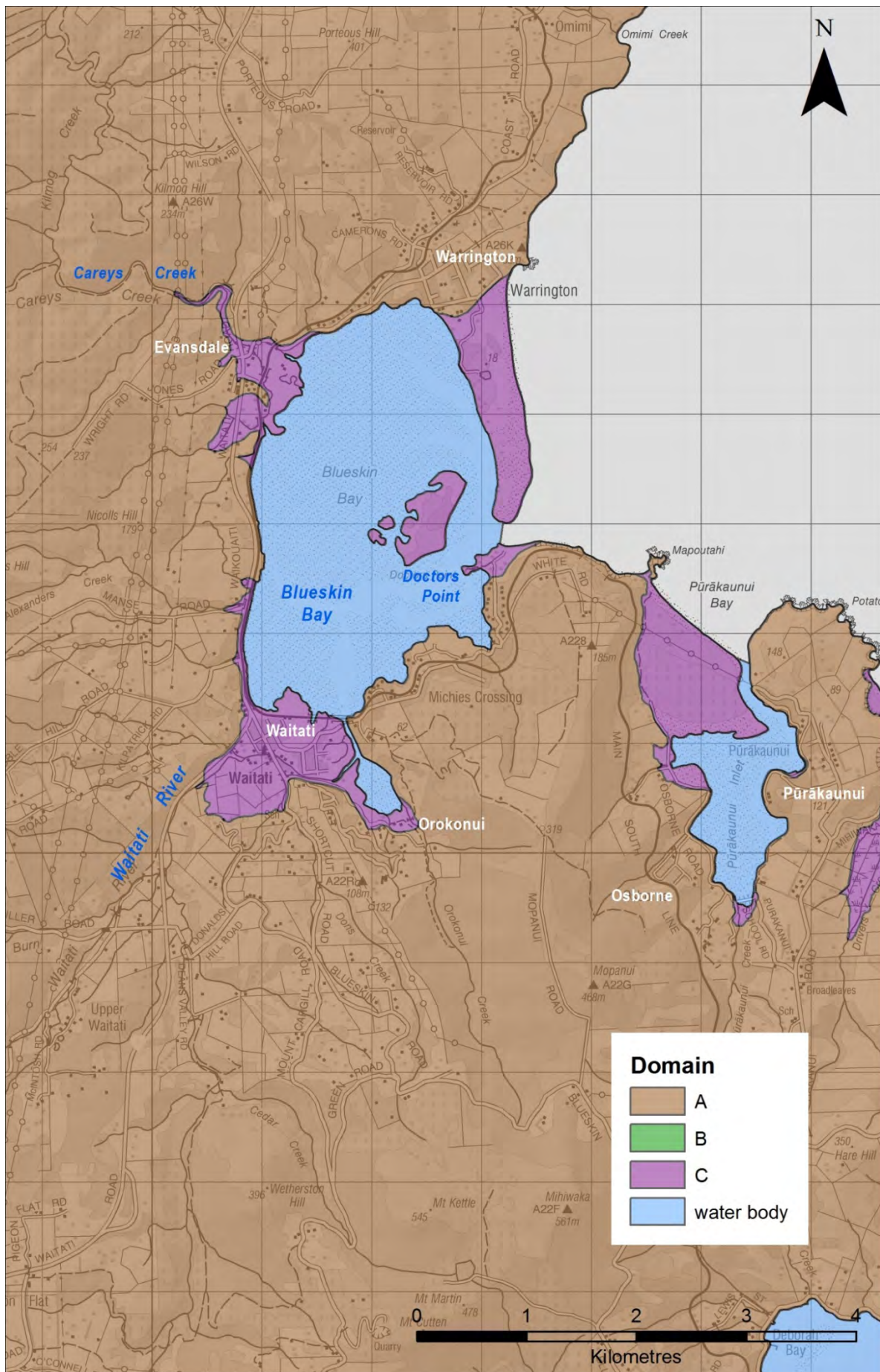


Figure A3.3f Location map for liquefaction susceptibility domains from Purakaunui to Warrington.

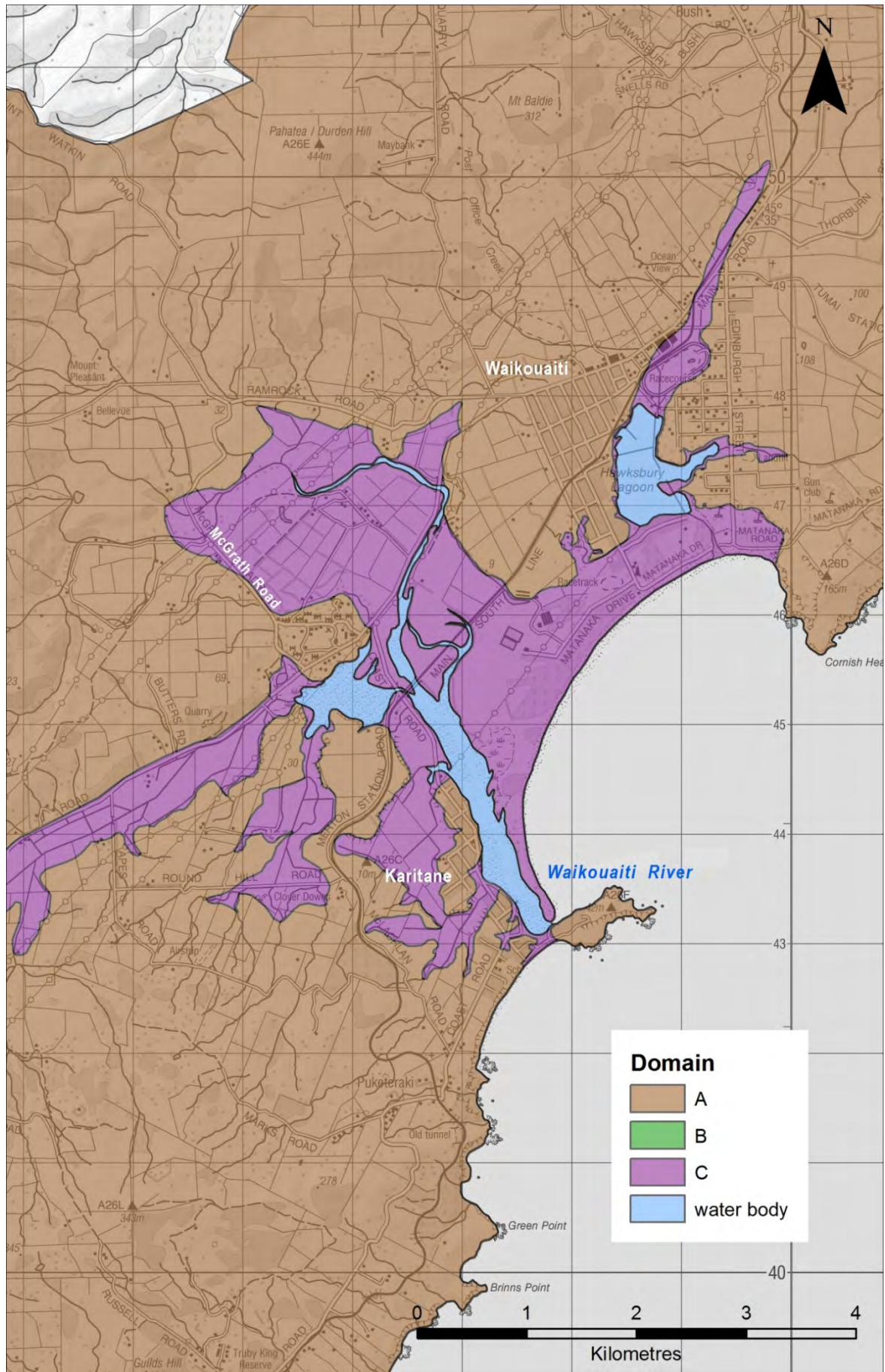


Figure A3.3g Location map for liquefaction susceptibility domains in the Waikouaiti area.

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 geomorphological 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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