TECHNICAL COMMITTEE AGENDA

Thursday, 1 August 2019

2 p.m., Council Chamber
Level 2 Philip Laing House, 144 Rattray Street, Dunedin

Membership

Cr Andrew Noone	*(Chairperson)*
Cr Ella Lawton	*(Deputy Chairperson)*
Cr Graeme Bell	
Cr Doug Brown	
Cr Michael Deaker	
Cr Carmen Hope	
Cr Trevor Kempton	
Cr Michael Laws	
Cr Sam Neill	
Cr Gretchen Robertson	
Cr Bryan Scott	
Cr Stephen Woodhead	

Disclaimer

Please note that there is an embargo on agenda items until 48 hours prior to the meeting. Reports and recommendations contained in this agenda are not to be considered as Council policy until adopted.

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1. APOLOGIES
No apologies have been notified.

2. LEAVE OF ABSENCE
No leaves of absence have been requested.

3. ATTENDANCE

4. CONFIRMATION OF AGENDA
Note: Any additions must be approved by resolution with an explanation as to why they cannot be delayed until a future meeting.

5. CONFLICT OF INTEREST
Members are reminded of the need to stand aside from decision-making when a conflict arises between their role as an elected representative and any private or other external interest they might have.

6. PUBLIC FORUM
No requests from members of the public to address the Council have been received.

7. PRESENTATIONS
No presentations have been scheduled.

8. CONFIRMATION OF MINUTES

Recommendation

That the minutes of the meeting held on 12 June 2019 be received and confirmed as a true and accurate record.

Attachments
1. Technical Minutes 20190612 **[8.1.1 - 4 pages]**

9. ACTIONS
Status report on the resolutions of the Technical Committee

Report	Meeting Date	Resolution	Status
Lake Snow technical workshop recommendations	18/10/18	*The CE engage on the with CEs at the regional CEOs meeting on 8 November 2018 on the primary objectives from the workshop.* *Invite Regional Councils and MPI to formally endorse and support the proposed research programme and to discuss funding arrangements.*	IN PROCESS

GM Report	12/06/2019	*Staff to write to the ministers of Biosecurity, Environment and Local Government with the aim of seeking direct government response and input towards combatting the threat of lake snow to the region's waterways*	ASSIGNED
10.2 Glendhu Forestry	12/06/2019	*Council requested the report be provided to CE City Forests Ltd and Southern Wood Council*	ASSIGNED

10. MATTERS FOR NOTING

10.1. General Manager Operations Report to Technical Committee

Prepared for:	Technical Committee
Report No.	EHS1857
Activity:	Safety & Hazards: Natural Hazards
Author:	Gavin Palmer, General Manager Operations Ben Mackey, Natural Hazards Analyst
Endorsed by:	Gavin Palmer, General Manager Operations
Date:	19 July 2019

PURPOSE

[1] To provide Council with an update on the following matters:
- Leith Flood Protection Scheme
- Regional Liquefaction Assessment
- Otago weather radar

RECOMMENDATION

That the Council:

1) **Receives** this report.

LEITH FLOOD PROTECTION SCHEME

[2] Works continue on the Dundas Street bridge stage of the Leith Flood Protection Scheme (Figures 1 and 2). Excavation for the new culvert at the western (right) side of the bridge is underway along with stabilisation of the western bank of the Water of Leith (Figures 3 to 8).

[3] WorkSafe undertook an *impromptu* site visit on 10 July 2019. They commented that the site is complex and has its challenges and they provided positive feedback to the contractor (Downer NZ Ltd) on what they saw on the day of their visit.

[4] As previously advised to Committee, the top three project-related risks identified jointly by ORC and the contractor are:
- Flood damage and uncontrolled river channel diversion during the critical phase of the bridge widening (culvert) excavation;
- Disruption to public water supply caused by accidental damage to the existing water main that crosses the bridge and culvert excavation;
- Health and safety and vandalism associated with persons accessing the very hazardous site after hours without permission.

Each of these risks has specific mitigation measures in place and are subject to ongoing monitoring and review.

[5] The construction site is very hazardous, especially at night, with deep excavations at both ends of the bridge. Persons entering the site without the authorisation of the

contractor continues to occur, despite fencing, signage, security guards and publicity. They are exposing themselves to the very real likelihood of serious harm or death, and this is a serious concern for staff and the contractor. This matter is subject to ongoing review by the contractor and ORC, in consultation with the University of Otago.

[6] One way of managing these risks is to minimise the duration of the works. However, completing this stage quickly must be balanced with doing the works safely and properly. Planning for stabilisation of the river bank and adjacent buildings (Figures 6 and 7) and working safely around the existing water main that services Dunedin Hospital and North Dunedin (Figures 3 and 4) has taken longer than expected. For these reasons the bridge will be reopened to vehicles and pedestrians in October 2019 rather than August 2019. This additional time will increase the cost of this stage – a financial update will be provided to Council on 15 August.

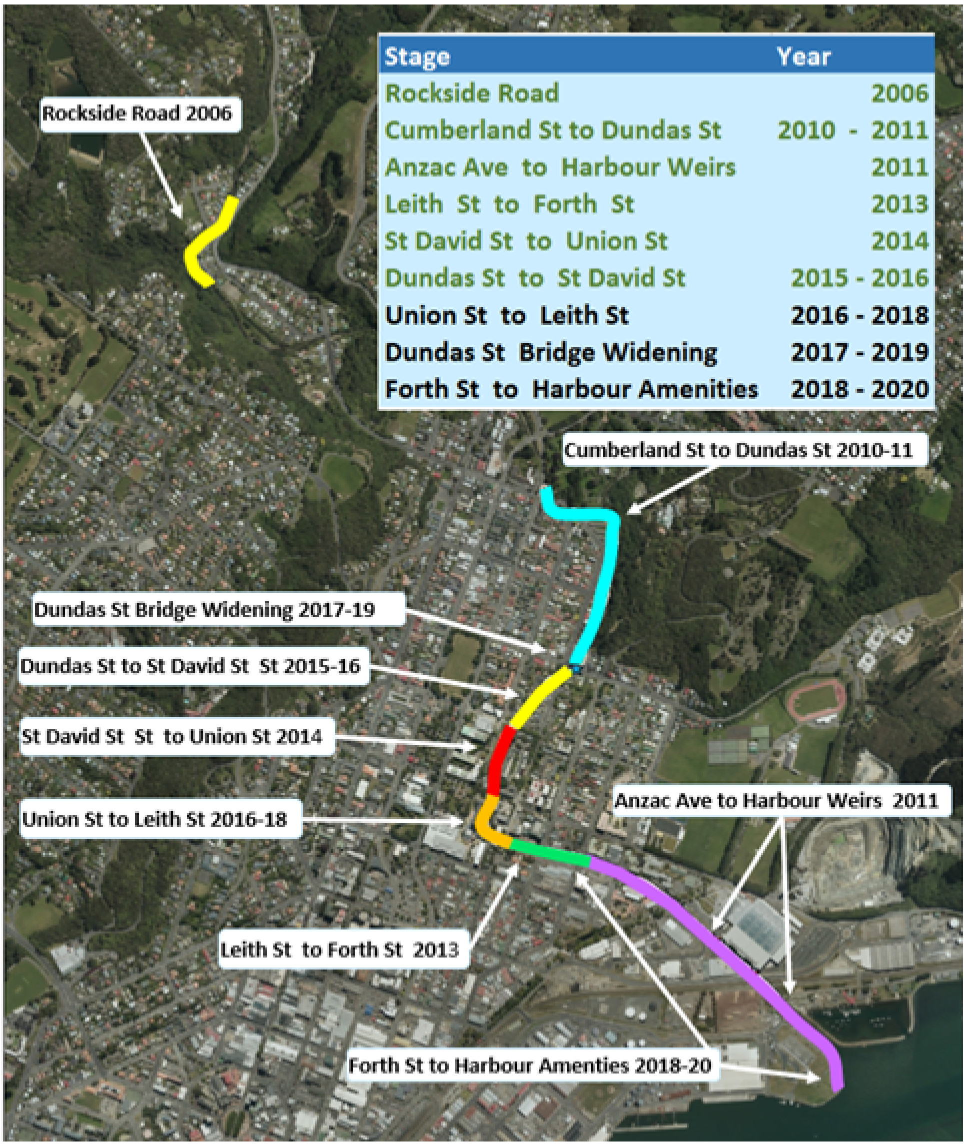

Figure 1 Staging of construction of Leith Flood Protection Scheme.

Figure 2 Dundas St Bridge stage of the Leith Flood Protection Scheme

Figure 3 Western (right) abutment of Dundas Street Bridge, Dunedin. Dunedin City Council water main (white pipeline) and temporary steel support beam in foreground.

Figure 4 Looking upstream at western (right) abutment of Dundas Street Bridge, Dunedin. Dunedin City Council water main (white pipeline) and temporary steel support beam in foreground.

Figure 5 Looking upstream to excavation behind western (right) abutment of Dundas Street Bridge.

Figure 6 Ground pinning and Shotcrete ground stabilisation on western side of Water of Leith (looking upstream, bridge at right).

Figure 7 Ground pinning and Shotcrete retaining works on western side of Water of Leith, upstream of Dundas Street Bridge. The top of the Shotcrete is at the level of the pre-existing river bed (prior to channel widening).


Figure 8 Excavation and communication ducts (green pipes) at western (right) abutment of Dundas Street Bridge.

REGIONAL LIQUEFACTION ASSESSMENT

[7] Liquefaction of the ground can occur when saturated, loose, fine-grained sediments are subjected to shaking during earthquakes. The effects of liquefaction at the ground surface include cracking, subsidence, lateral spreading, and ejection of silt and water. Liquefaction can damage foundations, cause differential settlement of structures, and break pipes and buried infrastructure. It was a major cause of damage during the 2010-2011 Canterbury earthquake sequence.

[8] GNS Science recently completed a study of liquefaction potential across the Waitaki, Central Otago, Queenstown Lakes, and Clutha Districts.[1] It is appended as Attachment 11.1. This work, commissioned by ORC, builds on a similar study in the Dunedin district competed in 2014[2] and completes the regional assessment. This new mapping supersedes the existing regional assessment undertaken in 2005 which was largely based on existing geologic maps. [3]

[9] The office-based study used existing datasets to identify where potentially liquefiable sediments may be present. Otago-based geotechnical experts also provided input to the work based on their knowledge of subsurface conditions. No specific geotechnical testing was undertaken as part of this study, which equates to a 'Level A' assessment outlined in recent MBIE guidelines[4].

[10] In general, areas which may be susceptible to liquefaction include river flats, lake margins, and low-lying coastal areas with marine and estuarine sediments. The districts were mapped into three domains based on their liquefaction susceptibility (Figure 9).

[11] Domain A – rock or firm sediments unlikely to liquefy. Includes bedrock, or areas with a deep groundwater table. Domain A comprises 95% of the four districts by area.

[12] Domain B – River or stream sediments with a shallow groundwater table where liquefaction susceptible sediments may be present. A sub-class, B1, is used where subsurface data confirm the local presence of liquefaction-susceptible materials. In Domains B and B1 damaging liquefaction of minor to moderate severity is considered possible. Domains B and B1 comprise 4% of the mapped area.

[13] Domain C – Areas underlain by poorly consolidated estuarine or marine sediments with shallow groundwater table. There is a moderate to high likelihood that liquefaction susceptible materials are present in parts of Domain C, and ground damage could be moderate to severe. Less than 1% of the four districts is identified as Domain C.

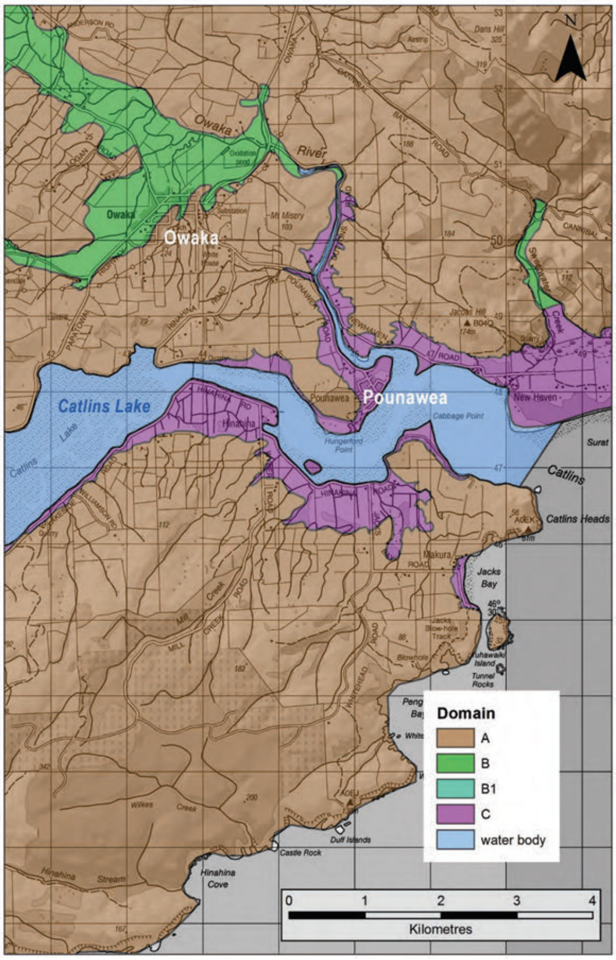

Figure 9 Example map from the report showing liquefaction potential near Owaka, Clutha District.

[14] The report identifies areas where ground conditions with the potential to liquefy may be present. Further site-specific information, such as ground testing and detailed liquefaction assessment may be required to inform development in these areas. MBIE provides guidance to developers and territorial authorities on the recommended level of liquefaction assessment when liquefaction susceptible conditions have been identified.

[15] The primary improvement over previous regional liquefaction maps is that this work considers both soil type and groundwater conditions, the key factors controlling liquefaction. Areas which had previously been identified as susceptible to liquefaction

based on ground conditions alone, but which have low groundwater levels (such as high river terraces), have been remapped as unlikely to be susceptible to liquefaction.

[16] The report and associated Geodatabase will be provided to the Territorial Authorities and will be incorporated into the ORC Natural Hazard Database.

Footnotes:

[1] Barrell DJA. 2019. Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago Region. Lower Hutt (NZ): GNS Science. 99 p. Consultancy Report 2018/67.

[2] Barrell, D. J. A.; Glassey, P. J.; Cox, S.C.; Smith Lyttle, B. 2014. Assessment of liquefaction hazards in the Dunedin City district, GNS Science Consultancy Report 2014/068. 66 p. Presented to the Technical Committee 04th June 2014.

[3] Murashev A, Davey R. 2005. Seismic risk in the Otago Region. Wellington (NZ): Opus International Consultants Limited. Report SPT 2004/23. 50 p., 27 maps and 2 appendices. Prepared for Otago Regional Council.

[4] [MBIE] Ministry of Business, Innovation and Employment 2017. Planning and engineering guidance for liquefaction-prone land. Wellington (NZ): Ministry of Business, Innovation and Employment. 134 p. Technical report; ISBN (online) 978-1-98-851770-4.

OTAGO WEATHER RADAR

[17] Metservice has advised that a site near Hindon has been selected for the installation of a weather radar. Details of the precise location are not yet available to the public. The radar is expected to become operational in May 2020.

[18] The radar will enable ORC to improve the information it provides to the public during floods and assist with management of the Lower Taieri Flood Protection Scheme and Leith Flood Protection Scheme. The 2019/20 Annual Plan makes provision for scoping of models that will use the radar data to forecast the distribution of rainfall during floods. This is expected to be operational by September 2020. Auckland Council has developed similar capability.

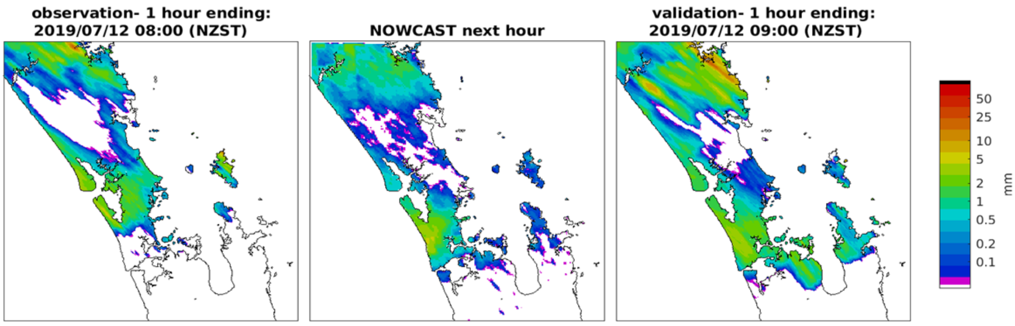

Figure 10). Figure 10 Example of quantitative precipitation estimation from radar observations (left and right panels) and ”nowcasting” (1 to 2 hours, middle panel) (courtesy of Auckland Council).

ATTACHMENTS

1. 11.1.1 GNS Science Consultancy Report **[10.1.1 - 107 pages]**

11. NOTICES OF MOTION

No Notices of Motion have been received.

12. CLOSURE

Technical Committee 20190801 Attachments

Otago Regional Council

Minutes of a meeting of the Technical Committee held in the Council Chamber, Level 2 Philip Laing House, Dunedin on Wednesday, 12 June 2019 at 4 p.m.

Membership

Cr Andrew Noone	*(Chairperson)*
Cr Ella Lawton	*(Deputy Chairperson)*
Cr Graeme Bell	
Cr Doug Brown	
Cr Michael Deaker	
Cr Carmen Hope	
Cr Trevor Kempton	
Cr Michael Laws	
Cr Sam Neill	
Cr Gretchen Robertson	
Cr Bryan Scott	
Cr Stephen Woodhead	

Welcome

Cr Noone welcomed Councillors, members of the public and staff to the meeting.

1. APOLOGIES
There were no apologies.

2. LEAVE OF ABSENCE
No leave of absence was requested.

3. ATTENDANCE

Sarah Gardner	*(Chief Executive)*
Nick Donnelly	*(General Manager Corporate Services and CFO)*
Gavin Palmer	*(General Manager Operations)*
Sally Giddens	*(General Manager People, Culture and Communications)*
Peter Winders	(*Acting General Manager Regulatory)*
Andrew Newman	*(Acting General Manager Policy, Science and Strategy)*
Liz Spector	*(Committee Secretary)*
Jean-Luc Payan	*(Manager Natural Hazards)*
Hugo Borges	*(Environmental Resource Scientist)*
Rachel Ozanne	*(Environmental Resource Scientist)*

4. CONFIRMATION OF AGENDA
The agenda was confirmed as tabled.

5. CONFLICT OF INTEREST
No conflicts of interest were advised.

6. PUBLIC FORUM
Mr John Glover addressed the Council on behalf of the Kinloch community, the Glenorchy Community Association and other stakeholders about concerns over continued flooding of Kinloch Road. The Committee members thanked him for the information.

7. PRESENTATIONS
No presentations were held.

8. CONFIRMATION OF MINUTES
Resolution

That the minutes of the meeting held on 1 May 2019 be received and confirmed as a true and accurate record.

Moved: Cr Lawton
Seconded: Cr Hope
CARRIED

9. ACTIONS

Status report on the resolutions of the Technical Committee

Report	Meeting Date	Resolution	Status
Lake Snow technical workshop recommendations	18/10/18	*The CE engage on the with CEs at the regional CEOs meeting on 8 November 2018 on the primary objectives from the workshop.* *Invite Regional Councils and MPI to formally endorse and support the proposed research programme and to discuss funding arrangements.*	IN PROCESS - the CE did table the issue of lake snow at the regional CE meeting with no action arising from the discussion. She will raise the issue again.

10. MATTERS FOR NOTING

10.1. General Manager Operations Report to Technical Committee

Dr Gavin Palmer, GM Operations and Dr Jean-Luc Payan, Manager Natural Hazards addressed the General Manager Operations Report. The report was provided to update the Committee members on several issues including a geotechnical drilling project in South Dunedin and Harbourside as part of ORC's work on climate change and natural hazards in collaboration with DCC and the University of Otago. Also reviewed with the Committee were recent flood events on the Dart River and the Manuherikia River at Ophir, lake snow in Lake Dunstan, and information about the Brassknocker Road stock truck effluent disposal facility. After a lengthy discussion, Cr Deaker made a motion:

Resolution

That the Council:

1) ***Receives*** *this report.*
2) ***Writes*** *to the Ministers of Biosecurity, the Environment, and Local Government with the aim of seeking direct government response and input towards combating the threat of lake snow to the region's waterways.*

Moved: Cr Deaker
Seconded: Cr Bell
CARRIED

Cr Laws left the meeting at 04:26 pm.
Cr Laws returned to the meeting at 04:27 pm.

10.2. Glendhu Forestry

ORC Environmental Resource Scientist Rachel Ozanne spoke to the Glendhu Forestry Report. The report summarised the data and outcomes of an 18-month investigation into pine forest harvesting in Glendhu which resulted in support of the water plan implementation programme in relation to diffuse suspended sediment and permitted activity rules. After a general discussion of the report, the committee members requested a copy of the report be provided to Mr Grant Dodson of City Forests Ltd and to the Southern Wood Council.

Resolution

That the Council:

1) ***Receives*** *this report.*
2) ***Notes*** *the report.*
3) ***Circulates*** *this report to the Southern Woods Council.*

Moved: Cr Noone
Seconded: Cr Lawton
CARRIED

Cr Neill left the meeting at 05:09 pm.

10.3. Catchment Monitoring Programmes 2017-18
Rachel Ozanne, Environmental Resource Scientist, spoke to the report which provided an overview of water quality monitoring by five irrigated catchment groups between July 2017 and April 2019, including the Upper Taieri, Bannock Burn/Shepherds Creek, Thomsons Creek, Waiareka, and Awamoko catchments. A discussion was held, and the committee asked that the report be provided to the Communications team to help promote applications to the ECO Fund by community catchment groups in need of start-up funding.

Resolution

That the Council:

1) ***Receives*** *this report.*
2) ***Notes*** *the progress with the Catchment Monitoring Programme.*
3) ***Circulates*** *this report to the Communications team to promote applications to the ECO Fund by catchment groups who might need start-up funding.*

Moved: Cr Deaker
Seconded: Cr Lawton
CARRIED

11. NOTICES OF MOTION
No Notices of Motion were made.

12. CLOSURE
There was no further business and Cr Noone declared the meeting closed at 05:24 pm.

__________________________ _________________________
Chairperson Date

Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago Region

DJA Barrell

GNS Science Consultancy Report 2018/67
June 2019

DISCLAIMER

Use of Data:

Date that GNS Science can use associated data: May 2019

BIBLIOGRAPHIC REFERENCE

Barrell DJA. 2019. Assessment of liquefaction hazards in the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago Region. Lower Hutt (NZ): GNS Science. 99 p. Consultancy Report 2018/67.

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EXECUTIVE SUMMARY

The susceptibility of land to earthquake-induced liquefaction has been assessed for the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago region. Liquefaction is a process whereby earthquake shaking causes poorly consolidated, groundwater-saturated, sediments 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 or a lake margin.

Using methods developed for liquefaction hazard evaluation in Canterbury following the 2010–2011 earthquakes, and applied in 2014 to the Dunedin City district, the approach used here differentiates 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 be able to liquefy, the materials close to the ground surface need to be poorly consolidated, fine-grained (between coarse silt and fine sand) and water-saturated.

The liquefaction assessment documented in this report is an office-based evaluation of existing available information. This equates to a basic desktop assessment as defined in planning and engineering guidelines for liquefaction-prone land released in 2017 by the Ministry of Business, Innovation and Employment. The information sources included geological maps, landform and soil maps, topographic information from maps, lidar surveys, aerial and ground photography, geological information from bore hole records, and measurements of depths to groundwater.

Using that information, a liquefaction-susceptibility map spanning all four districts was compiled in a Geographic Information System (GIS) and the GIS dataset is a companion to this report. As part of the project methodology, geotechnical specialists with expert knowledge from site investigations at numerous locations in Otago were engaged to review and provide advice on draft versions of the liquefaction-susceptibility map.

The map uses a three-fold classification of liquefaction susceptibility:

- Domain A. The ground is predominantly underlain by rock or firm sediments. It is unlikely that damaging liquefaction could occur;
- 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. A sub-class, Domain B1, is applied where geotechnical data indicate at least the localised presence of liquefaction-susceptible materials. In domains B and B1, damaging liquefaction is considered to be a possibility. If liquefaction-induced ground damage were to occur, it would probably be of minor to moderate severity;
- 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. Damaging liquefaction is considered to be a possibility. If liquefaction-induced ground damage were to occur, it may be moderate to severe.

Domains B and C are regarded as 'liquefaction awareness areas' and do not represent specific hazard zones. Rather, they highlight areas where there may the possibility of a liquefaction hazard. More than 95% of the land area in the four districts is classified as Domain A – terrain that has little or no liquefaction susceptibility. Domain B occupies less than 4% of the area of the combined districts, while land classified as Domain C comprises less than 1% by area.

In the Queenstown Lakes district, river, stream and beach sediment accumulations around the lake margins, and the floors of the main inflowing river valleys, are classified in Domain B. Due to their lakeside settings, localised parts of the built-up areas of greater Queenstown and Wanaka lie on Domain B, as do almost all parts of Kingston and Glenorchy. Very localised areas of Domain B occur at Albert Town and Arrowtown. Because Lake Hawea has been raised for hydroelectric water storage, ground that would have been identified as liquefaction awareness areas has been drowned. The modern lake fringe is classed as Domain A, and no liquefaction susceptibility is identified at Lake Hawea township, nor at Hawea Flat or Luggate.

In Central Otago, Domain B relates to areas of broad, low-lying river and stream valley floors, particularly in the Manuherikia and Taieri catchments. Most of the Clutha valley is Domain A, because there is a deep groundwater table under most of the river terraces. The township of Omakau, and villages of Lauder, Oturehua and Waipiata are the only built-up areas partly or entirely on ground classified as Domain B. No liquefaction susceptibility is identified at the built-up areas of Cromwell, Clyde, Alexandra, Roxburgh, Ettrick, Millers Flat, Ranfurly, Naseby and Patearoa, or the localities of Tarras and St Bathans.

The Clutha District has areas of Domain B associated with broad, low-lying river and stream valley floors, particularly in the Pomahaka, Tuapeka and Waitahuna catchments, and extensive areas of domains B and C in near-coastal reaches of most valleys, especially the Clutha, Tokomairaro and Taieri/Waipori systems. Parts of Heriot, Beaumont and Waitahuna, Lawrence, Balclutha, Owaka, and virtually all of Milton are on Domain B. The lower-lying parts of Kaitangata township, Taieri Mouth village, and all of the Pounawea, New Haven and Toko Mouth villages are on Domain C. Part of Waihola township is on domains B and C. No liquefaction susceptibility is identified at Tapanui, Clinton, Papatowai or Kaka Point.

The Waitaki District also has areas of Domain B associated with broad, low-lying river and stream valley floors, particularly in Shag, Kakanui and Waitaki valleys and other lesser streams, but the extent of Domain C is very localised. Most of Dunback, and localised parts of Palmerston, Hampden, Kakanui, Maheno, Enfield, Oamaru and the villages of Waitaki Bridge and Waitaki Mouth (south side) are on ground classified as Domain B. Although Domain C is mapped close to Kakanui township, none of the built-up area is on Domain C. No liquefaction susceptibility is identified at Moeraki, Weston or Herbert.

Information in this report is based largely on broad-scale inferences and should not be used in isolation for any purposes requiring site-specific information. The liquefaction susceptibility domains highlight areas where liquefaction hazard may warrant further scrutiny for future planning and development activities. This report and accompanying GIS dataset provide a step toward improved awareness and management of potential liquefaction hazards. Areas where liquefaction is considered a possibility (domains B and C) based on present information could be managed by territorial authorities through specifying levels of geotechnical investigation to determine ground conditions and assist in the design of liquefaction-mitigating measures. Additional geotechnical investigations would be necessary if there were a need to undertake more definitive assessments of liquefaction hazards. 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.

1.0 INTRODUCTION

1.1 Overview

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 may cause ground settlement, lateral spreading, loss of bearing capacity, and buoyant rise of buried structures such as pipes or tanks. Extensive liquefaction damage occurred in the Christchurch area 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.

In 2014, Otago Regional Council (ORC) contracted GNS Science to provide an assessment of liquefaction hazards for the Dunedin City district (Barrell *et al.* 2014). Subsequently, ORC engaged GNS Science to undertake a similar assessment for the other territorial authority areas in the Otago region (Queenstown Lakes District, Central Otago District, Clutha District and Waitaki District (Figure 1.1). This report presents the results of that assessment. The information in this report is intended to assist ORC in providing advice on liquefaction to those territorial authorities.

1.2 Scope of Work

The work comprised an office-based assessment of existing information following the methods used in the assessment of liquefaction hazards in the Dunedin City district (Barrell *et al.*, 2014).

As part of the work, GeoSolve Limited was engaged on subcontract to review and advise on draft versions of the liquefaction-susceptibility maps, especially in areas where their staff have expert knowledge of subsurface geotechnical properties, based on previous investigation data.

The main components of the project were:

- Review of existing relevant reports and datasets (Section 1.3);
- Compilation of a liquefaction-susceptibility map;
- Review of the liquefaction-susceptibility mapping by GeoSolve staff, and commensurate refinements to the map;
- Preparation of an explanatory report documenting the work undertaken, accompanied by digital map files and metadata.

The report presents a geologically-based assessment of information that is intended to create awareness of where liquefaction-related hazards may be present. The new mapping documented here draws upon readily available existing information, and no new site investigations were undertaken as part of this project. The approach accords with recent planning and engineering guidance for liquefaction-prone land (Ministry of Business, Innovation and Employment (MBIE) 2017).

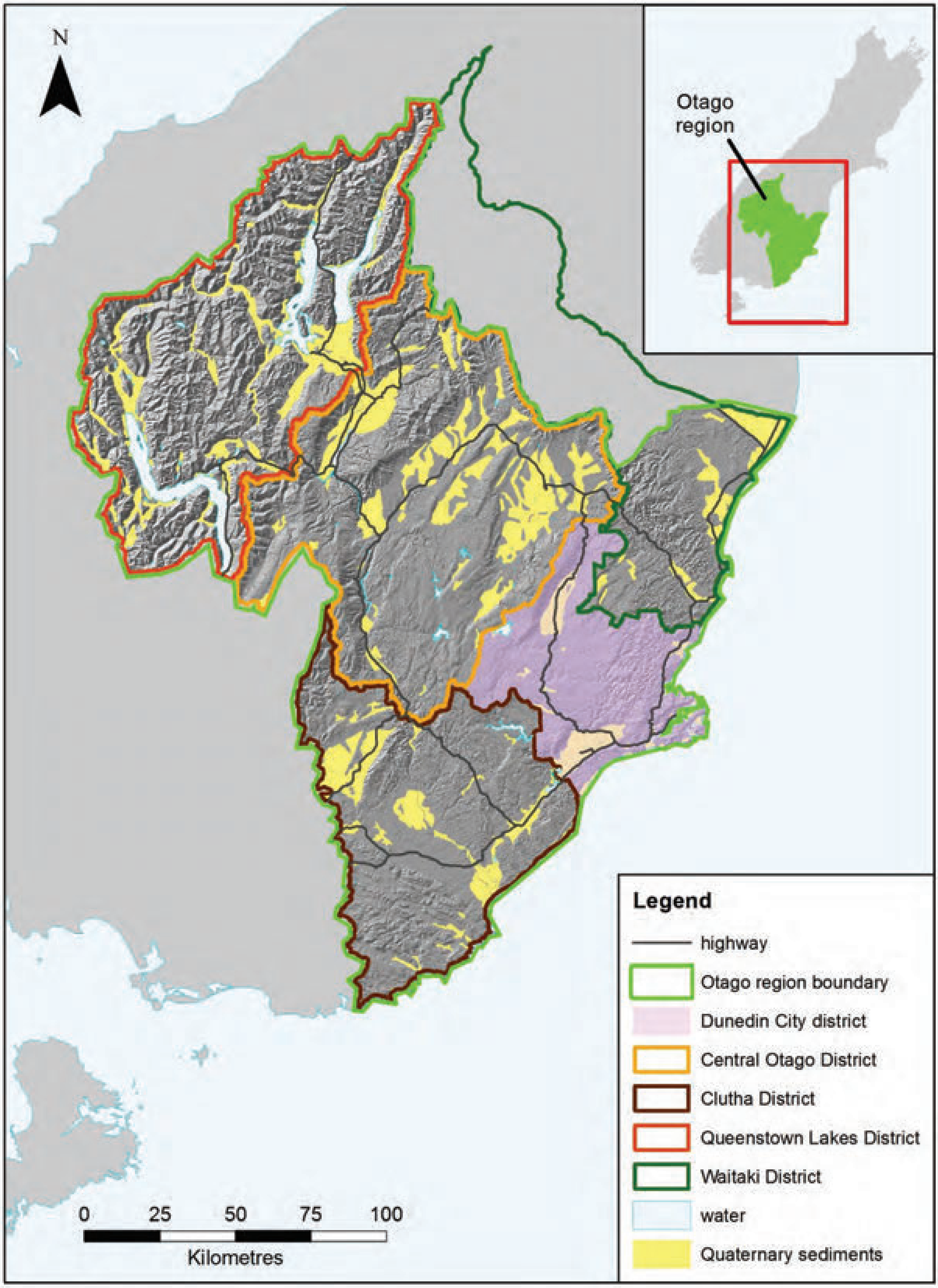

Figure 1.1 Location of the Otago region and its constituent territorial authority areas (district or city councils), along with Otago's distribution of Quaternary-age sediments. The latter is taken from the New Zealand 1:1 000 000-scale geological map (Edbrooke *et al.* 2014). Only those areas underlain 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. The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report. The background is a hillshade terrain model derived from topographic map elevation data.

The liquefaction-susceptibility domains delineated in this report are intended to highlight areas where liquefaction is a potential hazard that warrants consideration in 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.

1.3 Liquefaction Hazard Assessment Methodology

The liquefaction[1] hazard evaluation reported here is a regional-scale susceptibility assessment, using methodologies similar to those previously applied in eastern Canterbury (Brackley 2012) and in the Dunedin district (Barrell *et al.* 2014). More recently, the Ministry of Business, Innovation and Employment has issued guidelines for planning and engineering in relation to liquefaction-prone land (MBIE 2017). Those guidelines include comprehensive information on the nature of liquefaction, and approaches for determining and managing risks of liquefaction damage. Interested readers should consult the MBIE (2017) report, and only a summary of the nature and occurrence of liquefaction is provided here (Section 3).

The approach used here focuses on liquefaction susceptibility. This term relates to the physical state of ground-forming materials, as to whether they have the "ability" (suitable physical characteristics) to liquefy. The key physical characteristics are the presence of loose, water-saturated sand or silt layers or pods in the near-subsurface. The liquefaction susceptibility mapping approach used is principally based on geomorphology. The form and origin of the ground surface (geomorphology) generally reflects the nature of underlying geological materials, whether solid rock ranging through to 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 below the ground, as well as giving insights into the processes such as erosion and deposition that have shaped the ground surface. The aim of the mapping presented here, based on geological character and the nature of the landform, is to delineate areas where there is a possibility of liquefaction-susceptible materials being present. Areas that are assessed as having liquefaction susceptibility should also be considered to have lateral spreading susceptibility in areas close to 'free-faces', such as river bank edges or lake shore cliffs.

In the context of the MBIE (2017) guidelines, the methodology used here equates to a "Level A" basic desktop assessment, that is aimed at distinguishing between areas where liquefaction damage is unlikely to occur versus areas where liquefaction damage is possible. This approach differs from more comprehensive classes of liquefaction evaluation listed in the MBIE (2017) guidelines (Level B – calibrated desktop assessment; Level C – detailed area-wide assessment; and Level D – site-specific assessment). These more comprehensive classes of liquefaction assessment require detailed information on the geotechnical properties of near-surface sediments. Therefore, in order to make a firmer assessment of liquefaction risks, it is necessary to have site-specific geotechnical investigation data, from drilling and down-hole testing of the ground. Where such information is known, it has been taken into account in the mapping presented in this report, as explained in Appendix 3. As matters stand, in most of Otago, there is insufficient information for more quantitative assessments, such as are described in the MBIE (2017) guidelines.

[1] Any term that is defined in Appendix 1 is underlined at its first mention in this report

1.4 Data Sources and Mapping Methods

The starting point for the assessment was the GNS Science 1:250 000-scale geological database (QMAP; Heron 2014). Liquefaction, and the associated effect of lateral spreading, are phenomena associated with young, poorly consolidated, water saturated sediments, deposited during the Quaternary Period (see Figures 1.2 to 1.5). It is only the sediments of Late Quaternary age that are likely to have sufficiently poor consolidation and the water saturation necessary to pose a potential liquefaction hazard. Taking the generalised QMAP polygons as a guide, other information sources were used to delineate more detailed interpreted extents of liquefaction-susceptibility awareness area domains. The mapping was done directly with a computer using Geographic Information System (GIS) software (ArcGIS). Applying expert interpretation of landform features, boundaries between map polygons were positioned on screen relative to underlying base-map information. Specific resources used for that purpose include:

- The digital topographic map of the Land Information New Zealand (LINZ) 'Topo 50' 1:50 000-scale map series;
- A high-resolution digital aerial photograph mosaic collated from images taken between 2004 and 2015, and accessed as a base-map layer that comes via ArcGIS;
- A digital database of borehole information made available by ORC for this project;
- Lidar ('laser radar') datasets where available, provided by ORC. These provide highly-detailed information (1 m-grid cells) on ground elevations, and have also been processed to produce shaded terrain relief maps ('hillshade' models; e.g. see Figure 1.1);
- Archival printed black and white aerial photograph sets held by GNS Science for localised areas, generally dating from the period between the late 1940s and mid-1980s. Overlap between sequential photos in each run allowed them to be viewed stereoscopically. Erasable pencil interpretations were drawn on photos. These were scanned and georeferenced in ArcGIS, to aid the drawing of polygon boundaries.

Other resources used to aid mapping interpretations include Google Earth Street View, which provides 360° ground photos along all sealed roads, online digital soil maps (S-map; Manaaki Whenua Landcare Research), and publicly available reports or maps on topics including geology, geomorphology and groundwater. Those used to assist the mapping are mentioned where appropriate in Appendix 3. Those of general relevance include reports on alluvial fan hazards in Otago (Grindley *et al.* 2009; Barrell *et al.* 2009), geomorphological mapping along the Clutha District coast at 1:100 000 scale (Barrell *et al.* 1998), and 1:50 000-scale published geological maps that include the Wakatipu Basin (Barrell *et al.* 1994), and parts of the near-coastal areas of the Clutha District (Bishop 1994) and Waitaki District (McMillan 1999).

1.5 Report Layout

General background information is provided in Section 2, including Otago's geological setting and geological processes, and the origin and context of landform features relevant to liquefaction hazards. Also provided is an overview of the general nature of liquefaction and factors influencing its occurrence, an outline of seismicity in Otago, and a description of the approach and methods used here for assessing liquefaction susceptibility. Section 3 describes the liquefaction-susceptibility map units (domains), defines what they mean, and outlines the accuracy and limitations of the mapping. This is followed by a district-by-district summary description of the liquefaction-susceptible areas. Section 4 discusses the overall findings of the assessment and the uses of the information and conclusions are set out in Section 5.

Appendix 1 provides explanation of some of the technical terms used in the report. The regional-scale liquefaction-susceptibility map from a 2005 report (Murashev and Davey 2005) is presented in Appendix 2. Detailed descriptions of the criteria used for mapping liquefaction-susceptibility domains at specific locations, accompanied by detailed location maps, are contained in Appendix 3. The GIS dataset of the mapped liquefaction-susceptibility domains is described in Appendix 4.

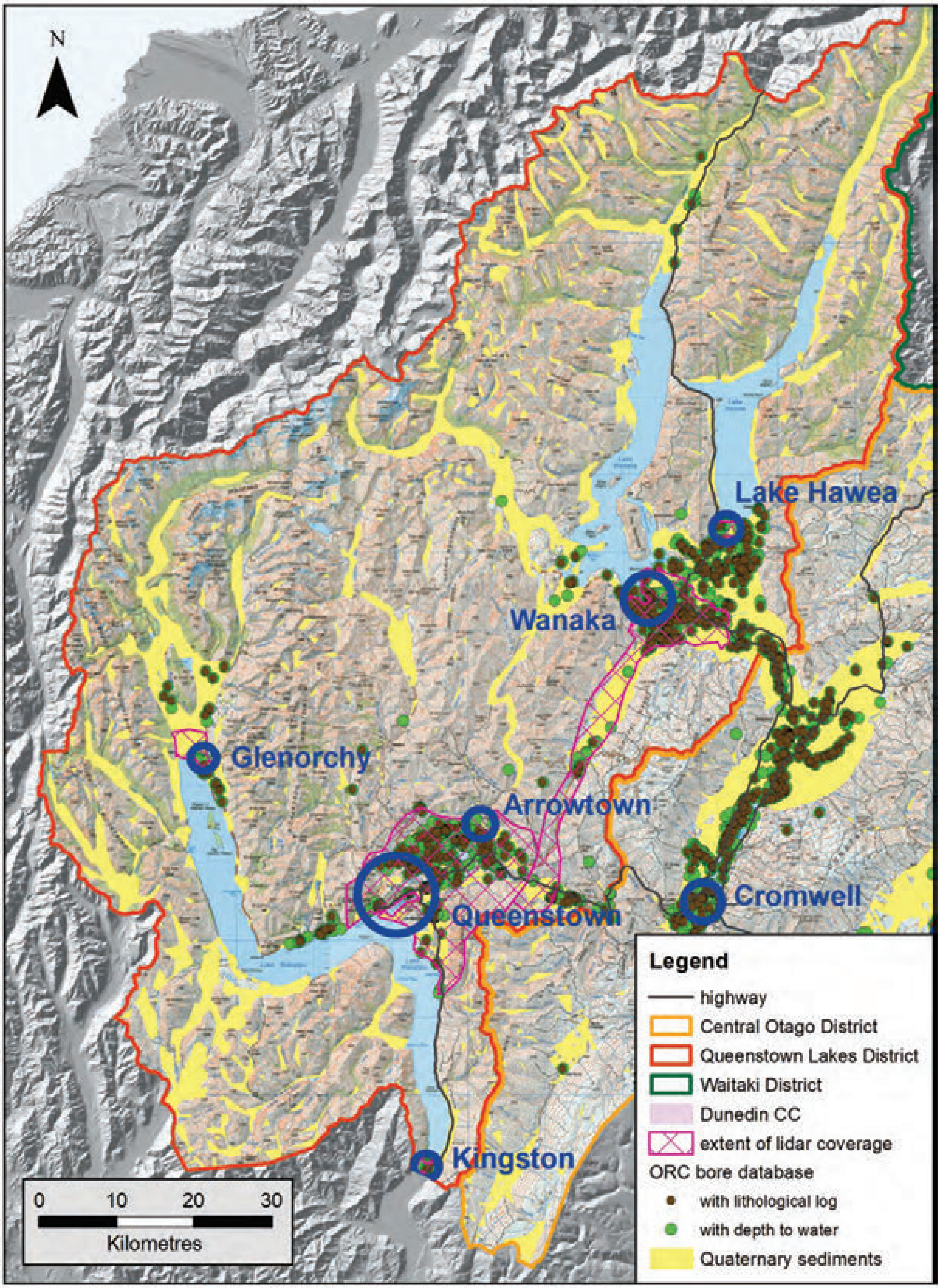

Figure 1.2 Background information sources for the Queenstown Lakes District. The map shows the extent of lidar coverage, locations of bores in the ORC database with water level data and/or records of geological materials (lithological logs), and the distribution of Quaternary sediments (New Zealand 1:250 000-scale geological map; Heron 2014). The coloured background is the LINZ Topo 250 map.

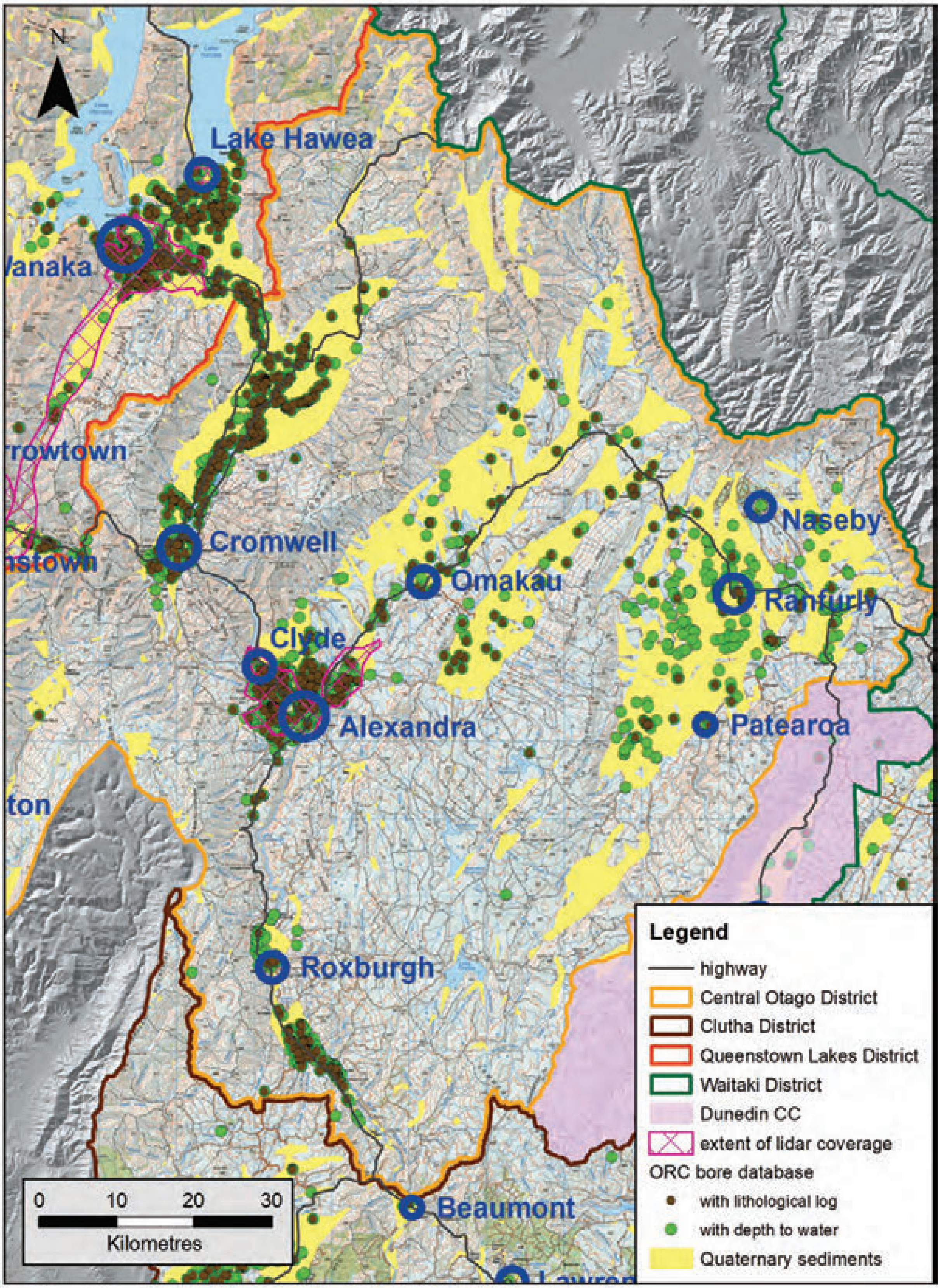

Figure 1.3 Background information sources for the Central Otago District. The map shows the extent of lidar coverage, locations of bores in the ORC database with water level data and/or records of geological materials (lithological logs), and the distribution of Quaternary sediments (New Zealand 1:250 000-scale geological map; Heron 2014). The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report. The coloured background is the LINZ Topo 250 map.

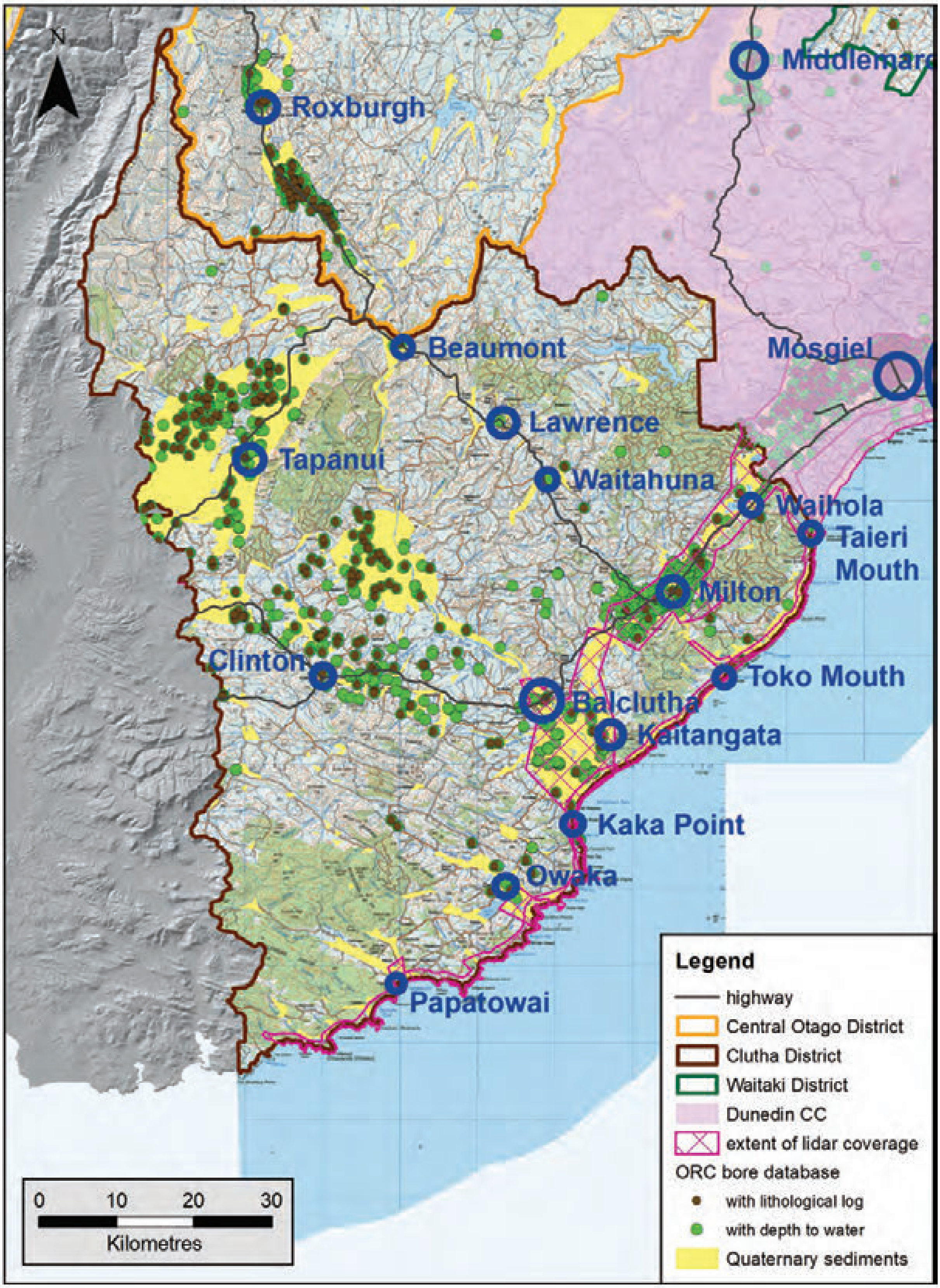

Figure 1.4 Background information sources for the Clutha District. The map shows the extent of lidar coverage, locations of bores in the ORC database with water level data and/or records of geological materials (lithological logs), and the distribution of Quaternary sediments (New Zealand 1:250 000-scale geological map; Heron 2014). The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report. The coloured background is the LINZ Topo 250 map.

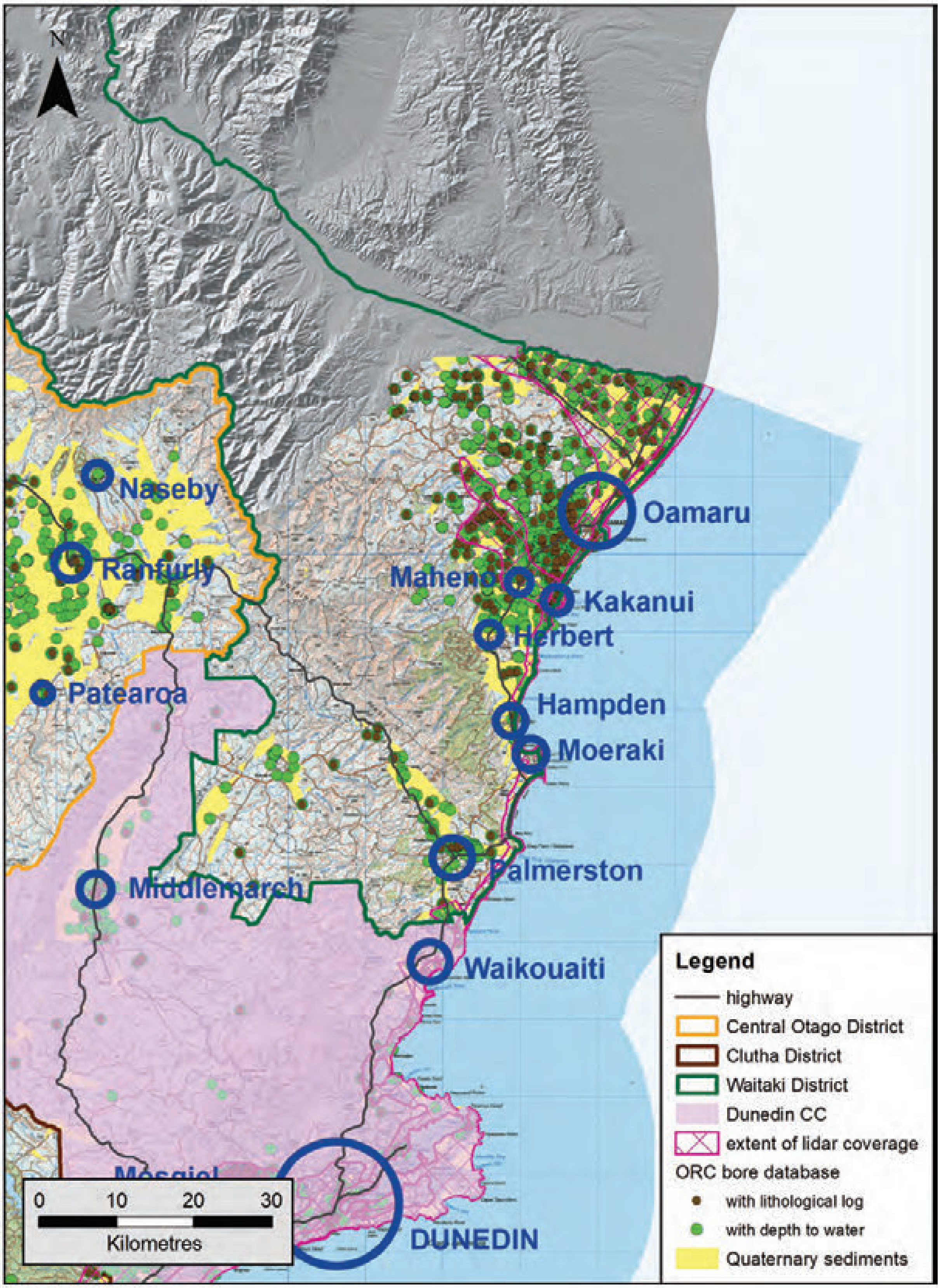

Figure 1.5 Background information sources for the Waitaki District. The map shows the extent of lidar coverage, locations of bores in the ORC database with water level data and/or records of geological materials (lithological logs), and the distribution of Quaternary sediments (New Zealand 1:250 000-scale geological map; Heron 2014). The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report. The coloured background is the LINZ Topo 250 map. Note that only the south-eastern sector of the Waitaki District (where the topographic base-map is displayed) lies in the Otago region.

2.0 BACKGROUND INFORMATION

2.1 Geological Setting

The geological sequence of the Otago region 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 greywacke and schist. Following its formation between 250 and 100 million years ago, erosion formed a flattish land surface across the basement rock, and this was later buried by younger sedimentary rocks (cover rocks), ranging in age from about 100 to about 2.6 million years. Since about 5 million years ago, tectonic deformation associated with movement along the boundary between the Pacific and Australian plates has produced the Southern Alps and the range and basin landscape of Otago. The ranges have been uplifted along geological faults, while the basins have experienced the least amount of faulting, folding or uplift. Most of the cover rocks have been eroded off the greywacke or schist ranges, though cover rocks are still preserved in many parts of the basins. It is in the basins and the river valleys of Otago that Quaternary-age sediments (younger than 2.6 million years) have accumulated, and it is these sediments that may be potentially susceptible to liquefaction.

During the Quaternary Period, cyclic shifts in global climate saw periods of generally cool conditions (glaciations, or ‘ice ages’) separated by periods of warmer climate (‘interglaciations’), such as exists today. During a glaciation, ice was not everywhere in New Zealand, but rather the climate became cool enough for extensive glaciers to form in high mountain areas. Ice from the Southern Alps flowed into the Wakatipu Basin, and the Wanaka-Hawea basin, and lakes Wakatipu, Wanaka and Hawea lie in the footprints of former glaciers. Ice was extensive in the upper catchments of Wakatipu, Wanaka and Hawea. Glaciers or local ice caps also formed on many of the higher ranges of Central Otago but did not extend down into adjacent basins. Little if any ice formed on the relatively low-altitude Kakanui Mountains or the Rock and Pillar Range. Other parts of the region remained ice-free.

Glacial cycles had a strong influence on coastal Otago, because sea level is affected by global volume of ice on land. During glaciations, water locked up in vast ice sheets that formed on Europe and North America dropped the level of the sea as much as 120 m lower than it is now. The last time of minimum sea level was about 18,000 years ago, after which the Northern Hemisphere ice sheets melted and sea level rose, stabilizing at its present level about 7000 years ago. The sea was last as high as it is now about 125,000 years ago, during the last interglacial period.

During glacial low sea levels, the Otago coast lay between 30 and 45 km seaward of where it is today, and an extensive plain would have existed on what is now the continental shelf. The continental shelf is narrowest offshore from the Clutha and Dunedin districts. The estuaries, inlets and harbours that indent the Otago coast southwest of about Shag Point are former river or stream valleys that had relatively steep courses to the shoreline during glacial low sea levels and were drowned during sea level rise. Northeast of Shag Point, the continental shelf becomes progressively wider, and low sea levels had much less effect on river and stream gradients. That is why there are fewer estuaries along that part of the Waitaki District coast. The drowned and infilled estuarine valleys are underlain by wet, saturated sediments, that include river sands and gravels, beach and dune sands, peats within swamps, and marine to estuarine sands or silts. Those sandy and silty sediments, in particular circumstances, are particularly susceptible to liquefaction.

During glaciations, the generally colder climate reduced the vegetation cover on the hills and mountains, encouraging erosion that delivered a general excess of sediment to the river and stream systems across Otago. This resulted in the build-up of sediment in the valley floors. The sediments of these environments tend to be dominated by gravel, but sand or silt layers or pods may be present and could be potentially susceptible to liquefaction. As the climate warmed into the present interglaciation, many rivers and streams cut down into their valley floors, producing terraces. The downcutting has tended to lower the groundwater levels beneath the terraces, resulting in lessening of any liquefaction potential there.

The retreat of ice at the end of the last glaciation brought major changes to the formerly glaciated catchments, with large volumes of fan- and fan-delta sediment accumulating in and around the glacial lakes, and the floors of valleys draining into the lakes. These environments offer considerable possibility for the presence of river or lake sand and silt that may have potential for liquefaction.

2.2 Seismicity

A general review of Otago's seismic risk is given by Murashev and Davey (2005), with a more detailed review of seismic risk for the Queenstown Lakes District provided by Mackey (2015). A distinction exists 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. Nearby earthquakes, if sufficiently large, are particularly damaging.

Historically, Otago has had a very low level of nearby seismicity, with very few earthquakes centred beneath the area (Stirling *et al.*, 2012). Most earthquakes that have been felt in the Otago region were examples of distant seismicity, centred outside the region, especially in the Fiordland area. However, several geological faults in Otago show evidence for having moved in the recent geological past (i.e. during Late Quaternary time; Appendix 1) and would have generated large earthquakes. Although the likelihood is considered low, the possibility exists for large earthquakes to be generated on geological fault within Otago.

Recent examples of distant seismicity felt in Otago are the 2003 Fiordland Earthquake and 2009 Dusky Sound Earthquake, both centred in Fiordland, and the 2010 Darfield Earthquake and 2016 Kaikoura Earthquake, both centred in Canterbury. In Otago, these earthquakes produced ground shaking that was noticed by many people but caused little if any damage in Otago. The 2003 earthquake caused minor liquefaction near Te Anau and Manapouri in the Southland region, close to the epicentre, but these effects did not extend as far as the Otago region (Hancox *et al.* 2003; Mackey 2015).

Few notably strong or damaging nearby earthquakes have occurred in Otago since European settlement. A sequence of three earthquakes in 1876 in the Oamaru area (Oamaru Earthquakes), of estimated magnitudes (M) up to 5.8, caused some damage to chimneys and buildings there (Downes 1995). The M 4.9 1974 Dunedin Earthquake, which is reviewed in detail by Murashev & Davey (2005), caused building damage in Dunedin. The 2015 Matukituki Earthquake, although M 5.8 and centred only 30 km from Wanaka, caused minor landslides and rockfalls close to the epicentre (Cox *et al.* 2015), but did not cause any building damage, according to newspaper reports at the time.

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 at shallow depth and epicentre close to the city, and consequently caused notable shaking damage.

2.3 The Nature and Occurrence of Liquefaction and Lateral Spreading

Strong earthquake shaking is required to induce liquefaction in susceptible sediments. The 2010–2011 Canterbury earthquake sequence highlighted many of the effects and consequences of liquefaction (Brackley 2012; Figure 2.1). Liquefaction can only occur in water-saturated sandy or silty materials, and therefore the depth to the groundwater table is a key factor in the occurrence of liquefaction. It was found in the Canterbury earthquake sequence that liquefaction only occurred where the depth to groundwater was less than about 5 m (for more information, see Barrell *et al.* 2014). For that reason, depth to groundwater has guided the interpretation of extent of liquefaction-susceptible ground mapped for this project.

A typical consequence of liquefaction is the ejection from the ground of liquefied sediment, usually along with copious amounts of groundwater. Relatively minor liquefaction may produce sand boils or sand 'blows', like little volcanoes (Figure 2.1A). 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 2.1B). The ejection of material commonly results in differential sagging (settlement) 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'.

Lateral spreading is a related phenomenon resulting from earthquake-induced liquefaction of underlying sediments. Liquefaction-induced loss of strength in the subsurface causes the ground to move almost horizontally toward any nearby free-face, such as a river bank or edge of an embankment, and typically results in cracking or deep fissuring of the ground, and differential ground settlement (Figure 2.1C). Lateral spreading is usually associated with coastlines, lakeshores, river channels, and the margins of reclaimed ground or raised embankments.

No instances of liquefaction have been recorded in Otago since at least the mid-1800s, when written record-keeping began (Murashev and Davey 2005). During the 2010–2011 Canterbury earthquake sequence, on notably susceptible ground, liquefaction that was minor in severity (sand boils) and localised/limited in extent was initiated by nearby earthquakes with magnitudes in the low 5s (Quigley *et al.* 2013).

The anticipated major earthquake on the Alpine Fault along the western edge of the Southern Alps and lying as close as ~75 km northwest of the Queenstown and Wanaka townships, and only ~45 km northwest of Makarora and Glenorchy, will likely cause some liquefaction in at least the north-western part of Otago. The Alpine Fault has experienced at least 27 earthquakes during the past ~8000 years. They have occurred on average once every ~300 years, although the interval between each earthquake can be as short as ~200 years or as long as ~400 years (Berryman *et al.* 2012). The fault has not experienced a major earthquake since about 1717 AD (301 years before 2018), based on tree ring studies. Statistical calculations indicate a 29% likelihood that the next Alpine Fault earthquake will occur within the next 50 years (Cochran *et al.* 2017). The more time that elapses, the more the likelihood increases.

Figure 2.1 Photos illustrating some effects of liquefaction and lateral spreading. **A**: Relatively minor liquefaction effects in a paddock near Taitapu, with pods of grey sand/silt that issued from the ground during the 2010 Darfield Earthquake. GNS Science VML ID: 1398421; D.J.A. Barrell, 5th Sept 2010. **B**: Severe liquefaction effects at Ferrymead, eastern Christchurch, where vast amounts of sand/silt issued from the ground, causing localised subsidence, during the 2011 Christchurch Earthquake. EQC/GNS Science VML ID:164424; A. King, 24th Feb 2011. **C**: Lateral spreading and ground subsidence along a river bank in Avonside, eastern Christchurch, resulting from the 2011 Christchurch Earthquake. EQC/GNS Science VML ID: 149293; R.D. Beetham, 4th March 2011.

3.0 ASSESSMENT OF LIQUEFACTION HAZARDS

3.1 Liquefaction-Susceptibility Domains

The focus of this project has been to identify areas that, from geological and geomorphological considerations, are underlain by sediments which may have some liquefaction susceptibility. This has included interpretation of whether groundwater levels are sufficiently close to the surface to make liquefaction possible. For this assessment, Late Quaternary sediments with an estimated groundwater table deeper than 5 m are placed in Domain A. This depth criterion aligns with that of the MBIE (2017) guidelines, which identify a groundwater depth of more than 4 to 6 m indicating that liquefaction damage is unlikely (Table 4.3 of the MBIE report).

The approach used here does not define hazard zones as such, but rather identifies liquefaction-susceptibility domains, as shown on the maps and contained in the associated GIS dataset. In terms of the MBIE (2017) guidelines, the project methodology equates to a “Level A” basic desktop assessment, that is aimed at distinguishing between areas where liquefaction damage is unlikely to occur (Domain A) versus areas where liquefaction damage is possible (domains B, B1 and C).

The liquefaction-susceptibility domains are defined as follows:

- Domain A. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring. In MBIE (2017) terms, liquefaction damage is unlikely;
- 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. In MBIE (2017) terms, liquefaction damage is possible;
- Domain B1. As for Domain B, but there is geotechnical evidence for the presence of liquefaction-susceptible materials at least in some locations in the subsurface;
- 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. In MBIE (2017) terms, liquefaction damage is possible.

For domains B and C, the level of information is not sufficient to assign liquefaction vulnerability categories, which is a step that requires investigations at Level C or D classes (MBIE 2017). For that reason, both domains equate to the ‘liquefaction damage is possible’ category. Nonetheless, it is considered useful to distinguish areas that have relatively lesser (domain B) and greater (domain C) probabilities of liquefaction susceptible ground being present.

3.2 What the Liquefaction-Susceptibility Domains Mean:

3.2.1 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);

- Risks related to future earthquakes primarily relate to damage from strong ground shaking, and landslide-related phenomena (if any). Those risks, and any minor residual risk from localised liquefaction, can be managed through adherence to NZ Building Code requirements and use of insurance.

3.2.2 Domains B, B1 and C

- The geological nature of the ground is such that future earthquakes may possibly cause land damage from liquefaction.
- Collectively, domains B, B1 and C represent what may be termed 'liquefaction awareness areas', in which liquefaction is a possible hazard that warrants being given consideration in relation to land development, land-use intensification and infrastructure.
- Being in liquefaction awareness area does not mean that a liquefaction hazard exists for any particular parcel of land. Rather, it indicates the possibility that a hazard may exist. Equally, site-specific investigations may show that a hazard does not exist.
- In terms of the MBIE (2017) guidelines (Table 2.2 of the MBIE report), domains B and B1 may include at least some areas that may experience minor to moderate liquefaction-induced ground damage in response to strong earthquake shaking. Domain C may include at least some areas that may experience moderate to severe liquefaction-induced ground damage.
- There is little or no information on the extents of potentially liquefiable ground within the liquefaction awareness areas mapped as part of this project. It is likely that geotechnical investigations of a liquefaction awareness area would identify some areas within domains B, B1 or C where there is little or no liquefaction susceptibility (low or very low vulnerability; MBIE 2017) and some areas that have some liquefaction susceptibility (medium or high vulnerability).
- Further work, involving the collection of more geotechnical investigation information, would be necessary to undertake Level C or D liquefaction assessments for areas mapped here as domains B, B1 and C, if liquefaction vulnerability maps (MBIE 2017) were to be developed. Existing assessments, such as the Tonkin & Taylor (2013) liquefaction hazard maps for selected urban areas in Queenstown Lakes District, go some way towards that. Higher-level liquefaction assessments would be useful for areas of existing or proposed future urban or infrastructural development.
- Based on present levels of information, consideration could be given to managing potential liquefaction risk in liquefaction awareness areas by general guidance or by regulatory provisions in district plans, for example. Options could include specifying degrees of geotechnical investigation (e.g. Tonkin and Taylor 2013), and/or the adoption of liquefaction-mitigating structural measures (e.g. MBIE 2016). For a new residential house in domains B and B1, a possible alternative to undertaking geotechnical investigations to determine foundation requirements could simply be to use strengthened foundations. The potential of areas of Domain C to experience more serious liquefaction provides an incentive to make geotechnical investigations for foundation design the preferred approach. In the case of residential subdivision developments, or the construction of commercial, industrial or high-importance buildings in liquefaction awareness areas, geotechnical investigations would be an expected component of planning and design.

3.3 Accuracy and Limitations of the Liquefaction-Susceptibility Mapping

Liquefaction-susceptibility domains have been mapped based on the information sources listed in Section 1.4. The weighting of the various components of geological, geomorphological and hydrological information used to map the extent of domains is indicated where appropriate in Appendix 3. The domain boundaries have been drawn based on those considerations.

All of Otago is covered by 1:50,000-scale Topo 50 topographic maps and high-resolution colour aerial photos. For most of Otago, these are the resources used for positioning liquefaction-susceptibility polygons, and the polygon boundaries should be considered accurate to plus or minus 50 m. This means that each domain polygon boundary equates to a 100-m wide zone, centred on the location where the line is drawn. In areas of lidar coverage, the mapping scale is nominally taken as 1:10 000, and domain boundaries should be regarded as 20 m wide zones. In towns and villages, where Google Earth Street View was available at the time of mapping, Google Earth ground photography was accessed to help in positioning domain boundaries. In those areas, the nominated mapping scale is 1:1000, and boundaries are considered accurate at the scale of property parcels and buildings. The Appendix 3 commentary explains where those more detailed scales apply.

The main limitation of the liquefaction-susceptibility map is that there is considerable uncertainty in the exact nature of the subsurface sediments whose character defines the extent of domains B and C. The mapped extents of each domain represent best estimates based on the interpretation of geological and geomorphological information, but the uncertainties are difficult to quantify from available data. For that reason, it is important that the GIS map of liquefaction-susceptibility domains be seen only as providing general guidance for planning, development and hazard/risk reduction. More specifically, the map's main value is to indicate areas where liquefaction is a possible hazard that may warrant consideration for matters relating to infrastructure, built assets or emergency management preparations.

3.4 Description of the Areas Mapped

3.4.1 General Description

A region-wide overview of the liquefaction-susceptibility map is provided in Appendix 3 (Figure A3.1), and liquefaction-susceptibility maps are presented for each district in Figures 3.1–3.4.

Domain C, which is regarded as having the greatest likelihood of liquefaction-susceptible ground being present, is confined to the lower reaches of the main valleys along the Clutha District coast, and the south-eastern part of the Waitaki District coast. Areas of Domain B are identified along the floors of many of the larger river or stream valleys in all districts, and in the Queenstown Lakes District, in places around the margins of lakes Wakatipu, Hayes and Wanaka. Also within the Queenstown Lakes District are areas within or close to towns where geotechnical data indicate the localised presence of liquefaction-susceptible materials in the subsurface. Those areas are identified as Domain B1, based on advice from GeoSolve (2018).

Where Domain B is mapped along valley floors, valley gradient is the criterion used for defining the up-valley limit of the domain. The reasoning is that in relatively low-gradient valleys, there is a greater likelihood of sand or silt being deposited as layers or in channels, compared to steeper-gradient valleys where water flows will be swifter, and gravel will be the main deposit while sand and silt remain in suspension. For this assessment, a valley where topographic map contours show an elevation change of less than 20 m per 2 km (referred to here as 'low-gradient') is assumed to be sufficient gentle for there to be some likelihood of liquefaction-susceptible sand or silt deposits being present. There is historical precedent in New Zealand for minor to moderate liquefaction occurring in a low-gradient river valley. During the 1929 Murchison and 1968 Inangahua earthquakes in the Buller District, ejection of sand occurred in several places, locally extensive, many tens of kilometres up-valley from the coast (Berrill *et al.* 1988).

3.4.2 Queenstown Lakes District

Both Lake Wakatipu and Lake Wanaka formerly stood at higher levels after their glaciers retreated at the end of the Last Glaciation. Inflowing streams and rivers built fan-deltas out into the higher lake, and these were left stranded as the lakes fell to their modern levels. A prominent example is the Shotover Delta that separates lakes Wakatipu and Hayes, which were formerly part of a single arm of enlarged Lake Wakatipu. In some of the bays, large accumulations of beach sediments formed, and have continued to form to the present day. Notable examples are at the southern ends of Lake Wakatipu at Kingston, and Lake Wanaka around Roys Bay (refer to Appendix 3 for location information).

There is considered to be some likelihood of liquefaction-susceptible ground being present in areas underlain by fan-delta or delta deposits, where the groundwater table is shallow. These include the lakeward margins of fan-deltas, and the inset valleys of streams where they have cut down into fan-deltas flowing the fall in lake levels, as detailed in Appendix 3. These areas also have topographic relief in the form of terrace edges, and lakeward cliffs or slopes, and the potential for lateral spreading should also be borne in mind.

Areas where there is more potential for liquefaction-susceptible materials in Domain B (i.e. moderate rather than low likelihood) are where beach or stream sediments rest on lake silts, in downtown Wanaka, at Kingston, and along the Horne Creek valley floor in the Queenstown urban area. In these places, geotechnical investigations have shown that potentially liquefiable materials are present (all are Domain B1), although how extensive those materials are in the subsurface, and the risk and severity of liquefaction occurring is not yet established. Other areas of Domain B where there is considered to be relatively more potential for liquefaction-susceptibility materials are the lower reaches of main rivers flowing into the lakes, specifically the combined valleys of the Dart River / Te Awa Whakatipu and Rees River, the Matukituki River downstream of the West Wanaka Road bridge, and the Makarora River downstream of the Wilkin River junction. The same status is considered appropriate for the broad valley floors adjoining Moke Lake.

The other areas of Domain B in the district relate to broad valley floors, and lowest terraces, of the larger rivers, including sectors of the main tributaries of Lake Wakatipu, a sector of the upper Shotover catchment, and the middle reaches of the Matukituki, Makarora, Wilkin and Hunter valleys. Also included is the Cardrona valley. In all these places, the Domain B classification addresses the possible localised presence of buried sand- or silt-filled channels. Overall, these areas are considered to have a low rather than moderate likelihood of liquefaction-susceptible materials being present. The periphery of Lake Hawea is assessed as having negligible liquefaction susceptibility, because its level has been raised artificially, and any natural beach or fan-delta sediments are well below modern lake levels. A point to note in relation to all these lakes is that lake-bed sediments can also liquefy due to earthquake shaking and is a factor to consider for any structures at lake shores or extending into a lake.

In summary, some liquefaction potential is identified at or close to most of the built-up areas of the Queenstown Lakes District, except for Lake Hawea township, Hawea Flat and Luggate.

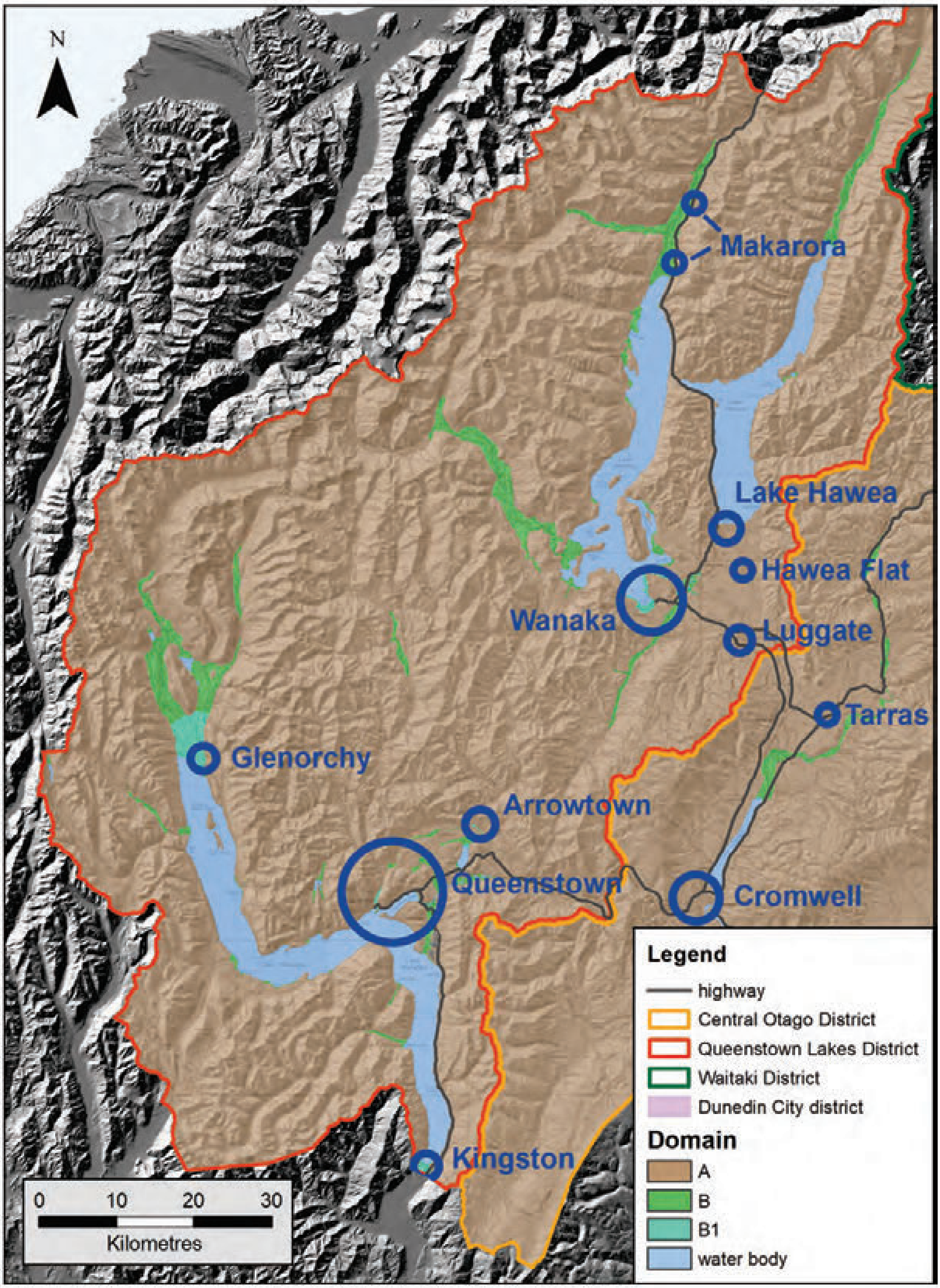

Figure 3.1 Overview map of liquefaction susceptibility domains for the Queenstown Lakes District. Refer to Section 3.1 for definitions of the domains.

3.4.3 Central Otago District

In the Central Otago District (Figure 3.2), localised areas of broad river or stream valley floor, along with the lowest associated terraces, are classified as Domain B. These include sectors of the Lindis River, the Manuherikia River including its Lauder Creek and Dunstan Creek tributaries, the Ida Valley, the Taieri River and several of its larger tributaries in the Maniototo basin (refer to Appendix 3 for location information). The classification addresses the possible localised presence of buried sand- or silt-filled channels. Overall, these are considered to have a low rather than moderate likelihood of liquefaction-susceptible materials being present, except along the Taieri River, where the likelihood is considered moderate. This is due to its very low gradient which raises the possibility that at least in places sandy and silty sediment may be more prevalent than gravelly sediment.

Most of the length of the Clutha River valley is placed in Domain A, because apart from the active floodplain, the flanking river terraces are many metres above river level, and the groundwater table is relative deep. The only exception is the Clutha valley floor and lowest terraces between The Lindis River and Lake Dunstan. The reasoning is that although the upper part of the Clutha River carries very little sand or silt, because it is sourced from two large, clear, lakes, the Lindis River is a substantial source of fine sediments, raising the possibility of there being buried sand-filled channels downstream of its confluence with the Clutha River.

The township of Omakau, and villages of Lauder, Oturehua and Waipiata are the only built-up areas that are partly or wholly on ground classified as Domain B. No liquefaction susceptibility is identified at the built-up areas of Cromwell, Clyde, Alexandra, Roxburgh, Ettrick, Millers Flat, Ranfurly, Naseby and Patearoa, or the localities of Tarras and St Bathans.

3.4.4 Clutha District

The Clutha District (Figure 3.3) has many scattered areas along valley and stream floors identified as Domain B, and locally extensive areas classified as Domain C close to the coast.

Areas classified as Domain B comprise low-gradient reaches of broad-floored river and stream valleys, including any terraces close to river or stream level. The largest areas of Domain B are in the Pomahaka River catchment, including the Tapanui and Heriot areas, and the Tokomairiro Plain near Milton. Estuarine valley sectors and low-lying plains, terraces or wetlands around the margins of numerous bays and inlets are classified as Domain C. The largest area of Domain C is the Inch Clutha Plain, downstream of Balclutha. This area was formerly a marine inlet or estuarine lake, following the culmination of post-glacial sea level rise. Lake Tuakitoto is the only remnant of this water body, the rest having been displaced by the accumulation of Clutha River sediment, forming the plain. The southwestern sector of the Taieri Plain, in the vicinity of Lake Waihola, also is classified as Domain C.

Appendix 3 provides detailed maps for towns and villages that lie on or close to areas of Domain B or C. The villages of Heriot, Beaumont and Waitahuna are at least partly on ground classified as Domain B, as are parts of the townships of Lawrence, Balclutha, Owaka, and virtually all of Milton. The lower-lying parts of Kaitangata township, Taieri Mouth village, and all parts of the Pounawea, New Haven and Toko Mouth villages are on ground classified as Domain C. Part of Waihola township is on areas mapped as domains B and C. No liquefaction susceptibility is identified in the built-up areas of Tapanui, Clinton, Papatowai and Kaka Point.

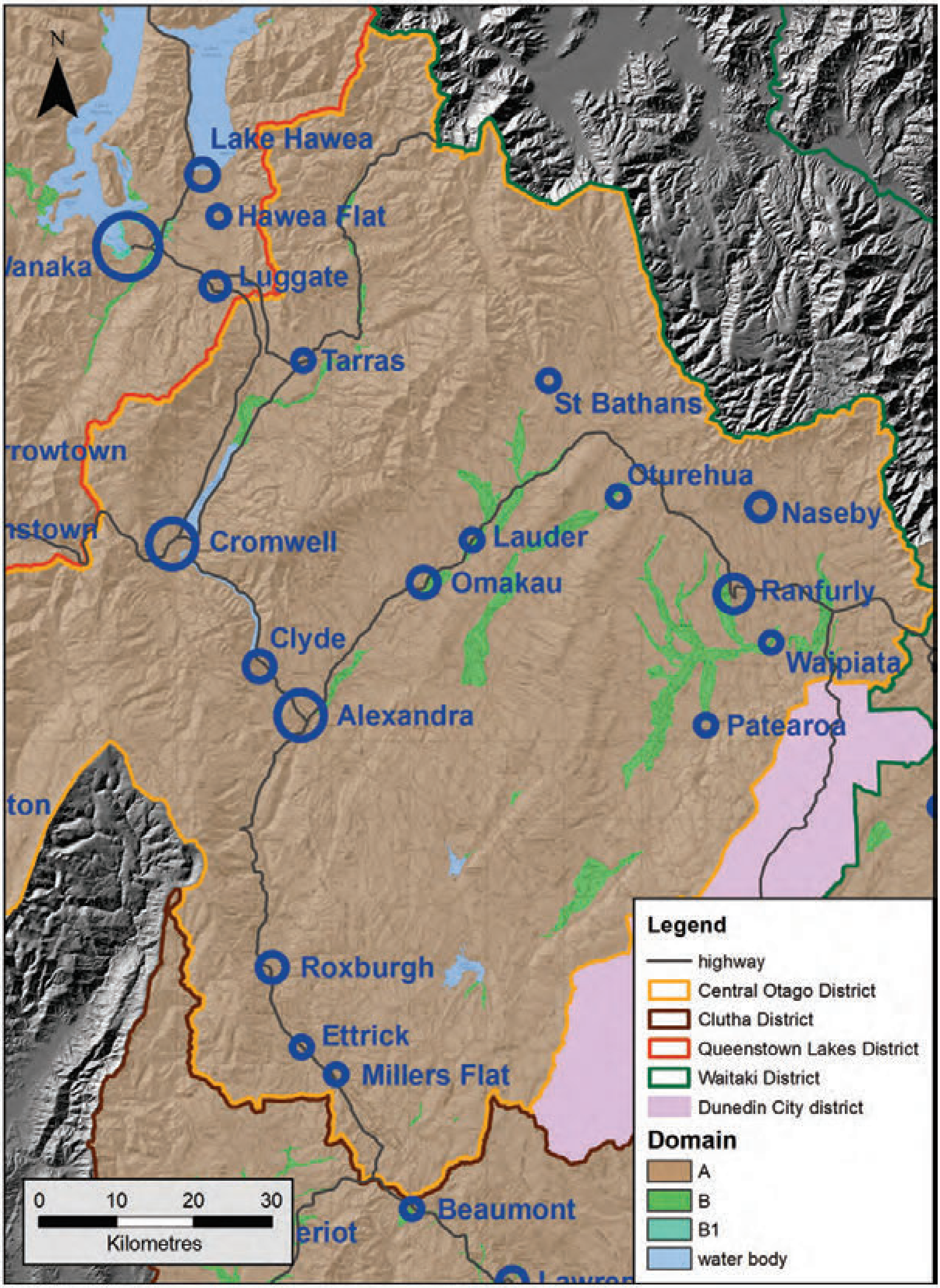

Figure 3.2 Overview map of liquefaction-susceptibility domains for the Central Otago District. Refer to Section 3.1 for definitions of the domains. The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report.

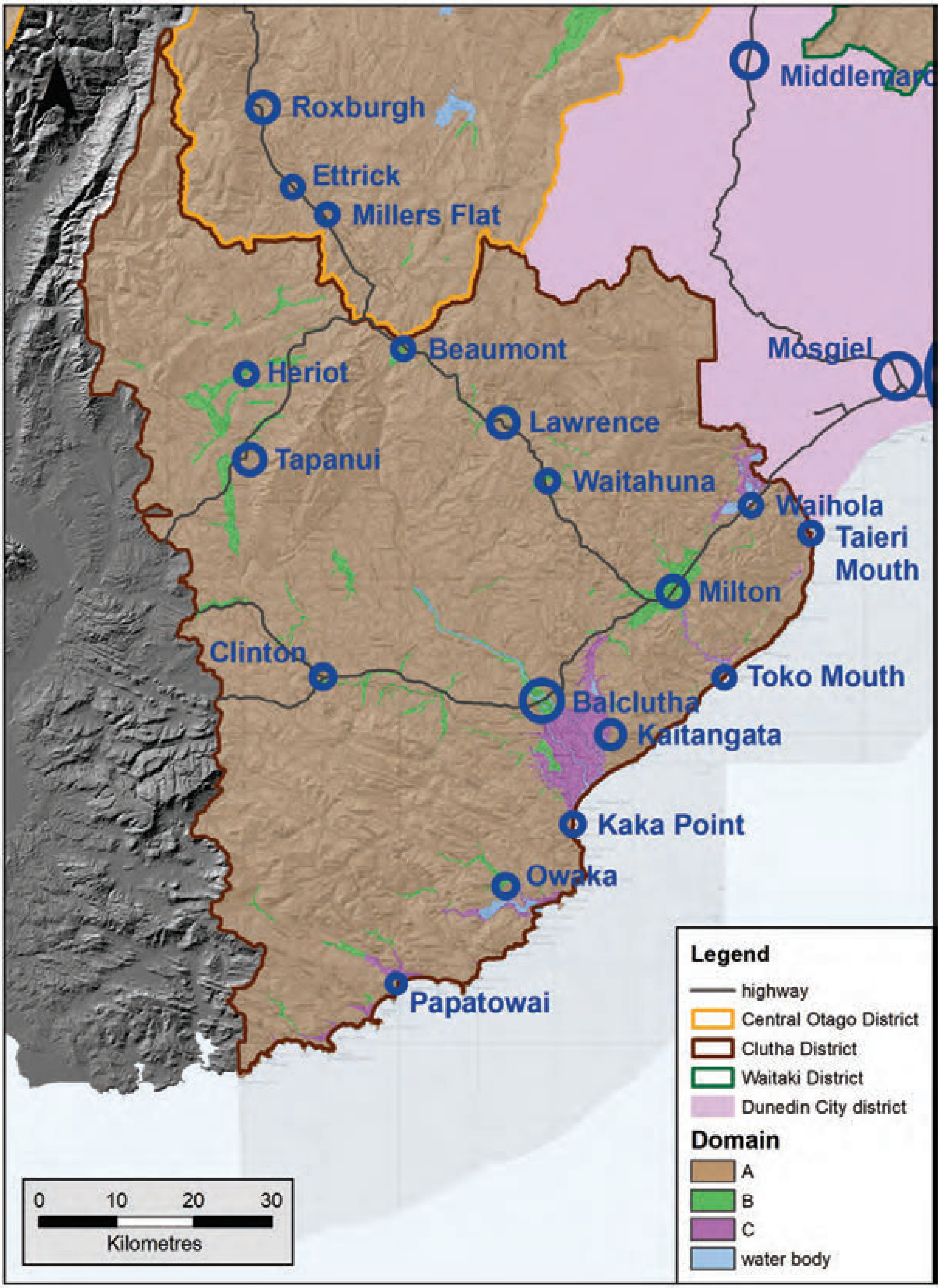

Figure 3.3 Overview map of liquefaction-susceptibility domains for the Clutha District. Refer to Section 3.1 for definitions of the domains The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report.

3.4.5 Waitaki District

In the Waitaki District (Figure 3.4), many of the larger river and stream valleys have sectors of their broad floors and lowest terraces identified as Domain B. Localised areas are classified as Domain C close to the coast, including estuarine reaches of Pleasant River, Shag River (Waihemo) and the Kakanui River. Appendix 3 provides more information on the locations mentioned below.

Areas classified as Domain B include the lower (non-estuarine) reaches of Watkin Creek and Pleasant River, the Shag River (Waihemo) and several un-named tributaries, Kurinui Creek, the Waianakarua River, extensive sectors of the Kakanui River and its Kauru River and Island Stream tributaries, much of the Waiareka Creek valley, parts of the Oamaru Creek valley, and the lower terraces of the Waitaki River. The Shag (Waihemo), Kurinui, Waianakarua, Kakanui/Kauru and Waitaki catchments are sourced from rugged hill to mountain terrain, and their alluvial deposits are predominantly gravelly. The identification of Domain B in these systems addresses the possible localised presence of buried sand- or silt-filled channels. These valleys are considered to have a low rather than moderate likelihood of liquefaction-susceptible materials being present. In contrast, the other valleys mentioned above, and the minor tributaries of the Shag River (Waihemo), are sourced from more gentle terrain, and sand and silt are likely to be a more prominent feature of their valley-floor deposits. They are considered to have a moderate likelihood of liquefaction-susceptible materials being present.

Visual comparison of Figures 3.3 and 3.4 highlights that Domain C is more extensive in the Clutha District than the Waitaki District. As explained in Section 2.1, this is because the continental shelf offshore from the Waitaki District is wider, and its gradient less, than that offshore from the Clutha District. Accordingly, the impact of natural sea level changes due to glacial cycles had less impact on the river and stream systems of the Waitaki District. The culmination of post-glacial sea level rise invaded the lower reaches of Waitaki District rivers to a much lesser extent than in the Clutha and Dunedin City districts (Barrell *et al.* 2014).

In summary for the Waitaki District, most of Dunback, and localised parts of Palmerston, Hampden, Kakanui, Maheno, Enfield, Oamaru and the villages of Waitaki Bridge and Waitaki Mouth (south side) are on ground classified as Domain B. Although Domain C is mapped in in proximity to Kakanui township, none of the built-up area there is on Domain C. No liquefaction susceptibility is identified in the townships of Moeraki, Weston and Herbert.

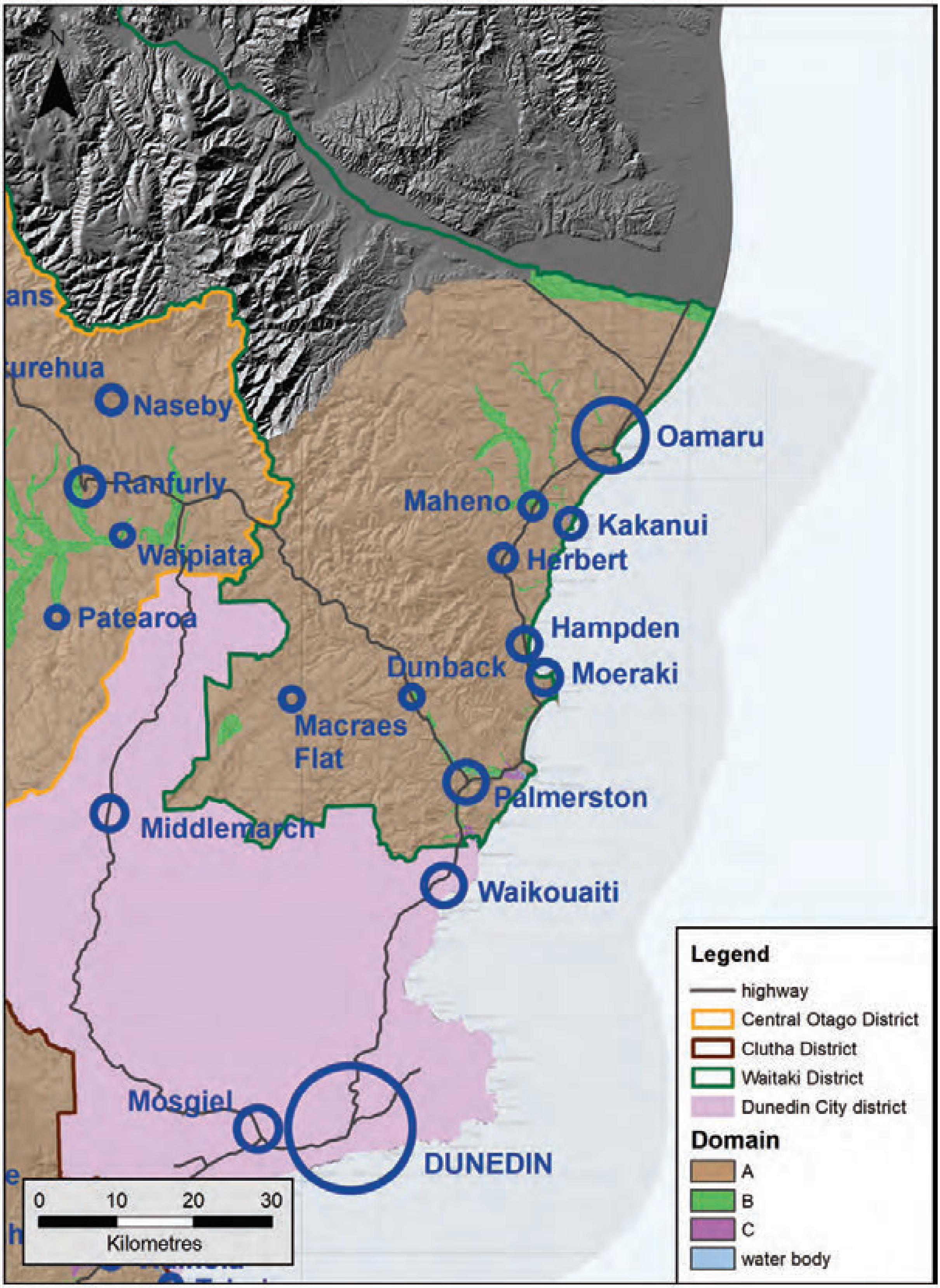

Figure 3.4 Overview map of liquefaction-susceptibility domains for the Waitaki District. Refer to Section 3.1 for definitions of the domains. The Dunedin City district is masked because it is addressed in the Barrell *et al.* (2014) report.

4.0 DISCUSSION

4.1 Comparison with Previous Work

GIS analysis of the four districts addressed in this report (Table 4.1) shows that Quaternary sediments underlie 15% of the land area. This is similar to the percentage area of Quaternary sediments (12%) in Dunedin district (Barrell *et al.* 2014). As an overall percentage of area, the liquefaction awareness areas (domains B, B1 and C) occupy less than 4% of the district land areas (Table 4.1). Domains B and B1 represent on average about 3% of the area of each district. Domain C is confined to the districts with coastal sectors, and Table 4.1 highlights that Domain C is much more extensive along the Clutha District coast (105 km^2 — 1.6% of the district), compared to the Waitaki District coast (7 km^2 – 0.2% of the district). For comparison, the Dunedin City district has 1.4% by area mapped as Domain B, and 4.9% by area mapped as Domain C (Barrell *et al.* 2014).

Table 4.1 Evaluation of the relative extents of liquefaction-susceptibility domains in the districts of Otago (excluding Dunedin). District areas (square kilometres – km^2) are calculated in the GIS and may differ from other published estimates (e.g., Wikipedia). The Waitaki District area is just that portion lying within the Otago region. The areas given for Domain A include water bodies. Extent and percentage area of Quaternary sediments, derived from the 1:1 000 000-scale geological map (Edbrooke *et al.* 2014), are presented just for the combined districts.

	Central Otago	Clutha	Queenstown Lakes	Waitaki	All Districts
District area (sq. km)	9970	6405	9386	2913	**28674**
Quaternary sediments (km2)	-	-	-	-	**4424**
% area Quaternary sediments	-	-	-	-	**15%**
Domain A (km2)	9634	6084	9103	2828	**27649**
% area Domain A	96.6%	95.0%	97.0%	97.1%	96.4%
Domain B (km2)	336	216	249	78	**879**
Domain B1 (km2)	-	-	34	-	**34**
% area Domains B and B1	3.4%	3.4%	3.0%	2.7%	3.2%
Domain C (km2)	-	105	-	7	**112**
% area Domain C	-	1.6%	-	0.2%	0.4%

If one compares the susceptibility classification map of the Queenstown Lakes, Central Otago, Clutha and Waitaki districts (Figures 3.1–3.4) with the regional liquefaction-susceptibility map presented by Murashev & Davey (2005) (Appendix 2 – their Map 20), 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 domains B, B1 and C of the present report are of much more restricted extent. This difference arises because the Murashev & Davey (2005) 'low susceptibility' zone includes extensive areas of predominantly gravelly, and/or older, sediments with relatively deep groundwater that, in this assessment, are placed within Domain A and considered unlikely to experience damaging liquefaction.

4.2 Overall Assessment

This project involved an evaluation of information relevant for assessing liquefaction susceptibility at a district scale. The assessment was office-based and drew upon regional-scale geological, geomorphological and hydrological information, and limited subsurface information. Following on from a companion assessment for the Dunedin City district (Barrell *et al.* 2014), a three-fold classification of liquefaction susceptibility has been applied to the other four districts of Otago. In the terminology of the MBIE (2017) liquefaction guidelines, the approach used in this project is a “Level A” basic desktop assessment.

The liquefaction-susceptibility domains distinguish areas where geological and/or groundwater conditions indicate that the occurrence of damaging liquefaction is unlikely (Domain A), and areas where damaging liquefaction may be a possibility (domains B, B1 and C). Domain B is assessed as having a low to moderate likelihood of being underlain, in part, by liquefiable materials, while Domain C is considered to have a moderate to high likelihood of being underlain, in part, by liquefiable materials (Domain C). In Queenstown Lakes District, there is a sub-category of Domain B, referred to as Domain B1, for areas where geotechnical data indicate at least a localised presence of liquefaction-susceptible materials in the subsurface.

Domain A comprises areas underlain by rock, or by sediments with a deep groundwater table. There is, however, the proviso that its mapping is based on highly generalised geological maps, and there may conceivably be localised patches of poorly drained, soft sediments, on the floors of stream valleys for example, that do not appear on those maps. This creates a possibility that Domain A include localised pockets of liquefaction-susceptible sediments.

Due to their likely geological character, domains B and B1 are assessed as being areas where any liquefaction-induced ground damage would probably be in the category of minor to moderate. In contrast, the geological character of Domain C could produce moderate to serious liquefaction-induced ground damage. It is important to appreciate that the presence and extent of any liquefaction-susceptible materials in domains B or C is not yet established. This is why they are designated as ‘liquefaction awareness areas’, and are not hazard zones, because the extent and degree of hazard, if any, is yet to be quantified. More intensive investigations would be needed to achieve a Level C or D liquefaction assessment, as explained in the MBIE (2017) guidelines. The Level A assessment undertaken for this project provides a basis for targeting more detailed assessments in places where more information is needed on liquefaction hazards.

The domains identified in this report highlight areas where liquefaction may possibly be an issue requiring consideration, in relation to existing and future development. In most cases, areas classified as domains B or C lack hard evidence 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. In areas of Domain B1, there is existing information indicating at least the localised presence of liquefaction-susceptible materials. A desirable future step, as more sub-surface geological and geotechnical information is obtained, 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. This may enable liquefaction assessments to be advanced to Level C or D status in selected areas.

Present levels of information could be used to assist in managing liquefaction hazards. In areas of Domain A, damaging liquefaction is unlikely to occur, and providing that any building and infrastructure development accords with existing standards (e.g., Resource Management Act and the Building Act), any residual liquefaction risk could be managed using insurance. For liquefaction awareness areas, options range from general guidance to regulatory measures. One approach developed for parts of the Queenstown Lakes District (Tonkin and Taylor 2013) specifies the levels of investigation, and foundation design, that should be used for areas of potentially liquefiable ground. As another example, liquefaction-mitigating structural measures (e.g. MBIE 2016) could be used for new residential houses in domains B and B1 as an alternative to undertaking geotechnical investigations to determine foundation requirements. Due to the potential of areas of Domain C to experience more serious liquefaction, geotechnical investigations for foundation design may be a preferred approach for residential dwellings. In the case of large-scale residential subdivision developments, or the construction of commercial, industrial or high-importance buildings in liquefaction awareness areas, geotechnical investigations would be an expected component of planning and design. Territorial authorities may wish to consider requiring geotechnical investigations carried out for consenting processes to be uploaded into the NZ Geotechnical Database. This would allow the presence or otherwise of liquefiable materials, and their associated hazards, to be refined in the future.

Areas within domains B, B1, 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. Specific mapping of lateral spreading hazard did not form part of the present project, as that would be more appropriate as part of more detailed level of liquefaction assessment. Information on lateral spreading assessment is provided in the MBIE (2017) guidelines. Another point to consider is that of embankments built on potentially liquefiable materials. These 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 information in this report is, for the most part, based on generalised assessments and broad-scale inferences, rather than detailed investigations. It should not be used in isolation for any purposes that require site-specific information.

5.0 CONCLUSIONS

The susceptibility of land to earthquake-induced liquefaction has been assessed for the Queenstown Lakes, Central Otago, Clutha and Waitaki districts of the Otago region in an office-based evaluation of geological and landform information relevant to liquefaction hazards, supplemented where possible with borehole geological information and groundwater data, and expert geotechnical knowledge. This approach equates for a "Level A" liquefaction assessment as described in MBIE (2017) liquefaction guidelines. A GIS-format liquefaction-susceptibility map was compiled and is described in this report. The map shows areas of similar liquefaction susceptibility using a three-fold classification of liquefaction susceptibility:

- Domain A. The ground is predominantly underlain by rock or firm sediments. Liquefaction damage is unlikely to occur;
- 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. A sub-class, Domain B1, is applied where geotechnical data indicate at least the localised presence of liquefaction-susceptible materials. Liquefaction damage is possible. The severity of any ground damage is likely to be minor to moderate.
- 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. Liquefaction damage is possible, and the degree of ground damage may be as much as moderate to severe.

The liquefaction susceptibility domains 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. A first step towards managing liquefaction risks is to ensure all building and infrastructure development accords with existing standards (e.g., Resource Management Act and the Building Act). For areas of Domain A, any residual liquefaction risk could be managed using insurance. For the liquefaction awareness areas (domains B, B1, and C), options include specifications for levels of geotechnical investigation and foundation design (e.g. MBIE 2016). For the case of single residential dwellings, one alternative to geotechnical investigations could be the use strengthened foundations.

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 5 m deep. More than 95% of the land area in the four districts is classified as Domain A – terrain underlain by materials that are non-liquefiable. Domain B occupies less than 4% of the area of the combined districts. Land classified as Domain C, comprising less than 1% by area, occurs along the coastal fringes of the Clutha and Waitaki districts. The Clutha District has by far the most extensive areas of Domain C.

6.0 ACKNOWLEDGMENTS

Michael Goldsmith and Ben Mackey of Otago Regional Council are thanked for assistance in developing the project scope and providing information that is held by the council. Katie Jones and Will Ries of GNS Science assisted with initial map compilation. The draft mapping was refined following expert geotechnical review and discussions with Colin Macdiarmid, Graeme Halliday and Fraser Wilson, among others, from GeoSolve Limited. This report has benefited from technical reviews by Phil Glassey and Sally Dellow of GNS Science.

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APPENDICES

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APPENDIX 1 EXPLANATION OF TERMS

This appendix defines terms that are identified in the main report text by an underline at their first mention. Terms that are defined elsewhere in this appendix are in **bold type**.

Epicentre	The epicentre is the location on the ground surface directly above the point underground where an earthquake initiated. That underground location is called the **hypocentre**.
Fan	A fan is an accumulation of sediments that forms a sloping landform, shaped like an open fan or segment of a cone. Fans form where a valley, channel or gully meets an area that is unconfined, or less confined. A typical location is where a smaller valley emerges from hill country onto a broad valley floor. Different types of fan may be recognised, according to their mode of formation. Fan-shaped accumulations of river or stream (alluvial) sediments are alluvial fans; fans of debris laid down by mass flows of sediment are debris-flow fans; fans built out into a lake or the sea are **fan-deltas**.
Fan-delta	A delta is a landform of broadly triangular extent, or alternatively lobe-like, formed where a river or stream flows into a body of standing water, such as a sea or lake. Sand and gravel cannot be transported by still water, so progressively accumulates at the shoreline, and in the near-offshore, to create the delta. Where the delta has been built by a relatively small stream, and has a **fan**-shaped surface, it is a fan-delta. A larger one formed by a river, with a less obvious fan shape, is often just called a delta.
Geomorphology	The scientific field dealing with the origins and characteristics of landform features.
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.
Georeferencing	Georeferencing means to align a feature such as a photograph or a map with specific geographic coordinates, so that it can be viewed in its correct geographic location. This is commonly done in a **GIS**, especially for aerial photographs.

Geotechnical investigations	Geotechnical investigation refers to 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.
GIS and polygons	A geographic information system (GIS) is a computerised mapping system designed to capture, store, manipulate, analyse, manage, and present all types of geographically-specific information. There are three main classes of GIS data: (1) information relating to a specific geographical point on the ground, such as a borehole (*point* data); (2) information associated with a linear feature such as a road (*line* data); and (3) information pertaining to specific areas of ground, such as a liquefaction-susceptibility map (*polygon* data).
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.
Lateral spreading	Lateral spreading refers to the movement of ground-forming materials towards lower ground, especially where there is a well-defined step down ('free face') to the lower ground. Assessment of lateral spreading risk is possible only at site-specific scales because it requires information on the ground strength and liquefaction susceptibility, but also on the form and height of the 'free-face' (e.g., a river channel edge). One rule of thumb is that lateral spreading can occur at a horizontal distance 20 times height of the free face, such as a river bank.
Liquefaction	Liquefaction can be defined 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. The effects of ground in the shallow subsurface include cracking of the ground and the ejection of sediment and water, resulting in uneven settlement of the ground.
Liquefaction-susceptibility awareness area (domain)	The map associated with this report ranks the ground according to the likelihood of liquefaction-susceptible materials being present in the subsurface. The map highlights areas where liquefaction may be a possible hazard to look out for, rather than implying that a hazard exists.

Quaternary Period	The period of geological time spanning the past 2.6 million years. It is subdivided in the older Pleistocene Epoch (2.6 million years ago to 11,700 years ago), and the Holocene Epoch from 11,700 years ago through to the present day. The Pleistocene is divided into Early, Middle and Late phases, with the Late Pleistocene spanning from 130,000 years ago through to the start of the Holocene. Together, the Late Pleistocene and Holocene are referred to as the Late Quaternary (130,000 years ago to present).
Stereoscopic	Stereoscopy is the examination of a pair of overlapping photographs so that they can be seen in a three-dimensional (3D) perspective. It is the same principle behind human 3D vision, because each eye sees things from a slightly different angle. Long-standing mapping practice has involving the taking of sequential vertical photos from an aeroplane in flight, to allow photos can be viewed stereoscopically, to aid the drawing of topographic map contours.

APPENDIX 2 PREVIOUS REGIONAL-SCALE LIQUEFACTION HAZARD MAP

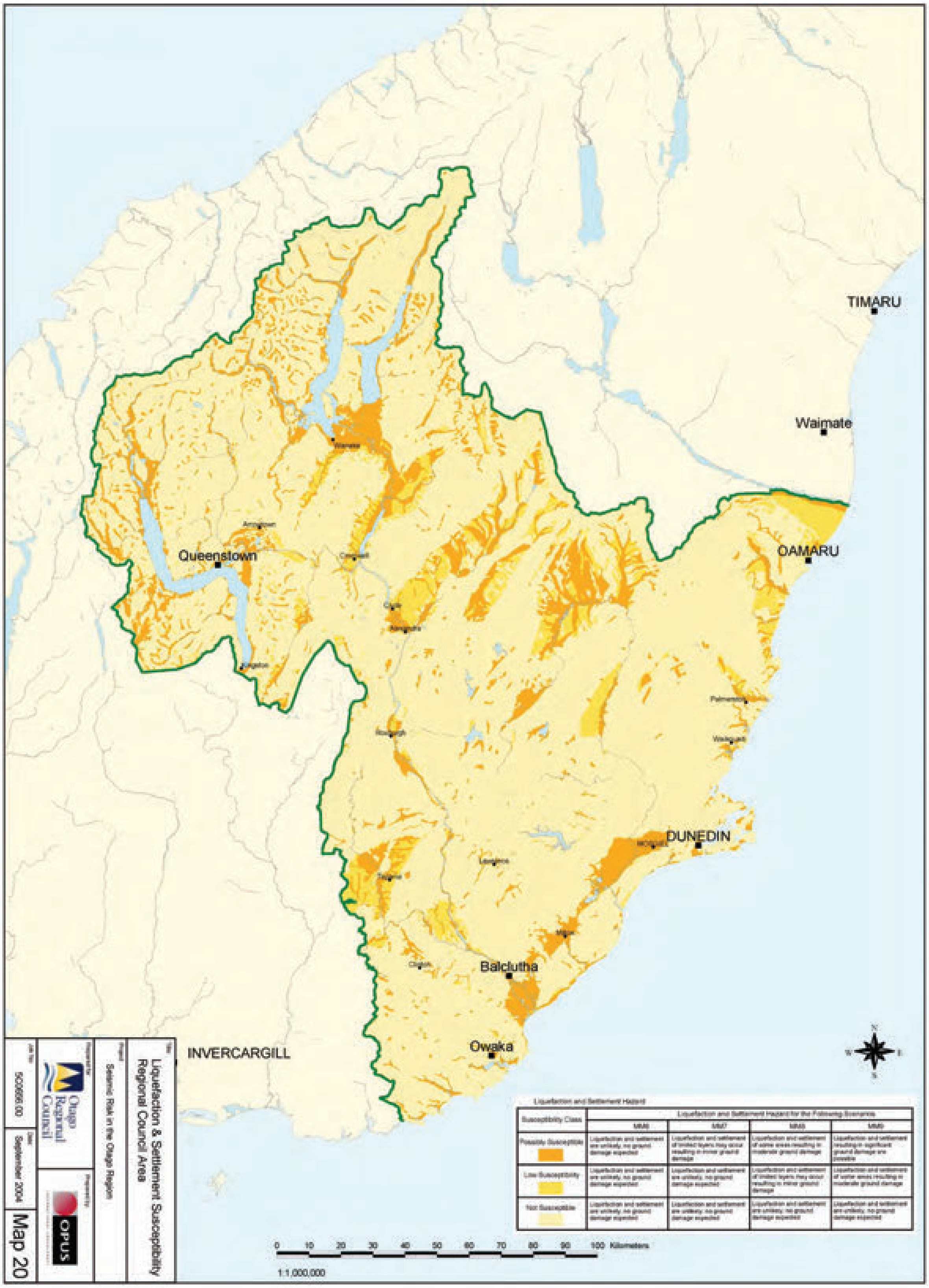

Figure A2.1 Liquefaction and settlement susceptibility, Otago region (Murashev & Davey 2005). See main report reference list for details.

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

This appendix presents a descriptive commentary on the liquefaction-susceptibility mapping on a district by district basis. The description focuses on areas where liquefaction-susceptible areas (domains B, B1 and C) are interpreted to be present, with all other areas classified as Domain A. An overview map (Figure A3.1) shows the location of detailed (1:50 000-scale) maps that include all the towns or villages that are at or close to areas of domains B, B1 or C (Figures A3.2–A3.41. No detailed maps are provided for towns or villages that are not in proximity to identified liquefaction-susceptible areas (e.g., Lake Hawea, Hawea Flat, Luggate, Cromwell, Clyde, Naseby, Roxburgh, Ettrick, Millers Flat and Herbert).

Interested readers of this appendix may benefit from accessing online topographic map imagery, such as www.topomap.co.nz, which at the time of writing is freely accessible. That online viewer enables viewing of many of the geographic locations described in this appendix and includes a search function for place names. Topographic base-maps are also accessible via some council websites. It is anticipated that the liquefaction-susceptibility map described here will be available online through the Otago Regional Council 'Otago Natural Hazards Database'. Additional detailed information on road and street names, especially in built-up areas, can be obtained through freely accessible online map applications from Google, such as Google Maps and Google Earth.

This descriptive commentary outlines the general reasoning behind the interpreted extents of the liquefaction-susceptibility domains in various places in the Otago region. Reference is made to numerous specific geographic locations, such as creeks or streams. However, the size of the region made it impractical to provide detailed topographic maps that include all those localities. Rather, the maps provided here focus on population centres, and low-lying, near-coastal, areas where liquefaction susceptibility is likely to be more significant than farther inland.

The mapping described here, especially the positioning of boundaries, is based largely on landform features. Topographic and photographic base-maps have been a key resource for the mapping. All of Otago has coverage by 1:50,000-scale topographic maps (LINZ Topo 50 map series) and high-resolution colour aerial photos, accessed digitally through the ArcGIS software used in this project. Unless stated otherwise, the mapping scale across the region is 1:50 000, and the boundary between domain polygons should be regarded as being a 100 m wide zone, rather than a line. In areas of lidar coverage, the mapping scale is 1:10 000, and domain boundaries should be regarded as 20 m wide zones. In towns and villages, where Google Earth Street View was available at the time of mapping, Google Earth ground photography was accessed to help in positioning domain boundaries. In those areas, the assigned mapping scale is 1:1 000, and boundaries are considered accurate at the scale of property parcels and buildings. The commentary indicates where these more detailed scales apply.

A3.1 Queenstown Lakes District

A3.1.1 Upper Wakatipu (Figure A3.2)

The Wakatipu lake margin between Kinloch and Glenorchy is taken from lidar and the ArcGIS base-map imagery, rather than the Topo 50 lake outline.

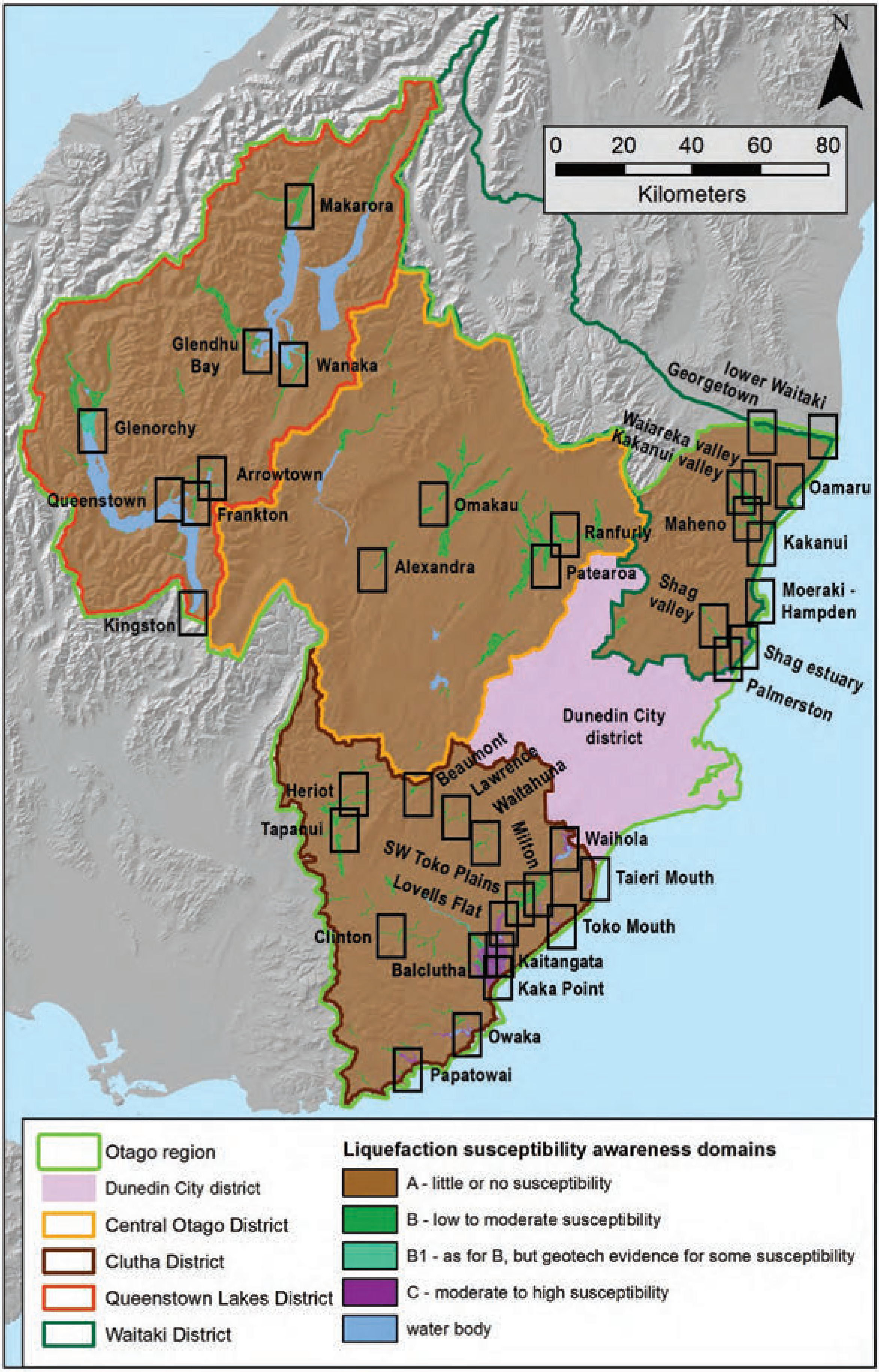

Figure A3.1 Index map showing locations of detailed liquefaction-susceptibility maps.

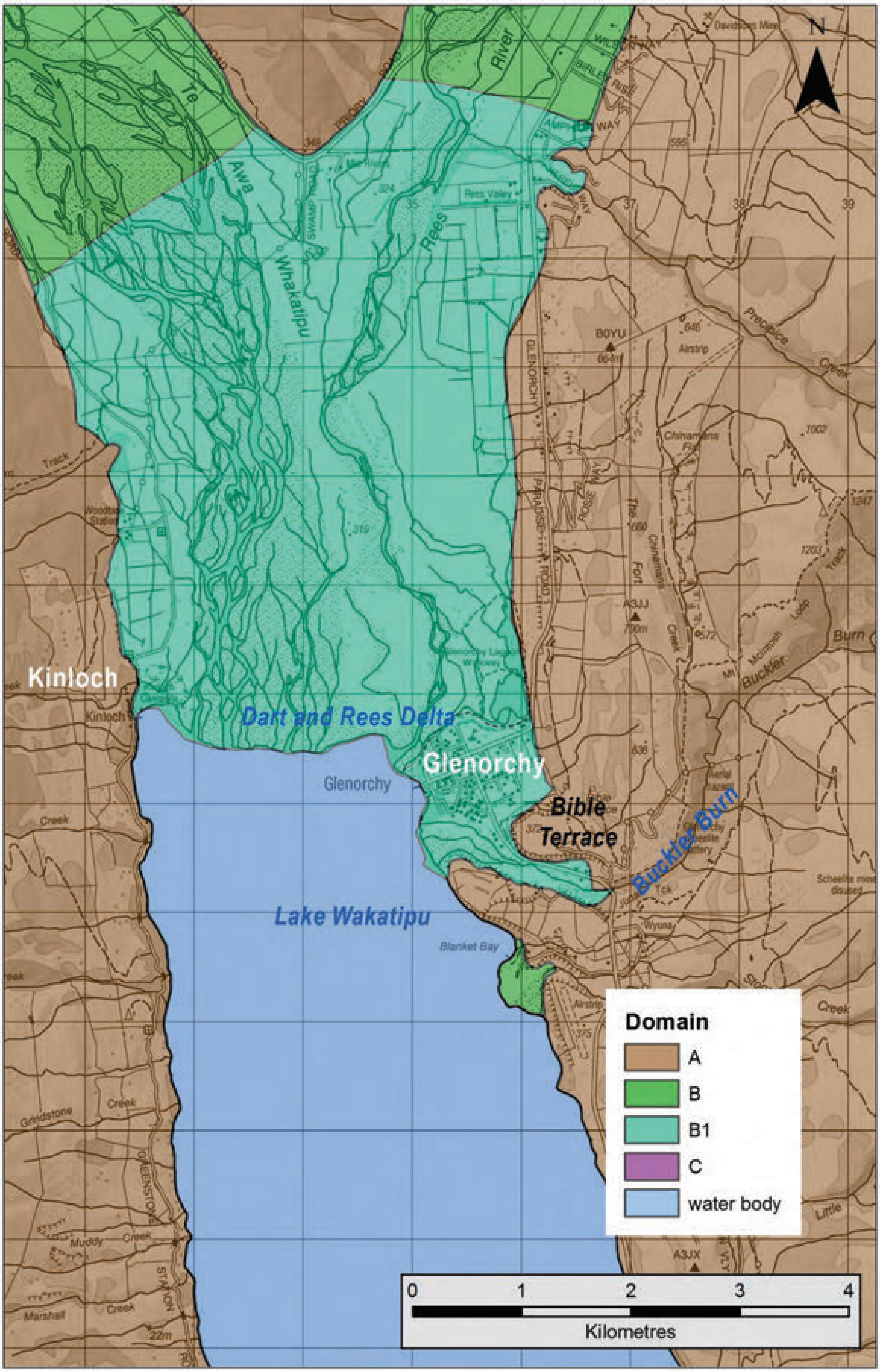

Figure A3.2 Liquefaction-susceptibility domains in the Glenorchy area. The key is generic to the dataset and not all units may be present on this map.

Localised geotechnical investigations at Glenorchy (Tonkin and Taylor 2013; GeoSolve 2018) have indicated that liquefaction-susceptible materials are present there. Therefore, that part of the Domain B area downstream of the Rees/Dart confluence is classified as Domain B1. Domain B/B1 is mapped across the Dart-Rees delta, including low-angle tributary stream fans no higher than 400 m a.s.l. The reasoning relates to evidence that the Lake Wakatipu post-glacial high-stand was up to ~367 m on the edge of the Bible Terrace at Glenorchy, and the possibility that there are buried fan-delta or lake sediments up to about that elevation. There appears to be a progressive increase in the lake high-stand shoreline to the north along Lake Wakatipu (Barrell, unpublished data), indicating progressively greater uplift (since the lake high-stand) northwards. Accordingly, the 400-m elevation contour is considered the most appropriate height to use for the upper parts of the Rees and Dart valleys 10 km or more north of Glenorchy. The overall presumption is that Lake Wakatipu formerly extended well up the Dart-Rees valleys, and so there are probably lake sediments buried well up-valley. The Domain B polygon is extended up the Dart to where the valley narrows between high river banks upstream of the 400-m contour. Where steep mountain sides, or conspicuous rocky terrain, abut the valley floor, the margin of Domain B is placed along the boundary between the valley floor and such terrain.

The Rees polygon sector is taken up the Rees to where the valley narrows just upstream of the 400-m contour. At Precipice Creek, the polygon is extended across the low inset terraces of the fan-delta but excludes the intermediate to higher fan-delta terraces on the presumption groundwater will be deep beneath those terraces. The intermediate and high fan-delta terraces around Camp Hill are also included, because they are below the Wakatipu high-stand level. Although sparse bore data in the ORC wells database indicates relatively deep groundwater (>15 m), there are included in the polygon on account of fine-grained materials and the possibility of perched groundwater within the deltaic deposits. Between Earnslaw Burn and the Rees valley, the northern margin is placed at the 400-m contour. The narrow fan-delta terrace west of Earnslaw Burn and north of Glenorchy Paradise Rd is excluded because of its narrowness and because the stream is incised as much as 20 m below the terrace surface, therefore the terrace is likely to have a relatively deep groundwater table.

In the upper Rees valley, there is a broad valley floor upstream of a large fan (Muddy Creek) built across the valley. The NW side of that fan has what appears to be a fan-delta face at an elevation slightly above the 480-m contour. It is tentatively interpreted that fan aggradation has previously impounded a lake in the Rees valley, later partly infilled and drained by erosion of the Muddy Creek fan. An area of Domain B is mapped up to about the 500-m contour, and 520 m contour in the main valley floor upstream, to acknowledge a possibility that there could be delta or lake sediments underlying the valley floor in this area.

Where the Route Burn emerges onto the main Dart valley floor, the polygon is ended at a narrow gorge which looks to be cut in rock, at about the 380-m contour.

A3.1.2 Lake Wakatipu perimeter

Fan-deltas that are notably steep are not included in Domain B, on the presumption that their sediment is predominantly medium to coarse gravel. Also, in general, fan-delta terraces associated with the Lake Wakatipu high-stand that are now well above lake or stream level are excluded, on the grounds that the groundwater table is likely to be deep. Only the fan-deltas of the relatively large tributaries are included in Domain B.

The low terraces and floodplain of the Greenstone River fan-delta included in Domain B, as is the low-gradient valley floor of its Caples River tributary. The reasoning for the latter inclusion is that high-stand Lake Wakatipu would have extended up the Caples valley, creating the possibility that its gravelly terraces and floodplain may be underlain by poorly consolidated deltaic or lake sediments. The Domain B polygon is extended up the Caples valley to approximately the 400-m contour.

Elsewhere along the Lake Wakatipu perimeter, areas fringed by fan-deltas with inset stream valleys, or broad perimeters of beach or fan-delta landforms, below the 320-m topographic contour (i.e. up to ~15 m above the present level of Lake Wakatipu), are placed in Domain B. The reasoning is the groundwater depth will be relatively shallow, thus presenting the possibility of liquefaction-susceptibility if there are sandy or silty sediments in the subsurface. Examples along the eastern shore include the inset fan of Stone Creek at Blanket Bay, the fan-delta fringe at Meiklejohns Bay along with the inset fan of Simpson Creek, the inset fan of Twelve Mile Creek, the fan-delta fringes of Bobs Cove and Closeburn, and near Jacks Point. Areas of Domain B delineated on the western shore of the lake include the inset fans and fan-delta fringes of the Von River near Mt Nicholas and Whites Bay, the Afton Burn inset fan terraces and fan-delta fringe, and the Beach Bay beach sediments, near Walter Peak. Also included in Domain B are the inset stream valley terraces and fan-delta fringes of Collins Creek at Collins Bay near Cecil Peak, and the Lochy River at Halfway Bay.

Those areas below the 320-m contour where lake margin fringes are formed in poorly consolidated sediments, but are narrow and associated with steep slopes, are placed in Domain A. The reason is that in those settings, slope instability hazard will be the primary consideration for any developments, infrastructure or land-use changes.

A3.1.3 Queenstown and Wakatipu Basin (Figures A3.3–A3.5)

The Wakatipu Basin, including the Queenstown and Arrowtown urban areas, has full lidar coverage and the mapping scale is 1:10,000. At Queenstown, the broad valley floor of Horne Creek has a low gradient, is positioned below the Lake Wakatipu high-stand, lacks incised drainage and therefore is likely to have a shallow groundwater table. Localised geotechnical investigations (Tonkin and Taylor 2013; GeoSolve 2018) indicate some liquefaction-susceptible materials are present in the subsurface, and a classification of Domain B1 is applied. Domain B1 is extended onto the lower reaches of alluvial fans in the Reavers Lane area and Horne Creek headwaters, because those fans have presumably been built out over lake sediments.

Despite the availability of Google Earth Street View throughout Queenstown, the considerable landscaping associated with urban development has obscured much of the original landform detail. Therefore, the boundary positions between domains B1 and A are only indicative in relation to property boundaries and buildings. A mapping scale of 1:10,000 applies throughout Queenstown, and domain boundaries should be regarded as 20 m wide zones.

Those sectors of the Queenstown foreshore withe beach or fan-delta deposits below the 320-m contour, and where the groundwater is likely to be at shallow depth, are placed in Domain B. This strip of Domain B, either side of the Domain B1 area described above, extends west from the Spinnaker Bay apartments to the Brunswick St area. Elsewhere, the lake margin fringe is narrow and steep, locally formed on or close to bedrock, and is placed in Domain A.

Figure A3.3 Liquefaction-susceptibility domains in the Queenstown area. The key is generic to the dataset and not all units may be present on this map.

The Shotover Delta forms a broad plain between Frankton and Lake Hayes, into which the Kawarau and Shotover river channels are incised. The delta was formed after retreat of the ice-age glacier from the Wakatipu valley, as sediment carried by the Shotover River accumulated in the Frankton-Lake Hayes arm of Lake Wakatipu. Beach sediments fringe the delta in the Frankton Arm and Lake Hayes areas. The maximum elevation of the high-stand shoreline here was ~355 m above sea level, notably lower than its elevation in the Glenorchy area (see Section A3.1.1).

Lake silt is exposed in places around the outer margin of the delta, notably at the south end of Lake Hayes and along the Kawarau River south of Frankton, and is generally presumed to be distal fan-delta sediments that filled the former lake bed. Inset river-cut terraces were formed along the Shotover and Kawarau rivers, as the river systems eroded down into the delta, and lowered Lake Wakatipu from its high-stand level.

It is unclear whether lake silts are extensive under the delta. For example, a borehole at the Five Mile Development, about 0.5 km north of the Queenstown Airport runway, encountered permeable sandy gravel to a depth of at least 90 m (Rekker 2014), i.e. at least ~20 m below the present Lake Wakatipu level. At that location, there appears to be an unconfined aquifer with water level close to lake level (Frankton Flats aquifer; Rekker 2014). This indicates that much of the Frankton sector of the Shotover Delta has a deep groundwater table, and even if liquefaction-susceptible sediments were present in the immediate subsurface, the absence of groundwater saturation would preclude liquefaction occurring.

Beneath the Shotover Delta between the Shotover River and Lake Hayes, groundwater bores show an aquifer (Windermeer aquifer; Rekker 2014) with a water table elevation of around 320 m as determined in 1995-96 (Rosen *et al.* 1997; Rosen & Jones 1998), while Rekker (2014) identified a range in water table elevation of between 320 m decreasing south to 310 m close to the Shotover-Kawarau confluence (and thus approximating river level). As the ground elevation averages ~355 m on the main delta surface, and ~340 m to 330 m on the main inset terraces, the water table appears to be at least 20 m deep, indicating that no potential liquefaction hazard exists here, irrespective of whether or not liquefaction-susceptible materials are present.

To acknowledge that close to lake (or river) level, groundwater will be progressively shallower, a strip of Domain B is mapped along the margin of the delta through the Frankton area, between the lake shore and the 320-m contour, as defined by lidar, from Perkins Road in the west, along the Frankton waterfront, and in a ribbon along the Kawarau River to the Shotover River valley. A similar ribbon of Domain B is mapped along the southern bank of the Kawarau river, where lake silts are present in the near subsurface.

The broad north-south valley floor south of the Kawarau River between the Peninsula Hill ridge and the foot of The Remarkables is included in Domain B. Thick lake silt is exposed along the northern edge of this valley alongside the Kawarau River. It is inferred that this valley is extensively underlain by sand or silt associated with formation of the Shotover Delta. The groundwater table is likely to be shallow throughout the valley, except close to the Kawarau River and close to where the southern margin of this valley abuts Lake Wakatipu. The Domain B polygon is tapered down to the lakeshore near Jacks Point. On the eastern side of the valley, the polygon is extended onto the lower flanks of alluvial fans built out from the foot of The Remarkables, to about the 360-m contour, except where this encroaches over areas of rocky outcrop or glacial landforms, which are classified as Domain A.

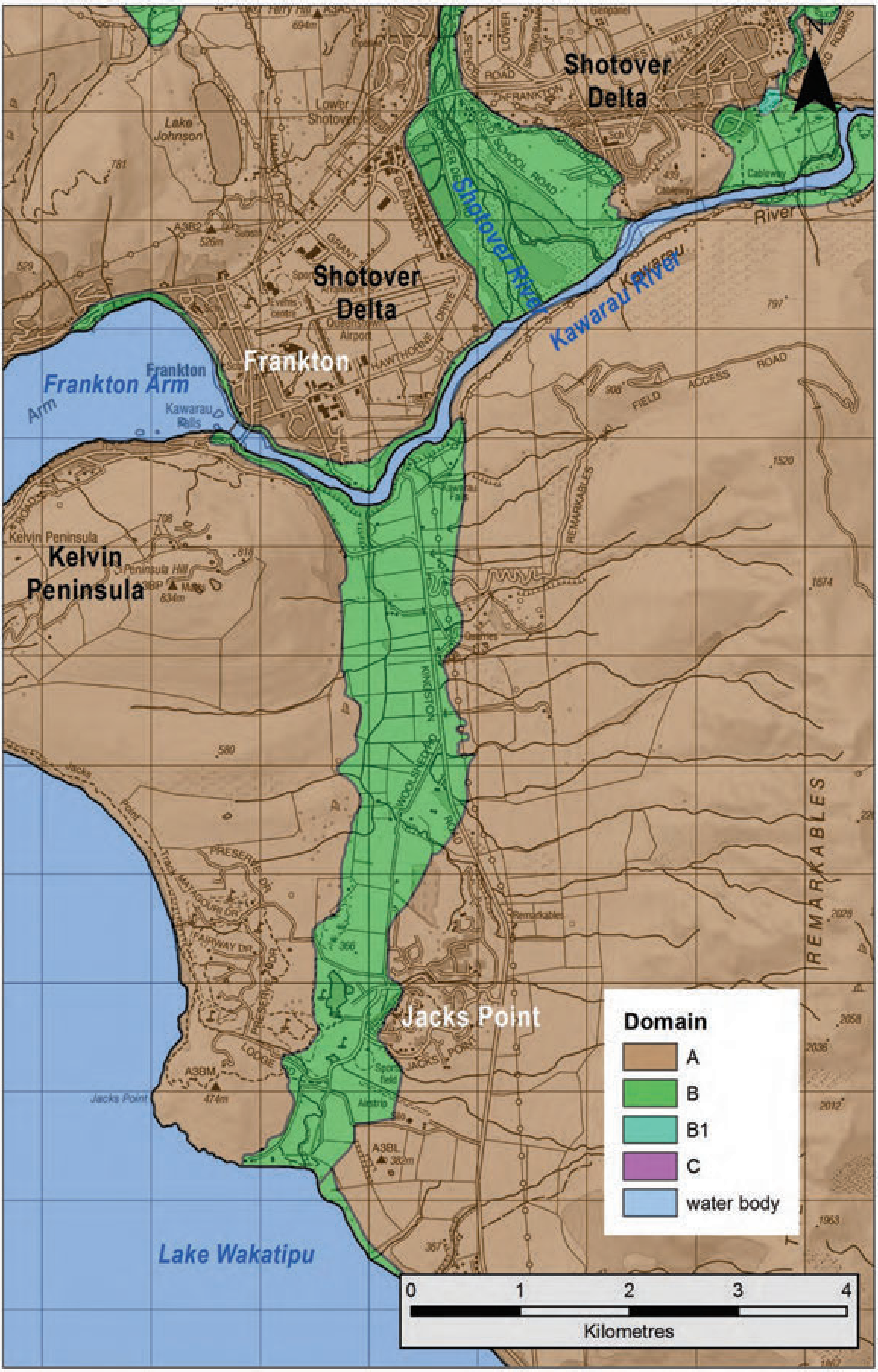

Figure A3.4 Liquefaction-susceptibility domains in the Frankton area. The key is generic to the dataset and not all units may be present on this map.

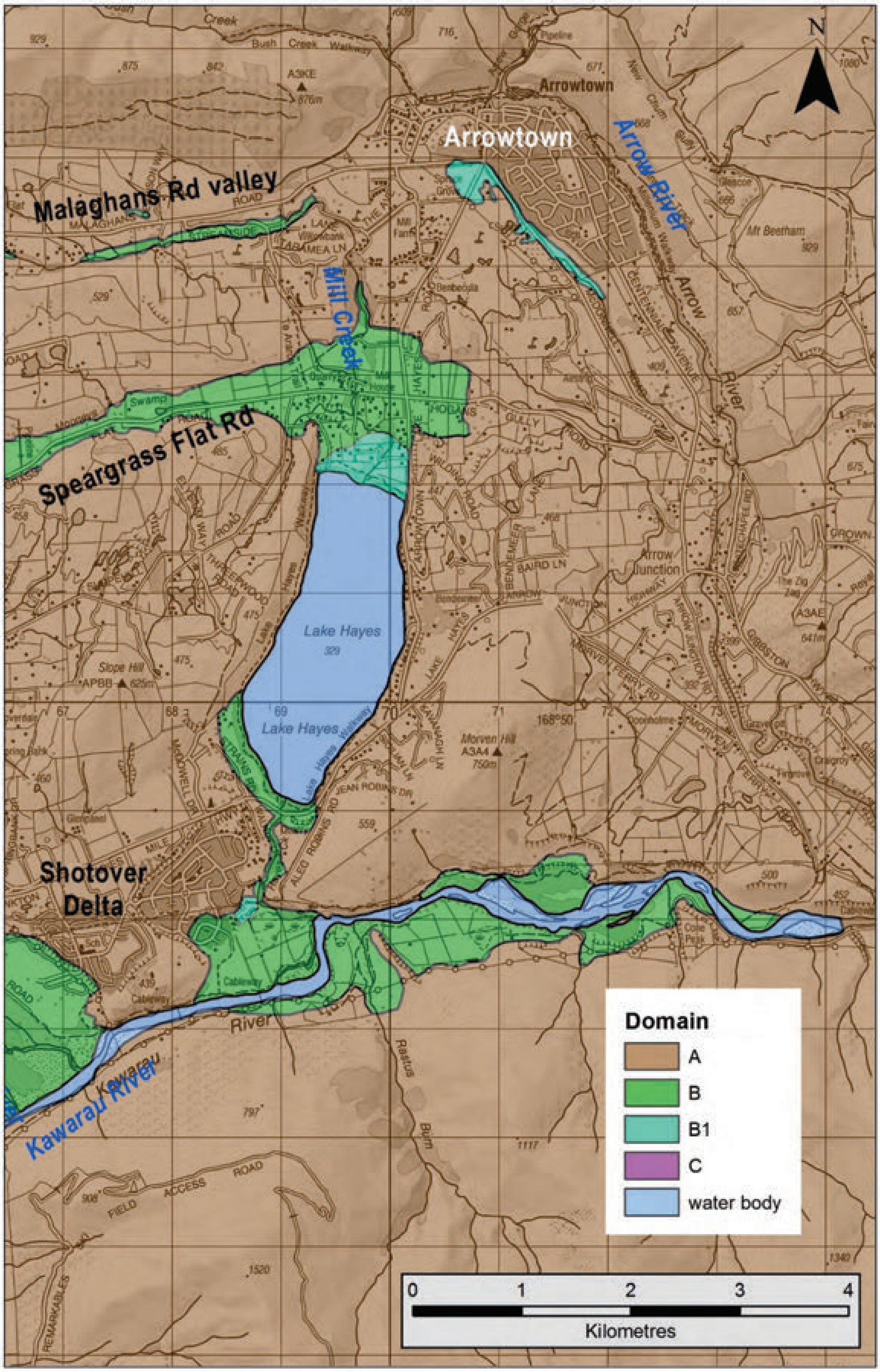

Figure A3.5 Liquefaction-susceptibility domains in the Arrowtown area. The key is generic to the dataset and not all units may be present on this map.

Due to the likely shallow groundwater table, the floodplains and low inset terraces of the Kawarau and Shotover rivers are included in Domain B. The Doman B boundary is placed at approximately 330 m topographic elevation either side of the Shotover River, and extended as a narrow ribbon up the Hayes Creek incised channel and around face of the Shotover Delta on the south side of Lake Hayes. Near the Hayes Creek — Kawarau River junction, geotechnical investigations have identified potentially liquefiable materials in the subsurface GeoSolve 2018), and a localised sector of a low-level terrace there is classified as Domain B1.

The Shotover floodplain and low terraces at Big Beach, immediately east of Arthurs Point, are also classified as Domain B.

A lobe of the Shotover Delta landform extends through the Speargrass Flat Rd area, and adjoins the Mill Creek fan-delta at the northern end of Lake Hayes. In the Domain Road area, groundwater is relatively deep (>10 m) and that sector of the Delta landform is placed in Domain A. From a few hundred metres east of Hunter Road, the lobe narrows through the Mooneys Swamp area. This sector of the Shotover Delta landform, along with the delta area near Mill Creek, and the inset terraces of Mill Creek, are included in Domain B. The reason for including the Speargrass Flat sector of the delta in Domain B is that it is topographically restricted, and an aquifer (Hawthorne-Speargrass aquifer) appears to have a groundwater table generally shallower than 10 m (Rekker 2014). The Mill Creek sector of the fan-delta is included in Domain B, because topographic restriction means that the groundwater table may be relatively shallow, and as this area is at the distal end of the Speargrass Flat lobe of the delta, there is enhanced likelihood that fine-grained sediments may be a more prominent component here than near Frankton, for example. Close to Lake Hayes on the inset fan of Mill Creek, geotechnical investigations have identified potentially liquefiable materials in the subsurface GeoSolve 2018), and a sector of the fan there is classified as Domain B1.

Upstream in the Mill Creek catchment, an old glacial meltwater channel extends from Arthurs Point to Arrowtown, along which Malaghans Road runs. In places, large alluvial fans have built out from the foot of the Coronet Peak range and have partly obstructed the drainage along the old channel, with poorly drained or swampy ground. The fan sediments are likely to include fine-grained materials, with shallow groundwater. Domain B is mapped along constricted parts of the old channel, and a short distance up the alluvial fans to the north. Along the southern edge of Arrowtown, a large alluvial fan has been built out into the Millbrook area from the Bush Creek catchment. Through Millbrook, the fan laps onto irregular rocky terrain, but has extended down an old river channel along McDonnell Road. GeoSolve (2018) reports having found possibly liquefaction susceptible materials in one area within the channel, and so it is classified here as Domain B1. The uphill limit of the domain is placed across the fan west of the Arrowtown-Lake Hayes Road. Within the Arrowtown urban area, the domain boundary is placed with aid of lidar, high-resolution aerial imagery and Google Earth Street View, at an approximate mapping scale of 1:1000 scale and is considered accurate at the scale of properties and buildings.

A3.1.4 Kingston (Figure A3.6)

There is localised lidar coverage at Kingston township, where the mapping scale is 1:10,000, with 1:50,000-scale mapping around the periphery of Kingston aided by Topo 50 and the ORC 2009 alluvial fans database (Barrell *et al.*, 2009). There is a large accumulation of lake beach sediment at Kingston. The only deep bore at Kingston with a lithological log in the ORC wells database shows many tens of metres of silt and sand underlying the beach gravel, presumably related to a glacial-age lake formed at or near the former glacier terminus.

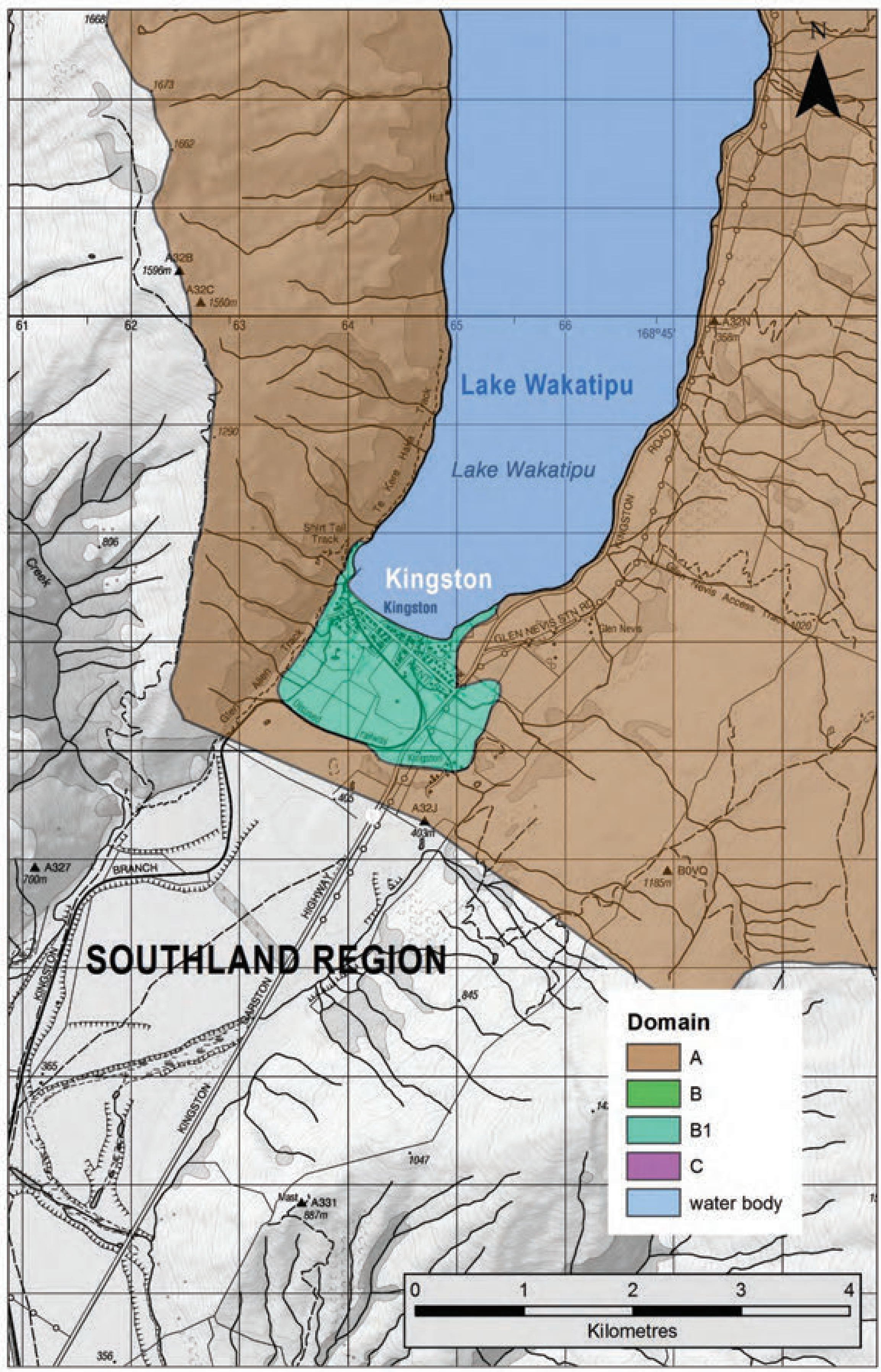

Figure A3.6 Liquefaction-susceptibility domains in the Kingston area. The uncoloured area is Southland region. The key is generic to the dataset and not all units may be present on this map.

Other bores at Kingston with water level records show a shallow groundwater table, and localised geotechnical investigations (Tonkin and Taylor 2013; GeoSolve 2018) indicate liquefaction-susceptible materials in the subsurface. Therefore, the area of beach deposits at and below the Lake Wakatipu high-stand and the lower reaches of alluvial fans draining onto the beach landforms, whose active channels merge to form Kingston Creek, are classified as Domain B1.

A3.1.5 Moke Lake

The broad valley floors adjoining Moke Lake are classified as Domain B. The maximum depth of the lake is ~40 m, which implies that the lake sits in what has formerly quite a deep topographic basin. It is likely that lake or delta sediments extensively underlie these broad valleys, with a shallow groundwater table.

A3.1.6 Shotover valley

A low gradient sector of floodplain and low terraces in the Shotover River valley in the area of ice-age glacier termini between Ironstone Creek upstream to Polnoon Burn has been classified as Domain B, on account of the potential for buried river channels filled with sand or silt. In this area, there are also aggradation fans of sluice tailings that are likely to be particularly poorly consolidated.

A3.1.7 Lake Wanaka perimeter (Figures A3.7–A3.8)

As with Lake Wakatipu, Lake Wanaka had a post-glacial high-stand. Lake Wanaka's high-stand was about ~20 m above modern lake level (~300 m above sea level). Accumulations of beach deposits and fan-deltas are graded to the high-stand, As the lake was lowered by incision of its outlet near Albert Town, some of the larger streams produced inset fan-deltas at lower levels.

Mostly, high-stand fan-deltas and beach deposits are not identified as liquefaction-susceptible, as they are predominantly gravelly and now have deep groundwater tables, associated with the lower modern lake. However, on the larger fan-deltas and beach accumulations, the sector lakeward of the 300-m topographic contour is included in Domain B, to account for the possibility that perched water tables and fine-grained beach or lacustrine sediments may lie in the subsurface. Localised areas of beach sediments below the 300-m contour was also placed in Domain B, such as at Colquhouns Flat, southwest of Mou Waho island.

Where there are inset fan-deltas graded out into the modern lake, these are likely to have shallow groundwater tables, and to have built out over the top of lake silt or sand deposits. Examples of this situation are the inset fan-deltas of Alpha Burn and Fern Burn at Glendhu Bay, and Quartz Creek in Dublin Bay. A more extensive area of fan-delta at Minaret Bay is included in Domain B, because the fan-delta has built out against a bedrock knob alongside the lake, and the groundwater is likely to be shallow, even on sectors of the fan-delta associated with the lake high-stand.

A3.1.8 Wanaka (Figure A3.7)

Wanaka township has lidar coverage, and the mapping scale there is 1:10,000, aided by aerial imagery. The extensive accumulation of beach sediments at the south-eastern end of the lake at Roys Bay (Wanaka township) are classified as Domain B1 because drilling shows that lake silts are extensively present beneath the beach sediments, and geotechnical testing has shown that pockets of liquefiable sediments are present. The landward margin is placed at about 300-m contour. Similarly, beneath the incised terraces of the Clutha and Hawea rivers near Albert Town, river gravels are underlain by lake silt, that was deposited in a former incarnation of Lake Wanaka that developed following glacier retreat from the Albert Town moraines (GeoSolve 2018). As these inset river terraces have a relatively shallow groundwater table, they are classified as Domain B. Localised geotechnical investigations (Tonkin and Taylor 2013; GeoSolve 2018) have indicated liquefaction-susceptible materials in the subsurface beneath Albert Town, and a classification of Domain B1 is applied there.

A3.1.9 Cardrona valley

Mapping scale is 1:10,000, aided by full lidar coverage aided by aerial imagery. The floodplain and lowest terraces of the Cardrona River, and the lowest reaches of two large tributaries, Branch Burn and Spotts Creek, are included in Domain B, upstream to about the 400-m contour. This accounts for the possibility of sand pockets in buried channels in the near subsurface, with a shallow groundwater table. This sector of the valley has a relatively low gradient of less than ~20-m fall per 2 km, which would be more favourable to the deposition of fine-grained sediment in channels, compared to steeper gradient valleys where gravel-dominated deposition is more likely.

Where the Cardrona River enters the Wanaka basin, it enters abandoned glacial landform topography. Two lobes of the post-glacial Cardrona river plain spread into low-lying glacial basins, one in the Cardrona Valley Road- Studholme Road area, and the other in the Faulks Road – Maxwell Road area. However, these are included in Domain A because the ORC well database indicates a relatively deep groundwater table in these areas, typically between 10 and 25 m below ground, and thus no liquefaction potential exists.

Downstream towards the confluence with the Clutha River, the Cardrona River is increasing incised into its post-glacial floodplain, and its terraces stand as much as ~30 m above river level. On the presumption that the groundwater table accords closely with the level of the Cardrona River bed, only the floodplain and lowest terraces are included in Domain B. The mapping of Domain B is compatible with sparse groundwater table elevation data presented by Rosen *et al.* (1997) and Rosen and Jones (1998), and data in the ORC wells database.

A3.1.10 Matukituki valley

The fan-delta and broad valley floor of the Matukituki River and lower Motatapu River are placed in Domain B. It is not known how far up the Matukituki valley the original, higher, Lake Wanaka extended, but it is inferred that its extension up the Matukituki was many kilometres. Therefore, it is assumed that the valley floor is underlain by deltaic or lake sediments, and the groundwater table is shallow. It is possible that the lake sediments are quite deeply buried by the river sediments. However, the latter are likely to include sand-filled buried channels. The Domain B polygon includes the lower reaches of tributary alluvial fans, up to between 10 and 20 m above the elevation of the main valley axis. The reasoning is for this limitation is that the fans are composed of gravel-dominated sediments, and a 10 to 20 m thick gravel cap should be sufficient to prevent liquefaction-related expulsion or settlement of fine-grained sediment bodies in the underlying river or lake sediments. Domain B is extended to just upstream of the Matukituki River west and east branch confluence. Farther upstream, the valley landscape is dominated by steep alluvial fans with a narrow river floodplain, and notable accumulations of fine-grained, potentially liquefiable, sediment are considered unlikely.

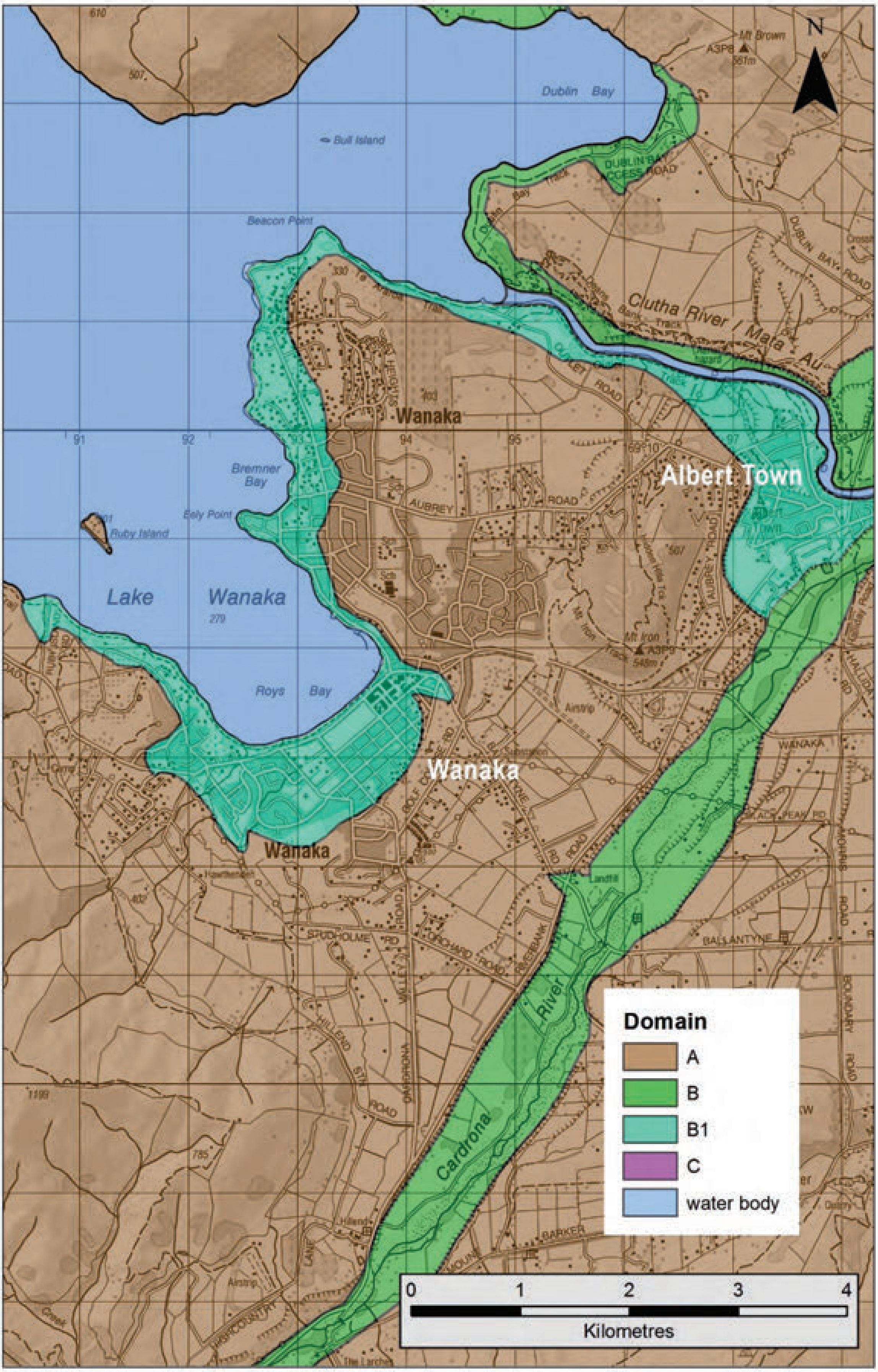

Figure A3.7 Liquefaction-susceptibility domains in the Wanaka and lower Cardrona area. The key is generic to the dataset and not all units may be present on this map.

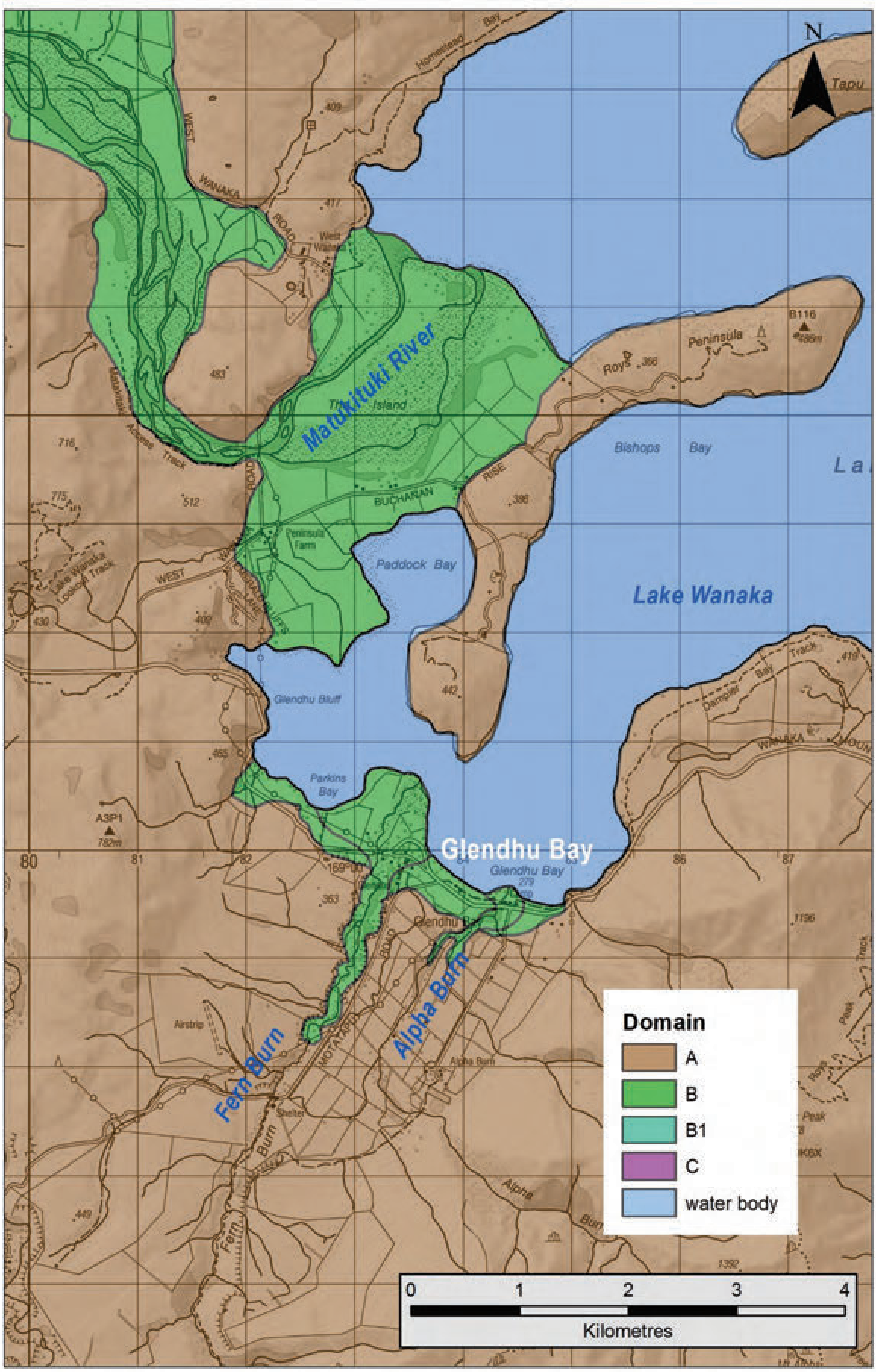

Figure A3.8 Liquefaction-susceptibility domains in the Glendhu Bay and lower Matukituki area. The key is generic to the dataset and not all units may be present on this map.

A3.1.11 Makarora area (Figure A3.9)

The fan-delta and broad valley floor of the Makarora River and lower Wilkin River are placed in Domain B. It is not known how far up the Makarora/Wilkin valley the original, higher, Lake Wanaka extended, but it is inferred that its extension up-valley was many kilometres. Therefore, it is assumed that the valley floor is underlain by deltaic or lake sediments, and the groundwater table is shallow. It is possible that the lake sediments are quite deeply buried by the river sediments. However, the latter are likely to include sand-filled buried channels. The Domain B polygon includes the lower reaches of tributary alluvial fans, up to between 10 and 20 m above the elevation of the main valley axis. Domain B is extended up the Makarora River to the Blue River confluence, upstream of which the gradient of the valley steepens, and is narrowed by fans. This is about the location where the 320-m contour crosses the valley floor. The polygon is extended up the Wilkin valley to the Siberia River confluence, also approximating the 320-m contour, upstream of which the valleys narrow and steepen.

A3.1.12 Lake Hawea area

Lake Hawea has been raised as much as ~25 m for hydroelectric water storage, and any former lake high-stand features, as well as the fan-deltas and floors of tributary valleys have been drowned. It is likely that Lake Hawea attained approximately its modern natural level (~323 m above sea level) shortly after the ice-age glacier withdrew (McKellar 1960; Barrell 2011). Therefore, in relation to the modern artificial lake maximum level, even todays lake-edge fan-deltas are likely to have at least 25 m of alluvial fan gravel over any fan-delta or lake sediments. Virtually none of the fans fringing Lake Hawea are considered to have liquefaction susceptibility. A sector of low-gradient fan, that encloses a small unnamed lake just west of Dingle Burn Station, is mapped as Domain B. The reasoning is that this may possibly be an infilled former arm of the lake.

Along the same thinking, any former fan-delta sediments associated with the main tributary, the Hunter River, are now well submerged under the raised lake, and up-valley any associated lake or deltaic sediments will likely be buried (e.g. ~25 m) by river sediments. But due to the potential for infilled channels of river sand or silt in the Hunter River system, the valley floor and lowest reaches of tributary fans (up to a few metres above Hunter River level), are categorised as Domain B. The polygon is extended upstream up to where the 400-m topographic contour crosses the valley floor. Upstream of there, the valley floor gradient increase to greater than 20 m fall per 2 km, and for the purposes of this assessment, the presence of dominantly fine-grained sediment is considered unlikely.

A3.1.13 Hawea River and upper Clutha River area

The upper Clutha and Hawea rivers are large gravel-bed rivers that, since the retreat of ice-age glaciers, have been starved of fine sediment, because sediment from their catchments has been trapped in lakes Wanaka and Hawea. Post-glacial activity of those rivers has been confined to their eroding down their gravel outwash plains. Accumulated post-glacial sediments, for example in meander loops in the Hawea River for ~3 km upstream from its confluence with the Clutha River, are likely to be gravel-dominated. For that reason, these areas are classified as Domain A. Bore records from the ORC wells database indicate that the subsurface materials of the Hawea Flat area are predominantly gravelly, compatible with a Domain A classification.

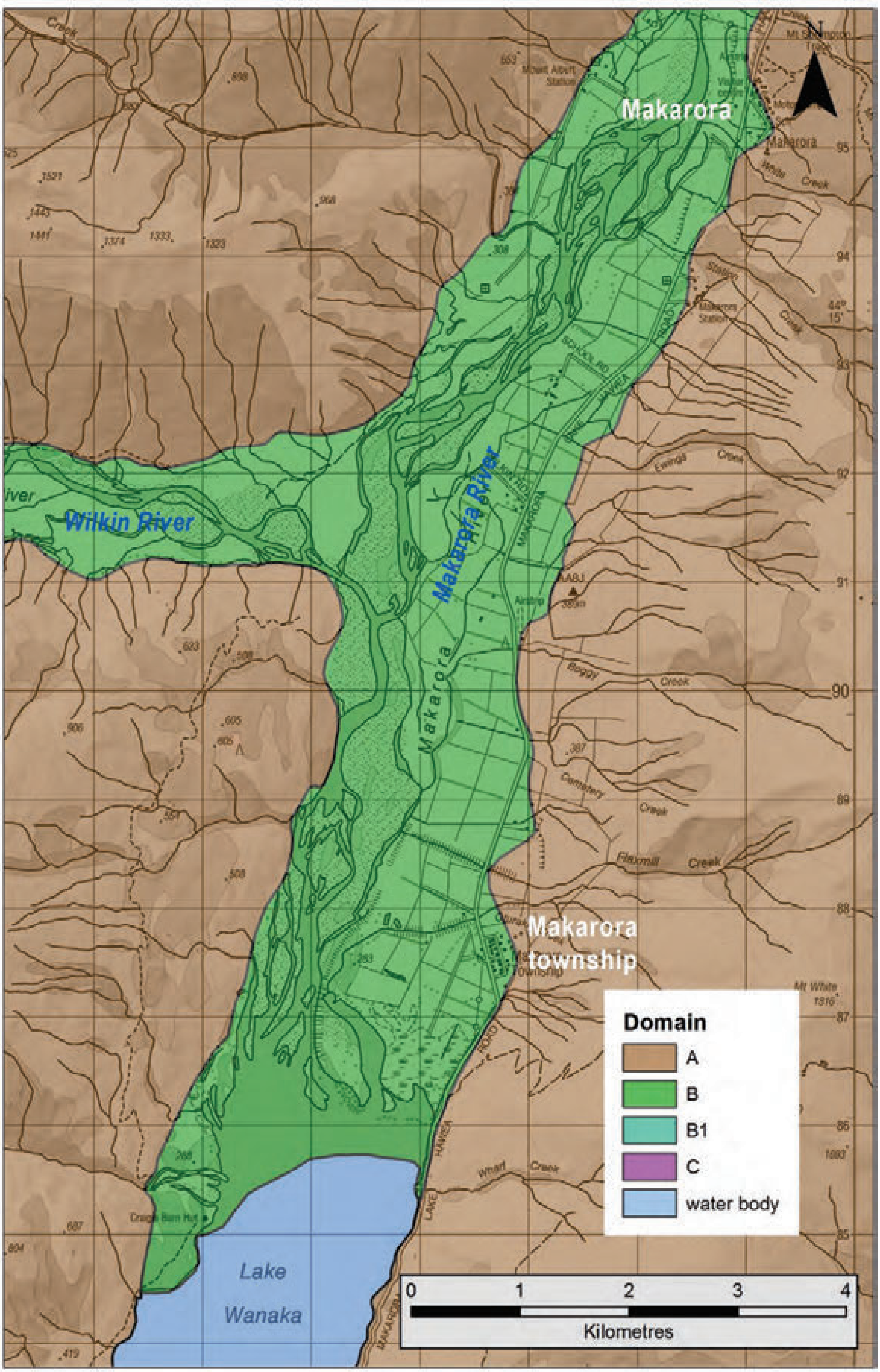

Figure A3.9 Liquefaction-susceptibility domains in the Makarora area. The key is generic to the dataset and not all units may be present on this map.

The area around Albert Town and Clutha/Hawea river confluence are discussed in the Wanaka sub-section. Downstream of Albert Town, the Clutha River is incised below extensive high terraces, beneath which the groundwater table is deep, and all are included in Domain A. The river and localised low terraces are gravelly, degradational terraces, which in places sit on much older lake silts from an earlier glaciation. In exposures previously examined by the writer, these silts are very dense, and no liquefaction potential is considered to exist.

A3.2 Central Otago District

A3.2.1 Upper Clutha valley

Downstream of the Clutha/Hawea river confluence at Albert Town, the Lindis River is first large influent tributary, and is a potential source of significant amounts of fine-grained sediment. For that reason, the floodplain and low terraces of the Lindis and adjacent and downstream parts of the Clutha River are included in Domain B, to account for the possibility of buried sand- or silt-filled channels, in conjunction with a shallow groundwater table (Houlbrooke 2010). The Domain B area is extended up the Lindis River where the gradient is gentler than 20 m per 2 km. It includes isolated pods of Domain B encompassing areas of locally extensive valley floor as far upstream as approximately the 460-m contour, near Morven Hills homestead.

No Domain B is mapped in the Cromwell area, because the main alluvial terrace stands well above the Lake Dunstan water level. Groundwater beneath the alluvial terrace approximates lake level, and thus the mean depth of the groundwater table is ~20 m (Rekker 2012). The well-drained nature of the near subsurface means no liquefaction potential exists, even if pockets of fine-grained sediments are present in the predominantly gravelly alluvial deposits.

A3.2.2 Alexandra area and Manuherikia valley (Figures A3.10, A3.11)

The river terraces adjacent to the Clutha River through the Alexandra basin (including the Clyde and Earnscleugh areas) stand relatively high above river level, and the groundwater table, within well-drained alluvial gravels, is generally deeper than about 10 m (Bekesi 2005, ORC 2012). For that reason, no liquefaction potential is identified in those areas.

The inset valley floor of the lower reaches of the Manuherikia River downstream of Chatto Creek is included in Domain B. The reason is that the valley gradient is very low approaching the confluence with the Clutha River, which raises the likelihood of channels or lenses of fine-grained sediment deposits, and also because this area has shallow groundwater, comprising the Manuherikia Alluvium Aquifer (Bekesi 2005, ORC 2012).

Farther upstream, three valley reaches have broad floors flanked in places by low terraces. In the Omakau-Ophir basin, the valley floor and lowest terrace on the northern (Omakau) side are placed in Domain B. This includes most of Omakau township, but Ophir township on the rocky southern margin of the basin has outcrops of schist bedrock close to the built-up area and is included within Domain A. Immediately up-valley of Omakau, the valley-margin terrain steps up onto higher terraces, which are likely to have a deeper groundwater table. Those terraces are classified as Domain A. Upstream of the Lauder Gorge, the broad valley floor and lowest terraces are placed in Domain B, which includes the Lauder village area. The Domain B area is extended up the broad floor of Lauder Creek, to the point where the valley gradient becomes steeper than 20 m fall per 2 km. The most upstream sector of Domain B comprises the broad floor and lowest terraces of the Manuherkia valley upstream of the Ida Burn confluence. This sector extends up the floor and lowest terraces of the Dunstan Creek valley to where the valley gradient becomes steeper than about 20 m per 2 km.

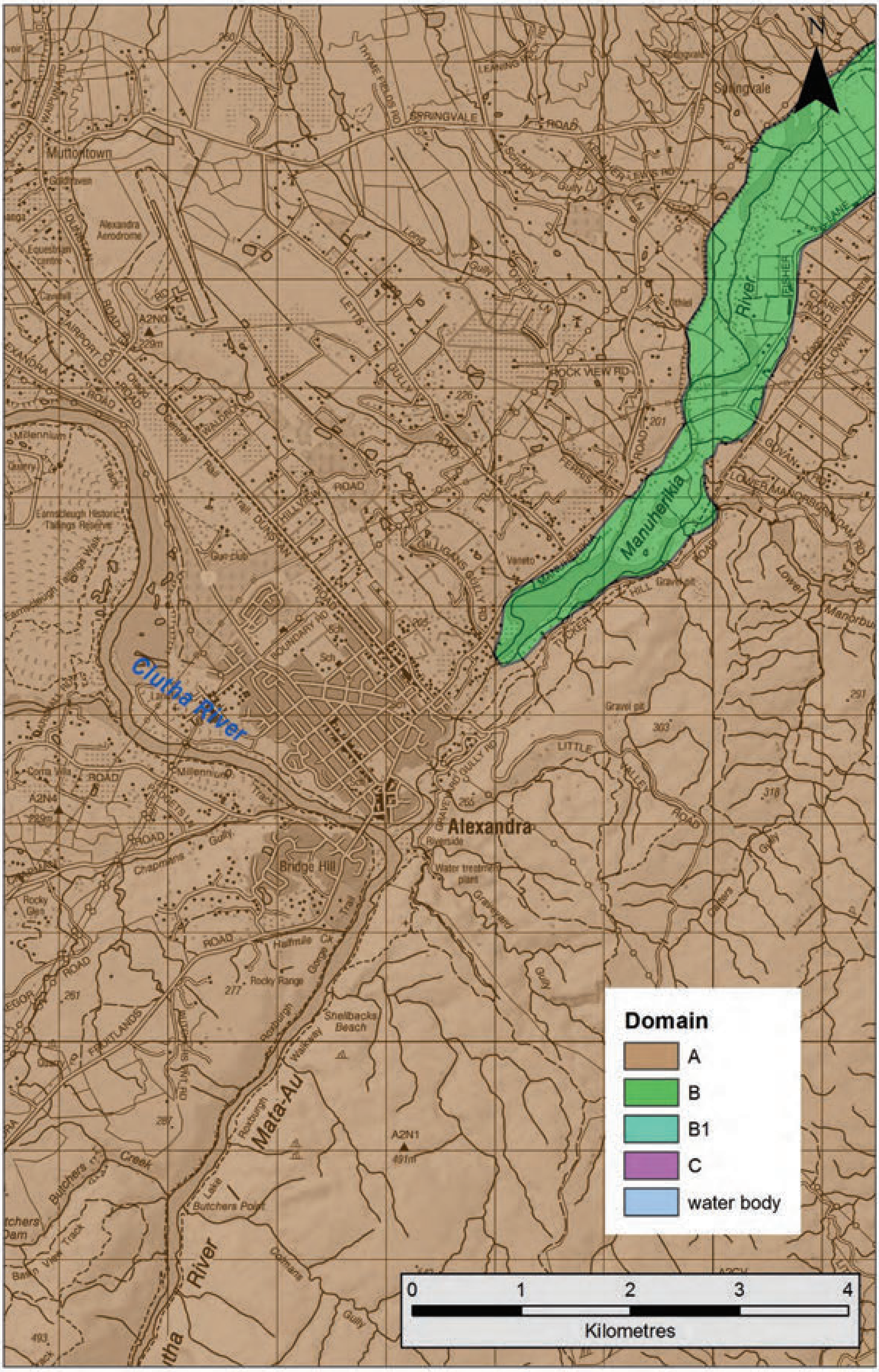

Figure A3.10 Liquefaction-susceptibility domains in the Alexandra area. The key is generic to the dataset and not all units may be present on this map.

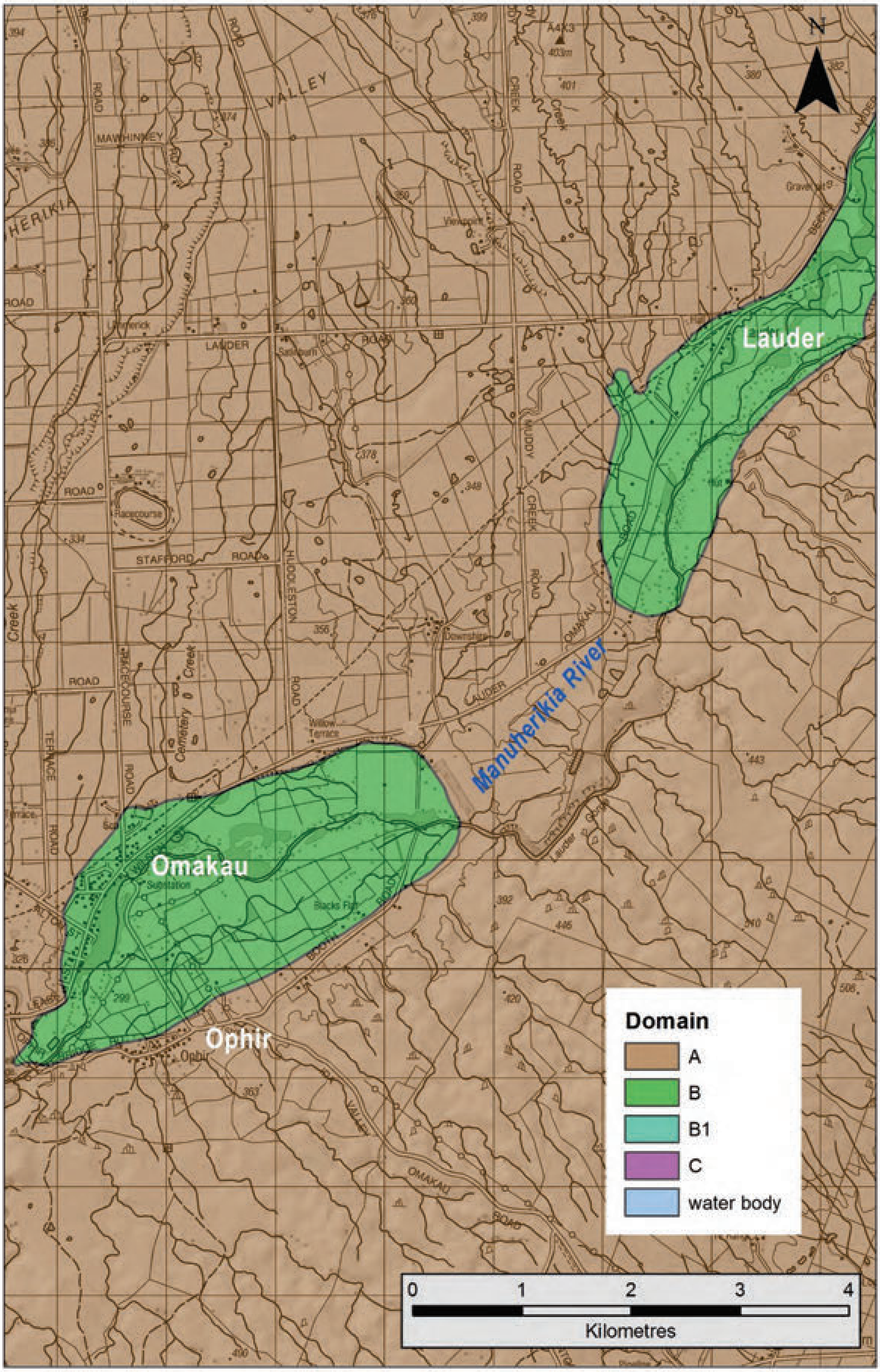

Figure A3.11 Liquefaction-susceptibility domains in the Omakau, Ophir and Lauder areas. The key is generic to the dataset and not all units may be present on this map.

A3.2.3 Ida Valley and Poolburn valley

The low-lying axis of the Ida Valley, and adjacent lower fringes of alluvial fans and low terraces of Ida Burn are placed in Domain B, as is the Pool Burn sector of the valley floor. There is sparse information on ground water but the generally poorly drained nature of the valley floor indicates a shallow groundwater table. Areas on QMAP mapped as being sediments of Middle Quaternary age or older, and areas where exposed bedrock is indicated, such as near Moa Creek, are excluded from Domain B. Groundwater exploration bores in the southwestern sector of Poolburn valley, west of Poolburn – Moa Creek Road, show Tertiary cover strata at shallow depths (Wilson and Rekker 2012), justifying placement of that area in Domain A. The Ida Valley Domain B polygon is not extended upstream of the Gorge Creek/Ida Burn confluence, because the streams are gravel-dominated, and gradients become steeper than 20 m per 2 km.

A3.2.4 Upper Pool Burn – Manor Burn

In the Pool Burn headwaters, upstream of Poolburn Reservoir, Pool Burn (wrongly labelled as Long Valley Creek on the Topo 50 map), has an area of broad valley floor with swampy ground, which is probably a result of constriction of valley drainage due to alluvial fan building farther downstream. I have previously visited the area and found that sector of the valley floor contains predominantly fine-grained (peat, silt, and with some fine gravel). It therefore may have some potential for liquefaction, hence its inclusion in Domain B.

Similarly, in the lower reaches of Long Valley Creek where it meets the Greenland Reservoir, the swampy valley floor is classified as Domain B.

A3.2.5 Maniototo basin (Figures A3.12, A3.13)

The low-lying floor of the upper Taieri Plain, and Serpentine Flat farther upstream, notable for swampy ground and 'scroll-plain' meander channels, are placed in Domain B. The floors and lowest terraces of main tributaries, where the valley gradient is less than 20 m fall in 2 km, are included in Domain B. To the northwest these include Stot Burn, Gimmer Burn, Wether Burn, Eden Creek and Ewe Burn, and the lower reaches of the Hog Burn valley near Waipiata, up to approximately the 390-m contour. On the south side of the basin, the Sow Burn plain is included in Domain B, but upstream towards Patearoa the plain is increasingly confined and the Domain B polygon is closed off just downstream of Patearoa, at the point where the valley floor becomes steeper and there is bedrock outcrop in the valley floor.

Downstream of Waipiata, sectors of the Taieri valley floodplain and lowest terraces, where broad, are placed in Domain B. Similarly, the Kye Burn valley floor and low terraces are placed in Domain B, upstream to where the valley gradient increases to more than 20 m fall per 2 km.

A3.2.6 Clutha valley and adjacent areas

The Clutha River valley has locally extensive terraces flanking the river, but the river is well incised below the main terraces, meaning that the groundwater table will be relatively deep. The ORC wells database indicates that depths to groundwater of around 10 m or more are typical (e.g., Roxburgh, Ettrick). At Millers Flat, one of the lowest terrace sectors, bore data indicate typical depths to water of between 8 and 10 m. On account of the deep groundwater, no areas of Domain B are mapped along the Clutha valley through Central Otago.

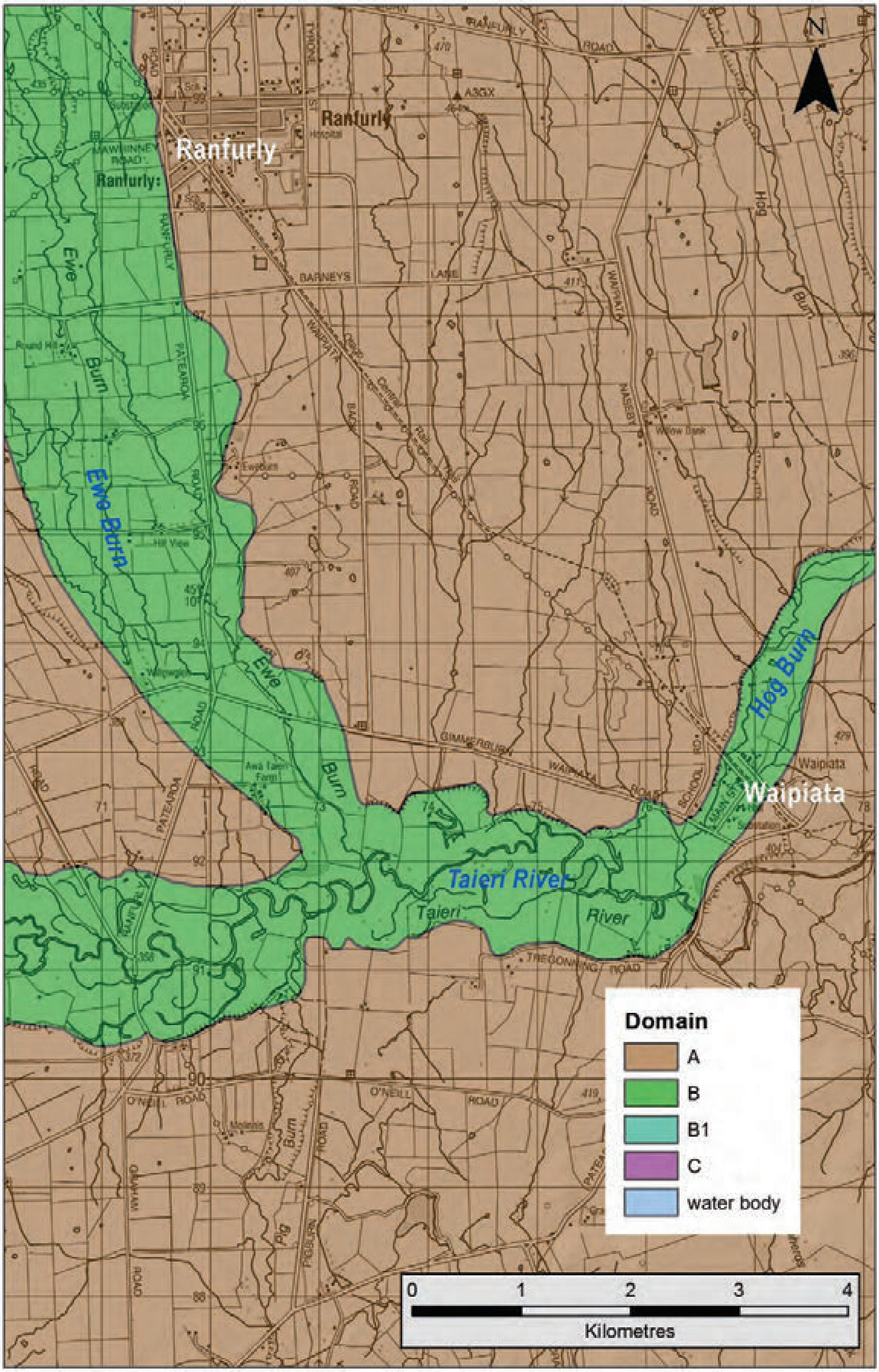

Figure A3.12 Liquefaction-susceptibility domains in the Ranfurly-Waipiata area. The key is generic to the dataset and not all units may be present on this map.

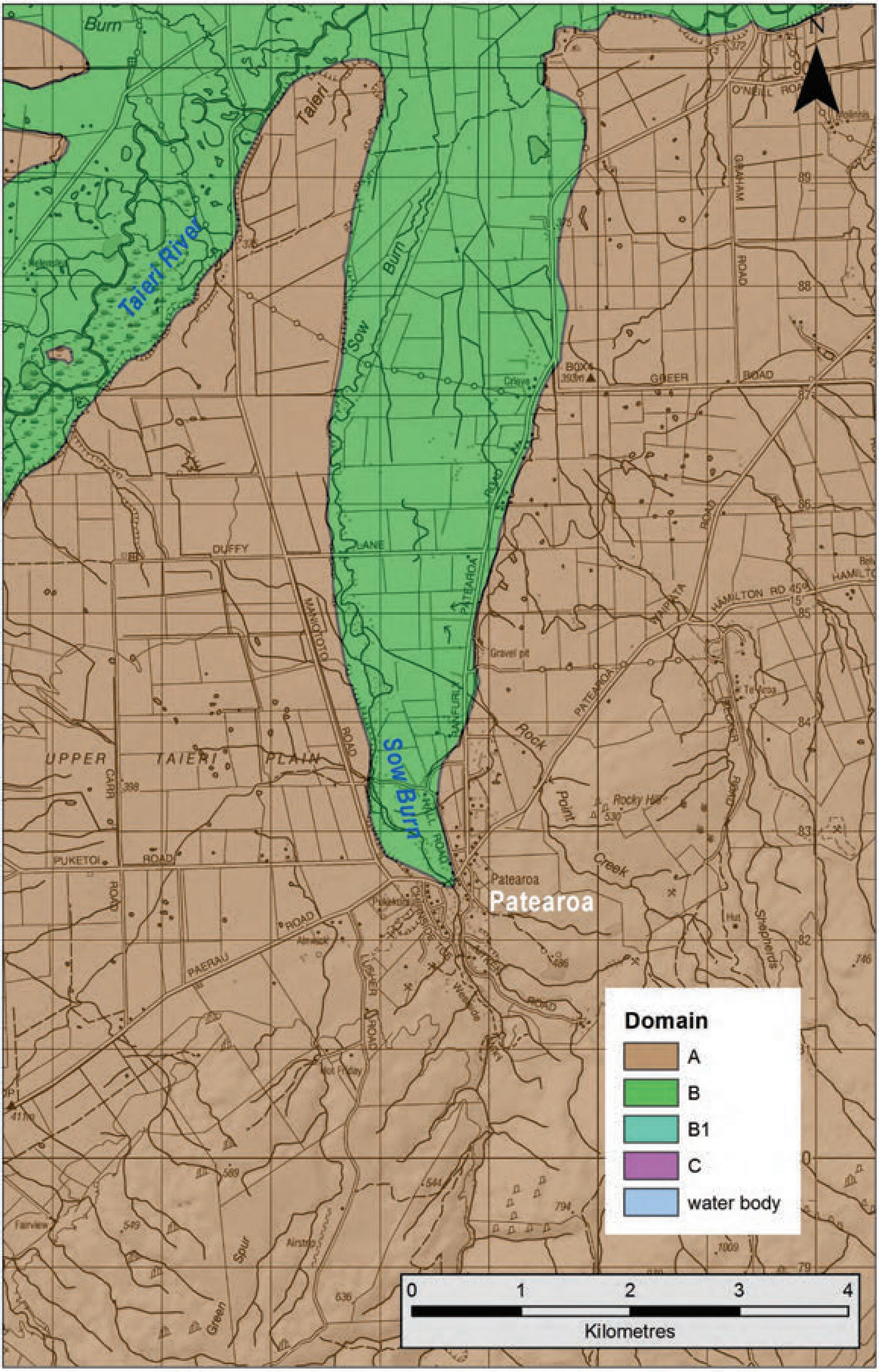

Figure A3.13 Liquefaction-susceptibility domains in the Patearoa area. The key is generic to the dataset and not all units may be present on this map.

Meandering scroll plains occupying the valley floors of the Lake Onslow tributaries, Teviot River South Branch and Fortification Creek, are included in Domain B, because they are likely to be underlain by saturated, predominantly fine-grained sediments.

At Raes Junction, Raes Junction Creek has a broad low-gradient floor, for ~2.5 km upstream of SH 8; downstream of there, the creek drops into an incised rock gorge draining to the Clutha River. The broad valley is placed in Domain B.

Near Beaumont Station, in the Talla Burn catchment east of the Clutha valley, a ~3.5 km long sector of Fruid Burn has a broad sediment-filled valley floor, and a sector of the Moffats Stream catchment lies in a broad swampy basin. Both are placed in Domain B.

A3.3 Clutha District

A3.3.1 Beaumont, Lawrence and Waitahuna areas (Figures A3.14–A3.16)

At Beaumont, the rock-floored Clutha River valley opens into a narrow basin. Downstream of conspicuous bedrock outcrop at and upstream of the Beaumont bridge, the low terraces of the valley floor appear to be formed in river sediments and are placed in Domain B. The adjoining broad floor of the Low Burn valley, and its southwestern tributary along which SH 8 runs, are also included in Domain B, on the presumption that these low-gradient valley floors are underlain by fine-grained stream sediments with a shallow groundwater table.

Several sectors of the Tuapeka River and Waitahuna River valleys and their larger tributaries have broad floors, likely underlain by poorly consolidated river or stream sediments. In places where they are considered likely to be associated with shallow groundwater tables, those sectors are classified as Domain B. Similar circumstances prevail in the middle reaches of Dull Burn, a west-draining tributary of the lower Waitahuna River, near Awamangu, ~15 km north-northwest of Balclutha, and its broad floor is mapped as Domain B.

The broad valley floors of the Tuapeka Creek and tributary valleys through Lawrence township are placed in Domain B. The valley floor margins (i.e. Domain B/A boundaries) have been positioned at ~1:1000 scale, using high-resolution aerial imagery and Google Earth Street View, and are considered accurate at the scale of properties and buildings. Broad sectors of the Tuapeka River valley, and its Bowlers Creek tributary, are placed in Domain B.

The Waitahuna River valley has a very broad floor in the general area of Waitahuna village, and is classified as Domain B. The domain is extended up the broad floor of Waitahuna Gully. There, there was gold mining era sluicing, which may have contributed to the infilled floor of the gully, and it is also unclear to what extent the main valley floor at Waitahuna was disturbed by gold mining. But the low-gradient valley floor, and likely very shallow groundwater table, are judged sufficient to warrant the identification of Domain B.

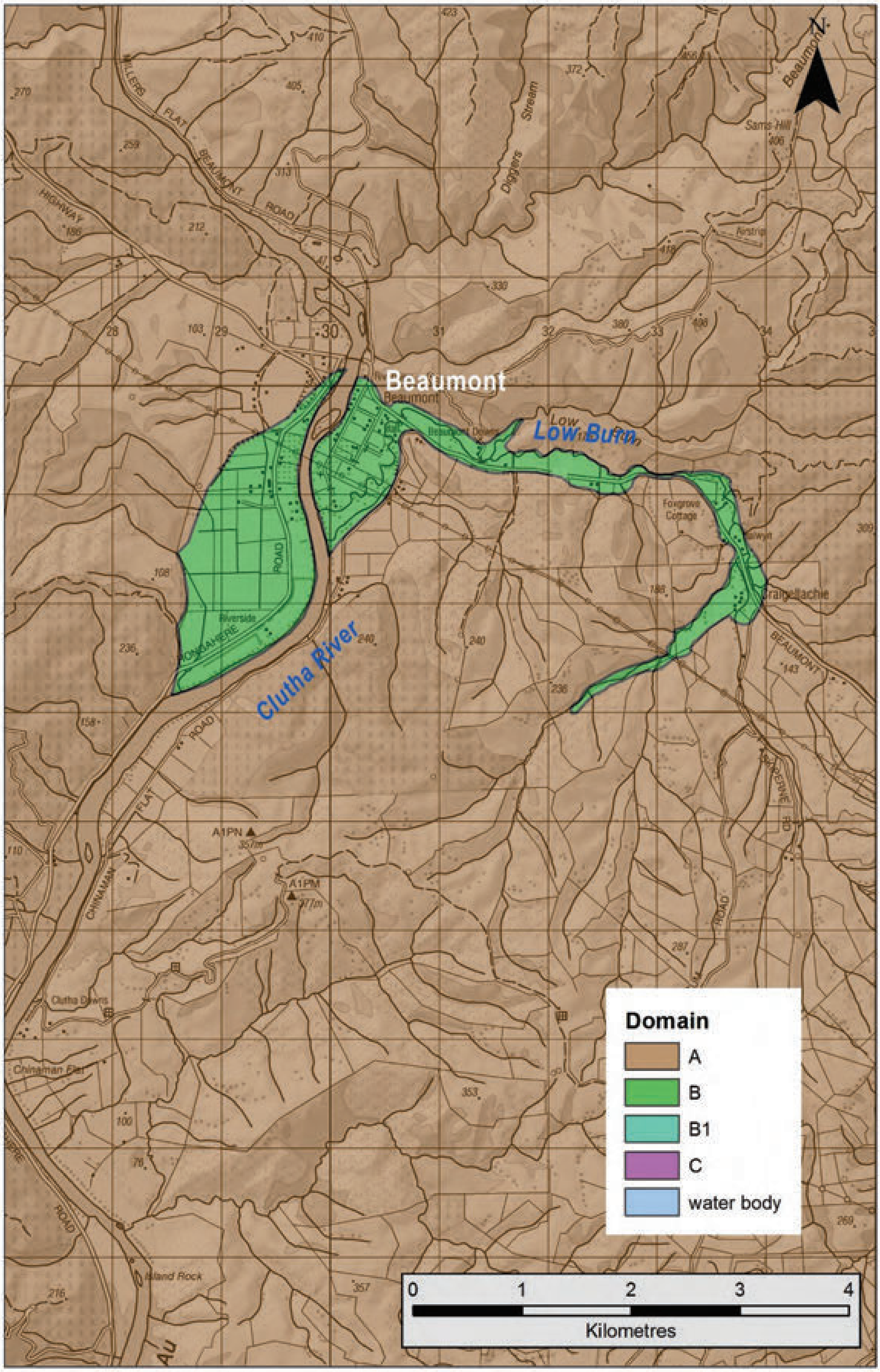

Figure A3.14 Liquefaction-susceptibility domains in the Beaumont area. The key is generic to the dataset and not all units may be present on this map.

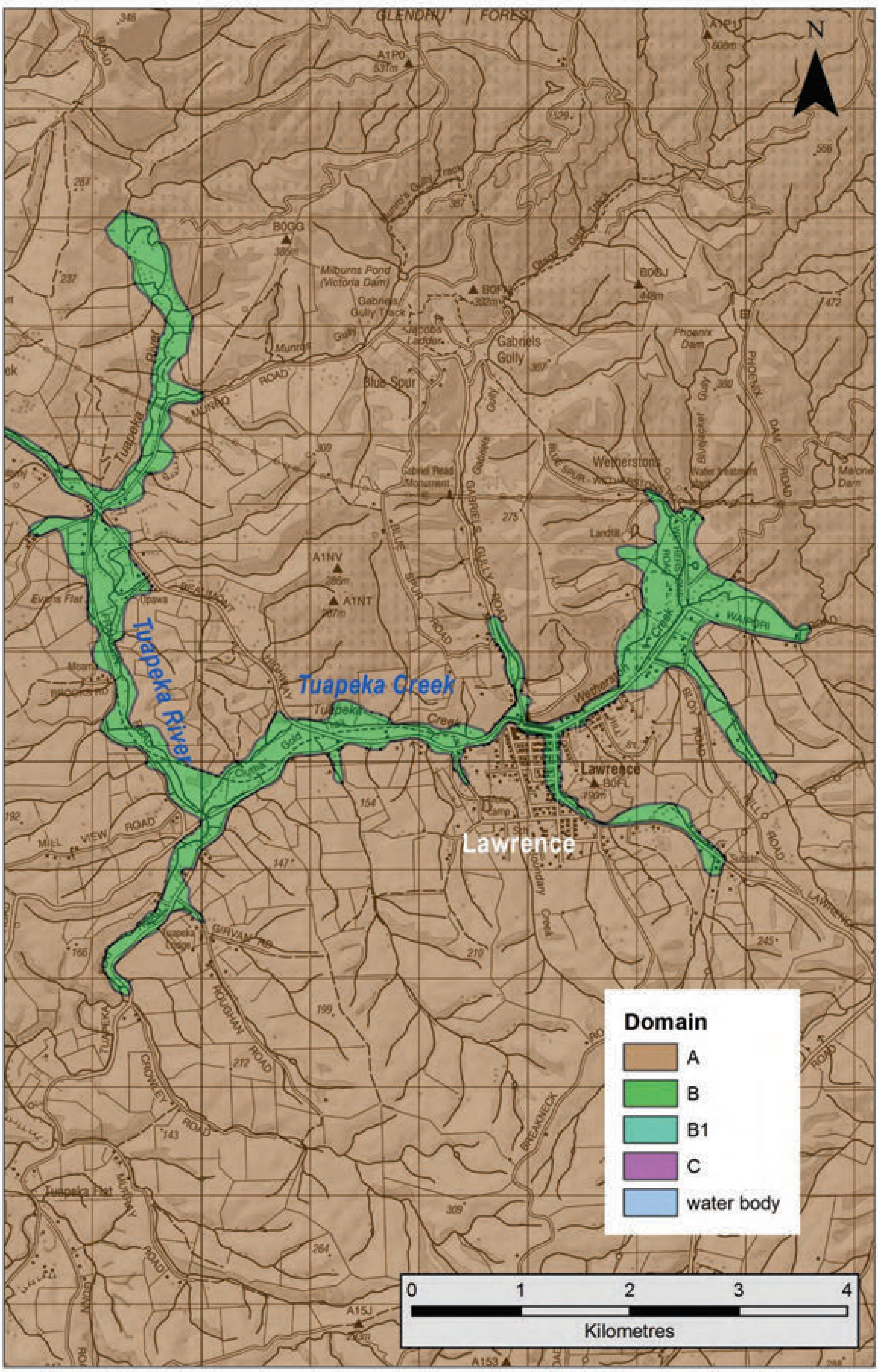

Figure A3.15 Liquefaction-susceptibility domains in the Lawrence area. The key is generic to the dataset and not all units may be present on this map.

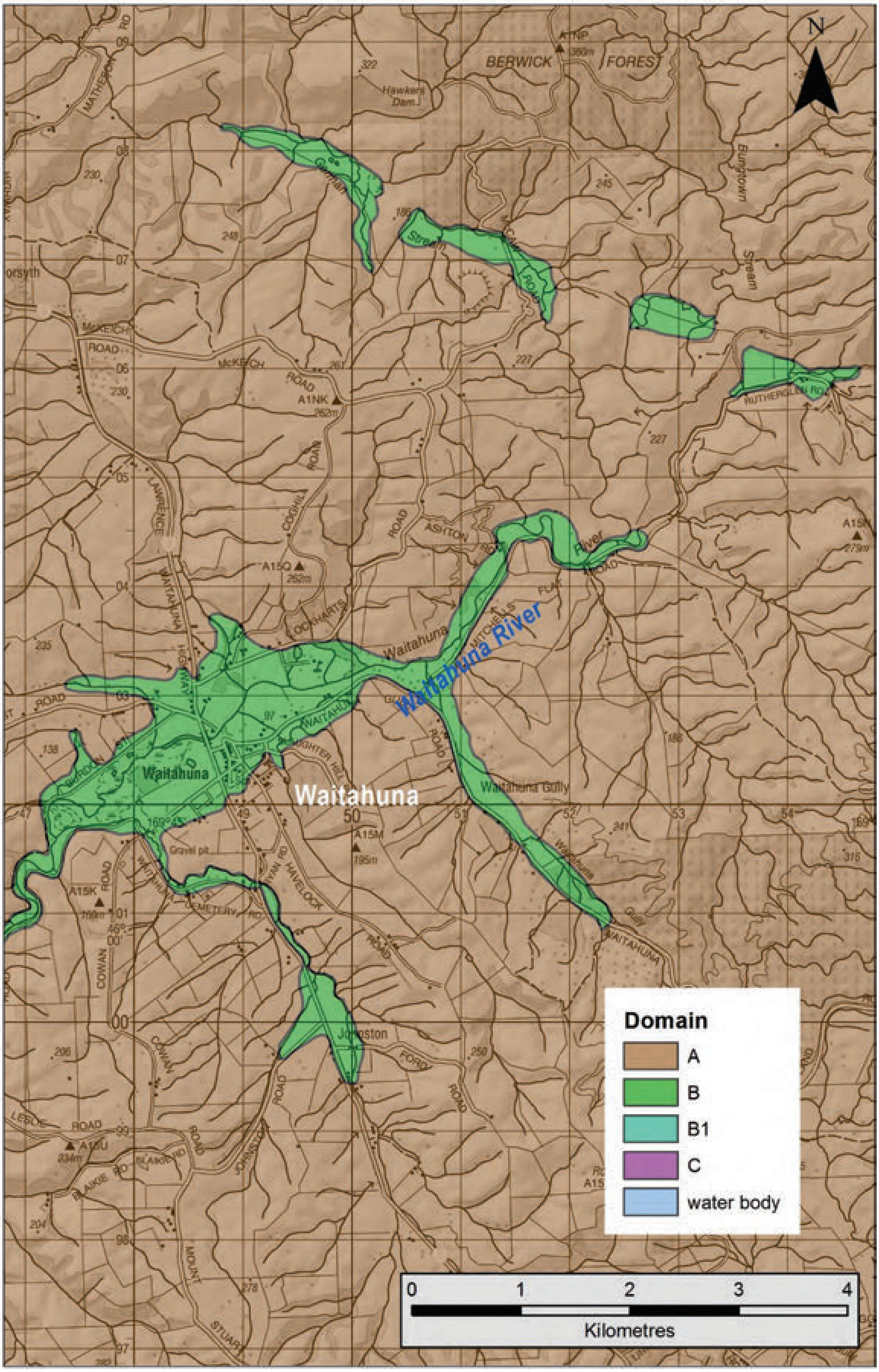

Figure A3.16 Liquefaction-susceptibility domains in the Waitahuna area. The key is generic to the dataset and not all units may be present on this map.

A3.3.2 Heriot and Tapanui areas (Figures A3.17, A3.18)

The broad low-lying valley floor, low terraces, and lowest reaches of tributary alluvial fans of the Pomahaka River, from Conical Hill upstream to about Seddon Hill Road, are included in Domain B (Figure A3.17). The geological map (Turnbull and Allibone 2003) shows patchy outcrop of bedrock along the river channel, but the low gradient and relict meander pattern of the river plain indicates the possibility of fine-grained river deposits, and likely shallow groundwater table. The lowest, ~2 km long, reach of Waikoikoi Creek is included in the domain, because of its meandering channel patterns, as is the low-gradient, broad floored sector of Flodden Creek. Farther upstream in Waikoikoi Creek, QMAP shows the creek as being incised into older strata (Gore Lignite Measures or Gore Piedmont Gravels), and it is assumed here that any potentially liquefiable sediments are very thin or absent, and a classification of Domain A is applied.

Upstream of the Kelso Gorge, the broad low-lying valley floor and lowest terraces of the Pomahaka River, Heriot Burn and Crookston Burn, and low-gradient sectors of minor tributaries, are included in Domain B (Figures A3.17, A3.18). Upstream of where all those smaller streams have incised gorges across the 'Wooded Hill Ridge' (including Anguilla Burn), they have low-gradient broad valley floors with meandering channel patterns, and those areas are also classified as Domain B.

A3.3.3 Pomahaka headwaters

The low-lying valley floor of Leithen Burn, for ~4 km upstream from the head of the gorge through the Leithen Hill ridge, is low-lying with a meandering channel form, and is included in Domain B. Farther upstream, the stream is increasingly incised into the valley floor, the groundwater table is likely deeper, and thus are included in Domain A.

Sectors of Spylaw Burn, and associated minor tributaries, have broad floors and meandering channel patterns, and are placed in Domain B.

A3.3.4 Arthurton to Balclutha tableland (Figure A3.19)

This extensive low-relief terrain consists of rolling hills with stream valleys. The main streams drain onto the tableland from short gorges across the Murihiku escarpment, and then take lower gradient paths northeast toward the Pomahaka or Clutha rivers. Within ~2 km of the Pomahaka River and ~5 km of the Clutha River, the main streams have somewhat steeper valleys set in bedrock. It is the middle reaches, where gradients are least and valley floors are broad with sinuous stream channel patterns, that liquefaction-susceptible fine-grained sediments may be present, and are classified as Domain B. These include the Waipahi River valley for ~9 km downstream of where it emerges from the Murihiku escarpment, sectors of the Wairuna Stream and larger tributaries, extensive reaches of the Waiwera River valley and its Kuriwao Stream tributary near Clinton (Figure A3.19), and parts of the Kaihiku Stream valley.

Near Popotunoa, the broad floor of the Pomahaka River valley has meander channel and bar patterns, and is included in Domain B. As there is bedrock outcrop in the general area, the river sediments are likely to be thin and the liquefaction potential is considered to be low rather than moderate.

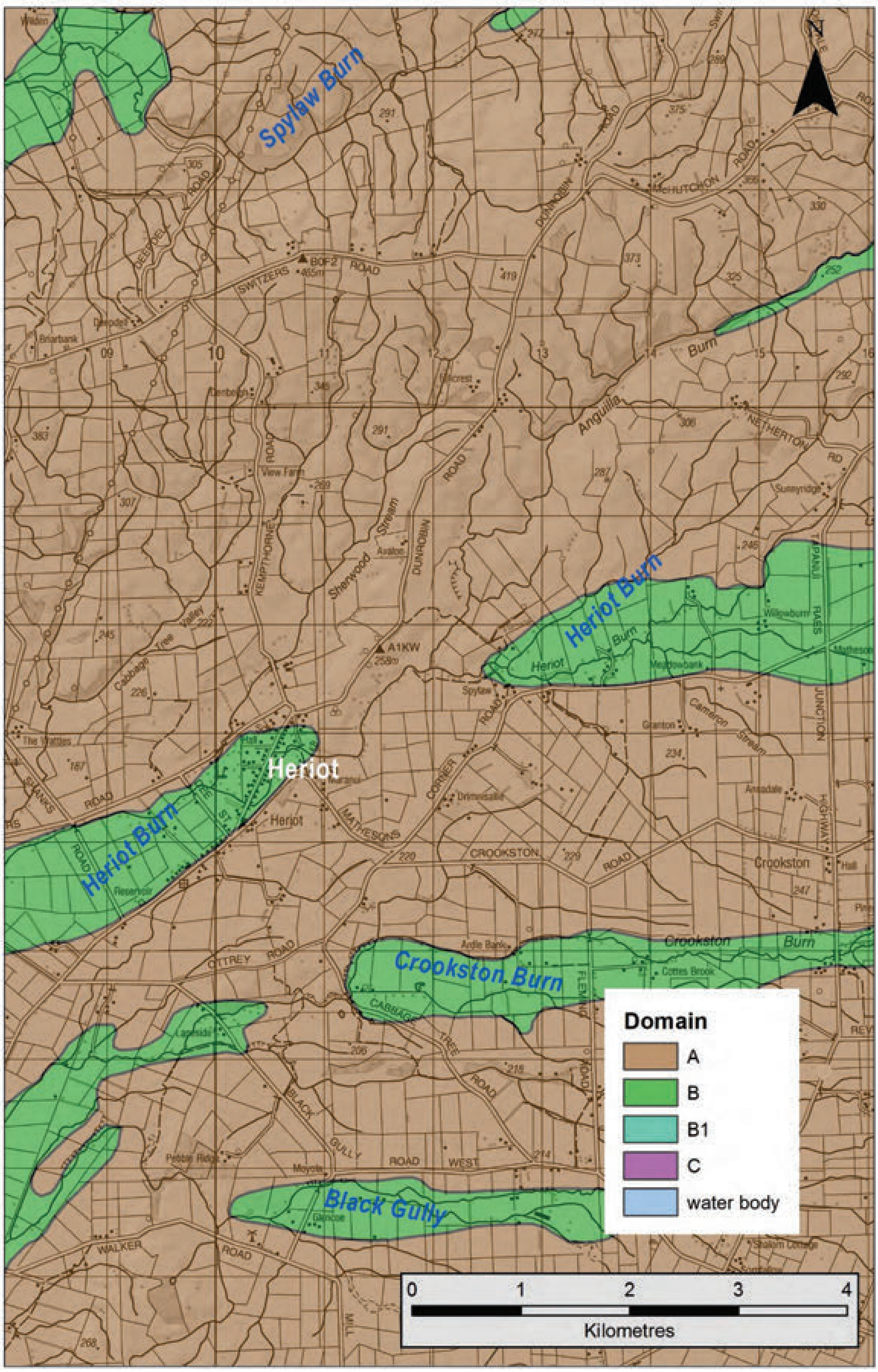

Figure A3.17 Liquefaction-susceptibility domains in the Heriot area. The key is generic to the dataset and not all units may be present on this map.

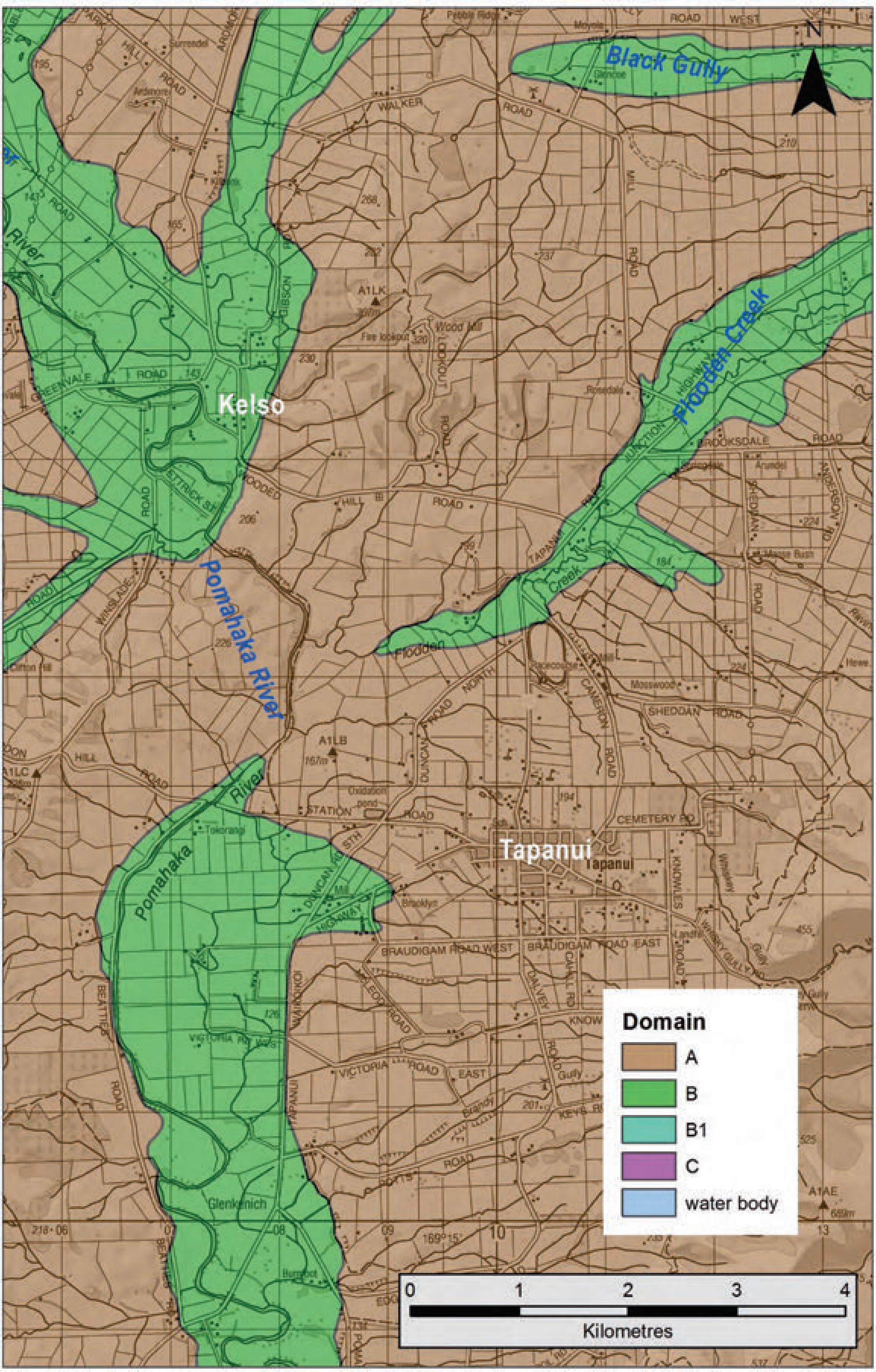

Figure A3.18 Liquefaction-susceptibility domains in the Tapanui area. The key is generic to the dataset and not all units may be present on this map.

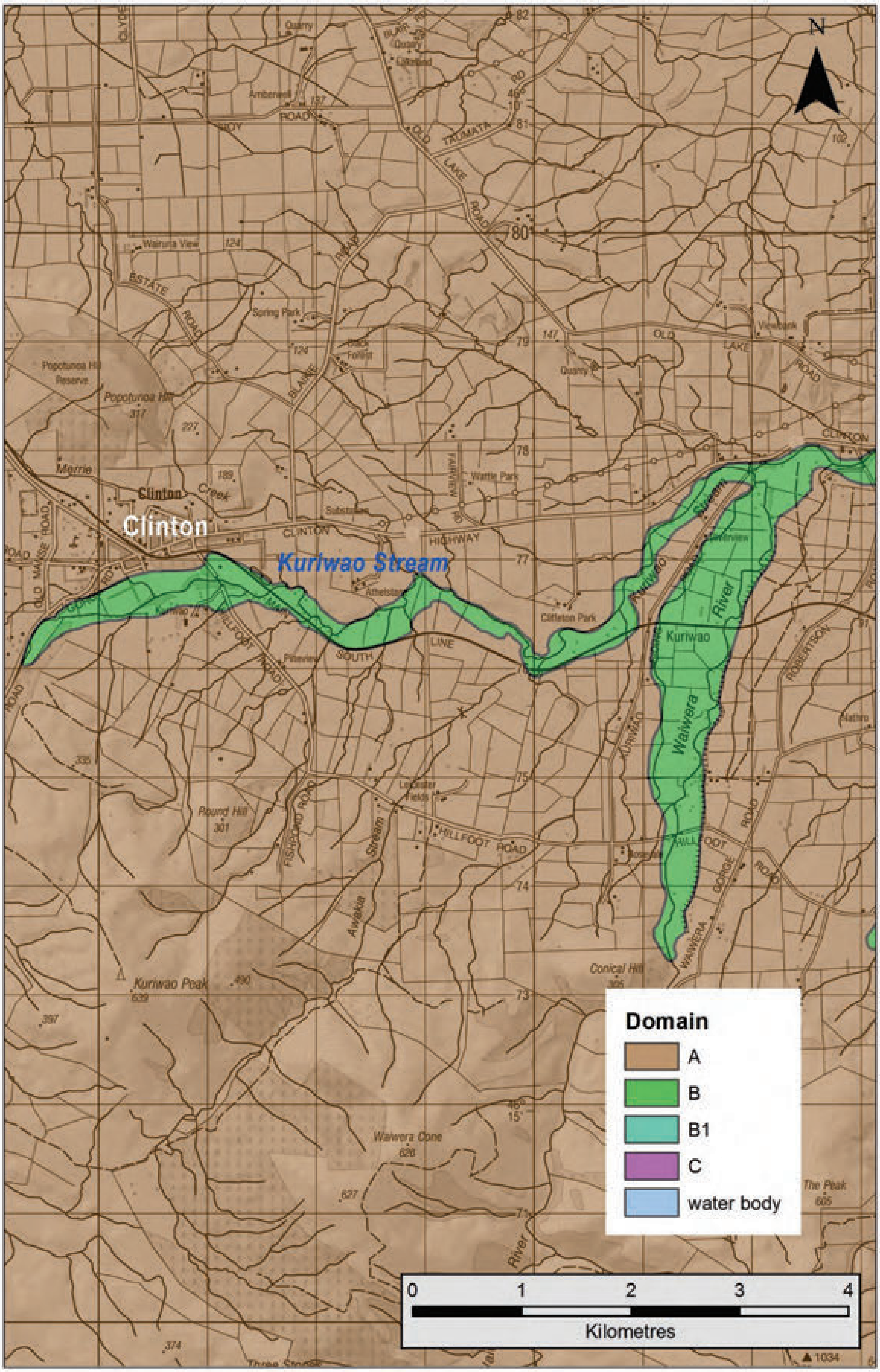

Figure A3.19 Liquefaction-susceptibility domains near Clinton. The key is generic to the dataset and not all units may be present on this map.

A3.3.5 The Catlins (Figures A3.20, A3.21)

The Catlins sector of South Otago, southwest of the Murihiku escarpment, is predominantly bedrock terrain with few areas of poorly consolidated sediments, and is mostly classified as Domain A. Domain C is identified in areas of accumulated coastal sediment around bays and inlets, and in the estuarine reaches of the main river valleys. Low-gradient upstream reaches of the larger rivers and streams, with broad valley floors or extensive low-lying terraces, as well as any broad-floored reaches of adjoining tributary valleys, are placed in Domain B. Around the coastal margins, the inland boundary of Domain C is placed at the foot of the former post-glacial sea cliff, formed prior to the sediment accumulations. The village of Papatowai is on relatively high ground, classified as Domain A. The largest population centre in the Otago sector of the Catlins is Owaka township, located in a broad basin close to the Catlins Lake marine inlet. This basin is interpreted to lie inland of former tidal influence, and its floor is classed as Domain B. Broad valley floors and low terraces adjacent to Catlins Lake as classed as Domain C, which includes the Pounawea and New Haven villages.

A3.3.6 Clutha valley and Balclutha (Figure A3.22)

Downstream from the Beaumont basin (Section A3.3.1), the Clutha valley passes through rocky terrain, where low-level benches beside the river have conspicuous rock outcrops, indicating that minimal river sediments are present, and a classification of Domain A is applied. Down-valley from Clydevale, the low-level terraces flanking the river lack rock outcrops and are presumed to be underlain by poorly consolidated sediments. These low-level terraces, up to a few metres above the river floodplain, are placed in Domain B, downstream through the Balclutha area. The change at Clydevale is likely related to the effect of post-glacial sea level rise on the Clutha River gradient, which resulted in sediment accumulation along its lower reaches, including the Inch Clutha Plain.

In Balclutha township, mapping was aided by lidar and Google Earth Street View. The mapping there is assigned an approximate scale of 1:1000 and is considered accurate in relation to property boundaries and buildings. West of the Clutha River, the Domain A-B boundary is placed where the valley floor plain abuts higher ground, approximately along the eastern side of Ryder Street, and including the broad lower reaches of gullies at Ayr Street and Oxford Street. Domain B is extended into a former gully (visible on 1946 air photos but now masked by artificial fill) south of South Otago High School, and northeast of Armstrong Street.

A3.3.7 Inch Clutha area (Figures A3.23–A3.25)

A cliff is present around the margins of the Inch Clutha Plain, and up the Lovells Stream valley to Lovells Flat (Barrell *et al.* 1998). The wave-cut cliff indicates that the entire area was formerly occupied by a water body, either an inlet of the sea or an estuarine lake. River and stream sediments have infilled the former water body, leaving Lake Tuakitoto as its only remnant. The area of the former water body within the limits of the former shoreline, and broad-floored lower reaches of adjoining stream valleys, are placed in Domain C, on the assumption that fine-grained river, estuarine and shallow marine sediments are likely to occur in the subsurface.

Towards Balclutha, the cliff-line dies out up-valley, marking the presumed inland limit of the former water body. This change occurs approximately midway between Balclutha and Finegand on the western side and between Balclutha and Stirling on the eastern side, and a cross-valley boundary is drawn there between Domain C of the Inch Clutha Plain and Domain B of the lower Clutha valley floor (including the Balclutha area).

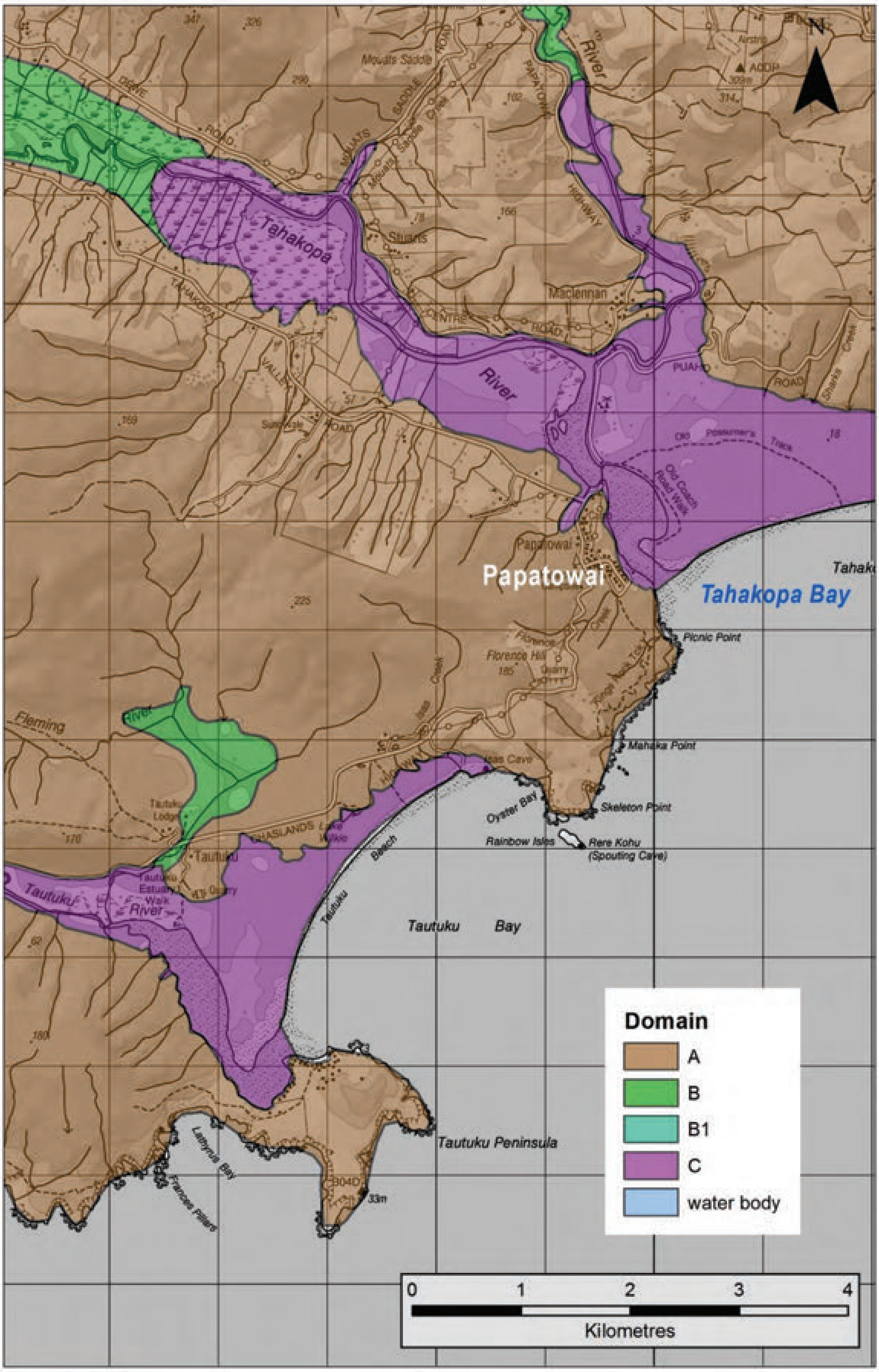

Figure A3.20 Liquefaction-susceptibility domains in the Papatowai area. The key is generic to the dataset and not all units may be present on this map.

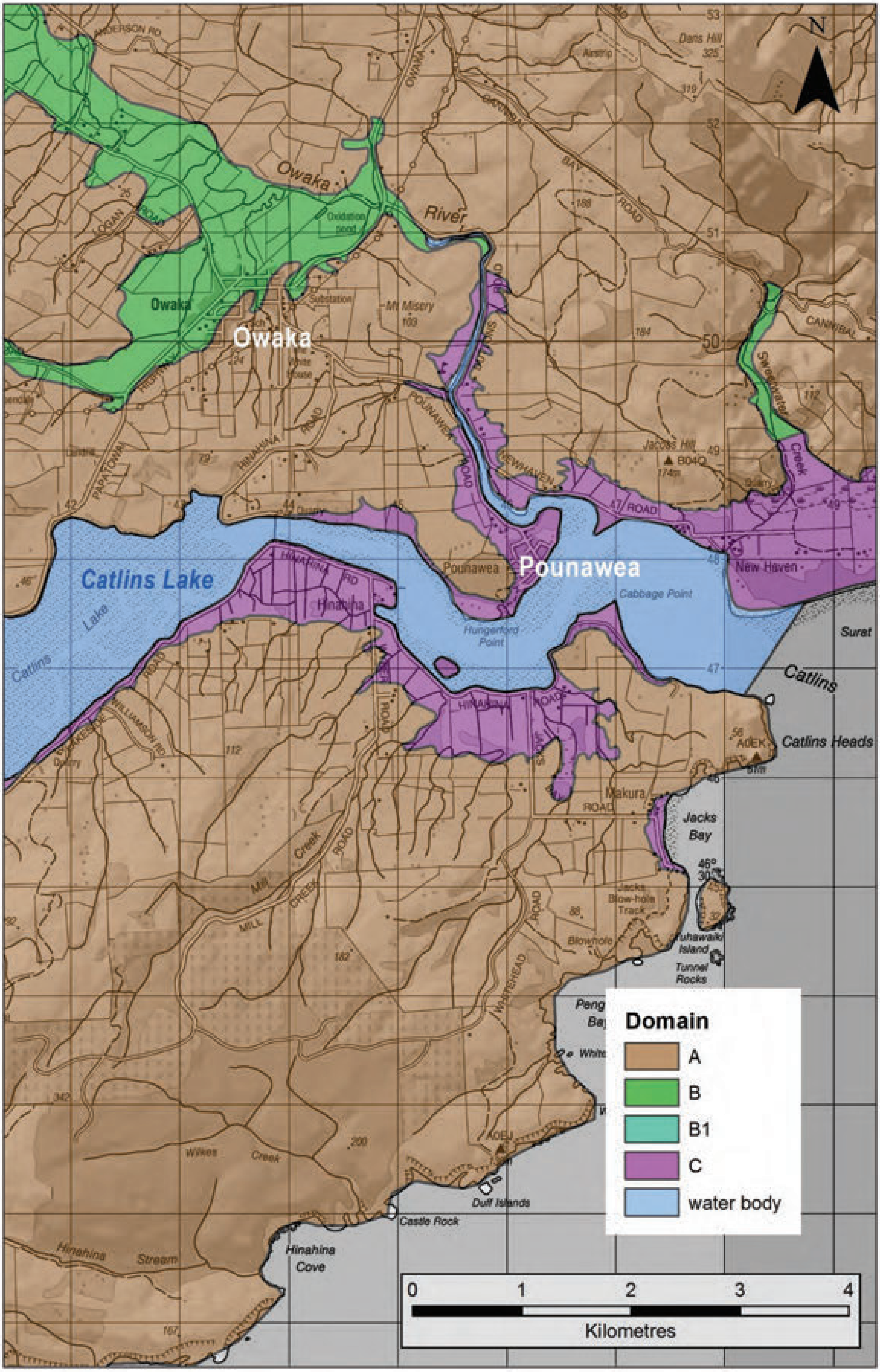

Figure A3.21 Liquefaction-susceptibility domains in the Owaka area. The key is generic to the dataset and not all units may be present on this map.

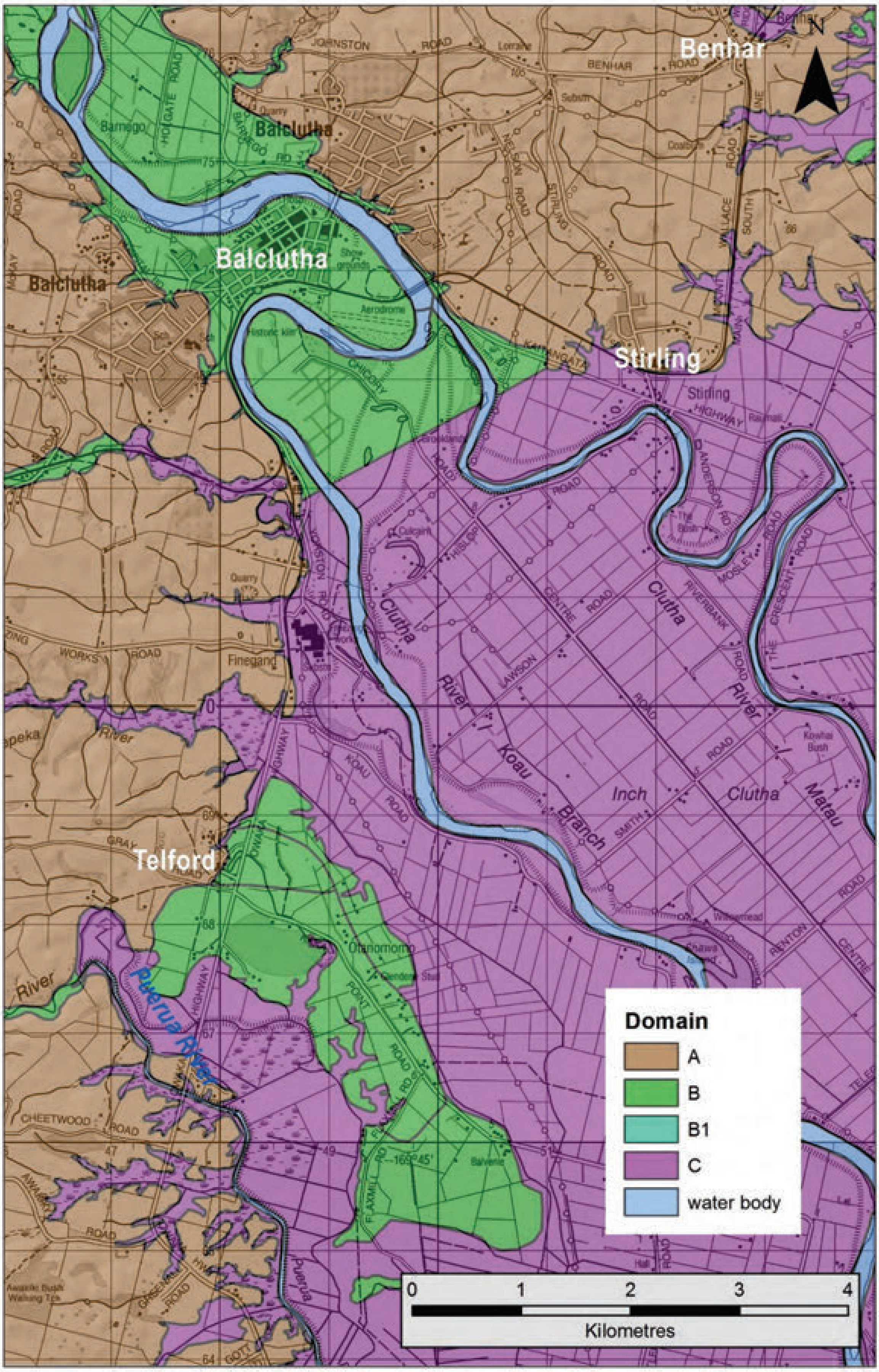

Figure A3.22 Liquefaction-susceptibility domains near Balclutha. The key is generic to the dataset and not all units may be present on this map.

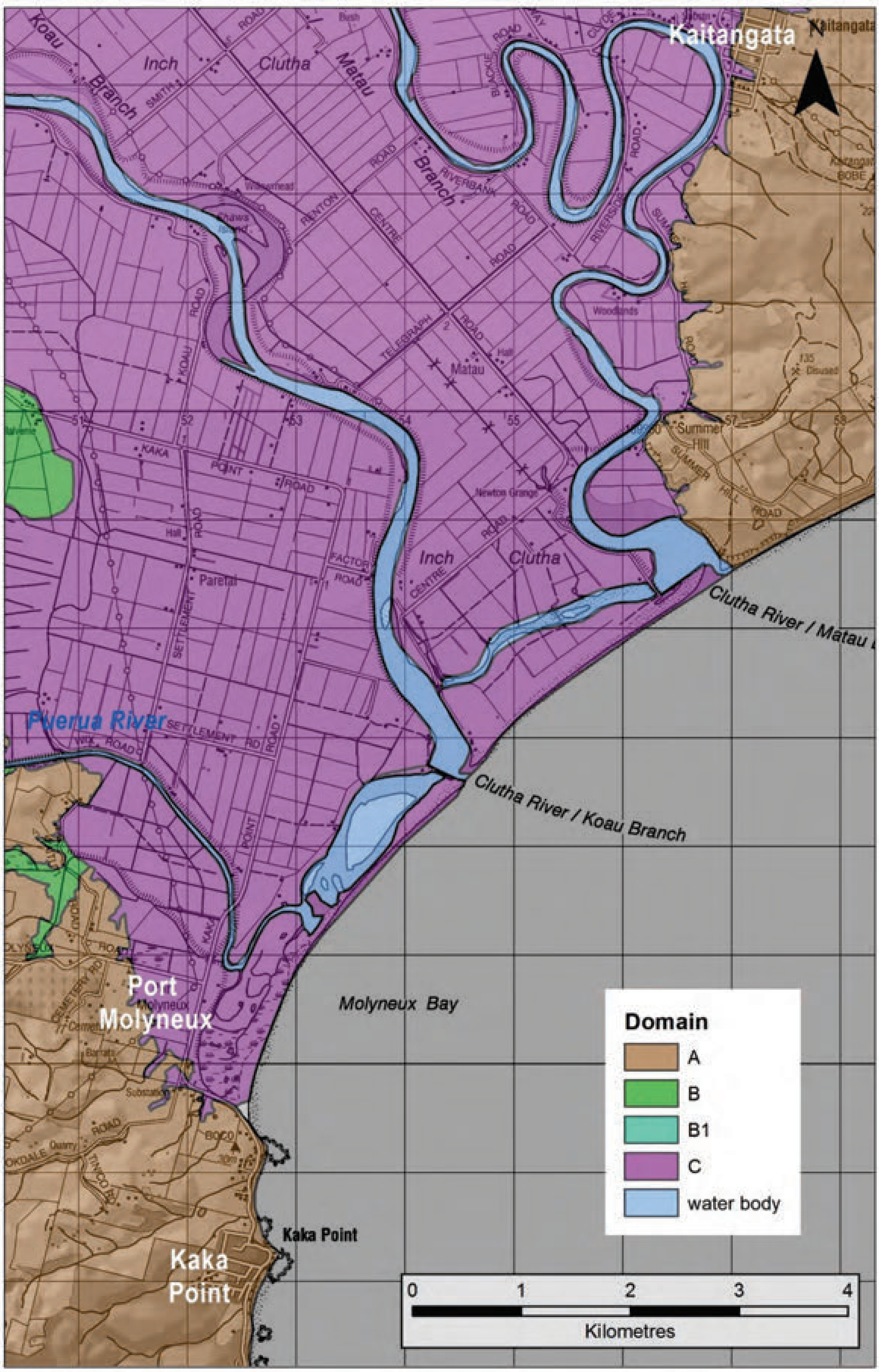

Figure A3.23 Liquefaction-susceptibility domains in the Kaka Point and southern Inch Clutha areas. The key is generic to the dataset and not all units may be present on this map.

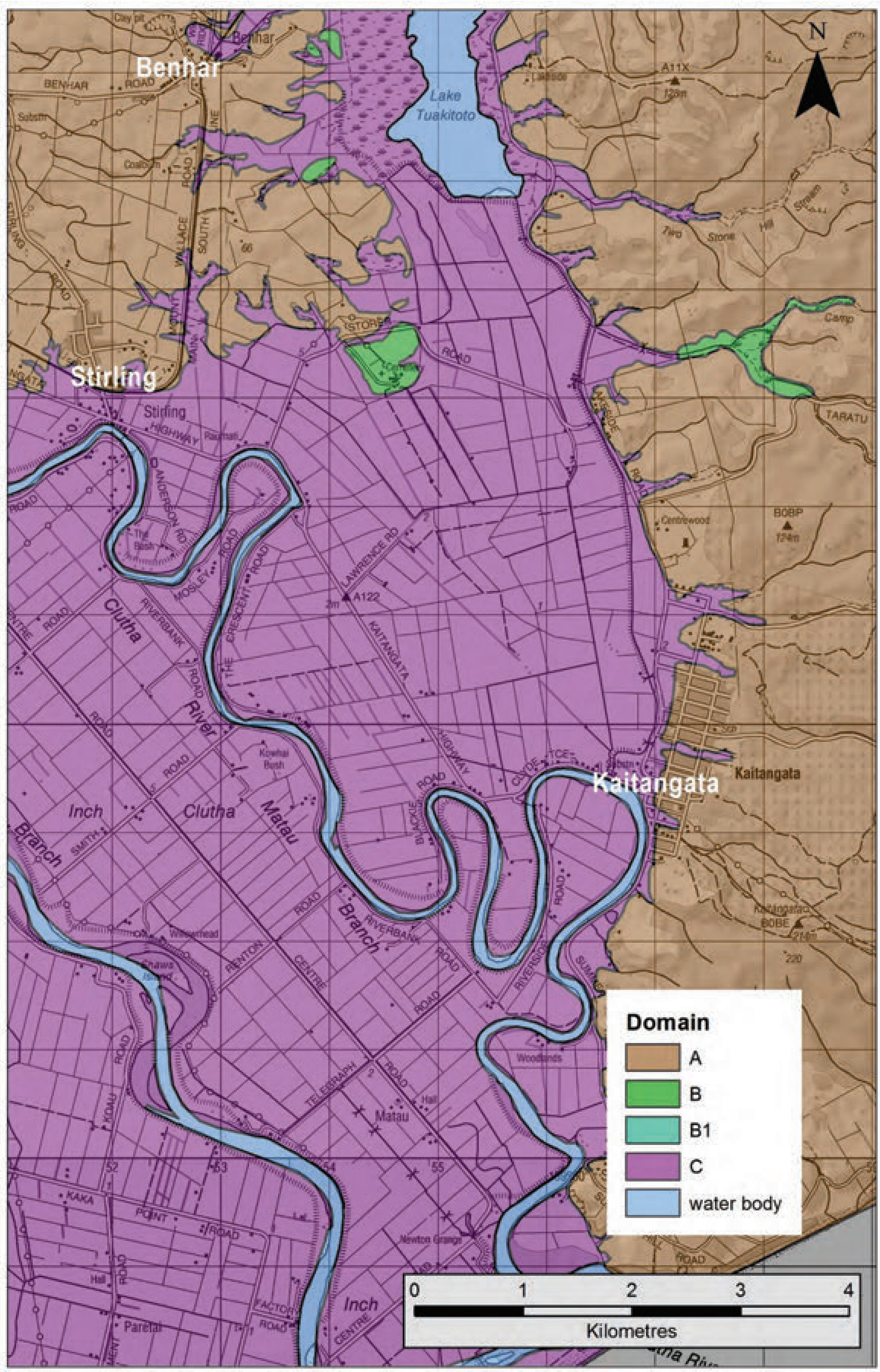

Figure A3.24 Liquefaction-susceptibility domains in the Kaitangata and eastern Inch Clutha areas. The key is generic to the dataset and not all units may be present on this map.

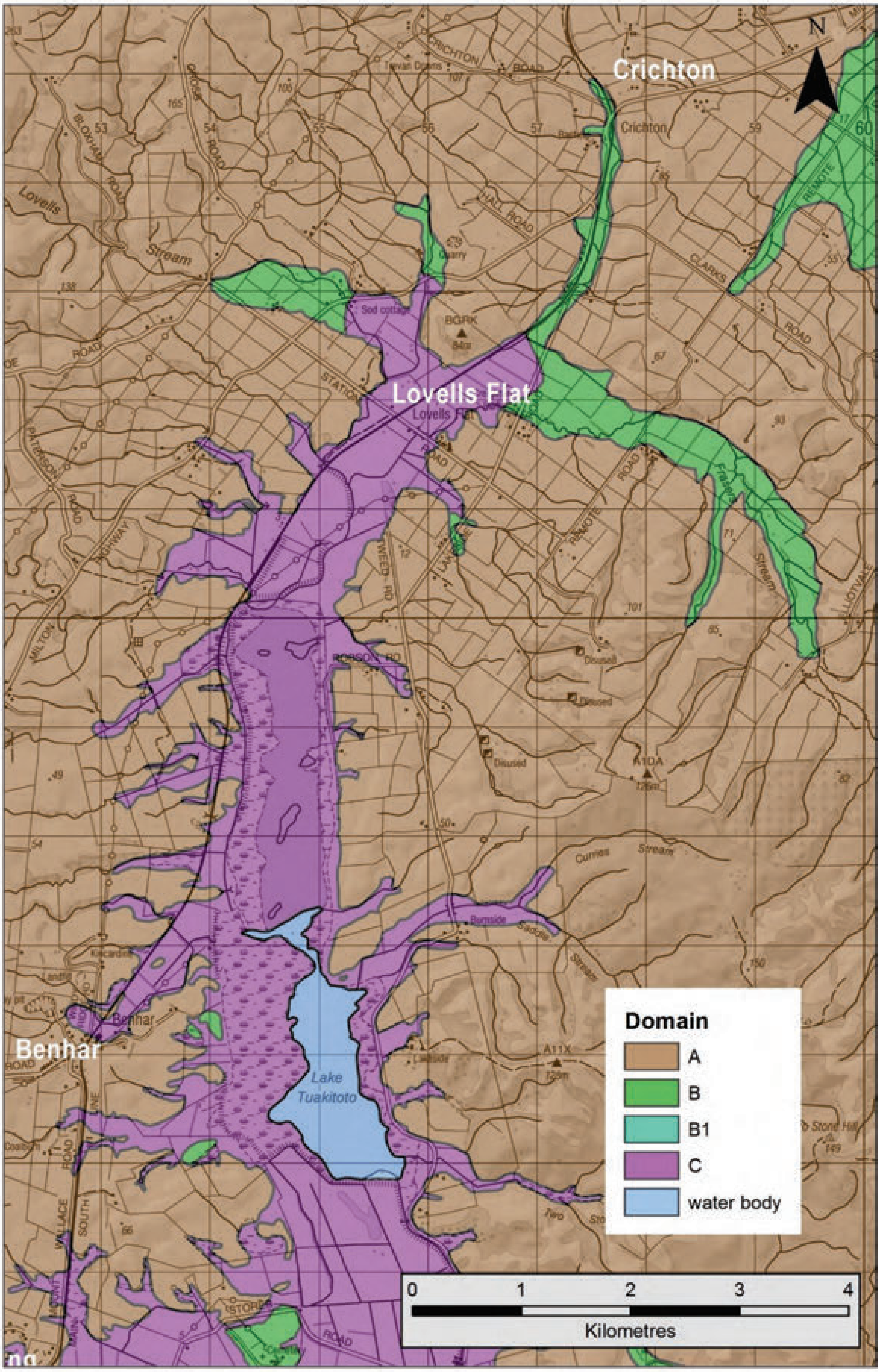

Figure A3.25 Liquefaction-susceptibility domains in the Benhar and Lovells Flat areas. The key is generic to the dataset and not all units may be present on this map.

Close to the margins of the Inch Clutha Plain and Lovells Stream valley, many of the inflowing tributary streams have broad valley floors, reflecting the build-up of post-glacial sediment in the lower Clutha valley related to the infilling of the former inlet water body. The infilled valley floors are classified as Domain C, passing to Domain B farther up the tributaries, in areas where their valleys are broad, and the channel patterns sinuous. Note that in the Waitepeka River and Toiro Stream catchments which drain onto the western side of the Inch Clutha Plain, stream channels shown on Topo 50 maps are in locations inconsistent with topographic contours. Domain boundaries there are positioned using aerial imagery.

Along the southwestern margin of the Inch Clutha Plain, the inland margin of Domain C is placed at approximately 3 m above sea level, as indicated by lidar datasets. The southern limit of Domain C is placed where Kaka Point Road meets the coast, south of which rock outcrop is conspicuous in the shore platforms, and in many road cuts. That area, including Kaka Point township and the coastline extending around to the Catlins Lake area, is placed in Domain A.

The belt of dunes fringing the coastline of the Inch Clutha Plain are included in Domain C, for simplicity, even though the dune sand above the groundwater table will not have potential for liquefaction. Were liquefaction hazard zonation to be undertaken, the higher sectors of sand dunes would likely be assigned a lesser liquefaction hazard than the adjacent low-lying plain.

In the Telford-Otanomomo area, an area of broad low terraces separates the Puerua and Clutha rivers. The terraces are underlain by fine-grained sediments, at least in places (Barrell *et al.*, 1998), but as they stand between 2 and as much as 11 m above the Inch Clutha Plain, the groundwater table is likely to be about as deep as the terraces are high above the main plain surface. As the deeper groundwater is likely to reduce the potential of damaging liquefaction occurring, they are placed in Domain B. The highest terrace is also classified as Domain B, tentatively, as its height is such that is has a lesser likelihood of having groundwater that is sufficiently shallow to present a liquefaction hazard, even if susceptible sediments are present. This terrace, and other similar isolated terrace remnants, such as one beside Storer Road between Stirling and Lake Tuakitoto which is known to be underlain by fine-grained sediment (Barrell *et al.*, 1998), and others near Benhar, have flat surfaces suggesting that they are underlain by sediments rather than bedrock; all are tentatively placed in Domain B. An array of comparable low terraces along the western margin of the plain, west of the Puerua River, are included in Domain A, because numerous road-cut exposures show bedrock close to the ground surface, and these terraces likely comprise relatively thin sediments on bedrock.

A3.3.8 Otago coast — Clutha River to Taieri River (Figures A3.26, A3.27)

For the most part, the coastline northeast of the mouth of the Clutha River Matau Branch is cliffed and eroding. This means that the coastal reaches of streams are in an erosive rather than depositional setting, reducing the likelihood of there being accumulations of poorly consolidated sediments.

Near Wangaloa, Washpool Stream has cut a broad valley where it crosses the coastal plain. This is interpreted to be a glacial-age valley formed under low-stand sea level, due to the relatively steep continental shelf. There is minimal post-glacial modification of the valley. It is classed as Domain A.

Different circumstances prevail at Measly Beach, at the mouth of Wangaloa Creek, where the coast has migrated seaward due to the accumulation of sand dunes and sand plains. The shoreline is now as much as ~400 m seaward of the formerly active coastal cliff. This has greatly lengthened the coastal reach of Wangaloa Creek, resulting in accumulated young sediments in the lower reaches of the creek and its tributaries. Domain C is mapped in the creek valley, and along the coastal margin. Farther north, the active dune belt is not differentiated from Domain A, except where it has impeded the lower reaches of streams and resulted in sedimentation in the lower reaches of stream valleys.

The dune and beach plains of Chrystalls Beach, and southwest of Tokomairiro Mouth, are included in Domain C. These mapped areas are separated in the dataset from the valley floors of both Rocky Gully Creek and the Tokomairaro River[2], even though they also are included in Domain C. Also separated in the dataset are the valley floors either side of the Akatore Fault rupture scarp, which crosses the Tokomairaro valley about 1.5 km upstream of the coast. This scarp relates to earthquake uplift events on the fault over the past few thousand years (Litchfield and Norris 2000; Hayward *et al.* 2007; Taylor-Silva 2017) that have raised the southpeast side of the fault by several metres, including the valley floor and coastal plain (and the Toko Mouth village). The uplift will have deepened the unconfined groundwater table under the low-lying terraces southeast of the fault, somewhat reducing the liquefaction susceptibility relative to that of the valley-floor sector upstream of the fault. Although all are placed conservatively in Domain C, the positioning of a domain polygon boundary along the fault is intended to aid any future assessments of liquefaction hazards in this area.

Northeast of Chrystalls Beach, and upstream of the Akatore Fault scarp, localised broad sectors of the low-lying floors of the Nobles Stream, Bull Creek and Big Creek valleys are placed in Domain B. A sector of the upper part of the Akatore Creek valley has a broad floor, and is also classified as Domain B.

The only other locations of poorly consolidated sediment accumulations are surrounding the Akatore Creek estuary, and associated broad-floored tributary valleys, and around the estuary and broad-floored tributary valleys of an un-named stream at the Taieri Beach sector of the Taieri Mouth village. All these areas are classed as Domain C.

A3.3.9 Tokomairaro River valley

Like the Clutha River, the Tokomairaro River had a steeper gradient during the low sea level of the Last Glaciation, and the valley became filled with sediment during and since the post-glacial sea level rise. The lower Tokomairaro River valley is estuarine for about 7 km inland from the coast, and sluggish for a further 4 km upstream, a location about 2.5 km downsrtream from Milton township, and where the river surface is ~5 m above sea level. That is interpreted to be the upstream limit of the influence of post-glacial sea level rise. From there downstream, the broad floor and lowest terraces of the main valley, and lower reaches of adjoining tributary valleys, are classified as Domain C. Upstream from there to the edge of the Tokomairiro plain, the valley floor and lower reaches of tributary valleys are classed as Domain B.

A3.3.10 Tokomairiro plain (Figures A3.28, A3.29)

The Tokomairiro plain forms the floor of a large inland basin, filled with river or stream sediments. There is a shallow groundwater table, and the relatively low gradient and small size of the rivers and streams draining into and through the basin increases the likelihood that the near-surface sediment will include sand or silt layers. The lower-lying parts of the basin are therefore classified as Domain B, including Milton township.

[2] In August 2016, the name of the 'Tokomairiro' River (main stem and two upstream branches) was officially changed to Tokomairaro'. The informal term Tokomairiro plains remains unchanged.

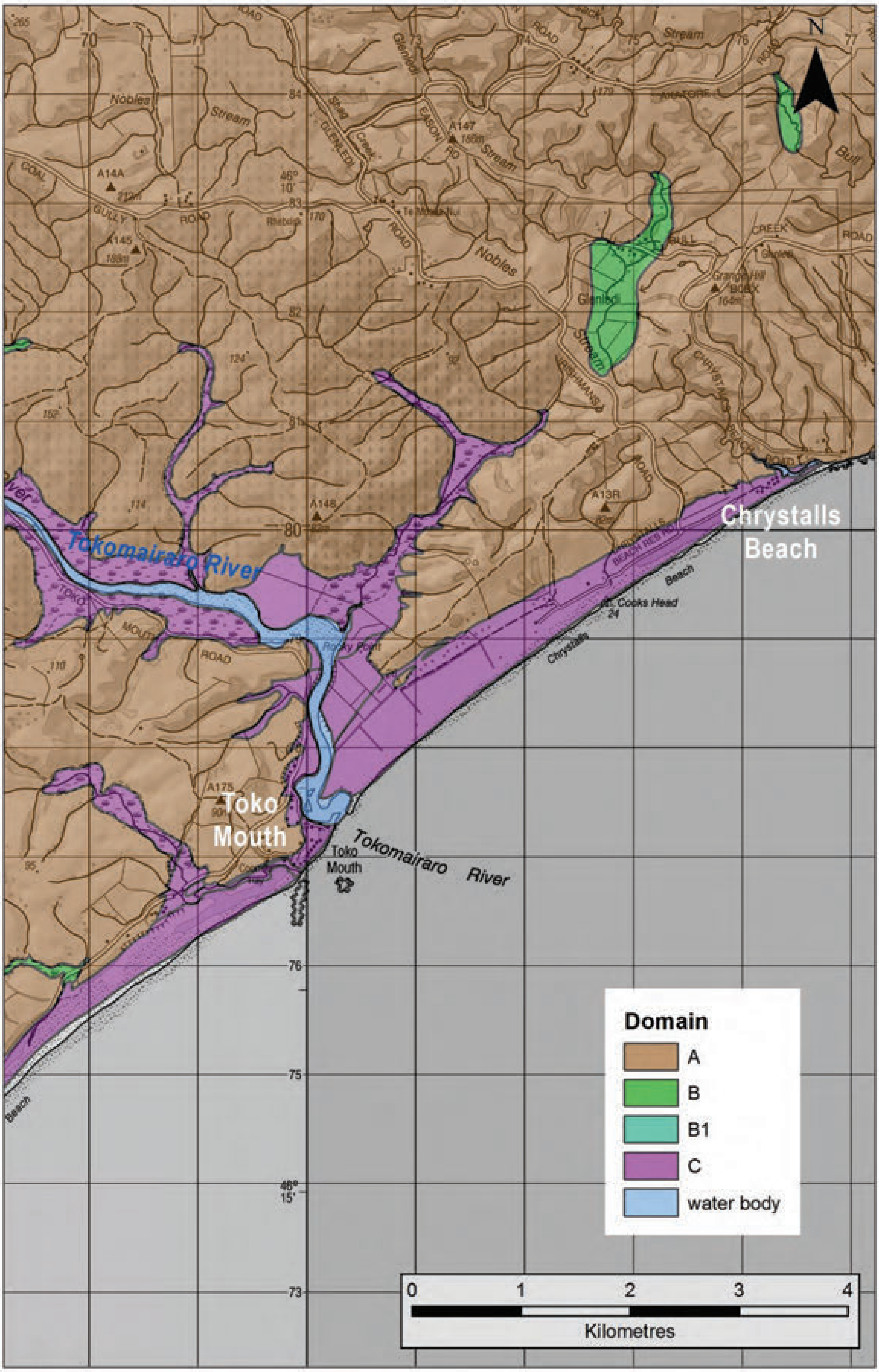

Figure A3.26 Liquefaction-susceptibility domains near Toko Mouth. The key is generic to the dataset and not all units may be present on this map.

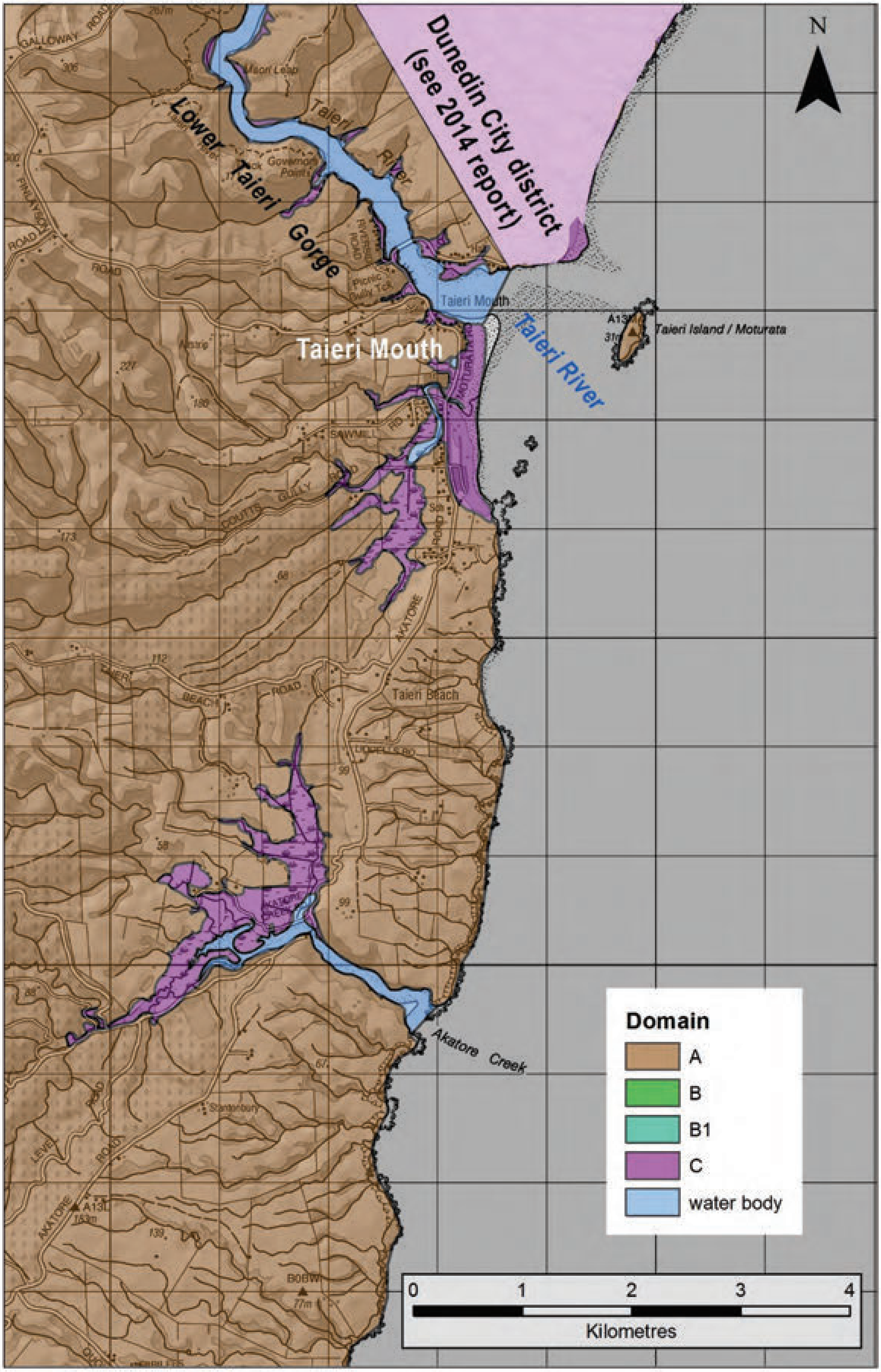

Figure A3.27 Liquefaction-susceptibility domains near Taieri Mouth. The key is generic to the dataset and not all units may be present on this map.

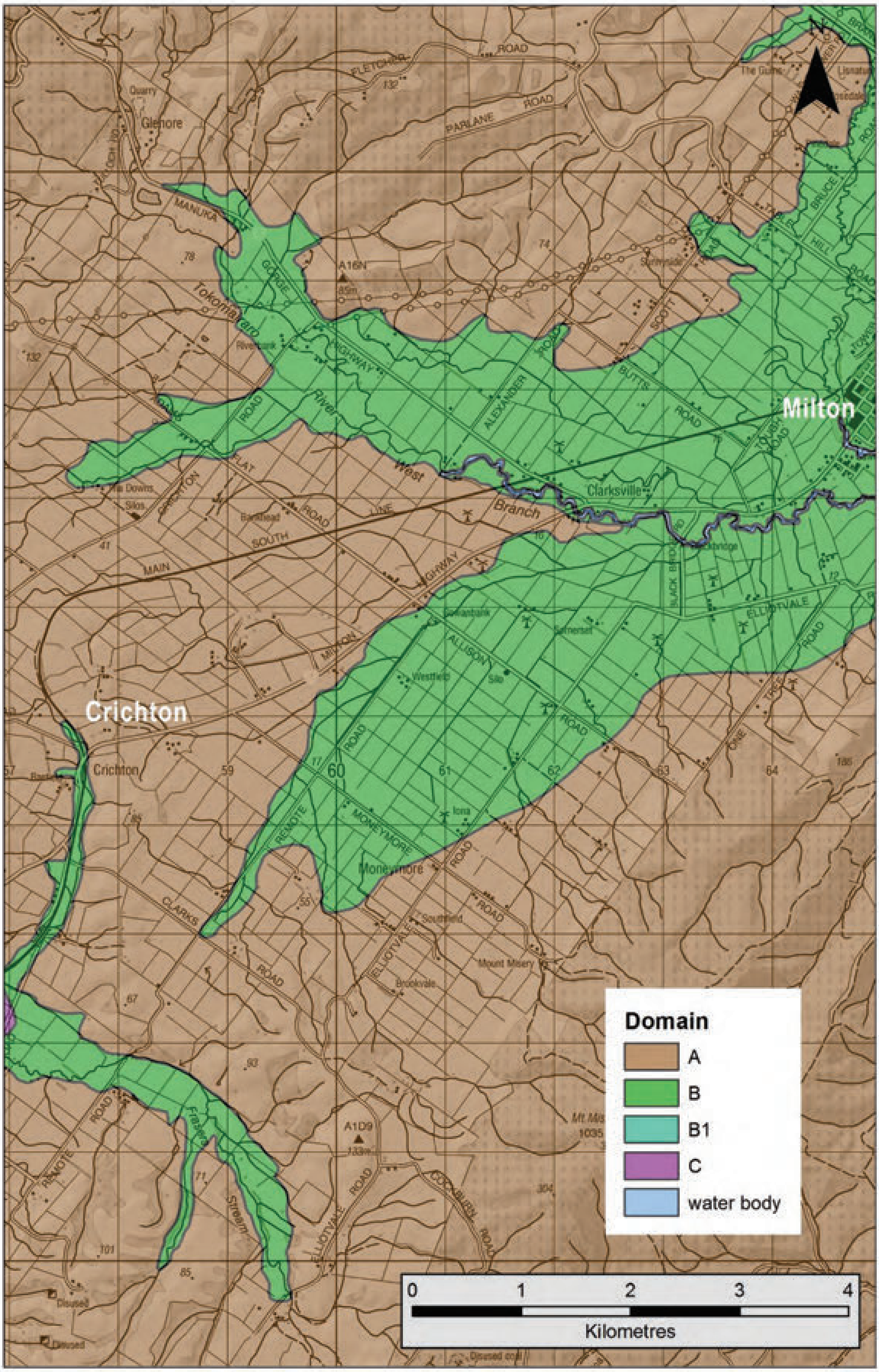

Figure A3.28 Liquefaction-susceptibility domains in the southwestern sector of the Tokomairiro plain. The key is generic to the dataset and not all units may be present on this map.

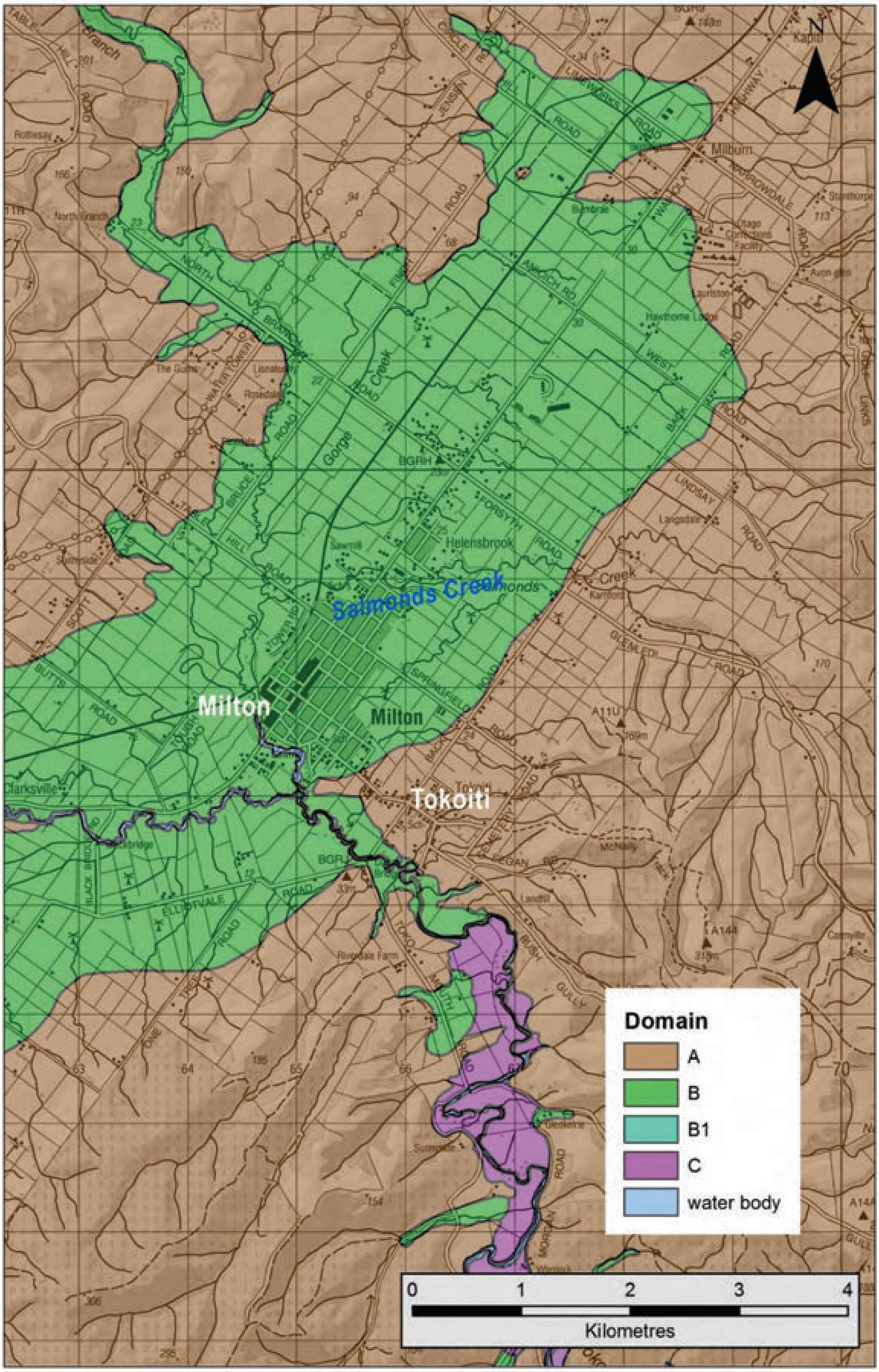

Figure A3.29 Liquefaction-susceptibility domains near Milton. The key is generic to the dataset and not all units may be present on this map.

The southwestern sector of the plain comprises aprons of gently-sloping alluvial fans that grade to the Tokomairaro River West Branch. Parts of the fans that have gradients of less than ~20 m fall per ~2 km are classified as Domain B, because it is possible that they contain fine-grained sediments and a shallow groundwater table. For the north-eastern sector of the plain, the gradient criterion means that the eastern margin of Domain B lies at about the location of Back Road, but near Milburn, swings northward because the fans there being steeper, plus the presence of two spurs of higher ground near Circle Hill Road, probably formed on promontories of bedrock. Similarly, the area around near Tokoiti is excluded from Domain B, due to higher ground, steeper fans, and proximity to the incised Tokomairaro River floodplain, which likely means that the groundwater table is relatively deep under Tokoiti.

The Tokomairaro River West Branch sector of the plains is classified as Domain B up-valley towards the Manuka Gorge. The valley floor, west of State Highway 8, for ~1.5 km sector down-valley of the Tulloch Road intersection, is excluded as it has been deeply dredged as part of the Glenore alluvial gold mining area.

A3.3.11 Waihola area, southwestern Taieri Plain and lower Taieri gorge (Figure A3.30)

The sea extended up the lower Taieri gorge into the Taieri Plain basin during post-glacial sea level rise, and this area remained a marine inlet for several thousand years, before becoming largely filled with sediment (Barrell *et al.* 1998, 1999, 2014). Lakes Waihola and Waipori are the remnants of this inlet and remain tidally influenced today. Northeast of Waihola township, the lower reaches of tributary valleys to the plain have notably broad floors, related to their being closer to the former Taieri River valley, whose floor was ~25 m below sea level prior to its flooding during post-glacial sea level rise. The post-glacial sediment fill is likely to be thickest in that area, compared to the Lake Waihola sector of the basin, where the fill is likely to thin progressively westward, reflecting the former valley drainage gradient towards the Taieri River.

The floor of the Waihola sector of the Taieri Plain and its wetlands, along with broad-floored lower reaches of adjoining tributary valleys, are placed in Domain C. Broad-floored reaches of the tributary valleys, upstream of the interpreted limit of the former tidal inlet, are mapped as Domain B. In the Waipori River valley upstream of Berwick, along the margin of the Dunedin City district, the Domain B/C boundary is placed where bore hole data indicate a predominance of gravel in the subsurface up-valley, as described in more detail by Barrell *et al.* (2014).

South and west from Lake Waihola, extensive alluvial fans have built out into the basin, and a cliff, marking the shoreline of the former inlet, is cut along the toes of some of the fans. All areas lakeward of the cliff are placed in Domain C, including the broad swampy valley floor at the western end of Lake Waihola. Towards the head of the basin to the west, the low-gradient valley floor axis, close to present drainage, is classified as Domain B. The alluvial fans that have built out into the basin are relatively steep, and are placed in Domain A.

Part of Waihola township lies on the alluvial fan of Waihola Creek. The sector of the fan, and associated beach plain, that has built out lakeward of the former cliff-line is classified as Domain C, whereas the more inland sector in placed in Domain B, on the reasoning that the catchment of the creek is small, and there is unlikely to be much accumulation of poorly consolidated post-glacial sediment. State Highway 1 approximates the position of the former cliff-line, and the Domain B/C boundary is drawn along the highway.

The floor of the lower Taieri gorge downstream of Henley Ferry Bridge, and the lower reaches of adjoining tributary valleys are mapped as Domain C, as is the low-lying coastal fringe at Taieri Mouth village.

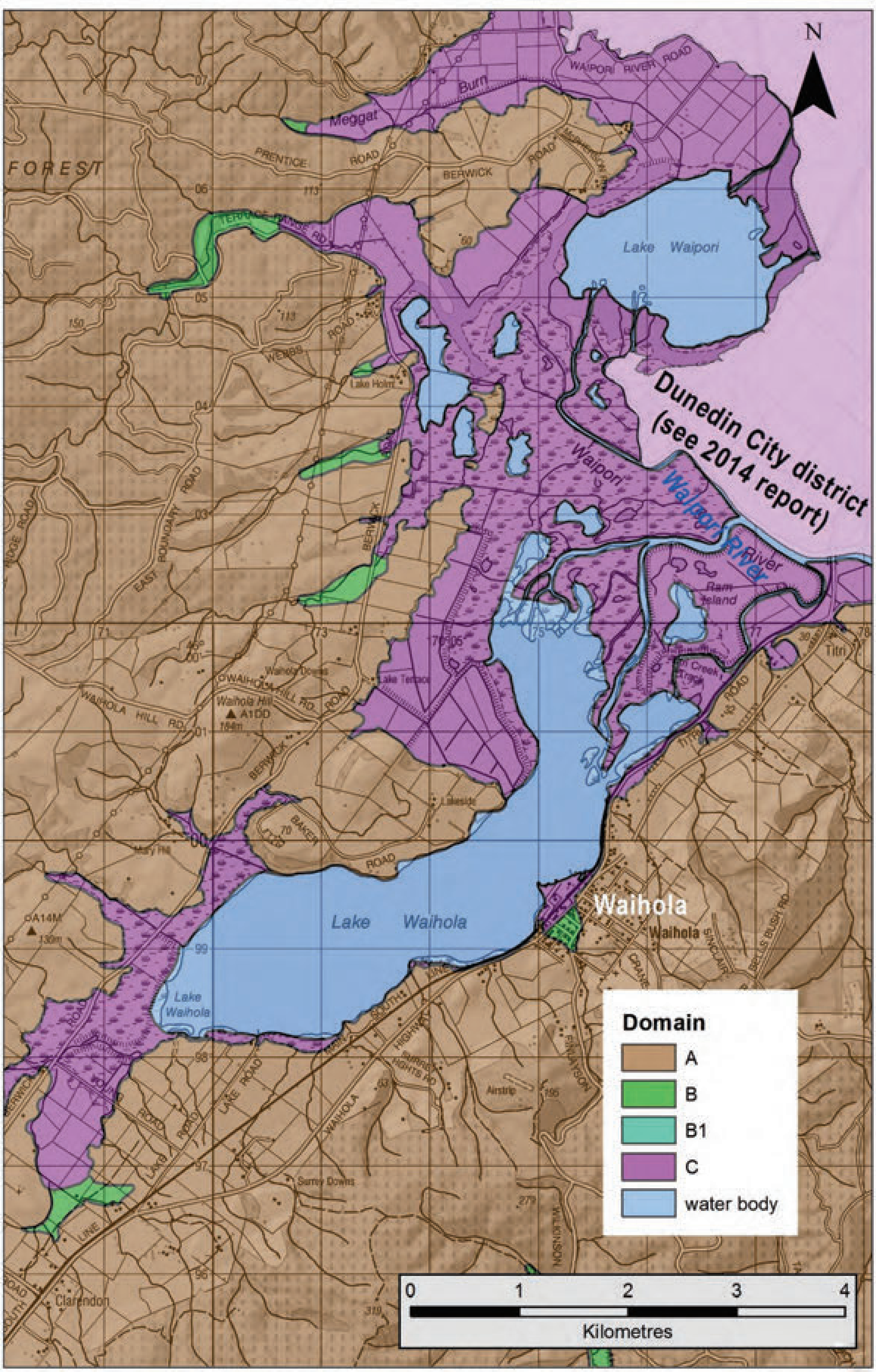

Figure A3.30 Liquefaction-susceptibility domains near Waihola. The key is generic to the dataset and not all units may be present on this map.

A3.4 Waitaki District

A3.4.1 Moonlight Flat

At Moonlight Flat, southwest of Macraes Flat, is a basin that has formerly been occupied by a lake. The extent of the lake sediments has been taken directly from QMAP, and is classified as Domain B.

A3.4.2 Goodwood area (Figure A3.31)

The extensive estuarine flats of the Pleasant River estuary and the lower reaches of the river valley, up to ~5 m above sea level, are placed in Domain C, as is the floor of the Watkin Creek tributary, based on elevations indicated by lidar. Farther upstream, the broad floors and lowest terraces of the Pleasant River and Watkin Creek valleys are classified as Domain B. In the Watkin Creek valley, Domain B is extended up the increasingly narrow and incised valley to Willow Brook. In the Pleasant River valley, and its Trotters Creek tributary, Domain B is extended up the valley floor and lowest terraces to just upstream of the 20-m contour.

A3.4.3 Palmerston area (Figures A3.31–A3.33)

State Highway 1 crosses the Shag River (Waihemo) valley floor at about the upstream end of the estuarine reach of the river. The valley floor downstream of there is classified as Domain C, because estuarine or shallow marine sediments are likely to underlie the valley floor. Close to the coast, Domain C is extended for ~2 km up the floor of the un-named tributary valley near Walsh Road, giving way to a Domain B classification that is taken upstream to where the 20-m topographic map contour crosses the valley.

Upstream of State Highway 1, the broad floor and low terraces of the Shag River (Waihemo) valley, and lower reaches of broad-floored tributary valleys, are classified as Domain B. The upstream limit of Domain B in the main valley is placed at Glenpark, ~7 km up-valley from Palmerston, where the valley emerges from a rock gorge. Farther upstream, two isolated broad-floored basins with low terraces, near Inch Valley and Dunback-Waynes, are classified as Domain B. Upstream from there, the river is increasingly incised below its terraces, with a groundwater table likely to be increasingly deep; those terraces are included in Domain A.

On the southern side of the main valley downstream from Palmerston is an intermediate-level terrace that stands as much as 5 m or more above river level and is dissected by gullies that drain to the lower terraces. As the groundwater table beneath this intermediate terrace is likely to be equilibrated with the river, it is included in Domain A.

The broad valley floor of the un-named stream that passes through Palmerston township is classified as Domain B, to account for the possibility that the valley is underlain by fine-grained stream sediments, and the groundwater table is likely to be shallow. The valley floor margin (i.e. the Domain B/A boundary) has been positioned with the aid of high-resolution aerial imagery and Google Earth Street View, at an approximate mapping scale of 1:1000 scale and is considered accurate at the scale of properties and buildings.

The Shag valley river deposits are predominantly gravelly, and the Domain B classification in the main valley acknowledges the possible presence of sandy or silty layers or pods related to buried channels, with the presence of liquefaction-susceptible materials judged a low rather than moderate likelihood. However, sandy or silty sediments are more likely to predominate in the in the minor tributary valleys, where the likelihood is considered moderate.

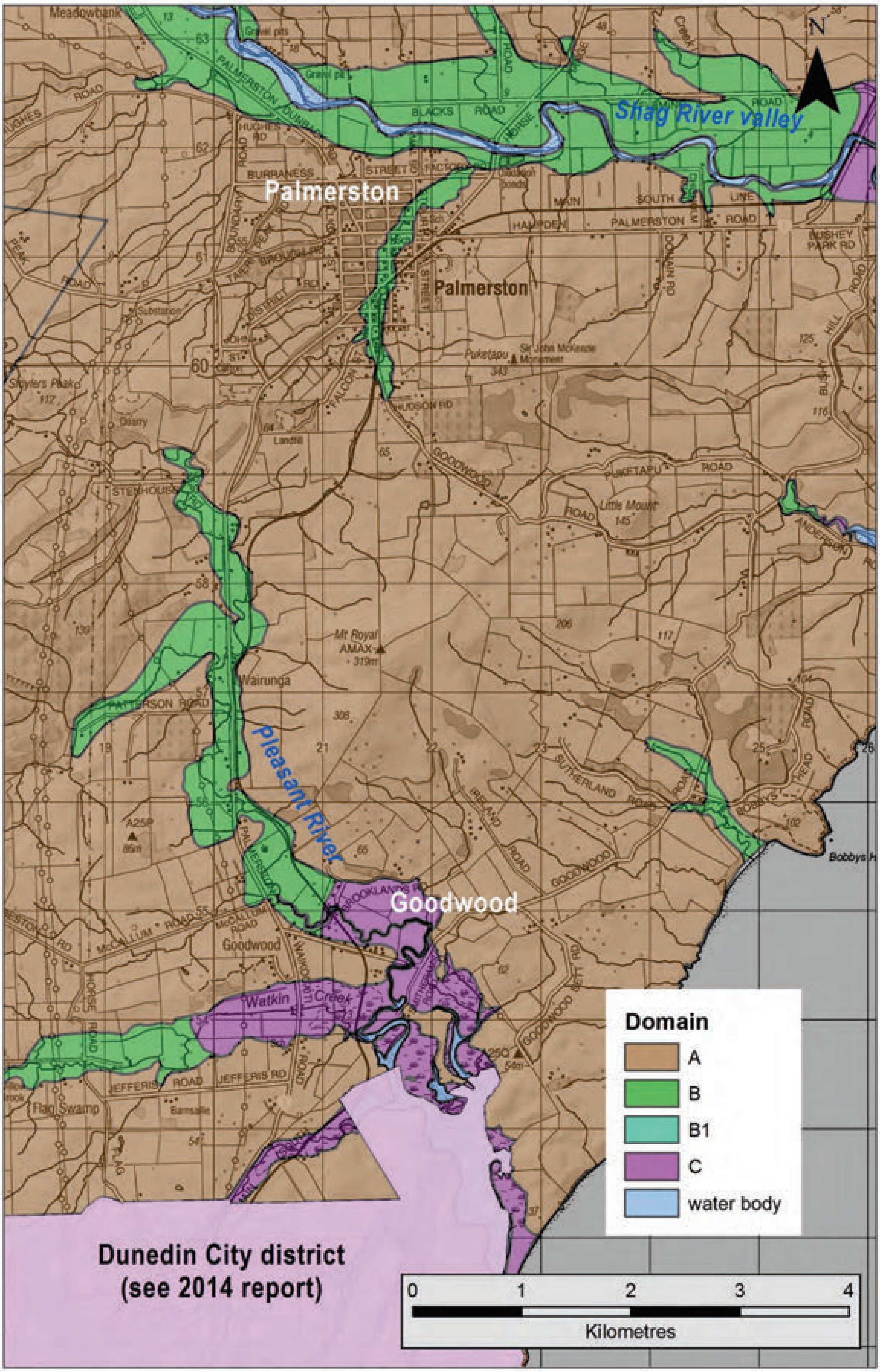

Figure A3.31 Liquefaction-susceptibility domains in the Goodwood to Palmerston areas. The key is generic to the dataset and not all units may be present on this map.

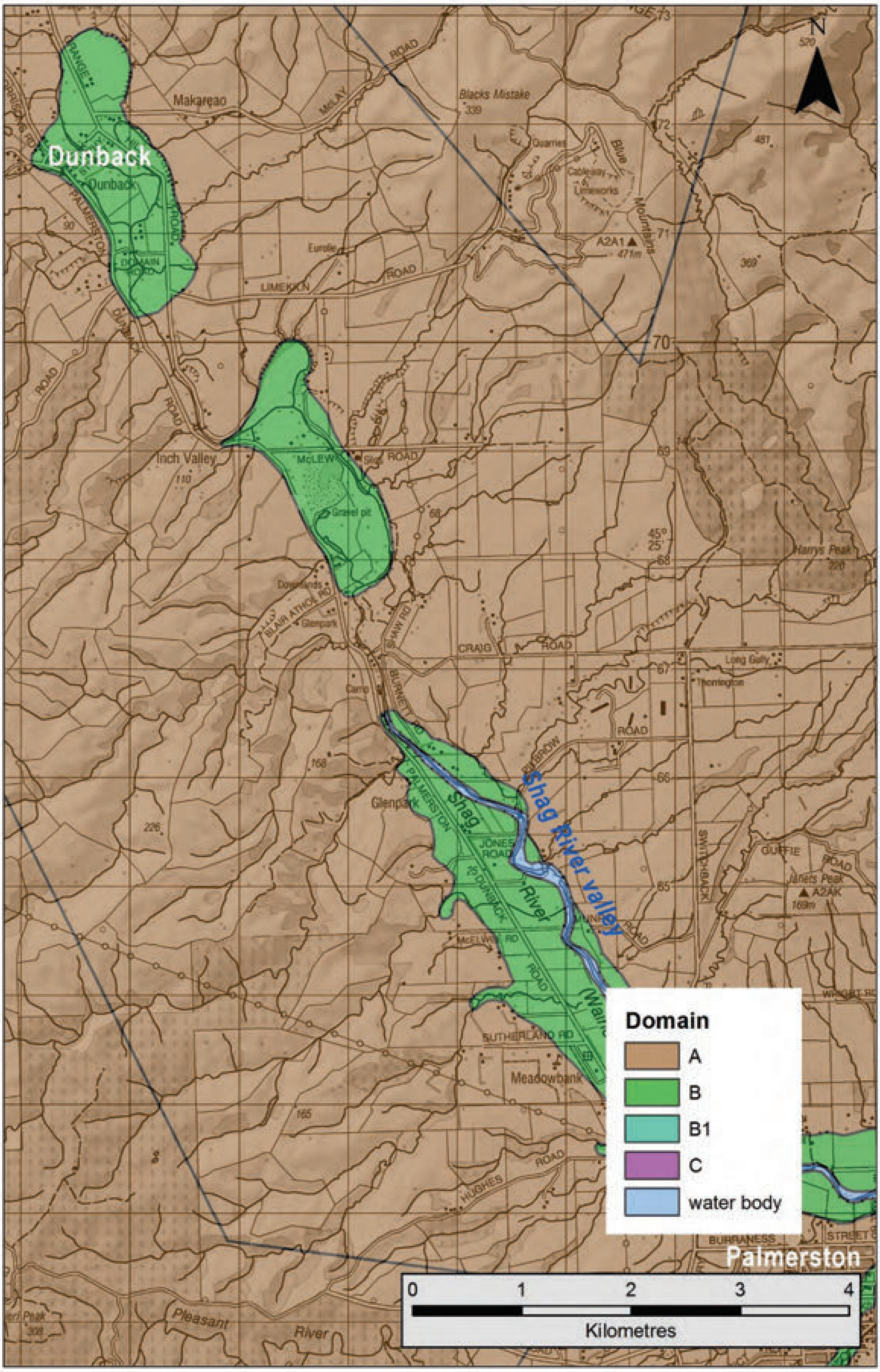

Figure A3.32 Liquefaction-susceptibility domains in the Shag River (Waihemo) valley area. The key is generic to the dataset and not all units may be present on this map.

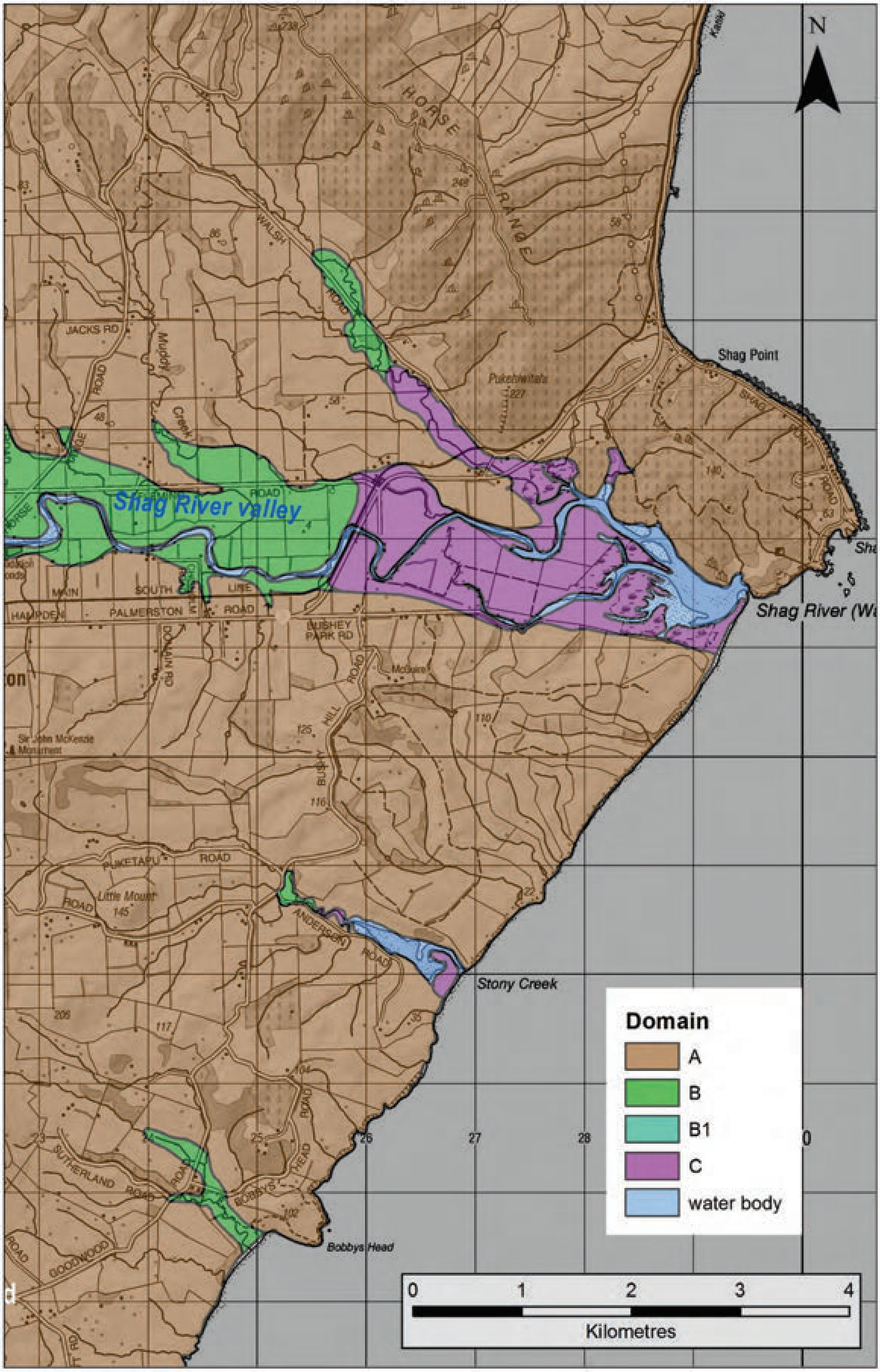

Figure A3.33 Liquefaction-susceptibility domains in the lower Shag River (Waihemo) valley area. The key is generic to the dataset and not all units may be present on this map.

A3.4.4 Otago coast – Shag Point to Kakanui (Figures A3.33–A3.35)

Remnants of a last interglacial marine terrace, standing between 5 and 10 m above sea level, are preserved at Katiki Beach, and along parts of the coastline north from the Waianakarua River to Kakanui. Due to its height about sea level, and likely deep groundwater table equilibrated with sea level, this terrace is included in Domain A.

Along Katiki Beach, the larger streams draining to the coast have incised valleys into the marine terrace and have broad-floored lower reaches. The broad floors of Tarapuke Creek and Back Creek are placed in Domain B, while their lowest coastal reaches, and associated coastal dunes, are placed in Domain C. The largest stream (Trotters Creek) is different, in having an incised, terraced, valley all the way to the coast. As the Trotters Creek bed is typically incised ~6 m into its main valley floor terrace, it is assumed to have a groundwater table too deep to afford liquefaction potential, even if susceptible sediments are present. Only the nearest coastal reach of the Trotters Creek inset valley is placed in Domain C, the remainder is classified as Domain A.

The broad floor and lowest terraces of Kurinui Creek at Hampden are placed in Domain B, as are the lower reaches and lowest terraces of Kakaho Creek and the Waianakarua River. The latter is mapped as Domain B only as far upstream as State Highway 1, and the valley of the South Branch is excluded because bedrock outcrop is visible in the riverbed and terrace edges at State Highway 1.

Northeast of the Waianakarua River, the valley floor, lowest terraces and coastal dunes at the drowned lower reaches of Bow Alley Creek and Orore Creek are mapped as Domain C, with an adjoining broad-floored reach of the Orore Creek valley upstream of about 5 m above sea level (defined by lidar) placed in Domain B.

A3.4.5 Kakanui River and Waiareka Creek catchments (Figures A3.36–A3.38)

The broad floor and lowest terraces of the Kakanui River valley, and its Kauru River and Island Stream tributaries, are classified as Domain B, except for the near-coastal, tidal, reach of the Kakanui River, where the valley floor and lowest terraces are placed in Domain C. On the northern side of that reach, a slightly higher terrace at Kakanui township is placed in Domain B, because the groundwater table is likely to be somewhat deeper. An extensive intermediate terrace on the south side of the Kakanui valley between Maheno and Kakanui, is about 10 m above river level, likely has a relatively deep groundwater table and is included in Domain A. The broad valley floor of Island Stream and its Serpentine Stream tributary are placed in Domain B for a considerable distance upstream, due to their low gradients and likely shallow groundwater table.

Broad sectors of the Waiareka Creek valley floor and lowest terraces are placed in Domain B, well into the headwaters on account of the low gradient of the valley. It is likely that the poorly consolidated sediments are relatively thin, but the groundwater table is likely to be shallow.

The Kakanui and Kauru river deposits are predominantly gravelly, and the Domain B classification in their valleys relates to the possible presence of sandy or silty layers or pods in buried channels. The presence of liquefaction-susceptible materials there is considered a low rather than moderate likelihood. Sandy or silty sediments are likely to predominate in the Island Stream and Waiareka Creek tributary catchments, and there is a moderate likelihood of liquefaction-susceptible materials being present.

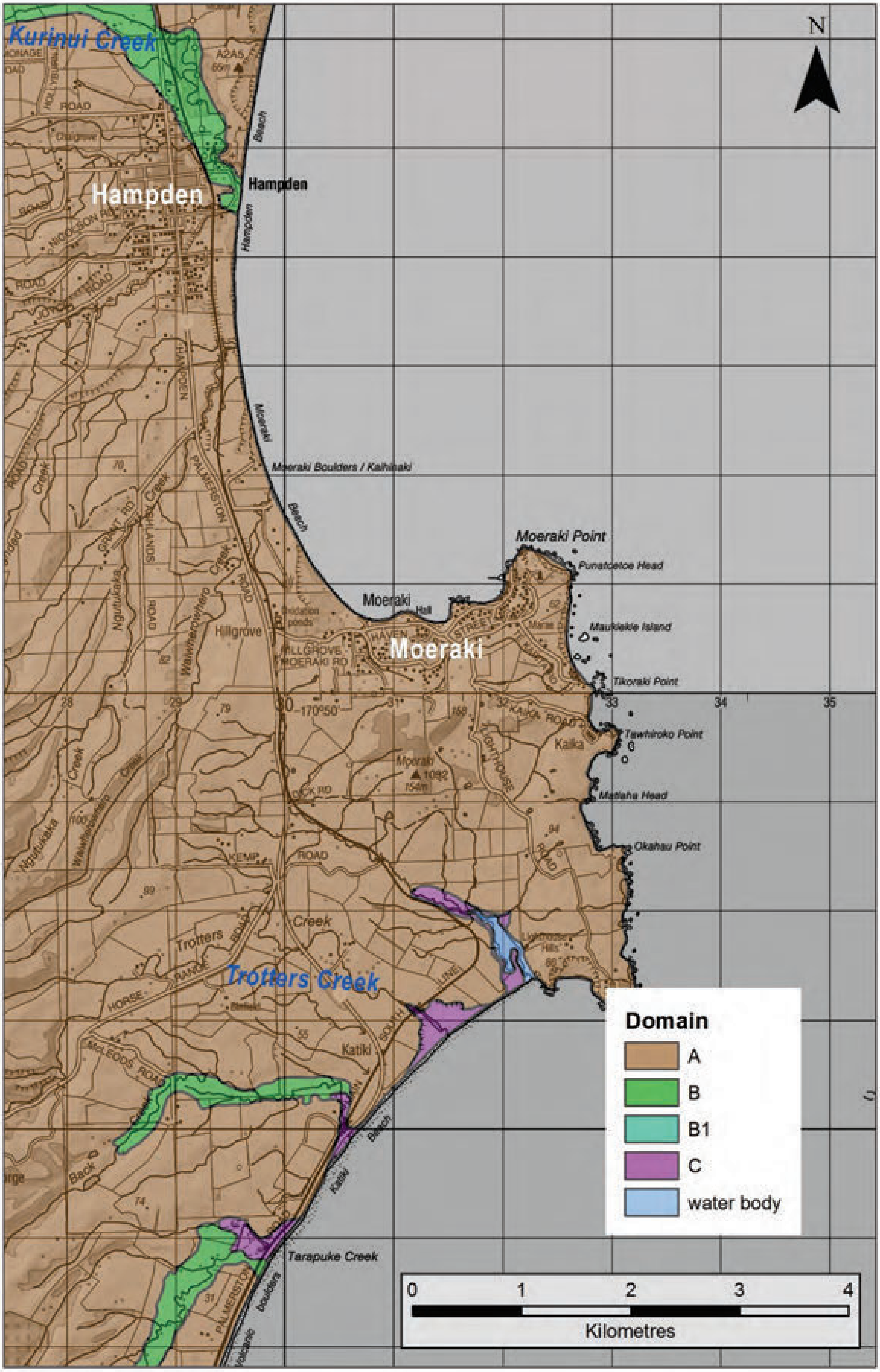

Figure A3.34 Liquefaction-susceptibility domains in the Moeraki and Hampden areas. The key is generic to the dataset and not all units may be present on this map.

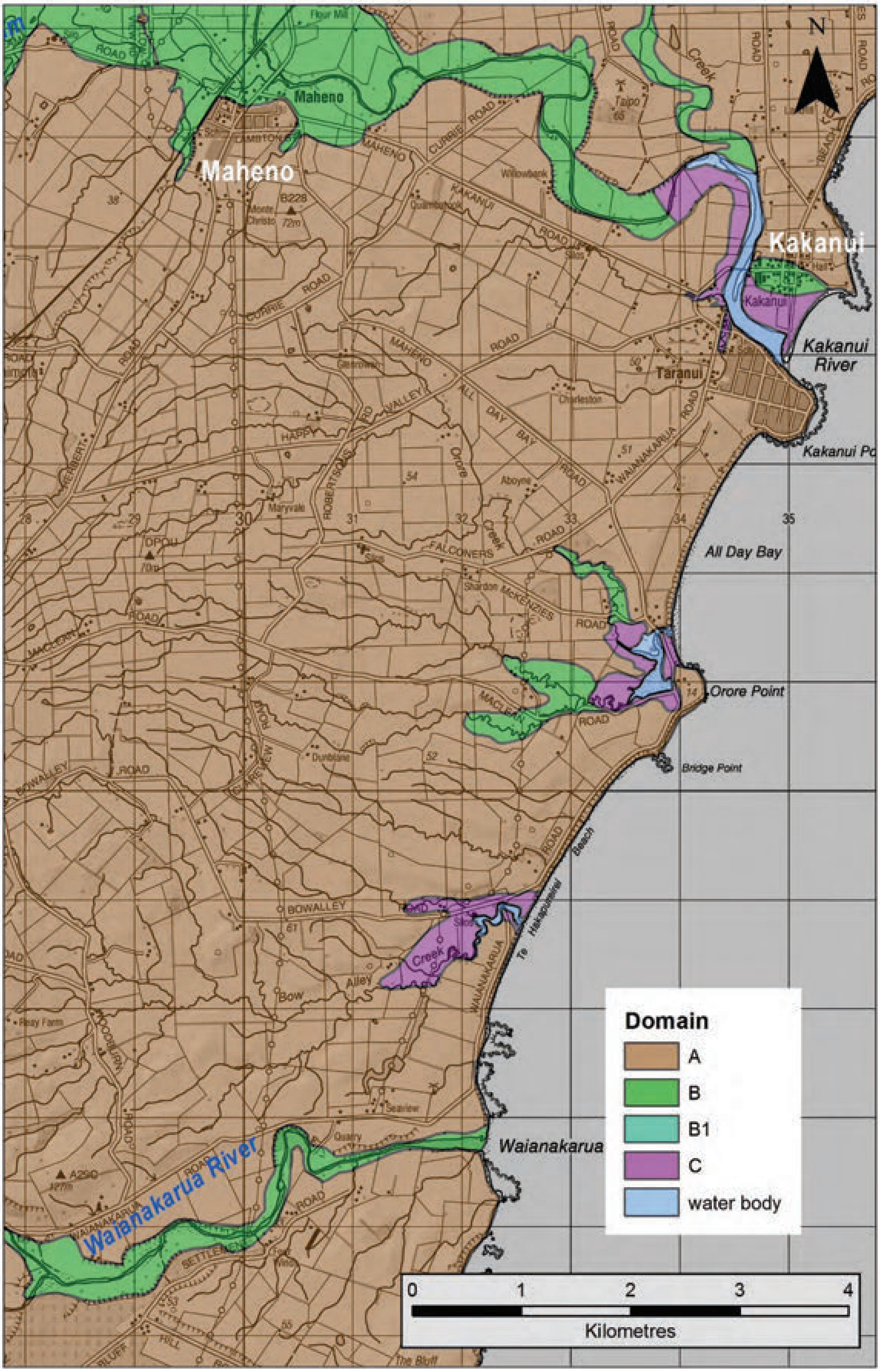

Figure A3.35 Liquefaction-susceptibility domains in the Waianakarua to Kakanui areas. The key is generic to the dataset and not all units may be present on this map.

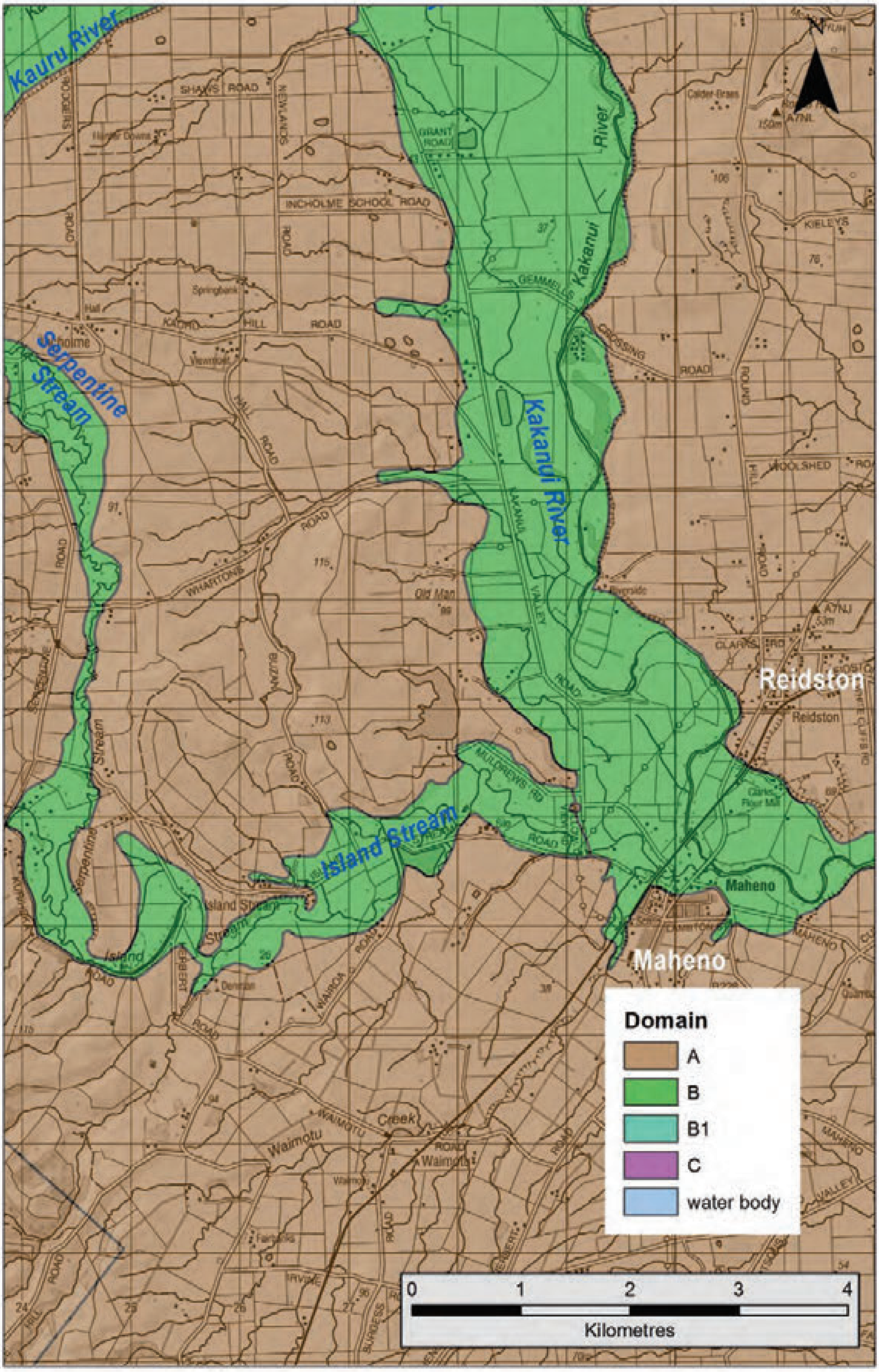

Figure A3.36 Liquefaction-susceptibility domains in the Maheno area. The key is generic to the dataset and not all units may be present on this map.

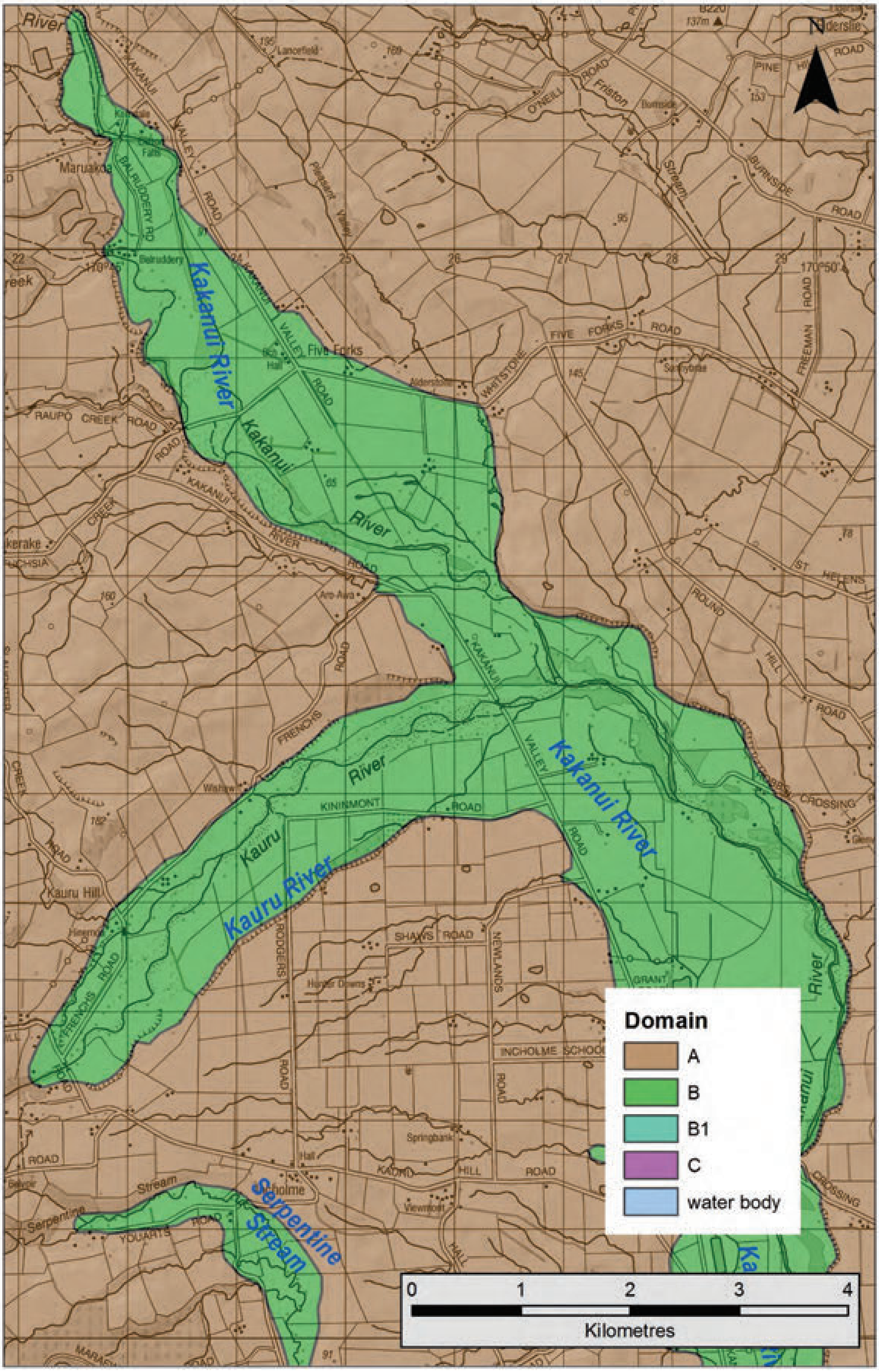

Figure A3.37 Liquefaction-susceptibility domains in the Kakanui and Kauru valley areas. The key is generic to the dataset and not all units may be present on this map.

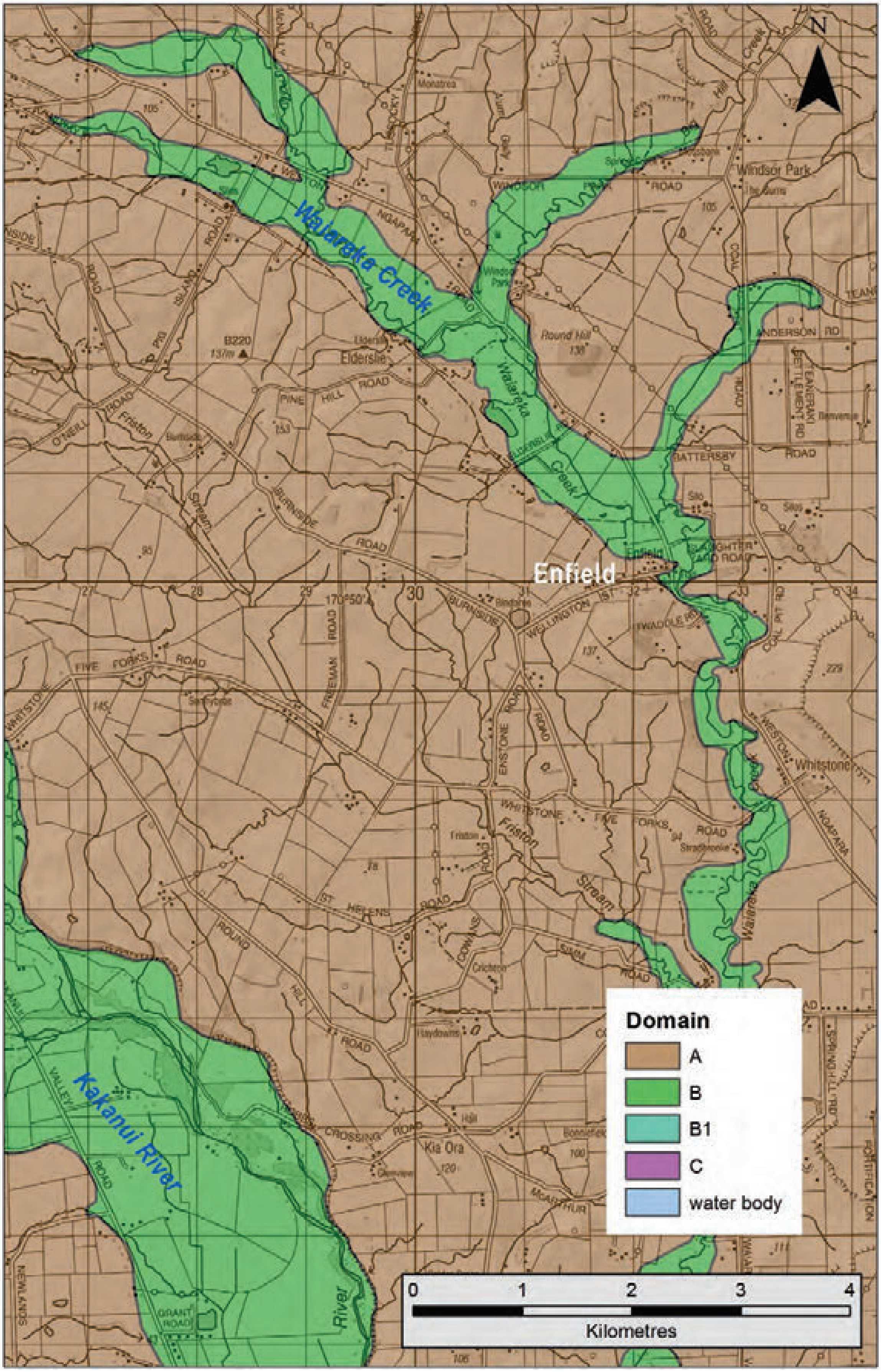

Figure A3.38 Liquefaction-susceptibility domains in the Waiareka Creek catchment area. The key is generic to the dataset and not all units may be present on this map.

A3.4.6 Oamaru area and Lower Waitaki Plain (Figures A3.39–A3.41)

The lowest reaches of Oamaru Creek and its alluvial fan where it issues onto the coastal plain are placed in Domain B, because of the possibility of fine-grained sediments in the subsurface, and likelihood of shallow groundwater. The Domain B area is extended along the low-lying coastal fringe around Oamaru port, which likely includes some reclamation fill. The boundary between Domains A/B have been positioned with the aid of lidar, high-resolution aerial imagery, and Google Earth Street View, at an approximate mapping scale of 1:1000 scale and is considered accurate at the scale of properties and buildings.

In the upstream part of the Oamaru catchment, there are two sectors of broad valley floor, one near Ardgowan, and another upstream of the Devils Bridge lake, that are also placed in Domain B. As the area is outside lidar coverage, the high-resolution aerial imagery and Google Earth Street View were used to position domain boundaries.

The coastal plain between Oamaru and Pukeuri is an extension of the Lower Waitaki alluvial plain, underlain by loess up to 5 m thick on top of river gravel. In addition, as the plain surface is more than 10 m above sea level, the groundwater table is relatively deep, and this area, and much of the Lower Waitaki Plain is placed in Domain A. Close to the Waitaki River channel, a flight of terraces is incised into the Lower Waitaki Plain. On account of shallower groundwater, the river channel, and flanking terraces up to about 10 m above river level, are classified as Domain B. The Waitaki River deposits are predominantly gravelly, and the Domain B classification acknowledges the possible presence of sandy or silty layers or pods in buried channels, with a low rather than moderate likelihood of liquefaction-susceptible materials being present.

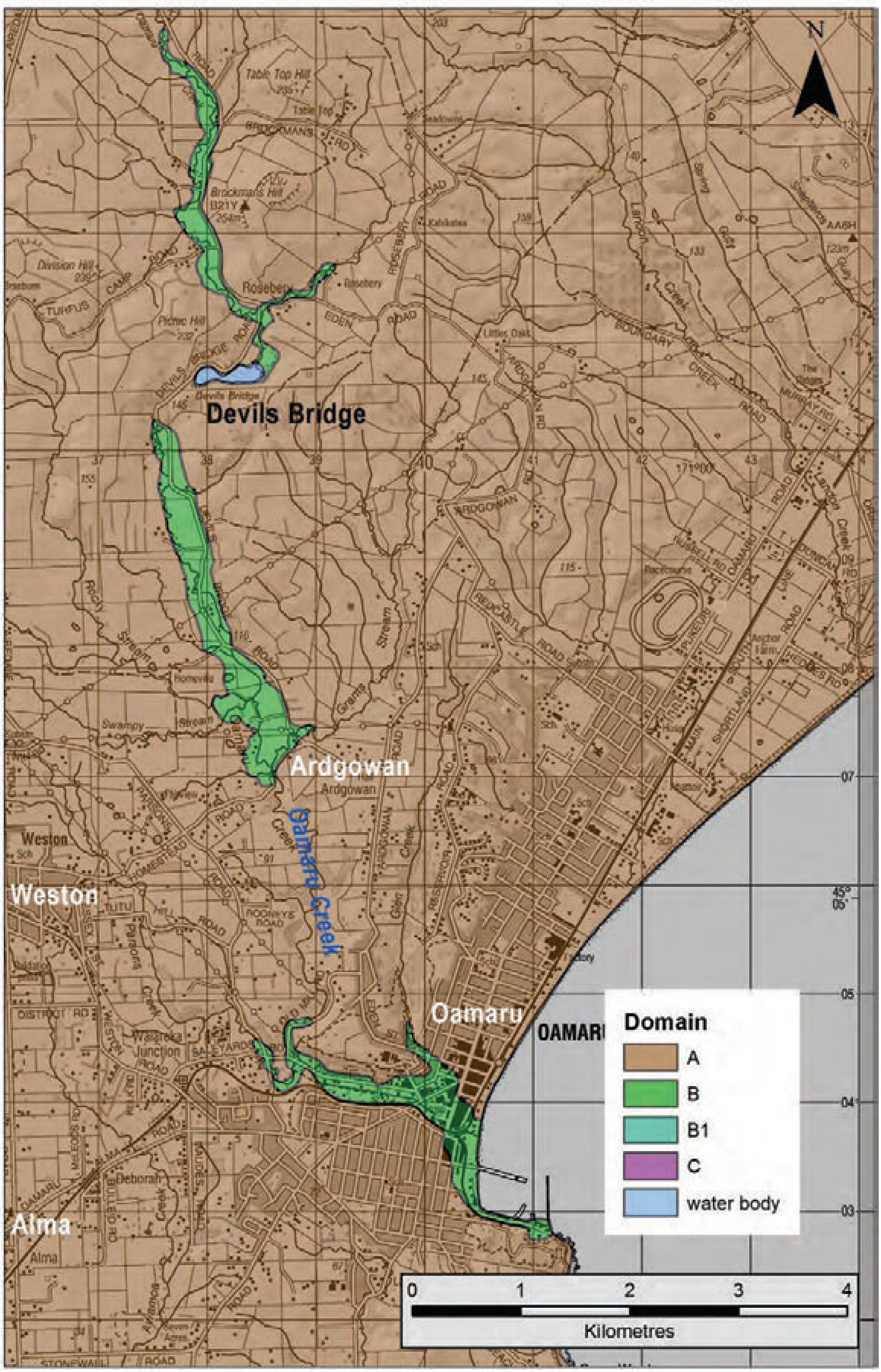

Figure A3.39 Liquefaction-susceptibility domains in the Oamaru Creek area. The key is generic to the dataset and not all units may be present on this map.

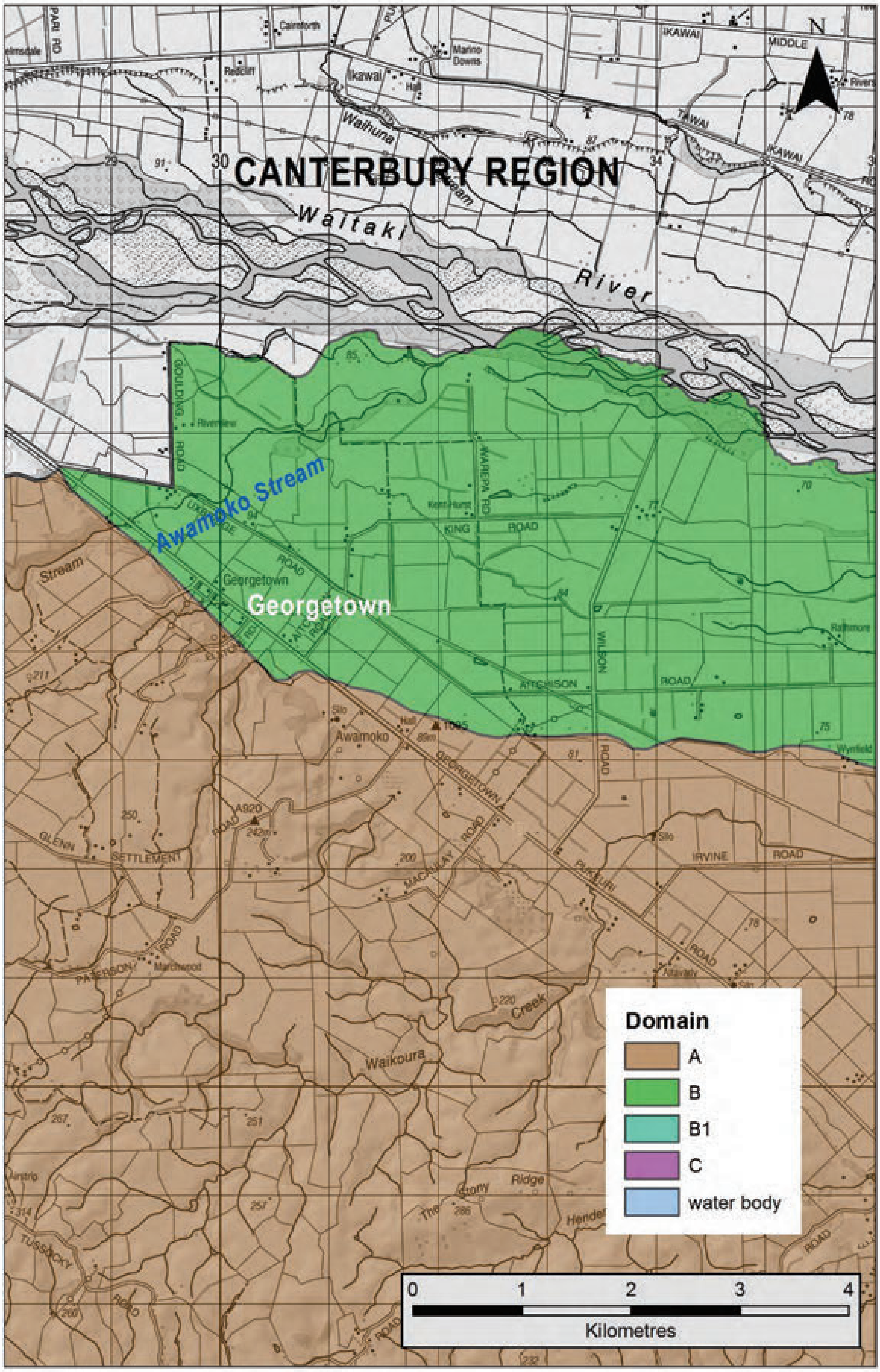

Figure A3.40 Liquefaction-susceptibility domains in the Georgetown area of the lower Waitaki valley. The key is generic to the dataset and not all units may be present on this map.

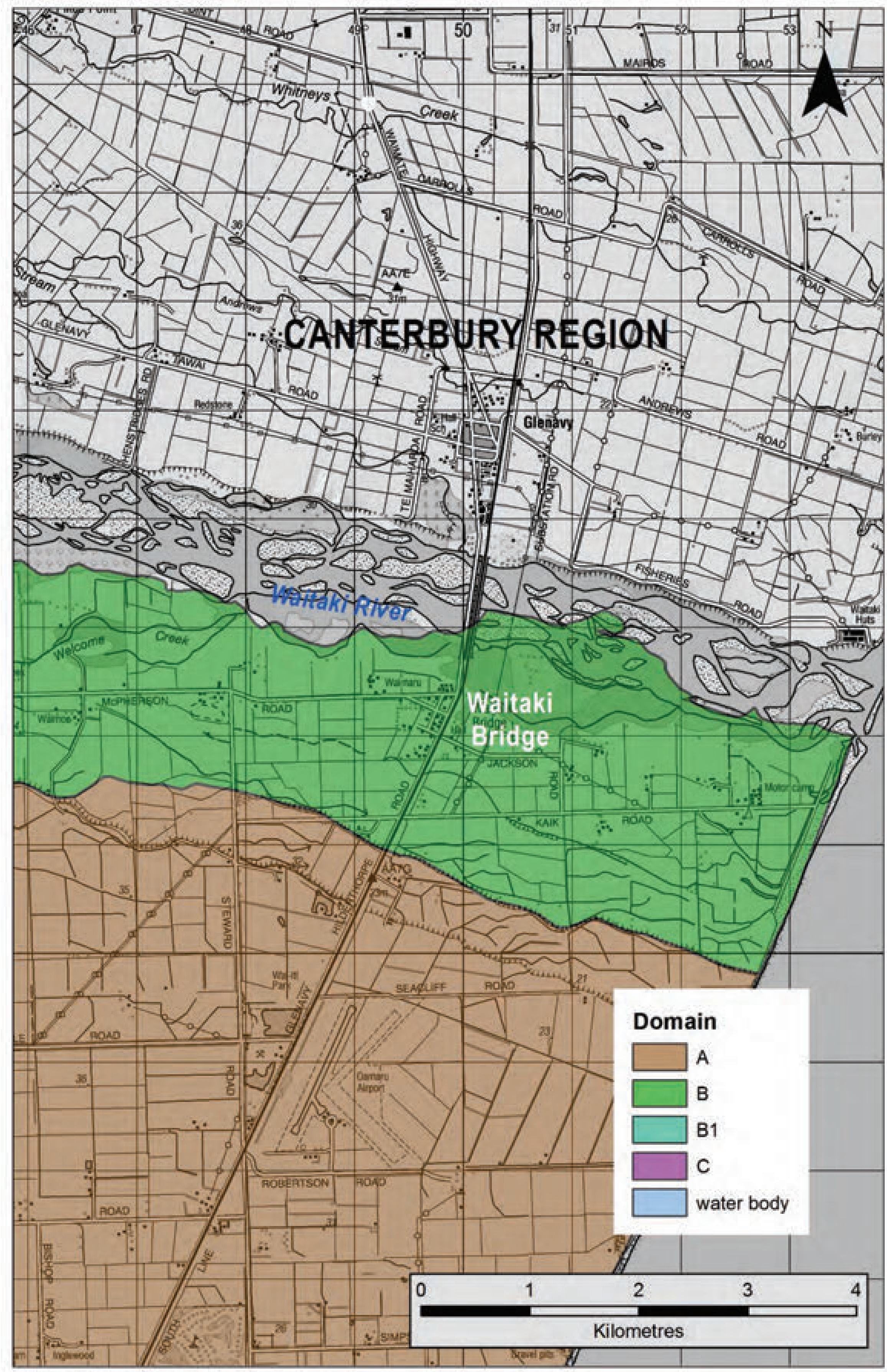

Figure A3.41 Liquefaction-susceptibility domains in near-coastal reach of the lower Waitaki valley. The uncoloured area is Southland region. The key is generic to the dataset and not all units may be present on this map.

A3.5 APPENDIX 3 REFERENCES

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APPENDIX 4 DESCRIPTION OF THE GIS DATASET

The GIS dataset referred to in this report comprises an ArcGIS file geodatabase, containing one Feature Class:

- ORC_OtagoLiquefactionSusceptibility_2019

This feature class comprises an interpretation of the extent of ground that is potentially susceptible to earthquake-induced liquefaction, in the Central Otago District, Clutha District, Queenstown Lakes District, and that part of the Waitaki District lying within the Otago region. This map dataset is based on an office-based (i.e. 'desktop') assessment of available information on geology, geomorphology (i.e. landforms), groundwater conditions, and other data where relevant. This feature class contains areas (polygons) representing the interpreted extent of potentially liquefaction-susceptible ground.

The feature class contains five attribute fields that provide information on each mapped polygon. The DOMAIN field classifies the polygon into one of the 4 liquefaction-susceptibility domains (A, B, B1, C), or a fifth category of water body, as described in the report text. The DESCRIPTION field provides a generalised interpretation of the geological character of the ground beneath the polygon (except where the polygon is a water body). The JUSTIFICATION field provides a brief statement on the landform and/or geographic character of the polygon. The CREATOR field identifies, by initials, the person or people who made the geological and/or landform interpretation and drew the polygon. The SOURCE field lists the information sources used to map and interpret the polygon.

The positioning of boundaries between domain polygons is based largely on landform features. The main topographic and photographic base-maps used to aid the mapping were the 1:50,000-scale LINZ Topo 50 map series, and high-resolution colour aerial photos, accessed digitally through the ArcGIS software. The general mapping scale was 1:50 000, and the boundary between each domain polygon should be regarded as being a 100 m wide zone, rather than a line. In areas where lidar coverage was available for the mapping, the mapping scale is 1:10 000, and domain boundaries should be regarded as 20 m wide zones. In towns and villages, where Google Earth Street View was available at the time of mapping, Google Earth ground photography was accessed to help in positioning domain boundaries. In those areas, the assigned mapping scale is 1:1 000, and boundaries are considered accurate at the scale of property parcels and buildings. The commentary in Appendix 2 of this report indicates where these more detailed scales apply.

The geographic coordinate system for the data is New Zealand Geodetic Datum 2000.

The dataset is based largely on broad-scale inferences and should not be used in isolation for any purposes requiring site-specific information. The main purpose of the dataset is to delineate areas where liquefaction hazard may warrant further scrutiny for future planning and development activities.