Identification of areas possibly susceptible to landsliding in the coastal sector of the Dunedin City district

D.J.A. Barrell B. Smith Lyttle

GNS Science Consultancy Report 2015/34

June 2015

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to Otago Regional Council. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of or reliance on any contents of this report by any person other than Otago Regional Council and shall not be liable to any person other than Otago Regional Council, on any ground, for any loss, damage or expense arising from such use or reliance.

Use of Data:

Date that GNS Science can use associated data: June 2015

BIBLIOGRAPHIC REFERENCE

Barrell, D.J.A.; Smith Lyttle, B. 2015. Identification of areas possibly susceptible to landsliding in the coastal sector of the Dunedin City district, *GNS Science Consultancy Report* 2015/34. 38 p.

CONTENTS

FIGURES

TABLES

APPENDICES

EXECUTIVE SUMMARY

Previous evaluations of landslide occurrence in the Dunedin district have focused on map inventories delineating the locations of past landslide occurrences. These include historical observations of landslide movements as well as prehistoric landslide movements inferred from distinctive landform features. A limitation of such inventories is that they do not readily define areas where future ‘first-time’ landslides may develop, or where existing landslides may reactivate and become larger.

This report presents an office-based assessment of ways to identify potentially landslide-prone areas in the near-coastal sector of the Dunedin district. The assessment area extends from Goodwood south to the Taieri/Waipori River system, and includes all of Otago Peninsula. The work aims to identify and delineate areas where there may be a propensity (susceptibility) towards landsliding, whether or not existing landslides have been identified. The results of the assessment are intended to aid local authorities in identifying and managing land instability hazards, and help to guide land-use planning.

The work is based on review and analysis of existing digital datasets, including topographic information, landslide databases, and digital map information on soils and geology. Topographic information was used to generate a slope angle map for a representative area of coastal Otago. The landslide database was compared against geology, soils and slope angles to assess how well each of these factors explained the mapped landslide distribution.

Slope angle was identified as a key factor, and reflects the fundamental role of gravity as a driving force for landslides. Slopes steeper than about 12° are potentially susceptible to landsliding, although that is not to say that slopes of this and greater steepness are inherently unstable. Rather, it means that where slopes are steeper than about 12°, slope stability is something that should be taken into account for new developments or changes in land-use. This slope-angle criterion, which is relevant for deep-seated landslides developed in the underlying rock (bedrock landslides), as well as shallow-seated landslides developed in the soil profile (surficial landslides) appears to be appropriate for all rock types in coastal Otago except for a sequence of weak sedimentary rocks that include Abbotsford Formation, Green Island Sand and Burnside Mudstone. These rocks have known propensity to instability in certain settings, even where the ground slopes are gentle (e.g. ~5°).

The approach proposed here involves using three single-factor datasets that collectively provide information on potential susceptibility to landsliding. **Slope Awareness Areas** are differentiated into three classes, ‘moderate’ (12° to 20°), ‘steep’ (20° to 35°) and ‘very steep’ (greater than 35°). All of these classes highlight areas where slope stability is a factor that should be taken into consideration. A 100-m-wide perimeter (buffer) added to these areas highlights land that is close to a Slope Awareness Area. **Landslide Awareness Areas** represent the extents of landslides recorded in existing map inventories, and their perimeters are marked by buffers between 50 and 200 m wide, depending on overall size of the landslide. The Landslide Awareness Areas delineate localities where slope stability should be taken into consideration. Finally, the areas of weak sedimentary rocks mentioned above are identified as **Geologically Sensitive Areas**, where caution is warranted in regard to developments involving major earthworks or other activities that may adversely affect slope stability. These awareness areas are not hazard zones as such, but serve to delineate areas that may potentially be susceptible to landslide movement and where slope stability is a factor that should be considered in future land-use planning and development.

1.0 INTRODUCTION

Landsliding is one of the potential natural hazards of the coastal Otago area (Goldsmith & Sims 2014). Landslides have been identified at numerous places in the hilly terrain of coastal Otago, and have been mapped in a variety of ways and at various scales (e.g. Benson 1940, 1946; Leslie 1974; McKellar 1990; Bishop & Turnbull 1996; Stewart 1996). In recent years, landslide information, including their locations and extents, has been digitized using Geographic Information System (GIS) technology. A recent compilation of landslide information for the Dunedin City territorial area (Dunedin district; administered by Dunedin City Council - DCC) by Glassey & Smith Lyttle (2012) was supplemented with the addition of more information (attributes) on the characteristics of the mapped landslides in that area by Glassey et al. (2014). Many of the landslides have been identified from the presence of distinctive landform features, indicative of prehistoric landslide movement, and few of the landslides have been mapped on the basis of direct observation of landslide movement (Glassey et al. 2014).

These previous evaluations of landslides in the Dunedin district have focused on map inventories of the locations of past landslides, either historic or prehistoric. A limitation of this approach for land-use planning and hazard management is that it does not readily define areas where future ‘first-time’ landslides may develop, or where existing landslides may reactivate and become larger.

In order to address this question, Otago Regional Council (ORC) commissioned GNS Science to undertake an office-based assessment of susceptibility of hill slopes to landsliding in the near-coastal sector of the Dunedin district from Goodwood in the north to the Taieri/Waipori River system in the south, including all of Otago Peninsula (Figure 1; coastal Otago map area). The aim of the work is to identify and delineate areas where there may be a propensity (susceptibility) towards landsliding, whether or not existing landslides have been identified. This report presents the results of that assessment, and is intended to assist local authorities in identifying and managing land instability hazards to people and infrastructure, and help to guide land-use planning.

1.1 SETTING OF THE ASSESSMENT AREA

The coastal sector of the Dunedin district (Figure 1) has a varied landscape of hills and valleys, with a coastline indented by bays, estuaries and inlets, including Otago Harbour. Beyond the currently-built environment, land-use is mainly agricultural, with pastoral grazing on the hill country, with some cropping and dairying in lowland areas. Plantation forestry is common in some parts of the hill country, particularly north and northwest of Dunedin.

Geologically, schist rock predominates inland, but towards the coast is buried beneath a blanket of younger rocks of sedimentary or volcanic origin. Poorly consolidated sediments form the youngest part of the geological sequence, and occur mainly beneath valley floors and along the coastal fringe. Section 2.4 provides more information on the geological sequence. Various different types of soils mantle the geological substrate. Some soil types are derived from the weathered residue of the underlying rock, while others are developed in surface layers of wind-blown silt (loess) or sand, or river-laid sediments. In this assessment, attention is focused on the characteristic depths to which the soil type extends, as set out in Section 2.5.

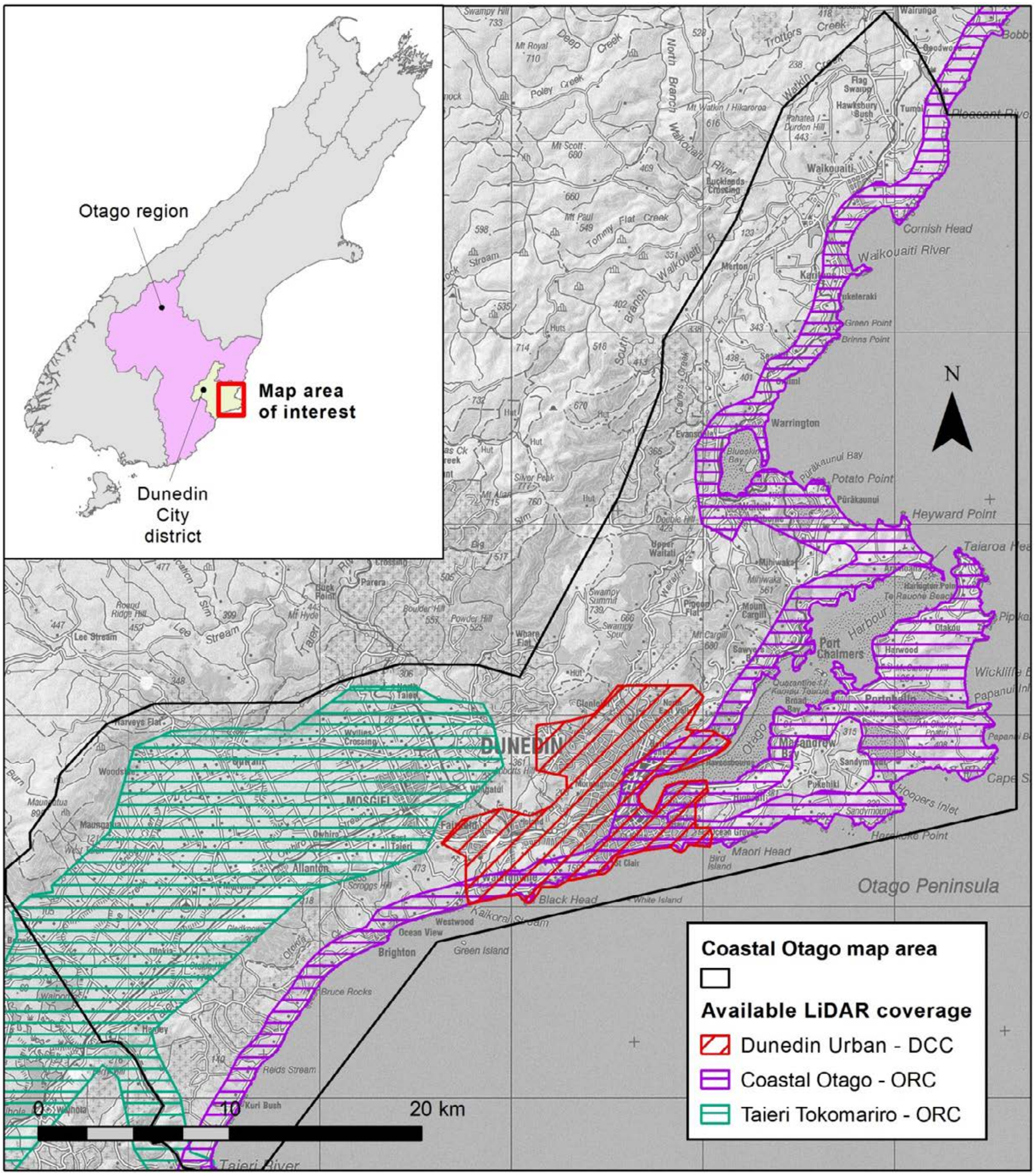

Figure 1 Location diagram. The map frame encompasses the area used for assessing slope instability factors (Analysis area; see Figure 2). Also shown are the extents of lidar coverage, and the map area that is the focus of this report. Background map is the 1:250,000-scale Topo250 topographic map, rendered in grey.

Current knowledge of landslides in coastal Otago is based largely on map databases showing the locations and extents of past landslide movements, as outlined in Section 2.3. Glassey et al. (2014) distinguished between landslides that are ‘deep-seated’ and involve movement in the underlying geological strata (‘bedrock landslides’) versus ‘shallow-seated’ landslides whose movement occurs within the soils on the bedrock (‘surficial landslides’). They also introduced a classification of the ‘certainty’ of identification of landslide, with options of ‘definite’, ‘likely’ and ‘possible’. Another important consideration is that many of the landslides are mapped on the basis of landform features indicative of past landslide movements, rather than direct observation of ground movement. Therefore, many of the landslides are prehistoric, and the estimation of when they last moved is, at best, informed guesswork. This prevents the meaningful estimation of the probability of future landslide occurrence in coastal Otago. A practical alternative, adopted in this report, is to identify areas that may possibly be susceptible to landsliding based on the presence of factors that, generally speaking, are unfavourable for slope stability.

Gravity is a primary driver of landslide movement. Where a slope is sufficiently steep, the effects of gravity can overcome the strength of the geological materials. Strong rock can stand in very steep slopes, whereas weak rocks or soils may fail on moderate slopes. Generally speaking, steeper ground has a greater likelihood of landslide movements. In addition, erosion by rivers, streams, or the sea can undercut the lower parts of slopes, and induce landslide movement. Areas of gently sloping or flat ground may be at risk of inundation by landslide debris from nearby steep slopes, and landslides can also undermine flat or gentle ground at the crests of slopes. Land-use may influence the occurrence of landslides. For example, the removal of trees or scrub may increase water infiltration, resulting in heavier, and potentially less stable soils, particularly if seasonal wetting and drying of the soil has produced deep cracks that enhance water infiltration. Activities such as modifying slopes by cutting or filling, and modifying natural run-off and drainage, are potentially important negative influences on slope stability. The direction towards which a slope faces (‘slope aspect’) may play a role in the occurrence of landslides, through the idea that south-facing slopes get less sun, and remain relatively wet, whereas north-facing slopes are generally drier. On the other hand, this may be balanced by the consideration that north-facing slopes (i.e. sunnier) are more likely to suffer drying and cracking, thus enhancing water infiltration and potential instability. In this report, slope aspect is judged to be a relatively unimportant factor, and is not the subject of any specific analysis.

2.0 ASSESSMENT OF FACTORS INFLUENCING SLOPE INSTABILITY

2.1 METHODS

The approach used was to take a representative sector of coastal Dunedin, and evaluate the extent to which the mapped distribution of landslides may be linked to other factors (Figure 1). The nature of the GIS technology necessitated defining a rectangular area for the analysis (Analysis area; e.g. see Figure 2). For these analyses, the geological substrate, soil depth, and slope angles were selected as the most likely factors that are important for influencing landslide distribution. The choice of these parameters was guided by the availability of existing regional-scale digital data that could be utilised. In contrast, there is no uniform broad-scale data set on groundwater conditions, especially in the hill country, for coastal Otago. This prevents the investigation of what influence, if any, groundwater conditions may have had on landslide distributions.

The analyses are largely comparative and qualitative, rather than quantitative, and visual comparison along with the generation of relative percentages, were relied upon to assess interrelationships between the parameters. This section ends with an evaluation of the findings, and identifies suitable methods for delineating areas of potential slope instability in the coastal sector of the Dunedin district.

2.2 TOPOGRAPHIC INFORMATION

There are two main sources of information on topographic relief in the assessment area. Full coverage is provided by the New Zealand ‘8-m’ digital terrain model (DEM) which is generated from 20-m interval topographic contours, and spot height values, on the nationwide 1:50,000-scale topographic maps (Land Information New Zealand). The contour and spot height data were processed to generate a grid of squares (cells) each representing 8 m by 8 m on the ground. The DEM is an example of a ‘raster’ dataset, which has a grid data structure with a single numeric value stored in each cell. In the DEM, a single representative elevation value, in metres above sea level, was assigned to each cell. The main strength of this DEM is that the contour and height information is derived from photogrammetric methods using aerial photos, and so represents the contour of the ground as it existed at the time the photos were taken (in most cases the 1980s). Surface features such as trees or buildings were ignored in the contouring, and thus the 8-m DEM provides the most comprehensive representation of the ground surface. The main disadvantage is that the contour interval of 20-m elevation does not provide a very detailed characterisation of the ground in areas of highly irregular relief.

In recent years, lidar (laser radar) surveys have been undertaken in parts of Otago. In the vicinity of Dunedin, coverage is currently limited to areas along the coastal strip, the main Dunedin urban area, and the Taieri plain (Figure 1). Lidar provides very detailed and precise measurements of the elevations of land surface features, but because the laser beams can be reflected by any reasonably dense surface entity, they may be returned by the ground surface, by buildings or by sizable trees, for example. There are various processing techniques for filtering out most of the reflections from buildings and trees, but it is difficult to rely entirely upon the lidar DEMs as providing a complete picture of the ground surface.

The precision of DEMs derived from the lidar is far superior to that of the 8-m DEM, but because of the limited coverage of the lidar DEMs in the analysis area, the 8-m DEM was used for assessing topographic controls on landslide distribution.

2.3 LANDSLIDE INFORMATION

This assessment used the landslide datasets described by Glassey & Smith Lyttle (2012), and as modified by Glassey et al. (2014). The data set includes landslides that have been mapped as areas ('polygons'), as well as landslides whose location is indicated by a single point (Figure 2).

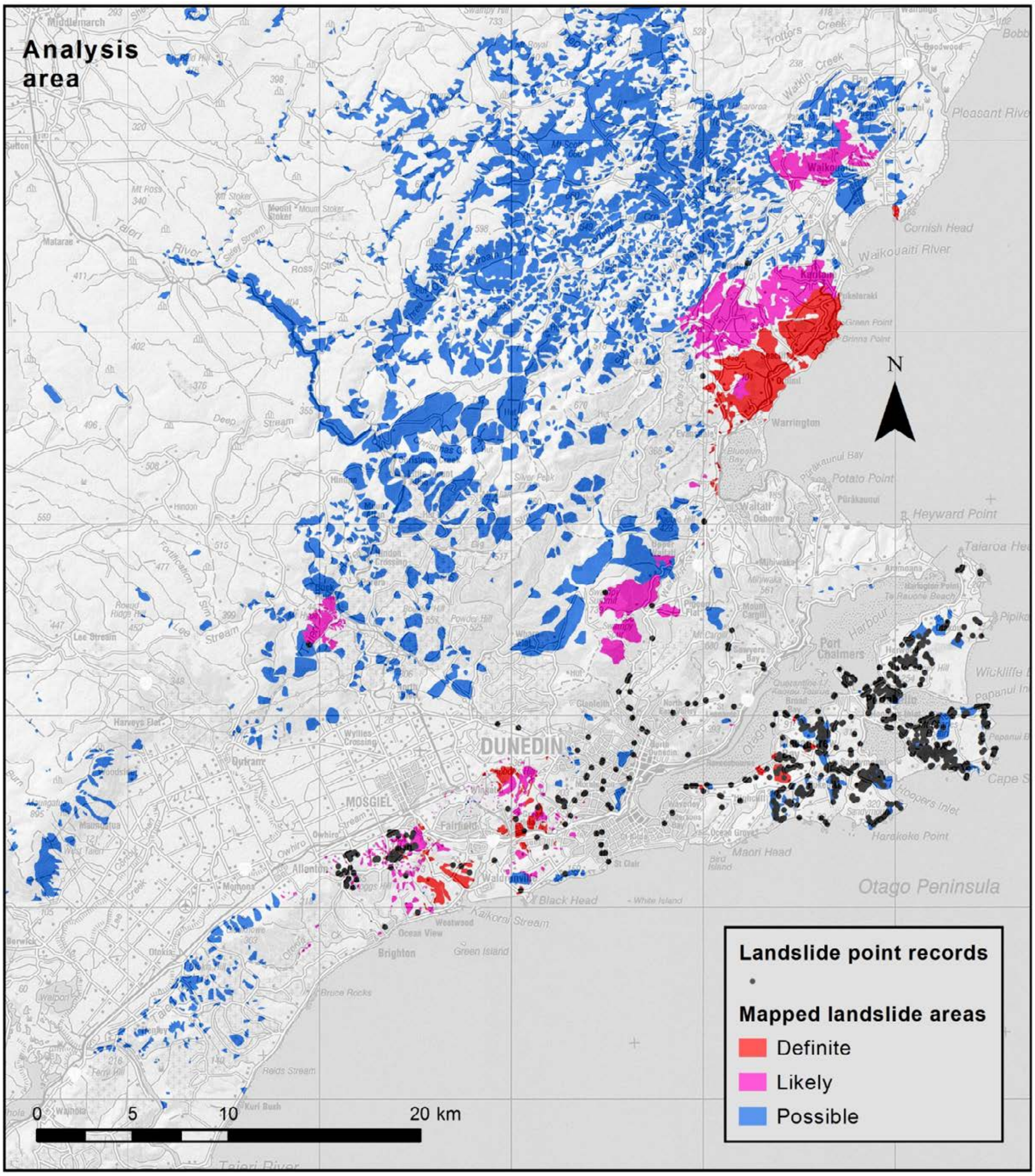

Figure 2 Mapped landslide distribution in the analysis area. The landslide areas are coloured according to the 'certainty' attribute, which indicates whether the mapped feature is definitely of landslide origin, or whether a landslide origin is judged to be 'likely' or just 'possible'. Almost all the landslide points are attributed as 'definite'.

The mapping of polygons has been more methodical across the analysis area as a whole, for example based on examination of aerial photographs in the course of preparing geological maps (e.g., McKellar 1990; Bishop & Turnbull 1996; Forsyth 2001), but there is considerable variation in the detail and precision of the mapping, because of the different scales at which it was undertaken.

In contrast, the landslide point mapping focused on the general vicinity of the Dunedin urban area, and on Otago Peninsula (e.g. Leslie 1974; Stewart 1996). The absence of landslide points elsewhere does not necessarily mean that landslides have not occurred there. Generally speaking, the landslides mapped as points are likely to be of small extent.

2.4 GEOLOGY

For the purposes of the evaluation in this report, the geological sequence of the coastal sector of the Dunedin district is classified into 5 components, as set out in Table 1, along with the constituents of each component. The intent is to provide as simple as possible a classification that adequately represents the general properties of the geological strata.

Table 1 Generalised classification of geological units in the analysis area (refer to Figure 3). The constituent names are from the QMAP database (Heron, 2014), 'key_group_name' field. Representative local formation names are in parentheses. Approximate age range for each of the constituents is given in millions of years (Ma).

Classification	Constituents	Approx. age
Poorly consolidated sediments	All sediments of Holocene and Pleistocene age	0 to 2.6 Ma
Dunedin Volcanic rocks	Dunedin Volcanic Group (Initial, 1st, 2nd & 3rd eruptive phases)	10 to 13 Ma
Cover rocks (younger)	Otakou Group (Goodwood Limestone, Caversham Sandstone) Kekenodon Group (Concord Greensand, Scroggs Hill Limestone)	16 to 25 Ma
Cover rocks (older)	Onekarara Group (Burnside Mudstone, Green Island Sand, Abbotsford Formation, Wangaloa Formation, Taratu Formation) Matakea Group (Henley Breccia)	25 to ~100 Ma
Basement	Schist of Rakaia Terrane and of Caples Terrane	~115 to 200 Ma

The basement rock represents the geological foundation of the area. It comprises the bulk of the Earth's crust beneath the area and extends many kilometres beneath the ground surface. In the area of this assessment, basement consists of schist, formed by metamorphosis during the Jurassic Period to early part of the Cretaceous periods (between ~200 to ~115 million years ago), while New Zealand was still part of the Gondwana Supercontinent.

The cover rocks were laid down on top of the basement rock between the latter part of the Cretaceous Period and the Early Miocene Epoch of the Neogene Period (between ~100 and ~16 million years ago). The boundary between older cover rocks and younger cover rocks is about 25 million years old. The older cover rocks represent a progression from land-based deposits (Henley Breccia and Taratu Formation) to marine deposits (Wangaloa, Abbotsford, Green Island Sand and Burnside Mudstone formations). The Abbotsford Formation and Burnside Mudstone contain clay minerals that are prone to swelling when wet, and evidence for landsliding is common in places where these formations outcrop.

The basal part of the younger cover rocks is Kekenodon Group, comprising a thin (1 to 2 m thick) band of Concord Greensand, but in places is accompanied by the Scroggs Hill Limestone, which is as much as 30 m thick. The bulk of the younger cover rocks is Otakou Group. In most of coastal Otago, this comprises Caversham Sandstone, but to the north of Waikouaiti, the upper part of the younger cover rocks includes Goodwood Limestone, which sits on top of Caversham Sandstone.

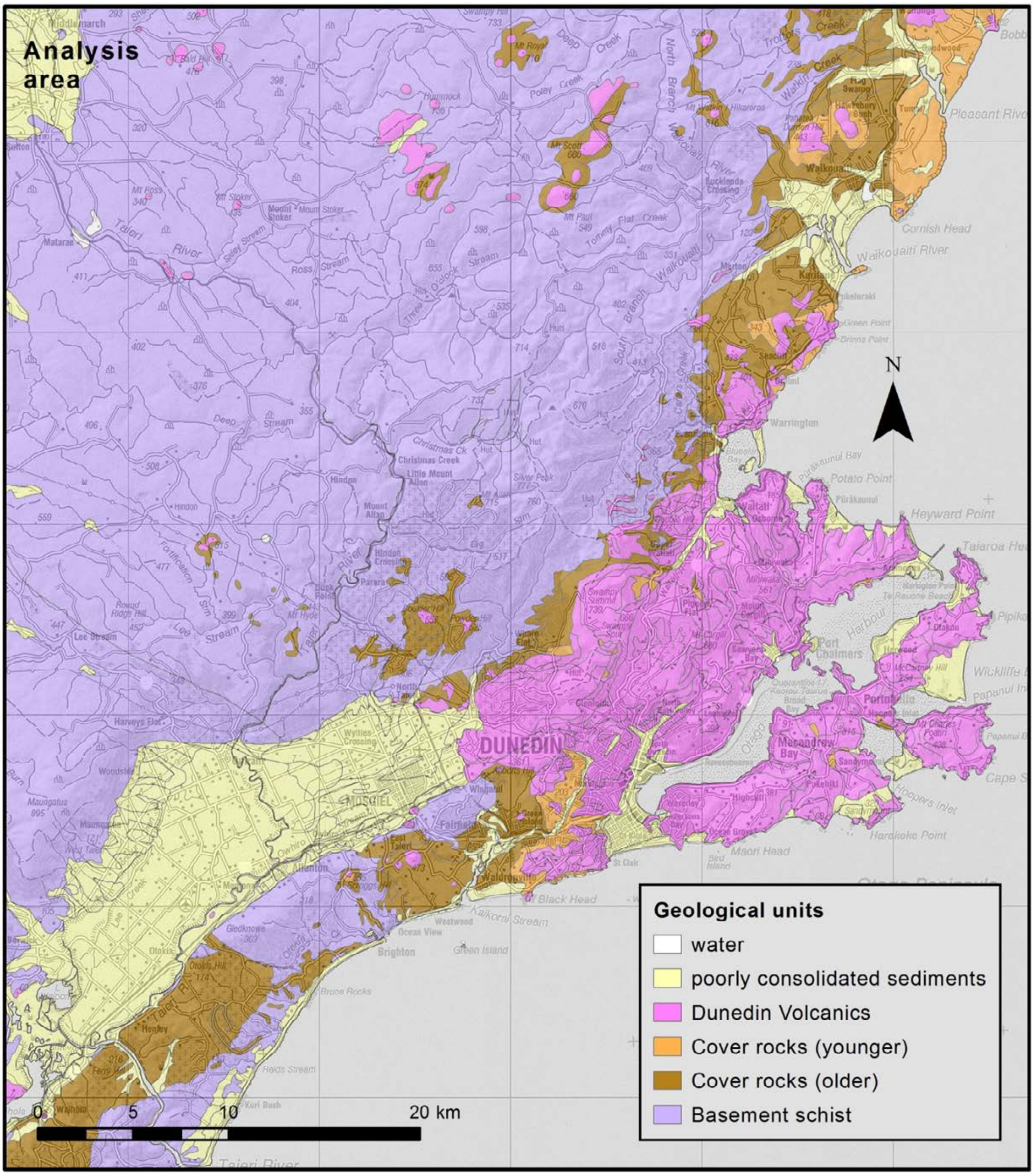

Figure 3 Geology of the analysis area, from the 1:250,000-scale QMAP database (Heron, 2014). Refer to Table 2 for information on the relative extents of each geological unit.

The Dunedin Volcanic Group consists of a variety of different types of volcanic deposits formed between 13 and 10 million years ago. Hard rock laid down by lava flows, or extruded in lava domes, is a prominent feature, but there are numerous layers of fine-grained ash deposits (tuffs) and bouldery conglomerates that were formed by streams draining down the volcanic massif, or in debris flows that descended down the volcano slopes. Erosion has removed much of the constructional form of the volcano, and what remains can be regarded as little more than a skeleton. In places, weathering has penetrated deeply into the volcanic deposits, imparting deep brown colours and notable weakness.

Prior to the onset of Dunedin volcanism, an episode of uplift and erosion removed parts of the cover rock sequence, and exposed the schist basement in many areas. The Dunedin volcanic rocks were erupted over this eroded landscape. As a result, the volcanic rocks overlie different parts of the older rock sequence. Near St Clair and Waikouaiti, volcanic rocks rest on younger cover rocks, but to the northwest the volcanics sit directly on older cover rocks. Towards Middlemarch, volcanic rocks were laid down directly on schist (Figure 3).

The youngest component of the geological sequence is the poorly consolidated sediments, which include a vast array of different types of deposits that mantle the older rocks. Geological maps show the locations of the thickest and most extensive of the poorly consolidated sediments, in particular the alluvial sediments deposited by rivers and streams in valleys or on plains, beach or estuarine sediments deposited along the coast or within bays or lagoons, and dunes of windblown sand. Also present are extensive, but thin (less than about 2 m), accumulations of windblown silt (loess) and debris on slopes (colluvium). Loess and colluvium are not usually shown on geological maps, but soil maps generally provide information on the type and character of these deposits. On a larger scale, the debris produced by landslide movement is a type of colluvium, consisting of disrupted materials of whatever rock or sediment type was involved in the movement.

Table 2 Relationship between geological units and landslides mapped as areas ('polygons') in the analysis area (Figure 4). Very few landslides coincide with areas of poorly consolidated sediments, and the 'adjusted' column recalculates the areal % of each geological class in the analysis area excluding the poorly consolidated sediments class. Column 4 gives the % of the total landslide area that occurs in each class; e.g. by area, basement rock occupies 70% of the analysis area, and 70% of the total landslide area coincides with basement rock.

Geological class	% of the analysis area	% of the analysis area (adjusted)	% of total landslide area	Comments
Poorly consolidated sediments	13.8%	not applicable	1.6%	Class occurs mostly on flat ground; few landslides expected
Dunedin Volcanic rocks	14.1%	16.3%	9.6%	Relatively small landslide % area
Cover rocks (younger)	2.0%	2.3%	2.2%	Landslides proportional to extent of the area
Cover rocks (older)	9.5%	11.1%	16.5%	Relatively large landslide % area
Basement	60.6%	70.3%	70.1%	Landslides proportional to extent of the area

An assessment was made of the relationship between geology and the mapped distribution of landslides using the 1:250,000-scale digital geological map of New Zealand ('QMAP'). The coastal Otago sector of the map was published on the Dunedin sheet (Bishop & Turnbull 1996) and the Waitaki sheet (Forsyth 2001). The digital data were recently refined and issued as a 'seamless' digital map by Heron (2014). The geological data sets were compared against the landslide area and point datasets described by Glassey & Smith Lyttle (2012) and Glassey et al. (2014). The evaluation of the mapped landslide areas (Table 2 and Figure 4) highlights that the percentage of the area mapped as landslide occurring in each geological class is approximately proportional to the area covered by each class. Two exceptions are Dunedin Volcanic Group rocks which have a relatively small proportion of mapped landslide areas, and the older cover rocks, with a relatively large proportion of mapped landslide areas. Landslides that coincide with poorly consolidated sediments may in some instances represent landslide debris that has run out from nearby hillsides. Deposits of windblown sand on hill slope areas may be incorporated in landslide movement involving older rocks beneath the sand deposits, and thus there is a possibility of false impressions of movement having occurred within the poorly consolidated sediment geological class.

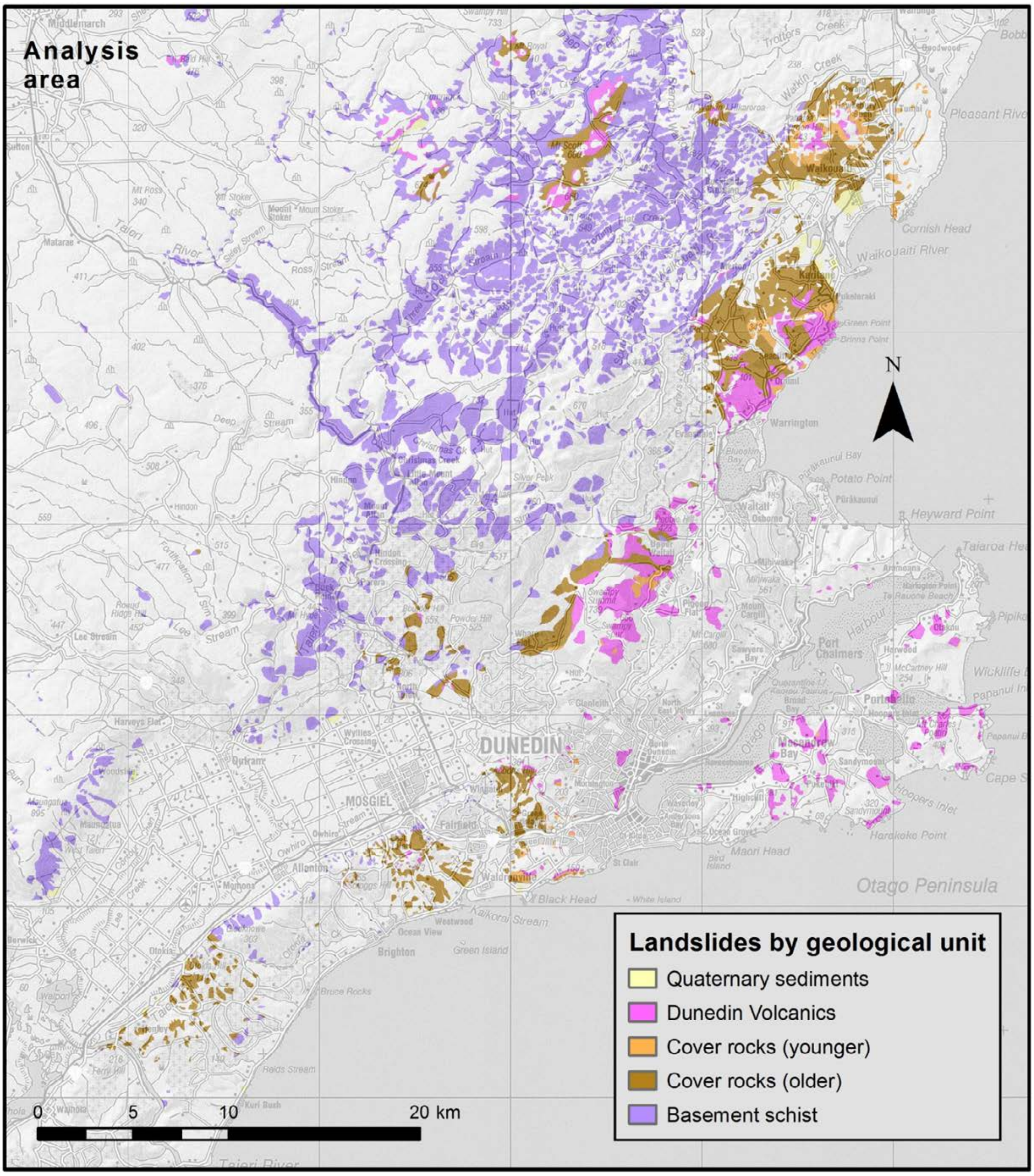

Figure 4 Mapped landslides of the analysis area coloured according to geological substrate.

The analysis indicates that the mapped landslide areas do not correlate strongly with a particular rock type, except for Dunedin Volcanics where there is a relatively small proportion of landslide area and the older cover rocks where there is a relatively large proportion of landslide area. The evaluation of geology in relation to landslides mapped as points (Table 3) is hindered by the non-uniform extent of the landslide point mapping (see Section 2.3). The mapping of landslides as points was undertaken mainly on Otago Peninsula and in the greater Dunedin urban area, where Dunedin Volcanic rocks predominate. The localised areas in which the landslide point mapping method means that no meaningful assessment can be made regarding the relationship of landslide points to underlying geology. Although most of the landslide points are at localities underlain by Dunedin Volcanic Group rocks, we do not consider that it has an bearing on the stability or otherwise of that rock class. For that reason, we have not made a plot of the point location landslides versus geology.

Table 3 Assessment of the relationship between geological units and landslides mapped as point locations. Because very few landslides coincide with areas of poorly consolidated sediments, the 'adjusted' column recalculates the percentage by area of the analysis area excluding the poorly consolidated sediments.

Geological classification	% by area of analysis area	% by area of analysis area (adjusted)	% of landslide points	Comments
Poorly consolidated sediments	13.8%	not applicable	1.5%	
Dunedin Volcanic rocks	14.1%	16.3%	86.0%	Landslide points over-represented due to localised mapping extent
Cover rocks (younger)	2.0%	2.3%	2.6%	
Cover rocks (older)	9.5%	11.1%	7.0%	
Basement	60.6%	70.3%	2.8%	Landslide points may be under-represented due to localised mapping extent

2.5 SOIL DEPTHS

Glassey et al. (2014) suggested that soil type and depth might have a bearing on the distribution of shallow-seated ('surficial') landslides. Most if not all such landslides are delineated in the landslide database as points, rather than as mapped areas that represent larger, deep-seated landslides. Digital soil maps from the Grow Otago database, and the national S-map database (see reference list) were examined. Of particular use is that the mapping of soil types, and the naming and classification of the soil units, takes account of the depth of the soil profile, and the nature of the parent material (i.e. the material on which the soil is developed). The parent material may comprise the underlying rock, whose character is identified and delineated on geological maps, but in many cases in coastal Otago, the parent material is a near-surface deposit such as loess or colluvium, which is not shown on geological maps.

Figure 5 plots soils from the S-map database. The first point to note is that S-map covers a relatively small part of the analysis area. Grow Otago coverage is more extensive, but not complete, because the focus of Grow Otago is on arable land, rather than hill terrain. It is also important to appreciate that, similarly to geological maps, the maps are generalised compilations of field observations, and indicate the typical character of the soil in a general location, rather than providing detailed information at a point. Figure 6 plots the landslide points coloured according to soil depth, with statistics compiled in Table 4.

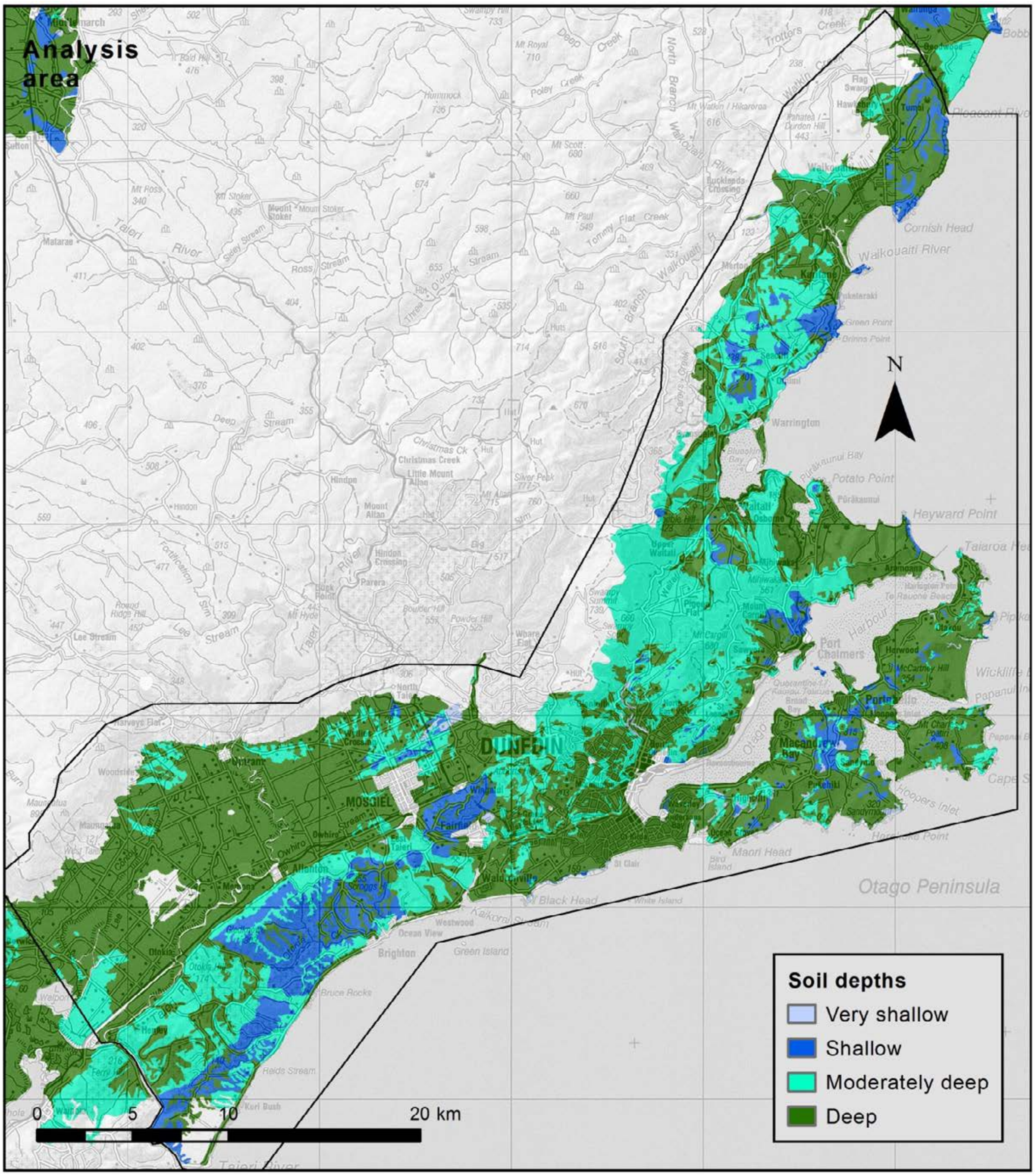

Figure 5 The S-map data set for the analysis area, coloured by soil depth. Because of the limited extent of the soil map, the assessment has been confined to the coastal Otago map area (outlined).

Table 4 Analysis of the relationship between S-map soil units classified by depth and landslides mapped as points. Evaluation is limited to the coastal Otago map area (Figure 6), and the percentage by area refers to the total extent of soil mapping coverage in the map.

Soil classification	Soil depth	% by area of map area	% of landslide points	Comments
Very shallow	<20 cm	0.8%	2.5%	also see Table 8
Shallow	20 to 45 cm	9.7%	10.4%	
Moderately deep	45 to 100 cm	30.2%	18.1%	
Deep	>100 cm	59.4%	69.0%	

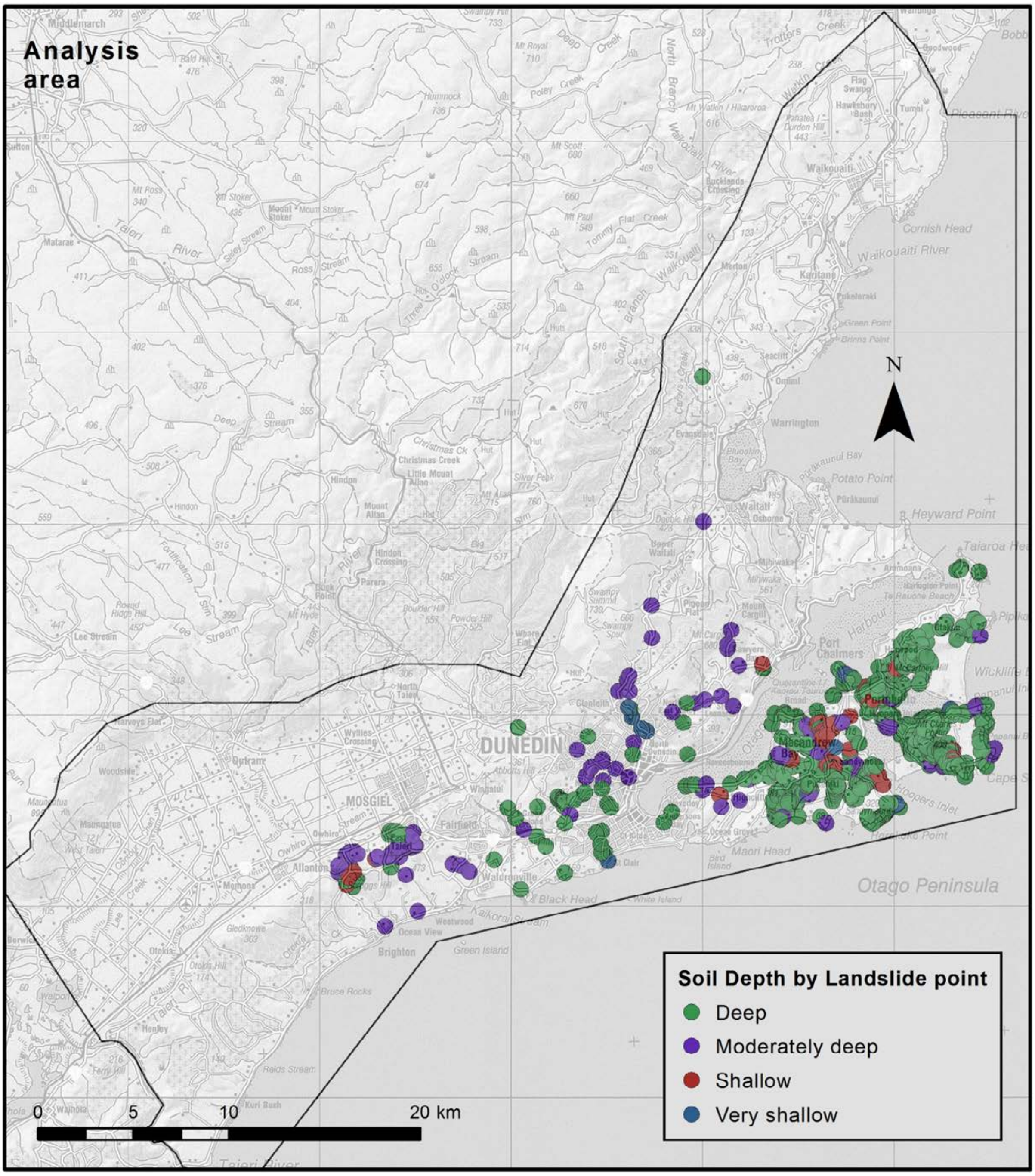

Figure 6 Mapped landslide points of the coastal Otago map area, coloured according to soil depth. Refer to Table 4 for depth range for each class.

At face value, the percentage of landslide points is broadly proportional to the percentage of the total area covered by each soil class (Table 4). One possible explanation for this is that soil depth is not a major influence on the distribution of landslides mapped as point locations. However, this may be misleading because considerable extents of deep soil occur on flat land, such as the Taieri Plain, where there are no landslides. A closer look was then taken at soil depths in relation to slope angle in hill terrain, as is described in Section 2.6.

No attempt was made to assess soil depth with mapped landslide areas (polygons). The rationale for this is that few if any of the landslides that are sufficiently large to be mappable as areas will be sufficiently shallow (e.g. less than a few metres) to bear any relation to the mapped soil types.

2.6 SLOPE ANGLE

Slope is an important factor in slope instability, because gravity is a fundamental driver of landslide movement. The steeper a slope is, the greater the gravitational potential energy of the rock or soil materials underlying that slope. In a study of Otago Peninsula, Leslie (1974) found that 98% of identified landslides had occurred on slopes steeper than 12°. In his study, the landslides were mapped as point locations, and the data from his study form a substantial proportion of the landslide point locations in the Dunedin district landslide inventory.

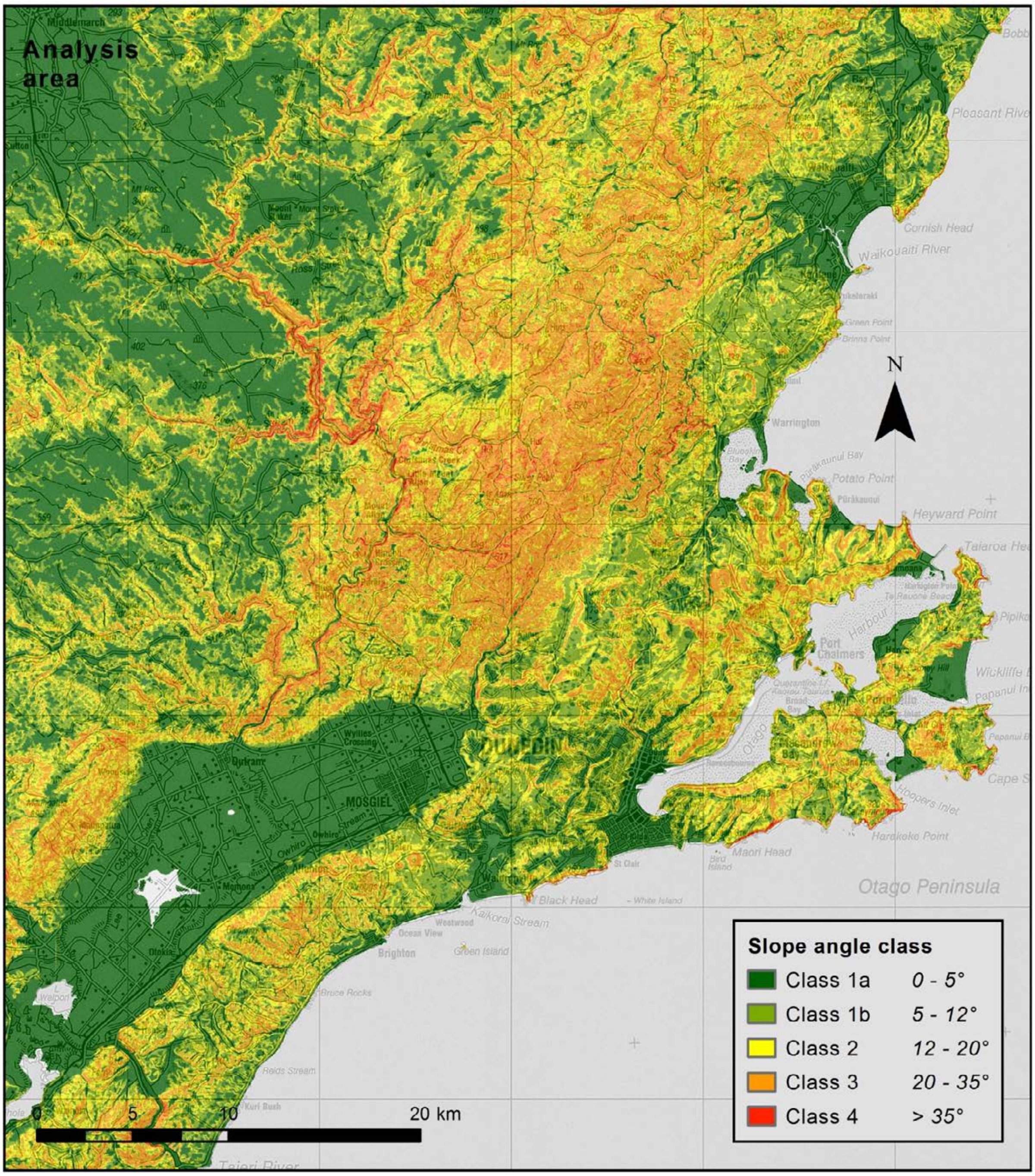

Figure 7 Slope angle map (raster) of the analysis area.

A slope angle raster was calculated for the analysis area from the 8-m DEM (Figure 7), using a grid of 8-m by 8-m cells, the same cell size as the DEM. The slope angle values were calculated by interpolation using the elevation values of nearby cells, according to the methodology described in Appendix 1.

The choice of slope angle classes was based on Leslie's (1974) finding of an important threshold for landslide occurrence at a slope of 12°. Class 1a (0° to 5° slope; flat or nearly flat ground) represents areas that by themselves are unlikely to be sites of landslide initiation, other than by the failure of localised features such as river banks or excavated cuttings. We considered that it would be useful to identify a Class 1b (5° to 12° slope; gently sloping ground) for the purpose of analysis, in particular to test the applicability of the 12° threshold in a wider area. In both classes 1a and 1b, there is potential for inundation by landslide debris from adjacent higher, steeper, ground, or by undercutting where the flat or gentle ground occurs on hills and is adjoined by steeper lower slopes. Class 2 (12° to 20°; moderately sloping ground), Class 3 (20° to 35°; steeply sloping ground) and Class 4 (greater than 35°; very steep slopes) are areas where the occurrence of slope instability should come as no surprise.

Table 5 compares the relative extents of each of the geological units (Figure 3) with the slope angle classes (Figure 7). About 34% of the analysis area is slope Class 1a, 25% is Class 1b, 21% is Class 2, 19% is Class 3 and 1.6% is Class 4. There is a broadly even distribution of slope classes 1a to 3 across areas of basement rock, whereas at least 90% of slopes developed on cover rocks are Class 2 or lower. In contrast, almost 18% of slopes on Dunedin Volcanics are class 3 or 4. Almost all (~98%) of the poorly consolidated sediments have slopes of class 1a or 1b.

Table 5 Assessment of the relationship between geological classes and slope angle classes in the analysis area. Areas are expressed in square kilometres and also as a percentage of each geological class.

Geological classification	**Units**	**Slope angle classes**					**Total area**
		Class 1a	**Class 1b**	**Class 2**	**Class 3**	**Class 4**	
Poorly consolidated sediments	km^2	287.1	18.3	4.0	1.3	0.2	**310.8**
	%	92.4	5.9	1.3	0.4	0.0	
Dunedin Volcanic rocks	km^2	41.1	117.3	102.6	53.7	2.7	**317.4**
	%	12.9	37.0	32.3	16.9	0.8	
Cover rocks (younger)	km^2	10.7	20.3	11.5	2.4	0.2	**45.1**
	%	23.8	45.1	25.5	5.2	0.4	
Cover rocks (older)	km^2	40.5	92.9	60.1	21.5	0.3	**215.3**
	%	18.8	43.1	27.9	10.0	0.1	
Basement	km^2	393.2	304.5	286.5	351.5	32.7	**1368.4**
	%	28.7	22.3	20.9	25.7	2.4	
Total % of area		**34.2%**	**24.5%**	**20.6%**	**19.1%**	**1.6%**	**2257**

Comparison was then made between slope angles and landslides mapped as polygons (Figure 8). Results are summarised in Table 6, and show that approximately 70% of mapped landslide terrain coincides with slopes of Class 2 or greater.

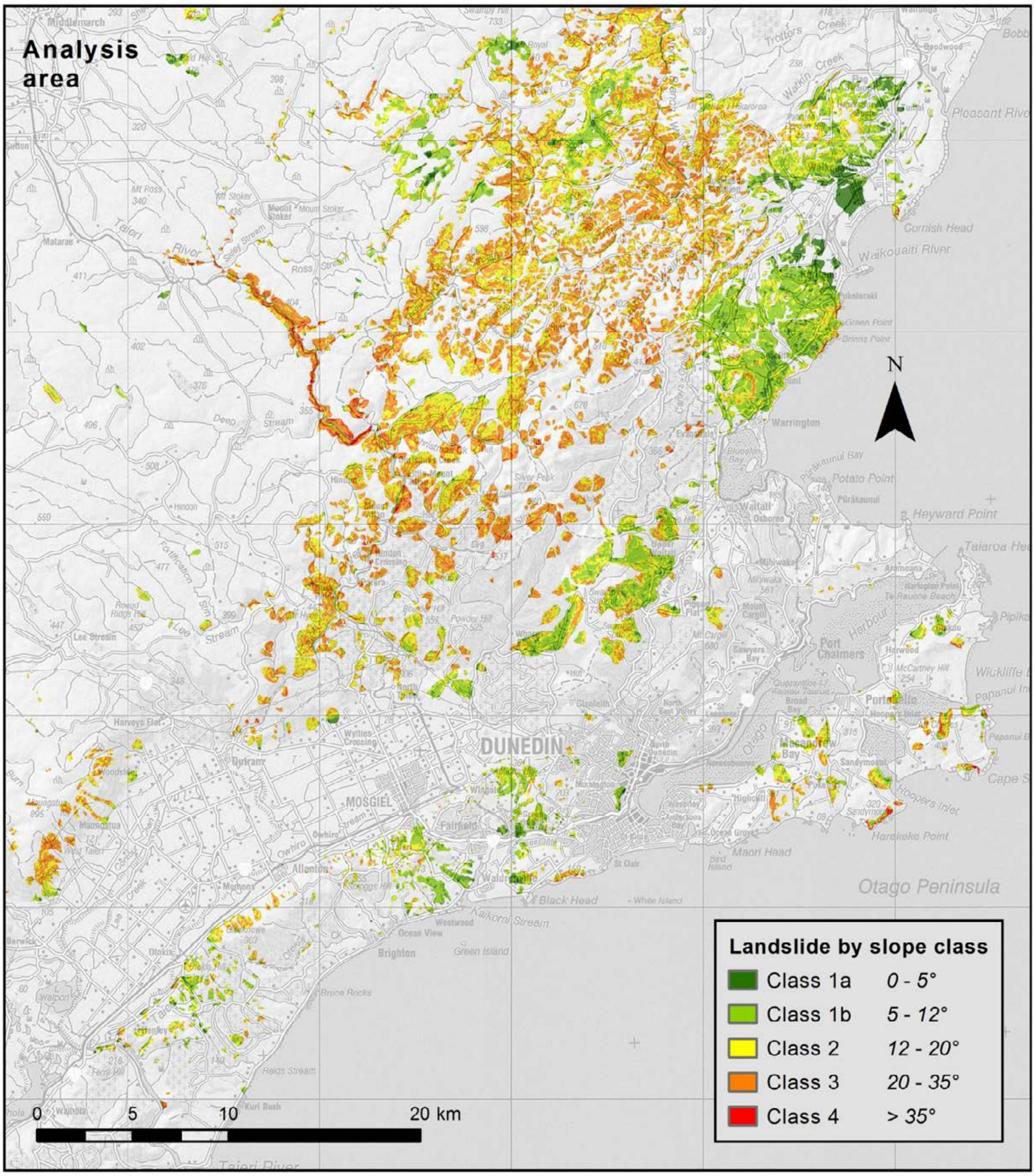

Figure 8 Mapped landslide areas of the analysis area coloured according to slope angle.

Table 6 Relationship between slope angle and landslides mapped as areas (polygons) in the analysis area.

Slope angle class	Areal % of analysis area	% of total landslide area in this class	Comments
Class 1a (0-5°)	34.2%	6.0%	Relatively small landslide % area
Class 1b (5-12°)	24.5%	24.6%	Landslides proportional to extent of the area
Class 2 (12-20°)	20.6%	32.9%	Relatively large landslide % area
Class 3 (20-35°)	19.1%	34.5%	Relatively large landslide % area
Class 4 (>35°)	1.6%	1.9%	Landslides proportional to extent of the area

At first glance, the coincidence of ~30% of the mapped landslide areas with slopes of less than 12° (Table 6) does not sit well with Leslie's (1974) findings from Otago Peninsula, where almost no landslides were identified on slopes of less than 12°. Visual inspection of Figure 8 does show, nonetheless, that most of the mapped landslide polygons on the peninsula are in moderately or steeply sloping terrain. Similarly, visual comparison between Figure 3 and Figure 8 shows that most of the landslides associated with slopes gentler than 12° are in areas underlain by the older cover rocks (i.e. Matakea Group and Onekakara Group; Table 1). We interpret this to mean that the 12° slope is a reasonable working criterion for slope stability/instability in rock types other than the older cover rocks. This issue is discussed further in Section 3.2.4.

Another consideration is that large landslides, most of which are prehistoric, have to some degree created their own topographies, by the formation of tilted blocks and benches in the upslope (head) area of the landslide, and by way of low-angle tongues of debris in the downslope (toe) areas. In these ways, some sectors of flat to gently sloping ground may have been created during landslide movement of what was originally a steeper slope. Finally, there are places where landslide debris may have run out over relatively flat ground, and so may have contributed to the coincidence of landslides with gentle or flat slopes.

Relatively few landslides are mapped in association with Class 4 ground (Table 6). Likely reasons for this include the common association between very steep slopes and relatively hard and strong rock, which is less susceptible to large-scale landsliding, and that in steep terrain, instability is typically via rockfall, and aprons of rockfall debris are usually not delineated as landslide polygons.

Comparing slope angle classes with landslides mapped as points (Table 7 and Figure 9) highlights that approximately 75% of mapped landslide points coincide with slopes of Class 2 or greater. The 21% of these points that are associated with slopes of Class 1b is a surprising result. It raises a question as to whether the correlation of landslides with slopes steeper than 12° slope proposed by Leslie (1974) is valid, particularly since most of the landslide point locations are from his 1974 report.

Table 7 Analysis of the relationship between slope angle and landslides mapped as point locations, in the analysis area.

Slope angle class	% by area of analysis area	% of landslide points	Comments
Class 1a (0-5°)	34.2%	4.1%	
Class 1b (5-12°)	24.5%	20.9%	See text discussion regarding landslide point accuracy
Class 2 (12-20°)	20.6%	42.6%	
Class 3 (20-35°)	19.1%	31.2%	
Class 4 (>35°)	1.6%	1.1%	

The original map of landslide points (Leslie 1974; his Figure 6) was presented at 1:50,000 scale, with no topographic reference information other than a generalised coastline, and it was from this map that the landslide point locations were digitised (Glassey & Smith Lyttle 2012). Leslie (1974; his Figure 19) plotted landslide point locations on a very generalised map of slope angle units (three classes; 0-12°, 12-28° and >28°). There is no explanation in his report as to how the slopes were mapped, nor how landslide locations were determined or plotted. The absence of information on how accurately the landslide locations were determined by Leslie, and on the precision with which they were plotted on his 1:50,000-

scale map, leads us to regard the landslide point locations from Leslie's map as having an accuracy of no better than ± ~100 m, and possibly up to ± ~200 m or more. This could easily result in mis-registration between landslide point location, and slope angle class. We think it very likely that Leslie (1974) selected the 12° slope threshold based on field observation of landslide features. In turn, this probably guided his selection of the 12-28° slope class for the purpose of landslide analysis. Even though the analyses undertaken in the present report raise concerns about the 12° threshold, the most likely explanation is that the mismatches reflect a combination of inherent uncertainties in landslide point locations and the relatively high level of accurate detail afforded by the slope angle map generated from the 8-m DEM.

One last aspect regarding the landslide point dataset is that some of the landslide points may represent very small slope failure events, of extents as small as a few square metres, such as minor slips from road cuts or banks. Topographic variations at the scale of a road cutting are generally below the resolution of a slope model generated from the 8-m DEM. Such failures would coincide with the average slope of the surrounding general area, rather than the true steepness of the cutting or bank that failed. It is likely that such small failures may be better characterised by a detailed slope model derived from lidar (where available), but only if the landslide location was determined to high precision (e.g. hand-held GPS device).

The final evaluation undertaken was to compare the relationship between soil depth and slope angle classes 2, 3 and 4 (Table 8). The results highlight that deep and moderately deep soils occur on between ~80% and ~50% of moderately to very steeply sloping ground. The ~50% coincidence between deeper soils and very steep slopes is surprising because deep soils are less likely to form, and survive, on very steep slopes. Close examination of the GIS data sets shows, however, that most areas of very steep slope are of such small extent that they have not been differentiated on the generalised soil map. Thus, the difference between the highly detailed slope angle map, and the generalised soil map, has resulted in deeper soils appearing to coincide with more areas of very steep than is probably actually the case. As presented in Section 2.5 and Table 4, 10%, 18% and 69% of landslide points coincide respectively with mapped areas of shallow, moderately deep and deep soils. Comparing these values with the percentage areas of the slope classes highlights that landslide point locations are notably more common in hillslope areas that have deep soils, and relatively less common where the soils are moderately deep or shallow. Noting the concerns discussed earlier in this section about the accuracy of the landslide point locations, we think that this is less of an issue in regard to the soil map, because that map is considerably generalised. Because each soil map polygon is relatively large, it is less likely that inaccuracy in a landslide point location will apparently place it over an adjacent soil map polygon.

Overall, the comparison of soil map classes, slope angle classes and landslide point locations indicates that there is a notable, though not strong, association between moderate to very steep slopes, deep soils and the occurrence of landslides.

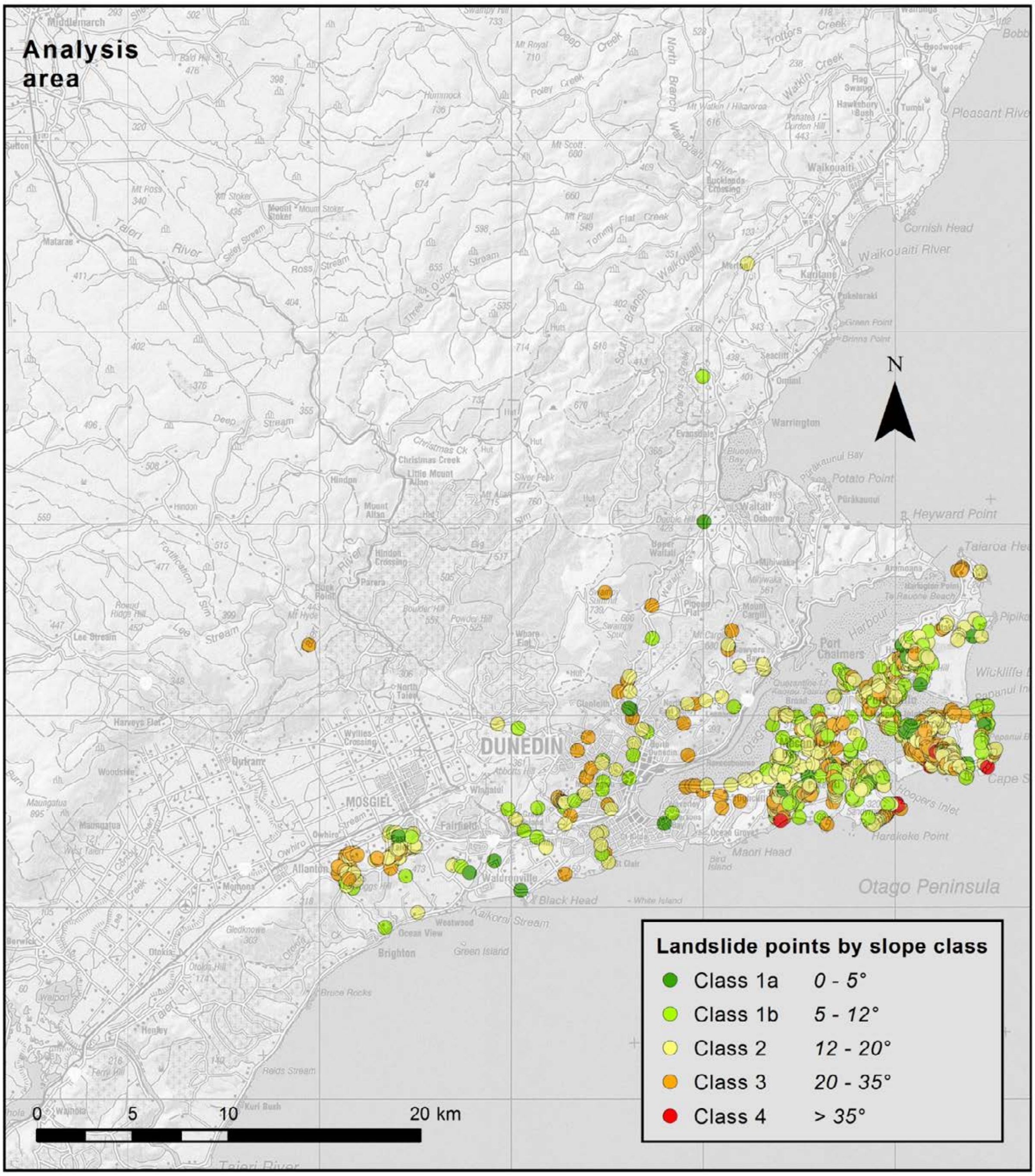

Figure 9 Mapped landslide points of the analysis area coloured according to slope angle.

Table 8 Analysis of the relationship between S-map soil units classified by depth and slope angle classes 2, 3, and 4, in the sectors of the coastal Otago map area where the soil map overlaps those slope angle classes.

Soil classification	Soil depth	% of Class 2	% of Class 3	% of Class 4	Average
Very shallow	<20 cm	0.6%	2.1%	26.1%	9.6%
Shallow	20 to 45 cm	18.6%	27.5%	24.9%	23.7%
Moderately deep	45 to 100 cm	41.8%	39.6%	16.8%	32.7%
Deep	>100 cm	39.1%	30.8%	32.1%	34.0%

2.7 EVALUATION

Mapped landslide areas represent locations of known or suspected past landslide movement. If proven to be correctly interpreted as landslide features, they demonstrate that the land at that location has previously experienced instability. Each mapped landslide area therefore raises a warning flag that slope stability is a factor to be considered at that location. The mapped landslide areas should not necessarily be assumed to be currently unstable, because the conditions under previous movement occurred (e.g. rainfall, groundwater and surface vegetation) may no longer prevail. Case-by-case assessment is advisable.

In regard to other factors, the analyses presented above indicate that the most important factor influencing landslide distribution in coastal Otago is slope angle. Slope angles of ~12° seem to afford a satisfactory threshold, whereby most landslides have occurred where the slope is steeper than that value. This criterion ceases to be satisfactory in areas underlain by the relative weak and sensitive sedimentary rocks of the Matakea Group (Henley Breccia) and the Wangaloa Formation, Abbotsford Formation, Green Island Sand and Burnside Mudstone of the Onekakara Group.

There are indications of some degree of correlation between landslides mapped as points (therefore presumably of relatively small extent) and areas of deep soils on moderate to very steep slopes. However, there is valid concern about the accuracy of landslide point locations, and it is considered in this report to be very doubtful that the landslide point are reliable indicators of the loci of past landslide movements at the scale of specific land parcels, and land parcel boundaries. In regard to evaluating potential landslide hazards, it is recommended here that landslide point locations should be set aside in favour of simply using slope angle as a tool for delineating areas that may be susceptible to landsliding. It may well turn out that soil depth is relevant in the occurrence of surficial landslides, but such an assessment would require a more precisely located inventory of past surficial landslides occurrences.

3.0 IDENTIFICATION OF AREAS POSSIBLY SUSCEPTIBLE TO LANDSLIDING

3.1 BACKGROUND

Some previous landslide susceptibility assessments have used a multi-factor approach to define landslide susceptibility classes. An example of this is a landslide susceptibility evaluation for ‘greenfield’ areas in South Auckland (Heron et al. 2012). In that assessment, the underlying geological data and slope angle information generated from a DEM were used as inputs to a landslide susceptibility model programme using GIS software. The landslide susceptibility model divided the area of each geological unit into 5 landslide susceptibility classes (‘Negligible’, ‘Low’, ‘Moderate’, ‘High’ and ‘Very High’) based on the slope angles within that geological unit ,and consideration of the strength of the geological material. In most cases, the geological factor was moderated manually, so that slope angle became the dominant influence on the classification. In addition, a companion programme used the pattern and distribution of slope angles to identify areas potentially subject to landslide debris run-out, or to ‘collapse’ due to failure of adjacent slower slopes. Some additional description of this method is provided in Appendix 2.

Potential limitations of the approach used in South Auckland is that the models do not take account of existing landslide features, and it not so easy for a user to discern exactly the basis on which the classification is made for a particular location. A similar model approach was used to generate a landslide susceptibility classification that is applied in selected urban areas of New Zealand in online property hazard reports that can be purchased from Quotable Value New Zealand. A different approach is taken in this report, as outlined below.

3.2 APPROACH

Following from the analyses presented and discussed in Section 2, the approach taken here for delineating areas of the near-coastal sector of the Dunedin district that may possibly be susceptible to landsliding was to generate a set of relevant single-factor GIS data layers that can be interrogated relative to land parcels or other specific locations (e.g. building site). Technical information relating to the generation of these datasets is provided in Appendix 1.

3.2.1 Slope angle polygon dataset

The first step was to reclassify the slope angle values in the raster dataset illustrated in Figure 7, to broader slope classes. The raster was then generalised, in order to filter and remove small outlying values, and also to smooth some class boundaries within the raster dataset. A polygon dataset was generated from the generalised raster dataset and clipped to the coastal Otago map area (Figure 10). Compared to the raster dataset, the generalised polygon dataset has greater utility for generating buffers of specified size around a polygon of a particular class, and polygon data can be easier for the end user to query. The generalised slope class polygons were then used to produce the Slope Awareness areas.

3.2.2 Slope awareness areas

The polygons of slope classes 2, 3 and 4 are designated as Slope Awareness Areas (Figure 11). The awareness area classes draw attention as to the nature of the ground slope at any location, without making an implication as to the degree of hazard, which will depend on a range of considerations that are best evaluated during site-specific investigation.

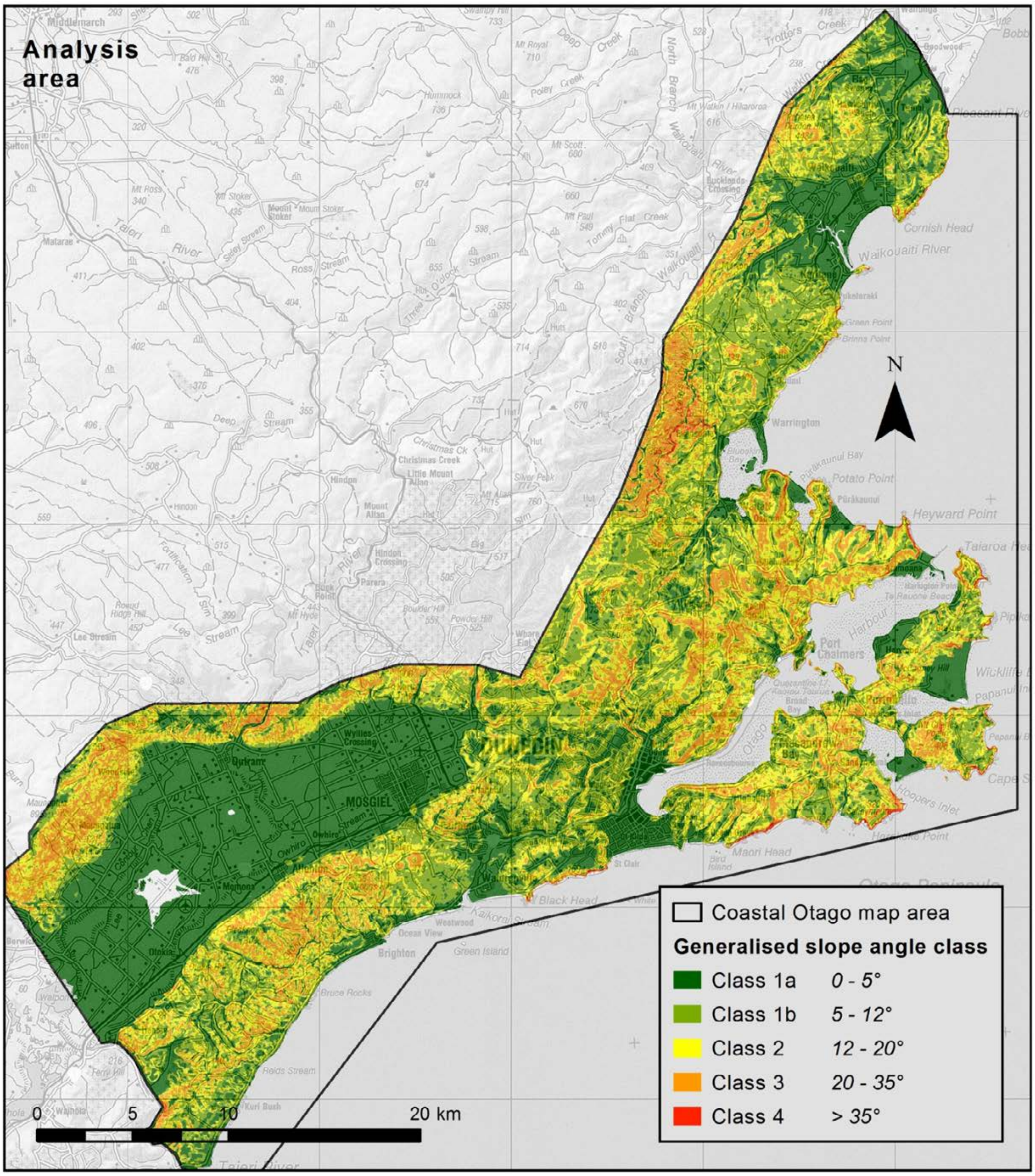

Figure 10 Generalised slope angle map (polygon) clipped to the coastal Otago map area and coloured by slope angle. Uncoloured areas on the Taieri Plain are classified as being as much as below sea level in the topographic contour dataset.

The three classes are: moderate Slope Awareness Area (slopes between 12° and 20°), steep Slope Awareness Area (slopes between 20° and 35°), and very steep Slope Awareness Area (slopes steeper than 35°). Each polygon representing a Slope Awareness Area is surrounded by a 100 m wide buffer outside its perimeter, with the buffer denoting the proximity of a Slope Awareness Area. Buffers for adjacent polygons overlap, thereby providing maximum information on nearby classes of Slope Awareness Area. The buffers serve at least two purposes. One is to highlight an inherent uncertainty in defining the extent and location of moderately sloping ground. In areas of moderately sloping ground, the 20-m topographic contours, from which the 8-m DEM, and subsequently the slope angle classes, were generated, are relatively widely spaced, and thus there may be inaccuracy in the position of the modelled boundaries with adjacent polygons.

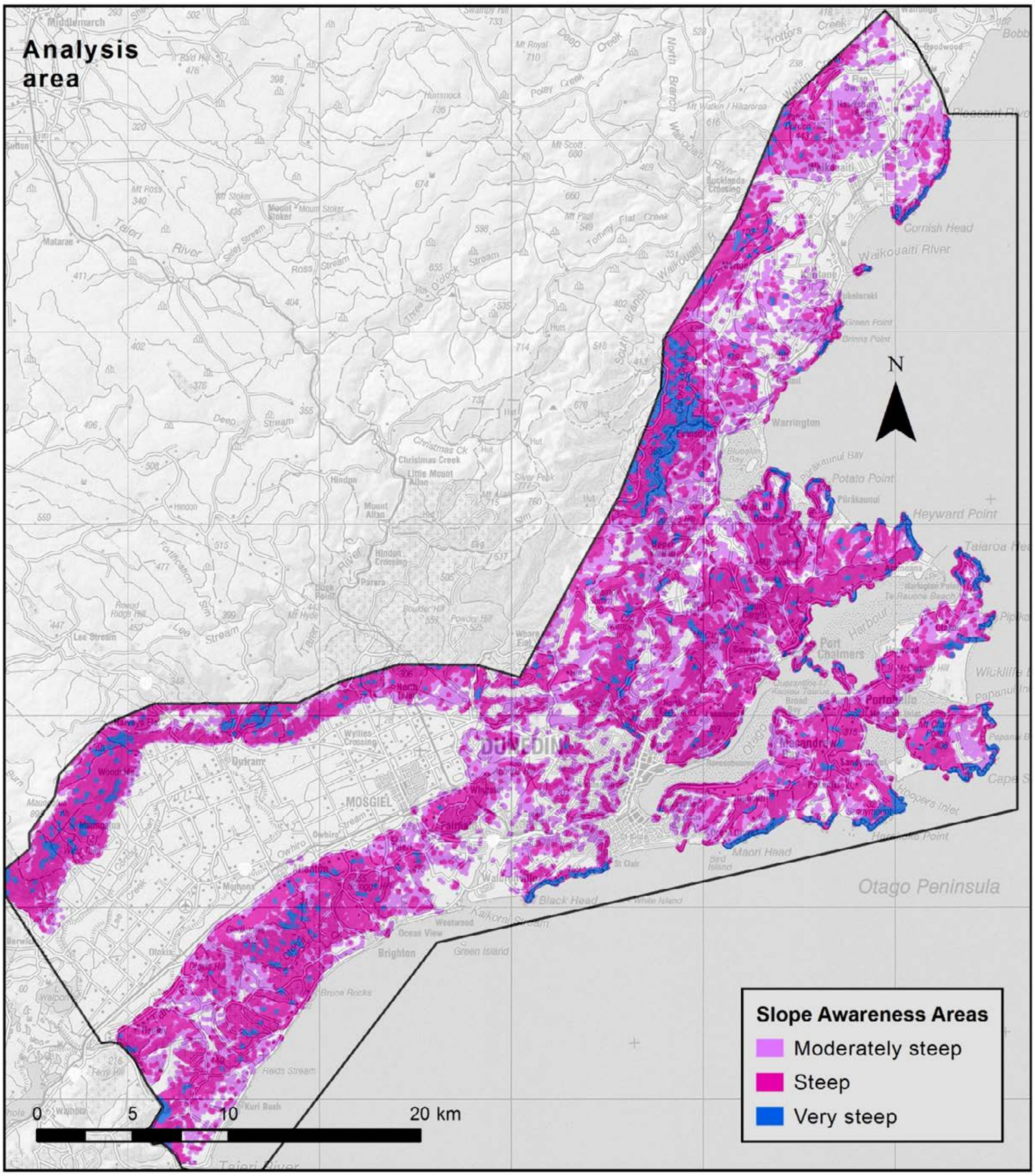

Figure 11 Slope Awareness Areas in the coastal Otago map area, derived from slope angle classes 2, 3 and 4 from the generalised slope angle polygon data set (Figure 10). The plot includes 100 m wide buffers on each Slope Awareness Area polygon, displayed in the same colour as the awareness area. Uncoloured areas correspond to slope angle class 1a or 1b.

In contrast, the locations of steep and very steep slopes are more accurately delineated in the slope angle model, simply because they have more 20 m interval topographic contours defining them. However, these areas pose more substantive potential hazards than does the moderately sloping ground, in terms of the potential length of run-out of any debris, and the undercutting of areas beside the head of a slope. Thus, a 100 m buffer on these steeper areas can be thought of as providing a more explicit perimeter on a well-defined area of potentially greater hazard. Conversely, a 100 m buffer on the perimeter of a polygon of moderately sloping ground primarily indicates uncertainty in the position of a change in slope.

3.2.3 Landslide awareness areas

Identified landslides are an important consideration in evaluating future landslide hazards, because they denote places where slope instability has occurred previously, and thus indicate a possible propensity towards instability at that general location. Mapped landslide polygons from the Dunedin district landslide database (Glassey & Smith Lyttle 2012; Glassey et al. 2014) in the coastal Otago map area are identified as Landslide Awareness Areas (Figure 12). Each Landslide Awareness Area polygon was buffered in order to denote the proximity of a Landslide Awareness Area, with buffers ranging in width from 200 m for landslide areas of more than 70 ha extent to 50 m for landslides of mapped extent less than 17.5 ha (see Appendix 1 for more information).

The following reasoning was used for the selection of buffer widths. Large landslide areas have generally been taken from regional-scale maps (i.e. QMAP; compiled in generalised form at 1:50,000 scale, for presentation at 1:250,000 scale), and thus there is commensurate imprecision in the mapping of landslide boundary positions. A 200-m buffer provides nominal accommodation of that uncertainty, as well as affording a nominal contingency for encroachment or undermining of adjacent ground in the event of future movement of the landslide. In contrast, small landslide areas have undoubtedly been taken from larger scale maps, intended for presentation at 1:50,000 scale or better, and thus better precision can be expected in the positioning of landslide boundary positions. Similarly, lesser amounts of future encroachment or undermining can be expected in association with a small landslide.

As explained in Section 2.7, the landslide point locations are considered to be insufficiently accurate for delineating the exact positions of past landslide activity at the scale of specific land parcels, and land parcel boundaries. Instead, the Slope Awareness Area classification is considered likely to adequately embrace the majority of locations of past, relatively small-size, slope movements that may have been identified as landslide points.

3.2.4 Geologically sensitive areas

The Geologically Sensitive Areas (Figure 13) comprise places where the relatively weak geological formations of the Matakea Group (Henley Breccia) and Onekakara Group, excluding Taratu Formation, form the main geological substrate. The Onekarara Group strata included in the Geologically Sensitive Area classification are Wangaloa Formation, Abbotsford Formation, Green Island Sand, and Burnside Mudstone. These four formations are included because they are mapped as a single unit in the QMAP database. Although the Wangaloa Formation is marine sandstone that is not known to have been involved in notable slope instability, it cannot be separated from the other formations in the existing map database. The mapped Geologically Sensitive Areas include places where those rocks are covered by poorly consolidated sediments, for example near Waldronville and Waikouaiti, where sand dune deposits are draped over the weak geological formations. The reason for including these areas is to highlight the presence of underlying weak strata, which may be at shallow depth (e.g. a few metres) and this may be relevant to some types of development. The 200 m buffers are intended to accommodate imprecision in the positioning of geological boundaries on the regional-scale map from which the polygons are taken.

This classification identifies areas where the subsurface geology includes formations that are known to have a tendency to be unstable in certain settings. The intent is not to restrict everyday activities, or imply the existence of any specific geological hazard, but rather highlight that caution is needed in undertaking major modifications to slopes, or undertaking activities that may potentially reduce stability (e.g. discharge of waste water to ground).

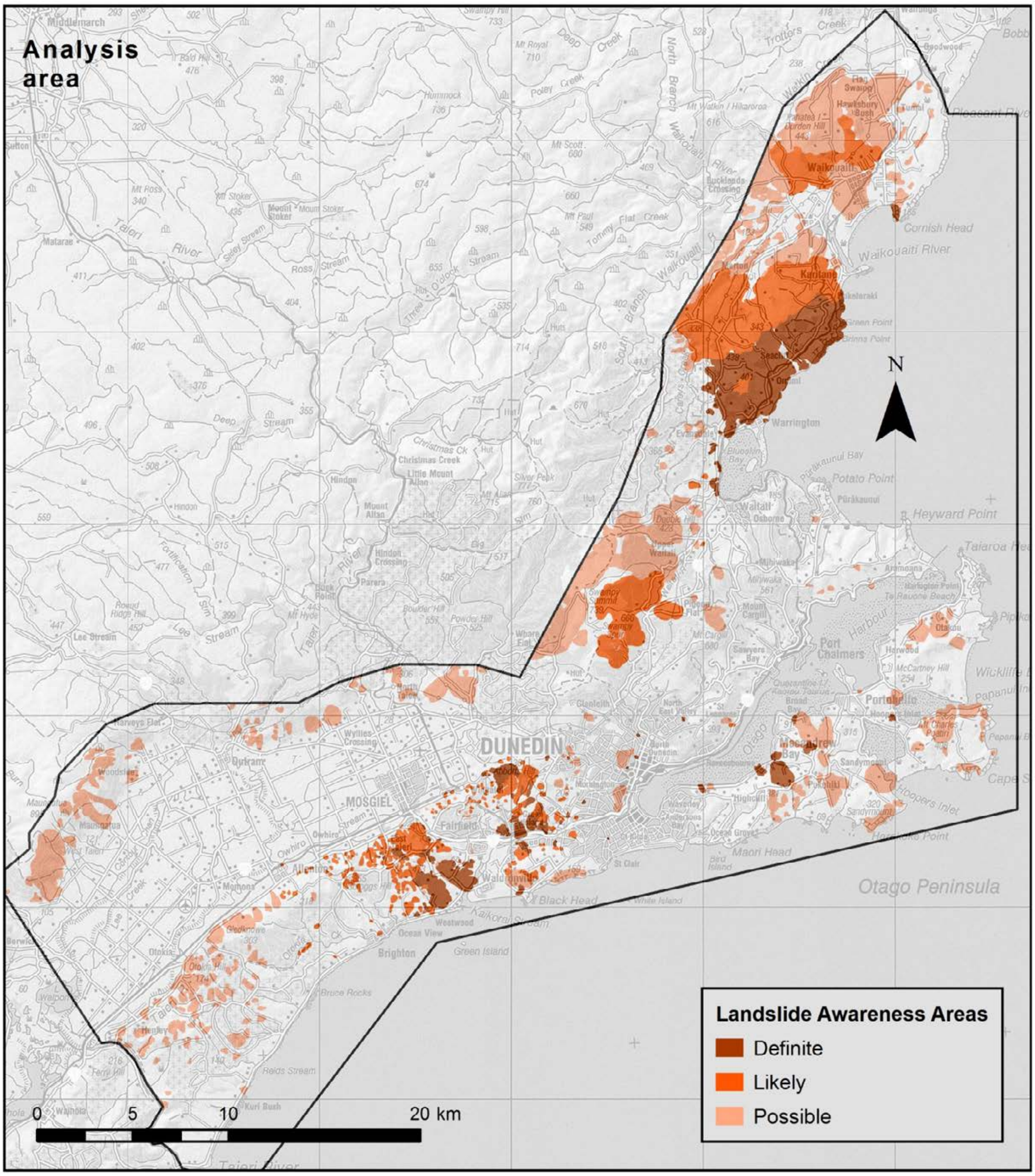

Figure 12 Landslide Awareness Areas, in the coastal Otago map area, derived from the landslide area polygon data set. The plot includes the landslide polygons as well as their buffers, displayed in the same colour as the awareness area; see text for more information on the buffers.

3.3 DISCUSSION

The awareness areas identified in this report should not in themselves be regarded as equating to hazardous areas. Taking the Slope Awareness Areas for example, there are numerous locations within the existing urbanised parts of Dunedin where moderate and even steep slopes have been subdivided and built upon since European settlement, and which have not experienced widespread slope instability problems. Examples include parts of City Rise, North East Valley and Kew. In this regard, the development has in itself provided a successful test of the medium-term stability of those slopes (e.g. acceptable in regard to provisions of the Building Act 2004). On the other hand, some urban development has occurred over land that subsequently turned out to be unstable, with examples such as the prehistoric but still active Howard Street Slide at Macandrew Bay, the Cargill Street Slide at City Rise, and the infamous East Abbotsford Landslide of 1979.

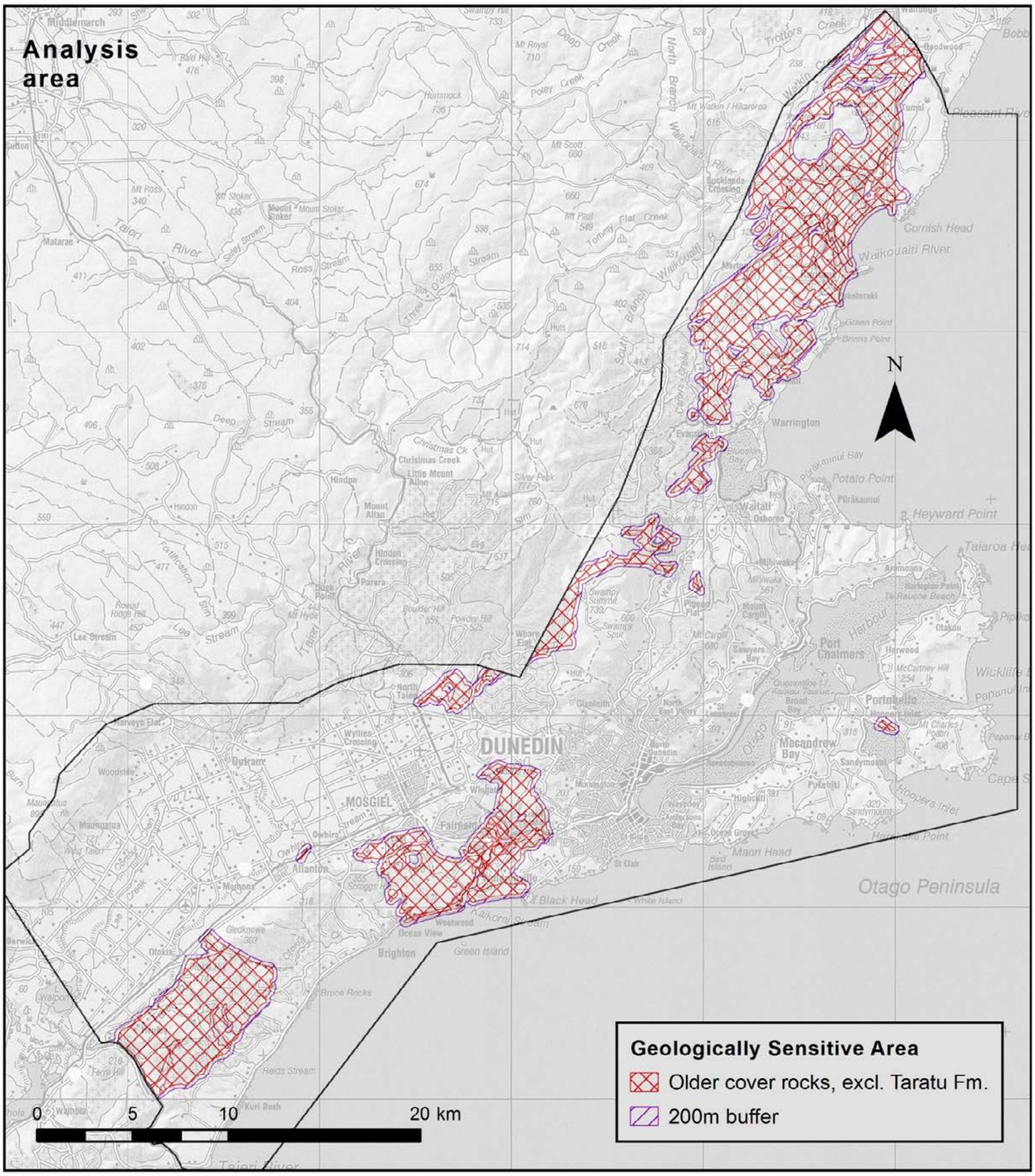

Figure 13 Geologically Sensitive Areas of the coastal Otago map area, derived from the QMAP geological map database.

With regard to the Landslide Awareness Areas, an example worth considering is the prehistoric West Abbotsford Landslide, on which much of the Abbotsford suburb was built, unwittingly, in the early 20th century. Aside from minor reactivation during construction of a motorway at the toe of the slide in the late 1960s, and some localised subsequent creep movements, the majority of houses on this landslide feature have not been adversely affected by movement. This illustrates that development on a pre-existing landslide feature, if it is inactive, is not necessarily inappropriate from a life-safety or asset-security perspective. The underlying reasoning is that once initiated, landslide movement continues until the moving mass of material has attained a stable configuration, and movement stops. Providing that activities unfavourable to the stability of the landslide feature are avoided, then it is not necessarily an inappropriate place for some types of development. This example highlights the merit of examining the potential hazards in a Landslide Awareness Area on a case-by–case basis, and avoiding generalisations regarding suitability for particular types of land-use or development. If the existing stability condition of an area previously involved in landslide movement can be quantified by geotechnical investigation, and measures implemented that will robustly maintain or improve its stability, then slope instability ceases to an issue for that land. It should be noted that a high threshold would be expected for the robustness of such a geotechnical investigation and assessment, and such a pathway to prove the stability of a former landslide area would likely involve considerable expense. Generally speaking, it would be more prudent and cheaper to plan to locate future assets on land that has little or no propensity towards instability.

Similarly for the areas identified in this report as being underlain by geologically sensitive rocks, these areas are not necessarily unstable, but it is important for people to be aware that there may be a delicate balance in such areas between the maintenance of stability, and onset of instability. The 1979 East Abbotsford Landslide is a case in point, and is located within an area where the underlying rocks are identified in this report as Geologically Sensitive. Human factors, such as quarrying at the toe of the slope, and the presence of leaking water mains, were identified as contributing factors to the landslide movement.

3.4 DATASETS PROVIDED

Four primary GIS datasets have been generated as part of the assessment, and provided to the local authorities (ORC and DCC). As set out below, a scale limitation is provided for each dataset. This defines the most detailed scale at which the dataset should be used. For example, the most detailed scale at which a map of the Slope Awareness Areas should be plotted is 1:10,000 (1 cm on the map represents 100 m on the ground). If plotted at a more detailed scale of say 1:5,000, the accuracy of the dataset relative to other features, such as a building platform location, should not be relied upon. This underscores why it is important to use the datasets only for general advice, and why site-specific evaluations are needed for hazard assessment of specific land parcels.

- Slope angle classification (polygon) – illustrated in Figure 10, scale limitation 1:10,000;
- Slope Awareness Areas (polygon) – illustrated in Figure 11, scale limitation 1:10,000;
- Landslide Awareness Areas (polygon) – illustrated in Figure 12, scale limitation 1:25,000;
- Geologically Sensitive Areas (polygon) – illustrated in Figure 13, scale limitation 1:50,000;

3.5 USE OF THE AWARENESS AREA DATASETS

Given the generalised nature of the maps and datasets that were utilised in this project, and some of the inherent uncertainties of interpretation and accuracy, the datasets should be regarded as being primarily of advisory value rather than providing definitive information on slope instability at any particular location.

It is envisioned that as part of any assessment for proposed new developments, proposed intensification of land-use, or activities involving substantial earthworks, the property parcel would be interrogated against the datasets described in Section 3.4 above.

3.6 CURRENT LIMITATIONS AND FUTURE REFINEMENTS

The digital datasets described in Section 3.4 are derived from pre-existing datasets of topographic information, landslide inventory information and geological information. All are subject to varying degrees of uncertainty, as illustrated by the minimum scale specified at which they should be used. These datasets provide indicative advice on likely conditions at a particular location, but do not in themselves represent interpretations of slope instability. Rather, collectively they provide guidance on issues that are potentially important for assessing slope stability conditions, and delineating areas that may have a susceptibility to landsliding. In particular, site-specific assessment should be undertaken to confirm actual conditions at a site, in a manner appropriate for the nature of the awareness area and the type of activity proposed.

The awareness areas identified in this report have been generated using the methodologies specified. Other methodological approaches have previously been used, such as the landslide susceptibility modelling classification available in online property hazard reports that can be purchased from Quotable Value New Zealand. A broadly similar interpretation is likely to be obtained for a particular land parcel, via the landslide susceptibility model through Quotable Value, or from interpretation of the awareness areas presented in this report. A benefit of the awareness area approach is that the nature of the factors relevant to slope stability are more explicit.

These awareness area datasets should not be regarded as representing static information. For example, improved mapping, interpretation and characterisation of landslides at particular locations may allow refinements to be made to the landslide inventory, especially the mapped extent of landslides, or to the ‘Certainty’ attribution. Following such refinements, an updated iteration of the Landslide Awareness Areas dataset could be generated.

A further future refinement would be to obtain improved information on the age of landslide features, such as when they last moved. That information could form a basis for risk-based analysis of landslide hazards, as an adjunct to the approach used in the present report.

4.0 ACKNOWLEDGEMENTS

We thank ORC and DCC for provision of lidar datasets, and Michael Goldsmith (ORC) and Sally Dicey (DCC) for advice and discussions. The report has benefited from peer review by Phil Glassey and Sally Dellow (GNS Science).

This page is intentionally left blank.

5.0 REFERENCES

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. Prepared for Otago Regional Council. 66 p. Accessible at www.orc.govt,nz, search term < natural hazards >.

Benson, W.N. 1940. Landslides and allied features in the Dunedin District in relation to geological structure, topography and engineering. Transactions of the Royal Society of New Zealand 70 (3): 249-263.

Benson, W.N. 1946. Landslides and their relation to engineering in the Dunedin District. Economic Geology 41(4): 328-347.

Bishop, D.G.; Turnbull, I.M. 1996. The geology of the Dunedin area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 21. 52 p.+ 1 folded map.

Forsyth, P.J. 2001. Geology of the Waitaki area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 19. 64 p.+ 1 folded map.

Glassey, P.J.; Barrell, D.; Forsyth, J.; Macleod, R. 2003. The geology of Dunedin, New Zealand, and the management of geological hazards. Quaternary International 103: 23-40.

Glassey, P.J.; Smith Lyttle, B. 2012. Attributing and reconciling source of landslide data within the Dunedin City Council area. GNS Science Consultancy Report 2012/279. Prepared for Otago Regional Council. 17 p. plus appendices. Accessible at www.orc.govt,nz, search term < natural hazards >.

Glassey, P.J.; Barrell, D.J.A.; Smith Lyttle, B. 2014. The hazard significance of landslides in and around Dunedin City, GNS Science Consultancy Report 2013/339. Prepared for Otago Regional Council. 32 p. Accessible online at www.orc.govt,nz, search term < natural hazards >.

Goldsmith, M.; Sims, A. 2014. Coastal hazards of the Dunedin City District. Otago Regional Council. ISBN 978-0-478-37678-4. 122 p. Accessible at www.orc.govt,nz, search term < natural hazards >.

Grow Otago. Comprehensive maps of climate and soil for the Otago Region. Available on CD from Otago Regional Council; accessible online at www.orc.govt,nz, search term < grow otago >.

Heron, D.W. (custodian) 2014. Geological map of New Zealand 1:250,000. GNS Science Geological Map 1. Available on CD, and accessible online at www.gns.cri.nz, search term < QMAP >.

Heron, D.W.; Lukovic, B.; Dellow, G.D. 2012. Modelled landslide susceptibility for South Auckland greenfield areas – Glenbrook, Karaka, Kingseat, Paerata and Pukekohe, GNS Science Consultancy Report 2012/225. Prepared for Auckland Council. 22 p.

Leslie, D.M. 1974. Effects of basement lithology, regolith, and slope on landslide potential, Otago Peninsula, New Zealand. New Zealand Soil Bureau Scientific Report 12.

McKellar, I.C. 1990. Geology of the Southwest Dunedin urban area – Scale 1:25,000. New Zealand Geological Survey Miscellaneous Series Map 22. 1 sheet and 63 p.

S-map. The digital soil map for New Zealand. Accessible online at www.landcareresearch.co.nz, search term < S-map >.

Stewart, D.L. 1996. Landslides triggered by the 17–19 March 1994 rainstorm, Dunedin Area. Institute of Geological and Nuclear Sciences Science Report 95/42.

This page is intentionally left blank.

APPENDICES

A1.0 DATA PROCESSING PROCEDURES

A1.1 GENERATION OF SLOPE ANGLE DATASETS

Slope represents the average difference between two points of elevation, expressed as an angle in degrees relative to horizontal. The values for elevation come from digital elevation models, as described in Section 2.2 of the main report.

Initially, an 8 m x 8 m floating point raster dataset was calculated for slope in degrees. The slope raster was reclassified into an integer raster dataset defining five slope angle classes as described in Section 2.6 of the report.

All the initial assessments of relationships between geological unit and slope; landslide area and slope; landslide point and slope; and soil depth and slope, were made using this slope angle class raster dataset.

The slope angle class raster dataset was filtered for anomalous values and generalised prior to constructing a polygon feature class referred to in Section 3.2.1 of the report.

ATTRIBUTE definition for **SlopeClassGeneralised**

CLASS - text field	The slope angle class values of the polygons. Class 1a = 0 - 5°; Class 1b = 5 - 12°; Class 2 = 12 - 20°; Class 3 = 20 - 35° and Class 4 > 35°.
FEATURE - text field	Description of feature type in this feature class. e.g. Slope Class 2

This generalised polygon feature class was reselected for slope angle Class 2, Class 3 and Class 4 to make the 'Slope Awareness Areas' feature class, and buffered by 100 m, as described in Section 3.2.2 of the report. This dataset is intended to draw attention as to the nature of the ground slope at any location, without making an implication as to the degree of hazard.

ATTRIBUTE definition for **SlopeAwareArea**

CLASS - text field	The slope angle class values of the polygons. Class 2; Class 3; Class 4
FEATURE - text field	Description of feature type/buffer size in this feature class. e.g. Slope Class 2 - 100m buffer
AREA - text field	Description of ground slope at any location. Moderate; Steep; Very steep

A1.2 GENERATION OF LANDSLIDE AWARENESS AREAS DATASET

A subset of mapped landslide polygons from the Dunedin district landslide database (Glassey & Smith Lyttle 2012; Glassey et al. 2014) was clipped out for the coastal Otago map area. The landslides polygons were buffered, applying a maximum buffer width of 200 m for landslides having a mapped surface area of more than 70 ha extent. The applied buffer width was decreased proportionally to the landslide surface area to a minimum width of 50 m for landslides with a mapped surface area of less than 17.5 ha.

The landslide polygons and their associated buffers are the 'Landslide Awareness Areas' feature class referred to in Section 3.2.3 of the report.

ATTRIBUTE definition for **LandslideAwareArea**

LANDSLIDE_ID - Long integer	Identifier linked to Dunedin district landslide database.
CERTAINTY - Long integer	Degree of certainty of the interpretation that the mapped feature is actually a landslide. 1 = Definite; 2 = Likely; 3 = Possible
FEATURE - text field	Description of feature type and/or buffer size in this feature class. e.g., Landslide polygon - subset only; Landslide polygon subset - 195.23m buffer

A1.3 GENERATION OF THE GEOLOGICALLY SENSITIVE AREA DATASET

A subset of geological units from Geological Map of New Zealand 1:250 000 database (Heron 2014) consisting of relatively weak late Cretaceous to Paleogene sedimentary rocks was clipped out for the coastal Otago map area, to make the Geologically Sensitive Area feature class, and buffered by 200 m, as described in Section 3.2.4 of the report.

ATTRIBUTE definition for **GeologicallySensitiveArea**

KEY_GROUP_NAME - text field Name applied to intermediate level groupings of geological mapping units in Geological Map of New Zealand 1:250 000 (Heron 2014).

i.e. Onekakara Group; Late Pleistocene sediments

FEATURE - text field Description of feature type and/or buffer size in this feature class.

late Cretaceous - Paleogene sedimentary rocks;

lK - Pg sedimentary rocks - 200m buffer

A2.0 SOUTH AUCKLAND LANDSLIDE SUSCEPTIBILITY MODEL

This section provides a brief description of the method used to generate a landslide susceptibility model in the South Auckland area, as an example of one approach for delineating landslide susceptibility.

Heron et al. (2012; see main report reference list) described a landslide susceptibility model used in a landslide hazard evaluation of greenfield areas in South Auckland. The landslide susceptibility model uses geology and slope information as inputs and divides the area of each geological unit into 5 susceptibility classes ('Negligible', 'Low', 'Moderate', 'High' and 'Very High') based on the slope angles within that geological unit. The model assumes that geological units have characteristics that controls slope stability and the maximum slope angle that a unit can sustain, and that erosion will cause steep unstable slopes to become less steep and more stable. As a result the slope angles bounding landslide susceptibility classes are different for different geological units. Two models were generated, an initial ‘standard’ model, and a subsequent ‘modified’ model, as described below.

In the initial ‘standard’ model, slopes flatter than 5° and steeper than 45° were extracted and respectively assigned a 'Negligible' and 'Very High' landslide susceptibility classification.

Slopes between 5° and 45° were then overlain with the geology layer and each geological unit was converted to a grid with a slope angle value attached to each cell. For each geological unit the 33.3 and 66.6 percentile slope angles were used as the upper bound for 'Low' and 'Moderate' landslides susceptibility classes respectively. As a result a third of the cells (those with the lowest slopes) were assigned a 'Low' landslide susceptibility, a third (those with the steepest slopes) were assigned a 'High' landslide susceptibility and the remaining cells (the middle third) were assigned a 'Moderate' landslide susceptibility.

The slope model was then analysed for areas adjacent to steep slopes that could be impacted by run-out from landslides forming on slopes above the site, or by undermining (‘collapse’) from landslides forming below the site. All sites within a 30° shadow from the top of a slope were assessed for run-out. Sites which had an average slope angle from the site to the base of a slope greater than 35° were assessed for collapse hazard. Sites identified as having a susceptibility to run-out from or collapse of an adjacent slope were reclassified on the basis of the area of the adjacent slopes that might impact the site.

The results of the ‘standard’ model were then evaluated. The geological units within the study area were classified into three types; those that form erosional landforms, those that form depositional landforms (e.g. volcanic, beach and alluvial deposits) and other units such as construction fill. After a careful assessment of susceptibility class slope limits it was considered that the ‘standard’ model required adjusting as it was probably overstating the susceptibility of the units forming depositional landforms. The class limits were manually defined so that 'High' susceptibility areas within these units coinciding with slopes of less than 15° were reassigned 'Moderate' susceptibility and 'Moderate' susceptibility areas coinciding with slopes less than 10° were reassigned 'Low' susceptibility. These revised slope susceptibility class limits were then used to generate a ‘modified’ model. The results of the ‘modified’ model were considered more reliable than those of the ‘standard’ model.

Analysis of slopes between 5° and 45° shows that for most geological units occurring in that study area, the slopes defining the boundary between 'Low' and 'Moderate' susceptibility classes range from 6.6° to 9°. For the majority of geological units, the slopes defining the boundary between 'Moderate' and 'High' susceptibility classes ranged between 9.9° and 12.8° with the remainder having higher values. Analysis of the spatial extent of those geological units that have a narrow range of slopes defining higher bounds of 'Low' and 'Moderate' susceptibility classes showed that they cover the majority of the modelled area and almost all of the individual greenfield areas. This indicates that the majority of the geological units are present with a similar range of slopes and that within this study area slope is more important than geology when assessing slope instability susceptibility. The adjustments made to the modified model further strengthened this by totally removing the influence of geology from the model for 8 out of 12 geological units in the study area.

An additional processing step was introduced in an attempt to remove or reduce the impact of the imperfections in the original DEM. A majority filter was applied to both the ‘standard’ and ‘modified’ landslide susceptibility models to simplify the result by setting each 3 m cell to the majority value of its contiguous neighbours. This tended to remove single or pairs of cells with values different from most of their immediate neighbours.

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657