Landslides in the Dunedin area resulting from the June 2015 rainstorm

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EXECUTIVE SUMMARY

A severe weather event that affected the Dunedin City district between the 3rd of June 2015 and midday on the 4th of June 2015 (the June 2015 rainstorm) caused flooding and numerous rain-induced landslides. This report catalogues the landslides associated with the June 2015 rainstorm and discusses the factors that may have influenced where, when and why they occurred. A digital database and GIS package accompanies this report.

At least 295 new landslides were catalogued from road inspections, helicopter reconnaissance, Earthquake Commission (EQC) reports, media sources, Dunedin City Council road maintenance logs and field interviews.

A minimum (conservative) estimate of the total amount of slope-forming materials that was mobilised is approximately 150 000 m^3. Landslides are interpreted to largely be shallow-seated, typically 0.5 to 1 m deep, occurring in the soil rather than the underlying bedrock, as is typical for rain-induced landslides. About 88% of the June 2015 landslides occurred on slopes steeper than 12°; those that occurred on slopes gentler than 12° were typically associated with human-modified ground (e.g. road cuttings, fill embankments). There is a considerable general coincidence between the areas affected by landsliding in June 2015 and areas affected in a similarly exceptional rainstorm in March 1994. Despite a notable association between landslide locations and areas underlain by Dunedin Volcanic rocks, this is attributed to a predominance of relatively steep slopes in areas of volcanic rock terrain rather than any direct association with that rock type. Overall, the presence of moderately steep to very steep slopes (>12°; both natural and human-modified slopes) and proximity to areas of previous shallow-seated landsliding are identified as the most significant associations with the distribution of landslides resulting from the June 2015 rainstorm.

The occurrence of three significant landslides was pinpointed as having coincided with peak hourly rainfall intensity, or in the few hours immediately following the peak hourly rainfall, between 3 and 6 pm on the 3rd of June 2015. The rainfall in the month preceding the June 2015 rainstorm was close to normal, suggesting that soil moisture conditions prior to the 3rd of June was not a significant factor associated with the landsliding.

The June 2015 landslides were generated by a rainstorm event that involved peak hourly rainfall intensities exceeding 12 mm, and a cumulative rainfall of as much as 100 mm over 12 hours. Any similar future rainfall event is likely to produce comparable effects; areas with slope angles greater than 12°, or where previous surficial landslides have occurred, are where the majority of future rain-induced landslides can be expected.

Eighty-eight percent of landslide locations from the June 2015 rainstorm occurred within one (or more) of the three single-factor datasets (awareness areas) used to highlight potential landslide susceptibility as provided by GNS Science (Barrell & Smith Lyttle, 2015).

1.0 INTRODUCTION

A prolonged period of heavy rain affected coastal Otago, including Dunedin City urban area, from about midnight on the 2nd/3rd of June 2015 through to around midday on the 4th of June 2015 – referred to as the "the June 2015 rainstorm" hereafter. Rain totalling as much as 189 mm was recorded in the Dunedin City district during that 36 hour period and resulted in high river and groundwater levels, flooding, property damage and rain-induced landslides (Goldsmith *et al.*, 2015) – the latter being the subject of this study. Rain-induced landslides are typically seated at shallow depths (<1 m to 10 m), usually within the soil profile rather than in the bedrock beneath (Crosta & Frattini, 2008) and have been termed 'surficial landslides' (e.g. Glassey *et al.*, 2014). The shallowness of rain-induced landslides means they tend to be of smaller volume than bedrock landslides (Larsen *et al.*, 2010), however, their frequency means they can cause significant economic disruption, such as seen during the June 2015 rainstorm.

In the days following the June 2015 rainstorm GNS Science staff undertook a reconnaissance of Dunedin urban area and its environs to record landslides related to the June 2015 rainstorm (Figure 1). This was followed by a helicopter reconnaissance with Otago Regional Council staff on the 16th of June 2015. The result of the reconnaissance work was to understand that the number of landslides (>100) was comparable to those documented during previous major rainstorms that induced landsliding in the Dunedin area, for example in April 2006 (Glassey *et al.*, 2014; Barrell & Smith Lyttle, 2015) and March 1994 (Stewart, 1996). Subsequently, GNS Science was commissioned by Otago Regional Council to collate and analyse rain-induced landslide information from the June 2015 rainstorm and asses the likely causative factors of the landslides. This report presents that analysis and assessment, and is accompanied by a Geographic Information System (GIS) dataset of landslide information.

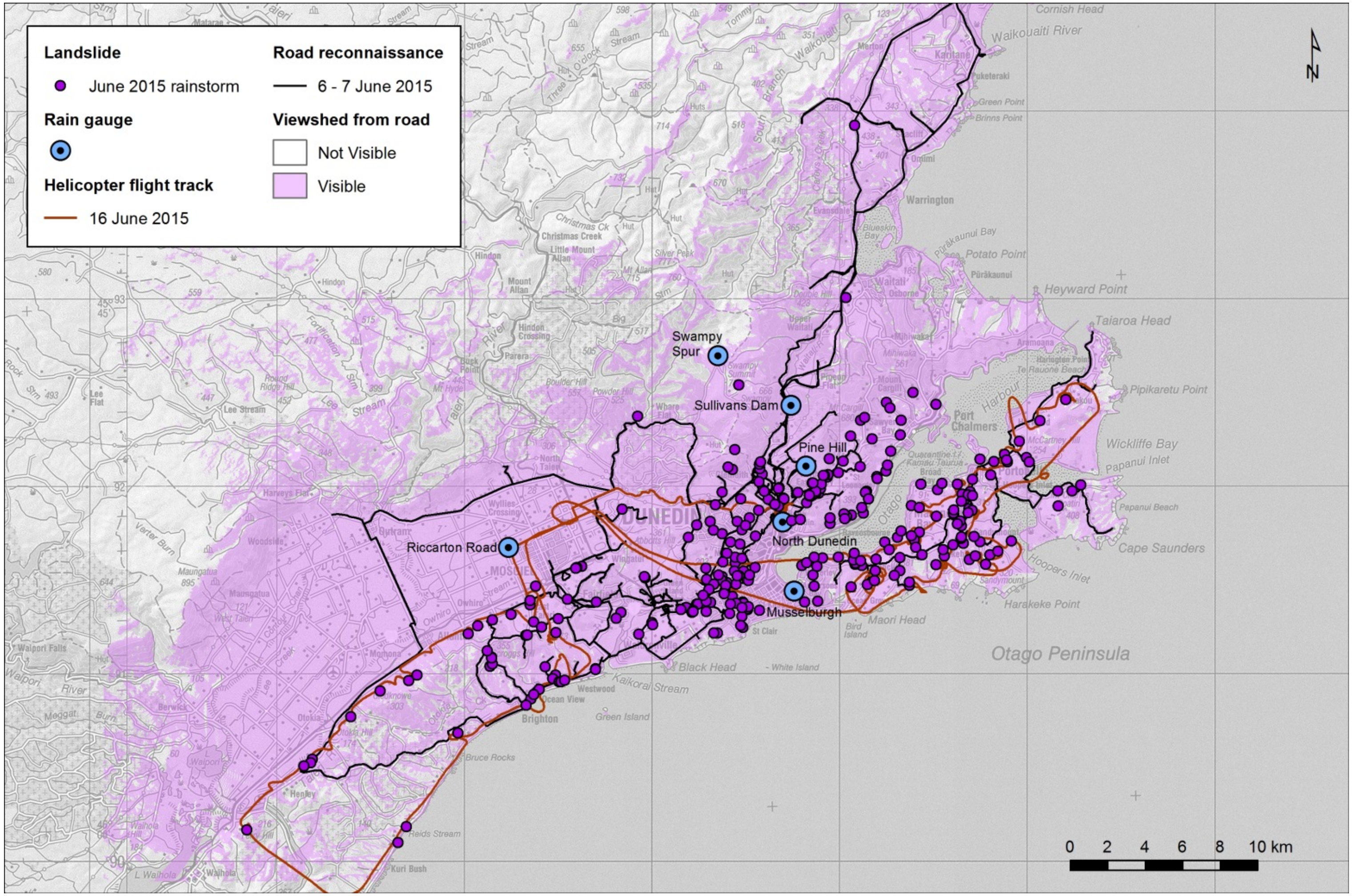

Figure 1 The point location of landslides related to the June 2015 rainstorm. The location of rain gauges and observation paths from car and helicopter are also indicated. The area visible from the vehicle reconnaissance paths was calculated using an ArcGIS tool (Viewshed) and taking into account topography, it shows the maximum viewable distance (pink shading), though in practice, a 1-2 km buffer around the vehicle reconnaissance path and a 5 km buffer around the helicopter flight path is a realistic maximum estimation of the reconnaissance area. Areas not inspected fall outside this calculated view area.

1.1 SCOPE OF WORK

The focus of this work has been to compile a database of landslides from the June 2015 rainstorm and to provide a report discussing the causes of landsliding. The following work programme was agreed upon:

1. Compilation of landslide data from the June 2015 rainstorm, from sources that include vehicle-based inspections, helicopter-based inspections, EQC reports, Dunedin City Council road maintenance records, media reports and field interviews.
2. Production of a GIS database based on the existing Otago Regional Council / GNS Science Landslides Database, along with relevant additional information where available.
3. Prepare a report evaluating the 2015 June rainstorm landslides with respect to rainfall and landscape factors (e.g. slope, geology). The report will include the following information:
    a. Where reconnaissance for landslides occurred but no landslides were observed versus areas that could not be accessed, seen or were not checked.
    b. The relationship of landslide locations to various factors including geology, rainfall, slope, etc.
    c. The relationship of the landslides from the June 2015 rainstorm to previous rain-induced landslides, in particular the March 1994 event.
    d. The correlation between areas identified as potentially susceptible to landsliding in Dunedin City district (Barrell & Smith Lyttle, 2015) and the June 2015 rainstorm.

2.0 LANDSLIDE OCCURRENCE AND DATA

2.1 DATA SOURCES AND ACCURACY

Landslides are a well-known and widely distributed feature of the Dunedin area and have been mapped and recorded at various scales (Benson, 1940; Benson, 1946; Leslie, 1974; McKellar, 1990; Bishop & Turnbull, 1996; Glassey & Smith Lyttle, 2012; Glassey *et al.*, 2014; Goldsmith & Sims, 2014; Barrell & Smith Lyttle, 2015). The most common way of showing a landslide on a map is as an area, whose boundary delineates the position of the landslide margins. Such mapped areas are known as 'polygons' within GIS terminology. Another way of showing a landslide location is as a single point on a map. Although it is rarely stated, it is usually presumed that the point is located at the approximate geometric centre of the landslide area. This does however introduce some locational uncertainty, and provides no information on the size or extent of the landslide. Mapping landslides as point features is usually done for practical convenience, for example during rapid reconnaissance work, e.g. if reconnoitring from a vehicle or an aircraft, because time does not allow the accurate drawing of the landslide extent. For logistic reasons and time constraints, the June 2015 rainstorm landslides were mapped as points, as were those from previous rainstorms in April 2006 and March 1994. The June 2015 rainstorm landslide data were enhanced by the recording of a visual estimate of the size of each landslide that is represented as a single point, along with other information (see Section 2.2).

There are two previous episodes of Dunedin rain-induced landsliding for which sufficient information exists to make a comparison with the June 2015 rainstorm landsliding, one in April 2006 and one in March 1994. Twelve landslide point locations were recorded from the 2006 event with an accuracy of ±50 m: this was from a very limited reconnaissance of Mt Cargill and along State Highway 1 north of Dunedin. The locational accuracy of points in the 1994 dataset is estimated to be no better than ±100 m because the data points were plotted on a 1:50,000 scale topographic map, and digitised from that map. In addition, many of the landslide points were collected during an aerial reconnaissance in a fixed-wing aircraft, which allowed the mapper little time to accurately estimate the point locations using a topographic map. Recent work has focussed on the digital capture and recording of Dunedin landslide information into GIS databases (e.g. Glassey & Smith Lyttle, 2012) and this has been supplemented with GIS-based modelling to delineate areas possibly susceptible to landsliding (Barrell & Smith Lyttle, 2015). As part of the current project, the June 2015 rainstorm-induced landslides were integrated into that existing database structure, facilitating comparison of the June 2015 rainstorm landslides with those from previous rainstorms and with susceptibility models.

Landslide data were recorded by GNS Science staff in the days following the June 2015 rainstorm and with Otago Regional Council staff by helicopter. In total 123 landslides were identified in this manner. The location accuracy of these data is as good as ±10 m in the best cases where the landslide was physically inspected on the ground and location taken using hand-held GPS. In other instances, accuracy is regarded as ±50 m or ±100 m where the location was determined with reference to a topographic map, or viewed from a distance, either on the ground or from the air.

Other sources of landslide location data were the Dunedin City Council road maintenance reports and Earthquake Commission (EQC) claims. The latter are assumed to have a spatial accuracy of ±50 m and remain anonymous. For the road maintenance reports and EQC claims (172 landslides) only a point location was available. Various attributes can be assigned to these locations such as geology, soil depth and slope angle. However, other information such as volume or a photographic record is not available. Where a landslide had been recorded by more than one source (for example road inspection and EQC claim), the source with the higher level of detail was kept. In these ways, all of the most significant landslides (in terms of size and consequence) are regarded as well attributed. In a small number of cases, the time when an individual landslide occurred could be determined from media reports or field interviews with members of the public who heard or saw the movement.

While it is unlikely that every landslide from the June 2015 rainstorm has been recorded, this episode of rain-induced landsliding is the most thoroughly investigated and documented to date for the Dunedin area.

2.2 DATA STRUCTURE

Available information about the landslides from the June 2015 rainstorm has been compiled into a geodatabase that accompanies this report. The **Landslides_point** and **Sources** datasets and the **landslide_source** table within this geodatabase follow the structure established in the existing **DCC_Landslides_ORC** Database created for Otago Regional Council by GNS Science (e.g. Glassey *et al.*, 2014) and will be compatible with that database. These new data should be appended to these specific existing datasets/tables held by the Otago Regional Council and the Dunedin City Council to update existing databases. New data provided with this report are collated in a table, **LandslidePointRelate,** within this geodatabase. This table can be related to the existing **Landslides_point** dataset based on the attribute field **landslide_id**. A dataset derived from these new data (**June2015Landslide_point)** is also included in the geodatabase. Attributes fields for these new data are listed in Table 1 below.

Table 1 Database attributes.

Attribute	Example	Comment
Landslide ID	11400	Unique landslide number
E_NZGD2000	1406764	Location easting
N_NZGD2000	4918911	Location northing
Dimension	10m x 10m x 0.5m	Visually estimated size of landslide area
Area_m^2	100	Calculated from dimension
Volume_m^3	50	Calculated from dimension
Path_length_m	2	Distance moved, estimated in the field
Feature	Shallow colluvium failure	Observer comments
Consequence	Road lane closed	Notes associated damage or cost
Slope Nature	Human modified	Origin of the slope, e.g. human modified or not
Geology	Cover rocks (younger)	Assigned from 1:250,000-scale QMAP GIS
Precision	±10 m	Assessed locational accuracy
Slope Modification	Human	Notes any obvious change made to the slope
Slope Class	1b	Assigned from 8 m cell size DEM
Slope Angle	5 - 12°	Assigned from 8 m cell size DEM
Name	Duke St	Location description
Time of initiation	3 June 2015	Date movement occurred
Last known movement	Jun-15	Date last known movement occurred
Source Report	Martin & Smith Lyttle, 2015	Report where landslide is recorded
Map Source	GNS/Simon Cox	Observer
Point Type	landslide	Type of observation made
Soil depth code	Deep	Assigned from S-map dataset GIS
Soil Depth (cm)	>100	Assigned from S-map dataset GIS
Geologically Sensitive Areas	no	Assigned from polygons in Barrell & Smith Lyttle (2015)
Slope Awareness Areas	yes	Assigned from polygons in Barrell & Smith Lyttle (2015)
Landslide Awareness Areas	no	Assigned from polygons in Barrell & Smith Lyttle (2015)
Overlaps with areas susceptible to landsliding	Yes	Assigned from polygons in Barrell & Smith Lyttle (2015)

2.3 RAINFALL

Between approximately midnight on 2nd/3rd June 2015 and midday on the 4th of June 2015, as much as 189 mm of rainfall was recorded at several rain gauges in the Dunedin area and farther afield (Figure 1; Table 2). Cumulative rainfall during this period was measured from low altitude sites in the Dunedin urban area (e.g. North Dunedin; Table 2) and the Taieri Plain (e.g. Riccarton Road; Table 2), and at higher altitude sites on the hills immediately surrounding, and forming part of, the Dunedin urban area (e.g. Pine Hill; Table 2; Goldsmith *et al.*, 2015). This was the second wettest June at the Musselburgh rain gauge since records began in 1918 (NIWA, 2015b) and is estimated to be a one in 63 year rain event (Goldsmith *et al.*, 2015).

The month preceding the June 2015 rainstorm was 'near normal' for Dunedin with 57 mm of rain recorded at Musselburgh (NIWA, 2015a). The daily rainfall totals and the cumulative rainfall totals for Pine Hill are shown in Figure 2 and highlight the exceptional nature of the event.

Table 2 Rain gauge summary.

Station		Cumulative Rainfall (mm)		Peak 1 hr Intensity	
		within 24 hours*	within 36 hours#	(mm)	Time‡
North Dunedin	Low altitude	152	163	13	12-1 pm
Musselburgh	Low altitude	136	144	11.8	11-12 pm
Sullivans Dam (Water of Leith)	Hills surrounding Dunedin	159	175	14.5	3-4 pm
Pine Hill (Water of Leith)	Hills surrounding Dunedin	168	184	15	2-3 pm
Swampy Spur (Silver Stream)	Hills surrounding Dunedin	162	189	12	3-5 pm
Riccarton Road (Silver Stream)	Taieri Plain	162	167	22.5	3-4 pm
Deep Stream Ỵ	Farther afield	84.5	89	11	7-8 am

* The 24 hour period of the 3rd of June 2015

The 36 hour period of the 3rd of June to midday on the 4th of June 2015

‡ The peak 1 hour intensities all occurred on the 3rd of June 2015

Ỵ The Deep Stream rain gauge is located ~40 km northwest of the Dunedin urban area and highlights the lesser amounts of rain that occurred away from the coastal areas

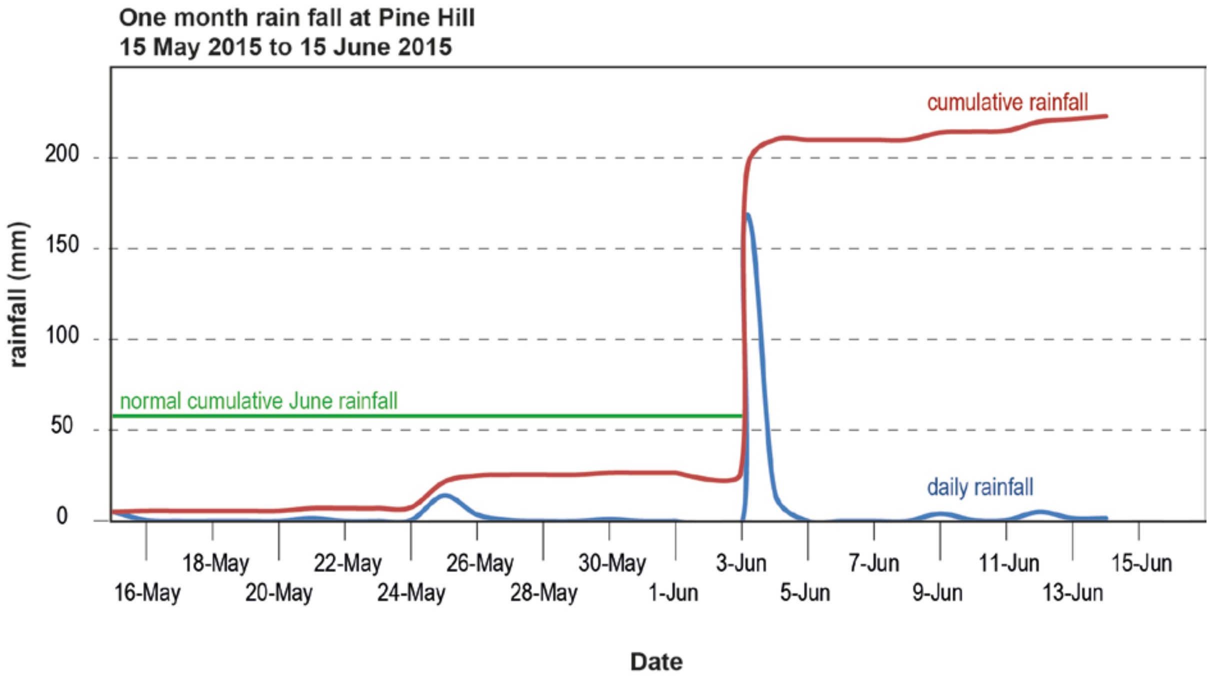

Figure 2 Rainfall recorded at Pine Hill (see Figure 1 for the location) in the weeks preceding and following the June 2015 rainstorm. The 'normal cumulative June rainfall' is calculated from rainfall data at the Musselburgh rain gauge (see Figure 1 for the location) between 1981 and 2010 (NIWA, 2015b). The cumulative rainfall (red line) and daily rainfall (blue line) highlight that the June 2015 rainstorm total far exceeded the normal cumulative rainfall for the month of June (green line) in Dunedin.

2.4 LANDSLIDE FEATURES

A total of 295 rain-induced landslides were identified as having occurred as a result of the June 2015 rainstorm (Figure 1). Landslides have particular concentrations in several localities, for example the hill suburbs around the Dunedin urban area from St Clair to Mornington to Roslyn, also in North East Valley, Leith Valley, on the Otago Peninsula, on and around Scroggs Hill and Saddle Hill and around Ocean View. In several areas inspected from car (predominantly), foot or helicopter, no landslides were observed (Figure 1). Areas that were not inspected are indicated on Figure 1. An ArcGIS tool (Viewshed) was used to determine all of the locations visible along the vehicle reconnaissance paths (pink shading on Figure 1). The Viewshed calculation took into account topography, but not vegetation or the reasonable distance over which an average observer could be expected to make accurate identifications of a landslide. In practice, the area inspected for landslides is at most 1-2 km from the vehicle reconnaissance paths and 5 km from the helicopter flight path shown on Figure 1.

The landslide occurrences that were recorded by GNS Science had their volume visually estimated, and this process identified an aggregate volume of landslide material of about 150 000 m^3. The area of each landslide was also estimated and totalled some 117 000 m^2. Both total volume and total area estimates should be considered a conservative, lower limit because the landslide locations that came from the EQC and from the road maintenance records did not record volume or area and could not contribute to the calculated totals.

The depths of most of the landslides were interpreted to be shallow, typically between 0.5 and 1 m deep, seated in the soil profile rather than the underlying bedrock. There was a coincidence between slope modification, for example road cuttings or fill embankments, and landslide location. Photographs of many of the landslides are included with the GIS data package. Landslides that occurred on farmland (for example the Otago Peninsula) tended to be larger in volume and to have longer runouts. The path lengths of these runouts were typically as much as 100-200 m, but in rare instances up to 700 m runouts were observed. Where a runout hit a gully obliquely, the landslide runout tended to divert downstream along the gully. Where a runout reached a gully nearly perpendicularly, the landslide runout tended to stop.

3.0 GEOLOGICAL AND LANDFORM INFLUENCES ON THE JUNE 2015 RAINSTORM LANDSLIDES

3.1 SLOPE

Slope angle was calculated from a digital elevation model (DEM) for the coastal sector of the Dunedin City district by Barrell & Smith Lyttle (2015; Figure 3). A general threshold slope angle for the occurrence of landslides on Otago Peninsula of ≥12° was proposed by Leslie (1974) and Barrell & Smith Lyttle (2015) considered this to be a useful value to apply more widely across the coastal area of Dunedin. Barrell & Smith Lyttle (2015) divided slopes equal to or steeper than 12° into three classes (Class 2: 12-20°; Class 3: 20-35°; Class 4 >35°), and subdivided flatter areas into Class 1a (0-5°; flat or nearly flat ground) and Class 1b (5-12°; gently sloping ground). In discussing the slope angle in relation to landslide occurrence, several caveats should be noted. Firstly, that landslide location is recorded as a point, but the landslide runout may extend over adjoining slopes of different classes. Secondly, that landslide point locations, such as from the 1994 event, are estimated as no more accurate than ±100 m and thus these locations may not coincide accurately with calculated slope class values. Thirdly, there are likely to be many instances of small landslides that occurred on locally steep angle slopes (for example stream banks or road cuttings; see Figure 4), that are of too small an extent to be adequately captured in the interpolations using the 8 m cell size DEM. For these reasons, we conducted the analysis using the ‘Slope Awareness Area’ dataset of Barrell & Smith Lyttle (2015), in which a 100 m buffer is applied around the perimeter of each area of slope classes 2 to 4 (Figure 3). Superimposition of the landslide data on the Slope Awareness Area dataset illustrates that 88% of landslides from the June 2015 rainstorm occurred on slopes that were moderately steep to very steep (Class 2 to Class 4; i.e. slopes >12°). Bearing in mind these caveats, and taking account of personal observations, many of the landslide points that are in areas classed as flat or nearly flat coincided with locally modified slopes that are >12° (e.g. Figure 4). It appears that slope angle was a major controlling factor to landslide occurrence during the June 2015 rainstorm.

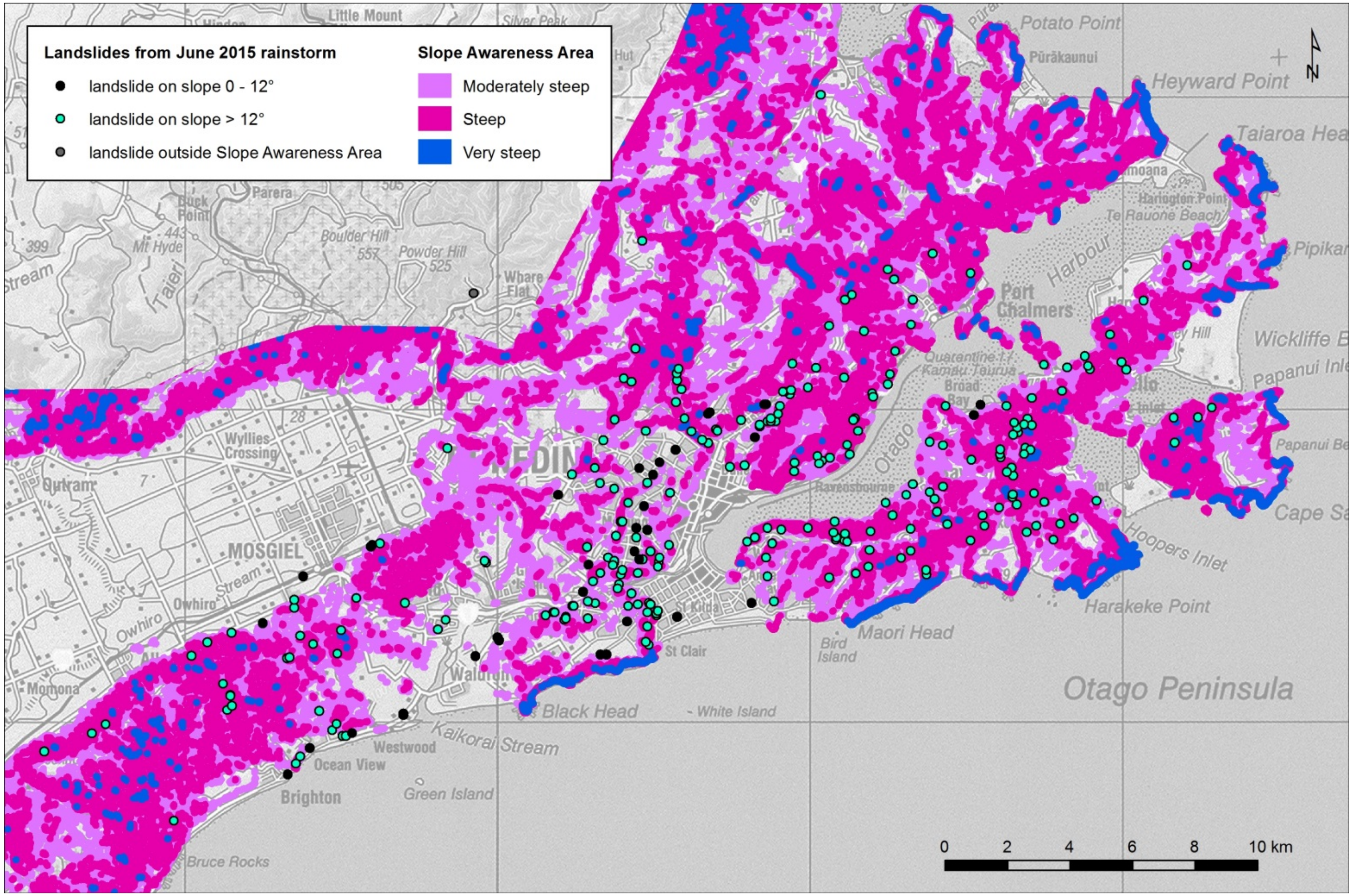

Figure 3 Slope Awareness Areas, derived from slope angle classes 2, 3 and 4 (all >12°) from the generalised slope angle polygon data set. The plot includes 100 m wide buffers on each Slope Awareness Area polygon, displayed in the same colour as the awareness area. Uncoloured areas correspond to slope angles <12°. The background image is the Topo250 topographic map, rendered in greyscale. The locations of landslides from the June 2015 rainstorm are shown for comparison.

Figure 4 An example where the general slope classification is Class 1 (<12°), but locally the slope is >12°. In this view looking southwest from Morris Road in Fairfield, a stream channel bank experienced landslide movement associated with the June 2015 rainstorm, most likely due to the presence of a steep (>12°), human-modified bank beside the stream channel.

3.2 GEOLOGY

As noted in Section 2, most of the June 2015 rainstorm landslides are thought to be of the surficial type, seated within the near-surface soil materials rather than in the underlying bedrock. Geological maps depict the nature of the underlying bedrock, and generally omit information on the near-surface soils. Nevertheless, it was thought useful to make a comparison between landslide point locations and the underlying geology, as soil types (and hence soil properties) are strongly influenced by the rock type from which it is sourced. In this comparison, the 'seamless' 1:250 000 scale QMAP geological dataset (Bishop & Turnbull, 1996; Heron, 2014) was used.

A full outline of the geological make-up of the near-coastal parts of the Dunedin City district is provided by Barrell & Smith Lyttle (2015), and interested readers should refer to that report for more information. In that report, the geological sequence is subdivided into 5 general components (units). The same subdivision was followed in this report and the units are listed in the geological classification column of Table 3. The subdivision comprises, from oldest to youngest: basement rocks, which in the Dunedin area consists of schist; cover rocks (older); cover rocks (younger); Dunedin Volcanic rocks, and; poorly consolidated sediments comprising all deposits of Holocene and Pleistocene age. The cover rocks (younger) consist of Otakou Group (Goodwood Limestone, Caversham Sandstone) and Kekenodon Group (Concord Greensand, Scroggs Hill Limestone). The cover rocks (older) consist of Onekarara

Group (Burnside Mudstone, Green Island Sand, Abbotsford Formation, Wangaloa Formation, Taratu Formation) and Matakea Group (Henley Breccia). Landslides from the June 2015 rainstorm coincided with areas of differing types of rock as summarised in Table 3, but coincided most commonly with Dunedin Volcanic rocks (62% of the occurrences), even though Dunedin Volcanic rocks make up only 14.1% of the survey area (for consistency, the area calculated is the same as used in Barrell & Smith Lyttle, 2015). The common occurrence of landslides with volcanic rocks (Table 3) most likely reflects that this rock type is associated with steep slopes, because most of the landslides are interpreted to have occurred in the soil profile rather than the underlying rock. Thus, gravity rather than rock type, is considered to a more important factor in the observed landsliding.

Table 3 Assessment of the relationship between geological units and landslide points from the June 2015 rainstorm data set.

Geological Classification	% by area of analysis area	Geological description	#	% of landslide points
Dunedin Volcanic rocks	14.1	Dunedin Volcanic Group	183	62
Cover rocks (younger)	2.0	Neogene sedimentary rocks. Otakou Group and Kekenodon Group	42	19
Poorly consolidated sediments	13.8	Quaternary sediments	31	10
Basement rocks	60.6	Mesozoic greyschist rocks. Caples Terrane and Rakaia Terrane	21	7
Cover rocks (older)	9.5	Cretaceous-Paleogene sedimentary rocks. Onekarara Group and Matakea Group	18	2

Barrell & Smith Lyttle (2015) identified areas they termed ‘Geologically Sensitive Areas’ (see that report for more information). These highlight the locations of potentially unstable bedrock formations. No meaningful relationship is expected between surficial landslides seated in overlying soils and the Geologically Sensitive Areas, and this is confirmed by only 19 of the 295 landslides (6%) coinciding with a Geologically Sensitive Area (Figure 5).

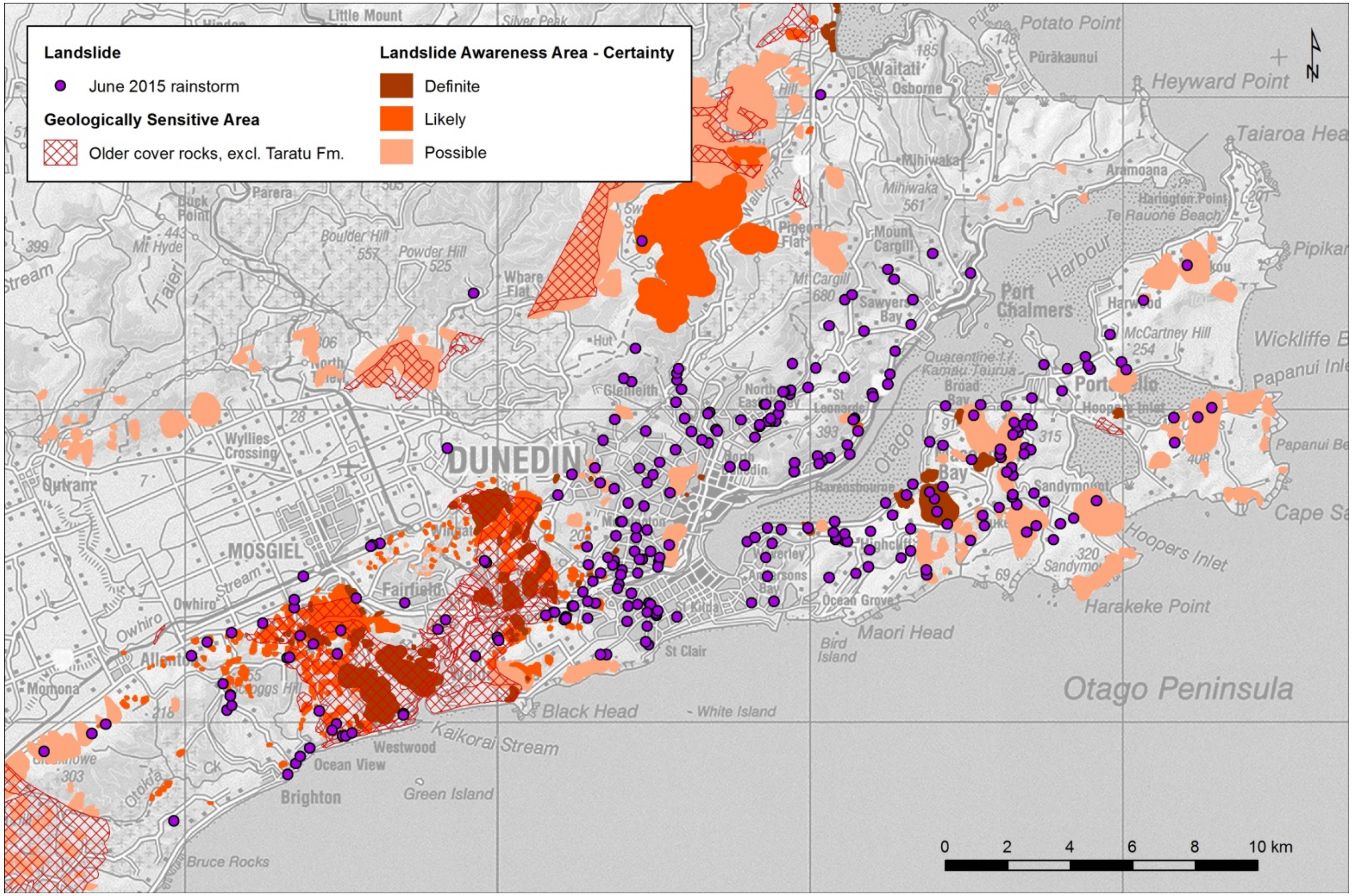

Figure 5 A map showing Landslide Awareness Areas and Geologically Sensitive Areas (Barrell & Smith Lyttle, 2015). Along with Slope Awareness Areas (Figure 3), these three single-factor datasets provide information on areas potentially susceptible to landsliding. The landslide locations for the June 2015 rainstorm are shown for comparison. Excl. = excluding.

3.3 SOIL

Barrell & Smith Lyttle (2015) undertook an analysis of soil depths in relation to the locations of landslide points. For the purposes of analysis, the Grow Otago (Grow_Otago) and the national S-map (S-map) databases of soil information were examined, and they decided to use the S-map dataset for the analysis due to its more extensive coverage across hill terrain. The S-map database quantifies soil depth in 4 classes; deep (>100 cm), moderately deep (100-45 cm), shallow (45-20 cm) and very shallow (<20 cm) soils. More detail is provided by Barrell & Smith Lyttle (2015) and interested readers should refer to that report for further information. That report obtained an inconclusive result from the comparison between landslide point locations and soil depth. Although the large majority of landslide points (88%) coincided with areas mapped as moderately deep or deep soils, further analysis showed that most (67%) of the hill terrain steeper than 12° was mapped as having moderately deep or deep soils. This made it difficult to discriminate between the relative influences of soil depth versus slope angle on the occurrence of landslides.

The analysis described by Barrell & Smith Lyttle (2015) was rerun using the 295 landslide points from the June 2015 rainstorm. Nine landslides (3%) occurred at locations outside of the S-map soil coverage, and so no assessment could be made about the possible influence of soil depth. Of the 295 landslide points, 85% occurred in areas mapped as having moderately deep or deep soils. This shows remarkable similarity to the findings of the Barrell & Smith Lyttle (2015) report, while noting the caveat that it remains difficult to distinguish between the potential influences of soil depth and slope angle.

3.4 PRE-EXISTING LANDSLIDES

3.4.1 Comparison with previous rain-induced landslide episodes in Dunedin

The March 1994 rain-induced landslides were, prior to this report, the most thoroughly documented episode of rain-related slope instability in the Dunedin area. A total of 187 landslides were identified as having resulted from the 1994 rainstorm. Figure 6 shows, in general, that landslides from the June 2015 rainstorm occurred in similar areas to those from the 1994 rainstorm. The observation and recording of landslides from the 1994 rainstorm was less comprehensive than in 2015, so where landslides were recorded from the June 2015 rainstorm but not from the 1994 event (for example at Ocean View), it is interpreted as a null result (i.e. the location was not observed in 1994) rather than a nil result (i.e. the site was observed but no landslides were noted).

Some 78.5% of landslides from the 1994 event occurred on Class 2 slopes or above (i.e. >12°), and slope angle was interpreted as a key factor in the location of rain-induced landslides during the 1994 event (Barrell & Smith Lyttle, 2015). Only a limited number of observations were made from the 2006 rain-induced landslide event in Dunedin; of these some 84% occurred on Class 2 slopes or above. The coincidence of landslides from the June 2015 rainstorm with the March 1994 rain-induced landslides suggests re-activation of pre-existing landslides was an important factor controlling the location of landslides during the June 2015 rainstorm.

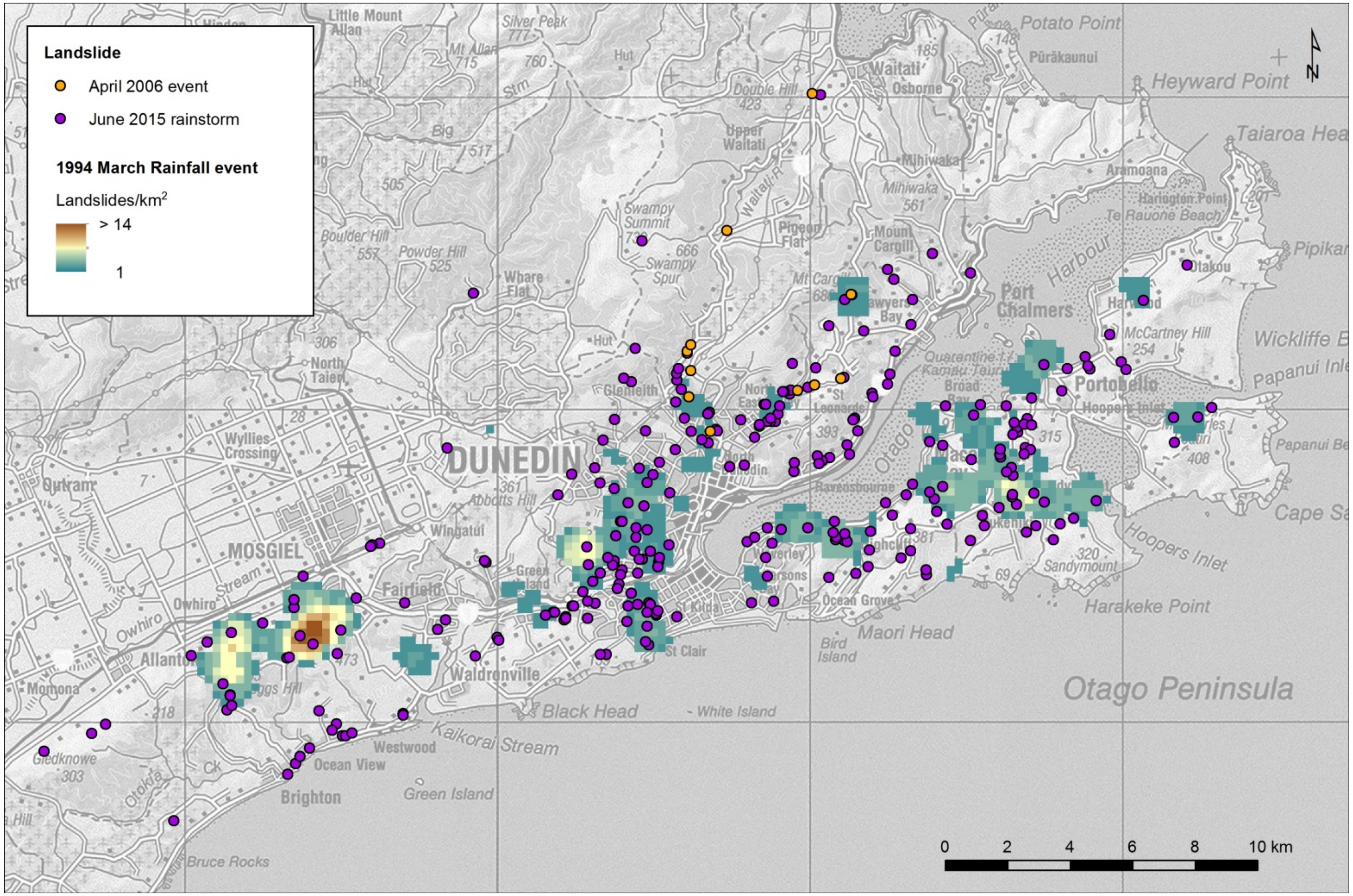

Figure 6 The frequencies of recorded landslides from March 1994 are shown as a density map. The locations of landslides from the June 2015 rainstorm and from the 2006 rainstorm are shown for comparison. There are notable similarities between the location of landslides from 2015 and 1994.

3.4.2 Existing landslide areas

Barrell and Smith Lyttle (2015) used mapped landslide polygons to define what were termed 'Landslide Awareness Areas', which comprise mapped landslide polygons with 'buffers' generated around their perimeters (see that report for more information). Although the landslide polygons for the most part represent landslides seated in the underlying bedrock, and thus are not directly comparable to the rain-induced landslides that are largely of the surficial type seated within near-surface soils, it was thought useful to make a comparison between the Landslide Awareness Areas and the June 2015 rainstorm landslides (Figure 5). That comparison highlights, as expected, that there is no particular association between the landslide points and the larger landslide areas.

4.0 DISCUSSION

Rainfall in the month preceding the June 2015 event fits ‘near normal’ parameters described by NIWA (NIWA, 2015b) and the rainfall recorded at Pine Hill gauge (Figure 2) shows that some parts of the city had experienced below-average rainfall. This dry month preceding the June 2015 rainstorm implies that soil moisture conditions were likely to be low, relative to average June values, and precursory soil moisture was unlikely to have been an exacerbating factor in landslide triggering. The cumulative rainfall across the city was broadly comparable across all sites, irrespective of altitude, in contrast to previous rainfall episodes where significant variations occurred (Goldsmith *et al.*, 2015; Figure 7a and b). In detail, the hourly rain intensity on the 3rd of June for the low-altitude rain gauge sites at Musselburgh and North Dunedin peaked earlier (midday to 1 pm) than at rain gauges in hill country north of the city centre and on the Taieri Plain (3 pm to 5 pm; Figure 7b). As a result, the cumulative rainfall total at Musselburgh was comparable to other rain gauge sites until 2 pm on the 3rd of June (Figure 7a), after which the cumulative rainfall trend flattened and the 36 hour cumulative total at Musselburgh was 23 mm less than the nearest value (Riccarton Road gauge) and 31 mm less than the next nearest value (Sullivans Dam). In North Dunedin, the cumulative rainfall was comparable to cumulative rainfall totals recorded at other rain gauges to around 9 pm (3rd June; Figure 7a), and after 36 hours the cumulative total was only 4 mm and 12 mm less than the 36 hour cumulative totals recorded at Riccarton Road and at Sullivans Dam.

The timings of three significant landslides have been pinpointed from field interviews and media reports and they provide some constraint to the relationship between rainfall and landsliding (Figure 8). A landslide on the northwestern, Pine Hill, side of North East Valley undermined house foundations at 3 pm (3rd June 2015) causing severe structural damage to the property (Elder, 2015). This landslide coincided with peak hourly rainfall intensity recorded at the Pine Hill gauge (15 mm; Figure 8). In The Glen, a central Dunedin suburb, a landslide occurred near 6 pm (±1 hour) causing one property to be evacuated and coincided with a 2-hour period of 12 mm per hour rainfall, 2-3 hours after the peak hourly rainfall was recorded at the Pine Hill gauge (Figure 8). On Highcliff Road on the Otago Peninsula, two cars overturned after driving into a hole caused by a landslide undercutting the roadway (Morris, 2015). The road failure occurred between 5 and 6 pm, 3-4 hours after the peak hourly rainfall intensity recorded at the Pine Hill gauge (Figure 8). The timing of these three significant landslides overlaps with peak, and immediately post-peak, hourly rainfall intensities. There appears to be a notable association between peak rainfall intensity and when significant landslides occurred.

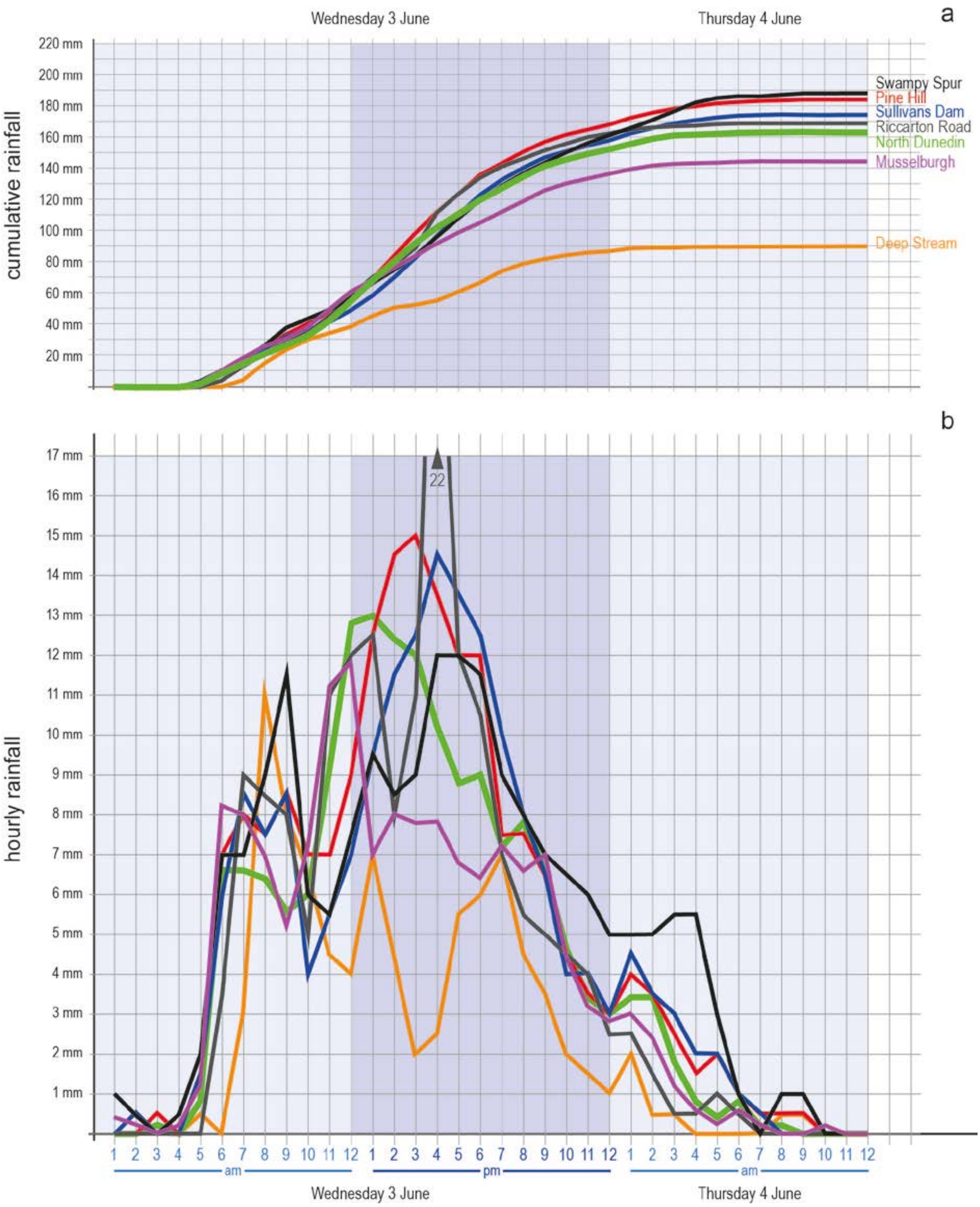

Figure 7 The cumulative (a) and hourly (b) rainfall data from several rain gauges in the Dunedin area for the June 2015 rainstorm. The rain gauge locations are shown in Figure 1.

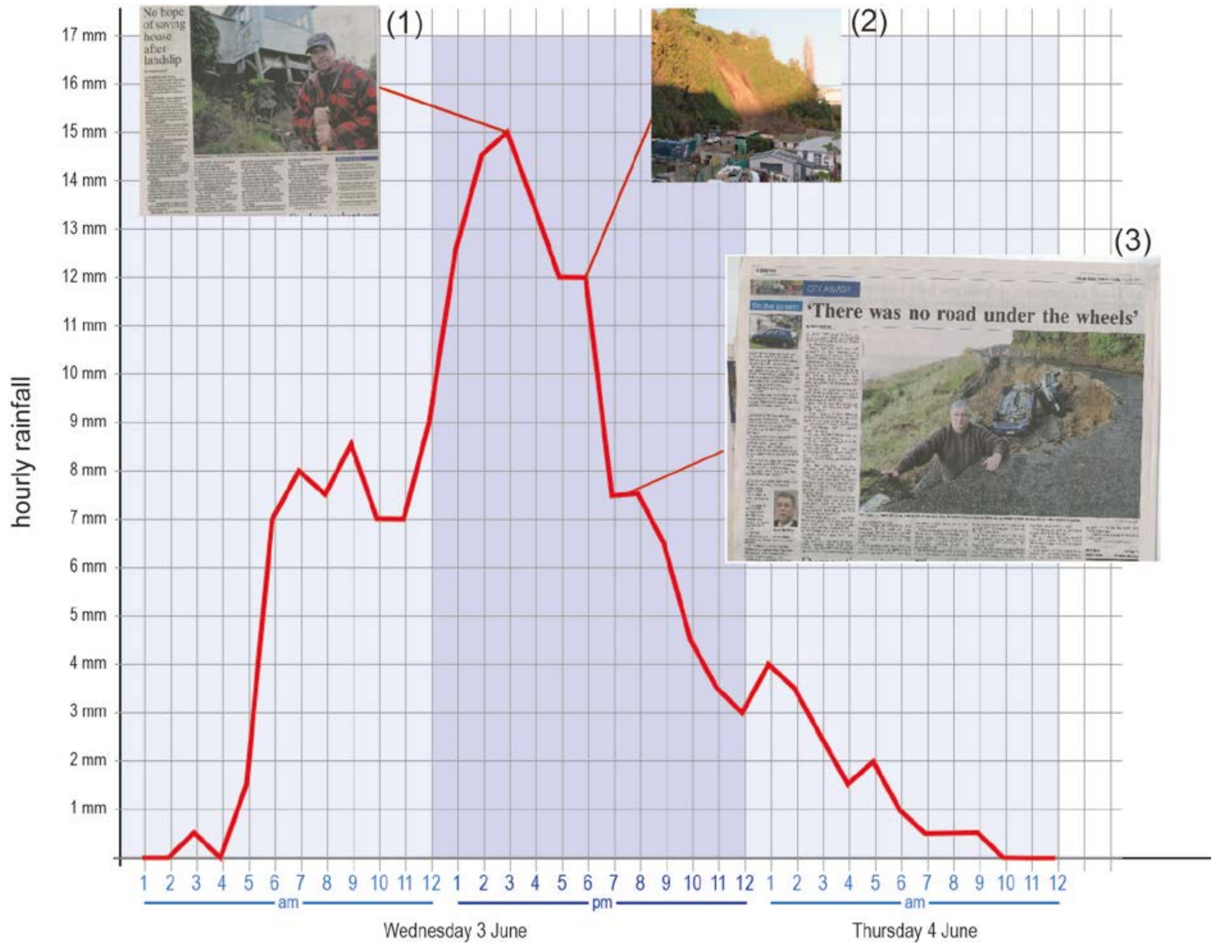

Figure 8 The timing of significant landslide events in relation to hourly peak rainfall recorded at the Pine Hill gauge. These three landslides occurred at the same time as, or in the few hours immediately after, peak rainfall. (1) Pine Hill landslide (Elder, 2015); (2) The Glen landslide (inspection from the road and interviews); (3) Highcliff Road landslide (Morris, 2015).

Landslides from the June 2015 rainstorm coinciding with a Class 1 Slope Awareness Area (<12°) were very commonly associated with human-modified ground, where the slope angle in the immediate vicinity of the landslide was >12°. Some 88% of landslides from the June 2015 rainstorm occurred on slopes >12° (Figure 3), and slope angle, hence gravity, appears to be a dominant factor in controlling where landslides occurred. There was also a propensity for landslides from the June 2015 rainstorm to have occurred in areas of previous landslide activity, as can be seen in the comparison with landslide data from the March 1994 rainstorm (Figure 6). Soil depth does not appear to have been a notable factor in landslide location.

5.0 SUMMARY AND CONCLUSIONS

During the June 2015 rainstorm as much as 189 mm of rainfall was recorded in a 36 hour period on the 3rd of June through to about midday on the 4th of June. The heaviest rainfall occurred between 11 am and 5 pm on the 3rd of June. Peak hourly rainfall of between 11 and 15 mm was recorded at several rain gauges, with 22.5 mm recorded on the Taieri Plain between 3 and 4 pm. Rain-induced landslides, the subject of this study, resulted from this exceptional rainfall, classified as a once in 63 year event.

At least 295 landslides were observed, and mobilised at least 150 thousand cubic metres of soil (a conservative, lower estimate). Most, if not all, of the landslides are interpreted to be surficial landslides seated within the soil profile, rather than within the underlying bedrock. The most notable association between landslide locations and underlying geology is with Dunedin Volcanic rocks. Although these rocks occur in only 14% of the assessment area, 62% of the landslides occurred on that rock type. However, because most of the movements are thought to have occurred in the soil rather than the underlying rock, this correlation is attributed to a predominance of relatively steep slopes in areas of volcanic rock terrain rather than a direct association with that rock type.

The time of occurrence of three significant landslides coincided with peak rainfall, or a several-hour interval immediately following peak rainfall between 3 and 6 pm. Rainfall for the month preceding the June 2015 rainstorm was ‘near normal’ for Dunedin, with some rain gauge sites recording slightly below-average rainfall, which suggests that preceding ground moisture conditions were relatively low.

At least 88% of landslides occurred on slopes steeper than 12°, and those that occurred on slopes gentler than 12° were typically associated with human-modified ground (e.g. road cuttings, fill embankments). There is a strong correlation between landslide occurrence from the June 2015 rainstorm, steep slopes and previously recorded shallow-seated landslides. Given that cumulative rainfall totals were fairly uniform across the Dunedin area, it is slope angle and previous shallow-seated landslide occurrence that most strongly indicates where the landslides occurred. The locations of 88% of the landslides during the June 2015 rainstorm coincided with one or more of the three ‘awareness areas’ previously identified by GNS Science for the Dunedin area.

The June 2015 rainstorm event involved peak hourly rainfall intensities exceeding 12 mm, in conjunction with a cumulative rainfall of as much as 100 mm over 12 hours, and generated numerous landslides. It is reasonable to assume that should such rainfall conditions be repeated, much surficial landsliding is to be expected. Areas previously identified as possibly susceptible to surficial landsliding (Barrell & Smith Lyttle, 2015), i.e. with slope angles greater than 12°, or areas where previous, surficial landslides have occurred (this study), are likely to be good approximations of where future landslides would be concentrated.

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