The Natural Hazards of South Dunedin

July 2016

Otago Regional Council
Private Bag 1954, Dunedin 9054
70 Stafford Street, Dunedin 9016
Phone 03 474 0827
Fax 03 479 0015
Freephone 0800 474 082
www.orc.govt.nz

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Report writers:	Michael Goldsmith, ORC Natural Hazards Manager
	Sharon Hornblow, ORC Natural Hazards Analyst
Reviewed by:	Gavin Palmer, ORC Director Engineering, Hazards and Science
External review by:	David Barrell, Simon Cox, GNS Science, Dunedin

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1. Summary

This report describes the environmental and community setting of the South Dunedin plain. The physical characteristics of the plain include its low-lying topography, underlain by poorly-consolidated sediment (mainly sand and silt), its proximity to the ocean and harbour, a shallow water table with strong connectivity between sea and groundwater, and an exposure to heavy rainfall events. The plain is vulnerable to natural processes which occur reasonably frequently (such as coastal storms),[1] and also events which occur rarely but have significant consequences (such as major earthquakes on nearby faults).[2] The South Dunedin plain is densely populated, with approximately 10,000 permanent residents, and contains infrastructure and other assets which are important at a local, district and regional level.

The physical characteristics of the plain mean it can be affected by water ponding on the surface (i.e. flooding) and it is this hazard which poses the greatest risk to community wellbeing, infrastructure and other assets. The most recent example of major flooding was in June 2015, as a result of heavy rainfall, surface runoff, and a corresponding rise in groundwater. However, this report shows that there are a number of naturally occurring physical processes and human activities which together, or separately, could affect flood hazard on the South Dunedin plain. These are listed below, along with a summary of observed trends, future predictions, and interdependencies with other factors. A summary table on the following page highlights the wide range of factors which can influence flood hazard, and that future changes in mean sea level, climate and groundwater level are the processes most likely to exacerbate the effects of this hazard.

This report shows how these effects will vary across the plain, with some areas likely to be affected sooner than, or to a greater extent, than others.

Figure 1. Flooding on the South Dunedin plain, 4 June 2015. Source: Otago Daily Times.

[1] See ORC, 2015
[2] See Barrell et al., 2014

Factors which can influence flood hazard	
Heavy rainfall	• Many recorded instances of rainfall leading to surface flooding.[3] • Heavy rainfall events have occurred frequently over the last decade. • Potential for storm events to bring heavier rainfall, due to effects of climate change.
Sea level	• Records show mean sea level has been rising at Dunedin since 1900, and the rate of global sea level rise is predicted to increase. • Further increases in mean sea level would translate into a rise in the mean groundwater level. • Groundwater level fluctuates (by up to 0.5 m near the coast) on a twice-daily cycle in response to normal ocean tides.
Ground-water	• There is already a shallow water table beneath South Dunedin. • An increase of the median annual groundwater levels will, in time, result in permanent / intermittent surface ponding on parts of the plain. • Higher groundwater levels would mean that surface ponding in response to rainfall or elevated sea levels would occur more frequently.
Ground subsidence	• There is some evidence of a decrease in land elevation over time across the wider Dunedin area, in the vicinity of 1 mm/year.[4] • Consolidation of sediment beneath the South Dunedin plain may also contribute to an overall reduction in land elevation. • If ground subsidence is occurring, then the effects of sea level rise and heavy rainfall will be further compounded, and be felt sooner than expected.
Storm and wastewater networks	• Groundwater seeps into the aged storm and wastewater pipes beneath the plain, which drain (or are pumped) to the sea, suppressing the water table. • Much of this network is due for replacement, which would reduce seepage of groundwater into pipes. Groundwater level could increase as a result. • The residual risk should the pumping system(s) fail is large, with significant groundwater ponding likely to occur through Tainui and Musselbrough areas, even on a dry, summer day.
Shoreline change	• An overall trend of shoreline retreat has been observed along much of the St Kilda / St Clair dune system, although some accretion has occurred towards Lawyers Head. • Extensive flooding on the plain would occur if erosion of the dune system meant it could not provide a buffer against direct inundation from the sea. Tsunami and storm surge events could damage and erode the dunes extensively.
Seismic	• There are several known or suspected geological faults in the Dunedin area which may have a potential to generate large earthquakes. • Large earthquakes could result in increased flood hazard on the South Dunedin plain, due to liquefaction-related land subsidence or direct, sudden, changes in land elevation relative to sea level.[5]

[3] The June 2015 flood was estimated by insurer IAG to have social and economic costs of up to $138 million, based on research commissioned from Deloitte Access Economic by the Australian Business Roundtable for Disaster Resilience and Safer Communities (Davies, 2016, pers. comm., 7 June).
[4] Recent research, as yet unpublished and subject to peer review.
[5] Other effects of large earthquakes may include damage to buildings and infrastructure, particularly buried services such as freshwater supply and storm and wastewater pipes.

2. Environmental setting

2.1. Geographical setting

The South Dunedin plain is located in the Dunedin City District, between the Otago Harbour upper basin and the Pacific Ocean, and comprises a large flat area of approximately 600 ha (6 km^2), most of which is less than 3 metres above mean sea level (MSL).[6] The more elevated parts of the plain are generally on the margins, and include parts of the suburbs of Caversham and Forbury in the northwest, St Clair to the southwest, the commercial district to the northeast, and the dune system to the south (Figure 2 and Figure 3). The lowest-lying residential area is in the southeast (parts of the suburbs of Tainui and Musselburgh), with other low-lying land scattered throughout the suburbs of St Kilda and South Dunedin, and adjacent to Forbury Park Raceway.

The major localities and the topography of the South Dunedin plain are shown in Figure 3. With the exception of the Chisholm Links Golf Club, and other reserves and playing fields, the area is entirely urban. A description of the community setting is provided in section 5.

[6] The local MSL datum is Dunedin Vertical Datum – 1958 (DVD-58). Section 7 provides an explanation of this and other technical terms used in this report. Unless otherwise stated, all elevations referred to in this report are relative to this datum.

Figure 2. The South Dunedin plain, 16 June 2015. Top: the western part of the plain, including the suburbs of St Clair, Forbury and Caversham. Bathgate and Tonga parks can be seen in the centre-left of the image. Middle: the central plain, including the South Dunedin commercial area and St Kilda. Lower: the eastern plain, including Tainui and Musselburgh, with Bayfield Park and Andersons Bay/Otago Harbour in the foreground. Source: Alan Dove Photography.

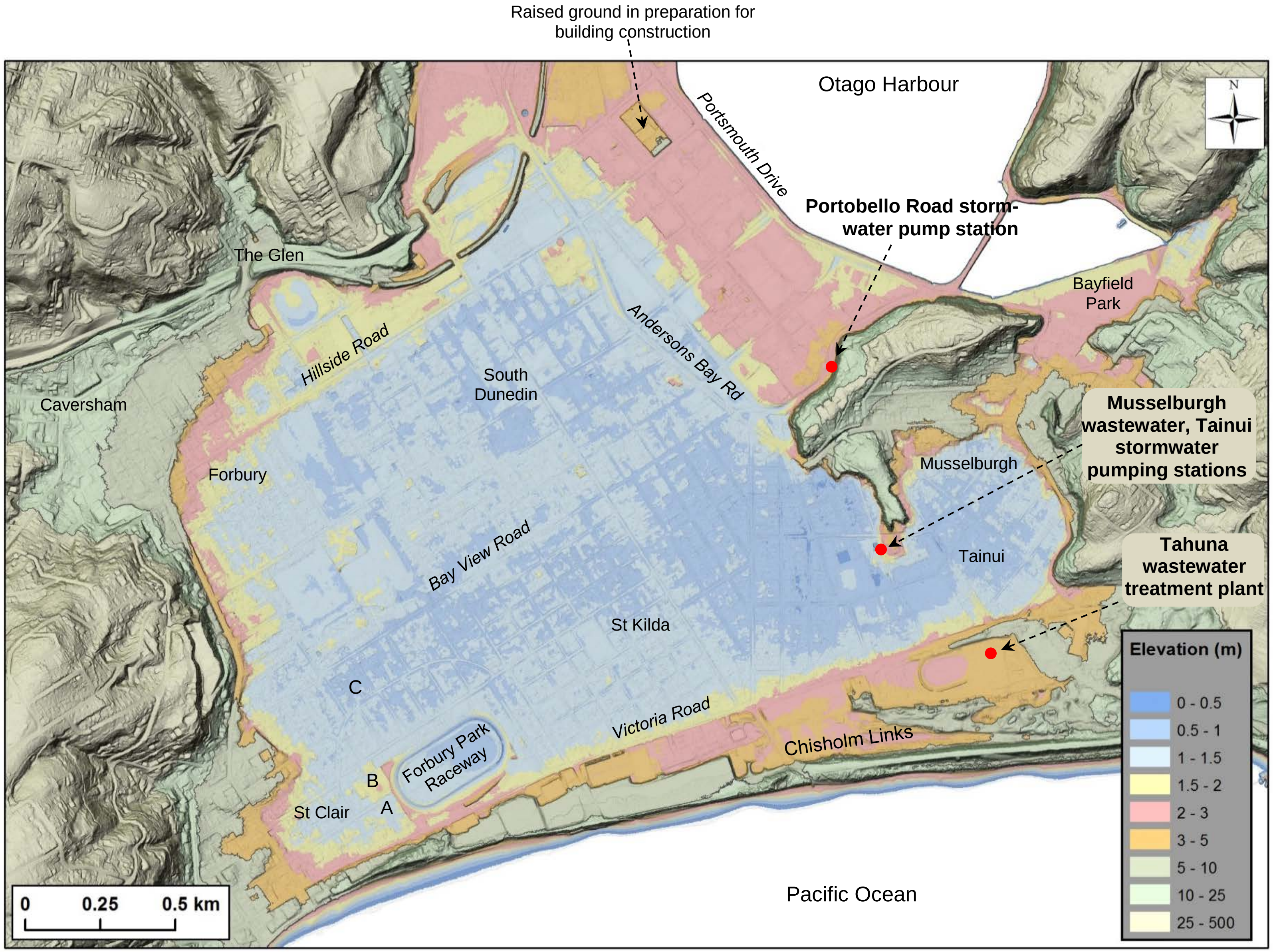


Figure 3. Topography and localities on the South Dunedin plain. Topographic features labelled A-C are shown in Figure 20. Background image is Dunedin City LiDAR, flown 2009, and coloured according to elevation. Elevation is in metres above MSL (mean sea level).

2.2. Geological and marine processes

The South Dunedin plain has been formed, in geological terms, very recently. During the most recent glacial period (or 'ice age'), which ended about 18,000 years ago, sea level was at least 120 m lower than it is now. As a result, the coastline lay as much as 35 km offshore from where it is now. At that time, the Water of Leith catchment is thought to have drained to the Pacific Ocean through the area now occupied by South Dunedin, via a broad, now-buried valley flanked by the hills of the peninsula to the east and the hills of St Clair and Kew to the west (Figure 4) (Barrell et al., 2014).

Following the peak of the last glacial period, sea level began to rise, reaching its present level about 7,000 years ago. The Otago Harbour, as well as most of the other indentations along the Otago coastline, is a former stream valley that was 'drowned' by rising sea level (Barrell et al., 2014). At the culmination of the post-glacial sea level rise, an open ocean passage extended through what is now the South Dunedin plain, and on up the Otago Harbour. Powerful wave action cut sea cliffs along the foot of the hills at Tainui, Musselburgh and Vauxhall. A prominent sector of this sea cliff can be seen near the intersection of Ravelston and Rona streets in Musselburgh. Subsequently, a dune barrier formed between St Clair and Lawyers Head, with material sourced from the long-shore drift of fine sediment from the Clutha River and other smaller catchments. After that barrier formed, fine sediments accumulated in the sheltered water at the head of the harbour, and the sea became increasingly shallow. Sediment accumulation eventually built up to just above sea level, producing a coastal wetland (the South Dunedin plain) that forms a land-bridge between the mainland and the Otago Peninsula.

The geology of the South Dunedin plain and the surrounding area (as illustrated in Figure 4) comprises bedrock overlain by poorly consolidated sediments in the low-lying areas (Bishop and Turnbull, 1996). The bedrock consists of Caversham Sandstone, overlain by volcanic rocks of the Dunedin Volcanic Group. Caversham Sandstone outcrops in the Caversham Valley area, while volcanic rocks form the hills flanking the harbour and South Dunedin. Poorly consolidated sediments are as much as 65 m thick beneath the South Dunedin plain, and include a variety of sandy, muddy and clayey sediments, deposited under marine to estuarine conditions, and sandy and gravelly sediments laid down in stream valleys. Large accumulations of dune sand have formed along the southern coast. The poorly consolidated sediments beneath the South Dunedin plain are saturated with groundwater and form an aquifer (Fordyce, 2013). Groundwater levels in the aquifer are influenced by the daily cycles of astronomical ocean tides.

At the time of European settlement in the mid-19th century, much of the South Dunedin area comprised salt marshes, wetlands and lagoons (as illustrated in the following three figures), with vegetation composed of tussock, rushes and flax. This wetland system was named Kaituna, which means to eat eels, indicating this native fish was probably abundant in the local area prior to European settlement. A shallow lagoon at the core of this system had its exit through the sand dunes near present day St Clair.

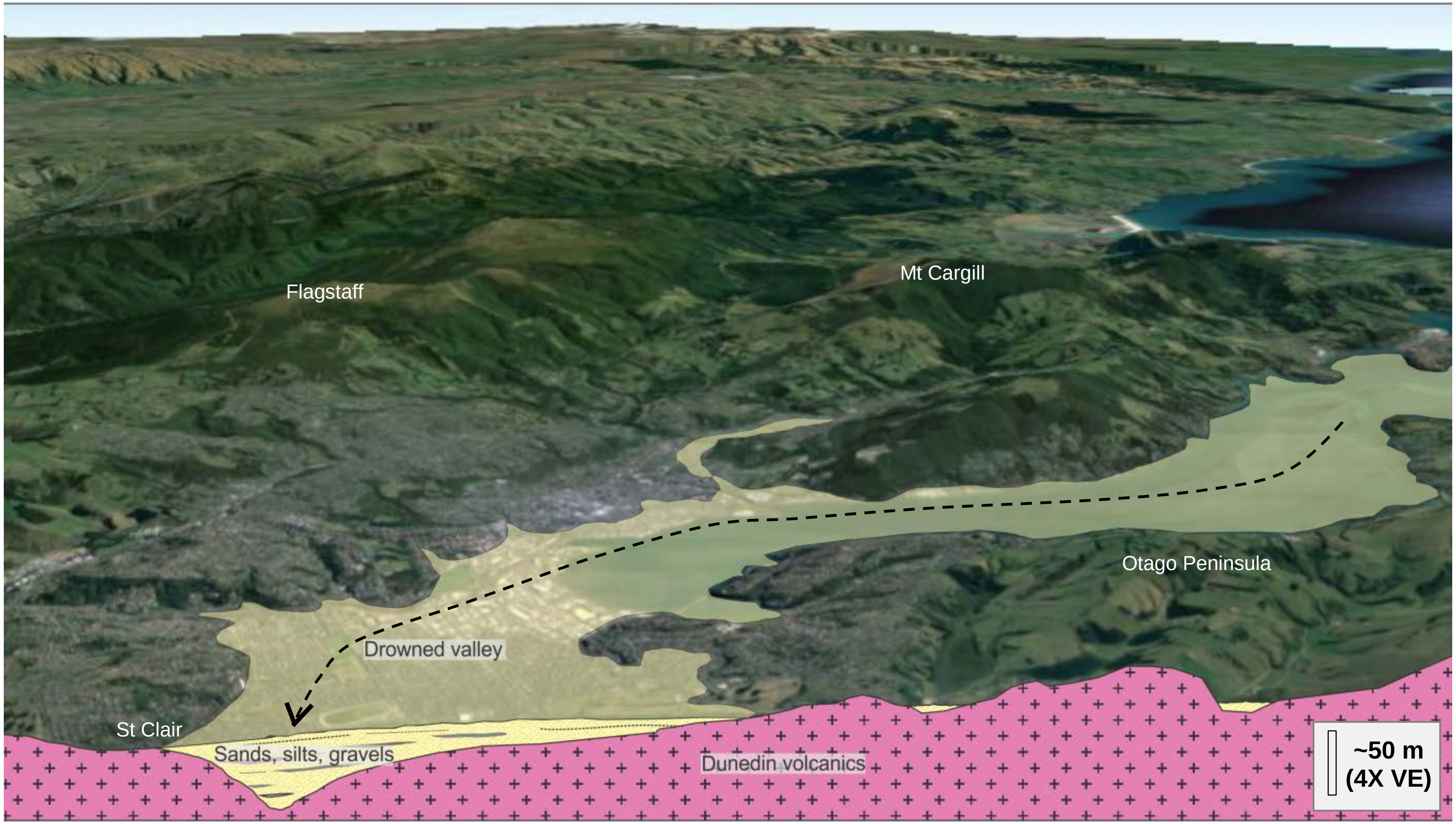


Figure 4. Simplified geological cross section through South Dunedin, showing volcanic bedrock and valley-infill sediments. A dashed line indicates the direction of drainage towards the coast during the last glacial period when sea level was up to 120 m lower than present and the shoreline was as much as 35 km further out. The valley is now buried beneath the poorly consolidated sediments which comprise the South Dunedin plain. The hills to the east and west are composed mainly of volcanic rock.

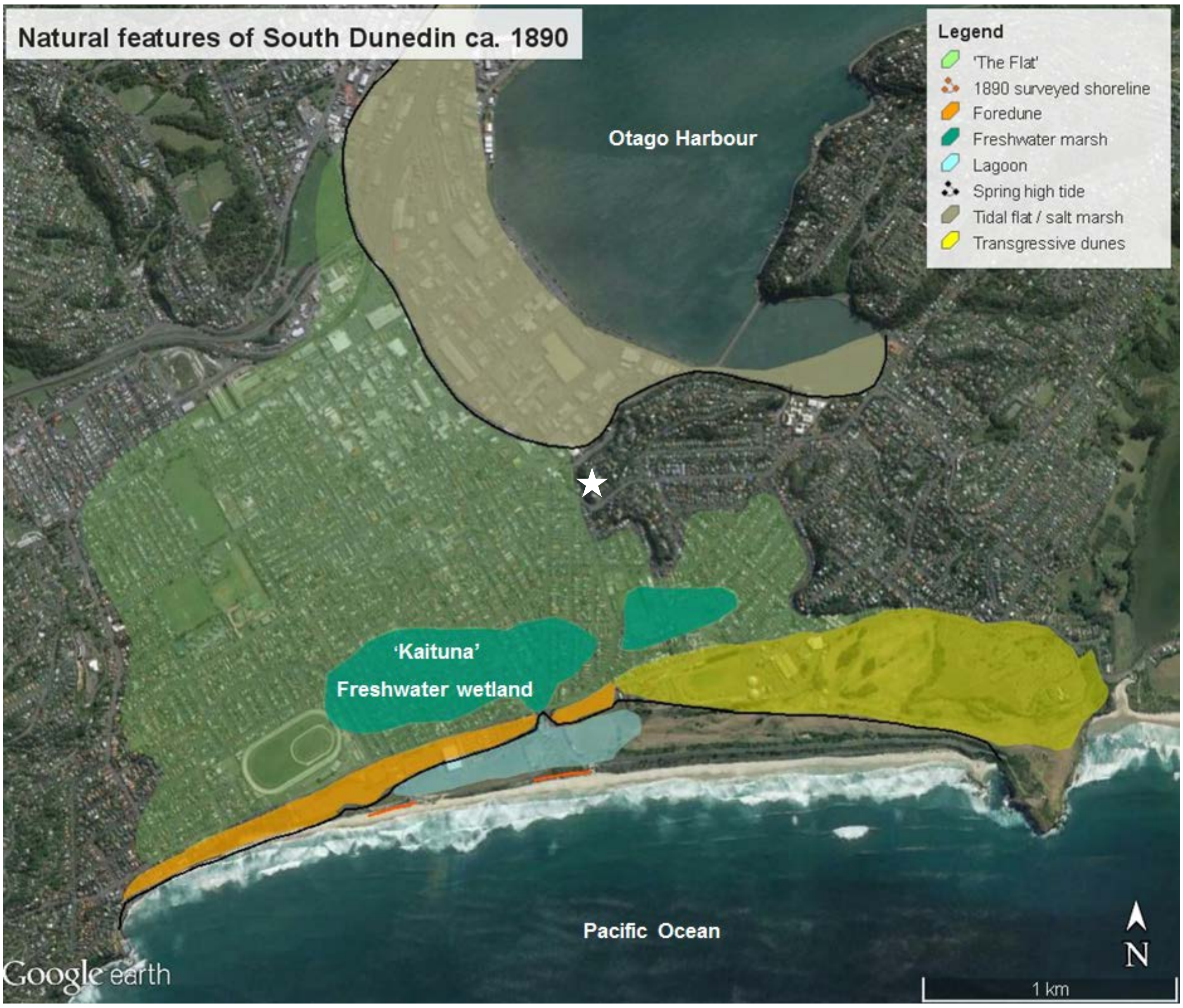


Figure 5. Aerial imagery with main features of the South Dunedin plain in about 1890. Landscape features are from Hilton (2010). Dashed black line depicts approximate storm high tide mark. White star shows viewpoint of Figure 6.

Figure 6. Dunedin in 1864. This painting depicts a view from the hill at Musselburgh looking across the upper Otago Harbour towards what is now the central city, with the South Dunedin plain to the left. (Hocken collections).

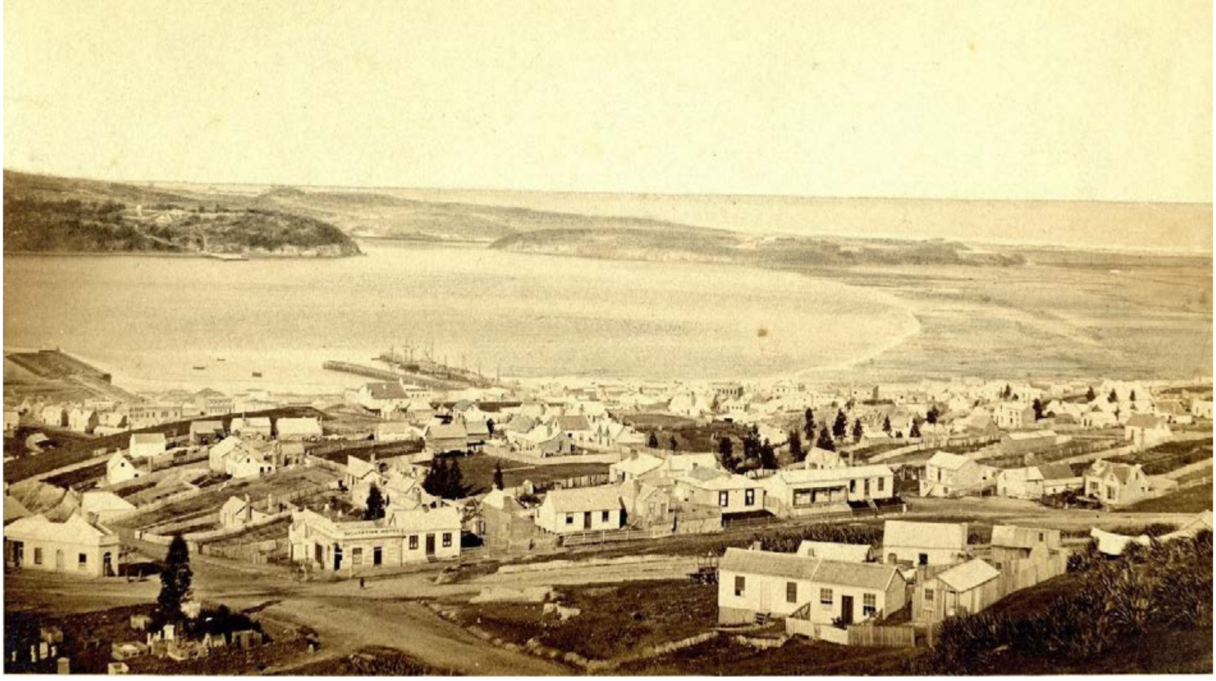


Figure 7. View across the upper Otago Harbour and the South Dunedin plain from Tainui at right to Andersons Bay and Vauxhall at left. This scene was captured from the edge of the Town Belt, above Rattray Street, looking southeast, 1865. (Single view of Dunedin, Joseph Perry. Hocken collections).

2.3. European land-filling

The period of rapid European settlement which occurred in Dunedin from the mid to late 19th century saw demand for level, dry land increase considerably. The European settlers undertook 'reclamation' activities, which amounted to in-filling or topping up of wet, low areas with any available fill material (ORC, 2012a). Initially this reclamation occurred in the central business and port areas, but soon extended out to the south. Sand mined at the coastal sand dunes from the 1870s onwards was taken by rail to be used in reclamation at the harbour margin and in South Dunedin. Due to the finite sand resource, there was competition for St Kilda sand and conflicts over the possibility of increasing the risk of flooding through the reduction of the dunes (ORC, 2012a; DTEC, 2002). Dunes in the central section of Ocean Beach initially had a flat, longer profile with the wetland of southern South Dunedin draining to a saltwater lagoon in the dune complex (Figure 5). Planting of marram grass and building of sand-catching structures along the beach from the late 1800s onward created the high, steep dunes now present south of Victoria Road (Hilton, 2010).

In general, land-filling was completed to a land surface which was just above the local height of the water table at that time. This practice minimised the amount of fill material that was needed, while providing for some level of drainage and relatively dry foundations. This resulted in a modern ground level throughout South Dunedin that strongly reflects the elevation of the groundwater table as it was in the late 1800s (up to 17 cm lower than the present day) (ORC, 2012a). As early as 1874 housing being built ~1 m below the high tide mark was reported by local surveyors, and the drainage of the wetland area through the dunes had been blocked off to prevent storm tides coming through the dunes (see Figure 5).

Reclamation of the area between Andersons Bay Road and Portsmouth Drive was completed more recently (1960s – 1970s) and to a higher level than the earlier reclamation to the south (Figure 3), using dredging spoil from the harbour (Figure 8 and Figure 9). This reclaimed part of the plain is now mainly used for commercial activity, with some key infrastructure such as the Portobello Road pumping station.

Figure 8. Reclamation underway on the 'Otago Harbour southern endowment', looking south towards Musselburgh Rise. (Photograph taken 1969. Hocken collections).

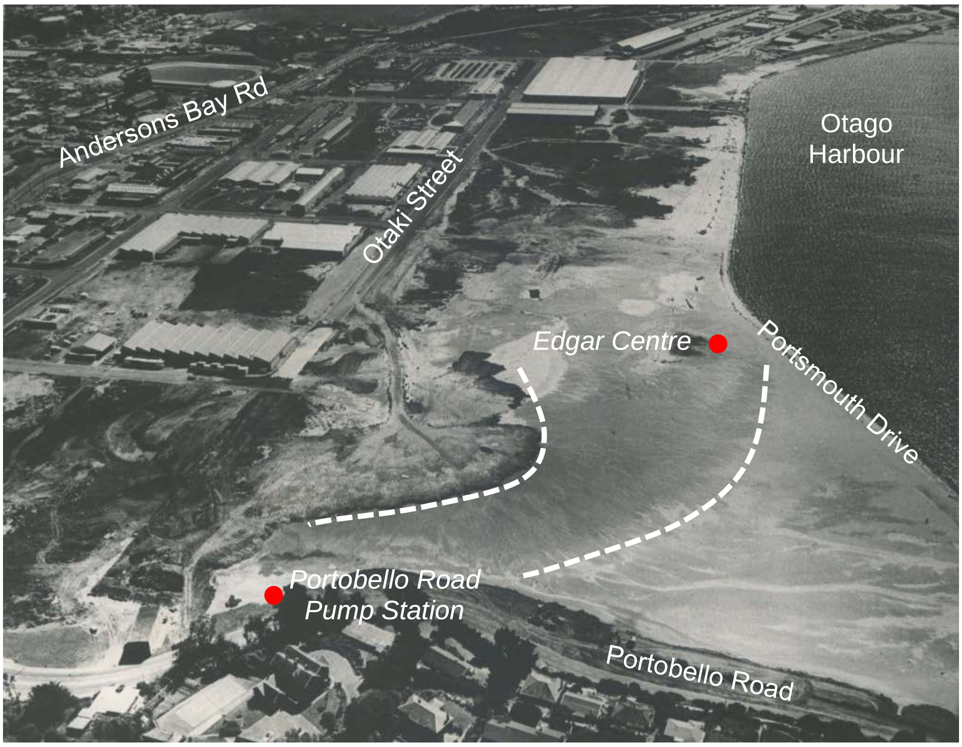


Figure 9. Reclamation underway between Otaki Street, Portobello Road and Portsmouth Drive 1971. A similar technique to that shown in Figure 8 is being applied, with a 'fan' of sediment (dashed white lines) being built out from a central pivot point. The locations of the present day Edgar Centre and Portobello Road Pumping Station are shown. (Photograph source: Otago Daily Times, report on Otago Harbour southern endowment scheme, October 1971).

2.4. Meteorological setting

The weather events that impact on Dunedin are major drivers in determining the natural hazards which affect the city, and combine to create the overall climatic picture. Fitzharris (2010) characterised the climate of the Dunedin urban area as follows - “Rainfall is 500 mm to 900 mm and is evenly distributed throughout the year, but with a slight winter minimum. Winds tend to be from the southwest, or from the northeast along the coast.” The Musselburgh rain gauge has the longest continuous rainfall record in the Dunedin area, and is situated adjacent to the Musselburgh wastewater pumping station (Figure 3).

Figure 10 shows that annual rainfall totals at Musselburgh have consistently been lower than normal since the start of this century, and have averaged about 670 mm since 2001. A statistically significant reduction in annual rainfall in the wider Dunedin area since 1953 was also noted by Cameron et al. (in review).

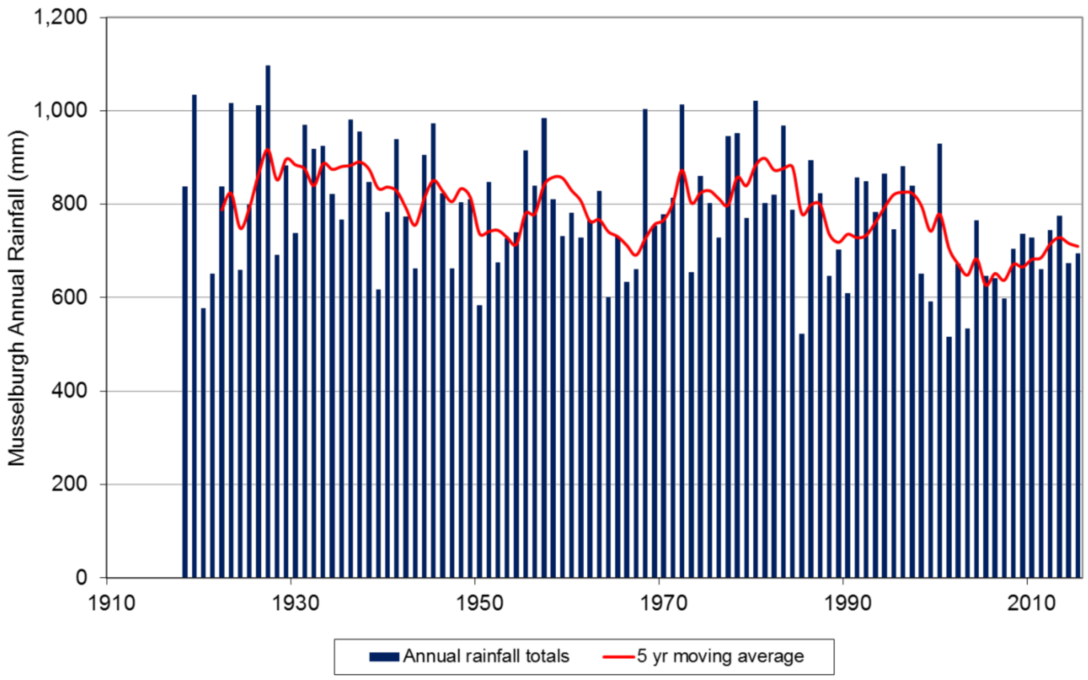


Figure 10. Annual rainfall totals at Musselburgh, 1918 (when records commenced) to 2015.

Of more importance to weather-related natural hazards such as flooding are the characteristics of extreme rainfall events (storms). Very heavy rain can be experienced within Dunedin City, and the Musselburgh site has recorded a rainfall total of over 200 mm in a 24-hour period (Table 1). Meteorological conditions that can result in surface flooding in the South Dunedin area include:

- Extended periods of moderate-to-heavy rainfall from the eastern quarter, which can result in high flows in coastal catchments such as the Water of Leith and significant surface runoff and stormwater flow in the South Dunedin catchment.
- A south to southwest airstream, which can also bring moderate to heavy rainfall, strong winds and occasionally heavy snow. Rainfall events associated with a southerly change are generally short lived, although they can result in high flows if catchments are already saturated from previous rainfall.

- Extremely heavy, but short-lived, rainfall events can occur over the city in summer (Figure 13). These events may temporarily overwhelm stormwater networks, causing localised ponding and can initiate shallow landsliding on susceptible slopes.
- Various combinations of the above. Rivers and streams rise particularly rapidly when catchments are already saturated from previous rainfall (section 2.5).

Daily (9am) rainfall totals have been recorded at Musselburgh since 1918, and 'continuous' (hourly) records commenced in 1997.[7] The continuous data can be used to determine the period of greatest rainfall intensity for a particular event, which may not necessarily occur between 9am on two consecutive days. There are a number of other rainfall monitoring sites in Dunedin City, but these are generally located on the hills to the north. They include Otago Regional Council (ORC) sites at Swampy Spur (Silver Stream catchment), Pine Hill and Sullivans Dam (Water of Leith catchment), and Dunedin City Council (DCC) sites at Mt Grand and Port Chalmers. These sites have shorter records than the Musselburgh site, but are useful in determining the spatial extent of particular storm events. Data from ORC rain gauges and the Musselburgh site are available on the ORC's Water Info website (http://water.orc.govt.nz/WaterInfo).

The five highest daily manual (9am) readings (since 1918), and the five highest totals observed over any 24 hour period (since 1997) at Musselburgh are shown in Table 1 and Table 2**Table 2** respectively. Table 2 shows that the 142 mm of rain which fell over a 24-hour period in early June 2015 was the largest observed since continuous monitoring commenced, but was considerably less than the 9am reading for the April 1923 event (Table 1). Table 2 also shows that other heavy rainfall events which have occurred since 1997 (July 2007, April 2006, February 2012 and October 2011) do not rank among the top five daily manual (9am) totals.

Table 1. The highest daily manual (9am) rainfall totals observed at Musselburgh since records began in 1918. Source: NIWA Climate Database

End of event date	Amount (mm)
23 April 1923	229
5 June 1980	119
4 June 2015	113
4 Dec 1938	113
20 March 1929	104

[7] Data available from the National Climate Database (http://www.cliflo.niwa.co.nz).

Table 2. The highest 24-hour rainfall totals at Musselburgh (for individual storm events) since records began in 1997. Source: NIWA Climate Database.

End of event date / time	Amount (mm)
4 June 2015 4am	142
20 July 2007 10pm	86
26 April 2006 10am	83
23 Feb 2012 9pm	82
19 Oct 2011 midnight	67

Figure 11 shows that 'extremely wet days' (a day with 39 mm or more of rainfall, as defined in section 7) were observed at the Musselburgh site reasonably frequently over the last decade, with one or more such events every year between 2003 and 2013 and then again in 2015.

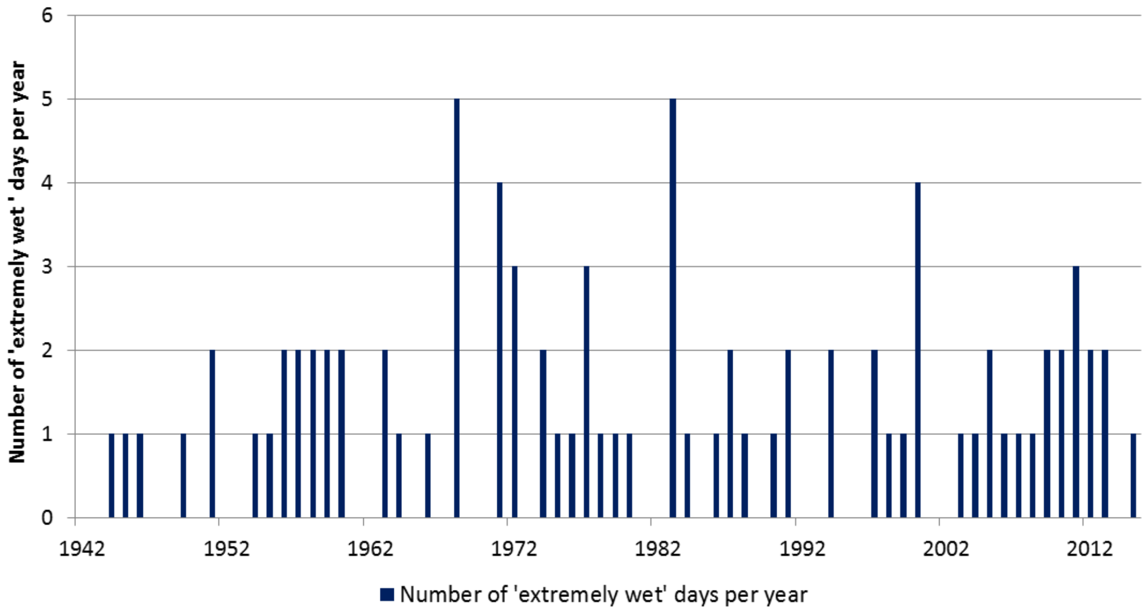


Figure 11. The number of extremely wet days per year at Musselburgh between 1942 and 2015, as determined by Cameron et al. (in review).

It is noted that during a major storm event in 1968, approximately 160 mm of rain was observed at Musselburgh over a 24-hour period up til 8pm on 9 March[8] (i.e. more than recorded in June 2015, but less than the April 1923 storm event). This 24-hour total was not used in the estimation of annual return periods by ORC in 2015. The effect of adding this value to the record is to change the estimated return period of the June 2015 rainfall total at Musselburgh from 63 years to about 50 years (Appendix 1). Collectively, the historical rainfall

[8] Hourly rainfall records obtained from a 1968 Dunedin Drainage and Sewerage Board publication. The daily manual totals sourced from the Climate Database were 91 mm at 9am on the 9th of March 1968, and 71 mm on the following day.

data confirm that the rainfall observed in June 2015 had precedent and verified existing knowledge (i.e. it was large, but not exceptional).

Given that a warmer atmosphere can hold more moisture, there is potential for storm events to bring heavier (or more intense) rainfall in the future as global temperatures increase (MfE, 2008, 2016). Heavy rainfall events, similar to those observed in recent years, could therefore be expected to become a more common occurrence, as the annual mean temperature in the eastern South Island is predicted to increase by about 2°C over the 21st century (MfE, 2008).

2.5. Hydrological setting

Surface water and groundwater flow in the South Dunedin area is fed by rainfall on the low-lying ground, and runoff from the surrounding hill catchments. The natural catchment area for the South Dunedin plain is about 14.8 km^2 (Figure 12), with a number of sub-catchments contributing water through defined channels such as Glen Creek, via surface runoff, and through the stormwater network.[9] Although there are a number of small streams which drain the hills surrounding South Dunedin (Figure 12), there are no natural watercourses which cross the plain.

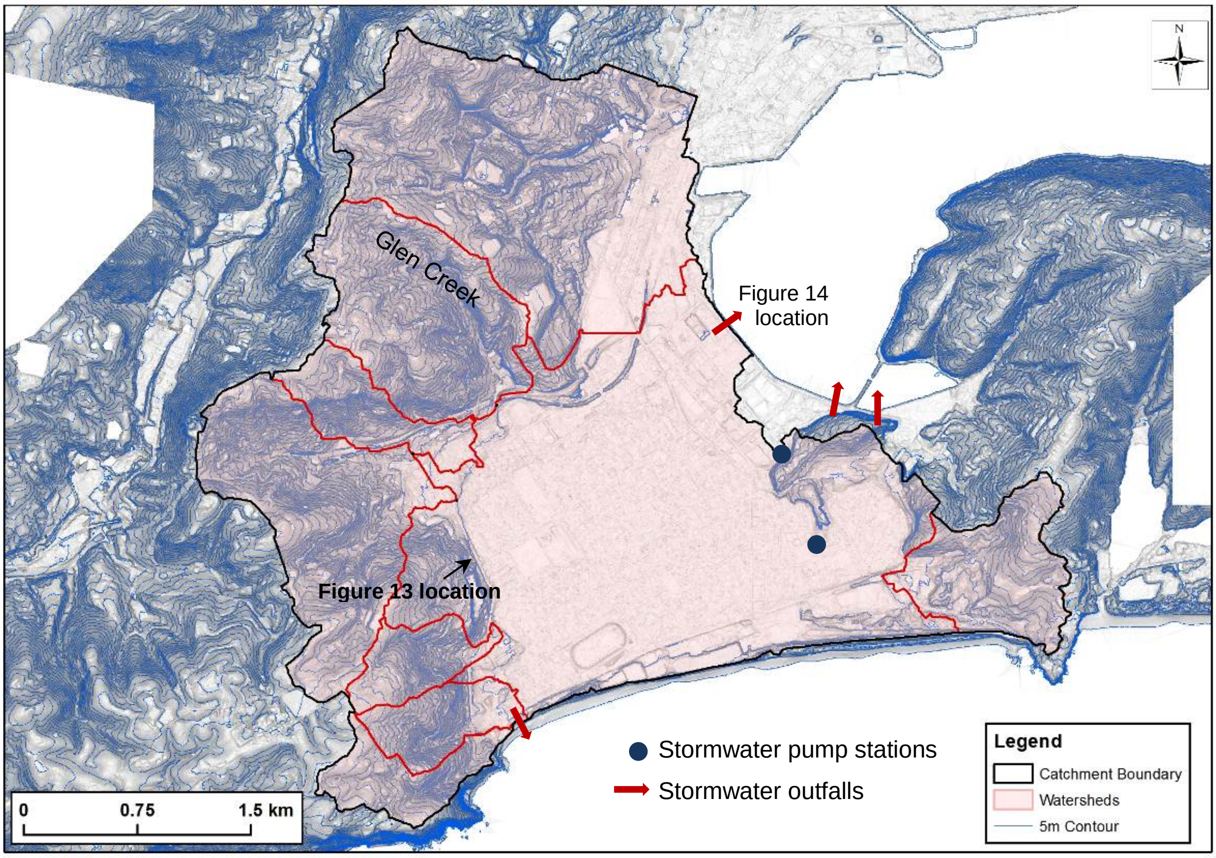


Figure 12. Contour map showing the natural boundary of the South Dunedin catchment (black line) and sub-catchments (red lines). Stormwater pump stations and outfalls are also shown.

[9] It is noted that the DCC stormwater network does not necessarily follow the natural catchment boundary. In particular, some stormwater from the northern-most sub-catchment (bounded by upper Stuart Street in the north and Eglinton Road in the south) may be diverted away from South Dunedin by DCC stormwater drains.

The sub-catchments around the periphery of the South Dunedin plain are generally steep, urbanised (with a greater proportion of impervious surfaces such as buildings, concrete and asphalt), and particularly exposed to storm events sourced from the eastern quarter. As a result, the runoff from these catchment areas onto the plain that is associated with heavy rainfall events occurs rapidly (Figure 13).

Figure 13. Runoff onto Forbury Road during the June 2015 flood. Source: Otago Daily Times.

The natural catchment of South Dunedin is slightly larger than that of Lindsay Creek in North East Valley (12.5 km^2) which, for comparison, had a peak flow of about 30 cubic metres of water per second (m^3/sec) during the June 2015 flood. Unlike Lindsay Creek however, the South Dunedin catchment does not have a single large channel to convey floodwater to the ocean. Instead, the South Dunedin plain has a highly modified and widely distributed hydrology, associated with its piped stormwater system. Rain which falls on the plain is caught in kerb and channel and then conveyed into stormwater pipes. These pipes discharge stormwater mainly to Otago Harbour (Figure 14), but also directly to the Pacific Ocean (at the St Clair esplanade), via gravity outfall or pumping stations (Figure 12).

Figure 14. Stormwater outflow to Otago Harbour, near the intersection of Orari Street and Portsmouth Drive, June 2015. Source: Otago Daily Times.

Once the stormwater pipes reach capacity, excess water will flow overland to pond in the lowest-lying areas (Figure 15). This water will then either infiltrate to groundwater, naturally evaporate, or eventually be removed by the stormwater system once the period of peak flow has passed. Man-made features such as fences and buildings, and natural topographic features can act to impede or re-direct stormwater during storm events. In addition, the large proportion of the South Dunedin plain that is now covered by impermeable surfaces (buildings, concrete and asphalt) can restrict the infiltration of surface water into the ground. The imperviousness of the South Dunedin plain has been assessed as 60% overall, although this is much higher in the commercial and industrial areas in the north, where imperviousness can reach 100% (URS, 2010).

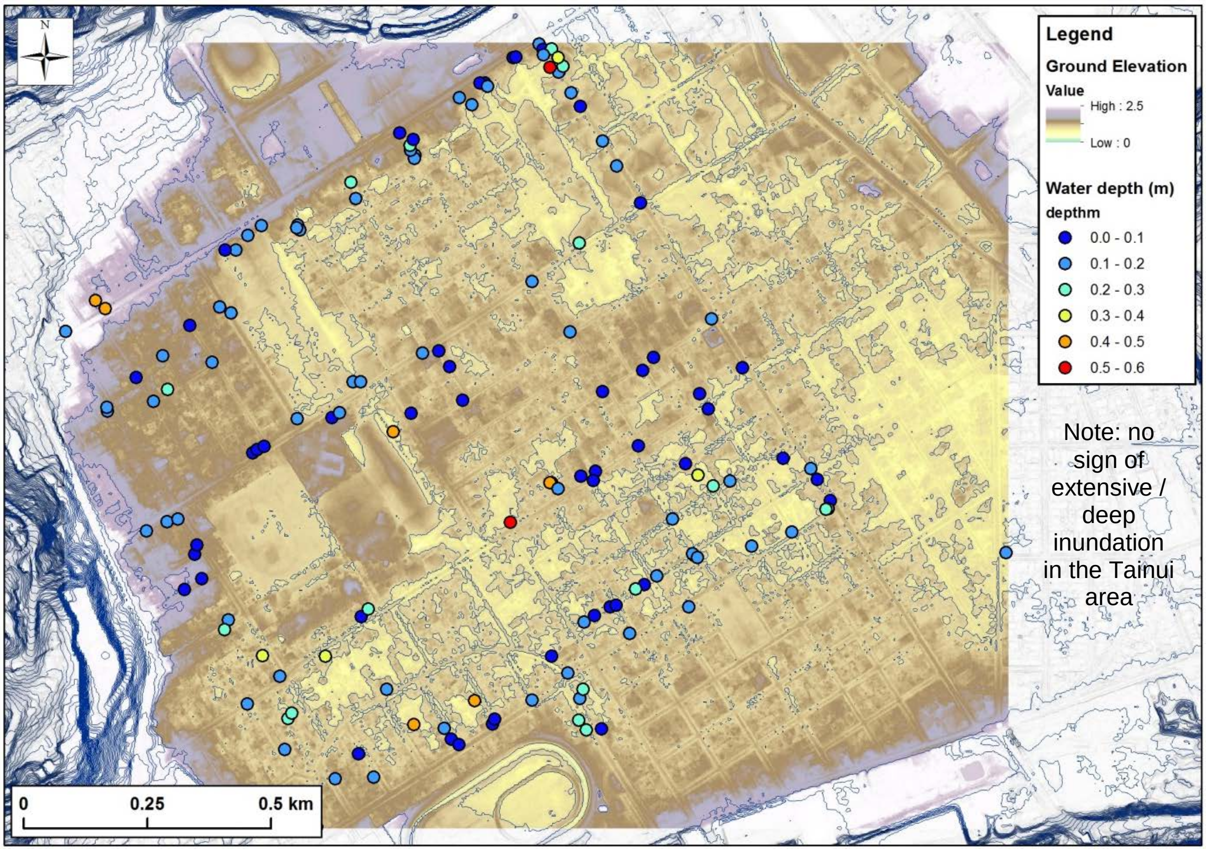


Figure 15. Map of the South Dunedin plain, showing the maximum depth of above-ground surface ponding during the June 2015 flood. Depths calculated by determining the difference between the elevation of the surveyed debris marks and ground level at that location. Elevation colour scale shows ground elevation between 0 and 2.5 m above MSL. Contour interval is 1 m.

2.6. Coastal aquifer and groundwater characteristics

The first part of this section describes the general characteristics of the aquifer which lies beneath the South Dunedin plain, while the second part provides an update on groundwater monitoring data collected from ORC's South Dunedin bores, from information provided in earlier ORC reports (2012a, 2014a). The updated information is used to describe the potential hazards associated with the South Dunedin aquifer, based on currently available knowledge.

The characteristics of the South Dunedin aquifer have been described by the ORC (2012a) and the University of Otago Geography Department (Fordyce, 2013). The ORC work investigated the relationship between mean sea level and groundwater, while Fordyce primarily considered the relationship between rainfall and groundwater. This section provides a summary of these investigations and other relevant work.

Data Sources

To enable a better understanding of the characteristics of the water table, ORC established four shallow groundwater-monitoring bores in South Dunedin between 2009 and 2014 (Figure 16). Each bore penetrates 6 m below ground level, with a 1 m long screen at the base of the bore standpipe. The bore collars were surveyed relative to the MSL datum and the collars are at about the same level as the surrounding ground (Figure 17).[10] The samples

[10] Except for the Bathgate Park bore, where the bore collar stands about 0.25 m above the surrounding ground

of cuttings from each bore revealed inter-layered sand and silt deposits typical of estuarine sediments, which is to be expected, given their geological setting (section 2.2). Automatic measuring and logging equipment was installed to record water level at 15-minute intervals. ORC intends to collect data from all four bores automatically via its telemetry network from August-2016 onwards. A model of the aquifer has also been created (section 4.1).

Some additional short-term water table monitoring at 13 other 3-m-deep bores was completed during a 6-month period in 2012-2013, by the University of Otago Geography Department (Figure 18). A small number of bores have been drilled by other agencies, including at the Tahuna wastewater treatment plant for the DCC.

Figure 16. Location of ORC monitoring bores, Musselburgh wastewater pumping station and rain gauge, and Green Island sea level recorder. The location of the cross-section (Figure 20) is also shown (red line). The Green Island sea level recorder is illustrated in Figure 31.

Figure 17. Typical example of an ORC bore installation, with bore collar and instrumentation box, at the Culling Park site.

Figure 18. Location of monitoring boreholes established by the Univeristy of Otago Geography Department (blue circles). The location of the first three boreholes established by ORC in 2009 are also shown (orange circles). Source: Fordyce (2013).

Aquifer overview

As outlined in section 2, the South Dunedin plain is underlain by young sediment, typically interlayered sand and silt at shallow levels, becoming dominated by sand at greater depths. These sediments reach a maximum depth of approximately 65 m, and form a coastal aquifer with an unconfined (phreatic) water table close to the surface.

It is noted that almost all monitoring to date has been in shallow boreholes and the state of groundwater at depths greater than 10 m is essentially unknown. Apart from sporadic observations made during drilling, there is little knowledge of any vertical flow, such as downward drainage or upward recharge, or whether or not there are any extensive low-permeability silt horizons that might locally confine groundwater in sand at elevated pressures. The shallow water table beneath South Dunedin may simply be the upper limit of a continuous aquifer which extends down to the bedrock. Alternatively, this water may sit on top of other low-permeability layers, with other, permeable components of the aquifer lying at depth.

Fordyce (2013) created a map of the mean elevation of the water table during dry conditions, across the wider South Dunedin plain (Figure 19). This shows higher groundwater elevation in the central / southwest part of the plain, and also pockets of slightly elevated groundwater levels in the Tainui and Musselburgh areas, but that overall the groundwater level is relatively flat, implying horizontal flows are not strong.

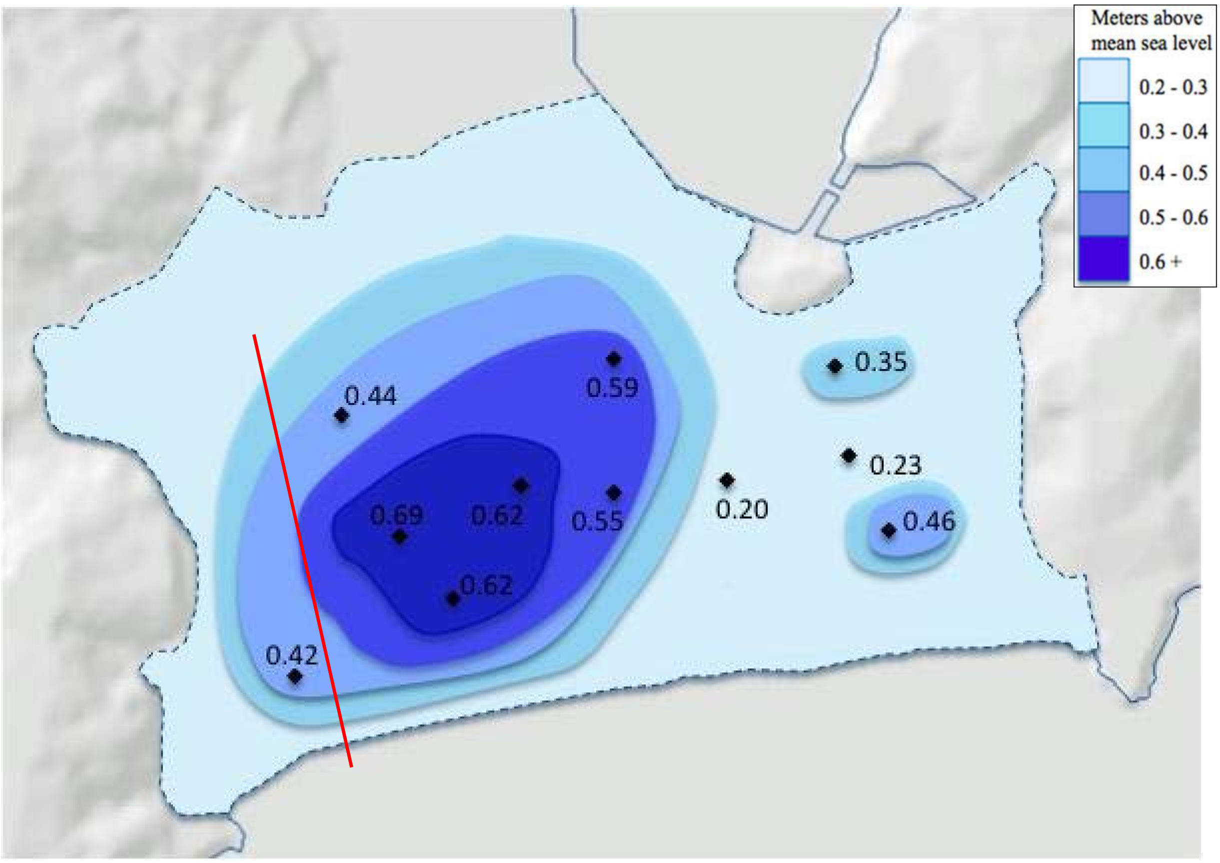


Figure 19. Map showing the mean elevation of the water table in metres above MSL, across the South Dunedin plain, over a one-week period in July 2012 without rainfall. The markers indicate the location of the bores used to determine mean water table elevation, with the contour lines inferred. ORC bores were not included in this analysis. Map source: Fordyce, 2013. The red line marks the position of the cross section shown in Figure 20.

A cross section (vertical slice through the ground) across part of the South Dunedin plain (Figure 20) presents updated groundwater data from the ORC bores, which are projected onto the line of the cross section (see Figure 16). The median groundwater levels observed at ORC bores in this area are between 0.55 to 0.7 m above MSL (Table 3), and show a similar picture to the findings of the July 2012 measurements shown in Figure 19.

However, Figure 20 and Table 3 show the water table is normally slightly higher at Bathgate Park than at Tonga Park, which is different to the pattern shown in Figure 19. This difference is probably due to the interpolation (or estimation) of typical groundwater levels between monitoring bores, and the short length of record used to produce Figure 19.

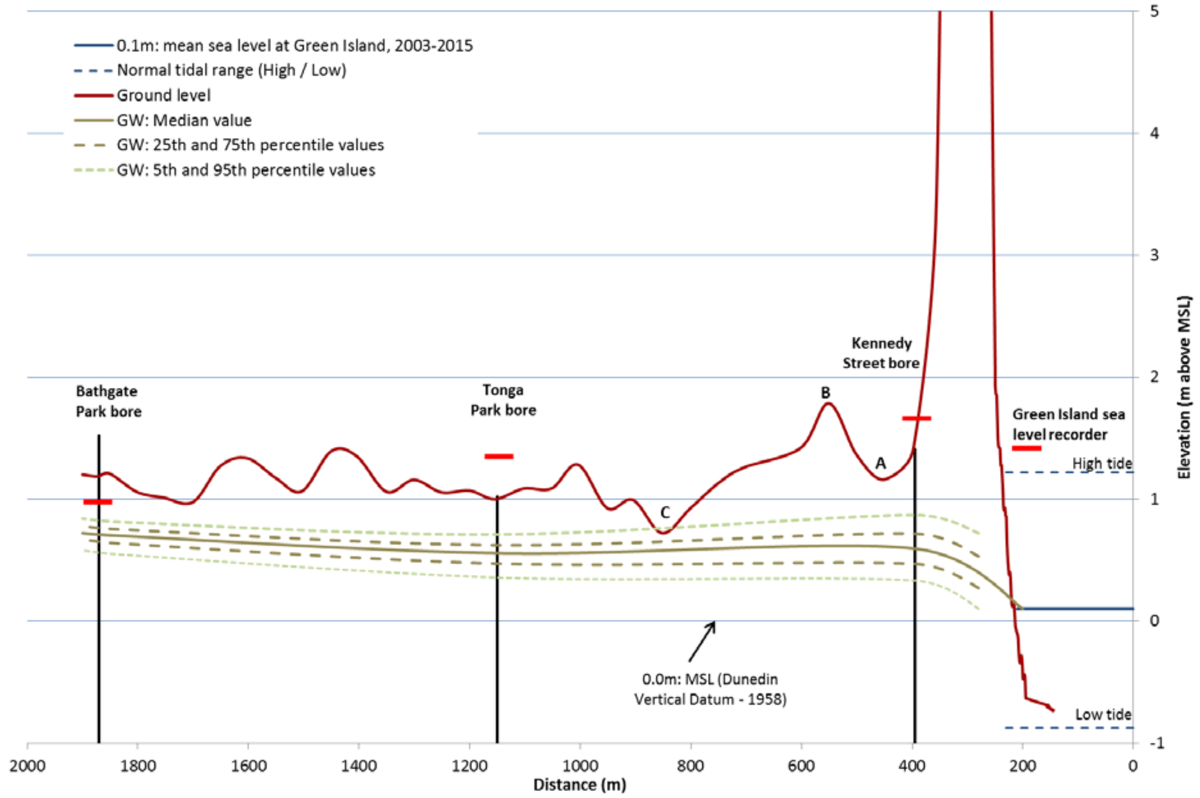


Figure 20. Cross-section from Bathgate Park to the Pacific Ocean, showing ground level[11], mean sea level at the Green Island sea level recorder between 2003 and 2015, the normal tidal range of the Pacific Ocean[12], the location of three ORC monitoring bores (vertical black lines), median groundwater levels at those sites (solid green line), and the typical range[13] of observed groundwater level (dashed green lines).[14] Maximum groundwater level and maximum sea level at Green Island, as observed during the June 2015 flood is shown (red marks). Three topographical features (low and high points) labelled A, B and C, as mapped in Figure 3, are indicated. (Vertical exaggeration = 200x). Cross section location is shown in Figure 16 and Figure 20

[11] Determined from a digital surface model, created from LiDAR collected in 2009. Ground level represents a typical swath of topography, and is interpolated from points between buildings, trees etc.

[12] As measured at the Green Island sea level recorder between 2003 and 2015

[13] The 5th and 95th percentile values (dashed light green lines), and the 25th and 75th percentile values (dashed darker green lines) are shown. These were calculated using all data values (collected every 15 minutes) between October 2009 and May 2016.

[14] Note that groundwater level between the three bores is interpolated

Table 3. Ground level and median groundwater level at ORC bores since records began

Site	Records commenced	Surveyed level of bore collar (m above MSL)	Median groundwater level (m above MSL)[15]
Bathgate Park	Oct 2009	1.52	0.70
Tonga Park	Oct 2009	1.02	0.55
Kennedy Street	Oct 2009	1.41	0.59
Culling Park	May 2014	0.83	0.03

One of the more important factors in terms of the effect of the aquifer on the South Dunedin urban area is the depth at which the water table lies below the ground. The median depth to groundwater at the four ORC bores, for each year of complete record, is shown in Figure 21. The water table is normally the shallowest at the Tonga Park bore, where the median groundwater level is 0.4 to 0.5 m below the ground. Median depth to groundwater at the other three ORC bores is 0.8 to 0.9 m below the ground. A shorter (6 month) record from a larger number of bores, with a wider distribution across the plain (Figure 18), found that the water table was, on average, 0.45 to 0.86 m below the ground surface (Fordyce, 2013).

It is noted that the surveyed ground level at Culling Park is up to 0.7 m lower than at the other three ORC bores. However, the depth to groundwater is similar to that at Kennedy Street and Bathgate Park, as the median groundwater level is also lower at Culling Park (Table 3). If median groundwater level at Culling Park was similar to that at the other three ORC bores, then surface ponding could occur much more regularly.

The information above shows that the water table beneath the South Dunedin plain is shallow, even during relatively dry conditions. This is particularly true on the western side of the plain, at the Tonga Park bore. This means that heavy rainfall events and elevated sea levels (the two main influences on groundwater in this area) can cause groundwater level to rise quickly to a point where it is close to, or even above ground level. The following two sections describe these effects in more detail.

[15] Start of record to 2015, complete years only

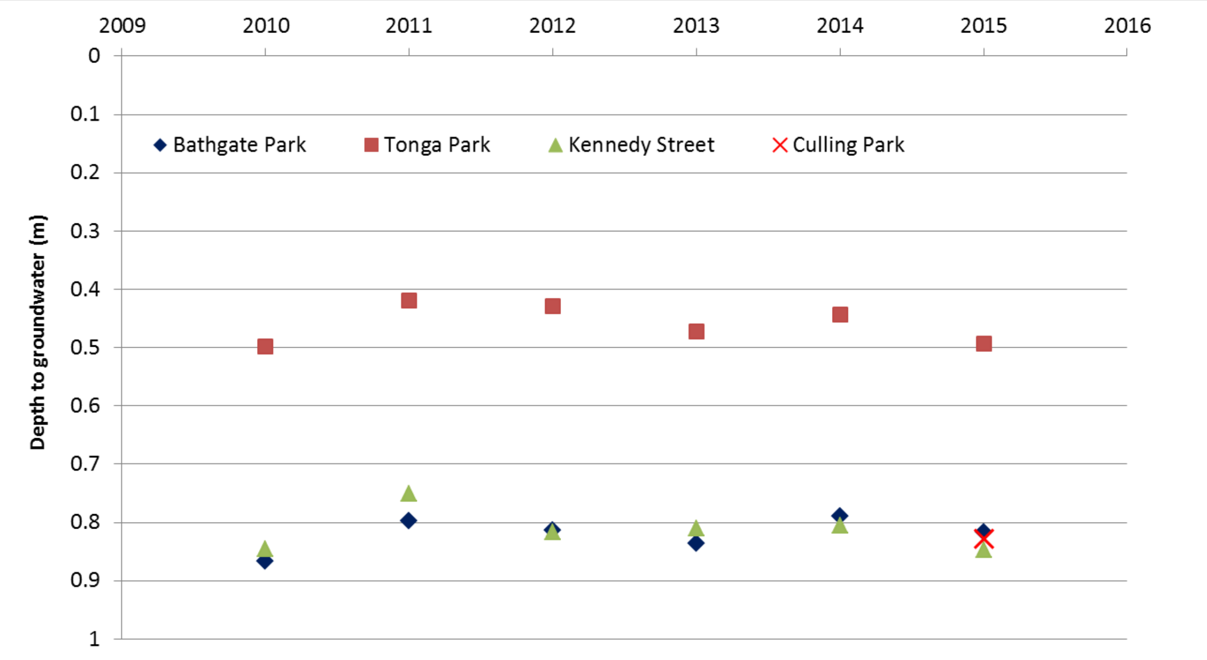


Figure 21. Median annual depth from the surveyed bore collar to groundwater level at ORC monitoring bores (complete years of record only). Note that the depth to groundwater at the Kennedy Street bore fluctuates by about 0.5 m as groundwater responds to the twice-daily ocean tidal cycles. It also rises and falls depending on the presence of low pressure storm systems and spring/neap tide monthly variations (see Figure 23).

Influence of heavy rainfall.

Rainfall exerts a major influence on groundwater levels beneath the South Dunedin plain (Fordyce, 2013). Records from the four ORC bores show that water level can rise rapidly, and an example is shown in Figure 22 where groundwater level increased by 0.7 m in 10 hours at the Culling Park bore during the June 2015 rainfall event. This characteristic of the aquifer means that groundwater can rise from a low level to near or even above ground level in a short space of time.

Fordyce (2013) also found that groundwater flooding can occur as a result of rainfall events with a reasonably frequent recurrence interval.[16] Fordyce's work concluded that the sites at greatest risk are those where the water table is already reasonably close to the ground surface. This is also illustrated in Figure 22, where, prior to the June 2015 event, groundwater level was already higher than normal due to a moderate rainfall event that occurred 10 days earlier. Fordyce also found that locations where layers of sand overlie silt (which can impede infiltration of rainfall) are also at greater risk of surface flooding, due to the rapid groundwater response to rainfall observed at those sites.

[16] 48-hour rainfall totals with a return period of 5 years or more

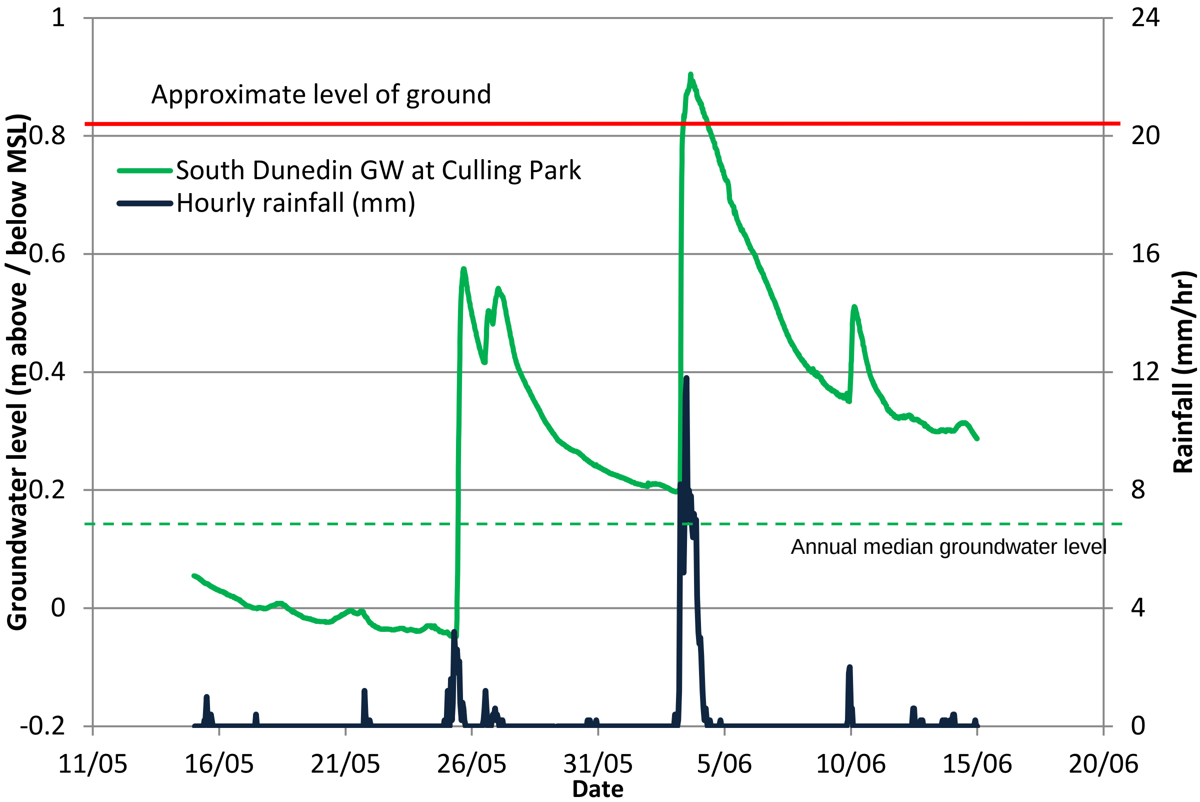


Figure 22. Culling Park groundwater record, and daily rainfall rate at Musselburgh, from 15 May to 12 June 2015. The surveyed level of the bore collar is 0.83 m above MSL.

During the June 2015 event the water table at three of the four ORC bores was elevated to a point where it was above the level of the ground, with deepest ponding occurring at Tonga Park and Kennedy Street, and shallow ponding at Culling Park (Table 4).

Table 4. Maximim recorded groundwater levels at ORC bores since records began.

Site	Records commenced	Maximum water level (all observed during June 2015 event)	
		Maximum level (m above MSL)	Height relative to bore collar (m)
Bathgate Park	Oct 2009	0.988	-0.532
Tonga Park	Oct 2009	1.366	0.346
Kennedy Street	Oct 2009	1.671	0.261
Culling Park	May 2014	0.905	0.075

Influence of the sea

The Otago Harbour and Pacific Ocean form the northern and southern boundaries to the South Dunedin aquifer. Seawater intrudes into the aquifer around its coastal fringes,[17] and tidal-induced fluctuations in groundwater level are evident. Monitoring results show that normal tidal cycles influence the water table below South Dunedin, particularly those areas closer to the sea. A strong relationship between these two parameters is shown in Figure 23. This shows changes in sea level at the Green Island sea level recorder due to normal astronomical tides, and changes in the water table at the Kennedy Street bore during a reasonably dry month, when the effects of rainfall on groundwater level were minimal. The largest fluctuations in groundwater occur when the tidal range is greater, and higher (spring) tides result in higher peaks in groundwater. A regular, but less obvious, response to the tidal cycle is seen at ORC's Culling Park bore during periods of low rainfall, and ORC (2012a) also noted a slight (1-2 cm) tidal fluctuation in the groundwater level record at Tonga Park.

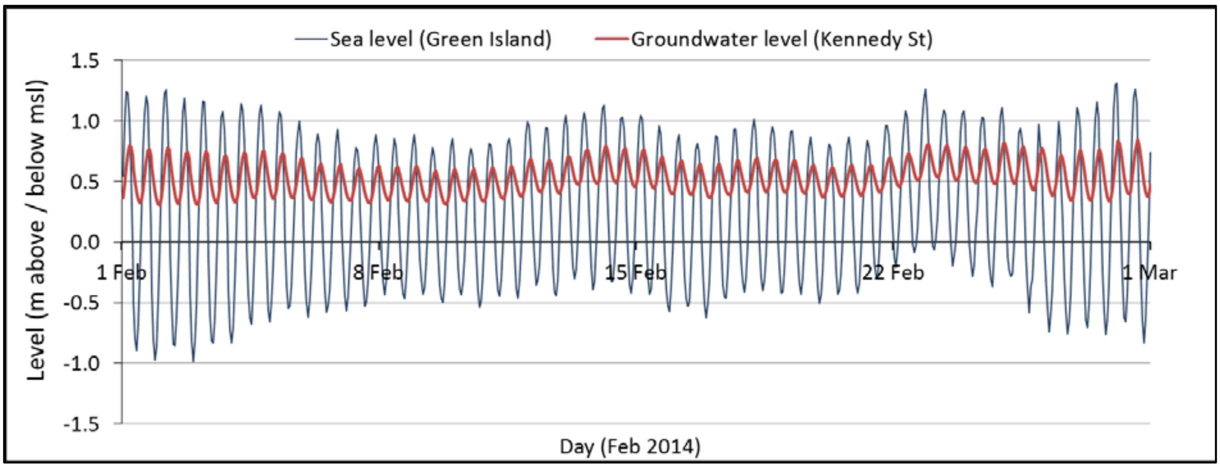


Figure 23. Sea level at the Green Island sea level recorder (Figure 16) and groundwater level at Kennedy Street, during February 2014. The surveyed level of the bore collar at the Kennedy Street bore is 1.4 m above MSL. Note that the median water level at the tide gauge is ~25 cm above the MSL datum. This is due in part to the datum being established from 9 years of tidal data in the 1920s and 1930s, when sea level was ~15 cm lower than it is today. The warmer summer sea temperatures and other effects can also cause short-term sea level variations.

The connectivity between the sea and groundwater levels and the poorly consolidated sediments beneath South Dunedin means that the water table rises in response to elevated sea levels (e.g. spring tides, and coastal storm surge events). Data from the four ORC bores do not contain any periods where groundwater has risen above the level of the ground as a result of elevated sea levels only. However, other more low-lying areas which are not monitored by ORC may well experience limited surface ponding as a result of elevated sea level only.[18]

[17] Fordyce (2013) found that the central part of South Dunedin contained the most saline groundwater, which is potentially a relic from the area's history as a tidal salt marsh. She also noted local areas of perched freshwater, such as within sand dunes at St Kilda, which are probably disconnected from groundwater in the wider area.

[18] Figure 38 and Figure 39 show that water ponds on Teviot Street during spring high tides, due to the pressure of water in stormwater pipes. Location C (as shown on Figure 20 and Figure 3) is an example of low-lying land which may be susceptible to flooding due to elevated groundwater levels.

Observations to date show that low-pressure systems that bring heavy rainfall to the Dunedin area can also result in storm-tide levels which are higher than would occur under normal atmospheric conditions (ORC, 2015; NIWA, 2016). Sea level and rainfall are therefore crucial controls on flood hazard in the South Dunedin area. It is inferred that any long-term rise in mean sea level would translate into a rise in the mean water table level (ORC, 2012a), and this is discussed further in section 4.1.

Stormwater and wastewater network

The minimal gradient and low elevation of the South Dunedin plain means stormwater must be pumped via the Tainui low-level and / or the Portobello Road pumping stations and discharged to the Otago Harbour (Figure 3, Figure 12 and Figure 14). The network which drains wastewater from South Dunedin (as well as from most of the city) drains to the Musselburgh pumping station, which lifts the wastewater from below MSL, to about 8 m above MSL at the Tahuna Wastewater Treatment Plant, before it is treated and discharged to the Pacific Ocean. The diameter of the wastewater pipes beneath the South Dunedin plain ranges from 150 to 1500 mm, and these pipes are typically buried about 1.7 m below ground level (i.e. below the typical range of groundwater levels).

The wastewater network that serves South Dunedin is aged, and much of the network is due for renewal (see Figure 48). Closed Circuit Television inspections of the South Dunedin storm and wastewater networks have found the pipe work to be pervasively cracked and frequently butt-jointed (i.e. pipe lengths lain end-to-end with no socket enclosing the joint). Consequently, the potential for infiltration to these pipes is high (ORC, 2012a).[19] This is demonstrated in Figure 24 which shows inflows to the Tahuna wastewater treatment plant during the June 2015 flood event. The intention is that the wastewater network should not receive higher flow volumes after rainfall, as surface runoff is supposedly directed to stormwater pipes. However, Figure 24 shows that inflows increased from a background level of 200 litres per second (l/s) early on 3 June to 3,500 l/s by midday. This increase occurred over a seven hour period, and commenced within half an hour of the first heavy rain falling.

[19] *Infiltration* is where groundwater enters the network through leaky pipes and manholes. It is noted that water can also enter these networks directly through flooded gully traps, stormwater – wastewater cross connections, roof downpipes and submerged manhole lids (collectively known as *inflow*). See also definitions in section 7.

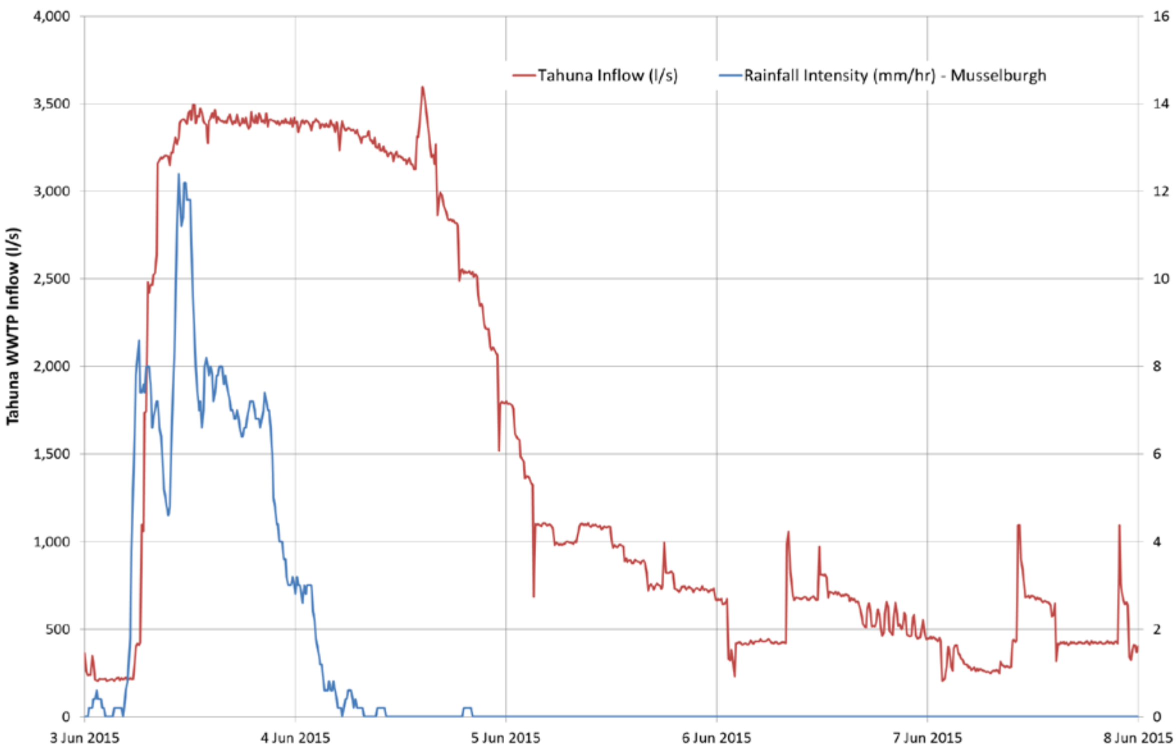


Figure 24. Inflow to the Tahuna wastewater treatment plant and rainfall intensity, 3/6/15 to 7/6/15.

A similar situation was observed by Fordyce (2013), who compared wastewater pipe flow at Botha Street in Tainui, the water table elevation at Lochend Street (Figure 18), and Musselburgh rainfall (Figure 16). Fordyce concluded that at this location, peaks in the wastewater pipe flow appear to coincide more closely with groundwater elevation than the rainfall itself (Figure 25). This suggests that increased flows in the piped network result from the increased pressure experienced when the water table becomes elevated.

Fordyce repeated this investigation in the central part of the plain at East Avenue (Figure 18), but found no significant response in wastewater flow volumes following a rise in the water table. A possible explanation for this is that the wastewater pipes surrounding East Avenue are generally newer, and therefore less prone to infiltration than the older pipes in Tainui. Fordyce was not able to confirm this however. It is noted that this work was undertaken during a short period of time, when groundwater levels and rainfall totals were not particularly high. Other antecedent conditions may result in a different response in wastewater flow.

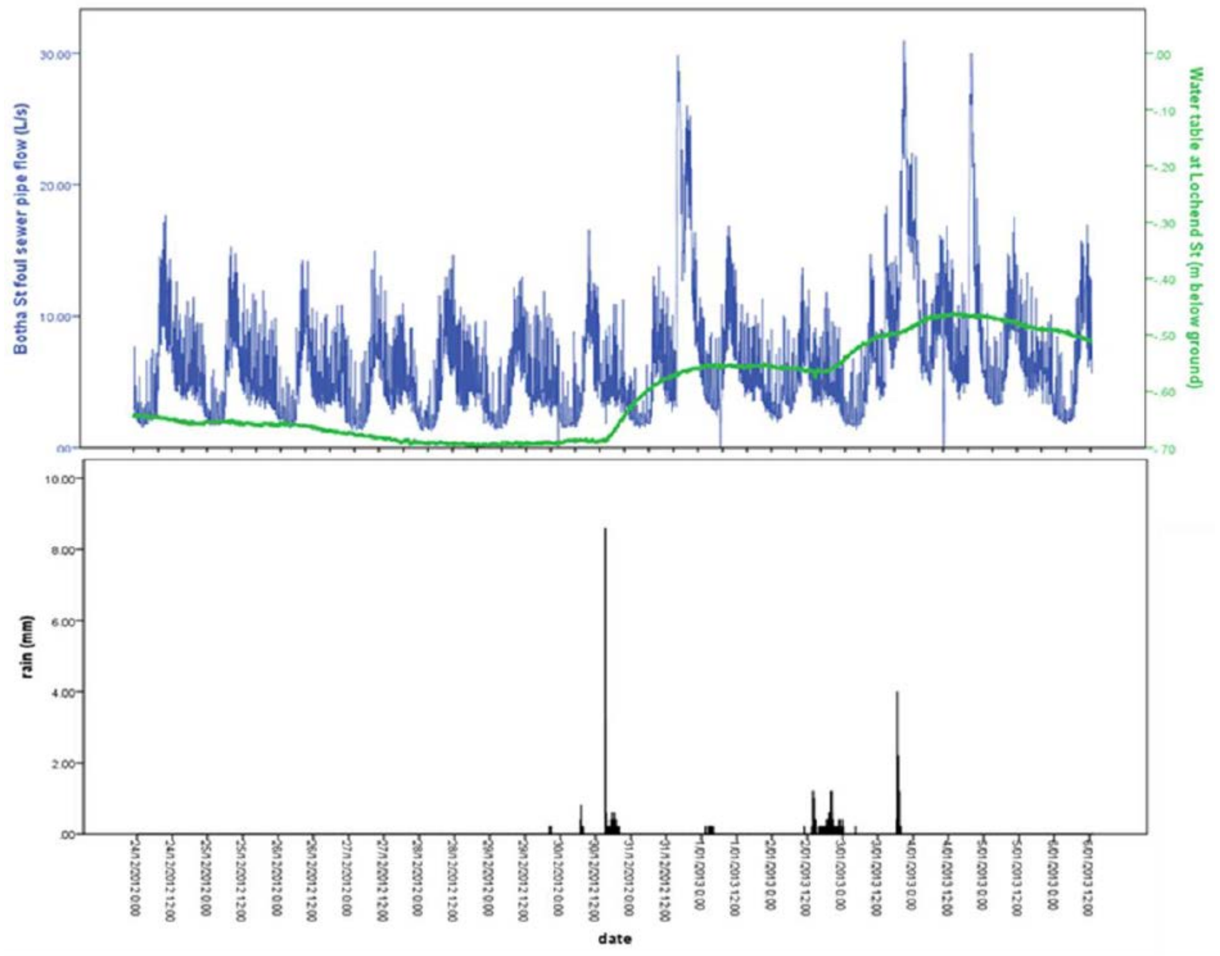


Figure 25. Graph of wastewater pipe flow at Botha Street (blue line), groundwater elevation at Lochend Street (green), and rainfall (black) between 24/12/12 and 6/1/13. Source: Fordyce (2013).

The two examples above demonstrate that infiltration of groundwater into the storm and wastewater networks fortuitously helps to suppress the water table, preventing surface ponding under normal conditions (ORC, 2012a). While these networks aid the drainage of South Dunedin's groundwater under dry conditions, their ability to drain groundwater rapidly diminishes during heavy rainfall events, meaning the water table rises and water ponds on the surface, for up to several days at a time.

2.7. Groundwater levels

This section summarises the long-term monitoring data collected by ORC from South Dunedin groundwater bores, with daily rainfall totals at Musselburgh also shown. There has been no significant change in median annual groundwater levels since monitoring commenced, which is not surprising given the short record and the variable influence of rainfall from year to year.

2.7.1 Kennedy Street groundwater bore

The Kennedy Street bore is situated just 115 m inland from the coast, and groundwater level at this site is influenced by sea level (Figure 23) and rainfall (Figure 26). The range of groundwater levels has remained relatively consistent since installation in 2009, apart from a peak during the June 2015 storm event, where groundwater level was above the level of the ground for about 7 hours,[20] and a three month period of relatively low levels following that event.

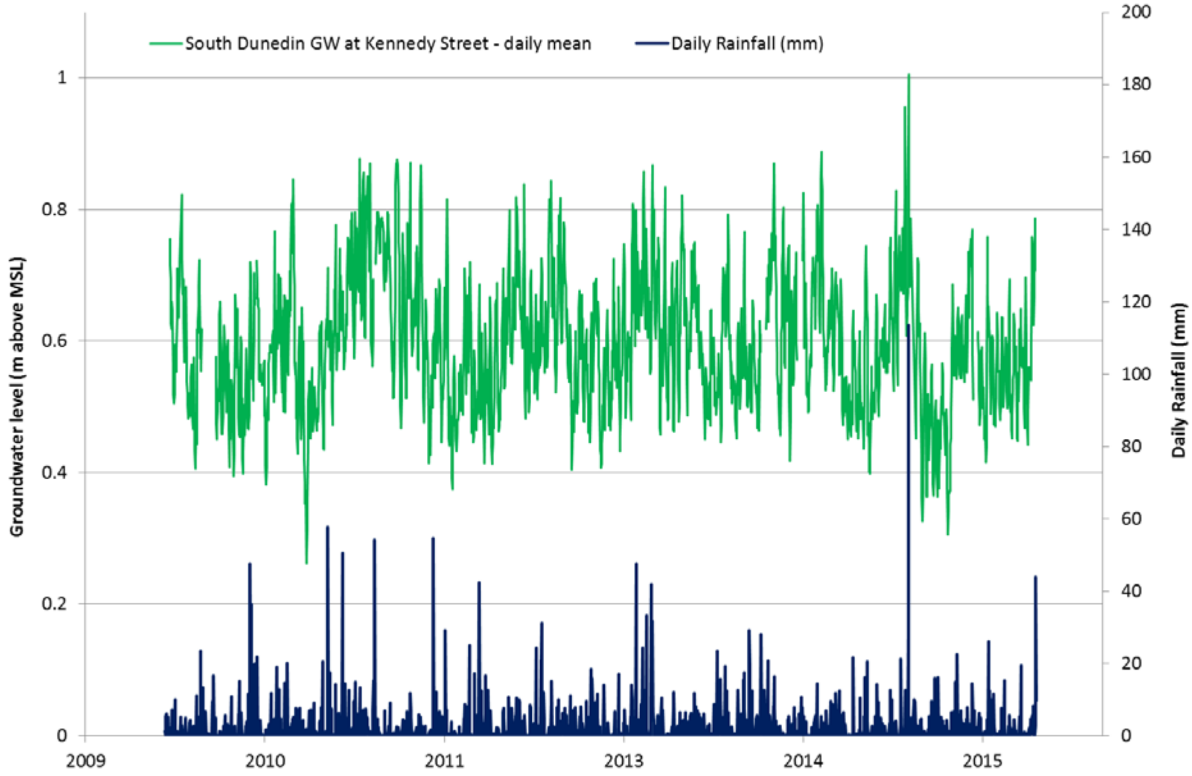


Figure 26. Kennedy Street daily mean groundwater record (12/10/9 – 22/5/16),[21] compared to daily rainfall totals at Musselburgh. The surveyed level of the bore collar is 1.41 m above MSL.

[20] Although the 15 minute readings were above ground level during this 7-hour period, daily mean groundwater on the 3 June (as shown in Figure 26) was less than the surveyed level of the bore collar

[21] Daily mean groundwater level is used for this graph to show trends more clearly, as the continuous data is 'spiky' with a regular pattern due to tidal influence.

2.7.2 Culling Park ground water bore

The Culling Park bore is situated in eastern St Kilda, ~0.6 km from the Pacific Ocean and 1 km from the upper harbour, and it has a shorter record than the other three bores. As at the other bores, groundwater level is affected by rainfall, with the largest single rise observed as a result of a relatively modest rainfall event in May 2016 (Figure 27). Groundwater level also rose rapidly during the June 2015 storm event, and was above the surveyed ground level for about 19 hours. Groundwater level continued to recede following that event, with occasional upward spikes due to rainfall events. Prior to the rainfall-induced rise in May 2016, groundwater level had fortuitously dropped to its lowest level on record, and was about 0.3 m below MSL.

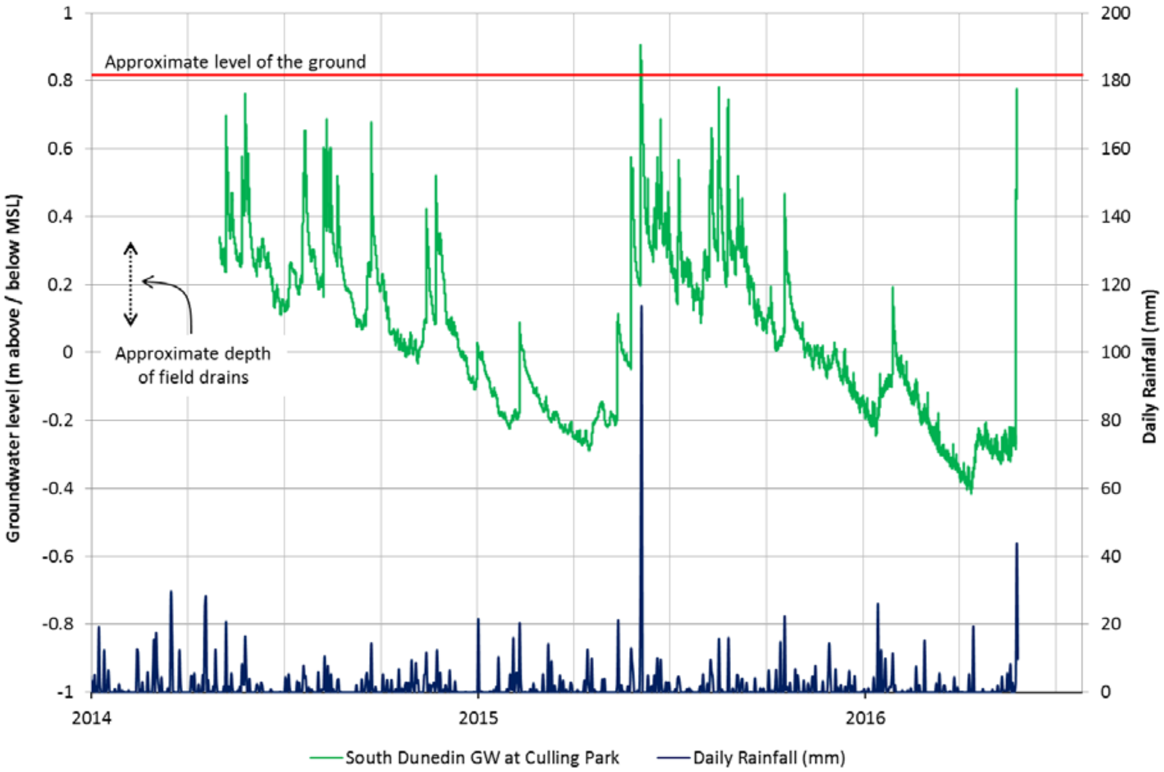


Figure 27. Culling Park groundwater level (2/5/14 – 23/5/16), compared to daily rainfall totals at Musselburgh. The surveyed level of the bore collar is 0.83 m above MSL (Figure 17).

Groundwater level is often below MSL at the Culling Park bore. This situation would not be expected to occur naturally (Rekker, pers. comm., May 2016), and the drainage system network (storm and wastewater) is probably acting to suppress groundwater level in this area. In addition, seven 100 mm diameter field drains, buried 0.5 to 0.75 m below the ground (as shown in Figure 27) drain water from Culling Park into the stormwater network.

Both stormwater and wastewater drain towards the lowest part of the South Dunedin plain at Tainui, and are pumped (i.e. lifted) from there either to the Otago Harbour[22] or the Pacific Ocean.[23] These pumping stations (Figure 3) have probably helped to relieve drainage problems which affected the area previously (e.g. Figure 28). Much of the aged waste- and stormwater pipe system in eastern St Kilda is due for replacement over the coming two decades (Figure 48 and Figure 49). This would reduce the ability of groundwater to infiltrate into these networks and subsequently be removed by pumping, so groundwater level might

[22] Stormwater, via the Portobello Road Pumping Station
[23] Wastewater, via the Tahuna Wastewater Treatment Plant

be expected to increase as a result.

Although the median depth to groundwater is about 0.8 m at the Culling Park bore, the depths were observed over a six-month period by Fordyce (2013) at two nearby bores (Lochend Street and Tahuna Road - Figure 18) were shallower, and less than 0.5 m.

Figure 28. Ponding of surface water at south end of Normanby Street, April 1923, following heavy rainfall. This area was not badly affected in the June 2015 flood. Source: Otago Daily Times.

2.7.3 Tonga Park groundwater bore

The Tonga Park bore is situated about 1 km inland from the coast and 2 km from the upper Otago Harbour. The pattern of groundwater fluctuation is similar to that of the rainfall, where groundwater levels rise rapidly in response to heavy rainfall, with a gradual recession during extended periods of low rainfall.

Since 2009 the range of groundwater levels has been relatively consistent, although there was an overall recession of almost a metre from the peak in June 2015 to April 2016 (Figure 29). The measuring equipment at this site recorded water levels higher than ground level (i.e. surface ponding) on nine occasions between October 2009 and May 2016 (a total of 14.2 days, or 0.6% of the time). It is possible that the site was measuring the level of surface ponding on those occasions however, and work is underway in 2016 to ensure that the monitoring data reflects actual groundwater level, even during times of heavy rainfall. As a result of the 55 mm of rain which fell on the 22nd and 23rd of May 2016, there was another upward spike in groundwater level, which peaked just 0.01 m (1 cm) below ground level.

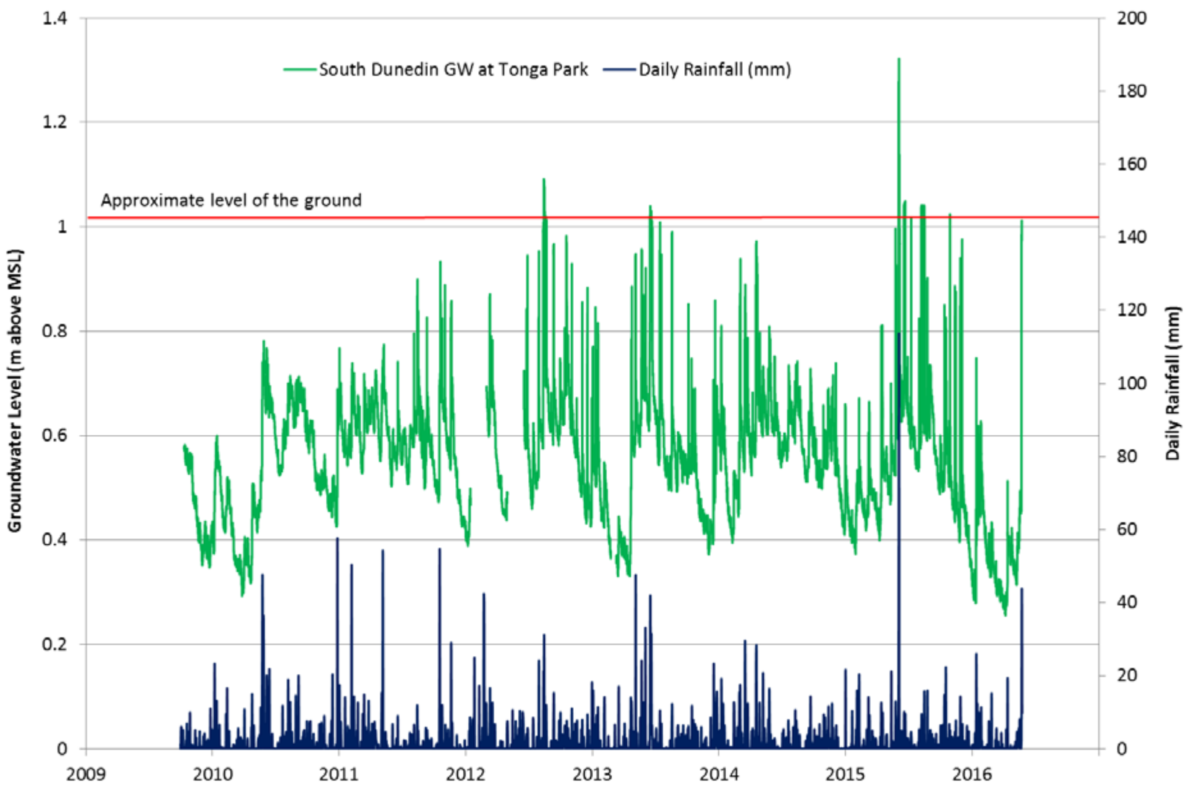


Figure 29: Tonga Park groundwater record (12/10/09 – 23/5/16), compared to daily rainfall totals at Musselburgh. The surveyed level of the bore collar is 1.02 m above MSL.

2.7.4 Bathgate Park groundwater bore

The Bathgate Park bore is situated approximately 1.5 km inland. As for the other bores, groundwater levels are influenced by heavy rainfall or periods of extended low rainfall by rising and falling respectively. Groundwater level has not risen above ground level during the period of record (Figure 30).

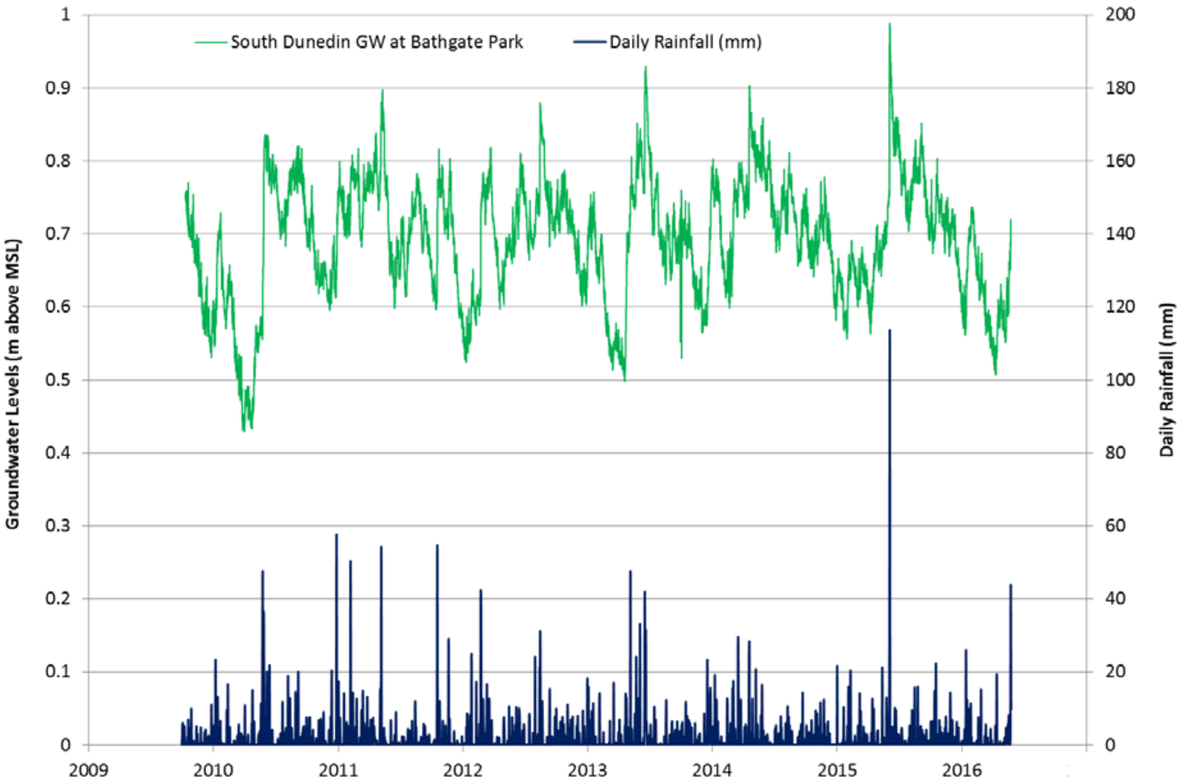


Figure 30: Bathgate Park groundwater record (12/10/09 – 23/5/16), compared to daily rainfall totals at Musselburgh. The surveyed level of the bore collar is 1.52 m above MSL, and is elevated about 0.25 m above the average ground surface in this area (Figure 20).

3. Natural Hazards of South Dunedin

3.1. Groundwater hazards

Flooding in South Dunedin due to heightened groundwater levels after heavy rain has been recognised as an issue for some time, and this issue was highlighted by data from the June 2015 flood (ORC, 2015). Section 2.7 shows clearly the link between heavy rainfall events and groundwater rise, and section 2.6 indicates the connectivity between sea level (e.g. tidal fluctuations) and groundwater levels. These factors, as well as the influence of a stormwater network that is constrained by a small difference in elevation across the South Dunedin plain, mean that natural drainage of the area is severely limited. The hazards posed by groundwater include circumstances where it lies so close below the ground surface that it greatly restricts drainage, or even worse, where groundwater rises so high that it seeps out onto the ground surface. The potential groundwater hazards, combined the high population density of the area, serves to enhance the severity of flood risk in South Dunedin during high intensity rainfall events, especially in winter when the groundwater is naturally closer to the ground surface.

3.2. Changes in sea level and the land surface

3.2.1 Sea level rise

Sea level at Dunedin, relative to the land, has increased over at least the last century, and Hannah and Bell (2012) found an increase in annual mean sea level of 1.3 +/- 0.1 mm/year at Dunedin wharf between 1900 and 2008 (Figure 32). Figure 33 shows recent (2003 to 2015) changes in annual mean sea level at ORC's Green Island sea level recorder (Figure 31), and at the Dunedin wharf tide gauge.

Figure 31. Green Island, off the coast of Dunedin (see Figure 16 for location). The red arrow shows the location of the sea level recorder (inset).

Significant changes in global sea level are predicted for coming centuries, in addition to the smaller increases that have been observed to date. However, it is important to note that there are two main factors which will influence the effects of sea level on the South Dunedin plain into the future:

1. Changes in the level of the sea, and
2. Changes in land surface elevation (such as may result, for example, from consolidation of the sediments that underlie the South Dunedin plain, or broader-scale tectonic changes).

The 'relative' rate of sea level rise is the combination of these factors – for example, if the global sea level is rising (known as *absolute* sea level) and the local land is subsiding, then the relative rate of increase will be greater than that due to global sea level rise alone. What is measured at sea level recorders, including the Dunedin wharf tide gauge, is *relative* sea level.

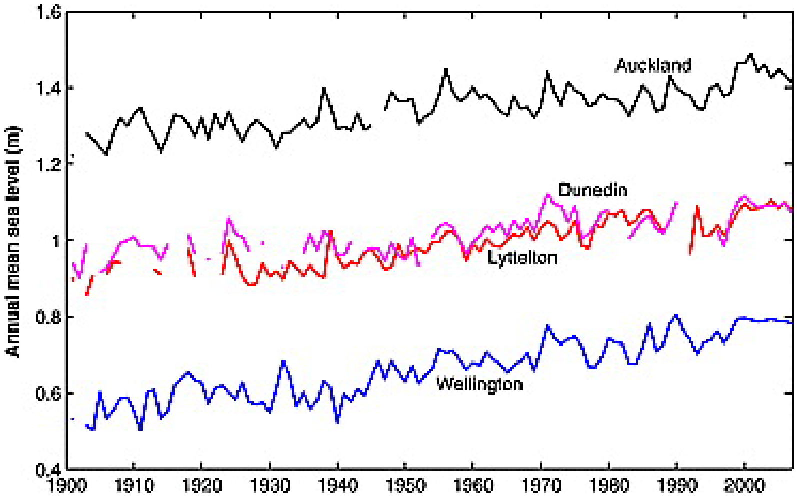


Figure 32. Annual mean sea level time series to 2008 from the four primary tide gauges in New Zealand (Auckland, Wellington, Lyttelton, Dunedin). Source: Hannah and Bell, 2012. These are relative levels, and are not corrected for local land elevation change (if any).

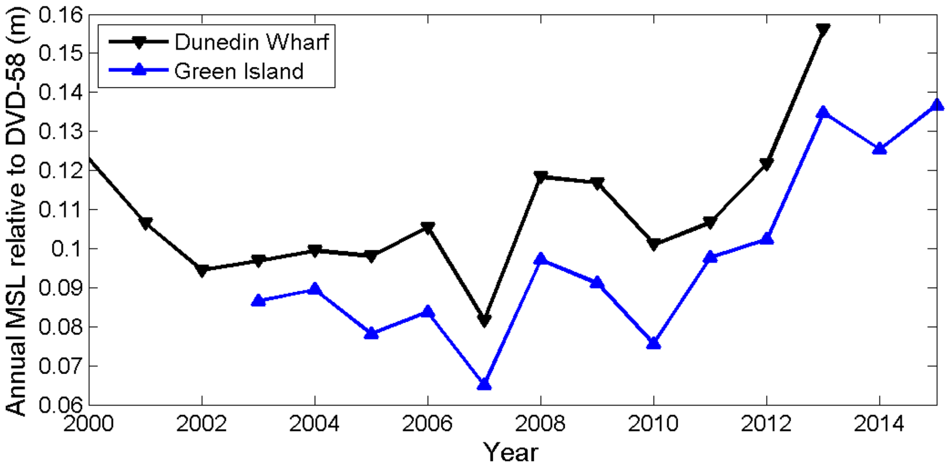


Figure 33. Annual mean sea level, relative to the MSL datum,[24] at the Green Island and Dunedin Wharf sea level recorders, 2000 to 2015. Source: NIWA, 2016. These are relative levels, and are not corrected for local land elevation change (if any). Fluctuations year-to-year are primarily due to variations in ocean temperatures and currents, with the ocean water experiencing thermal expansion during warmer episodes, reflecting El Nino / La Nina patterns.

[24] DVD-58 (see definitions in section 7)

Projections provided by the Intergovernmental Panel on Climate Change (IPCC) (Church et al, 2013) are that global mean sea level (that is, *absolute* sea level, not including any land elevation changes) will continue to increase throughout the 21st century, (Figure 34). The IPCC projections are based on four scenarios, each of which is based on a different Representative Concentration Pathway (RCP) – a trajectory over time of greenhouse gas emissions in the atmosphere. The greater amounts of sea level rise are projected under the 'very high greenhouse gas emissions' scenario (RCP8.5), and lower amounts under the 'stringent mitigation' scenario (RCP 2.6). The latest IPCC advice is that "it is virtually certain that global mean sea level rise will continue beyond 2100".

The ORC has developed a model to help identify where surface ponding, as a result of sea level rise, will start to affect the South Dunedin community (section 4.1). The model includes sea level rise scenarios of up to 0.6 m, but it is possible that sea level rise will eventually exceed this level.

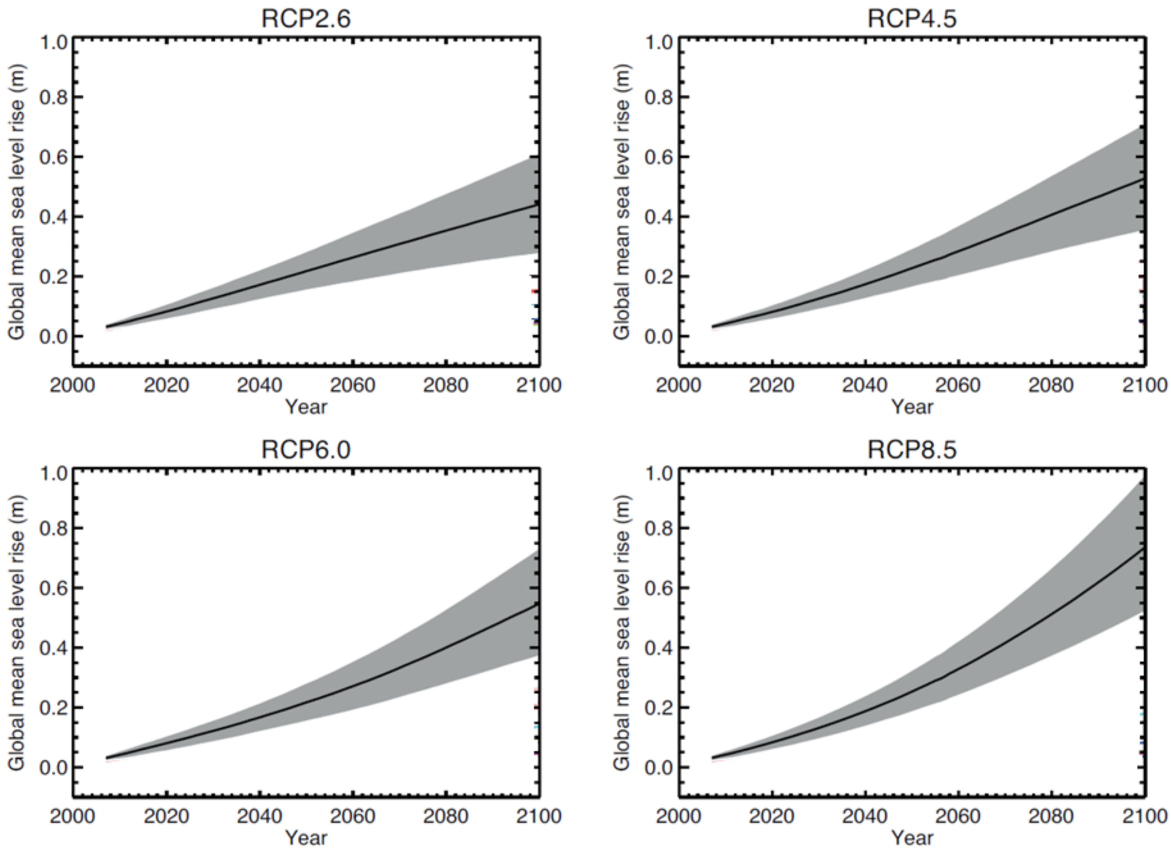


Figure 34. Projections of global mean sea level rise, relative to 1986-2005, for four IPCC scenarios (RCP 2.6, 4.5, 6.0 and 8.5). The grey bands represent the range within which actual sea level is predicted to increase, under each scenario. Adapted from Church et al. (2013).

3.2.2 Changes in land surface elevation

The University of Otago School of Surveying has been collecting data from a series of high-precision GNSS[25] survey stations since about 1996, with three of relevance to the Dunedin area at Port Chalmers, Highcliff Hill and the School of Surveying. GNSS observations up to 2012 for the Port Chalmers site (since 2000, but with a data break for 2009 and most of 2010) and the School of Surveying sites (since 1996) indicated an overall downward movement trend of 0.72 ± 0.29 mm/yr and 0.52 ± 0.30 mm/yr respectively (Fadil et al. 2013). Ongoing data collection (P. Denys, University of Otago, pers. comm., May 2016), indicates, from the lengthening data series, that the School of Surveying site has been going down at an average rate of 0.77 ± 0.11 mm/yr since 1996, somewhat more than the 2012 estimate. Continuing data from Port Chalmers indicate an overall average downward motion of only 0.20 ± 0.13 mm/yr since 2000, notably less than the preliminary estimate made in 2012.

Superimposed on these average overall motions are apparent upward movements that are modelled as coinciding with very large, distant, earthquakes from the Fiordland area (2009 Dusky Sound Earthquake, magnitude 7.8) and farther south (2004 Macquarie Ridge Earthquake, magnitude 8.1). The GNSS data appear to indicate that the earthquake events have caused uplift in the Dunedin region of as much as 5 mm per event. If one removes the effects of those indicated uplift events, as described by Fadil et al. (2013), the background rate of downward motion at each site is greater. Without the distant earthquake effects, the background downward motion at the School of Surveying site is 1.31 ± 0.11 mm/yr (P. Denys, University of Otago, pers. comm., May 2016). These estimates remain provisional, pending further analysis and the continuing collection of data.

Short-term measured rates of downward motion are similar to the magnitude of long-term (since 1900) relative sea level rise measured by the Dunedin wharf tide gauge. A report by Beca (2014), noted that “land in New Zealand is rising approximately 0.5 mm/year”. However, this is a very broad generalisation, because extensive sectors of the coast, for example the eastern Canterbury Plains, and the Marlborough Sounds, are known to be sinking. The GNSS results from the Dunedin area highlight the importance of obtaining local measurements, rather than relying on broad generalisations.

Modelling of satellite radar data is presently being carried out by GNS Science, as part of a Natural Hazards Research Platform project “Unknown faults under cities”. The first unpublished results using data from the Envisat satellite captured between 2003-2010 suggests land elevation changes may be measurable, at rates above the ±2 mm/year limits of detectability, and that some areas on the reclaimed land around the Otago Harbour margin may have been subsiding during that 7 year period at rates between 2 mm and 5 mm per year. Work has yet to be done to understand to what extent changes in land elevation are driven by tectonics, or by changes in land elevation associated with consolidation of the ground (S. Cox, GNS Science, pers. comm., May 2016).

The Otago Regional Council, together with the School of Surveying is preparing a permanent high-precision GNSS device for installation at the Green Island sea level recorder in August 2016 (Figure 31). This will determine if there are changes in land elevation occurring at this site, and help in the assessment of the relative contributions of land subsidence and changes in sea level to ‘relative sea level rise’ at that site. It is likely that it will take at least 2 years of GNSS data collection before any provisional trends will be detectable, and at least 4 years

[25] GNSS “Global Navigation Satellite System”. Generic term for satellite-based survey systems of which the GPS system is one. GNSS surveying can access a wider range of satellites than just those of the GPS platform.

before definitive trends emerge.

It is important to note that the present data on land elevation changes are very preliminary, and are the subject of ongoing research and assessment, as part of the GNS Science Natural Hazards Research Platform project, for example. Of particular note is that none of the current GNSS survey stations are located in South Dunedin itself, and the wider local significance of the data collected so far needs further evaluation, for example, whether they can be regarded as representative over longer term periods, such as decades to centuries. If the indications of sinking of the land measured at the GNSS stations is also affecting the South Dunedin area, then it can be expected that the rate of *relative* sea level rise will be faster than currently indicated by IPCC global sea level rise scenarios.

3.3. Seismic hazards

The South Dunedin area is vulnerable to a range of hazards associated with strong earthquake shaking. Historically, eastern Otago has had a very low level of seismicity compared to other parts of New Zealand, with very few earthquakes centred beneath the area (Barrell et al. 2014). However, there are several known faults in the Dunedin area that have potential to generate large earthquakes, and which could have significant consequences for the South Dunedin plain (Murashev and Davey, 2005). There may be direct negative impacts, such as damage to buildings from seismic shaking, or indirect impacts such as an increased flood hazard due to liquefaction-related land subsidence. Conversely, it is possible that earthquakes could produce some uplift of the land, that may be beneficial to flood hazard, for example.

3.3.1 Earthquakes

The South Dunedin plain may be affected by earthquakes on nearby faults, as well as large earthquakes that occur on faults located as much as several hundred kilometres away. The 2010 Darfield Earthquake, centred in Canterbury, resulted in some minor damage to property in the Dunedin area. It is moderate to large earthquakes on nearby faults that are expected to cause the strongest shaking and most damage (Stirling et al. 2012).

The only significantly damaging earthquake recorded in the Dunedin area occurred in 1974, and had a moment magnitude (M_W) of 4.9. This earthquake resulted in about 3,000 claims to the Earthquake and War Damages Commission (now EQC), and these were concentrated in the area underlain by poorly consolidated sediments in South Dunedin, with at least half involving damage to chimneys (Murashev and Davey, 2005). The epicentre of this earthquake was reported as being 7 km offshore to the south of St Kilda. The cost of this earthquake was estimated at $6.1 million.[26]

Earthquakes larger than the 1974 event are possible, and would be expected to result in significantly greater damage to buildings and infrastructure than the 1974 event, and cause major disruption to the community (Cook et al., 1993). Reclaimed land and alluvial / estuarine areas such as South Dunedin are more vulnerable to seismic shaking, and buried services such as sewers, water pipelines and stormwater pipes can be damaged. Sediment-filled basins such as the broader South Dunedin area have been shown to amplify earthquake shaking in comparison to bedrock sites.

The detailed consequences of a large earthquake close to South Dunedin cannot be estimated with any certainty beforehand, but some guidance can be obtained from the

[26] As estimated by Adams and Kean (1974), and inflation-adjusted to 2015

effects of historical large earthquakes on low-lying coastal towns and cities elsewhere in New Zealand in regard to the types of hazards that could be expected. These include measurable subsidence or uplift of the ground, liquefaction, lateral spread, landslides and rockfalls, as well as the ground shaking itself.

The 2010-2011 Canterbury Earthquake Sequence demonstrated that large earthquakes can occur on faults whose existence was not known about beforehand. This was a major reason for the funding of the current Natural Hazards Research Platform project “Unknown faults under cities” which seeks to identify whether there are any major active faults under the Dunedin area. Hypothetically, if there were to be a large earthquake centred directly under Dunedin, effects similar those observed in the 22 February 2011 Christchurch Earthquake could be anticipated. These might include broad-scale uplift or subsidence of as much as several tens of centimetres, some liquefaction of low-lying areas and associated disruption of foundations and buried services such as tanks and pipes, and rockfall from steep slopes, such as those bordering the margin of the South Dunedin between Forbury and St Clair, and around the Tainui-Musselburgh-Andersons Bay inlet areas..

3.3.2 Liquefaction

The most recent assessment of liquefaction hazard for the South Dunedin plain was in 2014 by Barrell et al. That report identified that, in general, there is a moderate to high likelihood of liquefaction-susceptible materials being present beneath some parts of the plain, due to the presence of extensive fine-grained sediments and a very shallow water table. However, the distribution of liquefaction-prone sediments beneath the plain has not been mapped in a comprehensive manner, as was undertaken in Canterbury following the 2010-2011 earthquake sequence.

The MBIE[27] technical guidance for residential development in Canterbury provides three technical categories (TC) for land: TC1, TC2 and TC3. Land zoned TC3 may suffer moderate to significant land damage from liquefaction, while it is expected that TC1 and TC2 land will experience less damage. In general, in order to build on TC3 land, you must supply the relevant council with a geotechnical report. Building new or replacement buildings on TC3 land may require additional engineering advice and foundation design.

Some of the work undertaken in recent years to understand subsurface conditions at discrete sites on the South Dunedin plain was summarised by MacDiarmid (2016). Results indicate that for moderate levels of peak ground acceleration (PGA)[28], only minor expression of liquefaction would be expected (occasional sand boils, some abrupt differential settlement at the surface), and liquefaction would be unlikely to cause significant damage to residential dwellings designed to modern standards. Based on the limited data assessed by MacDiarmid, it would appear that the liquefaction potential of soils in South Dunedin are comparable to TC1 and TC2 land in Christchurch, although it is possible that TC3 ground conditions might exist.

It should be noted that all but one of the sites tested lie within the north-eastern quadrant of South Dunedin, with a single site near the Musselburgh pumping station. Tests from this south-eastern site, in the lowest-lying part of the plain, indicate the area could experience liquefaction-induced settlement of up to 0.085 m (8.5 cm), in response to moderate PGAs. This level indicates the Musselburgh-Tainui flat is closer to TC3 category land than the other

[27] Ministry of Business, Innovation and Employment
[28] an indication of the intensity of seismic shaking

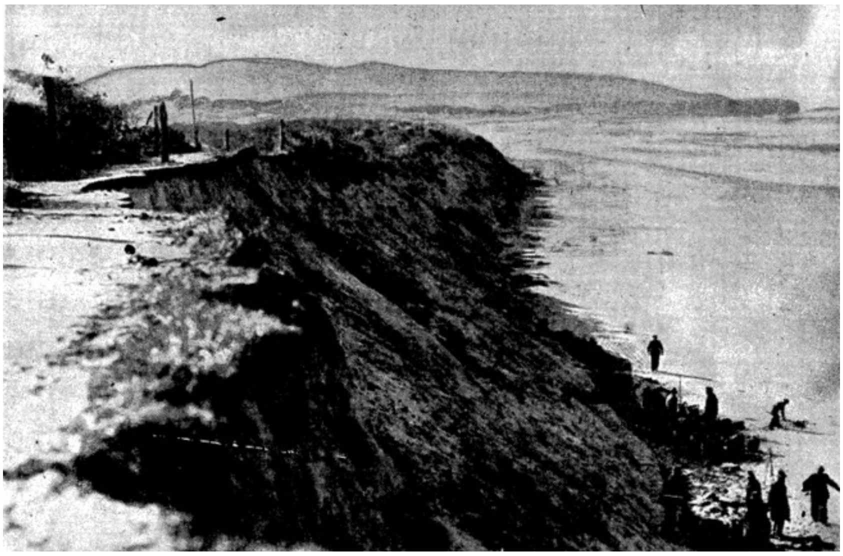
areas tested.

3.3.3 Lateral spreading

Lateral spreading results from liquefaction of underlying sediments, and commonly occurs in ground which is close to the edge of a bank, such as the side of a stream channel, coastlines and artificial embankments (Barrell et al. 2014). A loss of strength in the subsurface due to earthquake-induced shaking causes the ground to translate and stretch horizontally towards a free-face. Barrell et al. (2014) notes "Areas with Domain B or C (such as the South Dunedin plain) that lie close to 'free faces'… may potentially be subject to lateral spreading hazards in the event of…liquefaction-inducing earthquake shaking". Major features in South Dunedin with 'free faces' include the Southern Motorway (SH1) / South Island Main Trunk Line embankment from The Oval to Caversham, the harbour margin beside Portsmouth Drive, and parts of the St Kilda dune system. The lateral spreading hazard from these or any other features in South Dunedin has not been mapped or assessed in any detail.

3.4. Tsunami, storm surge and shoreline change

Previous modelling[29] and experience of storm surge and tsunami indicates that direct inundation of the South Dunedin plain from the Pacific Ocean is unlikely under present conditions, although previous storm events have had significant effects on coastal dunes and beaches (Figure 35). However, if the ability of the St Clair – St Kilda dune system to provide



[29] NIWA (2007,2008)

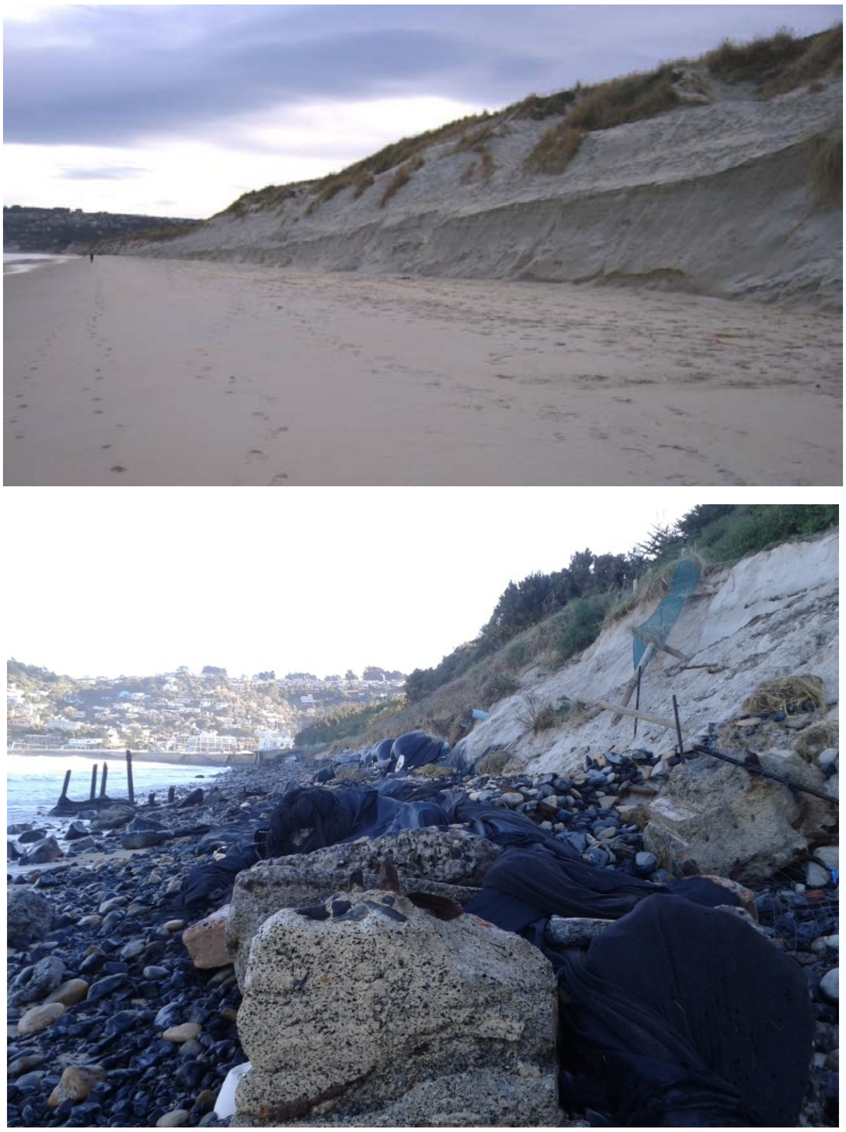


Figure 35. Evidence of erosion following storm events, from top to bottom in 1939 (Dunedin Amenities Society), 2007 (ORC) and the remains of 'sand sausages' in 2015 (ORC)

a buffer against these hazards was diminished, then the vulnerability of people and property in South Dunedin would increase, due to the low-lying nature of this area and its proximity to the coast (Figure 3, Figure 20).

Changes to the dune system may occur over a prolonged period (in response to sea level rise, changes in the supply of sediment, or changes in the frequency and magnitude of storm events), or more rapidly (for example in response to particular events – major storms, earthquake or tsunami). Previous experience shows that significant morphological change can occur during storm events, and efforts to mitigate these effects are generally unsuccessful over the long term (Figure 35).

Recent changes in the seaward position of the vegetated dune area between 2000 and 2013 are shown in Figure 36. During this period, erosion was the dominant process at the western and central portion of the beach, while accretion occurred towards Lawyers Head. The seaward extent of dune vegetation retreated by up to 25 m between the eastern end of the St Clair seawall and the tennis courts on Victoria Road, and Figure 37 further illustrates the effects of the June 2015 storm event in this area.

On the northern margin of the South Dunedin plain alongside the harbour, minor inundation about 0.2 m deep already occurs on a regular basis as a result of normal astronomical tides, with water flowing inland through stormwater pipes and pushing up through man-hole covers (Figure 38 and Figure 39). Modelling by NIWA (2008) shows that large storm surge events may result in inundation depths of 0.5 m or more in parts of Portsmouth Drive, Teviot and Midland streets and low-lying parts of Andersons Bay, under current sea level conditions.

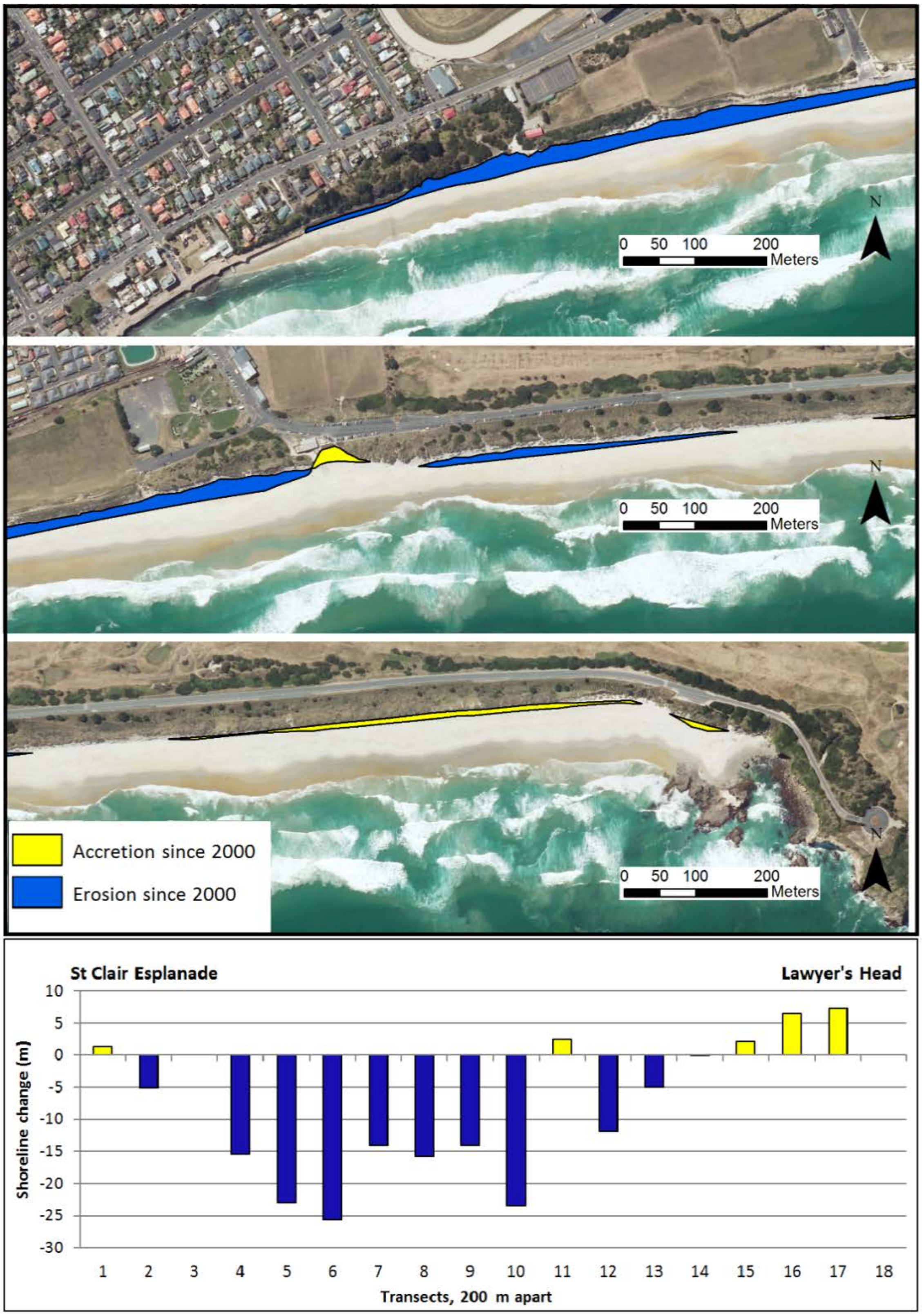


Figure 36. Change in vegetated dune position between 2000 and 2013. The top three panels show St Clair, Middle Beach and Lawyers Head areas and the extent of erosion or accretion of sand on the coastal dune over this period. The lower panel shows the horizontal shift in the seaward edge of the vegetated foredune at 18 transects across the beach.

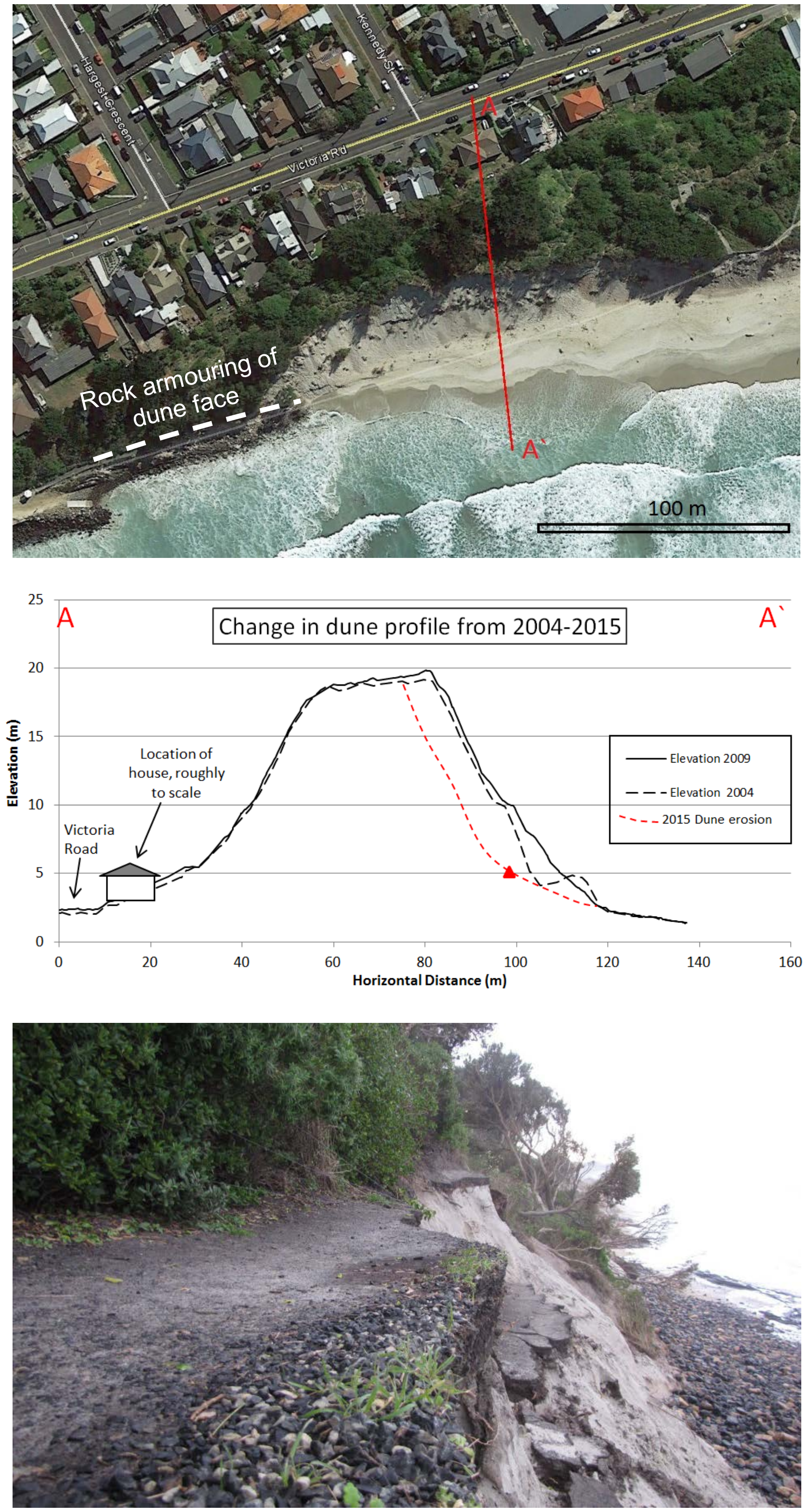


Figure 37. Top: aerial image taken in March 2016 showing recent erosion (mainly from June 2015) of the dune face at the eastern end of the St Clair seawall. Middle: cross-section A-A' from 2004 and 2009 LiDAR (non-ground features such as trees have been removed). The 2015 dune shape was estimated using the location of the dune base after the June 2015 storm, and assuming a similar pre- and post- storm slope on the dune face. Bottom: Photo taken immediately after June 2015 storm event, looking east along the beach (Source: Otago Daily Times).

Figure 38. Inundation on Teviot Street, June 2013, resulting from natural astronomical tides, in this case a particularly high king tide event. (Source: Otago Daily Times)

Figure 39. Sea water rising up through the stormwater system on Teviot Street at about high tide, 2:30pm on 6 May 2016. The pressure in the stormwater pipe below this man-hole cover is such that it has pushed water up above ground level. This was not the highest tide experienced during that month. Photograph source, ORC.

3.5. Section summary - the current hazardscape of the South Dunedin plain

The ‘hazardscape’ of the South Dunedin plain has been described using a range of information, including local topography, previous investigations of natural hazards, observations and local knowledge, and monitoring data. The physical characteristics of the plain include its low-lying topography, poorly-consolidated underlying sediments, proximity to the ocean and harbour, a shallow aquifer with strong connectivity between sea and groundwater,[30] and a history of heavy rainfall events with associated surface runoff. These characteristics mean that the hazard which is most likely to affect the South Dunedin plain is water ponding on the surface (i.e. flooding).

When combined with the intensive land-use across the South Dunedin plain (including residential, commercial and industrial activities), and its important infrastructure and transport links, the area has a high vulnerability to flooding and other natural hazards. In addition, limited experience of the full range of effects from high magnitude, low frequency hazards such as earthquakes and tsunami means that we do not have a complete picture of this vulnerability.

This section has also described observed and projected changes in sea level and the land surface. Over time, sea level rise will further exacerbate the effects of flooding and surface water ponding on the South Dunedin plain. If the initial findings of possible land subsidence are confirmed, then these effects would be further compounded, and be felt sooner than expected. Similarly, any increase in the frequency of heavy rainfall events may result in more regular flooding of houses and other assets, especially if that trend was to occur in combination with other processes such as sea level rise.

Based on the physical characteristics described in this report, it seems likely that future changes in relative sea level and climate will increasingly affect the performance of infrastructure (particularly buried services such as storm and wastewater pipes), and other assets such as roads, houses and other buildings, across the South Dunedin plain. As described in section 4.1, these effects will vary across the plain, with some areas more vulnerable than others.

[30] It is noted that there are knowledge gaps about the detail of the subsurface geological structure and deep groundwater (section 2.6). These uncertainties may affect technical solutions to hazard modelling and mitigation.

4. Future environmental changes

This section describes projected changes in the hazards associated with:

i. changes to groundwater levels due to increases in relative mean sea level, and
ii. direct inundation from the Otago Harbour onto the northern part of the South Dunedin plain.

It is noted that other changes which could occur in the physical environment are not described here. Examples include liquefaction or settlement of soft sediments during earthquake shaking, broader shifts in ground elevation or drainage due to a nearby large earthquake, or significant shoreline change between St Clair and Lawyers Head. Section 3 summarises the current state of knowledge regarding natural hazards and the physical environment, and demonstrates that residual risk associated with some hazards is significant.

4.1. Changes to South Dunedin groundwater levels

Model Description

A computer model of the aquifer which lies beneath South Dunedin has been created (ORC, 2012a). The aquifer model is 'contained' by impervious bedrock which lies to the east (Otago Peninsula), west (Dunedin hill suburbs), and at depth beneath the plain (Figure 4), but is connected to the Pacific Ocean and Otago Harbour to the south and north respectively. The best available knowledge was used to estimate the rates at which water will recharge and pass through the aquifer. The influence of the DCC's current network of stormwater pipes (which drain to the Portobello Road or Tainui pumping stations - Figure 3) was integrated into the model, but the effect of other drainage networks (such as wastewater pipes, and drains beneath sports fields) was not incorporated.

The base level for the model was the 2003-2015 mean sea level, as measured at the Green Island sea level recorder, and this level was progressively raised to simulate the effects of an increase in mean sea level. An additional scenario of a 0.6 m rise in mean sea level was also modelled, which was not presented in the ORC (2012a) report.

A series of maps showing the extent of ponding above the ground, due to the influence of rising mean sea level on the South Dunedin aquifer, are presented below. It is noted that the actual extent of ponding, as shown for each scenario, will vary over time, depending on rainfall and groundwater level, and the maps show the 'average' extent of ponding under different mean sea level rise scenarios. Therefore, land which is not shown to be affected by ponding may also be vulnerable to rising groundwater, either by inundation during times of heavy rainfall, or by groundwater levels which are just below the ground surface.

It is important to realise the exact details of the model outputs are strongly dependent on the data available and inclusion of features such as leakage to stormwater drains, which may change. The models serve to highlight that groundwater-surface water interaction is complicated. It cannot simply be assumed that inundation will directly relate to elevation of land relative to sea level. Instead, inundation reflects a balance between supply of water by recharge, runoff, land elevation and storage within the aquifer. Further discussion of the original model parameters, model calibration and potential pitfalls is included in the ORC (2012a) report, which can be accessed on the ORC website. That report includes the original model output images. In April 2016 the model was refined to reflect 2015 sea level data, artefacts around the harbour margin were removed, and recent groundwater levels from

ORC bores used. The model was run again using the same software, by the author of the original report. The refined model outputs are shown in Figures 40 to 43.

The boundaries of the five main Census Area Units (CAU's) which comprise the bulk of the South Dunedin plain (as described in section 5) are also shown, to aid in the description of the likely effects across the plain.

Spatial variability – comparison with Beca (2014)

The extent of above-ground ponding on the South Dunedin plain due to increases in mean sea level was also mapped by Beca (2014), using a different method to that used by ORC. The Beca report compared ground levels with a range of future sea levels, and made the following assumptions:

i. groundwater level is about 0.6 m above the MSL datum across the whole South Dunedin plain, and
ii. that this relationship will remain constant as mean sea level increases.

Data from the Culling Park bore were not available when the Beca report was produced. The additional data from this site (and other bores) show that the first of these assumptions is not valid for the entire aquifer, with average groundwater levels at, or below MSL on the eastern side of the plain (section 2.6).

The second assumption may also be questionable, as infiltration of groundwater into the storm and wastewater networks currently helps to suppress the water table, with water subsequently pumped to either the Pacific Ocean or Otago Harbour (section 2.6.1). This helps to prevent surface ponding under normal (dry) conditions. The effects of this process also appear to be more pronounced on the eastern side of the plain, which is where the pumping stations are located. The relationship between mean sea level and groundwater level is therefore unlikely to be constant,[31] and some parts of the plain will remain 'drier' for longer, due to the influence of groundwater infiltration and pumping.[32]

Therefore, the effects of increased mean sea level will probably vary across the plain. The results from ORC's model show the effects of an increase in mean sea level being more pronounced on the western side of the plain, particularly in areas which are within the current tidal range (less than 1 m above MSL). The ORC model shows the extent of surface ponding to be smaller (but with potential to be relatively deep) on the most extensive area of low-lying land around Tainui and St Kilda East.[33]

[31] The Beca report does note that infiltration rates may increase as groundwater level rise, but the modelling assumed a linear relationship between sea and groundwater levels.
[32] Note that this assumes that the current rates of infiltration continue
[33] Appendix 2 shows an example of the results from the Beca report, for a 0.3 m increase in mean sea level. The extent and depth of inundation differs significantly from that shown for a similar mean sea level increase, as modelled by ORC (Figure 41).

Model results

Scenario 1: Mean sea level increases by 0.11 m. Under this scenario, the ORC model shows ponding up to 0.2 m deep in Forbury and South Dunedin, which primarily affects land in and around Bathgate and Tonga parks. There is a similar depth of ponding in St Kilda West which includes a residential area between Hargest Crescent and Bay View Road. Ponding in two smaller patches in the Tainui and Musselburgh suburbs (in the Musselburgh CAU - Figure 45) is to a similar depth.

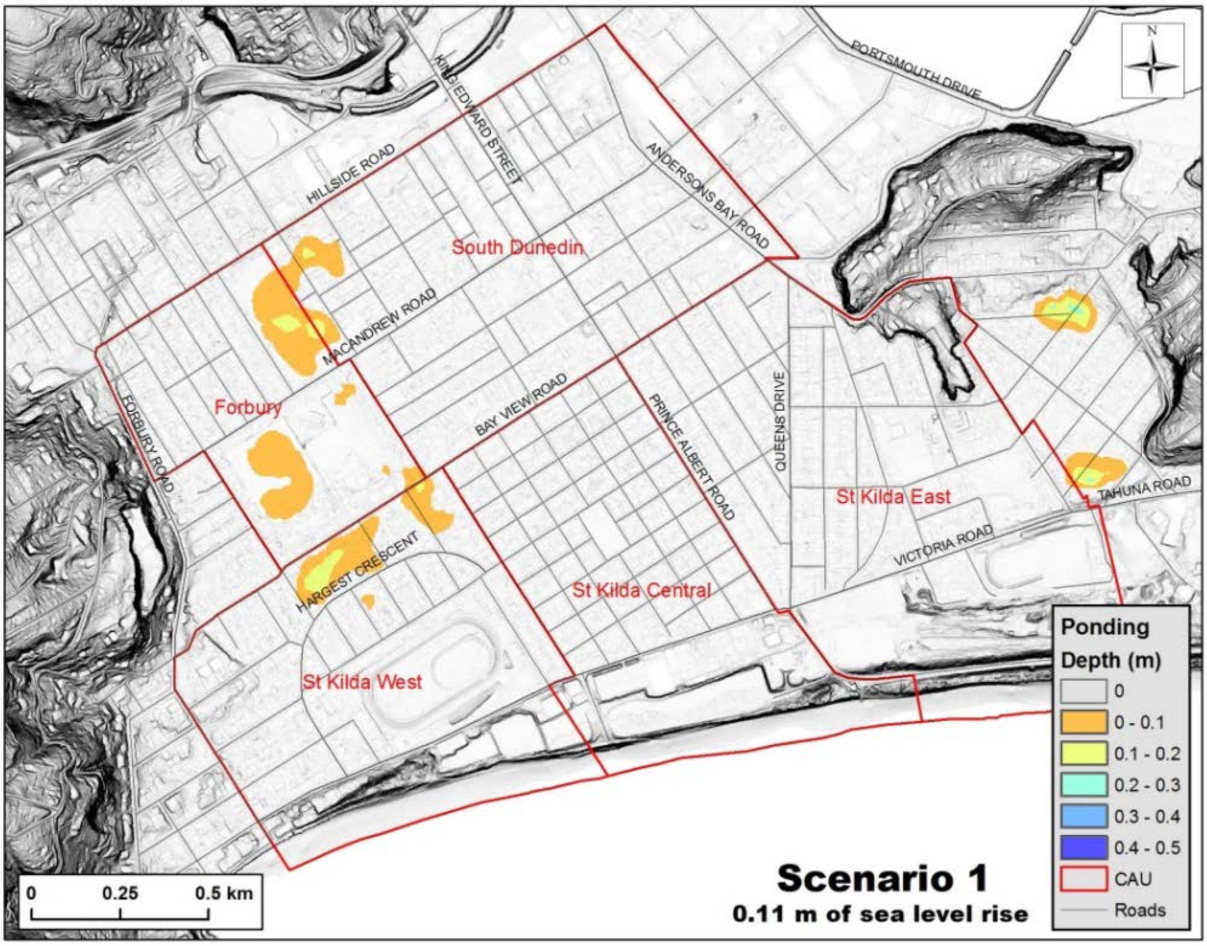


Figure 40. Above-ground ponding for 0.11 m of mean sea level rise, relative to the 2003-2015 average

Scenario 2: Mean sea level increases by 0.28 m. On the western side of the plain the extent of ponding has increased, with more properties affected in the area between Hargest Crescent and Bay View Road. The extent of ponding in Tainui / Musselburgh remains similar to scenario 1, although the depths have increased, up to 0.3 m in some places.

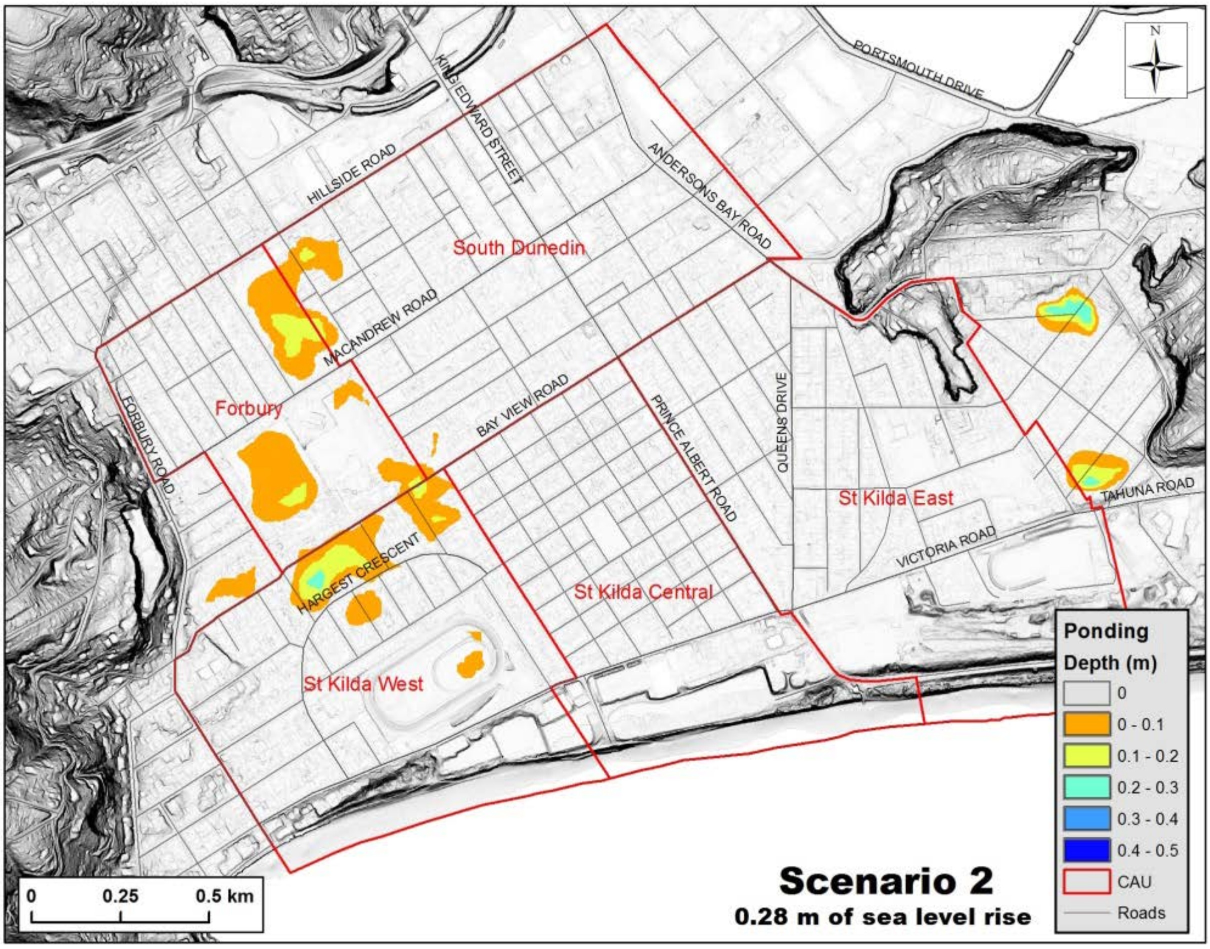


Figure 41. Above-ground ponding for 0.28 m of mean sea level rise, relative to the 2003-2015 average

Scenario 3: Mean sea level increases by 0.4 m. On the western side of the plain the patches of ponding at Tonga Park, Bathgate Park and the Hargest Crescent – Bay View Road area continue to expand, compared to the previous scenario. However, the deepest ponding (up to 0.4 m) is in the east, centred on the Lochend / Ravelston Street area in Tainui.

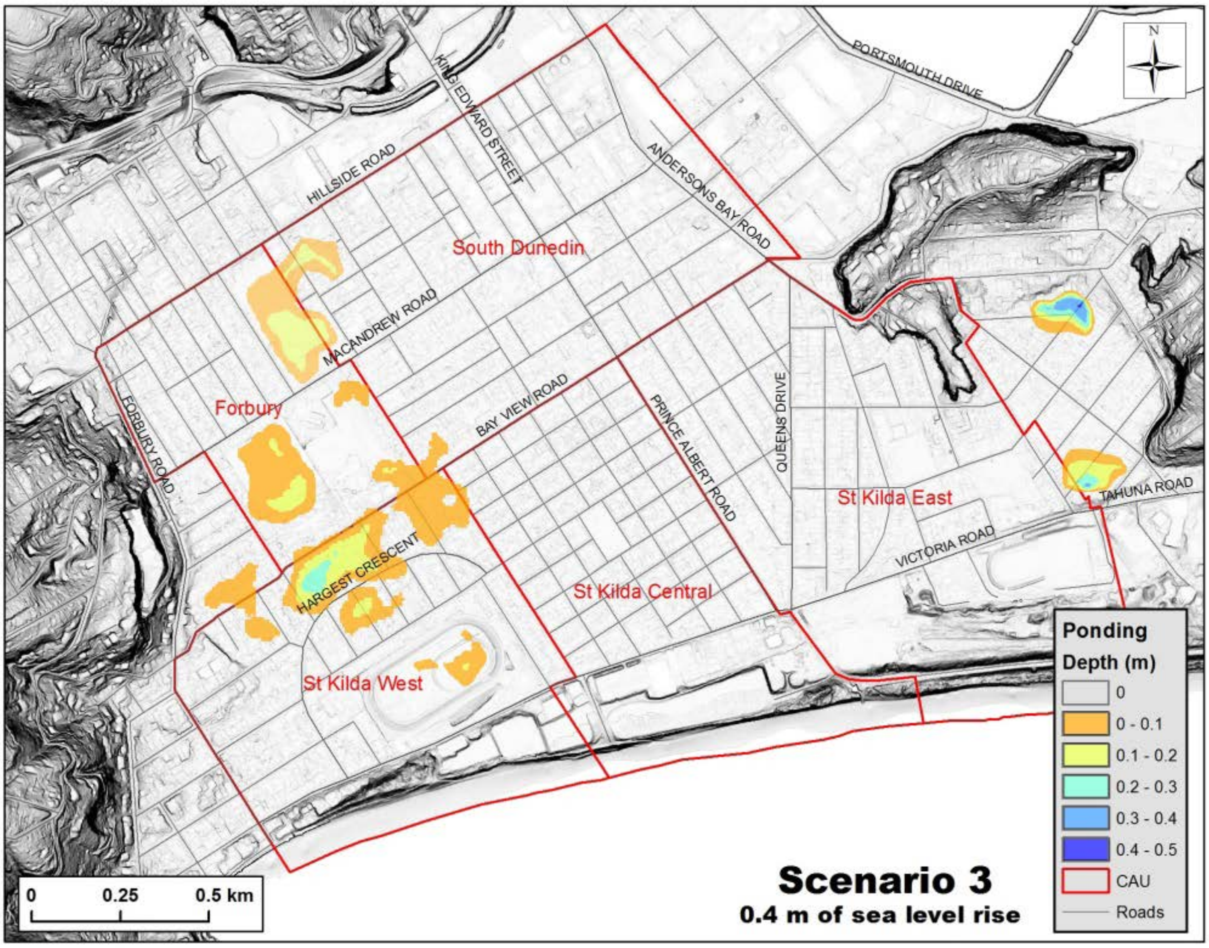


Figure 42. Above-ground ponding for 0.4 m of mean sea level rise, relative to the 2003-2015 average

Scenario 4: Mean sea level increases by 0.6 m. In St Kilda West, the patches of ponding between Hargest Crescent and Bay View Road have spread and coalesced, with depths of ponding approaching 0.4 m. The depth of ponding on Bathgate and Tonga parks has increased. The patch of ponding on Forbury Park Raceway has become larger and deeper, which is likely to be due to the increased influence of higher mean sea levels on low-lying land which is close to the Pacific Ocean. The patches of ponding in Tainui and Musselburgh have also deepened, up to 0.5 m.

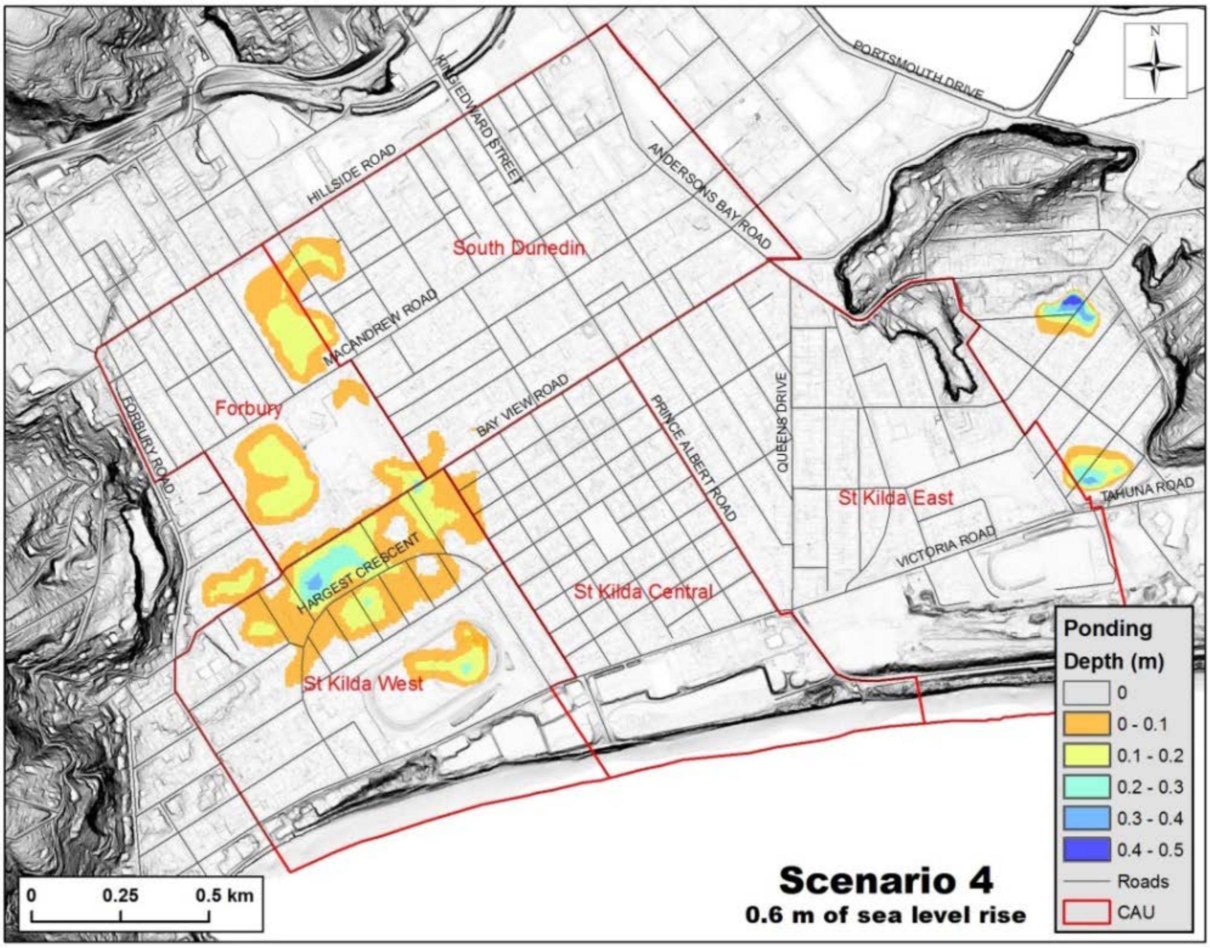


Figure 43. Above-ground ponding for 0.6 m of mean sea level rise, relative to the 2003-2015 average

4.2. Direct inundation from Otago Harbour

Mapping technique

The method used to map areas prone to direct inundation from the harbour is the same as used in a previous assessment of tsunami and elevated sea level (ORC, 2012b). The extent and depth of inundation for a low-magnitude, relatively high-frequency storm surge event is shown in Figure 44. The maps also show the maximum extent of wave run-up, which may extend beyond the inundation zone for some distance, due to the flatness of the South Dunedin plain. Locations within these limits are not predicted to be permanently inundated but may be susceptible to breaking surges. The maps show inundation for a 1:20 year storm surge scenario for current sea level, and with increases of 0.3 and 0.5 m in mean sea level.

It is noted that the extent of inundation will be influenced by local topography in this urban area, which includes buildings, roads and stormwater infrastructure such as kerb and channelling, and gully-traps. Some of these features are likely to have changed since the topographic (LiDAR) information was collected in 2009, and will continue to be modified into the future. Any large-scale changes in ground level will also influence the extent of inundation, as discussed in section 3.1.

Mapping results

The frequency, depth and extent of inundation resulting from storm surge events in the area bounded by Midland and Otaki streets, Portsmouth Drive, and Portobello Road areas will increase as sea level rises, as illustrated in Figure 44 for a moderate (1:20 year) storm surge event. As noted previously, the lowest parts of this area are already affected during maxima of the normal astronomical tidal cycle (Figure 38). Other low-lying land on the margins of the Andersons Bay inlet will also be increasingly affected by inundation from the Otago Harbour.

It is noted that coastal storm surge events can often coincide with storm events on the land, as they are often borne out of the same low pressure weather systems that also produce heavy rain, surface runoff and high river flows. This can have the effect of increasing the water level in low-lying coastal areas. The areas of ponding mapped below for a 1:20 year event are therefore a minimum only.

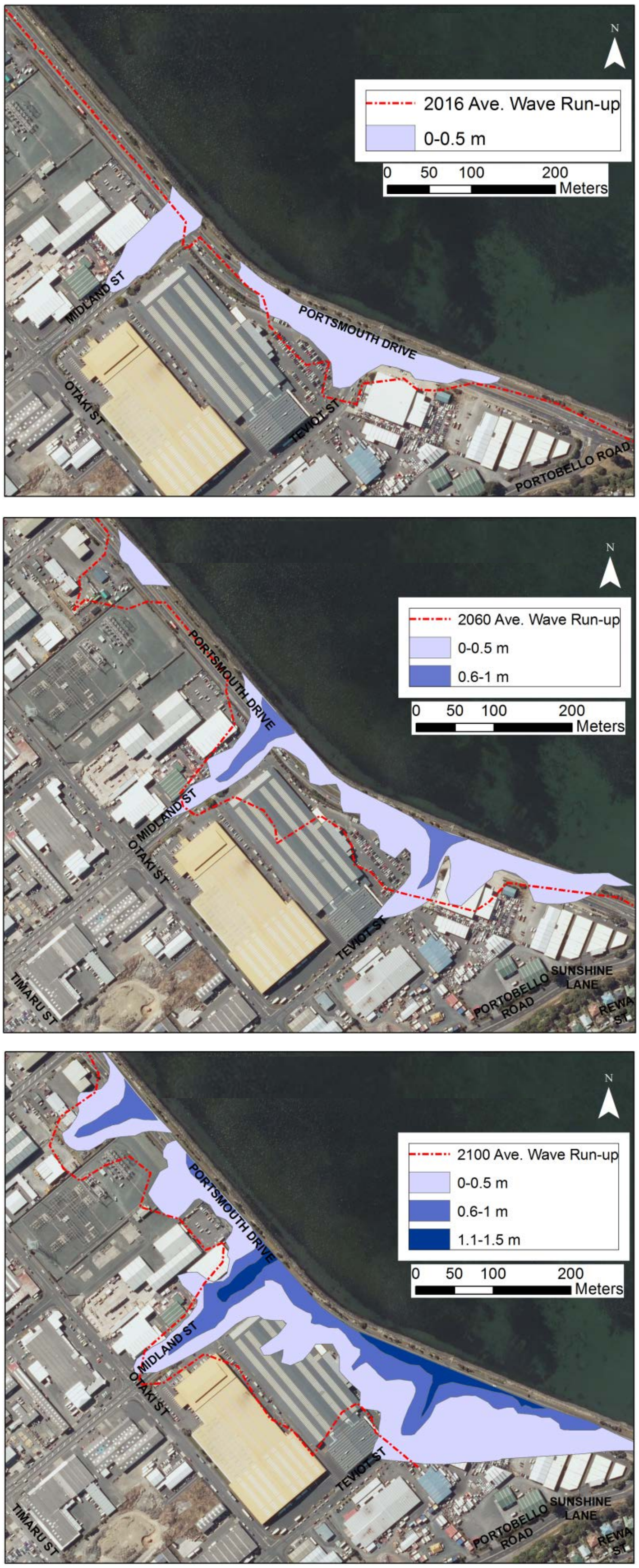


Figure 44. Likely extent and depth of inundation (shaded areas) and maximum extent of wave run-up (red-line) from Otago Harbour during a 1:20-year storm surge event at MHWS. Current sea level (top), 0.3 m mean sea level rise (middle), and 0.5 m rise (lower). Ave = average.

5. Community setting

'South Dunedin'[34] plays an important role in the wider community, at a local, district and regional level. This section summarises social indicators for the South Dunedin plain obtained from Statistics NZ and other sources, and also describes some of the important infrastructure that is situated on the plain. The five Census Area Units (CAUs) which comprise the bulk of the plain are Forbury, South Dunedin, and St Kilda West, Central and East (Figure 45). Parts of Caledonian, Harbourside, Musselburgh, Caversham and St Clair CAUs also form part of the plain, as the CAU boundaries are generally defined by roads rather than topography.[35]

Key indicators which help to describe the characteristics of this community are presented below.[36]

Figure 45. Census Area Units (CAU's) on the South Dunedin plain, and surrounding area. The five CAU's discussed in detail below are shown in bold.

5.1. Population

The population of the whole South Dunedin plain is approximately 10,000, about 8% of the population of Dunedin City district. Some key facts regarding this population are listed below:

- The total number of people living in the five main CAU's on the South Dunedin plain remained static at 9,555 people between 2001 and 2013. The population of South Dunedin decreased, while St Kilda Central and Forbury increased during this period (Table 5).

[34] Comprising the South Dunedin plain (as described above), the dunes and beach on its southern margin, and the Harbourside area to the north

[35] The Harbourside and Caledonian CAU's are mainly commercial, with few permanent residents

[36] Finer scale mapping (called 'meshblocks') has been used in some cases to better define some parameters

- The area is popular with older people due to its flatter terrain, and the percentage of people aged over 65 is higher than the national average, with twice as many people aged 65 or more in the South Dunedin CAU than the national average (Table 5).
- There are six rest homes located on the plain itself, providing a total of 289 beds. Another facility is located on low-lying land beside the Andersons Bay inlet (Marne St), while the Francis Hodgkins and St Andrews facilities are located on elevated land to the west (Figure 46). The Radius Fulton rest home was evacuated during the June 2015 flood, to ensure the safety of residents and staff.
- The South Dunedin plain has a high population density of 37 to 44 people per hectare[37] (Table 5). For comparison, the population density of the Maori Hill and Mornington CAU's is about 28 and 31 people per hectare respectively.

Table 5. Population and income statistics for South Dunedin CAU's (Statistics NZ website)

	2013 population	2013 population density (people / hectare)[38]	Population change - 2001 to 2013	2013 occupied dwellings	2013 percentage of residents 65 or older	2013 median income ($)
New Zealand	4.2 million				14.3	28,500
South Dunedin	2,421	40.5	-120 (-5%)	1,305	28.3	20,200
Forbury	966	37.2	+45 (+5%)	411	16.5	21,500
St Kilda West	1,845	37.9	-39 (-2%)	711	15.9	30,800
St Kilda Central	1,701	36.7	+117 (+7%)	774	18.5	23,300
St Kilda East	2,685	43.9	-3 (0%)	1,161	24.0	23,100

[37] 1 hectare is 10,000 m^2 (equivalent to 2 rugby fields)
[38] Calculated excluding reserves, dunes, and commercial / industrial areas (i.e. residential areas only)

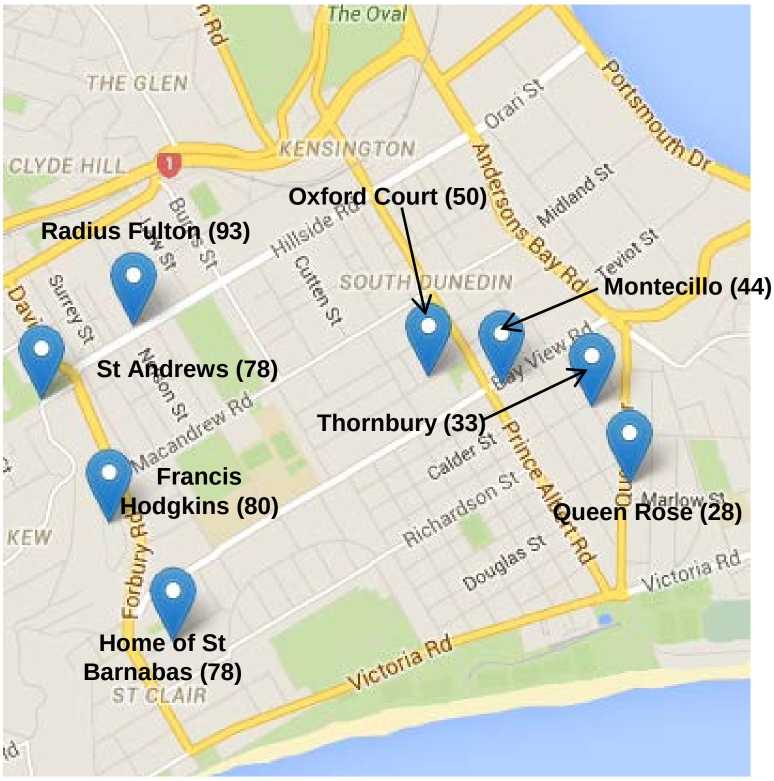


Figure 46. Location of rest homes on, or close to, the South Dunedin plain, with the number of beds in parentheses. Source: Ministry of Health website.

5.2. Housing stock and home ownership

There are about 4,800 occupied dwellings on the wider South Dunedin plain which is about 10% of the total housing stock in Dunedin City. The area is characterised by small sites, and smaller and older dwellings (DCC, 2009).

- The number of occupied dwellings on the five main CAU's increased from 4,320 to 4,362 between 2001 and 2013 (a 1% increase).
- Nearly 37% of the residential properties in this area are flats and units (DCC, 2009).
- The minimum lot size specified by the Dunedin City District Plan is 300 m^2. The second generation District Plan (2GP) was notified on 26 September 2015, and does not propose changing this limit. The 2GP does propose a coastal hazard overlay zone for the South Dunedin plain, which would require new sensitive development (e.g. buildings which would usually have people sleeping on-site) to be built above a minimum floor level, and to be re-locatable.
- Compared to the national average, there are more people who own their own home in the St Kilda West CAU, but less in the other four CAU's (Table 6). The largest proportion of residents who do not own their own home is found in the South Dunedin and Forbury CAU's (61 and 48% respectively).

Table 6. Percentage of dwellings owned or partly owned, and not owned (CAU level, 2013 Census. Sourced from Statistics NZ website)

Area	Owned, partly owned or family trust	Not owned
New Zealand	65	35
South Dunedin	39	61
Forbury	52	48
St Kilda West	73	27
St Kilda Central	57	43
St Kilda East	62	38

5.3. Income

The median personal income for the South Dunedin, Forbury, St Kilda Central and St Kilda East CAU's was 23% (or $6,500) lower than the New Zealand average, at the time of the 2013 Census (Table 5). However, there is localised variation in personal income as shown in Figure 47 and median personal income is higher than the national average in St Kilda West.

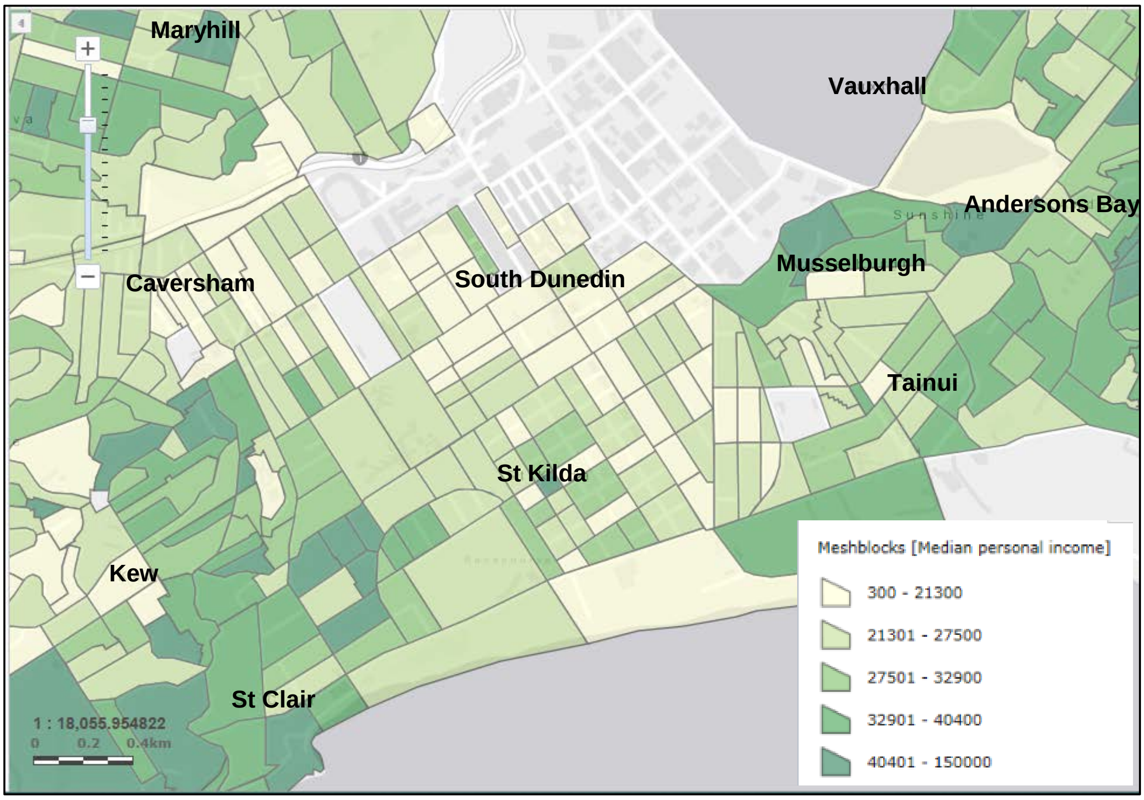


Figure 47. Median personal income for South Dunedin plain and surrounding areas (meshblock level, 2013 Census). Source: Statistics NZ website.

5.4. Schools rolls and catchments

- There are currently 12 schools located on, or close to, the South Dunedin plain, comprising 8 primary or full primary schools, 1 intermediate school, and 3 high schools. The combined roll of these schools was 4,098 as of July 2015, which is a 1.7% increase on the combined rolls of the 15 schools that existed in 2011.
- The schools which experienced the largest growth during this time were Kings High School (752 to 1037), St Clair Primary (369 to 435), and Musselburgh Primary (155 to 185). Schools which had falling rolls over that time were Bayfield and Queens high

schools.[39]

- The catchment areas for schools in this area are diverse. Many pupils attend their local school, but increasingly parents will opt to enrol their children in schools some distance from their home. Children travel from as far away as Aramoana and Port Chalmers to attend schools on the South Dunedin plain.
- It is noted that Kings and Queens high schools will become increasingly vulnerable to inundation from surface water ponding, as mapped in section 4.1. The area surrounding these schools was also affected by flooding during the June 2015 event (ORC, 2015)
- There are also at least six early childhood education facilities on the South Dunedin plain.

5.5. Infrastructure and assets

Some key pieces of infrastructure are located on, or close to, the South Dunedin plain. Some are important at the regional level and beyond – including State Highway 1 and the main trunk railway line. Important facilities such as the Edgar Centre, the Tahuna wastewater treatment plant (which treats wastewater from most of the Dunedin urban area) and the Otaki Street electricity substation are also located on the plain (CDEM, 2014). An extensive commercial district also provides an important function for the Dunedin City district, and as noted above, there has been significant investment in educational facilities on the plain. Other recreational facilities include a large number of sports fields, the Dunedin Ice Stadium, Forbury Park Raceway, and the Chisholm Links Golf Course.

Along with other public utility infrastructure, there is an extensive network of freshwater supply, and stormwater and wastewater pipes which lie beneath the surface of the South Dunedin plain.[40] This network is also important to the wider city. Figure 48 shows that much of the wastewater reticulation network is due for renewal this decade (2015-2025), along with some freshwater and stormwater pipes. As noted previously, infiltration of groundwater into the aged waste and stormwater networks helps to suppress the water table, preventing surface ponding under normal conditions. Much of the stormwater network in the south-central and southeastern part of the plain will reach the end of its expected life during the following decade (2025 – 2035) (Figure 49).

[39] Source: Ministry of Education website
[40] See http://www.dunedin.govt.nz/council-online/webmaps/waterservices to view maps of these pipes

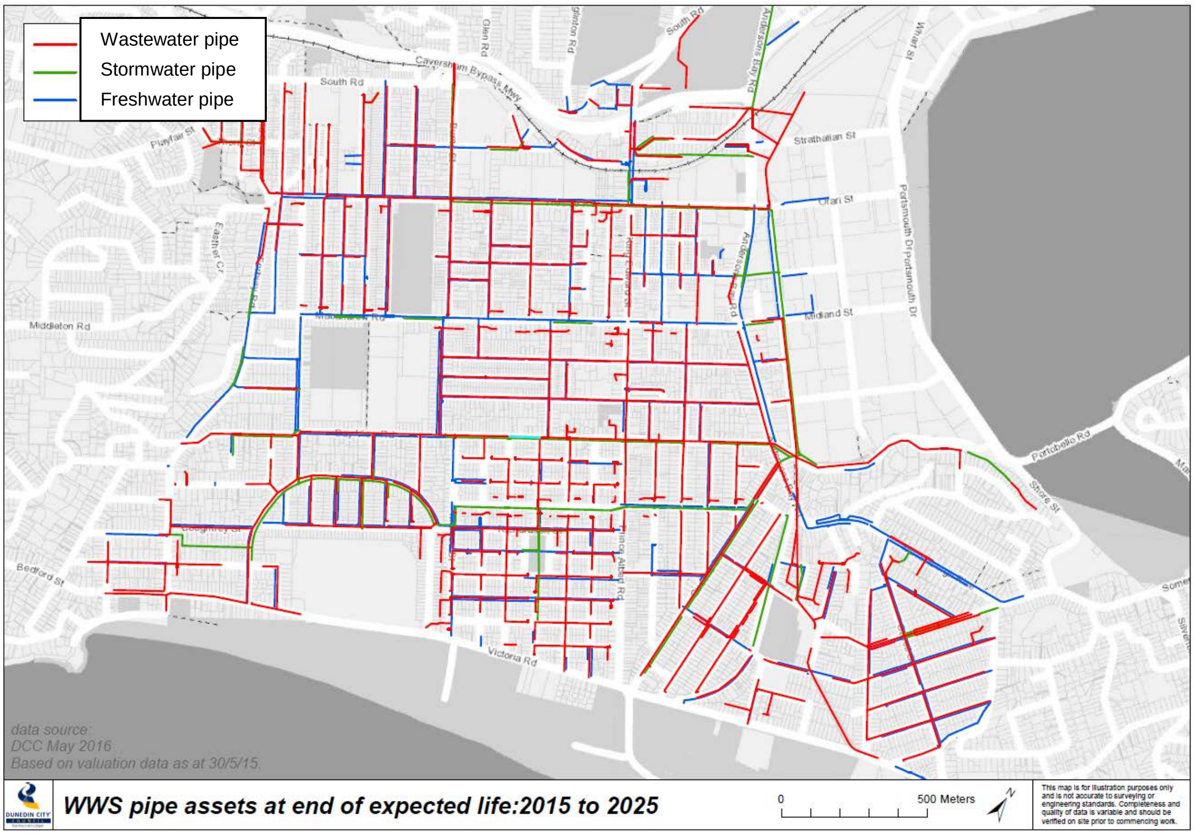


Figure 48. Water, stormwater and wastewater pipe assets due for renewal 2015-2025

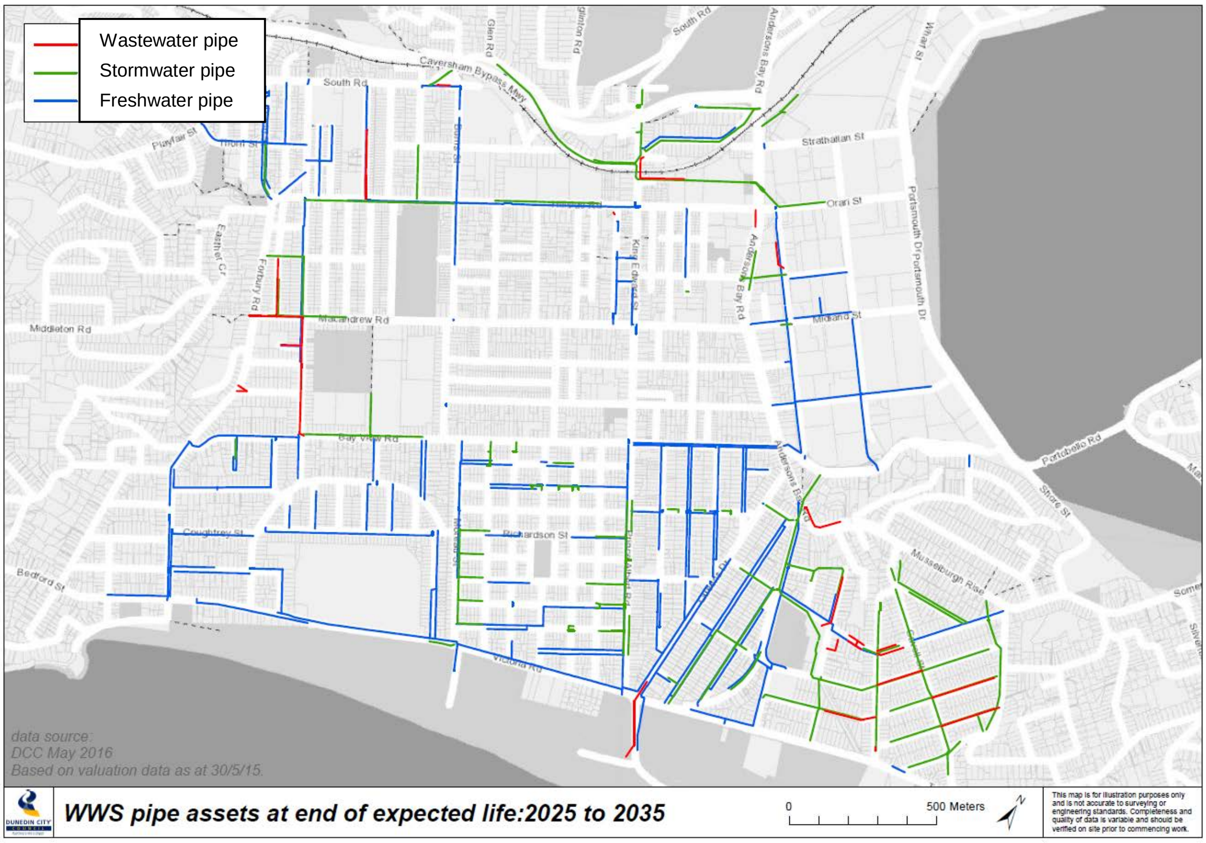


Figure 49. Water, stormwater and wastewater pipe assets due for renewal 2025-2035

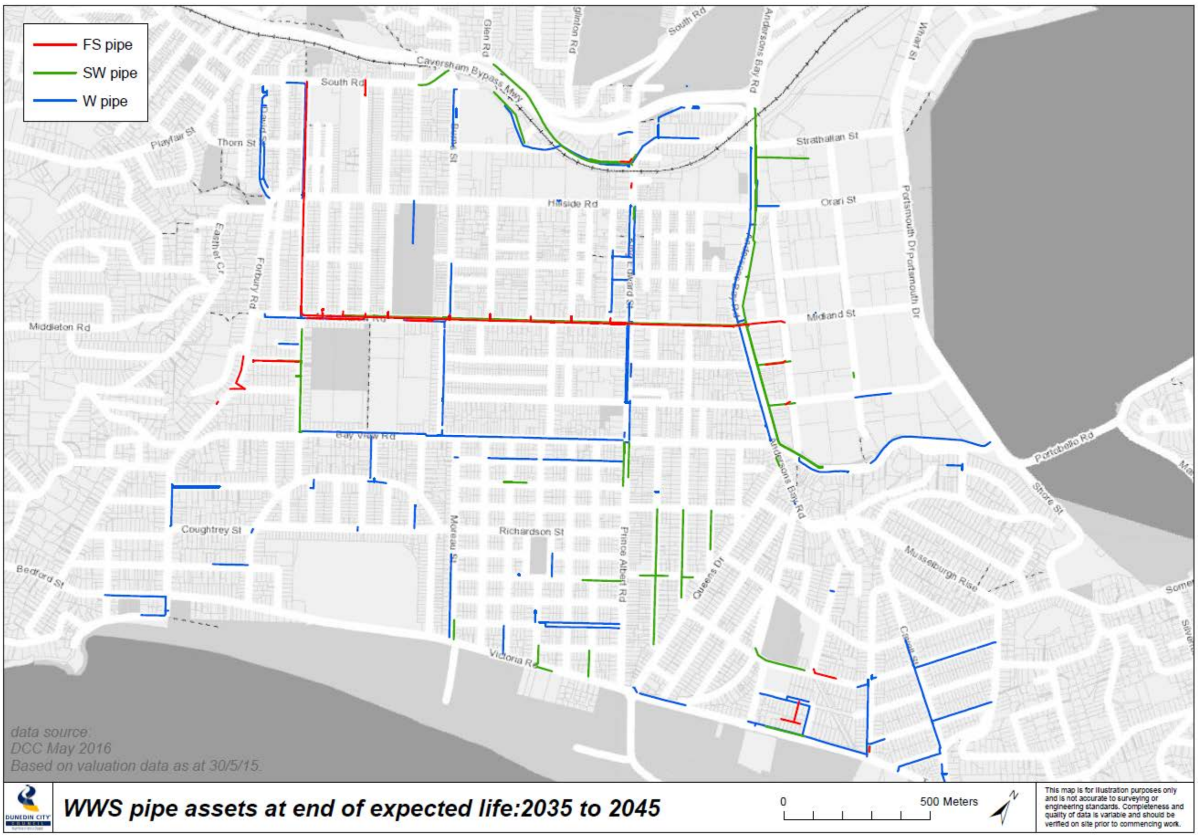


Figure 50. Water, stormwater and wastewater pipe assets due for renewal 2035-2045

6. Risk Context

Important decisions regarding the appropriate use of land, and investment in infrastructure will be required in South Dunedin. These decisions should give consideration to:

1. The prospect of being affected by *any* hazard. As described in this report, there are a range of hazards which can affect the South Dunedin plain.

2. The likelihood of an area being affected over the *longer term*. For example, the chance of this area being affected by high intensity rainfall in any given year may be relatively small, but the likelihood of such an event occurring at least once during the expected lifetime of a building or piece of infrastructure (50+ years) is much higher. It is noted that as mean sea level rises, the frequency with which hazards such as flooding, groundwater ponding and storm surges will affect people and assets will increase.

3. The cumulative effects of *repetitive events* on people and assets - where a series of natural hazard events occur over a short space of time, affecting the community several times in quick succession and before it has time to fully recover.

4. The likelihood of a *combination* of hazards occurring at the same time. For example, where the effects of flooding are exacerbated by already elevated groundwater levels.

These planning considerations are consistent with the approach to natural hazards identified in the Otago Regional Policy Statement, and were also intended to help inform the planning response to be included in the Dunedin City District Plan, which is currently being revised (ORC, 2014b).

7. Definitions

Aquifer. A body of permeable rock or sediment through which underground water flows.

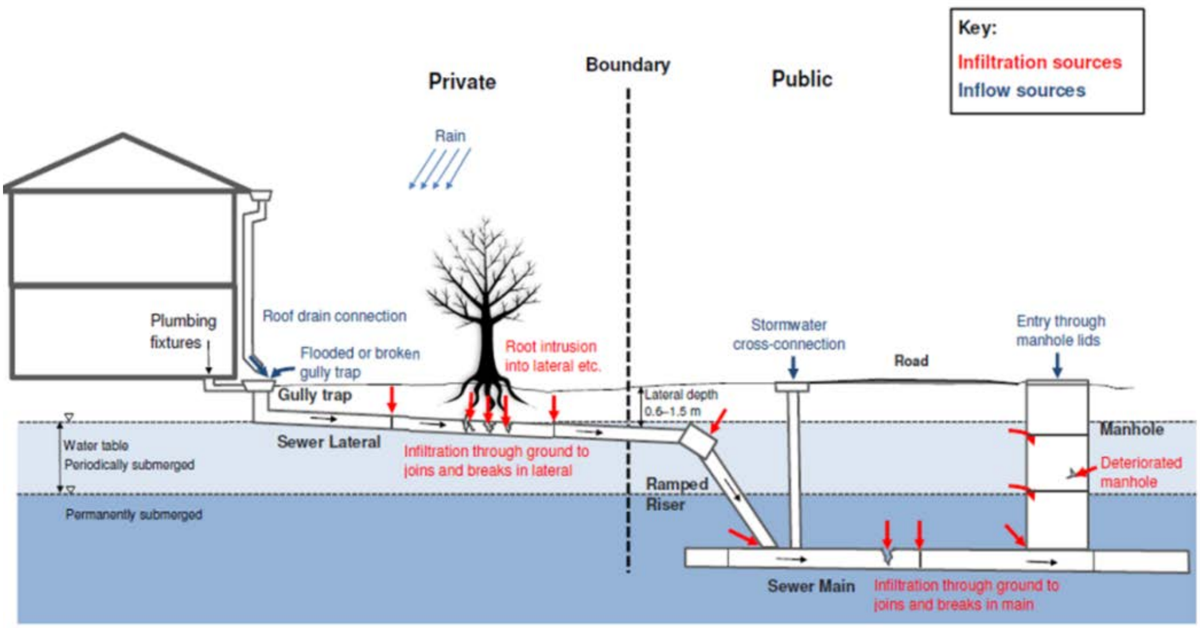
Dunedin Vertical Datum – 1958 (DVD-58). The MSL datum (or baseline) for Dunedin determined from nine years of tide gauge data collected in 1918, 23–27, 29, 35, 37. Unless otherwise stated, all levels described in this report are relative to DVD-58.

Envisat. Envisat (or Environmental Satellite) was a large Earth-observing satellite, launched in 2002 and operational until April 2012. Among other scientific data, it collected digital elevation data.

Extremely wet day. A day on which observed rainfall is above the 99th percentile of 24-hour rainfall totals at a particular site. For the Musselburgh site, Cameron et al. (in review) found that the threshold value for an extremely wet day was 38.6 mm, based on all rain days between 1961 and 1990.

Holocene. The more recent of the two components of the **Quaternary** Period. The Holocene Epoch began about 11,700 years ago and continues to the present day.

Infiltration. Water entering the stormwater or wastewater system through leaky pipes and manholes. Image below reproduced from www.odc.govt.nz/activities/wastewater/opotiki-sewer-project-faqs/

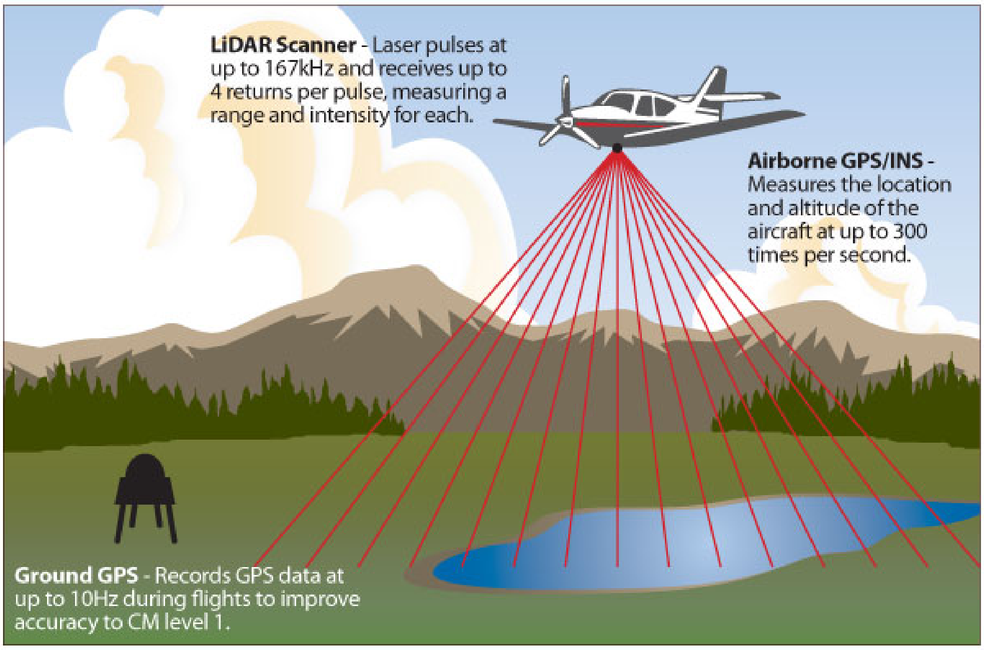


Late Quaternary. A geological time period, spanning from 126,000 years ago to the present day, and encompassing the Late Pleistocene and the **Holocene**.

LiDAR. Light Detection and Ranging. A mass of spot height information captured over a wide area using an aircraft mounted laser (see figure below). Each spot height has *x* and *y* attributes ('easting' and 'northing', to determine its location on the earth's surface), and a *z* attribute (its elevation above or below a vertical reference datum). The LiDAR data used in this report were obtained by the Dunedin City Council in 2009 and have a vertical accuracy of about +/- 0.1 m.

The topographic maps shown in this report (e.g. Figure 3) have been created by using the spot height information to create a digital model of the ground surface. This process involves interpolating the elevation of the land between surrounding spot heights, to create a 'surface' which represents the actual ground topography.

On steep rough ground, and where buildings and other 'non-ground' features such as trees have been removed from the original dataset, the accuracy of the interpolated ground elevations may be less than over flat open areas such as roads and parks.



Mean High Water Spring (MHWS). MHWS is the highest level to which spring tides reach on average over a period of time. This level is generally close to being the 'high water mark' where debris accumulates on the shore annually.

Mean Sea Level (MSL). The sum average of the tides (i.e. a middle level between high and low tides) over a set period. The MSL datum (or baseline) for Dunedin is referred to as Dunedin Vertical Datum 1958 (DVD-58). Due to relative sea level rise over the intervening period, the present mean sea level is higher than DVD-58.

Natural hazard. An unavoidable danger or threat to property and human life, resulting from naturally occurring events.

Quaternary. Geological time period, spanning from approximately 2.6 million years ago to the present, and comprising two epochs, the Pleistocene and the **Holocene**.

Residual risk. Residual risk is the threat that remains after all efforts to identify and eliminate risk have been made.

Risk. A measure of the probability that damage to life, property, and/or the environment will occur if a hazard manifests itself. This measure includes the severity of anticipated consequences to people, property and the environment.

Vulnerability. Liability or exposure to a hazard or disaster.

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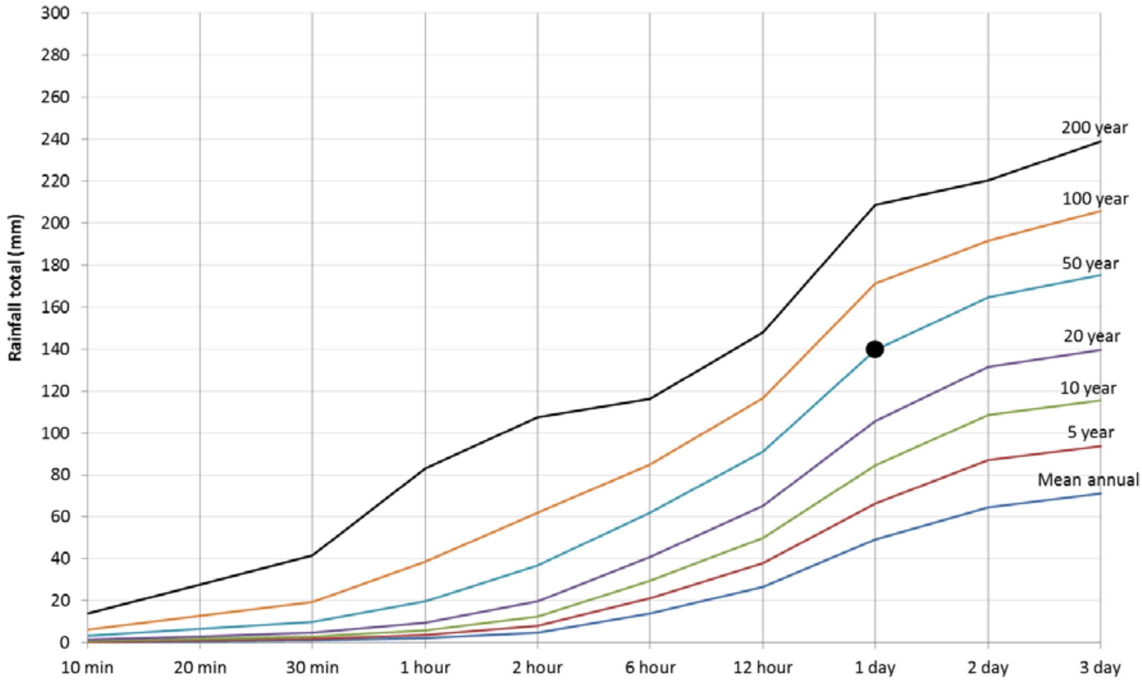
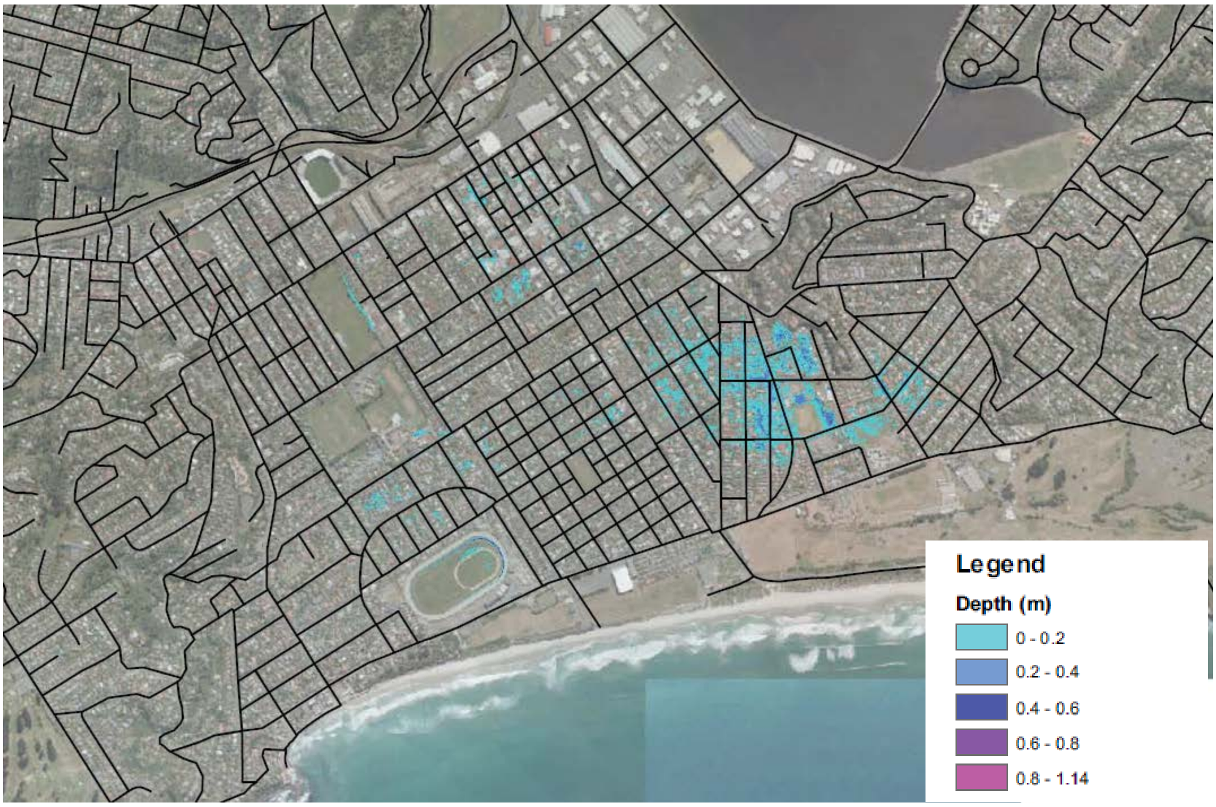
Appendix 1. Rainfall duration curve



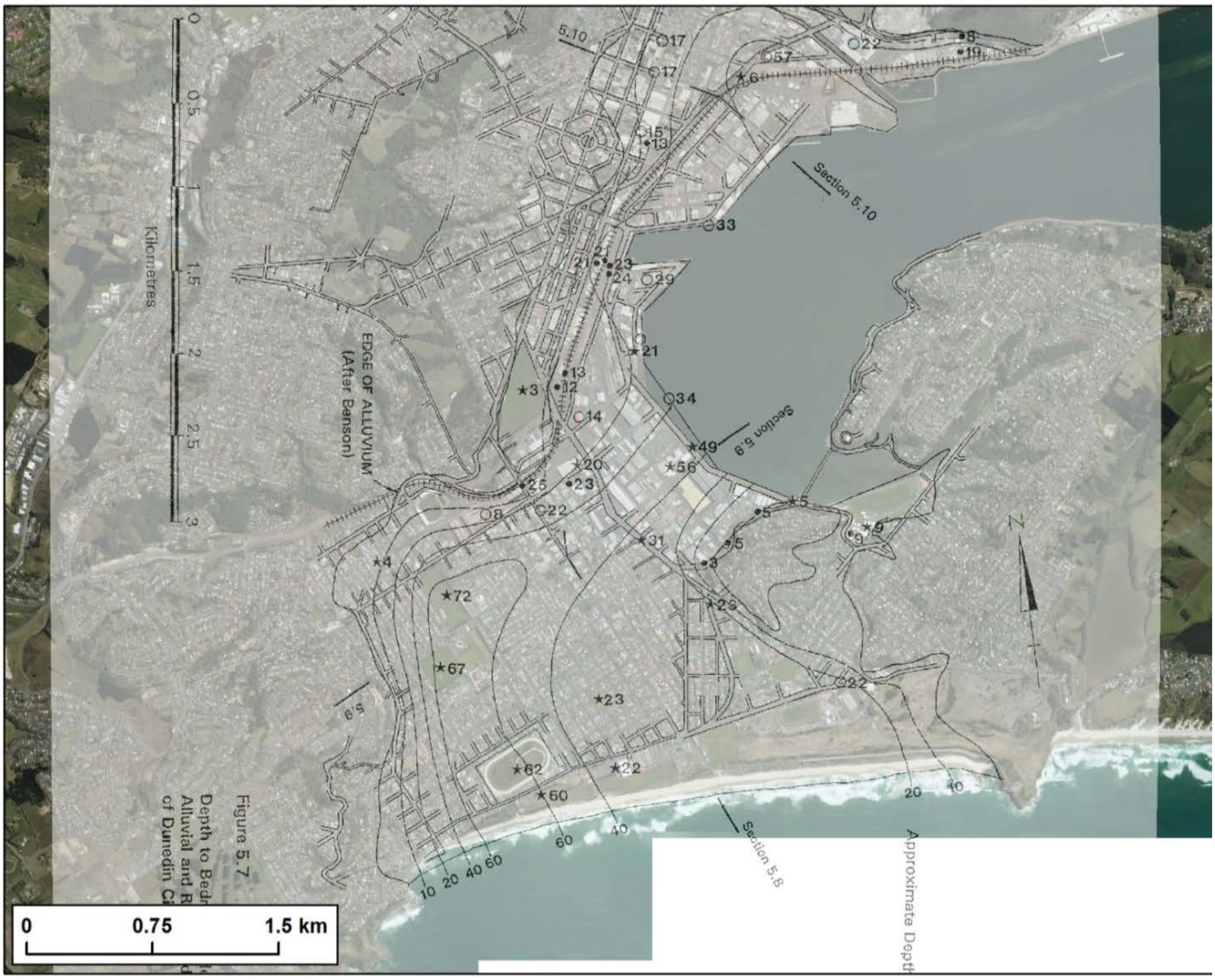
The plot shows estimated return periods at Musselburgh, using a combination of daily manual (9am) readings, 'instantaneous' data (15 minute readings), and manually recorded hourly readings from the 8-9 March 1968 storm. The combined dataset covers the period from January 1918 to May 2016. The vertical axis is rainfall in mm and the horizontal axis relates to different time periods. The black dot shows that a 1-day rainfall total of 140 mm has an estimated return period of 50 years. The data used to create this plot was generated using Hilltop Hydro software, applying a GEV distribution.

Appendix 2. Groundwater ponding modelled by Beca (2014)



This image shows the potential extent and depth of groundwater ponding that could be expected with an increase in mean sea level of 0.3 m (relative to 1990 levels), in the absence of groundwater control measures, as modelled by Beca, 2014. Note that this is just one of the four scenarios modelled by Beca, the others being increases of 0.8, 1.6 and 2.0 m in mean sea level, relative to 1990 levels.

Appendix 3. Depth to bedrock



This image shows estimated depth to bedrock under the South Dunedin plain, based on borehole information and resistivity soundings. Open circles are boreholes that were too shallow to intersect bedrock, with the maximum depth of the hole (in metres). Solid circles are boreholes that reached bedrock, with the depth to the top of the bedrock. Stars represent the location of resistivity soundings, with the interpreted depth to bedrock. Elevation contours (m below ground surface) illustrate the interpreted geometry of the top of bedrock/base of poorly consolidated sediments. Diagram from Cook et al. (1993).