The South Dunedin Coastal Aquifer & Effect of Sea Level Fluctuations

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Overview

Background

South Dunedin urban area, which is mainly residential, is generally low lying reclaimed land, having once been coastal dunes and marshes. The underlying area has a groundwater system (or coastal aquifer) with a water table very close to the surface. The water table is closely tied to the surrounding sea level at both the ocean and harbour margins.

The Otago Regional Council has been monitoring groundwater levels at three bores since 2009; results from which indicate that water table height is under the direct influence of climate and mean sea level, plus the drainage provided by the area's storm and wastewater drains.

The low lying land and already high water table makes the area vulnerable to any future rises in sea level. If the water table did rise any further it would create further pressure on the current drainage system and also increase the chances of surface ponding.

Groundwater modeling was used in this investigation to assess the effects of a range of different sea level rise scenarios.

What this study found

The water table height is strongly influenced by the mean water level in the adjoining ocean and harbour. The close association is highlighted by areas of the aquifer within 300m of the coast showing the effect of the tides by fluctuating water table levels. The sea level has risen slightly over the past 150 years (up to 0.2m), and the water table has probably responded in an equivalent fashion. Further rises in Mean Sea Level are highly likely to force further equivalent rises in the water table. Groundwater modeling of this effect suggests that even the mildest continuation of the current rise of sea level rise would create ponding in some parts of the South Dunedin urban area.

Water table levels are also in part controlled by the fortuitous draining through the stormwater and wastewater pipe network, which allows surrounding groundwater to enter through cracks or breaks in the system.

What should be done next?

Groundwater levels will continue to be monitored to assess any changes to water table levels. The network of bores will also be extended to further improve the accuracy of the model predictions. The information from this report can be used for future planning requirements.

Technical Summary

The South Dunedin urban area is low-lying having been reclaimed from coastal dunes, marshes and intertidal deposits since European settlement. The water table lies close to the surface, typically 0.3 m to 0.7 m under the urban area. A coastal aquifer comprising mostly sands, estuarine muds and alluvial gravels makes up the basin infilling between the Dunedin mainland and the Otago Peninsula. The coastal aquifer is exposed to the sea at the Harbour Basin and Ocean Beach (St Kilda Beach, Middle Beach and St Clair Beach).

Recent drilling investigations have characterised a sandy aquifer in hydraulic communication with the sea, including tidal fluctuations of the water table in proximity to the ocean. It is inferred that any long-term rise in the mean level of the sea would translate into a rise in the water table. Thus, groundwater modelling was used in this investigation to assess the magnitude of sea level rise effects on South Dunedin from groundwater causes.

Scenarios or projections of future sea level rise encompassing the 21st Century were used in formulation model scenarios. The following bullet points outline the results of computer modelling:

- Groundwater computer modelling suggests that even the mildest continuation of the measured rate of sea level rise would manifest in groundwater ponding of a few tens of centimetres in the parts of the South Dunedin urban area.

- Based on the LiDAR land surface data and the groundwater model-derived water table surface, the greater potential for groundwater ponding at the surface is within the Bayview Road – Hargest Crescent – Forbury Park area.

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1 Introduction

1.1 Background

The South Dunedin urban area is low-lying with much of the land surface lower than Mean High Water Springs. South Dunedin is largely underlain with sand deposits, both estuarine and sand dune. The ocean margin comprises Ocean Beach from St Clair Esplanade to Lawyers Head, while the harbour margin is ringed with sea walls from Portobello Road to the Port of Dunedin. In a geomorphic sense, the South Dunedin urban area occupies a coastal landform, termed a tombolo, in the isthmus between the Dunedin hills and the hilly Otago Peninsula. The tombolo surface has become consistently emergent above mean sea level only in most recent times, being previously salt marsh and sand dunes, cut by intertidal mudflats or tidal channels before European settlement.

Rapid 'reclamation' and human-accelerated sedimentation since the onset of European settlement from the 1850's has resulted in a low-lying and remarkably flat land surface with the water table lying immediately beneath. The underlying groundwater system is termed a coastal aquifer, although there is no utilisation of the groundwater within. The water table is thought to be closely tied to the surrounding sea level at both the ocean and harbour margins. Sea level is believed to be slowly rising and there is some evidence for the level having risen in the historical period (1850 – present). Projections of future sea level rise under the dual forcing of thermal expansion of the oceans and loss of ice cap volume have been made that imply an acceleration of historic sea level rise towards significant elevations over those of today.

The South Dunedin urban area is vulnerable to rises in the underlying water table. Otago Regional Council water table monitoring in South Dunedin since mid-2009 has indicated that the water table height is under the direct influence of climate and mean sea level, plus the fortuitous drainage provided by the area's storm and wastewater drains. However, rises in the sea water level at the margins could have a significant effect in destabilising the current equilibrium. Groundwater modelling has the capability of allowing predictions of water table conditions given projections of sea level rise into the future. Future sea levels can be artificially simulated in a groundwater model simply by specifying rising level through time. Provided the groundwater model is a realistic reflection of actual groundwater system, the response of the water table to changing sea levels would provide an indication of the effect on the South Dunedin urban area, including potential for overloading the current drainage systems and groundwater inundation.

1.2 Purpose & Approach

The thrust of the groundwater investigation outlined in this report can be summarised as follows:

1. Develop a groundwater computer model of the South Dunedin coastal aquifer and calibrate it to observed groundwater behaviour.

2. Verify the model and assess the sensitivity of the groundwater system.

3. Simulate scenarios for climate, sea level and infrastructure changes for their impact on the water table beneath the South Dunedin urban area.

1.3 Limitations

Any computer modelling based investigations such as this one, is subject to levels of uncertainty in the field data, assumption made in the conceptual mode and any mis-application of the model elements to the actual situation. The amount of field data from the South Dunedin coastal aquifer is very sparse, largely restricted to geophysical soundings and a handful of level monitoring bores. There are not yet any independent measurements of aquifer hydraulic conductivity, which is a highly sensitive parameter in an investigation of this nature. Similarly, there is significant uncertainty about the rates of freshwater recharge to the coastal aquifer. Consequently, the characterisation of the coastal aquifer and particularly the predictions of aquifer behaviour would be enhanced by future determination of these parameters.

Future predictions or scenarios of global climate change are highly uncertain. Similarly, translating projected climate trends into rates of sea level rise introduces more uncertainty. This investigation deals with this uncertainty by evaluating the effect of a wide range of sea level rise rates in order to outline the possible range of groundwater effects on South Dunedin over the next century. This investigation considers groundwater-related impacts of sea level rise in isolation from other effects such as coastal erosion, breaches of coastal defences or storm surges.

2 Background & Setting

2.1 Location & Land Use

The South Dunedin flats are located to the south of the Dunedin city central business district (CBD), between the Otago Harbour Basin and the Pacific Coast. It encloses the suburbs of South Dunedin, Tainui, St Kilda, Forbury, St Clair and Kensington. It includes residential, commercial and light industrial land uses. With the exception of a golf course and sand dune reserves, the area is wholly urban. The predominant land use is residential, with most of the South Dunedin urban area made up of medium density housing. The combined population of the South Dunedin flats is approximately 10,000 (2006 census), including about 4,800 occupied dwellings. The population density of South Dunedin is 1700 per square kilometre (/km^2), whereas the mean New Zealand population density is less than 16 /km^2. Census statistics point to the population of the area being predominately older, lower income and less likely to own their home than the rest of Dunedin. Outside of built-up areas there are city reserves, comprising the coastal dunes, a golf course and grassed playing fields.

2.2 Geological & Marine Processes

The basement rock for the Dunedin area is Haast Schist, metamorphosed semi-schist. However, the schist is locally overlain by a thick sequence of Cretaceous – Pleistocene sediments and the basement is not exposed at the surface at all within the South Dunedin urban area. The eroded remnants of the Caversham Formation and Dunedin Volcanic Complex, which mark the stratigraphic top of the Tertiary sedimentary sequence, are exposed at the edges of the South Dunedin flats. The flats comprise the following Quaternary sediments:

- **Estuary Deposits:** comprising loose, well sorted, sandstone-, schist-, and volcanic-derived gravel and sand; often quartzose; minor mud and peat.
- **Coastal Deposits:** containing loose well sorted sand deposited predominantly by marine and lesser aeolian processes; minor gravel and silt.
- **Fill Material:** loose sand tailings; reclaimed land, embankments, and landfills.

The land surface has been extensively modified in the historic period since European settlement in 1850. This includes the fill material that forms a veneer over main parts of the flats.

The South Dunedin flats have been formed in the geologically recent timeframe. Geologically, the Dunedin area is defined by the eroded remnants of Miocene aged volcanic activity overlying Tertiary age marine sediments. However, the South Dunedin Flats comprise Recent infilling between these eroded remnants. In the latest glacial period ("ice age") peaking around 20,000 years before present, sea level was 120 m lower than currently. The continental shelf that is currently submerged by the Pacific Ocean was exposed 20,000 years ago, with the coast line over 30 km further out than now. Global melting of continental ice sheets resulted in the world's oceans rising, quickening about 14,000 years before present due to a meltwater pulse. Global sea levels are considered to have "stabilised" in the last 10,000 years, a geological period termed the Holocene. However, even within the Holocene there has been at least 14 m of sea level rise as a result of de-glaciation. Sea levels have only been nominally stable in the last 2,000 years, and even during this time perceptible sea level rise is inferred. Since the use of high precision tide gauges and record taking began in 1880 AD (130 years before present), global sea level rise in order of 2 millimetres per year (mm/y) has been calculated. Dunedin is considered to have an accurate tide gauge record[1] (Douglas, 1997). Recent analysis of the Dunedin tide gauge record indicates a long-term sea level rise rate of 1.3 mm/y (Hannah, 2010), which is acceptably close to the global mean for a similar period.

The significance of sea level rise beginning at 20,000 years before present is that the area currently occupied by South Dunedin was undergoing erosive land-forming processes until the coast line approached with rising sea levels. Geological and geophysical profiling of the South Dunedin basin shows that the core of the basin was eroded and probably occupied by a river gorge flowing southeast through the area. The river was the proto-Leith, combining the Leith, Lindsay and Harbour catchments, which flowed south through South Dunedin. As sea levels rose to -60 m Mean Sea Level (MSL) and the sea began to occupy the South Dunedin area, sediments would have begun to be deposited in significant volumes. This marked the beginning of sedimentation that would eventually fill the Otago Harbour with sand banks and form an intertidal bridge between the South Island mainland and the island that is now Otago Peninsula. When Europeans first described Dunedin landforms, they remarked on the salt marshes between the mainland and Otago Peninsula. Between St Clair and Musselburgh there was in 1848 a low-lying freshwater wetland named Kaituna. It was vegetated with silver

[1] The Dunedin tidal record is largely immune to common sources of level inaccuracy, by being removed from a collisional plate boundary, having reasonable agreement at low frequencies with nearby tide gauges sampling the same water mass and lacking large post-glacial rebound effects on the continental crust.

tussock, rushes and flax. A shallow lagoon at the core of Kaituna had its exit through the sand dunes between Lawyers Head and St Clair.

The continental shelf off the Otago coast is nourished by the Southland Current bringing with it Clutha derived sand as long-shore drift. Near-shore wave action pushes sand from the shelf onto beaches between headlands. In this manner, drowned valleys along the East Otago coast have been in-filled with sandy sediments at Waldronville, South Dunedin, Tomahawk, Hoopers Inlet, Papanui Inlet and Aramoana. In some cases a lagoon lies behind a sand spit. In the case of South Dunedin, settlement sedimentation and land-filling has enclosed and drained the coastal lagoon or wetlands.
Figure 1 illustrates some of the pre-European settlement topography and physiography and could be determined by Otago Daily Times writers in an article published in May 2010.

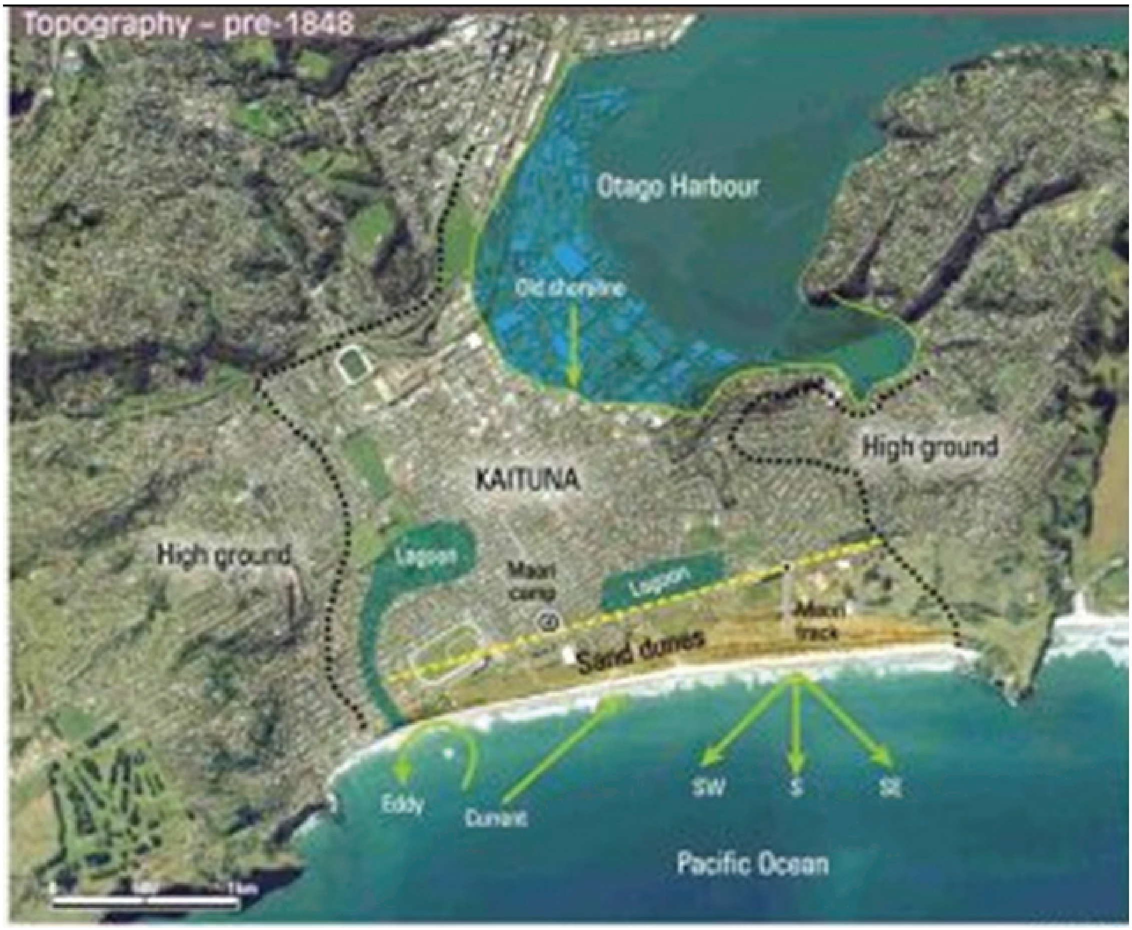

Figure 1: Pre-1848 map of South Dunedin sketched into the modern airphoto of the same area showing the shore lines, lagoons and pre-European features. Copyright Otago Daily Times, *Battle of the Dunes* article, 1 May 2010.

2.3 European Land-filling

The period following 1848 was characterised by rapid European settlement, and land-filling of the Otago Harbour basin and adjoining areas. The harbour shoreline in 1850 south of the Octagon followed Princes Street, Andersons Bay Road and Shore Street. Dunedin settlements initially lacked for the level, dry land that provided the easiest building platforms.

Consequently, the European settlers employed earth works termed ‘reclamation’. This amounted to land-filling of wet, low areas with any available fill material. The building up of embankments was usually the first step to reclamation of the harbour margins. Sometimes the embankments were associated with light rail or tram lines. Initially, reclamation was restricted to Dunedin CBD and its port area. By the 1870’s dune sand was being routinely quarried and used to fill low points to allow the building of houses. By 1874 housing in South Dunedin approximately 1 m below the high tide mark were reported by a local civil engineer implying that the flats were dry and had been cut off from intertidal areas.

Tram and light rail tracks were extended out in the South Dunedin flats, following the higher ground associated with sand dunes, also using bridges, culverts or infilling channels. Andersons Bay Road was among the first of these. A survey map of St Kilda of 1890 shows the alignment of the “Ocean Beach Railway” following the present-day alignment of Royal Crescent and Victoria Road. In the 1890 survey map Victoria Road passes by the foot of substantial sand dunes that would occupy the current Tahuna and Hancock parks. Significantly, a lagoon is sketched between the high sand dunes and the beach. Photographs of the period also show a large horse racing track between Victoria Road and Hargest Crescent, and market gardening in the Forbury to Bayview Road area. Sand mined at the coastal sand dunes from the 1870’s onwards was taken by rail to be used in reclamation in the harbour and South Dunedin flats. 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. In Dunedin, raised points of volcanic rock could be quarried for fill material. But in St Clair and St Kilda this was not feasible. Consequently, local sources of fill material, such as dune sand, were valued.

In the 20th century municipal landfills were established in the remnant dunes seawards on Victoria Road in a number of places, including Kettle Park playing fields. These landfills were essentially solid waste facilities that in-filled slacks between dunes and former sand-winning areas. By the 1960’s these land-filling practices had been significantly curtailed. Significant embankments were lain out along Andersons Bay Road and what is now the road base for Portsmouth Drive. During this relatively late phase of land reclamation in Dunedin, harbour dredging spoil made up the bulk of reclamation material. The area between Andersons Bay Road and Portsmouth Drive was finally filled by the mid-1960’s. Otago Regional Council administers land reclamation under the coast plan. The current policy is to avoid the filling and reclamation of further coastal land around Dunedin.

One of the chief constraints observed in all of the land settlement and reclamation works from 1850 to 1960 was the local height of the water table. In general, land-filling was completed to a land surface level “a couple of feet” above the water level. This practice minimised the amount of fill material that would need to be used while providing for drainage and dry foundations. There was no incentive for doing more reclamation than this approximate minimum. The result is a remarkably even surface across the flats bearing a strong reflection of the height of water table at the time of reclamation when mean sea level was 0.17 m lower than the present day.

2.4 Climate

The Dunedin climate is cool temperate, but strong influenced by coastal air flows from the Pacific Ocean. The long-term mean annual rainfall at Botanical Gardens is 930 mm. The median annual air temperature is 11.5°C. The balance of rainfall and evaporation is in excess, resulting in net runoff or groundwater recharge.

2.5 Hydrology

Hydrologically, South Dunedin is group within the Glen Creek catchment. However, the South Dunedin flats have a highly modified hydrology comprising a piped stormwater system for all built-up areas. Rain water is caught in curb and channel and dropped into storm sewer pipes. The storm sewer network is divided into several catchments associated with South Dunedin.

- **South Dunedin Catchment** discharging through the Portobello Road Pumping Station and thence to the Otago Harbour.
    - A subcatchment called **Tainui Downs** drains the suburb of Tainui, but storm flows require pump lifts at the Tainui and Musselburgh pumping stations before being piped to the Portobello pumping station.
    - Glen Creek rises in the Mornington suburb west of High Street. The creek is partly open channel and partly culverted until it reaches 'The Glen' behind Carisbrook, thereafter the creek is piped within the South Dunedin stormwater catchment.
- **Portsmouth Drive Catchment** discharging into Otago Harbour at Orari Street.
- **St Clair Catchment** draining Kew and St Clair suburbs and discharging into the Pacific Ocean at St Clair Esplanade.
- **Shore Street Catchment** discharging into Andersons Bay Inlet (Otago Harbour) at Shore Street.
- **Orari Street Catchment** draining the hill suburbs of Corstophine, Caversham, Lookout Point and Balaclava, piped under Hillside Road and discharging into Otago Harbour at Orari Street.

The sand dune remnants at Chisholm Park golf course, Kettle Park and the Ocean Beach Domain have no surface water bodies, nor drainage lines. Excess water is assumed to drain readily to the water table within the underlying sands.

2.6 Water Services

As mentioned above, the hydrology of the South Dunedin urban area is dominated by the channelled and piped storm water network. In addition to storm sewers, the area is served by foul sewers and a piped potable water supply. There is currently no utilisation of local water supplies. Historically, Hillside Railway Workshops utilised Glen Creek and seepage from the original Caversham rail tunnel. Limited use of wells was also practiced in the 1800's and into the first half of the 20th century (e.g. Atlas Match Company well). However, all water requirements are now provided by the imported DCC water mains, which derive water from Taieri, Silverstream and Swampy Summit catchments outside of South Dunedin.

The South Dunedin area's foul sewers drain towards the Musselburgh pumping station, which lifts the effluent to the Tahuna Wastewater Treatment Plant. Unlike the storm sewer network, the hill suburbs surrounding South Dunedin feed through the same storm sewer pipes to Musselburgh pumping station and the Tahuna Wastewater Treatment Plant. The Tahuna Wastewater Treatment Plant and the ocean outfall have been recently upgraded and were fully commissioned in 2010.

As already outlined in connection with discussion of hydrology, the South Dunedin flats and the runoff from surrounding hill catchments are drained using storm sewers buried beneath the streets and having their outfalls into Otago Harbour. In the case of the main South Dunedin storm sewer catchment, the flows are drained towards the Portobello Road Pumping Station and pumped out through an outfall to the harbour.

2.6.1 Sewer Infiltration

The storm and foul sewer networks have been separated throughout South Dunedin. However, the pipes are considered to be aged and moving towards the end of their economic lifetime, with the future requirement for refurbishment likely before 2050. Aged sewer networks are well known for either leakage or infiltration and the cracks in pipe walls and joints between pipe lengths. Closed Circuit Television (CCTV) inspections of the South Dunedin storm and foul sewers have found the pipe work to be pervasively cracked and frequently butt-jointed (i.e. pipe lengths lain end-to-end with no socket or sealing ring enclosing the joint). Consequently, the potential for sewer infiltration is high.

The recent commissioning of the secondary biological treatment portion of Dunedin foul wastewater at Tahuna Wastewater Treatment Plant had brought with it the realisation of saline inflows to the South Dunedin foul sewer network. An investigation of saline inflows was initiated in November 2008, focusing on the harbour catchments. The foul sewer at Bayfield High School displayed distinct peaking in salinity immediately following high tides, strongly suggesting the intrusion of saline groundwater when tide lifted the water table into the depth range of the sewer pipes and confirming groundwater infiltration in that location. There are other indications of sewer – groundwater interaction elsewhere over the South Dunedin coastal aquifer.

2.7 Coastal Aquifer

As outlined in connection with the South Dunedin area's geology, the infilling of alluvial and coastal sediments hosts an aquifer. The aquifer is unutilised as a fresh water source and there are indications from geophysical investigations and recent groundwater monitoring that it is contains patches of relict or intruded sea water[2]. The main area of undoubted fresh groundwater coincides with the distinct aquifer deepening beneath Forbury and St Clair. The areas with indications of saline groundwater include Bayfield, Tainui, St Kilda and Portsmouth Drive (McCahon, et al, 1993).

[2] Sea water may be present in groundwater in two principal ways; relict saline groundwater or saline intrusion. Relict saline groundwater is present when the groundwater was not flushed out of the ground following the transition from sea floor to land, typically as a result of reclamation. Saline intrusion is the landward ingress of sea water into an aquifer that was otherwise fresh. Intrusion is a result of a change in the aquifer's water balance and consequent flow reversal.

Otago Regional Council undertook the installation of three groundwater monitoring bores in the St Clair – Forbury area along a 2 km transect line. Each bore was installed to a depth of about 6 m, with the intake screen at depths approximating 5 m to 6 m. The rationale was to represent the ambient shallow water table in each locality. The DCC also commissioned geotechnical drilling in three locations surrounding the Tahuna Wastewater Treatment Plant upgrade. The drilling penetrated wind-blown dune sands, estuary sediments and a volcanic breccia against a basalt rock basement. Four piezometers, including a multi-level piezometer to measure differences in groundwater level with depth, were installed and monitored over an extended period.

2.7.1 Soils & Foundations' Investigations

The Soils & Foundations report to the New Zealand Earthquake Commission (McCahon et al, 1993) covered earthquake risk and vulnerability, including a focus on earthquake-initiated liquefaction. Liquefaction and the loss of foundation bearing strength as a result of earthquake ground shaking is something that structures on unconsolidated sediments are vulnerable to. The definition of earthquake liquefaction risk factors include:

Deposits most susceptible to liquefaction are young (Holocene-age, deposited within the last 10,000 years) sands and silts of similar grain size (well-sorted), in beds at least metres thick, and saturated with water.

The Soils & Foundation report observed that the harbour and South Dunedin areas comprised just these properties. The report attempted to characterise the Holocene deposits of Dunedin, but found only partial and low quality information on the subsurface from existing data. The available data generally comprised foundation investigation borings and water bore records. However, given the paucity of these records in the South Dunedin flats, the report authors attempted to supplement these sources with original geophysical soundings. The earth resistivity soundings conducted across low-lying Dunedin proved to be quite successful and in a couple of instances could be validated against independent descriptions of subsurface conditions from foundation bore logs. The resistivity soundings displayed the ability to distinguish the following lithologies:

- Dry sand
- Saturated sand
- Silty saturated sand
- Saturated silt
- Saturated silt and mud
- Weathered volcanic rock
- Fresh (unweathered) volcanic rock
- Fine grained Tertiary sediments
- Freshwater saturated sand
- Freshwater saturated sandy silt
- Saltwater (brackish) saturated sand

In this manner, a dozen resistivity soundings across the South Dunedin flats characterised the coastal aquifer. An area of fine-grained near-surface Holocene sediments, comprising marine silt and mud, were distinguished between Kensington and Andersons Bay. The depths of the

Pleistocene – Holocene sediments were also defined from these resistivity soundings. Bodies of saline water were distinguished from soundings near the harbour edge and the ocean coast line. The depths of the freshwater – saline interface were also estimable with the soundings, and they roughly conformed to the Ghyben-Herzberg ratios for freshwater and saline water in a coastal aquifer.

2.7.2 ORC Drilling Investigations

ORC drilled in three locations; corner of Victoria Road – Kennedy Street, Tonga Park and Bathgate Park. Each bore was installed at 6 m below ground level (BGL) and included a 1 m long screen at the base of the bore standpipe. The bore collars were surveyed to Otago Metric Height Datum (OMD) and automatic transducer – dataloggers were installed to provide records of groundwater level fluctuation. The bore closest to the ocean coast was fitted with a salinity reference electrode in order to observe salinity fluctuations.

The drilling investigations included logging of lithology. In general, all three bore holes reveal inter-layered sand and silt deposits characteristic of estuarine deposits. Greater organic (i.e. carbonaceous) content indicative of more stagnant environment of deposition was noted at Bathgate Park and greater influence of beach deposits was noted at Kennedy Street.

The water table was found within a short depth from the surface in each case. The Kennedy Street bore was discovered to be saline to brackish, while the Tonga Park and Bathgate Park bores further inland were found to contain wholly fresh groundwater. The implication of the presence of saline groundwater is that seawater has intruded the aquifer.

2.7.3 ORC Groundwater Monitoring

Groundwater level and salinity monitoring has been undertaken at the three South Dunedin bores since October 2009 when the bores were instrumented for long-term monitoring. The primary differences in level and salinity displayed in the continuous monitoring records relate to tidal influence, sea water mixing and response to heavy rainfall. The Kennedy Street bore levels display a highly cyclical pattern. The frequency of the cycle is 12 hours, twenty minutes and lags the ocean tide cycle by about two hours. The range through which the water table fluctuates at Kennedy Street is 0.25 m, about 17% of the ocean tidal amplitude measured at the coast.

Tidal fluctuation of about 0.01 m (10 mm) is discernable in the groundwater level record of the Tonga Park bore at a distance of 1 km from the ocean coast. No recognisably tidal fluctuation can be discerned in the Bathgate Park bore further inland. The implication is that the tidal fluctuation effect on the water table in the coastal aquifer is strongly attenuated by a combination of aquifer properties and distance from the coast line.

Salinity initially stabilised in the Kennedy Street bore at an electrical conductivity of 49.3 mS/cm. As the electrical conductivity of sea water is 53 mS/cm, the salinity in the Kennedy bore is indicative of 93% of the full sea water strength, implying a mixture of sea water and rainfall recharged groundwater. Following heavy rain in late May 2010, in which almost 300 mm of rain fell in a two week period, the salinity of the groundwater at Kennedy Street would drop to an electrical conductivity of 41 mS/cm during low tide. The salinity would be restored to 49.5 mS/cm at high tide. This implies that the infiltration of rainwater served to build up a superficial lens of freshwater above the saline groundwater. The infiltration and exfiltration of sea water during tidal fluctuation is the probable mechanism for fluctuation in salinity.

The electrical conductivity at Bathgate Park and Tonga Park is 0.56 mS/cm and 0.53 mS/cm, respectively. There is little apparent influence from intruded or relict sea water at these bores. The Bathgate bore displays responses in level to heavy rainfall or periods of extended low rainfall by rising or falling, respectively. The total recorded fluctuation at the Bathgate bore over the high rainfall period was approximately 0.4 m, indicative of approximately 40 mm of rain recharging the aquifer or about 10% of the rain that fell from late April to early June 2010.

2.7.4 ORC Tidal Fluctuation Analysis

The presence of a clear tidal influence on the Kennedy monitoring bore provided the opportunity to analyse the groundwater level record for indications of aquifer properties. The diffusivity analysis tool was used to estimate an aquifer hydraulic conductivity. The rise and fall of the tide at the coast results in a dampened, but corresponding rise and fall in the Kennedy Street bore. The concept and mathematics of diffusivity uses the degree of response to the external stimulus of the tide to estimate the transmissivity or hydraulic conductivity of the aquifer lying between the bore and beach. During the course of a single tidal cycle, the peak of water level in the Kennedy bore lagged the ocean by approximately 131 minutes. The difference in amplitude was significant. The tide rose and fell 1.67 m, while the water level in the bore fluctuated only 0.27 m in response, a difference of 1.4 m.

The diffusivity equation is written as follows: (Equation 1)

$$a = x^2 / 4\lambda^2 t$$

Where:

a =	diffusivity coefficient
erfc(λ) =	complimentary error function of λ, calculated using $\Delta H / \Delta H_0$
ΔH =	groundwater fluctuation induced by tide
ΔH_0 =	tidal fluctuation in ocean at coast
x =	distance between bore and beach
t =	duration of the tidal fluctuation (rise or fall)

Once the diffusivity coefficient is calculated, the aquifer's transmissivity can also be determined as the product of the coefficient and specific yield. The tidal fluctuations and other parameters were used to estimate the aquifer transmissivity as 1,350 square metres per day (m^2/d). With the depth of the sand beneath Kennedy Street known from resistivity sounding, the estimated hydraulic conductivity from the diffusivity calculations was 22 metres per day (m/d). This value is generally in accordance with other measures of beach sand made in other parts of the country.

2.7.5 DCC Tahuna WWTP Investigations

In order to ensure that foundations design conformed to the bearing strength present at the Tahuna Waste Water Treatment Plant (WWTP) site, the DCC commissioned CH2M-BECA to investigate geological and hydrogeological conditions at the site. A summary profile reproduced from the CH2M-BECA geotechnical report (Table 1) lists the summary geological profile found in drilling investigations.

Table 1: Summary lithological profile beneath the Tahuna WWTP site.

	Deposit	**Lithology**	**Approximate Height (m OMD)**
1	Quaternary Beach & Marine Terrace Deposits	Loose SAND	104.30
2	Estuarine Sediments	Firm SILT	99.50
3		SAND & Silty SAND	93.55
4		Stiff SILT	91.25
5	Weathered Beach Sand & Gravel	Dense to very dense SAND	88.65
6		SAND & Silty SAND	85.65
7	Dunedin Volcanic Group	Breccia, Basalt GRAVEL & SILT	82.25

The depth of the base of the estuary / beach deposits was found to average 21 m BGL. Four piezometers were fitted within boreholes drilled in 2005 and manually monitored from mid-2005 to early 2006. The shallow piezometers recorded a mean water table height of approximately 102.2 m OMD. A deep piezometer set within the volcanic rock recorded a mean water table height of 100.33 m OMD, indicating a slight downward gradient between the shallow estuary / beach deposits and volcanic basement.

3 Groundwater Modelling

The computer model code MODFLOW and the pre-processor / post-process software package known as Groundwater Vistas were selected to support the groundwater modelling process. The groundwater modelling would undertake flow modelling only, without the use of seawater interface simulations.

3.1 Model Framework

The South Dunedin Coastal Aquifer is a singular alluvial basin fringed by the basement rocks of the mainland and Otago Peninsula, and bathed by the sea of Otago Harbour and Pacific Ocean. Therefore there is little 'cross-boundary' interaction with other aquifers. The model framework has been trimmed at the lateral basement margins and extends a modest distance under the sea past the respective coasts.

The Sunshine – Musselburgh Rise basement block projects through the aquifer and is simulated using No Flow boundaries. A No Flow boundary is imposed along the Strathallan Street alignment between the Kensington basement block and Otago Harbour, even though a coastal aquifer probably extends beyond South Dunedin into Dunedin CBD. This alignment is assumed to be run parallel to groundwater flow lines, therefore assignment of No Flow boundaries is a valid practice.

The base of the single model layer is defined by the basement contact. The recorded bores that touched the basement contact were used to calculate the elevation of the base of the aquifer. A similar approach was used with the resistivity soundings where an individual sounding sensed the basement contact. These base elevation points were used to draw a set of contours for the aquifer base and the contour lines were used to model a base surface. The digital surface was imported into the MODFLOW model as the layer base property.

3.2 Assignment of Model Properties

The primary aquifer properties that require assignment in the model were as follow:

- Hydraulic conductivity
- Storage coefficients –
    - Storativity
    - Specific yield

In natural aquifer systems such as South Dunedin's, hydraulic conductivity values tend to be the most variable compared to storage coefficients. Specific yield is almost characteristic to the sediment type. Beach and dune sand has a range in specific yield from 10% to 28% (0.10 to 0.28), well less than a single order of magnitude. The same sand material has a range in hydraulic conductivity from 0.1 m/d to 100 m/d, or three orders of magnitude. Accordingly, hydraulic conductivity is the most important property of an aquifer.

Unfortunately, since the South Dunedin coastal aquifer is not a water supply aquifer and has no known water bores, no aquifer tests have been undertaken. Pumping and aquifer tests are the traditional means of characterising the distribution of hydraulic conductivity for an aquifer.

In the absence of aquifer test data on hydraulic conductivity, the hydraulic conductivity determined in groundwater fluctuation analysis (section 2.7.4 ORC Tidal Fluctuation Analysis) of 22 m/d was used as the initial hydraulic conductivity assigned to all model cells. Coastal sands tend to be dominated by fine to medium gain size with an effective diameter of 0.2 mm and uniformity coefficient of 1.2. Standard corrections from effective diameter to hydraulic conductivity (Hazen, 1893) place coastal sands in a mean hydraulic conductivity of 20 m/d. Model hydraulic conductivity was also subjected to adjustment during calibration.

3.3 Aquifer Recharge

3.3.1 Urban Recharge Rate Quantification

Groundwater recharge is the replenishment of water in an aquifer by infiltration of atmospheric water through its upper surface. Groundwater recharge through agricultural soils and extensive rural covers is relatively well known. However, South Dunedin is largely urban. The groundwater recharge of urban areas is poorly understood or quantified. Quantification of recharge rates into an aquifer beneath Nottingham urban area indicated the following proportions of recharge source:

- Foul sewer losses 4%
- Mains water leakage 65%
- Other sources 30%

The total rate of recharge into Nottingham groundwater was estimated at 211 millimetres per year (mm/y) (Lerner *et al*, 1999). The Nottingham research points out the role of leakage from water services such water supply pipes and sewers. An initial recharge rate of 200 mm/y was specified in the South Dunedin groundwater model, although this was progressively adjusted in the calibration process.

3.3.2 Recharge in Open Areas

The principal open areas in the South Dunedin flats are Chisholm Park Golf Course and assorted playing fields. The sand dune landforms include the golf course, Tahuna Park, Kettle Park and the residual Ocean Beach Domain. These open areas are relatively free-draining with no current requirement for drainage tiles. The soils are thin and skeletal with no limiting horizons. Hence, the sand dune landforms should have high groundwater recharge rates. There is little avenue to estimate the actual recharge rates. An initial estimate of groundwater recharge in the tapering coastal strip approximating these sand dune landforms is 400 mm/y, although this was progressively adjusted in the model calibration process.

3.4 Assignment of Model Boundary Conditions

Boundary conditions constrain the model simulation and can be used to simulation significant parts boundaries to the aquifer flow system. The basement margins, harbour and ocean are all significant boundaries to the South Dunedin coastal aquifer. The use of No Flow boundaries has already been outlined above (Model Framework). The sea margins were implemented in the model as follows.

3.4.1 Fixed Head Boundaries

The role of the harbour and ocean in imposing a fixed base level to aquifer water levels was simulated using fixed head boundaries. Sea level is normally constant in groundwater model and set at a constant level since it is effectively static for the term of most groundwater modelling exercises. Indeed, the steady state model simulation used for calibration set the sea boundary conditions at the Mean Level Of Sea (MLOS). ORC maintains a tidal recorder on the offshore island of Green Island. It was established in 2002 and the certified data set runs until August 2006. The three-year mean level relative to the survey datum of Mean Sea Level (MSL) was 100.1978 m, which was rounded up to 100.2 m OMD. This MLOS within Constant Head boundaries were used in for setting level at the harbour and ocean margins of the steady state version of the South Dunedin groundwater model.

The transient version of the South Dunedin groundwater model changed MLOS at the harbour and ocean boundaries through simulation time. This approach was chosen to match the expectation of progressively rising sea level. To facilitate the transient change in sea level, MODFLOW River boundaries were utilised to simulate the sea boundaries.

3.4.2 Drain Boundaries

As covered in the discussion of water services interaction with the water table above (section 2.6.1 Sewer Infiltration), the presence of sewers in the South Dunedin urban area requires explicit simulation with drain boundary conditions. The DCC had developed a pipe network hydrology model for the South Dunedin catchment in 2009 as part of the “Three Waters” project. The model information including the dimensions and invert elevations were extracted and transferred into MODFLOW for the specification of drain boundary parameters. The InfoNet model generated an ArcInfo shape file, which was used as input data for the specification of drains throughout South Dunedin.

South Dunedin has separate storm and foul sewer networks. The surveyed sump invert elevations from the storm network were used to generate a network of drains discharging towards ultimately to the Portobello Road pumping station. The storm network down to 200 mm pipe diameter covered most of the South Dunedin urban area. This network was used in model development in preference to the foul sewer network.

3.5 Model Calibration

Calibration used the ORC and DCC piezometers as described previously (ORC Groundwater Monitoring and DCC Tahuna WWTP Investigations). Mean groundwater levels in four locations across the South Dunedin Flats were specified in this manner. The calibration process utilised the automated parameter optimisation package with the acronym PEST. The PEST package uses mathematical goal seeking tools to find the optimal set of parameters that match best with the calibration targets.

3.5.1 Calibration Results

Parameter optimisation proved capable of achieving a reasonable matched to observed groundwater levels. The calibration statistics are shown in Table 2 below.

Table 2: Calibration Performance & Derived Statistics

Observation Bore	**Observed Water Level (m)**	**Computed Water Level (m)**	**Residual Error (m)**
Bathgate Park	100.59	100.45	0.14
Tonga Park	100.45	100.45	0.00
Kennedy St	100.56	100.4	0.15
Tahuna WWTP	101.20	101.11	0.08
	Observed Sewer Discharge (m^3/d)	**Computed Sewer Discharge (m^3/d)**	
Portobello Rd Pumping Stn.	430	2,275	
		Water Level Statistic	**Value (m)**
		Residual Mean	0.097
		Residual Standard Deviation	0.061
		Sum of Squares	0.053
		Absolute Residual Mean	0.097
		Minimum Residual	0.002
		Maximum Residual	0.159
		Range in Target Values	0.746
		Standard Deviation /Range (ratio)	0.083 or 8.3%

The final statistic in Table 2 is the ratio of standard deviation with the range of level measurements across the model domain. This statistic is generally thought of as a measure of the overall adequacy of the achieved calibration. A Standard Deviation / Range ratio of 5% is generally accepted as an adequate performance of calibration. In the case of the South Dunedin coastal aquifer model, the narrow range of recorded mean groundwater level measurements biases it towards higher percentages. In the course of the calibration and parameter optimisation process, a Standard Deviation / Range ratio of 8.3% was the best result while maintaining parameters within plausible bounds for the most sensitive parameters.

Table 3 lists the final model parameters following parameter optimisation as part of calibration of the model.

Table 3: Calibrated and Optimised Model Parameters

Parameter & Zone		(m/d)	(mm/y)	Dimensionless storage coefficients
Hydraulic conductivity		3.6		
Recharge	Zone 1*	0.0005	182	
	Zone 2¥	0.00137	500	
Storativity				0.001
Specific Yield				0.10
* Urban recharge area ¥ Dune recharge area				

All parameters fall within limits of plausible values for the setting and experience of other aquifer. The recharge parameter of 500 mm/y in the coastal dunes strip is at the upper end of plausibility, but not inconceivable. Hydraulic conductivity move an order of magnitude lower than that determined using tidal fluctuation analysis. It is not uncommon for the bulk hydraulic conductivity to be lower than values determined in smaller scale testing. The storage coefficients of storativity and specific yield could not be tested in steady state calibration and thus they were not altered from the initial assigned values.

3.6 Scenario Modelling

Having calibrated the groundwater model, the next step was to test a number of scenarios against the model in predictive mode.

The primary effect sought to be tested within the modelling project is that of sea level rise impact on the urban area. Thus scenarios would be established to simulate sea level rise at the sea margins of the coastal aquifer. However, projections of sea level rise are in the future and therefore fundamentally uncertain. Most predictions of projected sea level rise span the next 90 years until the end of the century.

3.6.1 Scenario 0: No Sea Level Rise

Despite observed sea level rise trends in the last 130 years, it is worthwhile to consider a base scenario of static sea level.

3.6.2 Scenario 1: 1.1 mm/y Sea Level Rise

This rate of sea level rise is drawn from the IPCC Fourth Assessment Report (IPCC, 2007) as the recorded rise from the period 1961 – 2003. This rise is considered to comprise the following components of rise:

Thermal expansion of the world's oceans	0.42 mm/y
Total global melting of glaciers	0.69 mm/y

3.6.3 Scenario 2: 2.79 mm/y Sea Level Rise

This rate is also drawn from the IPCC Fourth Assessment Report (IPCC, 2007) as the recorded rise from the period 1993 – 2003. The difference in rate is considered to reflect acceleration in sea level rise processes. This rise is considered to comprise the following components of rise:

Thermal expansion of the world's oceans	1.6 mm/y
Total global melting of glaciers	1.19 mm/y

Neither Scenario 1 nor Scenario 2 is considered to include any rise due to ice shelf disintegration.

3.6.4 Scenario 3: 4 mm/y Sea Level Rise

The IPCC Fourth Assessment Report (IPCC, 2007) included observations of modern sea level rise ranging from 1.8 mm/y to 3.1 mm/y. All of these scenarios considered the rise being largely derived from thermal ocean expansion with very minor contributions from the loss of mass on the Greenland or Antarctic ice sheets. Scenario 3 considers future sea level rise that falls into the IPCC (2007) range of rates of rise from 2 mm/y to 5.9 mm/y conjectured as part of the Fourth Assessment Report. This model scenario referenced the Meier et al (2007) paper, which estimated that sea level rise would lie in the mid-range to the IPCC AR4 scenarios at 4 mm/y.

Meier et al (2007) considered a total sea level rise rate of 4 mm/y from 2000 to 2100. Half of the total rise would be provided by thermal expansion of oceans. Of the remaining 2 mm/y due to global glacier ice loss, up to 40% would be contributed by the Greenland and Antarctic ice sheets.

3.7 Results of Scenario Modelling

3.7.1 Scenario 0: No Sea Level Rise

This scenario envisaging observed sea level rise halting and levels remaining static. Figure 2 shows the South Dunedin urban area with patches of water ponding determined for Scenario 0.

Figure 2: Above ground ponding of groundwater for Scenario 0 considering nil sea level rise.

Scenario 0 essentially considers sea level stabilising for a century. Clearly, Figure 2 illustrates seepage and ponding where there is currently no saturation. This scenario shows 0.1 m of above ground ponding in Bathgate Park, Tonga Park, Kings / Queens High School, two areas in Tainui and Bayfield High School. This scenario provides a measure of accuracy of predictions of ponding and the extent to which fine drainage network is not incorporated in the model (drains in Bathgate Park, Tonga Park and Bayfield Park are not implemented in the groundwater model).

3.7.2 Scenario 1: 1.1 mm/y Sea Level Rise

Scenario 1 envisaged a mild rate of sea level rise equivalent to the 20th century. Over 100 years the sea would rise 0.11 m to 100.31 m OMD. Figure 3 shows the resultant groundwater ponding pattern determined in groundwater model output following Scenario 1.

Figure 3: Above ground ponding of groundwater for Scenario 1 considering 0.11 m of sea level rise. Contours as to depth of ponding are graduated in 0.1 m.

Figure 3 illustrates the intersection of the modelled water table surface and the LiDAR land surface. Where the water table surface is higher than the land surface, the affected area is considered to be saturated. A comparison of the ponding intensities of the scenarios in Figure 2 and Figure 3 reveals that the extent and intensity of ponding is greater for Scenario 1 involving sea level rise over the century.

3.7.3 Scenario 2: 2.79 mm/y Sea Level Rise

Scenario 2 envisaged a sea level rise rate equivalent to moderate observations of previous sea level rise over the last 15 years. Over 100 years the sea would rise 0.28 m to 100.48 m OMD. Figure 4 shows the effect of the specified sea level rise at year 2100 in terms of above-ground water depths. The affected areas are more numerous and the extent larger than foregoing scenarios. Comparison of Scenario 1 and 2 ponding indicates that a greater number of properties would be potentially affected by ground saturation at the higher rate of sea level rise.

Figure 4: Above ground ponding of groundwater for Scenario 2 considering 0.28 m of sea level rise.

3.7.4 Scenario 3: 4 mm/y Sea Level Rise

Scenario 3 includes forward projections of sea level rise at rates exceeding the highest modern rates of increase. This is the most conservative of the scenarios envisaging higher future rates of rise. Figure 5 shows the increasing depth and extent of ponding as a result of sea level rise. Several of the patches at Forbury Raceway, Tonga Park and Bathgate Park begin to coalesce. The patches of flooding in Tainui deepen in Scenario 3.

Figure 5: Above ground ponding of groundwater for Scenario 3 considering 0.4 m of sea level rise.

3.7.5 Results in terms of Fluxes and Flows

The results of scenarios outlined above are expressed in terms of the effect on water table ponding (Figure 2 to Figure 5). However, significant information is also contained within the respective models' water balance output.

Table 4 lists the flows of groundwater modelled in the eleven scenarios. Throughout each scenarios the recharge is invariant. The flow rates of outflow to the sea and the piped drainage system vary in response to the rate of sea level rise or mitigation method.

Table 4: Resultant Fluxes and Flows for each Scenario modelled.

	Scenario	Recharge (m^3/d)	Sea Discharge (m^3/d)	Drainage (m^3/d)
Nil Sea Level Rise	0	6,633	4,237	2,282
Total rise of 0.11 m	1	6,633	4,176	2,345
Total rise of 0.28 m	2	6,633	4,076	2,445
Total rise of 0.4 m	3	6,633	4,002	2,516

3.8 Discussion of Model Results

The use of groundwater modelling traditionally balances uncertainty of input data and potential inaccuracy of model predictions against the facility of model predictions in defining future outcomes. In the case of south Dunedin's coastal aquifer the groundwater system is poorly to moderately well characterised. The geometry of the coastal sediments is moderately well-known, however the aquifer properties are poorly understood or quantified. The antidote to the high level of uncertainty that could result from the use of the groundwater model without better data is that most model predictions are restricted to relatively simple manipulations of the model boundary conditions, namely sea levels.

An inaccuracy of the modelled groundwater ponding plots from Figure 2 to Figure 5 is that Figure 2 reveals minor groundwater ponding in Bathgate and Tonga parks under present-day conditions. In fact, there is no current groundwater ponding in either park, although the water table is within 0.3 m of the surface. The sources of this inaccuracy may include the following:

- Calibration having derived a hydraulic conductivity that is lower than reality in the area of interest.
- Calibration having derived inaccurate drain conductance.
- The lack of playing field drainage in the model simulation[3].

Each of these uncertainties could have the effect of overestimating the groundwater ponding in the current setting.

[3] It is understood from DCC Parks & Recreation Department that these playing fields are extensively drained using tile drains.

Two pockets of groundwater ponding are displays in the figures at the south-east end of Portsmouth Drive and Bayfield High School. These areas of ponding are probably a model or display artefact. The scale and resolution of the model and manipulations of the display are poor in assessing the water table in these areas. In particular, boundary truncation errors are suspected for the Portsmouth Drive instance.

4 Summary & Conclusions

The characterisation of the South Dunedin coastal aquifer and the response to sea level rise can be summarised as follows:

4.1 Summary

- The aquifer comprises alluvial and coastal sediments deposited rapidly in response to sea level rise in the last 10,000 years.
- The landform over the South Dunedin flats was initially intertidal and unstable coastal features until stabilisation was undertaken by European settlers, beginning in 1848.
- Land-filling, drainage and urban settlement resulted in a land surface only just higher than the mean sea level of the time, and often lower than high tide.
- The sediments of south Dunedin are predominately sandy and moderately permeable.
- The aquifer is mostly flushed with fresh water derived from recharge through the surface of the south Dunedin flats. However, sea water is relict or has subsequently intruded in scattered areas within the coastal aquifer.
- The water table height is strongly bound by the following factors:
  - The mean water level of the adjoining ocean and harbour.
  - The drainage levels imposed by leaky pipe networks.
- The sea has risen slightly since European settlement by up to 0.2 m, and the water table has probably responded in an equivalent fashion.
- Areas of the aquifer within 300 m of the coast show the effect of tides in fluctuating water tables.
- The induced water table fluctuation is less than the tidal fluctuations driving the variations and lags the tide by approximately 2 hours at the Kennedy Street bore.
- Rises in the Mean Level of Sea are highly likely to force equivalent rises in the height of the water table.
- Groundwater computer modelling of this effect suggests that even the mildest continuation of the current rate of sea level rise would manifest in groundwater ponding in the parts of the South Dunedin urban area.

4.2 Conclusions

1. The South Dunedin coastal aquifer is exposed to changes in *mean* level of sea and would respond to sea level rise by exerting a rising water table, particularly in the Tainui, southern St Kilda and adjoining St Clair areas.

2. Even the most moderate rise in sea level over the 21st Century would result in a rise in the level of saturation, including the development of ponding at the land surface.

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