Groundwater dynamics of a shallow, coastal aquifer

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Abstract

Shallow coastal aquifers are dynamic groundwater systems. They can display considerable variability in groundwater levels over time. Complications arise when urban areas exist above such aquifers as groundwater can interact with underground infrastructure where they come into contact. Additionally, if the water table becomes elevated to the extent that it reaches the surface, groundwater flooding may occur. Low-lying coastal areas are also at the frontline of climate change. Yet the potential effects of climate change on groundwater in these environments are poorly understood. This thesis explores groundwater dynamics in a shallow coastal aquifer in the context of potential interactions with urban land use and future climate change. The South Dunedin aquifer serves as a case study for this purpose. South Dunedin consists of a low-lying urban area, bounded by ocean on two sides, with a shallow, heterogeneous aquifer of quaternary age below. The area has been identified as vulnerable to the effects of climate change and previous research has suggested that mean groundwater levels may become elevated in response to sea level rise in the future. The focus of this thesis is on understanding natural variability in the position of a water table, in particular, in response to rainfall events, and how this may interact with urban land use and the effects of climate change.

To explore this a groundwater monitoring network was established across South Dunedin and high frequency groundwater monitoring occurred between July 2012 and January 2013. Water table movements were found to display spatial variability, which can be linked to differences in sediment and therefore hydraulic conductivity between sites. Significant temporal variability in the position of the water table was also observed. A linear regression relationship has been established between rainfall and water table responses. This has allowed potential water table responses to heavy rainfall events with return periods of 2, 5, 10 and 50 years to be extrapolated. The results of this indicate that groundwater flooding could occur in response to rainfall events with return periods of 5 years or more at some sites in South Dunedin.

How the water table in South Dunedin may respond to future sea level rise has previously been modelled by the Otago Regional Council (ORC) indicating that sea level rise may force groundwater levels to rise. In this thesis the variability of groundwater levels in response to rainfall events is considered in conjunction with an elevation of mean groundwater levels due to sea level rise. These factors are found to combine to increase the risk of groundwater flooding in South Dunedin. While sea level rise alone may not result in mean groundwater levels reaching the surface for quite some time, South Dunedin could experience sporadic flooding occurring more and more often as sea level rise brings the water table closer to the surface. The closer to the surface the water table is located, the greater the opportunity for the natural temporal variability in groundwater levels due to rainfall to bring the water table to the surface, and into contact with underground infrastructure. While groundwater flooding is estimated to occur in response to one in five year rainfall events at present, with sea level rise of 0.1m or more, a one in two year rainfall event could lead to the same extent of flooding. Thus, we could consider one of the effects of sea level rise for South Dunedin as an increase in the probability of flooding due to rainfall events. There is also evidence from wastewater pipe flow monitoring suggesting that groundwater may be infiltrating into the South Dunedin stormwater and wastewater pipe network through weaknesses, and doing so at an increased rate when the water table is elevated in response to rainfall. Accordingly, this study points towards interactions between groundwater, climate change and urban infrastructure as important issues for the future management of South Dunedin.

These findings have implications for coastal cities with shallow groundwater conditions, as the problems South Dunedin faces will very likely be the problems encountered in similar environments in the future. Variability of groundwater levels is rarely represented in climate change impact studies. Yet this research demonstrates a long-term trend of sea level rise and short-term fluctuations due rainfall events interacting to affect groundwater levels. This highlights the importance of both investigating, and acknowledging, the role of natural variability when considering how climate change may impact hydrological systems.

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1 Introduction

Groundwater is a largely invisible, yet important element in the hydrological cycle. Due to its slow moving nature, groundwater is often conceptualised as a static, storage reservoir (Zektser and Loaiciga, 1993). But in reality groundwater is in a constant state of flux. One manifestation of this is variation in the position of a water table. Groundwater levels will vary both temporally and spatially across an aquifer, reflecting changes in the total volume of groundwater stored (Sophocleous, 2004). Of the various factors contributing to changes in groundwater levels, recharge from rainfall can be a major factor (Hanson et al., 2006; Stoll et al., 2011). Gaining an understanding of the relationship between rainfall, groundwater recharge, and water table levels is therefore fundamental to developing insight into groundwater movements. This research examines the variability of groundwater levels of a shallow coastal aquifer in an urban area, to understand the role of rainfall events as a factor governing groundwater levels.

Where shallow groundwater occurs (that is, within 5m of the ground surface), connectivity between groundwater and above ground processes can be particularly strong. These groundwater systems are dynamic and can respond rapidly to terrestrial hydrological processes such as rainfall (Timms et al., 2001). Any water table response to rainfall will be a complex function of permeability, specific yield, antecedent soil moisture conditions, the initial water table level, evapotranspiration, and rainfall volume and intensity (van Gaalen et al., 2012). The proximity of shallow groundwater systems to the surface can impart a susceptibility to impacts from human activities occurring at the surface, as well the potential to affect human activities in some cases (Khaled et al., 2011).

Concerns over groundwater levels most often centre on declining groundwater levels, as this can indicate over abstraction and unsustainable use of a groundwater resource (Scibek and Allen, 2006). However, for shallow groundwater systems, it can be rising groundwater levels that are of most concern. Where groundwater is already close to the surface there is a risk that any rise in level could bring groundwater to the surface, and therefore constitute a flooding hazard (Bichler and Fürst, 2012; Macdonald et al.,

2012). Flooding, in general, is a widely acknowledged hazard, yet only recently has groundwater flooding been recognised as a risk (Bichler and Fürst, 2012). The inclusion of groundwater flooding in the European Union Floods Directive in 2007 has contributed to an increased awareness, along with instances of serious groundwater flooding occurring in southern England and France occurring in 2000, 2003 and 2007 (Habets et al., 2010; Macdonald et al., 2012). A number of recent studies have also identified rising groundwater levels and flooding as a potential consequence of sea level rise and climate change (Bjerklie, 2012; Lebbe et al., 2008; Masterson and Garabedian, 2007; Rotzoll and Fletcher, 2012; Werner and Simmons, 2009).

Global temperatures are estimated to have risen by approximately 0.85°C since the 1800s due to anthropogenic greenhouse gas emissions (IPCC, 2013). Looking forward, temperatures are projected to exceed an increase of 1.5°C in (from 1850-1900 levels) by 2100 (IPCC, 2013). However, changes will depend on how greenhouse gas emissions are managed in the future, under a high emissions scenario an increase of up to 4.8°C by 2100 is projected (IPCC, 2013). As the hydrological cycle is inextricably linked to climate, any changes in global temperatures can be expected to influence the hydrological cycle and, consequently, the volume and fluxes of water in surface water bodies and in groundwater storage (Taylor et al., 2012). While the potential impacts of climate change on surface waters have received substantial attention, research into potential impacts on groundwater has lagged behind. This lack of attention was lamented in the International Panel on Climate Change (IPCC) 2007 report. While there has been a recent surge in research on climate change impacts to groundwater to address this gap in knowledge, current understanding still lags behind that for surface water (Earman and Dettinger, 2011; Green et al., 2011; Holman et al., 2012; Taylor et al., 2012; van Roosmalen et al., 2007).

Climate change may affect groundwater through changes in precipitation (amounts, timing and intensity), and evapotranspiration, both of which are of particular importance as they influence recharge (Bouraoui et al., 1999; Holman, 2006). Warmer temperatures also carry with them the prospect of sea level rise as a result of thermal expansion of oceans and melting of glaciers and ice caps (Ericson et al., 2006; McGranahan et al., 2007). Due to connectivity between groundwater and oceans in coastal aquifers, any changes in sea level may influence groundwater levels and the

position of the saline/freshwater transition zone (Rozell and Wong, 2010; Shrivastava, 1998; Werner and Simmons, 2009).

To detect the effects of climate change on groundwater levels there is a need to differentiate between natural variability of groundwater levels and changes due to climate change impacts (Hulme et al., 1999; Liu, 2013). Therefore an understanding of the natural temporal variability of a groundwater system is a prerequisite for understanding climate change impacts. When estimating how groundwater levels may change over time in response to climate change, it may be important to consider how short-term variability of the groundwater system may interact with long term trends in mean groundwater levels. This introduces a question of the time scale that is taken into account when assessing climate change impacts to groundwater. Temporary movements of the water table can be expected as well as long-term changes in mean groundwater levels occurring in response to gradual changes in mean climate and sea level conditions (Bjerklie, 2012; Kidmose et al., 2013). Thus, an appreciation of the variability of a system may be just as important as understanding average conditions when considering how groundwater may be affected by climate change.

It is also increasingly apparent that groundwater cannot be thought of in isolation from the wider environment; links with surface water, its role in the hydrological cycle, and interactions with society all indicate a broad view of the groundwater system is required (Holman et al., 2012). In terms of potential for groundwater to interact with society, a combination of shallow groundwater conditions and an overlying urban area present prime conditions for such interaction. Shallow groundwater conditions in urban areas can mean that building foundations and subsurface infrastructure can be damaged by flooding and the forces caused by the buoyancy of water (Howard, 2002; Morrison, 1994; Randall, 2013). Such interactions have been documented in cities including London (UK) and Dresden (Germany), where rising groundwater levels have damaged foundations, and New York (USA) where groundwater inflows to tunnels are problematic (Brassington and Rushton, 1987; Kreibich and Thieken, 2008; Lerner and Barrett, 1996; Timms et al., 2001).

South Dunedin, New Zealand, is an interesting example of an urban area with underlying shallow groundwater. This urban area is built on low-lying coastal land that previously formed a salt marsh before land reclamation drained and raised the land

surface (Rekker, 2012). Reclaimed land is often characterised by low elevations above sea level and shallow groundwater conditions. Despite this reclamation work, South Dunedin's elevation remains close to mean sea level and, with surprising consistency, groundwater is encountered within a metre of the ground surface (Rekker, 2012). Due to the shallow groundwater conditions, it is suspected that groundwater interacts with underground urban infrastructure, in particular the wastewater and stormwater pipe system (Osborn, 2011; Van Valkengoed, 2009). Furthermore, South Dunedin has recently been identified as vulnerable to the impacts of climate change (Fitzharris, 2010). How shallow groundwater conditions may contribute to and interact with climate change vulnerability is an issue of concern for city planning. As a result there has been fresh interest in, and effort towards, understanding the South Dunedin aquifer.

In 2009, three boreholes were installed in South Dunedin by the Otago Regional Council (ORC) to monitor groundwater levels and explore the relationship between sea level and the position of the water table. Tidal fluctuations of the water table were observed indicating hydraulic connectivity between the groundwater and the ocean (Rekker, 2012). By implication, any rise in sea level associated with global climate change can be expected to force a corresponding rise in groundwater levels. The ORC research concluded that, under even the most conservative scenario of sea level rise, groundwater in South Dunedin could become elevated to the extent that it reaches the surface, causing groundwater flooding in some parts of South Dunedin (Rekker, 2012).

The potential for groundwater to interact with stormwater and wastewater pipe networks specifically is poorly understood (Olsson et al., 2009; Randall, 2013; Willems et al., 2012). The same can be said for current understanding of the South Dunedin aquifer itself. As the aquifer is not used to provide a water supply it has not been thoroughly investigated. In particular, how the water table responds to rainfall has not been considered. It will be essential for planning for Dunedin City's future to understand the natural temporal variability in water table levels, along with long-term trends due to climate change impacts, and to gain a more detailed understanding of the risk of groundwater flooding in South Dunedin. The current research aims to address this need.

1.1 Research aims and objectives

South Dunedin provides a useful opportunity to examine how groundwater can interact with an urban area where there is already heightened concern around the possible effects of global climate change. The purpose of this thesis is to characterise the temporal variability of groundwater levels that occur in response to rainfall. An understanding of the variability of groundwater levels is important when considering climate change impacts and interactions with urban infrastructure. The key research questions addressed by this research are:

1. To locate where the water table is situated in relation to the ground surface across South Dunedin.

2. To estimate hydraulic conductivity and identify any spatial variation in this parameter across the South Dunedin area.

3. To characterise temporal variability of groundwater levels, in particular those in response to rainfall events.

4. To consider how the water table may respond to future rainfall events and potential implications for the wastewater pipe network and climate change impacts.

This research aims to expand on previous research around groundwater in South Dunedin and the potential impacts of climate change by considering the role of natural variability of the groundwater system. It is acknowledged that in order to effectively consider groundwater interactions with climate change and local infrastructure a good understanding of aquifer hydrogeology and groundwater movements is required. It is intended that this study will provide information about the South Dunedin aquifer that will promote prudent planning for the future.

However, while this research is focused on South Dunedin as a case study, similar challenges are faced by many low-lying coastal cities. South Dunedin is by no means unique in its combination of a low elevation above sea level and shallow groundwater conditions. For coastal cities, urban growth and demand for flat land often prompts an expansion towards the ocean involving land reclamation. In New Zealand, areas of Christchurch such as Bromley, are reclaimed from the Avon Heathcoate estuary

(Wilson, 1976). In Auckland, areas around the Mangere Inlet were reclaimed from tidal swamps and now exhibit shallow groundwater conditions (Schayen, 2004). Further afield, cities including Hong Kong and New Orleans are similarly built on reclaimed land and have a groundwater table close to the surface (Dunbar and Britsch, 2008; Guo and Jiao, 2007; Jiao et al., 2008). Perhaps most famously, large parts of the Netherlands, such as the Flevopolder, are entirely reclaimed land and tackle the ever present risk of flooding by constantly removing groundwater (Faneca Sànchez et al., 2012; Kwadijk et al., 2010; Middelkoop et al., 2001; Oude Essink et al., 2010). Accordingly, while this study aims to improve understanding of the South Dunedin aquifer, the approach used in this study, and the insights gained, are intended to be relevant to other locations. Furthermore, in a broad sense, this research is intended to encourage a wider appreciation of the range of impacts that may be associated with climate change and the role of natural variability of systems.

2 Dynamics of shallow groundwater: theoretical review

2.1 Introduction

Groundwater comprises approximately 21 percent of the freshwater on earth. If we consider only unfrozen freshwater (water not tied up as ice or snow), groundwater is the planet's largest store of available freshwater (McGranahan et al., 2007). To manage our relationship with this vital resource an understanding of groundwater processes is essential (Holman et al., 2012).

An important link between above ground and below ground hydrological processes is the infiltration of precipitation to groundwater. This forms an important part of the hydrological cycle. Recharge from precipitation is considered a main driver of the groundwater system (Stoll et al., 2011). Shallow unconfined aquifers can display particularly strong responses to precipitation. Their dynamic nature can be considered a consequence of their proximity to surface processes (Khaled et al., 2011). For shallow groundwater systems infiltration from precipitation can be the dominant factor influencing the position of the water table (Healy and Cook, 2002; van Gaalen et al., 2012; Viswanathan, 1983). Therefore, an understanding of the relationship between groundwater and rainfall is vital to an understanding of a groundwater system, especially for shallow groundwater systems (Park and Parker, 2008).

One of the settings where shallow groundwater is a common occurrence is in low elevation coastal areas. In coastal zones land elevations approach sea level, and at the same time groundwater flows towards the coast to be discharged to the oceans; these factors can combine to form shallow groundwater conditions (Glover, 1959; Guo and Jiao, 2007). By virtue of their proximity to the surface, shallow groundwater systems can be significantly impacted by, and impact on, the overlying environment (Khaled et al, 2011). It is noted that 'environment' may include a built environment and society where there are urban areas located above an aquifer.

Around 40% of the world's population lives in coastal zones and almost 60% of the world's cities with a population over 5 million have at least some land within this zone (Nicholls, 1995; Small and Nicholls, 2003). Coastal zones have been so attractive for populations that in many cities around the world land reclamation has sought to expand the area of coastal land available (Guo and Jiao, 2007). Swamps and marshes are notable targets for reclamation. However, by reclaiming land that previously provided a transition from marine to terrestrial systems we have shifted populated areas closer to the interface between land and ocean. With this comes an increased vulnerability to impacts from the ocean such as storm surges, tsunami and climate change induced sea level rise (Oude Essink et al., 2010). Reclaimed land is generally accompanied by shallow groundwater conditions and this adds a further dimension to the vulnerability of reclaimed coastal lands (Bondesan, 2000).

For urban centres, a shallow water table denotes the potential for groundwater to interact with below ground structures (Bjerklie, 2012). Furthermore, if groundwater levels become sufficiently elevated there is also the possibility of groundwater flooding (Macdonald et al., 2012). The vulnerability of coastal urban areas to flooding due to sea level rise is an issue that has gained attention in recent years. However the potential role of groundwater flooding has only recently been acknowledged (Bichler and Fürst, 2012). Due to hydraulic connectivity of coastal aquifers to the ocean, a rise in sea level could force a rise in adjacent groundwater levels.

The vulnerability of coastal urban areas to interactions with shallow groundwater will change with a changing global climate (Rotzoll and Fletcher, 2012; Vandenbohede et al., 2008). To understand this vulnerability we must first understand how the water table responds to stimuli (Holman et al., 2012). The dynamic nature of groundwater systems is often hidden when the water table is represented as a mean level. For some applications a mean groundwater level may be appropriate. However, when considering the risk of shallow groundwater rising towards the surface the natural variability of groundwater levels becomes important. Yet the variability of groundwater levels is rarely represented in research considering the potential impacts of climate change.

In response to this knowledge gap the research presented in this thesis attempts to characterise how a shallow water table in an unconfined coastal aquifer responds to rainfall events with reference to potential interactions with an overlying reclaimed

urban area and future climate change. This chapter introduces groundwater concepts that are particularly pertinent to this research, including the use of a water balance equation and factors influencing groundwater levels. This chapter provides an overview of the current state of knowledge around the issues of shallow groundwater in urban areas and the potential impacts of climate change and concludes by relating the gaps in knowledge identified to the objectives of this thesis.

2.2 Groundwater concepts

Groundwater balance

A water balance accounts for movements of water, in a specific area, over a specific time period (Zhang, 2002). This approach is based on the principal of conservation of mass. In its simplest form a water balance equation can be expressed as:

$$I - O = \Delta S \qquad (1.1)$$

Where I is inputs, O is outputs and ΔS is change in storage. A water balance approach can provide a means of conceptualising water fluxes within a system. It requires the quantification of inflows and outflows from a system and changes in storage (Xu and Singh, 1998). When applied to groundwater, a water balance approach can provide an effective tool for conceptualising the movement and storage of groundwater in an area (Nuttle and Portnoy, 1992). An example of a more detailed water balance equation, specifically for groundwater is:

$$R_r + R_s + I - A - D_s - O = \Delta S \qquad (1.2)$$

Where R_r is rainfall recharge, R_s is recharge from surface water bodies, I is inflows from other aquifers, A is abstraction, D is discharge to surface water bodies and O is outflows to other aquifers. A water balance also places groundwater within the larger hydrological cycle and shows links between surface and subsurface aspects of the hydrological cycle (figure 2.1). For example the connections between precipitation and groundwater are explicit in a water balance as recharge from rainfall contributes to changes in storage volume.

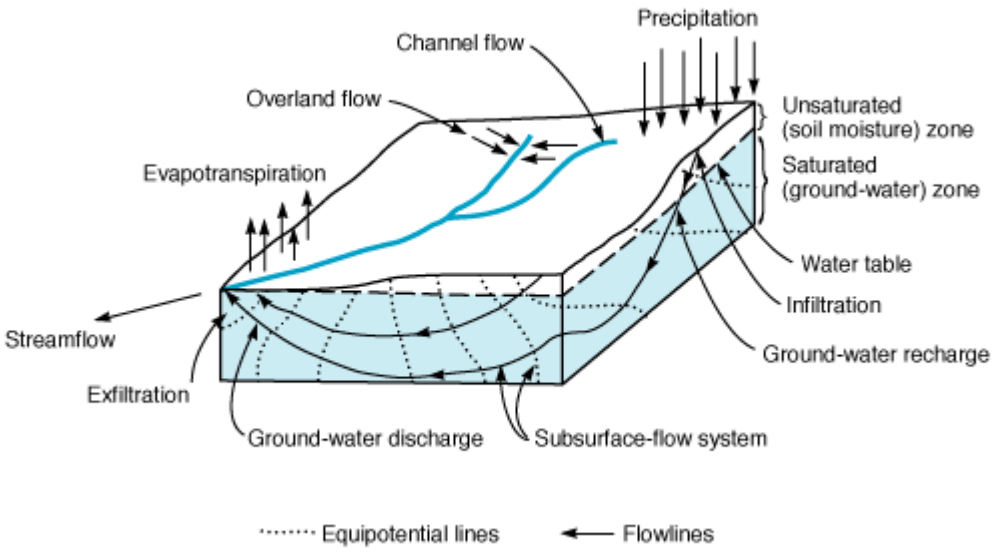


Figure 2.1: Diagram of hydrological cycle (source: Cherry and Freeze 1999)

Water balances can be daily, monthly, annual and can range from simply evaluating the inputs and outputs of a system to complex modelling of the physical processes involved. Simple versions can provide insight into the relative importance of different variables in a groundwater system. More complex models can represent feedbacks and interactions within the groundwater system (Xu and Singh, 1998). However, increased complexity requires more detailed data to drive it and therefore may not always be possible or preferable (Zhang et al., 2002). The level of complexity represented will be determined by the data available and the purpose of the exercise. As with any groundwater modelling, the success in accurately depicting groundwater fluxes relies on suitable and accurate data.

The variables represented in a water balance depend on the processes operating in an aquifer, thus the variables included in a water balance equation for an urban catchment will differ from those for an unmodified catchment (Bhaskar and Welty, 2012). A study by Mitchell et al., (2001) compares water balances in rural and urban areas. This study stressed that alterations to the hydrological cycle in built environments need to be represented when modelling urban areas.

While a water balance approach can be useful in depicting groundwater fluxes it is generally difficult to represent spatial variability in a water balance. Often a water

balance is calculated based on data from a particular site, and the results are then scaled up and applied to the catchment as a whole (Zhang et al., 2002). In this sense a water balance can be considered a lumped model. Similarly, incorporating temporal variation can also be an issue. Ideally water balance calculations would be repeated regularly at short intervals. Hourly, daily and monthly water balance models are considered to provide more accurate representations of a system, compared to annual models (Xu and Singh, 1998). However, in practice daily data may not be available for the variables involved and a long term average may be the best approach available (Zhang et al., 2002).

Factors influencing groundwater levels

The groundwater table can be conceptualised as a 'surface' below the ground; this surface broadly reflects the overlying topography, forming a muted version of the land surface (Cherry and Freeze, 1999). However groundwater is not static; variations in the position of the water table over time are one expression of the dynamic nature of groundwater. An appreciation of the processes contributing to movements of the water table is essential to developing our understanding of groundwater systems (Gillham, 1984).

Variations in the position of the water table over time can be considered to reflect changes in the volume of water stored in the aquifer (Sophocleous, 2004). Broadly, this can occur due to recharge, discharge and horizontal groundwater flow. For an unconfined aquifer recharge occurs as precipitation infiltrates through the unsaturated zone to reach the water table. The addition of water then causes the groundwater level to rise. Recharge and discharge can also occur from/to adjacent surface water bodies including lakes, rivers and oceans (Healy and Cook 2002). Groundwater levels tend to establish equilibrium with levels of hydraulically connected systems such as lakes and streams. If water levels in a connected water body rise, a gradient is created, and recharge to groundwater occurs; or the opposite can occur. This leads to complex interdependence between groundwater and surface water (Sophocleous, 2004; Yechieli et al., 2010).

Over short time scales changes in groundwater levels can occur in response to variation in barometric pressure, evapotranspiration, interactions with adjacent surface water

bodies, and precipitation. Infrequent events such as earthquakes can also alter groundwater levels temporarily (Healy and Cook 2002; Cherry and Freeze, 1999). Over longer time scales there may be cyclic changes in groundwater levels due to seasonal patterns (Kumar and Ahmed, 2003). On even longer time scales patterns in groundwater levels may occur in response to long term climatic cycles such as the El Nino-Southern Oscillation (Arnell, 2003; Weider, 2011). Superimposed on natural climate related groundwater fluctuations, human activities may also have an impact. For example, through changes in land use, abstraction of groundwater, and artificial recharge (recharge related to human activities, for example via irrigation excess) (Holman et al., 2012).

The position of the water table reflects the interaction of various factors influencing recharge, storage and discharge of groundwater (Sophocleous, 2004). When identifying trends in groundwater levels over time it is important to understand the influence of each of these factors and how they can interact. Recent studies have highlighted the need to resolve the effects of climatic changes and human activities on groundwater levels. For example Shamsudduha et al. (2009) used a seasonal trend decomposition procedure to identify seasonal cycles from a long term trend in groundwater level data from areas in Asia influenced by monsoon rainfall. This revealed for the first time a declining trend in groundwater levels indicating the unsustainability of groundwater abstraction in some areas. The declining trend was previously masked by seasonal cycles in groundwater levels. An important issue to acknowledge here is the potential for different forces to be acting over different time scales. In the study by Shamsudduha et al. (2009) seasonal trends cycle annually but this pattern is embedded within a longer term declining trend. There can be as many different time scales involved as there are different forces influencing the water table.

When considering an appropriate time scale and interval for groundwater monitoring programs we must include a consideration of the time scale involved in groundwater responses. It takes time for groundwater systems to respond to disturbances. Response times can range from seconds to millions of years (Sophocleous, 2012). Research by Knight et al., (2005) found that land use change resulted in relatively rapid responses in surface water flows, but noted that for groundwater, reductions in recharge took many years to manifest as reduced discharge.

Important factors controlling groundwater responses are the physical and hydraulic properties of the aquifer. The velocity of groundwater movement depends on the permeability of the material it moves through, which in turn depends on the shape, amount, distribution and connectivity of voids in the material. Thus, permeability can be thought of as the capacity of a material to transmit water (Cherry and Freeze, 1999). Porosity refers to the percentage of the total volume of material that is voids. Together, porosity and permeability allow the storage and movement of water under the Earth's surface (Kresic, 2006).

The term hydraulic conductivity (K) combines permeability of aquifer material with properties of the water (i.e. viscosity and density), and indicates the velocity at which a volume of water will be transmitted through a cross section of material over a unit of time (Cherry and Freeze, 1999). The importance of representing spatial heterogeneity in hydraulic conductivity is an ongoing issue in groundwater hydrology (De Marsily et al., 2005; Fiori and Russo, 2007; Seyfried and Wilcox, 1995; Woolhiser et al., 1996; Zemansky and McElwee, 2005). There are a range of methods for representing aquifer heterogeneity, from stochastic methods considering aquifer properties as random variables, to genetic models representing successions of sediment deposition to model layers of an aquifer (De Marsily et al., 2005). The extent of heterogeneity that needs to be represented will depend on the question being asked (Seyfried and Wilcox, 1995). For studies where groundwater flow is important, a pump test approach to permeability, providing a single value for a whole aquifer may be sufficient. For studies dealing with contaminant transport, a better understanding of small scale heterogeneity may be required (Bjerg et al., 1992). De Marsily et al. (2005) identifies hydrological processes occurring in the unsaturated zone, such as infiltration, saturation and overland run-off generation, as processes where heterogeneity is an important issue. Therefore, when considering movements of the water table in response to rainfall aquifer heterogeneity may be an important issue.

Groundwater response to rainfall

In unconfined aquifers infiltration of precipitation can be the most important pathway for groundwater recharge. Infiltration is the movement of water from the surface into the soil and movement away from the ground surface through the subsurface towards the water table (Cherry and Freeze, 1999). For recharge to occur enough water must

infiltrate through the unsaturated zone to reach the water table. To achieve this infiltration must overcome any losses en route to the water table due to evapotranspiration and due to water becoming held in pore spaces within the unsaturated zone by surface tension (Earman and Dettinger, 2011).

Groundwater recharge is therefore a sensitive function of precipitation (intensity, duration, timing), evapotranspiration, local geology and soil, topography, vegetation cover, connected surface water systems, coastal processes, and human land use activity (Sophocleous, 2004). Where shallow groundwater exists, infiltrating rain may travel through the unsaturated zone to reach the water table relatively quickly. This has been highlighted in a study by Winter et al. (2000) where water table hydrographs for shallow aquifers displayed more frequent and wider ranges of fluctuations compared to aquifers where the water table is deeper below the ground surface.

The close relationship between rainfall and water table rises allows recharge from individual storm events to be calculated and a relationship to be established through a regression analysis of precipitation and recharge (Wu et al., 1996). The use of a linear relationship between rainfall and water table elevations is common in groundwater management and literature (Armstrong, 1988; Ferdowsian et al., 2001; Smajstrla, 1990; van Gaalen et al., 2012; Venetis, 1971; Viswanathan, 1984; Wu et al., 1996). A linear relationship is attractive in its simplicity; however this approach may neglect the variability of groundwater responses caused by variability in antecedent conditions, rainfall intensity, and subsurface stratigraphy. Other examples of time series models relating rainfall to groundwater levels include Eriksson (1970) who analysed groundwater level variation using a Markovian stochastic model. More recently Chebud and Melesse (2011) developed this method further and used a Markovian stochastic model to forecast daily groundwater levels for a dynamic shallow aquifer in Florida.

An alternative approach is physically based models incorporating a groundwater flow equation; this approach has been used to relate water level movements to rainfall. These methods allow recharge to be estimated based on rainfall. A method presented by Rasmussen and Andreasen (1959) uses movements of the water table as indications of recharge allowing quantification of recharge to an aquifer. This method is known as the water table fluctuation method and has been used widely (Crosbie et al., 2005; Healy

and Cook, 2002; Park and Parker, 2008; Rai et al., 2006; Rai and Singh, 1995; Sophocleous, 1991).

Factors complicating the relationship between rainfall and groundwater levels include variability in rainfall volume, duration and intensity, variability in antecedent soil moisture conditions (including the role of the capillary fringe in groundwater responses), and spatial variability of responses due to aquifer heterogeneity (Park and Parker, 2008; Sophocleous, 1991; van Gaalen et al., 2012; Youngs et al., 1989). Research by Van Gaalen et al. (2012) found that including information about the initial water table elevation and rainfall event size improved the accuracy of a model describing water table response to rainfall by 30%. This acknowledges the cumulative effect of rainfall events on the position of the water table.

Variability within an aquifer in terms of water table responses to rainfall have been observed. For example a study by Chen et al. (2002) observed significant spatial variability between wells within an aquifer and linked these to differences in subsurface material. This highlights the role of spatial differences in permeability of aquifer material influencing the amount of recharge received and how a site responds to recharge. Winter et al. (2000) also highlighted the link between spatial variation in water table responses and spatial variation in soil stratigraphy through the use of hydrographs of water table elevations over time to visualise groundwater responses to rainfall.

Characteristics of rainfall events (volume, duration, intensity) will influence the water table response. Furthermore, during a rainfall event, rain will infiltrate into the soil at a rate that decreases over time. This relationship can be shown as a curve of infiltration capacity of the soil, also known as a limiting curve. Figure 2.2 shows an infiltration capacity curve where the initial infiltration capacity (f_0) is dictated by the moisture content of the soil. The decrease in capacity over time, eventually reaching a final infiltration capacity (f_c), occurs as soil pores become saturated (USACE, 1999).

If at any point the rate of water arriving at the surface is greater than the infiltration capacity then water will pond on the ground surface. It is this excess that forms the overland flow component of runoff, the other components being subsurface stormflow, and groundwater flow (Cherry and Freeze, 1999). A prolonged rainfall event can result in the infiltration capacity being reached. Once capacity is reached any subsequent

rainfall will contribute to overland flow (Négrel and Petelet-Giraud, 2005). Similarly a large volume of rainfall arriving quickly could bring a soil to infiltration capacity.

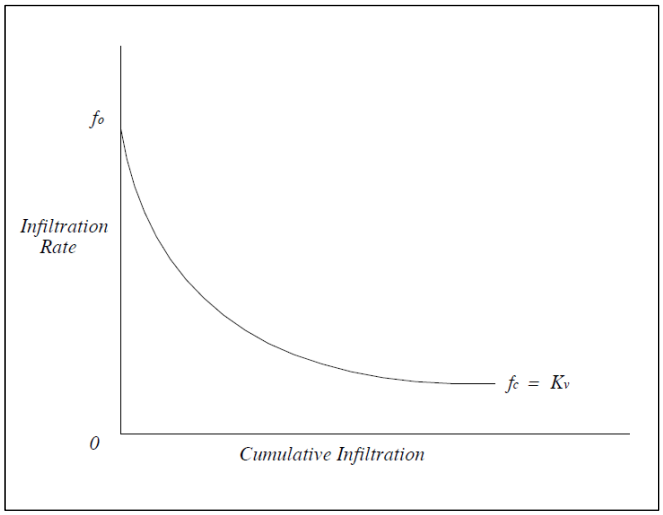


Figure 2.2: Infiltration capacity curve (source: USACE, 1999)

Aquifer properties will influence the infiltration capacity and groundwater response to rainfall. In coarse textured material with large pore spaces water can percolate through the material relatively quickly due to gravity and pressure from rainfall above. In fine textured material with small pore spaces surface tension forces can pull water into pores within the soil. The smaller the pores the more strongly the water is attracted and held. This can reduce the volume of water that reaches the water table, however it may also mean that the material retains water, rather than water draining, thus the material remain closer to saturation between rainfall events. Connectivity of pores can also be important for the infiltration of water towards the water table. Preferential pathways can allow water to reach the water table while other parts of the soil profile remain dry (Cherry and Freeze, 1999).

In shallow groundwater systems studies have observed particularly strong responses to rainfall (Jaber et al., 2006; Novakowski and Gillham, 1988). The role of the capillary fringe has been highlighted as important in rapid responses to rainfall. Due to the forces of adhesion and cohesion, water that is continuous with the saturated zone can be held above the water table (O'Brien, 1982). This is known as capillary action and results in a capillary fringe above the water table (Kresic, 2006). Shallow water tables can exhibit a response to rainfall significantly greater than that expected. Where a capillary fringe extends from the water table towards the surface a small addition of rain can result in a disproportionately large elevation of the water table (Gillham, 1984; O'Brien, 1982).

This is because in the capillary fringe area pore spaces are already partially filled with water hence it takes very little input of water to reach complete saturation; this is known as the reverse Wieringermeer effect (Gilham, 1984). A disproportionate elevation of the water table can also occur where air is trapped under water infiltrating towards the water table. This is associated with intense rainfall events where water moving downward through the unsaturated zone acts as a cap to air trapped beneath. The compression of trapped air results in an increase in pressure in the area above the capillary fringe, prompting the water table to rise to account for the pressure increase; this is known as the Lisse effect (Heliotis and DeWitt, 1987).

Coastal aquifers

Coastal zones are dynamic and complex environments influenced by both ocean and terrestrial processes. The coastal zone is where fresh groundwater, flowing from areas of recharge on land, reaches a point of discharge at the coast. Where an unconfined coastal aquifer is hydraulically connected to the ocean there will be a transition zone formed where fresh terrestrial groundwater moving towards the coast meets and mixes with saline oceanic groundwater as shown in figure 2.3 (Bobba, 2002).

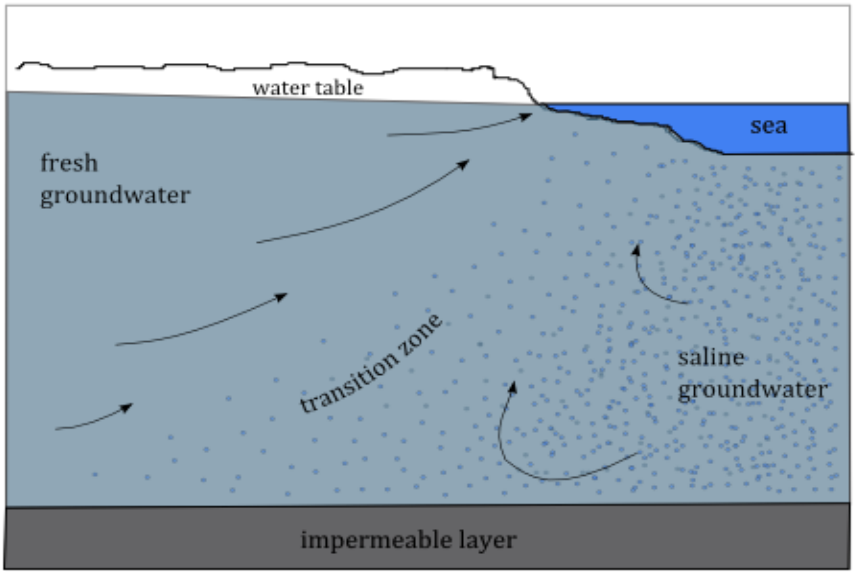


Figure 2.3: Diagram of the transition zone at the fresh/saltwater interface, modified from Cooper (1984).

Because freshwater is less dense it tends to remain above saline water in an aquifer, however rather than an abrupt interface there will be mixing of fresh and saline water forming a transition zone (Ataie-Ashtiani et al., 2001). The location and extent of the

transition zone will depend on a number of factors including the hydraulic conductivity of the aquifer, the rate of freshwater being discharged and the relative densities of the fresh and saline water. Ocean processes such as the movements of tides pushing and pulling saline water towards and away from the shore also contribute to the formation of the transition zone (Cooper, 1964).

In a groundwater balance equation there is generally a discharge component. A feature unique to coastal aquifers is discharge occurring as submarine groundwater discharge at the coastal boundary (figure 2.4). This hydraulic connectivity between groundwater and the ocean is an important feature of coastal aquifers. Groundwater can not only move towards to ocean as discharge but in some situations can flow from the ocean towards the aquifer. This means that ocean processes can exert control over inland groundwater levels (Nuttle and Portnay, 1992). Groundwater tends to maintain equilibrium with connected water bodies such as lakes, rivers and, in the case of coastal aquifers, the ocean. Where there are movements of sea level, it can initiate a movement of water into the aquifer, this is shown in figure 2.4 as *R*? (Horn, 2002).

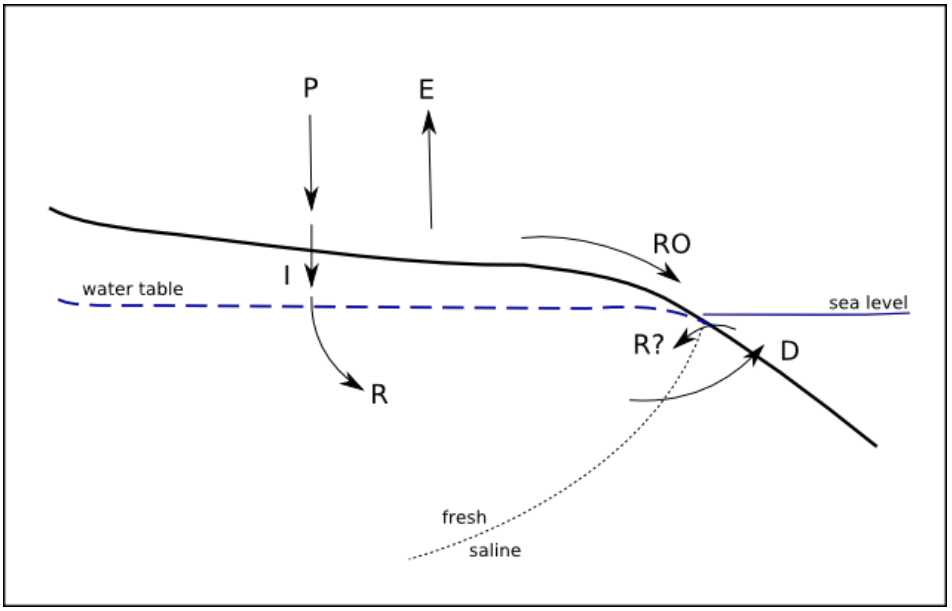


Figure 2.4: Coastal aquifer groundwater balance, showing input from precipitation (P), infiltration (I), recharge (R), evapotranspiration (E), submarine discharge (D) and runoff (RO), modified from Nuttle and Portnay (1992).

An example of the influence of sea level on coastal groundwater is that cyclic movements of tides in the ocean are known to induce fluctuations of the groundwater table in adjacent aquifers (Horn, 2006; Nielsen, 1990). This occurs as the rising and

falling of tides causes loading and unloading of pressure at the coastal boundary. This can result in pressure waves propagating inland through the aquifer. These pressure waves can be detected as fluctuations of the water table (Baird and Horn, 1996; Turner, 1998). The amplitude of water table fluctuations will decrease with distance from the coast as seen in figure 2.5. On the other hand, the lag time between fluctuations at the ocean and corresponding groundwater movements will increases with distance from the coast (Carr and Van Der Kamp, 1969).

Groundwater level in coastal aquifers have been observed to fluctuate in response to variations in ocean levels including those due to tides, waves and storm surges (Turner, et al., 1998). Factors influencing the distance tidal fluctuations travel inland include coastal morphology, tidal range, wave conditions, and aquifer properties (Turner et al., 1998).

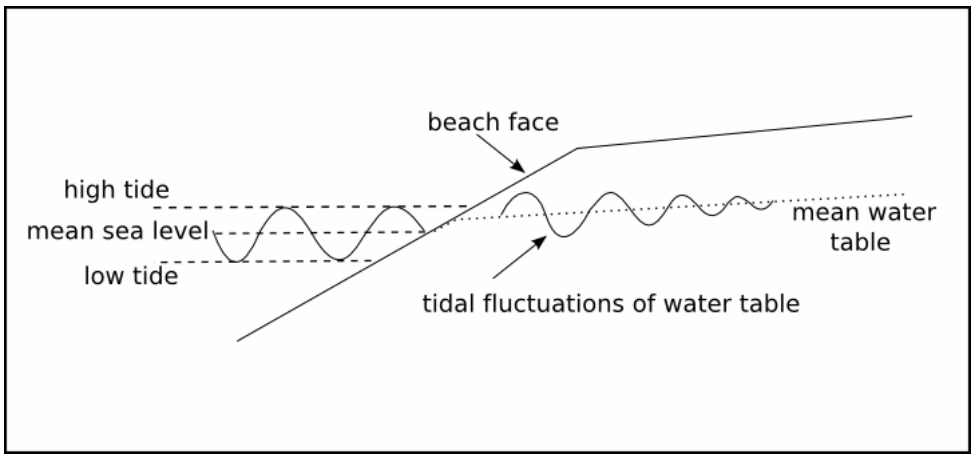


Figure 2.5: Diagram of tidal fluctuations of groundwater in response to tidal movements at the ocean boundary

Where tidal fluctuations are observed it indicates strong hydraulic connectivity between the aquifer and the adjoining ocean. A consequence of this hydraulic conductivity for coastal aquifer is that changes in sea level such as those projected associated with global climate change could influence groundwater levels (Masterson and Garabedian, 2007; Melloul and Collin, 2006; Rotzoll and Fletcher, 2012). Although tidal fluctuations rarely travel more than 1km inland, the effects of a change in mean sea level could reach much further inland. While a tidal fluctuation is a temporary event, a rising mean sea level would require a gradual adjustment of the water table to find a new equilibrium. Barlow (2003) suggests that, in a river delta setting, where both groundwater and a river would need to adjust to a change in sea level, the impact could

reach up to 20-50 km inland. Over geological time scales, the elevation of the water table is considered to be a function of sea level along with influence from climate and tectonics. Kocurek et al., (2001) suggest that the re-equilibration of the water table to changes in sea level may occur tens to hundreds of kilometres inland.

2.3 Groundwater in urban environments

Urban areas can drastically alter hydrological processes such as evapotranspiration, runoff and aquifer recharge. As these processes are components of the water cycle, urban areas have the potential to disrupt the water balance of an area. In terms of effects on groundwater, this can lead to changes in groundwater levels, groundwater quality, groundwater flow directions and groundwater interactions with hydraulically connected surface water systems including wetlands, rivers, lakes and the ocean (Howard, 2002).

If groundwater is used as a source of water human actions can further impact groundwater levels. Over abstraction can lead to declines in groundwater levels, reduced yields from wells and land subsidence (Lerner and Barrett, 1996). In coastal areas groundwater abstraction can also lead to saline intrusion as groundwater flow patterns are altered and saline groundwater is drawn inland (Vandenbohede et al., 2008). More recently, groundwater pollution from urban and industrial sources has become an increasingly prevalent issue. This can be from point sources such as leachate from landfills and underground storage tanks or diffuse sources such as leaking from sewage networks and contaminants dissolved in runoff subsequently infiltrating into soil to reach the water table (Lerner and Barrett, 1996).

Urban groundwater recharge

Urbanisation can significantly affect recharge and discharge components of the groundwater balance (Vázquez-Suñé et al., 2005). Previously it has been assumed that recharge in urban areas would be reduced as impervious surfaces reduce the amount of precipitation able to infiltrate into the subsurface. However observations in urban areas have revealed the opposite: urbanisation is in fact associated with an increase in recharge (Lerner, 2002). Reductions in direct recharge, which are associated with the

incidence of impervious surfaces, can be compensated for by increases in recharge from other sources, such as losses from water supply systems and stormwater systems, where cracks and weaknesses in pipes allow exfiltration of water into the subsurface. Exfiltration from septic tanks, soakways, and leakage from sewers can also contribute. This means the sources and mechanisms involved in recharge in urban settings can differ significantly from natural conditions (Lerner, 2002). Impervious surfaces can also reduce evapotranspiration which can contribute to offsetting the impact of reduced direct recharge from precipitation.

All pressurised water systems leak to some extent. However, indirect recharge from water supply and wastewater systems is very difficult to quantify. Measuring leakages involves practical difficulties, leaving urban water balance equations as a rather imprecise science (Vazquez-Sune et al., 2005). In general, leaks from water mains are considered more important than the effects of sewers (Garcia-Fresca and Sharp, 2005). Leakage rates of 20-25% are considered common and rates of up to 50% have been observed. For example, a leakage rates of 15-30% has been estimated for Tomsk in Russia, with 4-11 new leaks per kilometer of pipe estimated to develop annually (Lerner, 2002). Irrigation of parks and gardens can also contribute to recharge. An extreme case of excessive irrigation in Riyadh, Saudi Arabia has led to groundwater rising to the surface and flooding low-lying roads (George, 1992).

Rising groundwater levels in urban environments

In European cities the industrial revolution was often associated with an increase in groundwater abstraction as more numerous industrial operations required a water supply. This led to a period of high groundwater use and lowering groundwater levels beneath many cities (Brassington, 1990; Lerner and Barrett, 1996). More recently the use of urban groundwater has declined. This decline can be attributed to industrial operations moving further away from city centres, alternative water supplies becoming available, or due to groundwater becoming polluted and no longer suitable for use (Howard, 2002). Reduced abstraction has allowed groundwater levels to recover. This recovery can be augmented by additional recharge from leaking water supply and wastewater systems contributing recharge to an aquifer (Lerner, 2002).

Where a water table recovers or becomes elevated this can result in groundwater rising above underground infrastructure. These high water table conditions are referred to as under flooding and can affect the foundations of structures, reducing their load carrying capacity, with older structures being more vulnerable (Morrison and Taylor, 1994). Structures designed and constructed during periods of depressed groundwater levels can be unsuited to cope with rising groundwater levels. In many European cities this affects underground tunnels for transport, basements and other below ground buildings and infrastructure (Brassington and Rushton, 1987; Greswell et al., 1994; Hurst, 1986). Contamination of urban water can become more of an issue as the water table rises and starts to interact with urban structures. Where groundwater chemistry includes high levels of sulphates, groundwater can corrode foundations (Lerner and Barrett, 1996; Vazquez-Sune et al., 2005).

Where the water table exists above structures, a pressure gradient will exist which promotes groundwater infiltration through cracks and weaknesses in those structures (Johnson, 1994). In general, stormwater and wastewater pipes are the main below ground infrastructure. However, recent trends in urban areas involve placing communication networks and electrical cables underground to reduce above ground infrastructure (Johnson et al., 2001).

To indicate the prevalence of this issue, it is helpful to review some examples of cities experiencing detrimental effects of high water table conditions. In London groundwater levels were depressed by more than 70m due to abstraction, mostly for industrial uses, this is now recovering at a rate of approximately 1m per year. The main concern is a reduction in load bearing capacity of building foundation. The reduction in load bearing capacity due to rising groundwater levels has been estimated at 25-30%, which can be contrary to building codes and regulations (Lerner and Barrett, 1996).

Parts of Birmingham were originally marshland, but were gradually reclaimed as the city expanded. Groundwater abstraction for industrial water supply helped to dry out the subsurface, allowing below ground structures such as basements to be constructed. Since industrial groundwater abstraction has declined, the aquifer requires dewatering to prevent the water table interacting with below ground structures (Lerner and Barrett, 1996). Rising groundwater levels are considered to impose extra pressure on

Birmingham's storm water drainage systems and utilities buried beneath the ground (Greswell *et al.*, 1994).

Flooding of transport tunnels is experienced in Liverpool and Merseyside in the UK, Paris, New York, and a number of cities in Germany (Hurst and Wilkinson, 1986; Brassington and Rushton, 1987). In Uzbekistan elevated groundwater levels due to artificial recharge from water pipes and from irrigation canal networks have created high water table conditions below urban areas (Ikramov and Yakubov, 2002). In Eastern Ukraine reduced abstraction, combined with leaking water supply systems and sewers, has resulted in under flooding over large areas. These high water table conditions can contribute to landslides, for example an elevated water table was identified as the cause of a landslide that destroyed multiple buildings, including a nine-story block of apartments (Jakovljev et al., 2002).

Groundwater flooding has received less attention that surface water flooding as a hazard (Hughes et al., 2011; Kreibich et al., 2009; Robins and Finch, 2012). However recently there have been some notable attempts to project extreme groundwater levels that would result in groundwater flooding. Examples of studies include Birchler and Furst (2012) who applied a regional frequency analysis to estimate extreme groundwater levels for shallow aquifers in Austria. They estimated that 12 – 45% of the investigated area would experience groundwater flooding in response to an event with a return period of 100 years. Najib et al. (2008) presented an extreme value analysis method to estimate groundwater levels in response to a 100 year return period event in France. This method was further developed and applied to Silkeborg, in Denmark, by Kidmose et al. (2013) to explore the probability of groundwater flooding under current and future climate change scenarios. Pinault et al., (2005) has similarly considered how groundwater flooding risk may be influenced by global climate change. There have also been attempts to model spatial extents of groundwater flooding and develop maps of flood risks (Morris et al., 2007; Upton and Jackson, 2011).

Groundwater infiltration into wastewater and stormwater networks

Just as leaks in water supply pipes can allow water to leak out (exfiltrate) contributing to groundwater recharge, there is also the potential for groundwater to leak into stormwater and sewer pipes (infiltrate), where the water table is located above pipes.

Infiltration is groundwater entering a drain or sewer through broken or porous pipes or through defective joints. Infiltration occurs where pipes are surrounded by groundwater resulting in a pressure gradient with higher pressure outside the pipes than inside. This promotes water movement from the aquifer into the pipe interior (Ellis, 2001). The infiltration of groundwater into pipe networks can mean that stormwater and wastewater pipe system in urban areas provide a pathway for groundwater discharge (Karpf and Krebs, 2004). Infiltration and exfiltration are dynamic processes, affecting both sewer performance and groundwater. These interactions are likely to increase as the age of the sewer increases. Examples of evidence of exfiltration of sewage into groundwater from studies include finding faecal coliforms and nitrogen enrichment in groundwater near sewer pipes (Ellis, 2001).

Groundwater infiltrating into sewer pipe networks can reduce the efficiency of sewer systems and detrimentally affect structural integrity where pipe networks experience loads beyond their designed capacity. It can increase the risk of sewer overflow, flooding, pipe collapse, and result in overloading of the wastewater treatment plant (Heywood, 1997). Flow on effects include reduced wastewater treatment efficiency and untreated waste or poor quality discharge being released into a receiving environment. The increased capital and operational costs associated with groundwater infiltration have been appreciated in a number of studies (Ellis, 2001; Huber et al., 1988; Karpf and Krebs, 2004).

Shallow groundwater conditions are conducive to groundwater infiltration as elevated groundwater levels bring groundwater closer to below ground infrastructure. A further elevation of the water table due to a rainfall event can further contribute to groundwater infiltration. Infiltration has been found to correlate with groundwater levels, tide levels and rainfall (Ellis, 2001). Where rainfall is correlated with infiltration it is known as rainfall induced infiltration. This occurs where a water table response to rainfall elevates a water table to the extent that it comes in contact with stormwater and wastewater pipes. Rainfall induced infiltration usually displays a slow response and can take several days to decay compared to normal rainfall inflow into stormwater networks, which occurs rapidly as overland runoff enters pipe systems during and after rainfall events (Karpf and Krebs, 2011).

It can be difficult to quantify groundwater infiltration; most estimates approach this problem by using dry weather flow data. A study by Heywood (1997) estimated infiltration as 10% of dry weather flow for the UK. A similar study, also using dry weather flows, suggested infiltration rates of between 15% and 50% for the UK (Ellis, 2001). However due to rainfall induced infiltration this approach may underestimate total infiltration. Where increased infiltration occurs associated with rainfall events it will improve understanding to consider infiltration during storms (Heywood, 1997). A number of studies have approached this by using time series and linear regression models of infiltration rates based on groundwater levels and rainfall data (Huber et al., 1988; Karpf and Krebs, 2011; Mein and Apostolidis, 1992).

Where infiltration occurs, providing a pathway for groundwater discharge from the aquifer,r this may have a side effect of depressing groundwater levels. If the drainage function was to be removed by rehabilitation of sewers resulting in a 'tight' sewer system there may a change in the water table position and how it responds to rainfall events. The complex interactions between groundwater and wastewater pipe area an area of study where there is much uncertainty and further study is needed to understand the complex relationships involved (Karpf and Krebs, 2004).

2.4 Potential impacts of climate change on groundwater

Global climate change due to anthropogenic greenhouse gas emissions has the potential to affect groundwater levels, flow, and quality. On a global scale an average warming of 3-5^{o}C is generally expected to occur within the next 50 years (Earman and Dettinger, 2011). As the hydrological cycle is intimately linked to climate, any changes in temperatures will have significant effects on hydrological regimes. For groundwater the influence of warmer temperatures on precipitation patterns and evapotranspiration are of particular importance as these factors exert a strong control on groundwater recharge (Scibek and Allen, 2006). Warmer temperatures also carry with them the prospect of sea level rise. Sea levels have risen by around 22cm during the 20th century and are expected to continue to rise as temperatures increase, mainly due to thermal expansion of oceans and melting of icesheets (Earman and Dettinger, 2011). Due to the connectivity between coastal aquifers and oceans any changes in sea level could

influence groundwater levels in the coastal zone and the position of the saline/freshwater transition zone (Werner and Simmons, 2009; Rozell and Wong, 2010; Shrivastava, 1998).

Impacts associated with warmer temperatures with relevance to groundwater include an expected increase in evapotranspiration rates and altered precipitation patterns. Changes in precipitation projected due to climate change include changes to the temporal and spatial distribution of precipitation, the form of precipitation (e.g. snow, rain), the amount, and the intensity of precipitation received (Bony et al., 2006; Dore, 2005; Green et al., 2011; Meehl et al., 2005)). A general pattern of moist areas experiencing more precipitation, dry areas experiencing less precipitation, and an increase in extreme events is expected. However, there may be significant regional and local scale differences in effects (Dore, 2005; O'Gorman and Schneider, 2009).

Groundwater recharge is a sensitive function of precipitation, evapotranspiration, local geology and soil, topography, vegetation cover, connected surface water systems, coastal processes, and human land use activity. Thus it is expected that climate change will alter groundwater recharge to aquifers, mainly through changes in precipitation and evapotranspiration. For unconfined aquifers any changes in recharge imply changes to water table levels (Scibek and Allen, 2006). A range of studies support the idea that changes in precipitation and evapotranspiration would lead to changes in groundwater recharge (Earman and Dettinger, 2011; Green et al., 2011; Stoll et al., 2011; Scibek and Allen, 2006; Holman et al., 2012; Taylor et al., 2012). These changes may be beneficial or detrimental. For example Kovalevskii (2007) considered the effects of projected changes in precipitation on recharge across Russia and found that many areas would likely experience increased recharge as precipitation increased. For some areas increased recharge was considered to improve groundwater resources, while in other areas it may lead to waterlogged soils, drained lands returning to swampy conditions, increased landslide risks and a decrease in soil productivity.

Areas with shallow groundwater may be particularly susceptible to effects of climate change. Small shallow aquifers may show climate change influences more quickly than large deep aquifers. For shallow aquifers increases in precipitation events may lead to elevated groundwater levels. Instances of groundwater induced flooding are currently rare but some examples include the Somme Valley, France (Pinault et al., 2005), Chalk

aquifers in England (Hughes et al., 2011; Macdonald et al., 2012) and lowland coastal areas in Belgium and the Netherlands (Vandenbohede et al., 2008). As a water table rises closer to the surface the water balance may be further altered; a suggested flow on effect may be an increase in runoff. The mechanism for this is that a higher water table would result in reduced infiltration capacity, thus saturated conditions would be reached rapidly prompting surface runoff (Nuttle and Portnoy, 1992).

Coastal aquifers are particularly interesting areas to consider the impacts of climate change due to the interrelated nature of climate, surface water, groundwater and sea levels (figure 2.6). Interactions between these closely linked systems need to be considered when projecting the effects of climate change. Further complexity is also introduced by the need to take into account the considerable uncertainty involved in projecting the effects of climate change on groundwater systems.

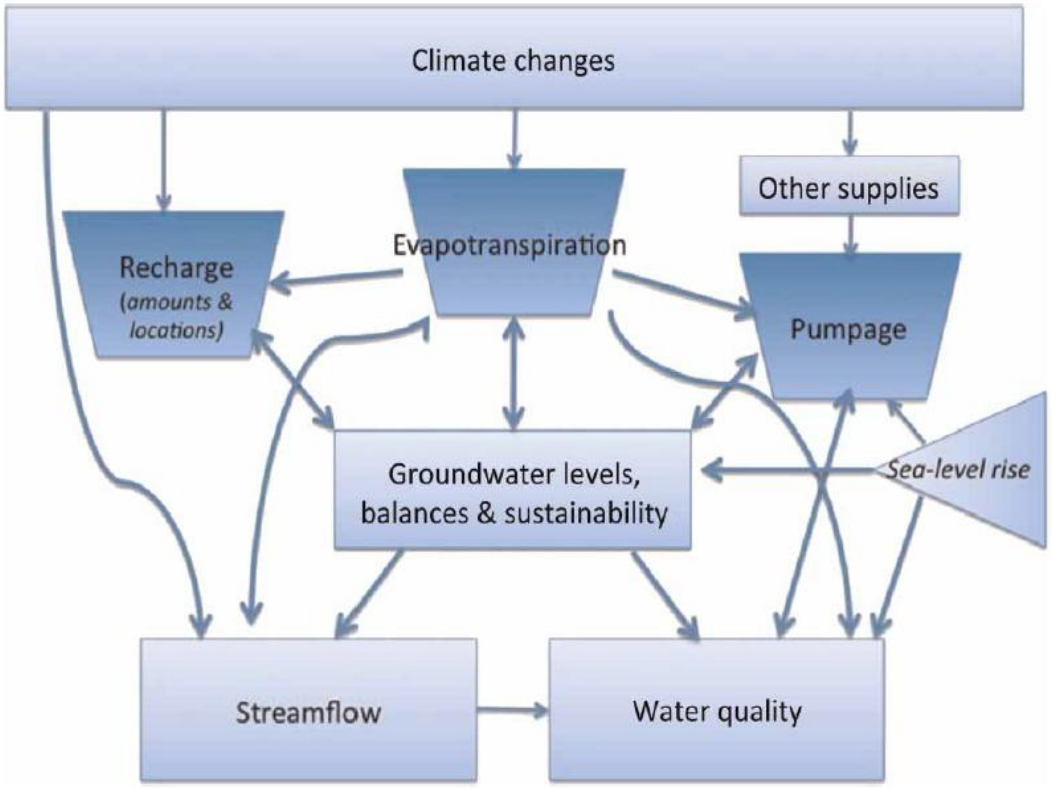


Figure 2.6: Diagram showing major links between climate change and groundwater (source: Earman and Dettinger, 2011)

For coastal aquifers, changes in sea level may lead to changes in water table elevation, a shift of the fresh/saltwater interface position and changes in submarine groundwater discharge (Kafri and Yechieli, 2010). The most often cited potential effect of sea level

rise, relating to groundwater, is saline intrusion i.e. the inland movement of the fresh/saltwater interface; there are numerous articles exploring this issue (Bobba, 2002; Essink, 2001; Rozell and Wong, 2010; Shrivastava, 1998; Werner and Simmons, 2009; Yechieli et al., 2010). A lesser recognised potential effect, but no less important, is that the water table may rise, and in some low-lying areas this elevation may mean the water table reaches ground level (Kocurek *et al.* 2001).

A study by Rotzoll and Fletcher (2013) focuses on rising groundwater levels as a result of sea level rise by modelling sea level rise effects on groundwater levels in the Oahu aquifer, Hawaii. They found that when rising groundwater levels were included in modelling of sea level rise, the area expected to experience flooding more than doubled, compared to estimates based on flooding due to inundation from the sea alone. Research already conducted in South Dunedin, New Zealand has also emphasised the role of groundwater flooding as an effect of rising sea levels, suggesting that even conservative estimates of sea level rise could lead to groundwater flooding in some areas (Rekker, 2012).

Limitation of groundwater related climate change impact studies

The potential interactions between climate, surface water, groundwater, sea level and humans are numerous and beyond the scope of any one study. However approaches considering only one aspect of these inextricably linked systems risk missing important interactions. The role of natural variability of groundwater and climate systems is a further factor that may play an important role in the response of groundwater to changes in climate. An integrated approach to considering the effects of climate change on groundwater is essential to appreciate the extent of potential effects.

Most studies considering the impacts of climate change on groundwater have considered either the effect of rising sea level (Masterson and Garabedian, 2007; Rotzoll and Fletcher, 2012; Werner and Simmons, 2009) or the effect of precipitation (Bouraoui et al., 1999; Holman, 2006; Jyrkama and Sykes, 2007; Scibek and Allen, 2006). Few have considered how these two may interact in coastal aquifer settings. An exception to this is a study by Bjerklie et al. (2011) on groundwater levels in New Haven Connecticut, which simulated a 12% increase in recharge precipitation and a 3ft rise in sea level. When the increase in recharge due to rainfall was added to the sea

level rise simulation it resulted in an addition 1 foot rise in groundwater levels. This clearly indicates that precipitation has the potential to exacerbate any changes in groundwater levels due to rising sea levels (Bjerklie et al., 2011).

Studies from the Netherlands have contributed a great deal to research on the impacts of climate change and sea level rise on groundwater (Oude Essink et al., 2010; Kwadijk et al., 2010; Middelkoop et al., 2001; Oude Essink, 2001;). Perhaps not surprisingly as approximately 27 percent of the Netherlands land area, and 60 percent of the country's population of 15.8 million people, is currently situated below sea level (Den Elzen and Rotmans, 1992). A comprehensive study by Oude Essink et al. (2010), which considers the effects of sea level rise, land subsidence, changes in recharge, salinisation, and two options of mitigation measures, is a rare example of an integrated approach considering potential interaction between various consequences of climate change. This study reported rising groundwater levels and increased salinity in areas within 10km of the coast, and expected detrimental impacts on water supply for drinking water, agriculture, industry and impacts to ecosystems in this area as a result of interactions between different aspects of future climate change (Oude Essink et al., 2010).

In general, studies considering the effects of sea level rise on groundwater have focused on saline intrusion at the expense of changes in groundwater levels. In some saline intrusion studies the potential for groundwater levels to become elevated is recognised. For example a study by Rozell and Wong (2010) at Shelter Island, New York State, acknowledged the potential for the water table to intersect with low-lying areas as it rises in response to sea level rise. However, it was only saline intrusion due to sea level rise that was modelled and quantified. A study assessing risks to Belgium associated with sea level rise and saline intrusion also mentions the risk of the water table reaching ground level as the water table rises in low lying areas (Lebbe, 2008). A study by Masterson and Garabedian (2007) modelled the effects of sea level rise and groundwater pumping for the lower Cape Cod aquifer system, (Massachusetts, USA) and reporting a general trend of groundwater levels increasing with time in response to rising sea level, but stopped short of considering flooding as a result. The potential for groundwater levels to become elevated in response to sea level rise requires further attention, particularly for locations where the water table is already shallow.

When projecting how physical systems may respond to future climate change there is significant uncertainty involved. It is essential to account for and represent this uncertainty when presenting information about the potential impacts of climate change (Stainforth et al., 2007). When considering how climate change will influence groundwater there are multiple points where uncertainty can enter into projections. Uncertainty arises in the projections of future greenhouse gas emissions, how emissions will impact climate variables including temperature and precipitation, and how changes in climate will impact related systems including surface water and groundwater hydrology, and sea levels (Holman, 2006). Furthermore, there may be feedback pathways between various aspects of climate change and interactions between impacts that are difficult to predict (Bony et al., 2006).

In research presenting how a system may respond to changes in climate, the natural variability of the system also needs to be considered. If groundwater levels are represented as a mean value, this ignores the dynamic nature of groundwater. More informative results may be obtained by taking into consideration the variability of groundwater systems superimposed on top of long term trends. Climate change impact assessments often represent changes in terms of changes to mean groundwater levels (Bjerklie, 2012; Masterson and Garabedian, 2007; Rotzoll and Fletcher, 2012; Rozell and Wong, 2010).

There have been calls to represent the inherent variability of natural systems when presenting information about climate change impacts in literature; however few studies actually to do so (Arnell, 2003; Hulme et al., 1999; Liu et al., 2013). Research by Hulme et al. (2013) emphasises the importance of natural variability; they estimated that between 2000 and 2050 the effects of natural climate variability would be more influential than the impacts of human induced climate change. Representing uncertainty in groundwater levels may be one option for including information about variability around mean groundwater levels. However explicit consideration of the role of natural variability and its potential interaction with the impacts of climate change would be a preferable approach. If this can be achieved, climate change impact studies may be able to provide more informative estimates for decision makers regarding the potential impacts of climate change on groundwater.

2.5 Objectives revisited

For urban areas with underlying shallow groundwater knowledge of water table movements and their drivers are valuable for urban planning. Potential consequences of shallow groundwater conditions include interactions with below ground infrastructure and a risk of groundwater flooding. In the future, global climate change has the potential elevate groundwater levels where sea level rise or increased recharge occurs. An important first step towards being able to consider how changes in precipitation may influence groundwater and interact with other climate change impacts is to understand current relationships between rainfall and groundwater levels.

With this in mind, this thesis aims to explore how groundwater levels in a shallow coastal aquifer respond the rainfall events. An important aspect of understanding groundwater dynamics is to understand the temporal and spatial variability of the system. Representations of the natural variability in groundwater levels are often omitted from climate change impact studies. In this thesis the relationship between rainfall and the position of the water table is characterised so that the natural variability in groundwater levels can be represented. The South Dunedin aquifer is used as a case study of a coastal urban aquifer with shallow groundwater conditions. This setting provides an opportunity to consider the complex interactions between groundwater, urban infrastructure and climate change for a shallow coastal aquifer.

3 Study Site

3.1 Introduction

Dunedin City is located on the east coast of New Zealand's South Island at 45º50'S, 170º33'E. South Dunedin is located, as the name suggests, to the south of the central business district of the city. It is an urban area with low elevations above sea level, and a shallow water table. At present South Dunedin is a densely populated residential area; however, in the past it comprised a salt marsh and sand dunes including a wetland area and at least two lagoons. Extensive land reclamation was required to build up the land surface to create the low lying area, known today as South Dunedin (Morris, 2008; Rekker, 2012).



Figure 3.1: Map of the South Dunedin with the study site area marked, (source: Google maps).

The South Dunedin flats includes the suburbs St Clair, St Kilda, Forbury, South Dunedin, Kensington, Tainui and part of Musselburgh (figure 3.1). The Tahuna Wastewater Treatment Plant (Tahuna WWTP) is located at Tahuna Park, in Tainui

(figure 3.1). The flats are bounded by the Otago Peninsula to the east, which previously formed the south eastern rim of the Dunedin Volcano, and the hill suburbs of Kew, Corstorphine and Calton Hill to the west. South Dunedin sits between these higher elevation areas with a sandy beach extending along the coastline. It could be considered an isthmus, connecting the Otago Peninsula to the mainland with the Pacific Ocean to the south, and the Otago Harbour to the north east (McCahon et al., 1993; Glassey et al., 2003).

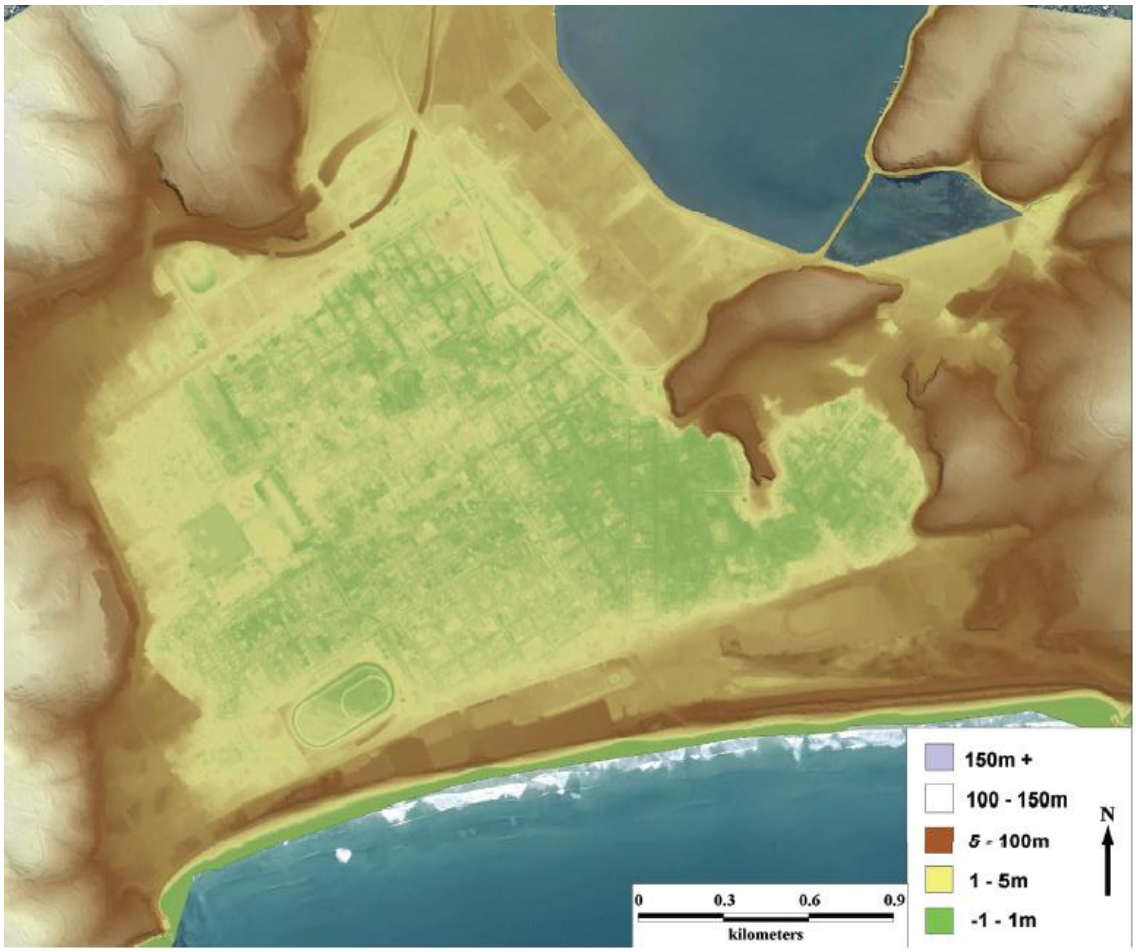


Figure 3.2: Map of the South Dunedin area showing elevation as height in metres above mean sea level (source: Goldsmith, 2012)

The area considered in this study corresponds with the area identified as the South Dunedin Catchment by the Dunedin City Council (DCC) Integrated Catchment Management Plans (2011). This is a 5.7km^2 catchment located between 0 and 140m

above mean sea level, with approximately 70% of the area no more than 5m above mean sea level (figure 3.2). The catchment has an average slope of just 0.008% indicating a very flat, uniform area with little gradient to promote surface or subsurface water flow (DCC, 2011; Goldsmith, 2012).

3.2 Hydrogeology

In broad terms, Dunedin lies on top of a weathered volcanic complex. South Dunedin itself is underlain by quaternary deposits, forming soft soils, surrounded by Miocene volcanic rocks collectively known as the Dunedin Volcanic Group (figure 3.3). The geology of South Dunedin has been broadly described as Holocene sand deposits, including estuarine deposits and coastal deposits, underlain by an impermeable base. These deposits form an aquifer reaching a maximum depth of approximately 60 m (Bishop and Turnbull; Glassey et al., 2003; Rekker, 2012).

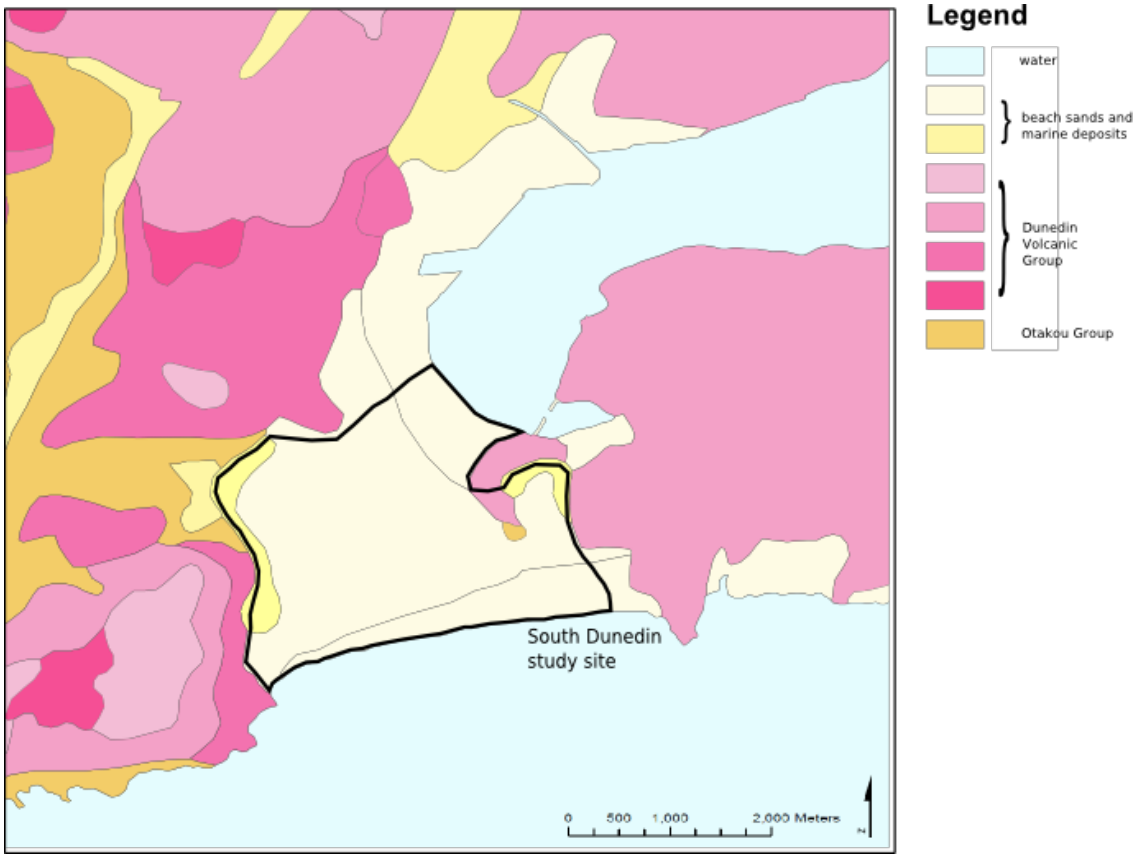


Figure 3.3: Geological map of Dunedin (source: Bishop & Turnbull, 1996 GNS 1:250000 Geological Map)

South Dunedin is relatively young in geological terms; it is essentially an alluvial area formed as material, eroded from the surrounding hills, has been carried towards the coast (Marshall, 1906). The shape of the base of the South Dunedin aquifer indicates a gorge running from North Dunedin towards the coast, this is likely to have been a river during the last ice age when sea levels were much lower than at present. As ice sheets melted, and sea levels rose over the past 20,000 years, the coastline has shifted further inland, triggering sedimentation. This process started the deposition which filled in the South Dunedin area between the eroded remnants of the Dunedin Volcanic Group (Rekker, 2012).

The South Dunedin aquifer is a shallow, unconfined aquifer. This body of groundwater will be referred to as an aquifer in this thesis although it is not utilised as a source of water. In 2009, the ORC installed 3 boreholes in South Dunedin and found the water table between 0.34 and 0.68m below the ground surface at these sites. Furthermore, anecdotal evidence of a shallow water table abounds in South Dunedin, with residents consistently reporting the proximity of groundwater to the surface (Rekker, 2012). Saline groundwater is encountered close to coastline, reflecting the transition zone from fresh to saline groundwater. The position of the transition zone is considered to fit with expectations based on the Gyben-Herzberg ratio (Rekker, 2012). There are no notable, natural surface water features of South Dunedin. Rather, the area has been highly modified and the surface hydrology of the area is now dominated by artificial channels for water flow. A stormwater pipe network collects and diverts surface flow to be discharged into the Otago Harbour (DCC, 2012).

Groundwater levels in South Dunedin are considered to be primarily controlled by climate, sea level and urban infrastructure. Tidal fluctuations of groundwater have been observed in South Dunedin, implying a close hydraulic connection between groundwater and the adjacent marine system. The relationship between sea levels and groundwater levels in South Dunedin has been investigated by Jens Rekker, of the ORC, utilising the three boreholes installed in a transect across South Dunedin. This allowed aquifer hydraulic conductivity to be estimated using the tidal method. Tidal fluctuations were recorded at the first and second boreholes, located 0.12 km and 0.9 km from the shore respectively. However, there was no tidal signal detected at the third borehole, located 1.6 km from the shore. Figure 3.4 shows an example of data obtained from the first borehole, in which the water table fluctuated by 0.22 m, compared with

the corresponding tidal range of the ocean of 1.51 m. The groundwater fluctuations lagged the tidal fluctuations by approximately 2 hours. Based on this data, hydraulic conductivity for the South Dunedin aquifer was estimated as 22 m per day using the tidal method (Rekker, 2012).

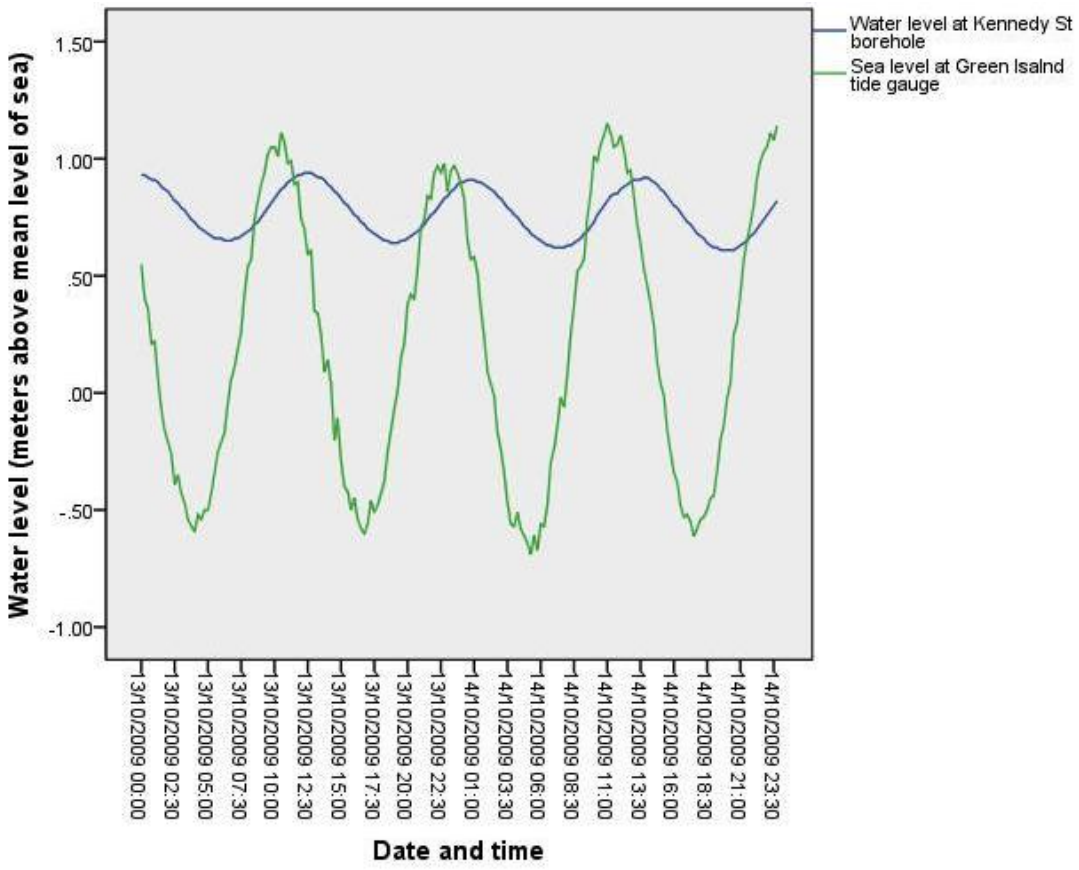


Figure 3.4: Graph of water level at the Kennedy St ORC borehole compared to sea level

The ORC research included a modelling approach to project the response of the water table to scenarios of sea level rise for South Dunedin. The sea level rise scenarios considered were 0, 1.1, 2.78 and 3.4 mm per year over the next 90 years. Simulations indicate that a rise in sea level would force equivalent rises in the height of the water table and that:

> "Even the mildest continuation of the current rate of sea level rise would manifest in groundwater ponding in parts of the South Dunedin urban area (Rekker, 2012)."

Instances of predicted groundwater ponding under sea level rise scenarios are concentrated in two areas: around Tainui and around St Clair, including Tonga Park

and Bathgate Park. The general pattern indicated by this modelling is that the higher the sea level considered the deeper and more widespread the resultant groundwater ponding (Rekker, 2012).

3.3 Climate

Dunedin has a cool-temperate, sub-humid, maritime climate. Despite this broadly temperate climate, Dunedin experiences large variability in weather, linked to sequences of anticyclones and low pressure troughs passing over the area. These sequences form a major synoptic climate feature influencing weather over the South Island of New Zealand. Due to New Zealand's location within the belt of mid latitude Southern Hemisphere westerlies, the predominant direction of the movement of pressure systems is from west to east (Wratt et al., 1996). The low pressure systems influencing New Zealand generally originate over the Southern Ocean and bring cooler temperatures. The sequence of anticyclones and low pressure systems forms a regular 3-10 day weather cycle with anticyclones bringing a day or two of fine weather followed by a low pressure trough, generally accompanied by one or more fronts, bringing rain and cloud (Mojžíšek, 2005).

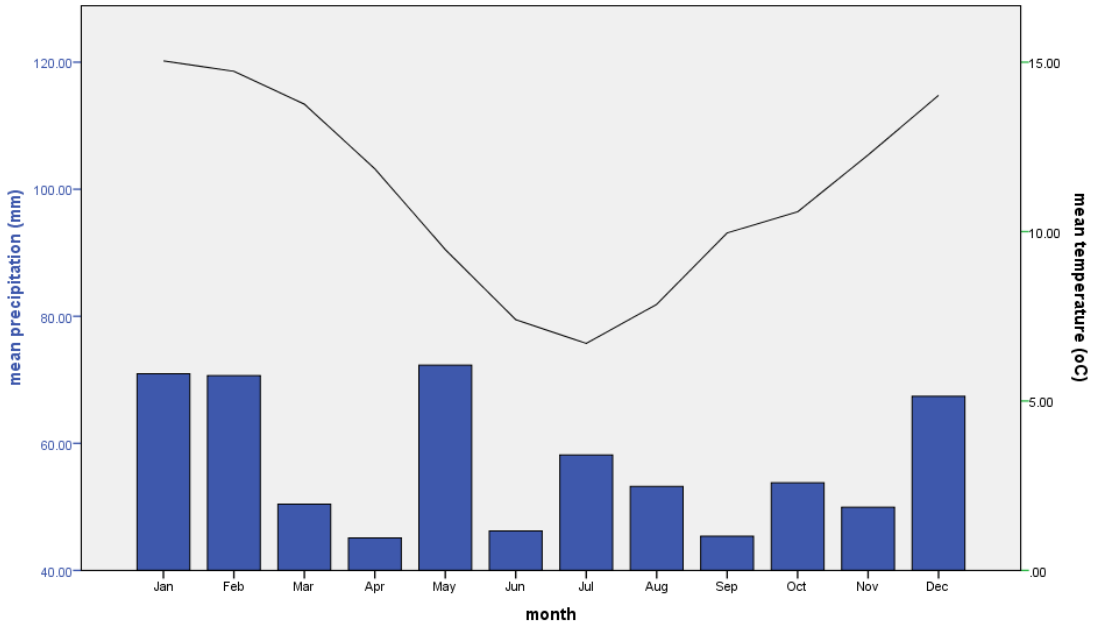


Figure 3.5: Mean monthly precipitation and temperature for South Dunedin based on 2000-2012 data from the Musselburgh weather station

Average annual temperatures are in the order of 10ºC, which is considered mild for Dunedin's latitude. The cool coastal sea breezes experienced as a result of Dunedin's coastal location are a major factor influencing temperatures in Dunedin. Figure 3.5 displays monthly mean temperature and precipitation for Dunedin to indicate seasonal variability in climate variables. Dunedin has been described as not having a clear seasonal pattern in rainfall (Fitzharris, 2010). The mean monthly rainfall from 2000 to 2012 indicates December, January, February, and May as having the highest rainfall and April the lowest (Cliflow, 2012).

Natural climate variability influences Dunedin and in a wider sense New Zealand. This can be over short time scales; for example, the variation occurring as anticyclones, fronts, and low pressure systems pass. Over longer time scales annual seasonal cycles from summer to winter will also contribute to variability. Cycles such as the El Nino-Southern Oscillation, the Inter-decadal Pacific Oscillation and the Antarctic oscillation may also contribute to long-term natural climate variability (Mojžíšek, 2005).

The occurrence of extreme events can be considered to represent the limits of variability. For this thesis extreme rainfall events are of particular relevance due to their influence on groundwater levels. The NIWA High Intensity Rainfall Design System (HIRDS) provides estimates of rainfall depths for rainfall events with average return intervals (ARIs) of 2 to 100 years (Thompson, 2011). This tool has been used to estimate extreme rainfall events for South Dunedin based on data from the Musselburgh weather station stored in the NIWA Cliflow Climate Database (table 3.1). The HIRDS estimates indicate that, at present, a 1-in-10 year rainfall event (for a 48 hour period) in Dunedin is considered to produce a rainfall depth of 100.4 mm, and a 1-in-50 year rainfall event as 142.3 mm (NIWA, 2013).

Table 3.1 NIWA HIRDS extreme rainfall assessment results for South Dunedin with average return intervals (ARI) of 2 to 100 years and annual exceedence probabilities (AEP), (source: NIWA, 2013).

Rainfall event		Duration									
ARI (y)	AEP	10m	20m	30m	60m	2h	6h	12h	24h	48h	72h
2	0.5	4.1	5.8	7.2	10.3	14.8	26.6	38.4	55.5	67.5	75.7
5	0.2	5.6	8	9.9	14.1	20	34.9	49.6	70.5	85.7	96.2
10	0.1	6.9	9.9	12.2	17.4	24.5	41.9	58.8	82.6	100.4	112.7
20	0.05	8.4	12.1	14.9	21.3	29.6	49.9	69.2	96.1	116.9	131.1
30	0.033	9.5	13.6	16.7	24	33.1	55.1	76	104.9	127.6	143.1
40	0.025	10.3	14.7	18.2	26	35.8	59.1	81.2	111.6	135.7	152.2
50	0.02	10.9	15.7	19.4	27.7	38	62.5	85.5	117	142.3	159.6
60	0.017	11.5	16.5	20.4	29.2	39.9	65.3	89.1	121.6	148	166
80	0.012	12.5	17.9	22.1	31.7	43.1	70	95.2	129.3	157.3	176.4
100	0.01	13.3	19.1	23.6	33.8	45.7	73.9	100.1	135.6	164.9	185

3.4 Land use and infrastructure

The nature of the South Dunedin area, pre-European settlement, can be seen in figure 3.6, which is a painting from 1864 showing a view of Dunedin from what is now Andersons Bay. As the population of Dunedin City grew rapidly during the gold rush period between 1883 and 1900, the salt marsh areas of South Dunedin were drained and reclaimed to allow for development (Morris, 2008). The newly available land was firstly used to develop market gardens, but eventually became an urban area as the city expanded (URS, 2011). The material used to build up the ground level was anything available. Sand mining of the dunes along the Saint Clair and Saint Kilda beaches provided much of this material (Rekker, 2012). By 1890 the sand mining activity had removed so much of the sand dunes that the sea broke through and flooded low-lying areas behind the dunes. In response to this sand mining was halted and a combination of sea walls, groynes and regenerated dunes has since protected South Dunedin from ocean flooding (URS, 2011).



Figure 3.6: Painting showing Dunedin in the 1800s, the view is from the start of the Otago Peninsula looking across the Otago Harbour towards the central city with South Dunedin on the left side (source: Hocken Library Collection, 1864).

Further reclamation has occurred more recently around Dunedin harbour with Portsmouth Drive being opened in the 1970s (Morris, 2008). Reclaimed land around the harbour area is now approximately 2m above sea level; however, areas that were reclaimed earlier tend to be closer to sea level as the land was filled in only to the minimum level that was needed to be able to build upon (Rekker, 2012). At present South Dunedin is dominated by high-density urban residential land use, with a population of around 11500 people (Statistics New Zealand, 2010). Most of the residential properties were built between 1940 and 1970. In the 1940s South Dunedin was the most densely populated area in New Zealand. Today there are approximately 1700 people per km^2, which, compared to the average for Dunedin of 30 residents per km^2, remains an especially high population density (Statistics New Zealand, 2010). Tied to the high density of housing is a high imperviousness across the South Dunedin catchment.

Due to the shallow groundwater levels much of the below-ground infrastructure in South Dunedin, such as the stormwater and wastewater pipe networks, is in direct contact with groundwater. The DCC has found evidence of groundwater infiltrating into pipe networks in South Dunedin through weaknesses in pipes and joints (Osborn, 2011; Van Valkengoed, 2009). This is thought to be having an unintended but beneficial effect by providing a drainage function to the aquifer and therefore supressing groundwater levels (PDP, 2011).

Below ground infrastructure in South Dunedin includes approximately 65km of pipe; this consists of wastewater sewer pipes and stormwater pipes and culverts laid at gentle gradients. The majority of the stormwater pipes have been assigned a theoretical life of 100 years. At present 11% of pipes are 90-110 years old, and 53% of pipes are 50 years or older (DCC, 2011). Pipe ages are displayed in appendix A. There are no streams or open channels in the catchment and so no other points for water to collect or discharge to. Stormwater from the South Dunedin catchment discharges into the harbour via the Portobello Road Stormwater Pump Station. Wastewater from the whole metropolitan Dunedin area passes through the Musselburgh Pumping Station to the Tahuna Wastewater Treatment Plant (WWTP) for treatment (DCC, 2011).

The planned upgrade of the Tahuna WWTP to secondary treatment has been mindful of variations in salinity levels of influent, as spikes in salinity negatively impact the bacteria used in secondary treatment. An investigation into salinity in wastewater around the harbour found spikes of salinity corresponding with high tides, indicating infiltration of saline water. This may come from seawater flowing into pipes, or from saline groundwater infiltrating into leaking pipes (Van Valkenhoed & Wright, 2009; Osborn & Sinclair, 2012). Inspection of the wastewater pipe network has found instances of cracked and butt-jointed pipes. Targeted pipe repairs and replacements have been successful in reducing infiltration of groundwater into pipe networks, and further repairs are planned (Osborn & Sinclair, 2012). Ironically, a potential flow-on effect of repairing the pipe network is that groundwater levels may become elevated if the drainage function currently provided by leaking pipes is removed.

3.5 Aquifer conceptual model

The importance of the South Dunedin aquifer has recently been highlighted by a number of studies, which demonstrated the relationship between groundwater levels and sea level (Rekker, 2012; PDP, 2011), and interactions between groundwater and urban infrastructure (Van Valkenhoed & Wright, 2009; Osborn & Sinclair, 2012; URS, 2011). Yet, despite this recent interest, groundwater behaviour in South Dunedin remains relatively poorly understood. To date groundwater level monitoring has involved just three boreholes at the western edge of the South Dunedin area, operating

from 2009, and important aquifer parameters remain uncertain. The current understanding of the South Dunedin aquifer is summarised in a conceptual diagram of the aquifer (Figure 3.7).

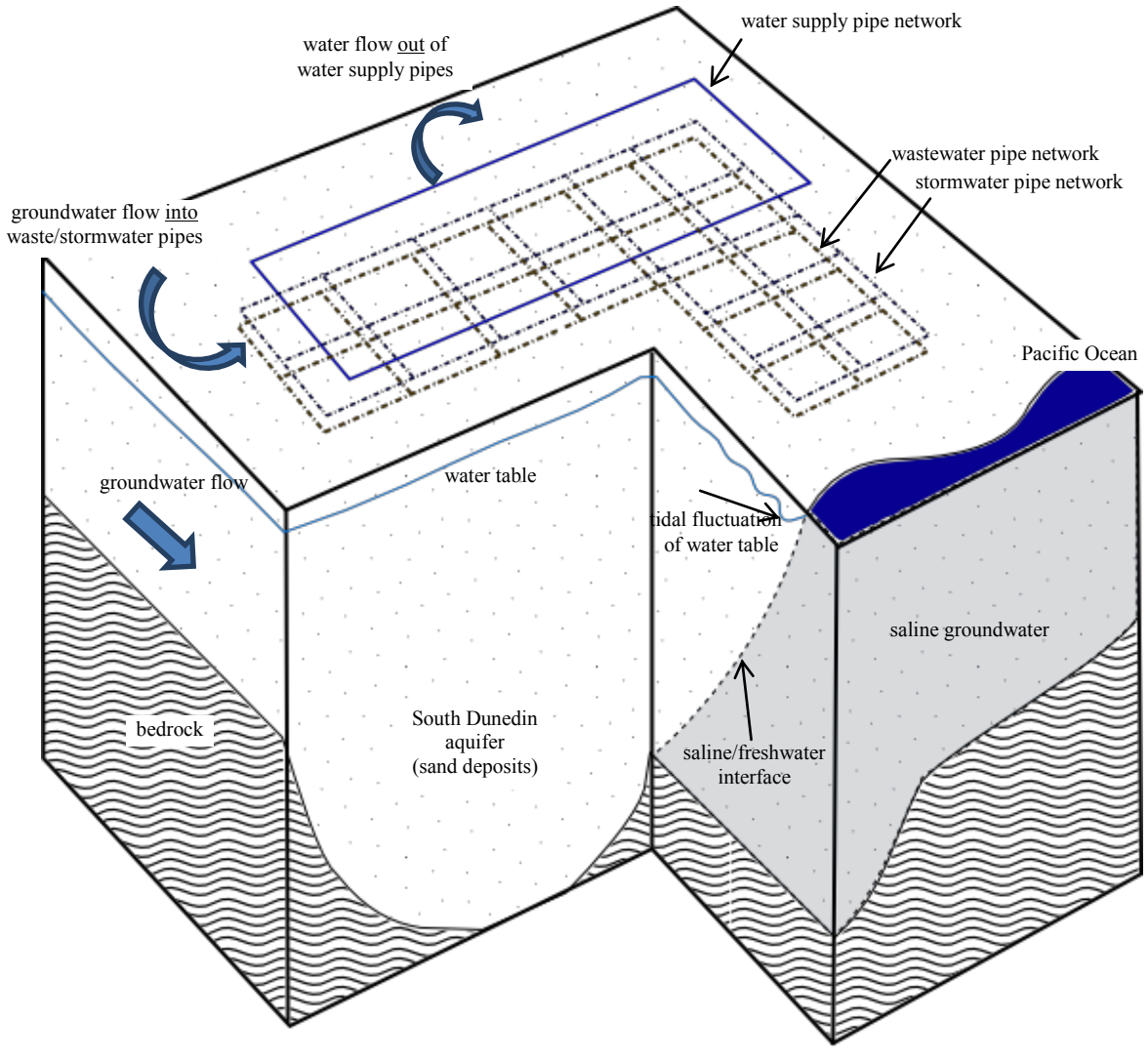


Figure 3.7: Conceptual model of the South Dunedin aquifer

This study aims to improve our understanding of groundwater behaviour in South Dunedin with a focus on how the water table responds to rainfall events. This is considered important as an understanding of the natural variability of groundwater levels is a prerequisite for being able to understand how the aquifer may respond to climate change in the future. These questions are highly pertinent for South Dunedin as

the water table is already uncomfortably close to the ground surface and any further elevation of the groundwater could negatively impact the overlying urban area, in particular stormwater and wastewater infrastructure that already interacts with groundwater. Previous research by the ORC has explored the relationship between sea level and groundwater. However, the relationship between rainfall and groundwater has thus far not been considered. When assessing a gradual trend in mean groundwater levels as a result of climate change it is also important to consider how the natural variability of groundwater levels could interact. Limitations of our knowledge of the South Dunedin aquifer highlighted by the ORC include limited field data, uncertainty in hydraulic conductivity, and uncertainty in recharge. This thesis is a step towards addressing these data gaps to improve understanding and provide information useful for future management of the South Dunedin aquifer.

4 Methods

4.1 Introduction

The approach used in this study considers spatial and temporal variability of groundwater levels with the purpose of exploring potential interactions with urban infrastructure and future sea level rise. Groundwater dynamics have been explored in this study by establishing a groundwater monitoring network across South Dunedin. This first section of this chapter describes the field work and laboratory analysis undertaken to investigate the South Dunedin aquifer. The second section presents the data analysis methods used, including the establishment of a relationship between rainfall and water table responses. This relationship is used to project groundwater responses to future rainfall events along with a consideration of potential interactions with sea level rise and underground urban infrastructure.

4.2 Field work and laboratory analysis

Establishing a groundwater monitoring network

A total of 13 groundwater monitoring sites were established. The majority of sites were on residential properties, the two exceptions being located on commercial premises. Locations of sites are shown in Figure 4.1 and a list of addresses is provided in appendix A. Sites were selected to be spaced across the low-lying South Dunedin area. As the ORC had established 3 sites at the western end of South Dunedin, coverage of the wider South Dunedin area was considered important. Each borehole was locates as far away from any structures involving foundations as possible, but ultimately this was constrained by the preferences of the property owners.

Boreholes were established using a hand auger with an auger head of 70mm internal diameter reaching a depth of approximately 3m. After removing topsoil and any large rocks with a shovel, the hand auger was used to move through sediments. When working in sand dominated sediments, below the water table, boreholes were prone to

collapse. To address this, a 200mm internal diameter PVC pipe was used as a casing to stabilise the borehole while the auger advanced through the unconsolidated, saturated sediment, this is similar to the method used by Finch and Peery (1998). The PVC casing had teeth cut into the lower end and a handle attached so it could be twisted into the ground. The hand auger was positioned inside the PVC casing and, by advancing both the auger and the casing, boreholes could be established to the desired depth without collapse. Water level loggers were deployed in boreholes at a depth of 2m below the water table as per manufacturer recommendations. This deployment depth requirement provided the rationale for aiming for 3m deep boreholes.

A length of PVC pressure pipe was installed at each borehole. Each pipe was just over 3m long, allowing 3m to be buried. The pipe had an internal diameter of 50mm with a pressure rating of PN12 and had holes drilled at 25mm intervals around, and up, the lower 2m section of the pipe. The lower end of the pipe was sealed with a cap and the perforated section was covered with a mesh (plastic fly screen) and a filter sock (200µm pore size) to exclude sediment from the pipe while still allowing unimpeded groundwater movement. The upper end of the PVC pipe had a removable cap. A sand and gravel mixture was poured around the pipe to create a filter pack around the screened section of pipe. The remaining hole was backfilled. As the boreholes were intended to be temporary structures, bentonite and cement caps were not used. An example of a completed borehole is shown in figure 4.2. Water level loggers were suspended from the centre of the top caps using fishing line.

A Leica TPS300 total station was used to survey sites to establish the elevation above sea level for the top of each pipe. A borelog was recorded noting the location of the water table, description of sediments encountered and samples, the final depth, pipe dimensions, and height of the top of the pipe above the ground. Sediment samples were taken each time a change in sediment texture or colour was noted. The depth where changes in sediment occurred is considered to be accurate to 0.3m as this is the length of the auger head. A sediment sample was also collected at the final depth. Samples weighing approximately 800g were obtained from a single auger head when possible.



Figure 4.1: Map of South Dunedin showing locations of monitoring boreholes established in this study and boreholes established in 2009 by the ORC



Figure 4.2: Photo showing completed borehole with PVC cap.

Groundwater monitoring

The instrument used to monitor groundwater levels in boreholes was the HOBO water level logger, model U20-001-04 (figure 4.3). The loggers recorded groundwater levels at 15 minute intervals over a 6 month period from July 2012 to January 2013 at nine sites. The sites monitored for 6 months were sites 1, 3, 4, 5, 6, 7, 8, 11 and 12 in figure 4.1. More sites were established than were able to be monitored so that spare sites would be available if any issues arose with a site. There were 10 water level loggers available, one of which was used to measure barometric pressure (so water level data could be corrected for this), allowing 9 sites to be monitored. Sites 2, 9, 10, and 13 were not used; sites 13 and 10 were the sites that reached the shallowest depths (around 2m, rather than the desired 3m), hence their exclusion. For sites 2 and 9, unusual signals in water level data were the cause of exclusion. Monitoring during December 2012 and January 2013 was undertaken to coincide with wastewater flow monitoring by the DCC. A 15 minute sampling interval was considered suitable to detect fluctuations occurring in response rainfall events and to tides (Gibbons, 1990). While a year or more of monitoring would be preferable the timeframe available in this study was limited.



Figure 4.3: Photo of a HOBO water level logger

HOBO water level loggers are pressure transducers; they are able to detect changes in water level by measuring the pressure exerted on the sensor by the overlying column of water. As a component of the pressure recorded will be due to the overlying atmosphere this needs to be removed from the data to isolate changes in pressure due to changes in water level alone (Toll and Rasmussen, 2007). To allow this barometric pressure was measured using a water level logger deployed above the water table at the Richardson Street site (figure 4.4).

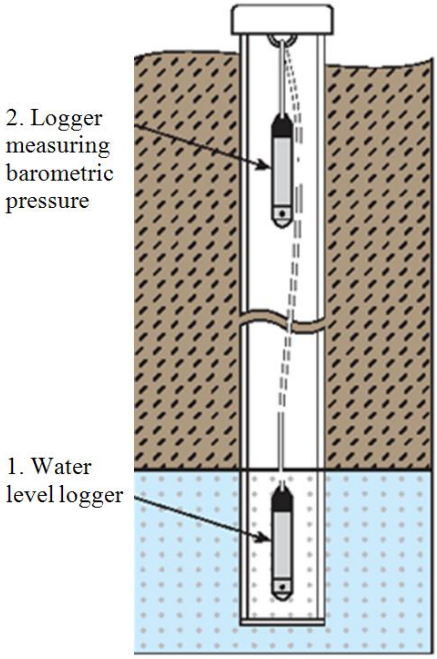


Figure 4.4: Diagram showing deployment of water level loggers in a borehole to measure water level and barometric pressure

This was considered representative of barometric pressure across the study area. An initial reference measurement of water level is needed to convert pressure readings into water level data. To obtain a reference measurement a contact meter (model: Seba KLL-mini) was used to measure the depth from the top of the pipe to the water level. A reference measurement was taken each time a water level logger was started or data was downloaded, which occurred fortnightly. Reference groundwater level measurements were repeated at least 3 times to increase precision. During July and August each time data was downloaded electrical conductivity of groundwater was measured.

A pilot monitoring period was undertaken while pipe design and borehole excavation technique were still being developed. Initial borehole excavation trials had been undertaken at Hargest Crescent in sand dominated substrate. However, at most other sites, silt dominated substrates were encountered. This was a surprising development as the aquifer had been previously described as sand deposits (Rekker, 2012; Glassey et al., 2003). It was noted that at silt dominated sites there was not a visible tidal fluctuation in the data from an initial monitoring period. This led to a reassessment of the methods of pipe construction to determine whether the lack of tidal fluctuations in the data was a result of methods used in this study or reflected the actual movements of the water table. All groundwater investigations installing structures below the water table will disturb natural groundwater movement to some extent and it is acknowledged that any pipe, no matter how porous, will delay water flow to a degree (Keller et al., 1989). The question for this study is whether the pipe design used disrupted groundwater flow to the extent that it would mask tidal fluctuations, giving misleading data.

To test the sensitivity of the pipes a trial was set up at the East Street site with two boreholes located 2m away from each other. East Street was selected for this trial as it is a silt dominated site. This allowed the excavation of a borehole without the concern of the borehole collapsing. The trial involved one hole with a pipe installed and the second hole left bare. Water level loggers were deployed in both boreholes to compare water table movements. For the borehole without a pipe the water level logger was surrounded by a filter sock. An example of the water table movements detected is provided in Figure 4.5. Based on this trial it is considered that the use of a pipe to house water level loggers does not alter the signal of water table movements detected to the

extent that it could remove tidal fluctuations. Comparison of data with a pipe, and with no pipe, returned a Pearson's correlation coefficient of 0.944. Further discussion of the reduced tidal fluctuations observed in this study is presented in section 6.2.

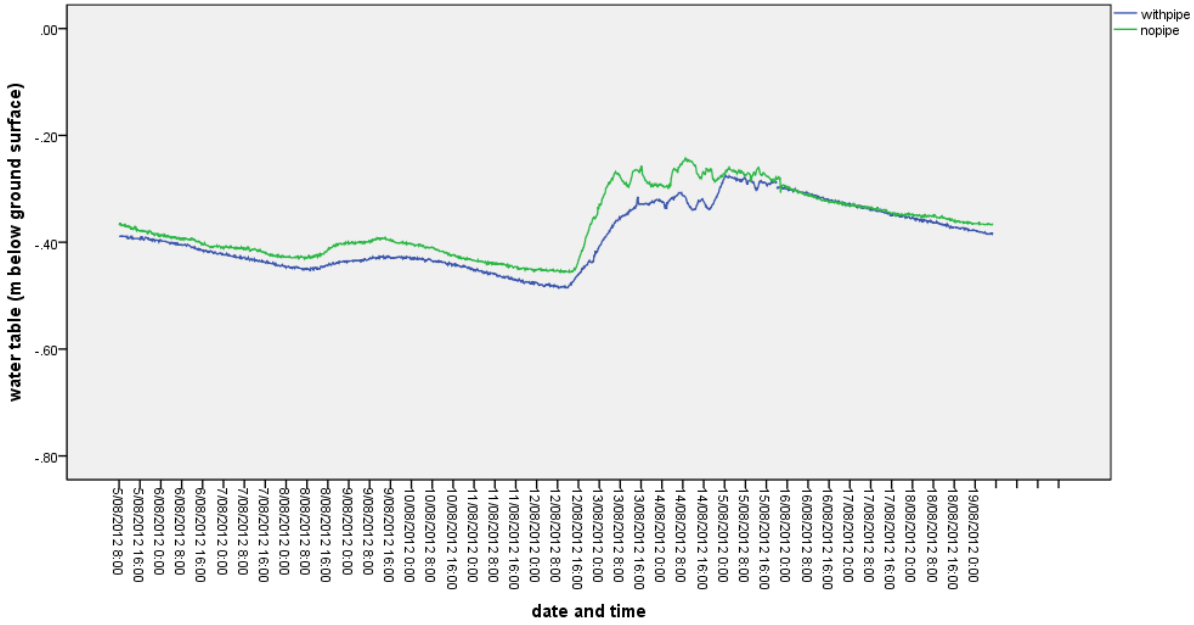


Figure 4.5: Graph of water table elevation in borehole with pipe, and borehole without pipe, at East St between 05/08/2012 and 19/08/2012

Aquifer characterisation

Hydraulic conductivity (K) is a measure of the ability of a material to transmit water when submitted to a hydraulic gradient. Accurate determination of hydraulic conductivity is essential to groundwater investigations and the results of groundwater modelling exercises tend to be highly sensitive to this parameter (Cherry and Freeze, 1999). There are a variety of methods available to estimate hydraulic conductivity including correlation methods, field methods, and laboratory methods (Oosterbaan and Nijland, 1986). Correlation methods are based on relationships between the hydraulic conductivity and properties of aquifer material including soil texture, pore-size distribution, and grain-size distribution (Cronican and Gribb, 2004). Laboratory methods involve intact samples of aquifer material tested under laboratory conditions. This is most commonly achieved with a permeameter where water is passed through a sample of aquifer material and discharge is measured (Oosterbaan and Nijland, 1986).

Common field tests include pump test and slug tests. Pump tests are often the preferred method and are generally considered the most reliable (van der Kamp, 2001). Pump tests involve abstraction of water at a constant rate over a period of time (e.g. 72 hours). Equations are used to relate the drawdown of the water table observed to aquifer transmissivity and storativity. In slug tests a known volume (slug) of water is added or removed from a well and the decline or recovery of the water level is monitored, allowing an estimation of hydraulic conductivity from the data (Cherry and Freeze, 1999; Zemansky and McElwee, 2005).

While pump tests may be preferable they are expensive and equipment intensive, in coastal aquifers they may also contribute to saline intrusion (van der Kamp, 2001). For the current study pump tests were not feasible. However, slug tests are considered a good alternative, and have been employed in this study, along with particle size analysis. It is noted that an alternative method available for coastal aquifers is the tidal method, which is based on the measurement of tidal fluctuations of the water table (Carr and Van Der Kamp, 1969). This method has been employed by the ORC giving a hydraulic conductivity estimate of 22m per day for the South Dunedin aquifer (Rekker, 2010). The use of slug tests and particle size analysis is this study complements previous work by providing more site specific estimates allowing assessment of any spatial variation in hydraulic conductivity.

Slug tests

Slug tests require an instantaneous change in water level and high frequency measurement of the water level recovery. Hydraulic conductivity can then be estimated based on the rate of water level response (Cherry and Freeze, 1999; USGS, 2010). To avoid interrupting groundwater level data collection, slug tests were not attempted during the 6 month monitoring period as they involve manipulating groundwater levels. Slug tests were carried out during January and February 2013 after the groundwater monitoring period. The rising head slug test procedure described by the US Geological Survey (USGS Groundwater Technical Procedure 17 v.2010.1) was followed. Displacement of the water was achieved with a mechanical slug and water levels were measured with HOBO water level loggers.

The slug was constructed from PVC pipe with a 32mm internal diameter. The pipe was filled with gravel and had caps secured to both ends using PVC solvent and PVC sealing tape. The slug was 1m long to ensure the slug could be positioned above a water level logger whilst being fully submerged. The slug was calculated to have a volume of 0.0019m^3 and achieve a 0.9m rise in water level in the borehole due to the displacement of 0.0019m^3 of water. A displacement or rise in water level of 0.2 to 1m is considered adequate for slug tests (USGS, 2010).

A water level logger was positioned as close as possible to the base of the pipe (without touching it) and the initial groundwater level was noted before a slug test was started. The falling head (or slug in) test consisted of placing the slug into the borehole quickly, but with minimum water disturbance, to a depth where it would be submerged by the initial water level. The slug was secured to maintain its position. The water level was checked with a contact meter periodically to detect when the water level had returned to within 0.01m of the initial water level. Once this had occurred, the rising head (or slug out) test directly followed the falling head test and consisted of withdrawing the slug quickly, but gently, and monitoring the water level until readings again returned to within 0.01m of the initial water level.

The water level monitoring interval used for the water level loggers depended on the type of sediment encountered at each site:

- For sandy sediment with rapid responses loggers were set up to record at 1 second intervals for the duration of the response
- For layers of sand and silt with variable responses loggers were set to record at 1 second intervals for the first ten minutes and at 10 second intervals thereafter.
- For silt sediments with slow responses loggers were set to record at 1 second intervals for the first ten minutes and at 15 second intervals thereafter.

Slug tests were carried out at 8 sites in dry conditions, i.e. no rainfall during slug test period. Slug tests were repeated at least 3 times at each site with the boreholes rested for at least 48 hours between slug tests. A number of sites were excluded due to concerns around borehole performance, specifically Richardson Street, Macandrew Road, Cavell Street, and Plunket Street. Dunedin Holiday Park was also excluded as there was not a sufficient depth of water to achieve a suitable displacement.

Particle size analysis

Particle size analysis was applied to characterise the sediment samples collected during borehole excavation. Pre-treated samples were analysed using a Malvern Mastersizer 2000 laser analyser. Pre-treatment comprised the following procedure adapted from Ryzak and Bieganowski (2011):

1. Sediment samples were wet sieved to exclude particles 2mm diameter and above (as this is the size limit of the Mastersizer 2000),
2. Samples were dried in an oven at 40ºC overnight, then ground.
3. A sample of 5g of sediment was placed in a plastic test tube with 20ml of hydrogen peroxide to remove organic matter.
4. Tubes were placed in a water bath at 30°C for 15 minutes or until reactions were observed. Samples were allowed to stand overnight for reaction to complete.
5. Samples were centrifuged at 1,000rpm for 10 minutes and then the hydrogen peroxide decanted.
6. To disassociate fines, 20ml calgon was added as a dispersant and samples were shaken for 30 minutes.

The Mastersizer 2000 analyses the particle size distribution of samples by recording the diffraction of red and blue light beams off the particles in a sample. Sediment samples were added drop by drop to a water bath feeding into the Mastersizer with constant stirring to ensure complete mixing. The volume of sample added varied between samples to achieve the 10-20% obscuration recommended for optimal performance of the Mastersizer 2000. The Mastersizer 2000 was run with a standard operating procedure involving measuring beam diffraction, and repeated three times, to return particle size distribution measurements.

4.3 Data sources and processing

Data sources

A list of the additional sources of data used in this research is provided below:

- Borelogs presented in an EQC report on Earthquake hazard in Dunedin study (McCahon, 1996).
- Borelogs and water level data from the ORC from the 3 boreholes established in 2009. The water level data covers from 2009 to 2012. The results of groundwater modelling undertaken in MODFLOW were also used including estimated values for recharge and discharge for the aquifer.
- Hourly rainfall data from the Musselburgh electronic weather station was obtained from the NIWA CliFlo National Climate Database for the period July 2012 to February 2013.
- The DCC provided flow volume data from monitoring in wastewater pipes at manhole FSM13669 and FSM12908 for the period 20/12/12 to 20/01/13 and information about the position of the stormwater and wastewater pipe network.
- Depth-duration-frequency of rainfall from an extreme rainfall event assessment for South Dunedin has been obtained from the NIWA HIRDS tool.

HIRDS uses hypothetical design storms as a means of describing extreme precipitation events. This is a commonly utilised approach in rainfall and flood frequency analysis (Semadeni-Davies, 2004). HIRDS provides estimates of rainfall return intervals based on Tomlinson's graphical method of rainfall frequency analysis. This analysis has been applied to monthly maximum rainfall records, for standard durations from 10 minutes to 72 hours, from the NIWA Climate Database, using data from 1998 to 2008 (Thompson, 2011). The data used in specific to South Dunedin in that it is calculated based on rainfall data from the Musselburgh weather station which is located within the study area.

The NIWA HIRDS estimates have been used in this study after a consideration of alternative sources of extreme precipitation data. In 2006 an assessment of rainfall

intensities for Dunedin was completed by Raineffects (2006) which was utilised in Blair Fitzharris' 2010 report on Climate Change Impacts on Dunedin. More recently, a rainfall analysis has been undertaken by URS in 2011 as part of the DCC Integrated Catchment Management Plans and 3 Waters Strategy. URS used an extreme value analysis (EV1) with Musselburgh rainfall data fitting a gumbel distribution for extreme rainfall events. Other relevant research includes modelling of the Water of Leith flood events (OPUS, 2006).

The work by Raineffects (2006) provided much of the base data utilised in the 2011 URS assessment; however these two reports differ in their consideration of long duration events. Raineffects (2006) considered a maximum duration of rainfall events of 120 minutes; this was considered unsuited to the current research. The URS 2011 report considers events of up to 24 hours duration and NIWA's HIRDS include durations of up to 72 hours. A further, and all-important consideration, is the representation of uncertainty provided by these different sources. NIWA provides standard errors with the rainfall depths for various average return intervals, this allows a representation of uncertainty in extreme rainfall events. This is notably absent from the URS assessment. The availability of standard errors has been the main factor contributing to the use of NIWA values in this thesis over other available alternatives.

Data processing

Initial processing of water level data involved correcting for barometric pressure. Where electrical conductivity indicated brackish conditions, water level data were also corrected to take into account the density of brackish water. Water level data were then referenced to the ground surface and to mean sea level. In subsequent analysis where it is the proximity of the water table to the surface that is of interest data are presented as depth below the ground surface.

Rainfall events, and associated water table responses, were isolated from water level time series data from each monitoring site. The objective of the data processing was to identify, for every rainfall event, the rainfall event size (mm) and duration, the water table level at the start of rainfall, the peak water table level reached, the water table rise associated with that event, and the lag between the rainfall maximum and the resulting maximum water table level. To define individual rainfall events, and associated water

table rises, the procedure used by both Wu et al. (1996) and van Gaalen et al. (2012) was followed. Hourly rainfall data were grouped in 48 hour rainfall events. A 48 hour interval was chosen as this produced rainfall events that corresponded to discernable responses of groundwater levels. A total of 48 individual rainfall events were identified, along with their associated water table responses (where present). Water table response to rainfall was identified as the difference between the water table level at time of start of rainfall and the peak water table elevation reached.

4.4 Data analysis

To provide context for the data analysis undertaken in this study, a conceptual model of the South Dunedin aquifer was developed. A water balance for the catchment was calculated based on recharge and discharge values from the ORC modelling of the South Dunedin aquifer indicating daily fluxes of groundwater. This conceptual understanding of the aquifer underpins the analysis and interpretation of results in this study. However, there is significant uncertainty around the values utilised in the water balance, as such the merit of the water balance presented in this thesis is as a method to visualise the relative importance of different groundwater fluxes in the aquifer, rather than accurate estimates of the volumes of groundwater involved.

Hydraulic conductivity

Hydraulic conductivity was estimated based on slug test data. 'Slug out' test data was analysed using the Bower and Rice method (Bouwer and Rice, 1976) following the procedure provided by the US Geological Survey (Jiao and Leung, 2003). The Bower and Rice method is suitable for a wide range of conditions including unconfined aquifers with partially penetrating screened wells (i.e. where the well casing does not extend to the full thickness of the aquifer), which is the case in South Dunedin. Hydraulic conductivity of sites was considered in conjunction with particle size analysis results and borelog profiles from this study, from the ORC, and from McCahon et al., (1996) to evaluate spatial variation in aquifer material across the South Dunedin area. A cluster analysis was undertaken in Mintab to group sites based on

hydraulic conductivity, percentages of clay, sand, silt from samples, number of distinct layers in borelog profiles and water table responses to rainfall.

Movements of the water table

Groundwater hydrographs were examined for evidence of tidal forcing and responses to rainfall events. Classical decomposition was used to deconstruct time series data into its various components. This was carried out in R Statistical Software (3.0.2) and indicates the seasonal variation (tidal movements), a random component (noise) and a trend component (rainfall induced movements of the water table). For the responses to rainfall events identified, linear regression was used to establish a relationship between rainfall and the water table response for each site. Linear regression using the least squares method was performed in SPSS. For each site, water table responses were plotted against associated rainfall and a line of best fit was computed.

Modelling water table response to rainfall events

The regression relationship between rainfall and water table response established in this study was used to estimate the response of the water table to future extreme rainfall events, and the resultant position of the water table in relation to the ground surface. To consider future rainfall events, rainfall depth-duration-frequency values for 48 hour events with return periods of 2, 5, 10 and 50 years were obtained from the NIWA HIRDS. The water table response to these rainfall events was projected for each site based on the established regression relationships with 95% confidence intervals. The projected water table response was added to the mean position of the water table to identify sites where the water table could intersect the ground surface.

Interactions with sea level rise and urban infrastructure

To consider how responses to rainfall events may interact with the effects of sea level rise, the projected water table responses for 2, 5, 10 and 50 year events were added to the position of the water table expected under sea level rise scenarios of 0.1m, 0.28m and 0.4m of sea level rise. The position of the water table in response to sea level rise scenarios is based on ORC modelling of groundwater levels in South Dunedin in response to sea level rise. The scenario of 0.1m represents the recorded rate of rise from 1961 – 2003 as presented in the fourth IPCC report (IPCC, 2007), the scenario of

0.28m of sea level rise represents the observed rate of sea level rise from 1993 – 2003 (IPCC, 2007), the scenario of 0.4m rise represents projections of future rates of sea level rise taking thermal expansion of oceans and melting of glacial ice into account (IPCC, 2007).

Interactions between groundwater and infrastructure in South Dunedin were examined by comparing flow volumes in wastewater pipes, groundwater levels and rainfall. Monitoring by the DCC occurred from 24 December 2012 to 6 January 2013 at Botha Street (manhole ID of flow monitor site: FSM13669) which was compared to the Lochend Street borehole (located approximately 2 blocks from the pipe flow monitoring site) and at East Avenue (manhole ID of flow monitor site: FSM12908) which was compared to water table elevations at the East Avenue borehole. Correlation between wastewater flow volume, groundwater, and rainfall was completed using SPSS.

4.5 Overview of methods

An overview of the research objectives and methods utilised is provided in figure 4.6.

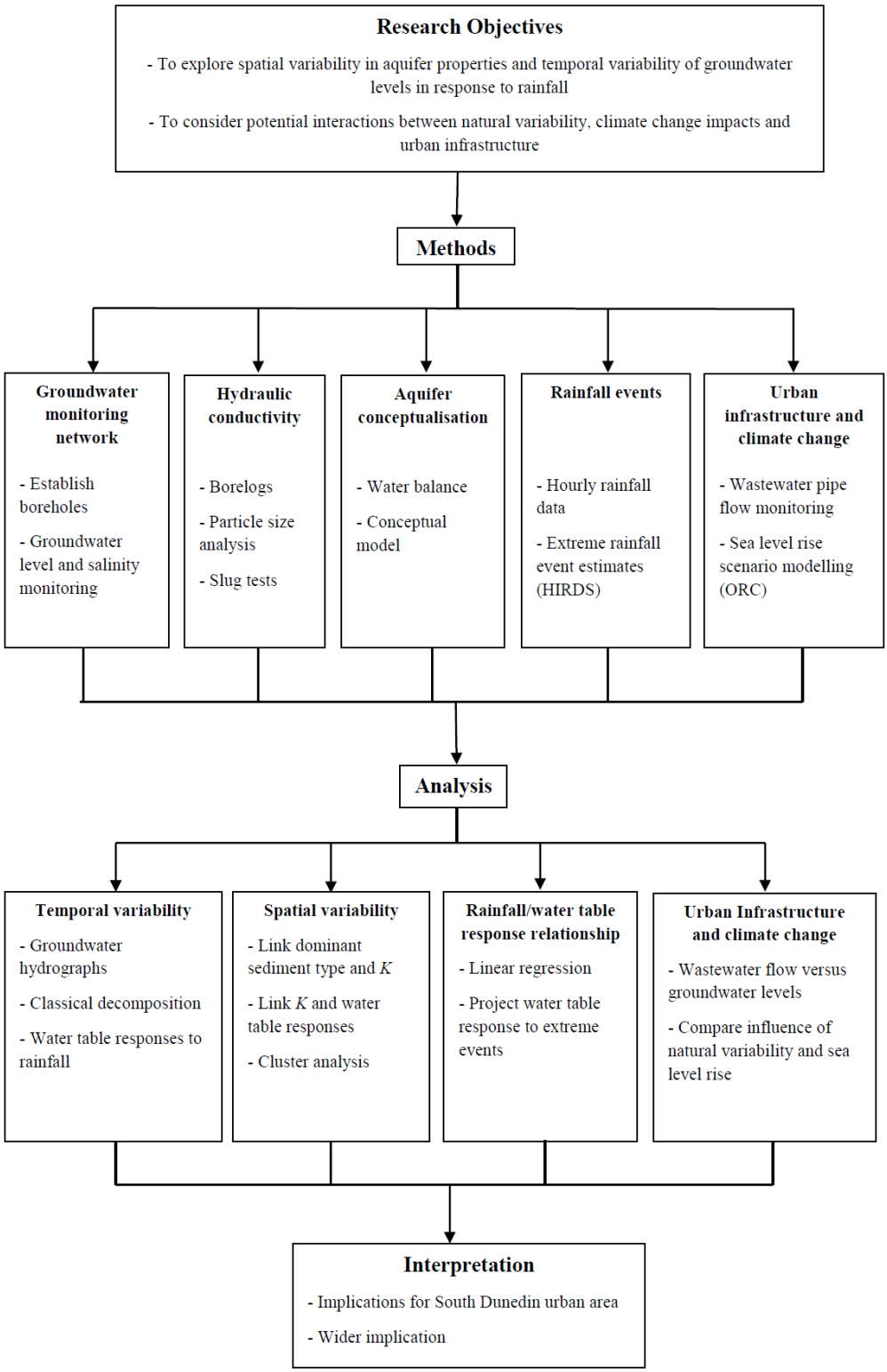


Figure 4.6: Flow diagram showing research objectives and methods

5 Results

5.1 Introduction

This chapter presents the results of an investigation of the South Dunedin aquifer. The overarching objective of this research is to explore spatial variability and temporal variability of groundwater levels, in particular those in response to rainfall events. Establishing a relationship between rainfall and the subsequent response of the shallow water table is expected to provide insight into how the aquifer may respond to future rainfall events. This subject is of importance as the aquifer in question is situated below the South Dunedin urban area and the shallow groundwater presents a flood risk and may interact with below-ground infrastructure.

This chapter is divided into 3 main sections. In the first section, the South Dunedin aquifer is characterised. This includes information from boreholes established during this research, supplemented by data from previously established boreholes. The position of the water table, subsurface profiles and hydraulic conductivity are described, and a groundwater balance for the aquifer is presented. The second section of this chapter presents time series data from groundwater level monitoring over a 6 month period. This section focuses on demonstrating movements of the water table in response to rainfall. In the third section, a relationship between rainfall and the water table response is established and used to project how the water table may respond to future rainfall events, including a consideration of potential interactions with the effects of sea level rise and urban infrastructure. The third section also includes a consideration of spatial variability of the water table response and how it is linked to spatial variation of the aquifer substrate.

5.2 Hydrology

Locating the position of the water table across South Dunedin was the first objective of this study. Figure 5.1 presents the mean groundwater elevation above mean sea level at the South Dunedin monitoring sites established during this study. The mean groundwater level was calculated over a 1 week period without rainfall (from 18/07/2012 to 25/07/2012). Over this period the water table was located at least 0.2m above mean sea level across South Dunedin. As South Dunedin has an average ground surface elevation within 5m of sea level, the water table elevations observed in this study indicate shallow groundwater conditions. If the groundwater levels shown in figure 5.1 are considered in terms of depth from the ground surface, the mean position of the water table ranges from 0.45m to 0.86m below the ground surface at sites across South Dunedin. This fits with previous investigations where the water table was encountered within 1m of the ground surface across South Dunedin (Rekker, 2012; McCahon, 1993).

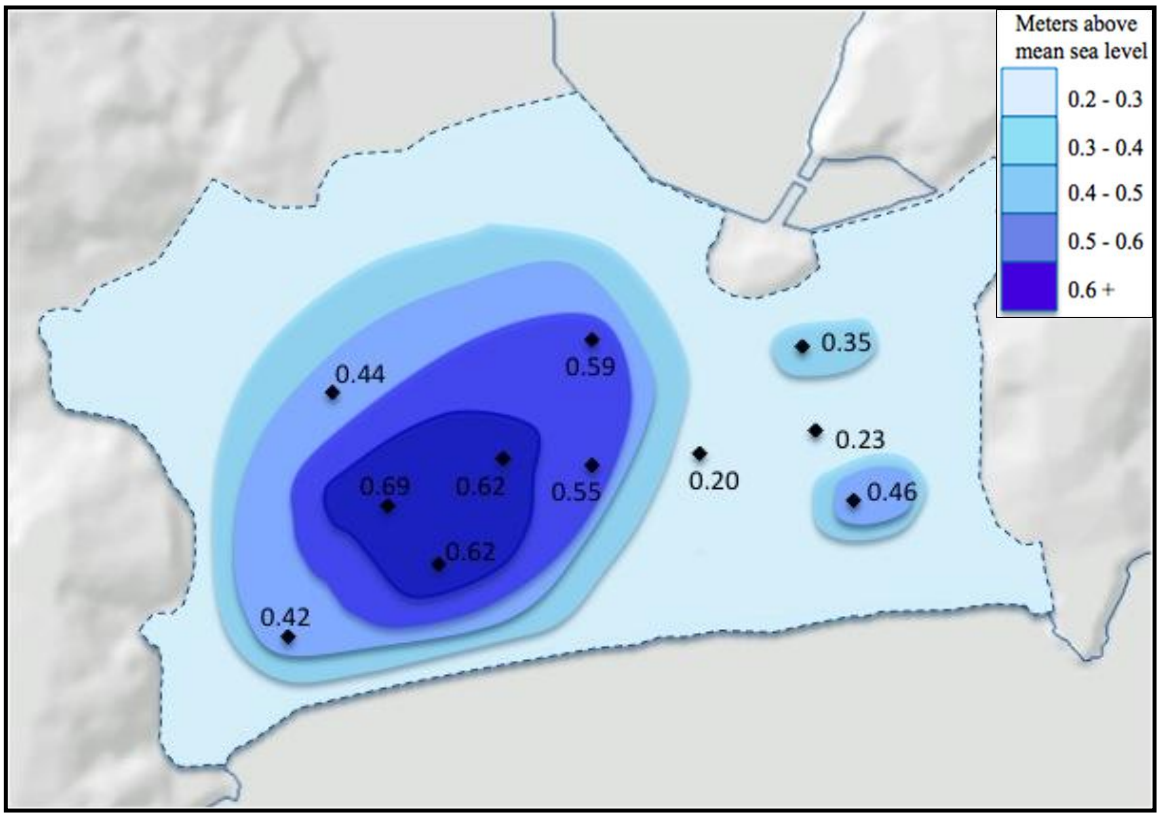


Figure 5.1 Map showing the mean elevation of the water table (no recent rainfall) in metres above mean sea level (AMSL) in South Dunedin and inferred contours

The position of the mean water table across South Dunedin exhibits spatial variation. Specifically, there is an area of elevated groundwater levels focused around the central Saint Kilda area of South Dunedin. There are also two pockets of slightly elevated groundwater levels in the Tainui and Musselburgh areas, on the eastern side of the aquifer.

Water table levels from two sites (OMES and Dunedin Holiday Park) deviated from the pattern observed across the rest of the aquifer. These two sites were the closest to the ocean, and as such, a strong tidal influence and the highest salinity values were expected, neither of which were observed. Electrical conductivity was measured to explore salinity of groundwater across the aquifer (figure 5.2).



Figure 5.2: Electrical conductivity values (mean value from 3 measurements during July and August 2012) at sites across South Dunedin

Both the OMES and the Holiday Park sites had a mean electrical conductivity below 2300µS/cm. These are the two lowest values observed across the aquifer and are comparable to freshwater. The highest electrical conductivity values were encountered in the centre of South Dunedin, roughly coinciding with the area of highest water table elevation. The low salinity at the OMES and Holiday Park sites, despite the proximity to the ocean, strongly suggests the boreholes established at these sites are not sampling groundwater continuous with the South Dunedin aquifer. These sites are located on old sand dunes and the groundwater encountered appears to be a perched water table of fresh water held in the sand dunes. The water level data from these sites has therefore not been included when representing the position of the South Dunedin aquifer water table in figure 5.1.

5.3 Hydrogeology

Borelog interpretation

The geology of South Dunedin has been broadly described as sand deposits (Glassey, et al. 2003; Bishop & Turnbull, 1996; Rekker 2012). However, in this study, when establishing boreholes to a depth of approximately 3m the main sediment encountered was a blue/grey silt. Notable exceptions include the Hargest Crescent site (the western-most site) where sands were the main substrate, the Lochend Street site (the eastern-most site) where an underlying layer of sand was encountered at a depth of around 2m, and the OMES and Holiday Park sites established on old sand dunes. Examination of borelogs from a previous study by EQC (McCahon, 1993), combined with borelogs from ORC and the current study, have been used to create cross-sections through South Dunedin demonstrating sediment composition (Figures 5.4 and 5.5). The location of the cross-sections and the sites used are shown in Figure 5.3.

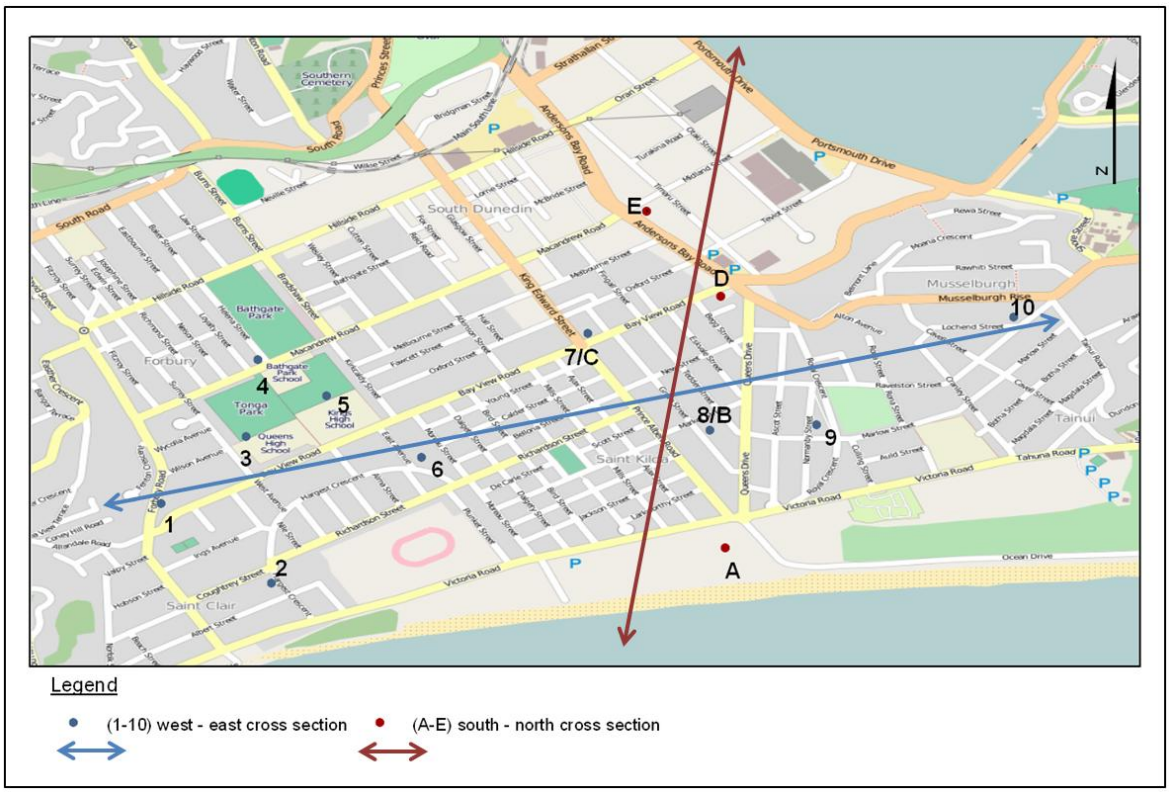


Figure 5.3: Approximate path of the west – east cross-section with sites numbered 1 - 10, and the south – north cross-section with sites lettered A – E. The cross-sections are presented in Figures 5.4 and 5.5.

The cross-sections in figures 5.4 and 5.5 indicate a layer of silt, of variable depth, focused around the centre of South Dunedin. The depth to which the silt layer extends is unclear; the maximum depth at which silt was recorded was 18m below the ground surface at site 4. The silt layer appears to extend deeper around the centre of South Dunedin and to a lesser extent at the eastern and western edges of the aquifer. The area with the thickest layer of silt roughly corresponds with the area of highest water table elevations, and highest salinity, in central South Dunedin. Below the silt layer, sand is encountered. Where records exist past 10m below ground level, sand was the dominant sediment recorded. There is some indication of multiple layers of silt existing at sites 4 and 7/C.

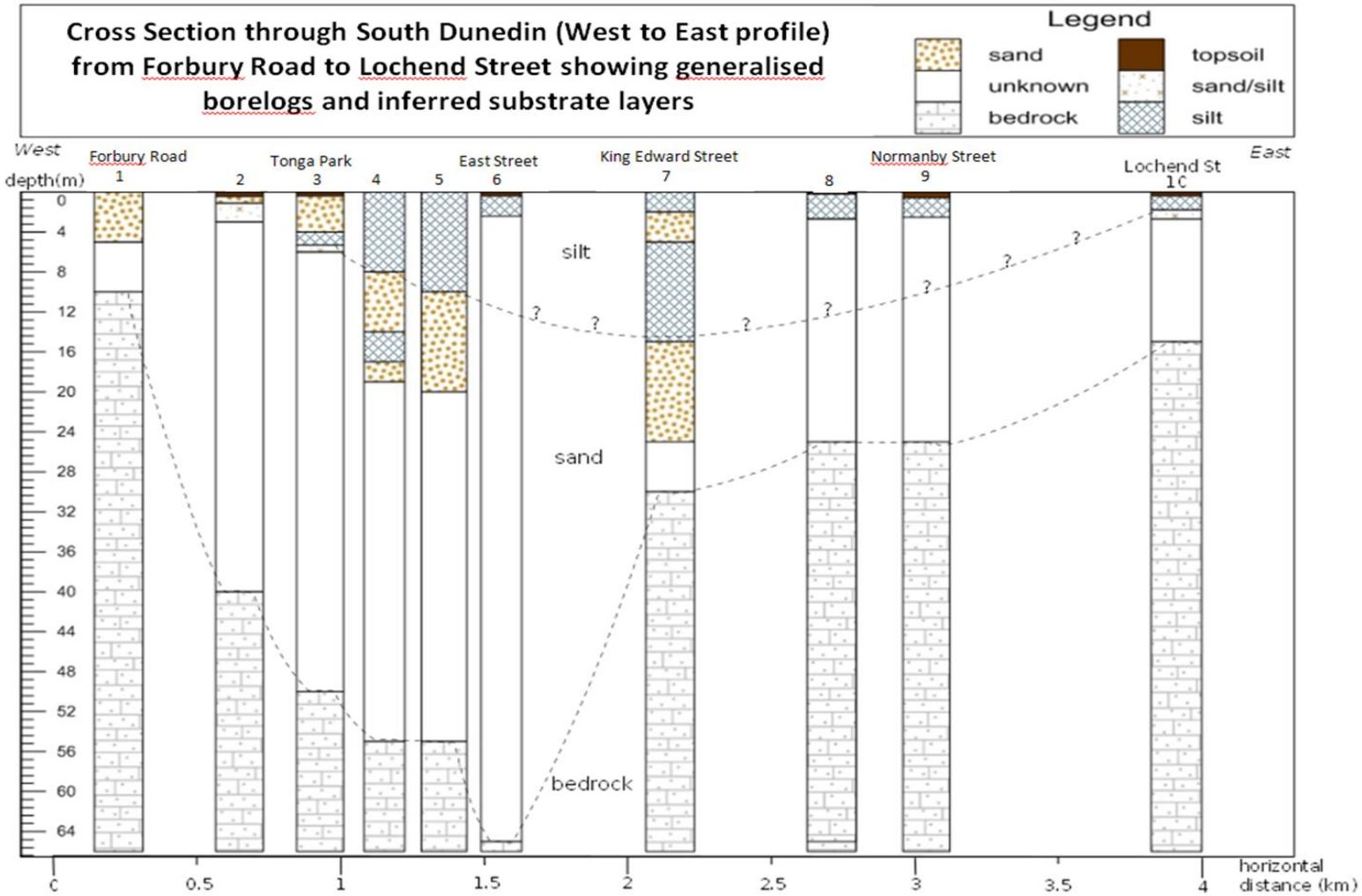


Figure 5.4: Cross-section through South Dunedin (West to East), Forbury Road to Lochend Street, showing generalised borelogs and inferred substrate layers

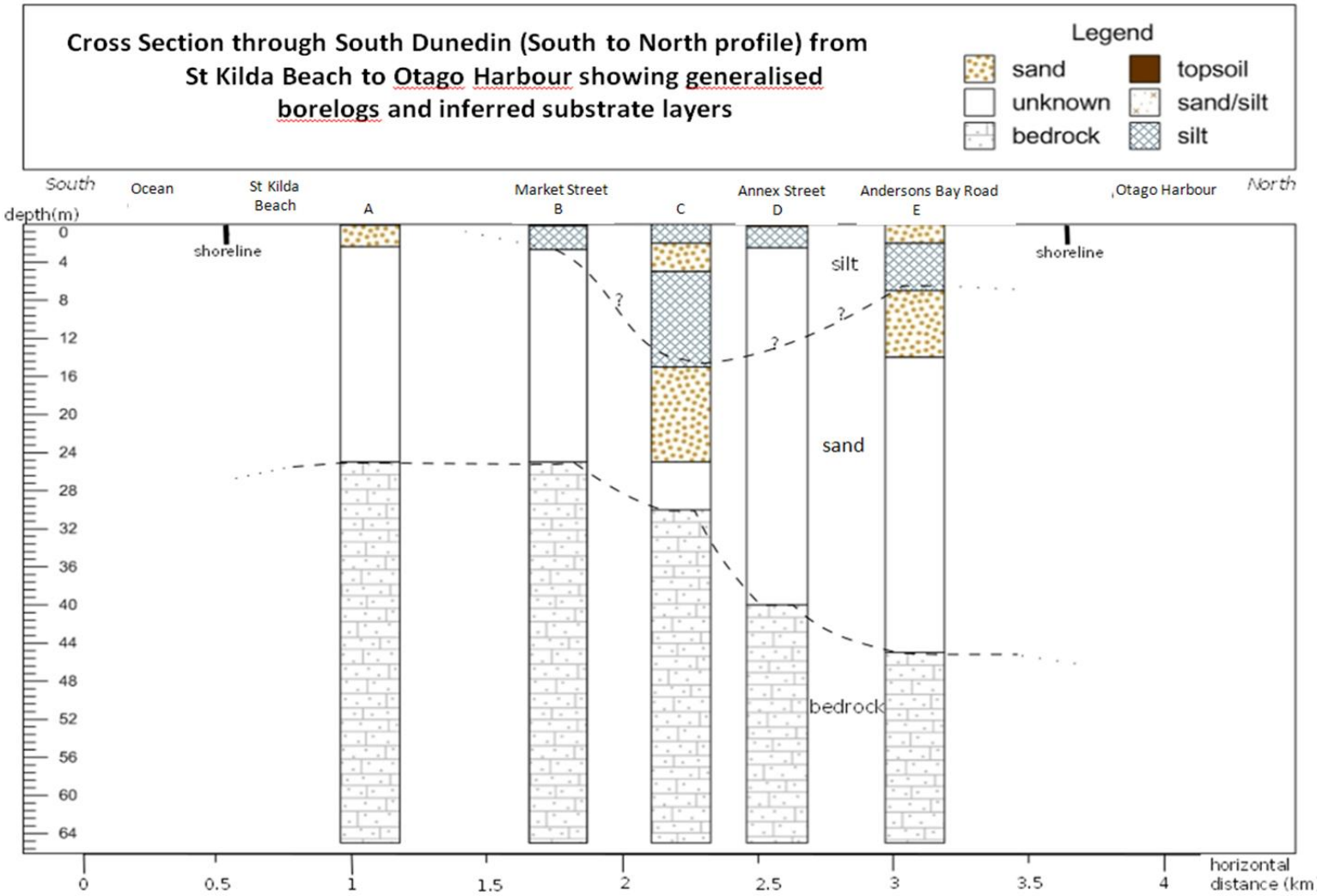


Figure 5.5: Cross-section through South Dunedin (South to North), St Kilda beach to Otago Harbour, with generalised borelogs and inferred substrate layers

Hydraulic conductivity

Particle size analysis and slug tests were used to characterise and explore the properties of sediments sampled while establishing boreholes. Table 5.1 shows the percentage of clay, silt and sand fractions of samples, and the depths at which samples were obtained. There is variation both within sites (with depth) and between sites. For within site variation, i.e. where there are distinct differences in substrate observed with depth, the layers of substrate are numbered 1, 2, 3 etc. There are three sites where sand is the dominant substrate (Hargest Cr, OMES, Holiday Park), two sites where silt is the dominant sediment (East St, Market St), and four sites where there are differences with depth resulting in layers of sand and silt (Annex St, Lochend St, Tahuna Rd, Normanby Ave).

Table 5.5.1 : Particle size analysis results for samples collected during borehole construction at sites in South Dunedin

site	layer	sample depth (m)	clay %	silt %	sand %	dominant fraction
Market St	1	1	5.65	82.09	12.27	silt
		2.7	4.27	80.29	15.43	silt
East St	1	1	5.61	88.83	5.55	silt
		2	4.93	83.19	11.88	silt
Normanby St	1	1	3.14	27.96	68.9	sand (some silt)
	2	2.4	2.92	82.6	14.47	silt
Holiday Park	1	1.5	0	0	100	sand
		2.5	0	0	100	sand
OMES	1	1.3	0	0	100	sand
		2.3	0	2.53	97.47	sand
Hargest Cr	1	0.8	8.54	56.43	35.03	silt/sand
	2	1.8	0.68	18.24	81.08	sand
Tahuna Rd	1	0.55	5.91	71.17	22.91	silt (some sand)
	2	1	3.85	42.88	53.27	sand/silt
	3	2.6	7.48	90.57	1.95	silt
Lochend St	1	0.75	6.64	68.89	24.48	silt (some sand)
	2	1	8.05	86.46	5.5	silt
	3	2	1.92	15.79	82.29	sand
		2.7	1.51	18.98	79.5	sand
Annex St	1	0.7	8.1	89.08	2.82	silt
	2	1.6	2.36	74.84	22.8	silt (some sand)
		2.4	2.03	73.05	24.91	silt (some sand)

Table 5.2 compares the particle size analysis results with hydraulic conductivity estimates obtained from slug tests. The highest hydraulic conductivity values are expected to occur in sediments with a dominance of larger particle sizes (i.e. sand). As slug tests provide hydraulic conductivity values specific to the depth of the screened section of the borehole (1-3m depth), only sediments from corresponding depths were included. Where multiple samples exist an average is presented. The hydraulic conductivity values estimated range from 0.0015m/day to 10m/day. Overall, the sites with the highest hydraulic conductivity correspond to the sites with sand dominated sediments and the sites with the lowest hydraulic conductivity values correspond to the sites with the silt dominated sediments. There are some sites that deviate from this general pattern. For example, Tahuna Rd has the highest silt content but does not exhibit the lowest hydraulic conductivity, and Lochend St indicates a sand dominated sediment yet a reasonable low hydraulic conductivity. It should be noted that these sites have a complex stratigraphy with multiple layers of sand and silt. This may indicate that where there are multiple layers of sand and silt, overlying layers can influence hydraulic conductivity. The spatial distribution of hydraulic conductivity and sediment is shown in figure 5.6. This indicates the presence of high silt content and low hydraulic conductivity around the centre of South Dunedin. This central area is framed by sand dunes along the coast with the highest hydraulic conductivity values and towards the edges of the aquifer (both East and West) sites with high sand content.

Table 5.2 : Table showing particle size analysis, slug test results, and observations from borelogs for substrate between 2m and 3m depth from boreholes in South Dunedin

site	observation from borelogs (2-3m depth)	Particle size analysis results				Slug test results	
		clay %	silt %	sand %	Dominant fraction	K (m/day)	substrate (expected based on K)
Market St	blue/grey silt	6	82	12	silt	0.0059	silt, loess
East St	blue/grey silt	5	83	12	silt	0.0015	silt, loess
Normanby Ave	blue/grey silt	3	83	14	silt	0.005	silt, loess
OMES	sand	0	3	97	sand	10	medium sand
Hargest Cr	sand (some fines)	1	18	81	sand	2.2	fine sand or sand/silt
Tahuna Rd	blue/grey silt	7	91	2	silt	0.0047	silt, loess
Lochend St	sand and blue/grey silt	2	16	82	sand	0.0066	silt, loess
Annex St	blue/grey silt	2	75	23	silt (some sand)	0.0064	silt, loess

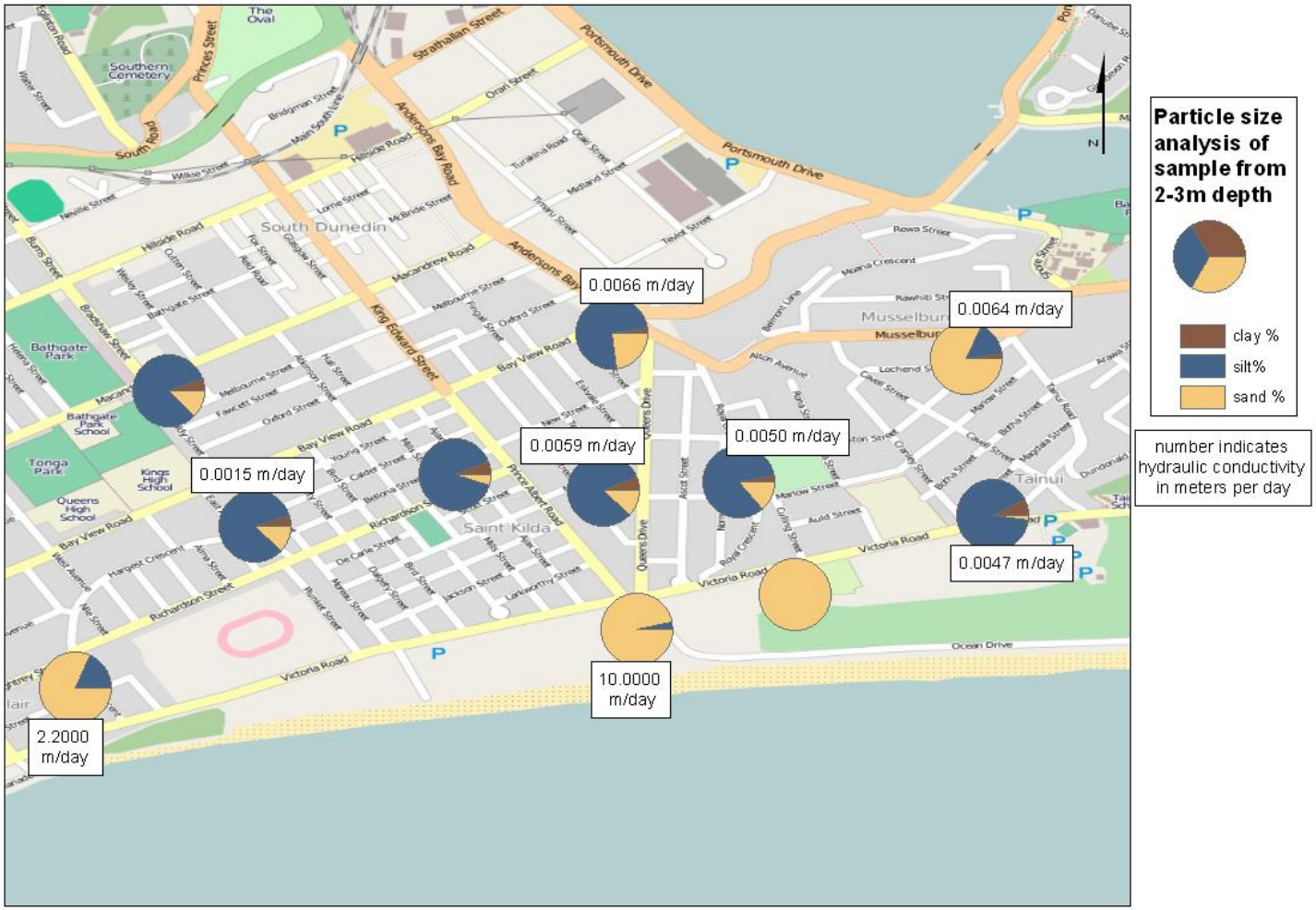


Figure 5.6 : Slug result derived hydraulic conductivity values and particle size fractions for South Dunedin sites

5.4 Conceptual model development

Water balance

In its simplest form a water balance equation can be expressed as:

$$I - O = \Delta S \quad (5.1)$$

where I is inputs, O is outputs and ΔS is change in storage.

A more detailed version of this specifically for groundwater is:

$$R_r + R_s + I - A - D_s - O = \Delta S \quad (5.2)$$

where R_r is rainfall recharge, R_s is recharge from surface water bodies, I is inflows from other aquifers, A is abstraction, D is discharge to surface water bodies and O is outflows to other aquifers.

As South Dunedin is a coastal urban area, there are a number of further considerations to include in a water balance. Inputs to the system may include leakage from water supply pipes and outputs may include groundwater infiltration into sewer and wastewater pipes. There are no major abstractions from the South Dunedin aquifer and while there are no surface water bodies, groundwater may instead interact with the ocean. It is assumed that flows to and from other aquifers are negligible for South Dunedin and while seawater intrusion is possible (particularly in the future due to rising sea levels), for the purpose of this study inflows from the ocean are considered negligible. This reduces the groundwater balance equation to:

$$R_r + R_p - D_o - I = \Delta S \quad (5.3)$$

where R_p is recharge from leaking water supply pipes, D_o is discharge to the ocean and I is infiltration of groundwater into sewer and wastewater pipes.

The water balance is based on figures from previous modelling by Rekker (2012):

R_r = 4685m^3/day

R_p = 1,995 m^3/day

D_o = 4,237m^3/day

I = 2,275 m^3/day

The value for infiltration is a computed value of groundwater discharged via the stormwater and wastewater system. Flow monitoring of wastewater discharge at the Portobello outfall provided a dry weather baseflow value of 430m^3 per day, which is considered to indicate the volume of groundwater infiltrating into the wastewater pipe system without rainfall. This was used as an input for modelling of the South Dunedin aquifer. Through model calibration and parameter optimisation this value was adjusted to a computed infiltration value of 1,995 m^3/day. The value for discharge to the ocean is purely an output of the groundwater modelling. For recharge, Rekker (2012) suggested average recharge rates of 500mm per year from rainfall and 182mm per year from leaking water supply pipes. In this thesis R_r has been calculated as 500mm per year received over 60% of the South Dunedin catchment due to imperviousness of 80 – 100% occurring across 40% of the land area (DCC, 2011). R_p was calculated as occurring across 70% of the catchment area as an estimate of the land area serviced by water supply pipes (DCC, 2011).

For South Dunedin the water balance is calculated as:

4685m^3/day + 1,995 m^3/day - 4,237m^3/day - 2,275 m^3/day = 168m^3/day (5.4)

The groundwater fluxes for South Dunedin are displayed on figure 5.7. The water balance indicates that recharge from rainfall is the dominant factor contributing recharge to the aquifer. Nevertheless, recharge from water leaking from water supply pipes could contribute nearly a third of the total recharge. This water balance assumes inflows from, and outflows to, adjacent areas are negligible. Since South Dunedin is lower that adjacent land areas, outflows to other aquifers are unlikely. However, water from surrounding hill areas may contribute water to the aquifer. This has been excluded from the water balance in favour of simplicity. Pathways for water to leave the aquifer include discharge at the ocean boundary and discharge via the wastewater and

stormwater pipe network following infiltration. This water balance indicates infiltration could account for approximately a third of the water leaving the aquifer.

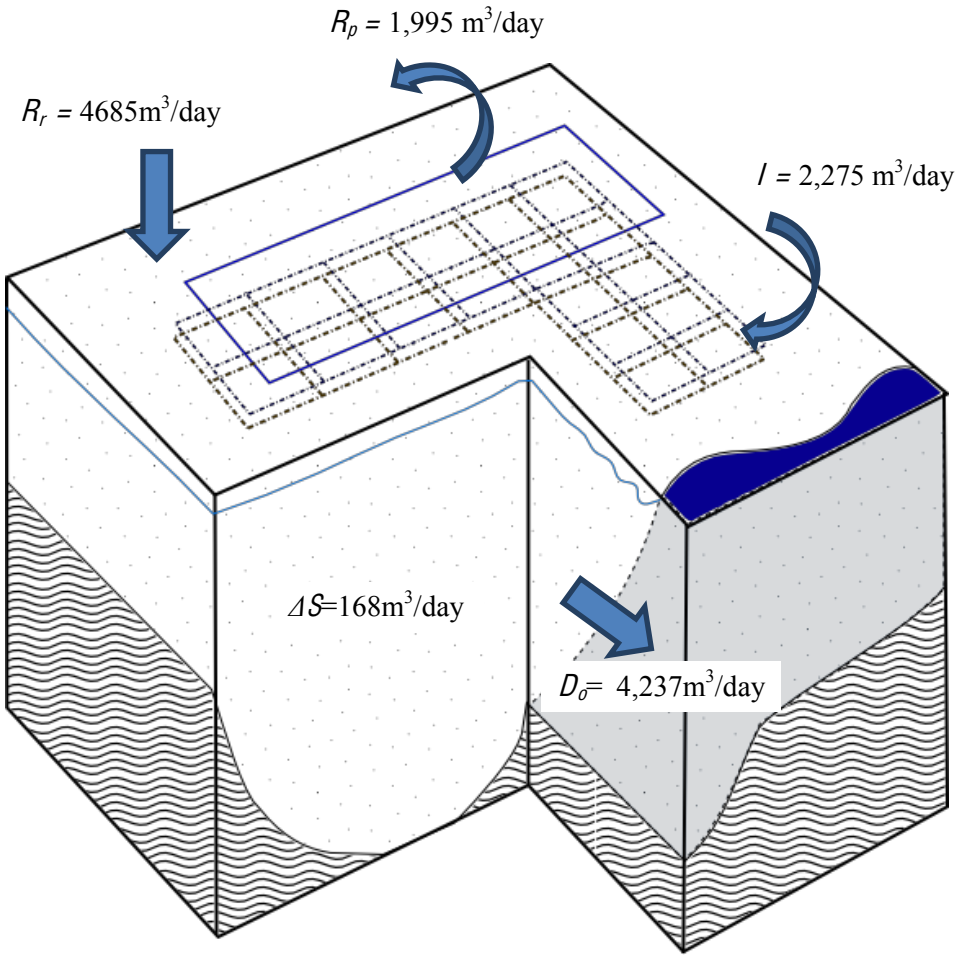


Figure 5.7: Conceptual hydrological model of the South Dunedin aquifer showing groundwater fluxes

5.5 Movements of the water table

The fluxes of groundwater in South Dunedin will, over long time scales, lead to the water balance outlined above. But over short time scales, the variety of forces influencing the South Dunedin aquifer may lead to changes in storage, expressed as

movements of the water table. Over the six month monitoring period significant variability in water table positions was observed. Table 5.3 displays descriptive statistics for selected sites in South Dunedin to indicate the variation in groundwater levels encountered during the six-month monitoring period. Tahuna Rd displayed the largest variation in water table elevations with depths below the ground surface ranging from -0.66m to -0.16m recorded (0.5m range). Market St displayed the smallest range in water table elevations of 0.2m. There are five sites where the water table is located on average within 0.5m of the ground surface (Market St, East St, Annex St, Lochend St and Tahuna Rd). It should be noted that the mean water table position over the entire six-month monitoring period is distinct from the dry weather mean water table position presented in figure 5.1, which is a mean value from a period without recent rainfall.

Table 5.3 : Descriptive statistics describing water table levels at South Dunedin sites from July 2012 to January 2013

	Mean	St. Dev.	Variance	Range	Minimum	Maximum
Normanby Ave	-0.82	0.051	0.003	0.32	-0.9	-0.58
Market St	-0.44	0.031	0.001	0.2	-0.5	-0.31
East St	-0.39	0.080	0.006	0.38	0.56	-0.18
Annex St	-0.46	0.066	0.004	0.45	-0.60	-0.15
Lochend St	-0.48	0.088	0.008	0.32	-0.65	-0.19
Tahuna Rd	-0.49	0.117	0.014	0.5	-0.66	-0.16
Hargest Cr	-0.71	0.045	0.002	0.24	-0.78	-0.55
OMES	-0.74	0.071	0.005	0.43	-0.86	-0.43

Tidal fluctuations

Movements of the water table can occur in response to a variety of natural and human induced factors. Tidal fluctuations of the water table were previously observed in South Dunedin by the ORC (Rekker, 2012). In the present study the influence of tidal fluctuations and rainfall events were explored using classical decomposition. Figure 5.8 presents an example of water level data from Hargest Cr decomposed into its various components. The ‘seasonal’ component represents the movements due to tidal forcing,

the ‘random’ component represents noise, both natural and instrument related. In this study factors other than rainfall are considered to have a negligible impact, therefore the ‘trend’ component is considered to represent movements of the water table due to rainfall. The amplitude of the tidal fluctuation observed in this example is 0.004m and the range in water table level due to rainfall is 0.21m.

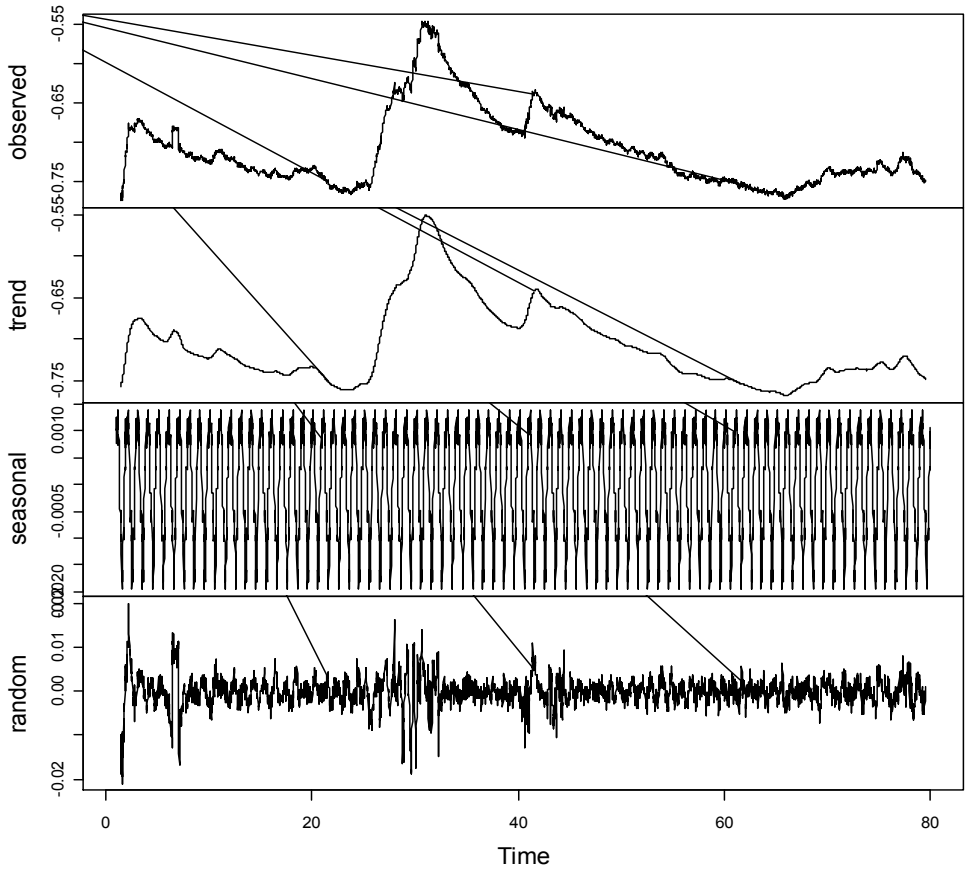


Figure 5.8 : Classical decomposition of Hargest Cr water level data

Previous research by the ORC detected tidal fluctuations with an amplitude of 0.25m at Kennedy St at a distance of 120m from the ocean boundary, 0.01m at Tonga Park (1,000m from the ocean boundary) and no detectable fluctuations 1,600m from the ocean at Bathgate Park (Rekker, 2012). The same pattern of decreasing amplitude with distance from the ocean boundary is seen in the current research. However, overall the tidal amplitudes are overall lower in this study compared to the ORC data. The efficacy of the boreholes in detecting tidal fluctuations was tested, as described in section 4.2. Thus dampening of the signal due to borehole construction technique is not considered a major factor contributing to the lower tidal fluctuations detected in this study. Factors

that are considered to influence the results are the depths of the boreholes and the sediment where the screened section is located.

The ORC boreholes reach a depth of 6m, while the boreholes established in this study reached approximately 3m depth. For the majority of the sites established in the present study the screened section occurs in silt dominated sediment. In contrast, the ORC boreholes extend past the silt layer, reaching the underlying sand. The dampened tidal fluctuations observed in this study may be related to the presence of a silt layer impeding the transmission of the tidal signal close to the surface.

Response to rainfall

To explore the water table response to rainfall events in more detail water level data was compared to rainfall event data. Hourly rainfall data was grouped into rainfall events that, when compared to water level data, resulted in detectable responses in the water table. For this study 48 hour periods were used as this resulted in rainfall events that corresponded to discernible peaks in groundwater levels, as shown in figure 5.9. The use of 48 hour periods resulted in a total of 48 rainfall events occurring between 14/07/2012 and 16/01/2013 (figure 5.10). The largest rainfall event occurred on 13/08/2012 and involved 38.2mm of rainfall occurring over a 48 hour period. During the following 48 hour period a further 35.6mm of rainfall was received, which is the second largest rainfall event recorded during the study period.

Figure 5.11 shows water table hydrographs for four sites (Tahuna Rd, Annex St, Lochend St and East St) and rainfall for the period 14/07/2012 to 31/08/2012. At all sites there is a visible water table response corresponding with rainfall events. While figure 5.1 represented a mean water table elevation, figure 5.11 indicates variability of the water table position over time. For example, at Lochend St the water table position ranges from 0.66m to 0.22m below the ground surface over the observed period.

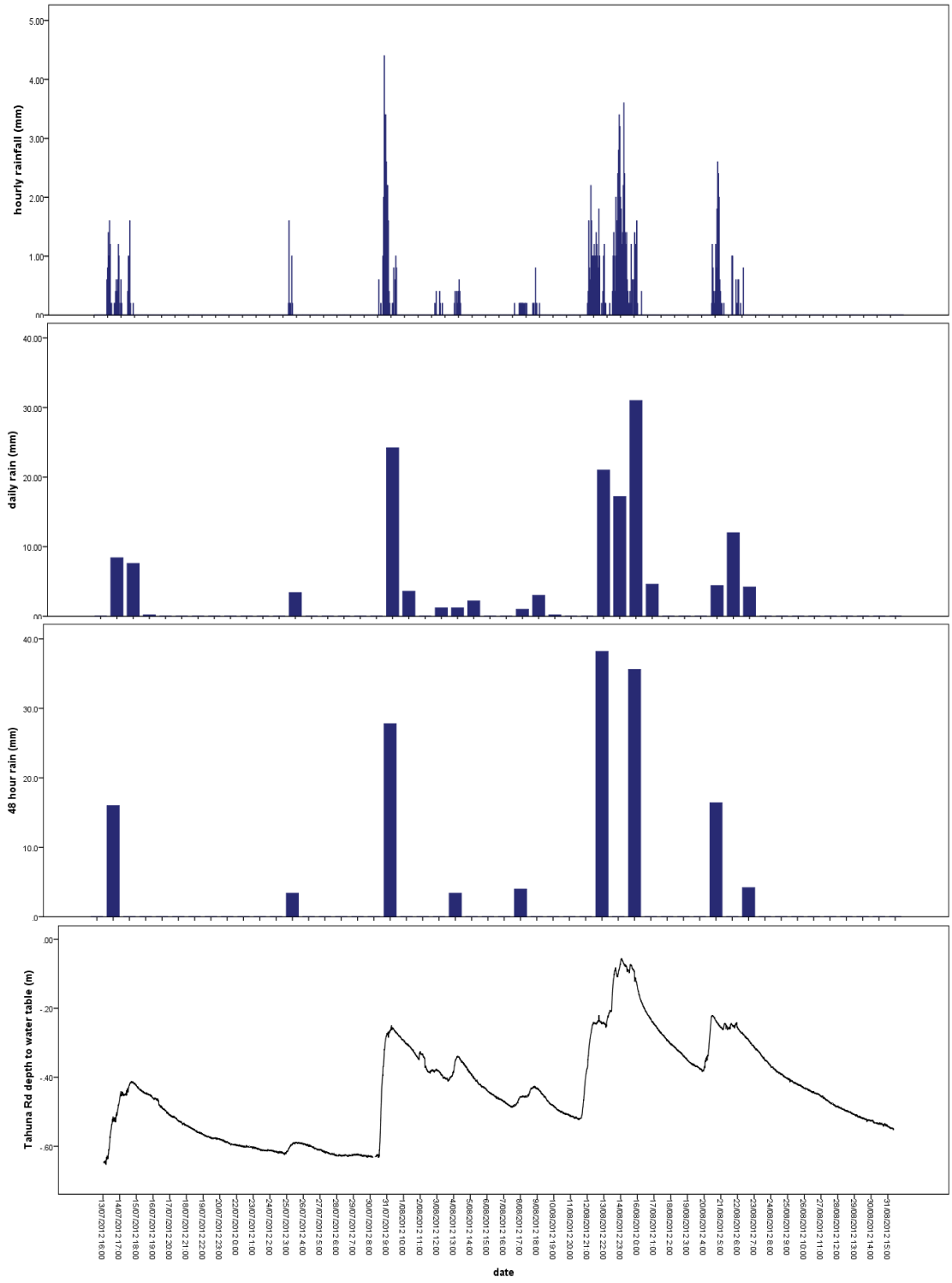


Figure 5.9: Time series graphs showing grouping of rainfall events from hourly rainfall data to 48 hour rainfall events with Tahuna Rd hydrograph to provide comparison of rainfall events with water table response.

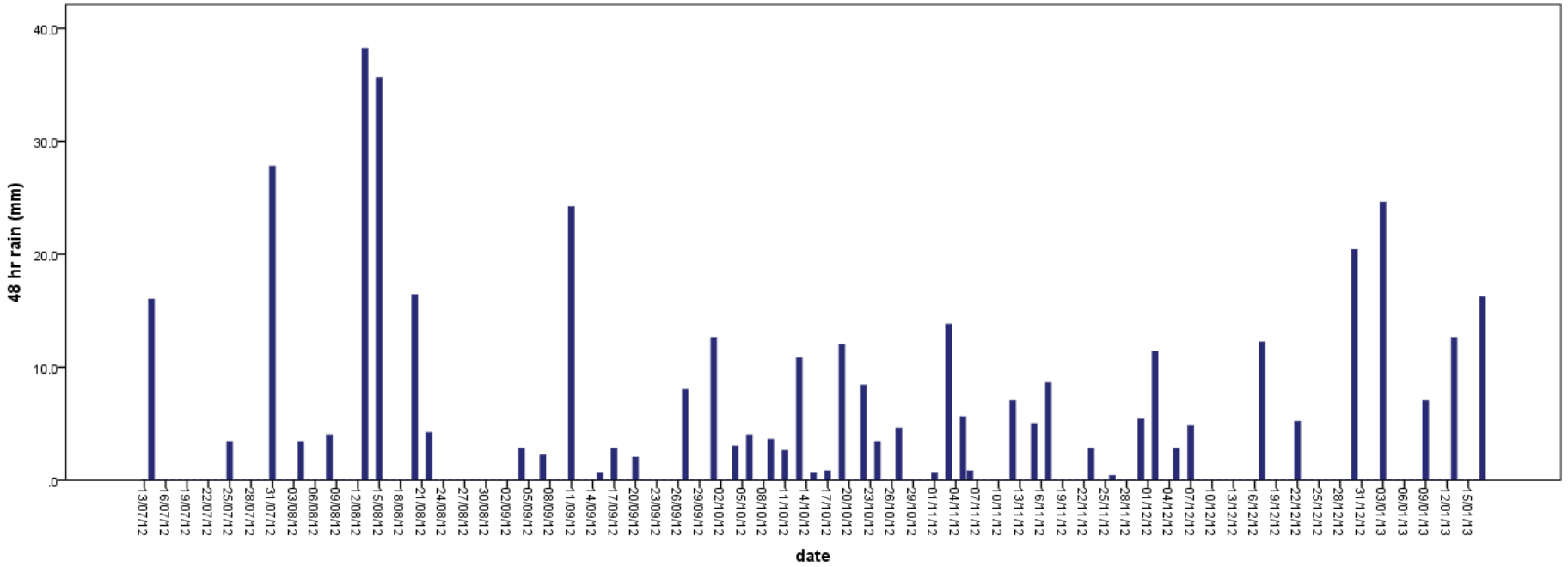


Figure 5.10: Graph of rainfall depth (mm) of 48 hour rainfall events from 13/07/12 to 16/01/13

There are disparities between sites in terms of magnitude of response, and rates of response and recovery. For example, the Tahuna Rd site exhibits a rapid response to rainfall with the water table quickly reaching a peak after the onset of rainfall, followed by a relatively rapid recession limb. In contrast East St displays a slower, more prolonged response to rainfall. There is a larger lag between the onset of rainfall and the peak of the water table response, and the water table takes longer to recede. The characteristics of sites in terms of their response to rainfall events and the factors contributing to this will be further explored in section 5.6.

An interesting situation evident in figure 5.11 is the water table failing to recover fully before a further rainfall event, leading to a cumulative effect on the water table level. For example, after 27.8mm of rainfall on 31/07/12 the water table did not return to its initial elevation at any site before further rainfall events on the 4/08/12 and 8/08/12. In fact, the water table did not return to its initial level for the rest of the period shown in figure 5.11. It seems that where the water table is already elevated due to previous rainfall, the water table response tends to be smaller. Further hydrographs are shown in appendix C.

Water table hydrographs such as figure 5.11 can display the magnitude of water table response to rainfall, the lag in response, and the time to recover to intial level. A further, useful piece of information is the presence of a threshold rainfall depth required to elicit a water table response. This will be site specific, as can be seen in figure 5.11, where a rainfall event of 3.4mm results in a response at Tahuna Rd, Annex St, and East St, but at Lochend St there is no discernible elevation of the water table.

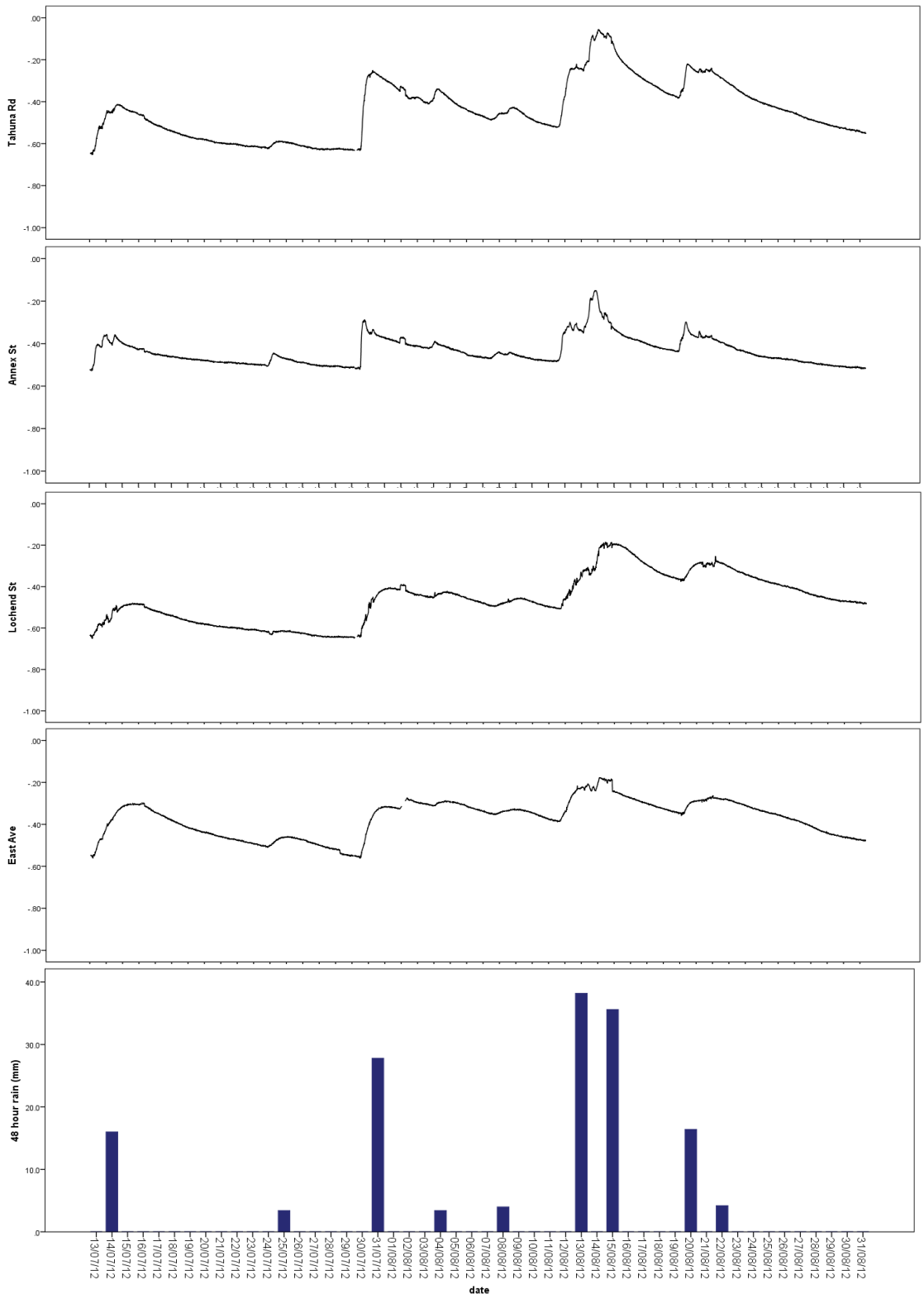


Figure 5.11: Water table hydrographs for East St, Lochend St, Annex St and Tahuna Rd groundwater monitoring sites from 13/07/12 to 31/08/12 and 48 hour rainfall depth (mm)

5.6 Characterising water table response to rainfall events

Rainfall/ water table response relationship

Linear regression was used to examine the relationship between rainfall and water table response. This was used to characterise sites in terms of their response to rainfall events and, where relevant, to highlight differences between sites. Figure 5.12 displays the water table response in m/hr plotted against rainfall in mm for South Dunedin groundwater monitoring sites. The slowest responses to rainfall were observed at East St and Market St sites (slope of the line 0.0001). At these sites the water table response can be described as lagged and prolonged. Both East St and Market St are sites with silt dominated sediment and low hydraulic conductivity values (0.0015m/day and 0.0059m/day respectively).

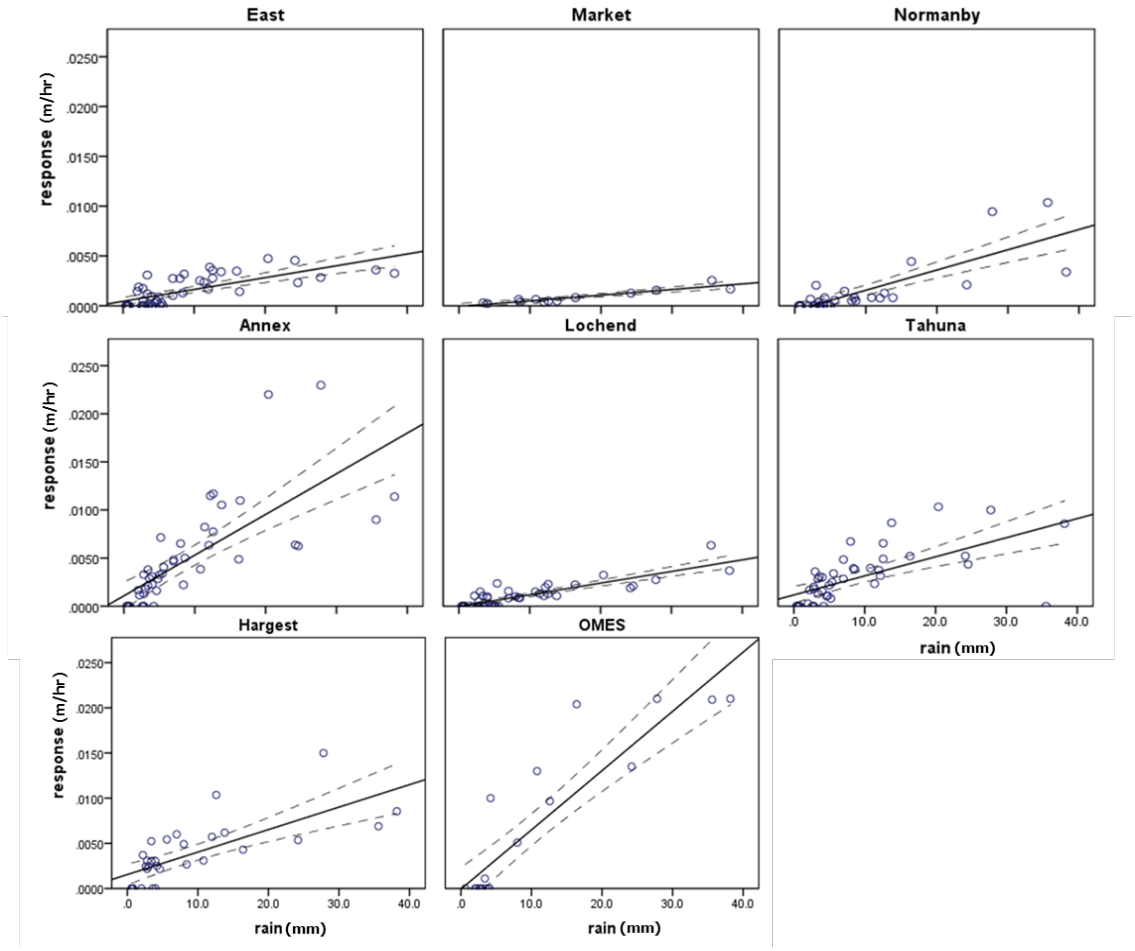


Figure 5.12: Plots of rainfall depth (mm) and water table response (m/hr) with 95% confidence intervals for South Dunedin groundwater monitoring sites.

The strongest response to rainfall was observed at the OMES site (slope = 0.0007); this is a site with sand dominated sediment and the highest hydraulic conductivity observed (10m/day). Hargest Cr and Tahuna Rd also display reasonably strong responses to rainfall (0.0003 and 0.0002 slope of regression line respectively). A strong response is associated with a small lag time between rainfall and peak water table elevation, and the water table receding relatively rapidly. Both Hargest Cr and Tahuna Rd sites are strongly affected by sand dominated sediments. For Hargest Cr, sand is the dominant sediment type encountered, while for Tahuna Rd there is a layer of sand above a silt layer. Annex St displays an unexpectedly strong response to rainfall events with a slope value of 0.0004. The sediment encountered at this site is silt with some sand (silt 75%, sand 23%) and the hydraulic conductivity was estimated as 0.0066m/day. This is the third highest hydraulic conductivity value after OMES and Hargest Cr. However, it is worth noting that the response at Annex St is stronger than at the Hargest Cr site. Detailed regression data, including R^2 values are shown in table 5.4. It is noted that the R^2 values of 0.55 (Annex St), 0.60 (Hargest Cr) and 0.63 (East St) indicate the line of best fit does not explain the spread of data very well.

Table 5.4 : Table showing regression equation and R^2 value for South Dunedin sites describing the relationship between rainfall depth (mm) and water table response (m/hr)

site	R^2 value	equation of line
Lochend St	0.75	y = 0.0001x - 0.00002
Annex St	0.55	y = 0.0004x + 0.0011
Hargest Cr	0.60	y = 0.0003x + 0.0015
OMES	0.82	y = 0.0007x - 0.00006
Market St	0.87	y = 0.0001x - 0.0006
Tahuna Rd	0.83	y = 0.0002x + 0.0011
East St	0.63	y = 0.0001x + 0.0004
Normanby Ave	0.66	y = 0.0002x - 0.0005

When characterising how the water table responds to rainfall, it is appropriate to consider the water table response in terms of metres per hour, as this is able to highlight differences between sites in terms of the speed of their response, i.e. whether it was slow or rapid. However, to use a relationship to projecting the position of the water table in response to future rainfall events, the magnitude of the response becomes more important than the speed. For this reason this section 5.6.2 will use data representing

the response of the water table in metres, rather than metres per hour. The response is considered to be the difference between the water table height at the start of a rainfall event and the maximum elevation the water table reached during or after the rainfall event. Figure 5.13 plots rainfall (mm) and the water table response (m) with a linear regression trend line indicating the relationship between the two variables, and table 5.5 provides details of R^2 values and slopes.

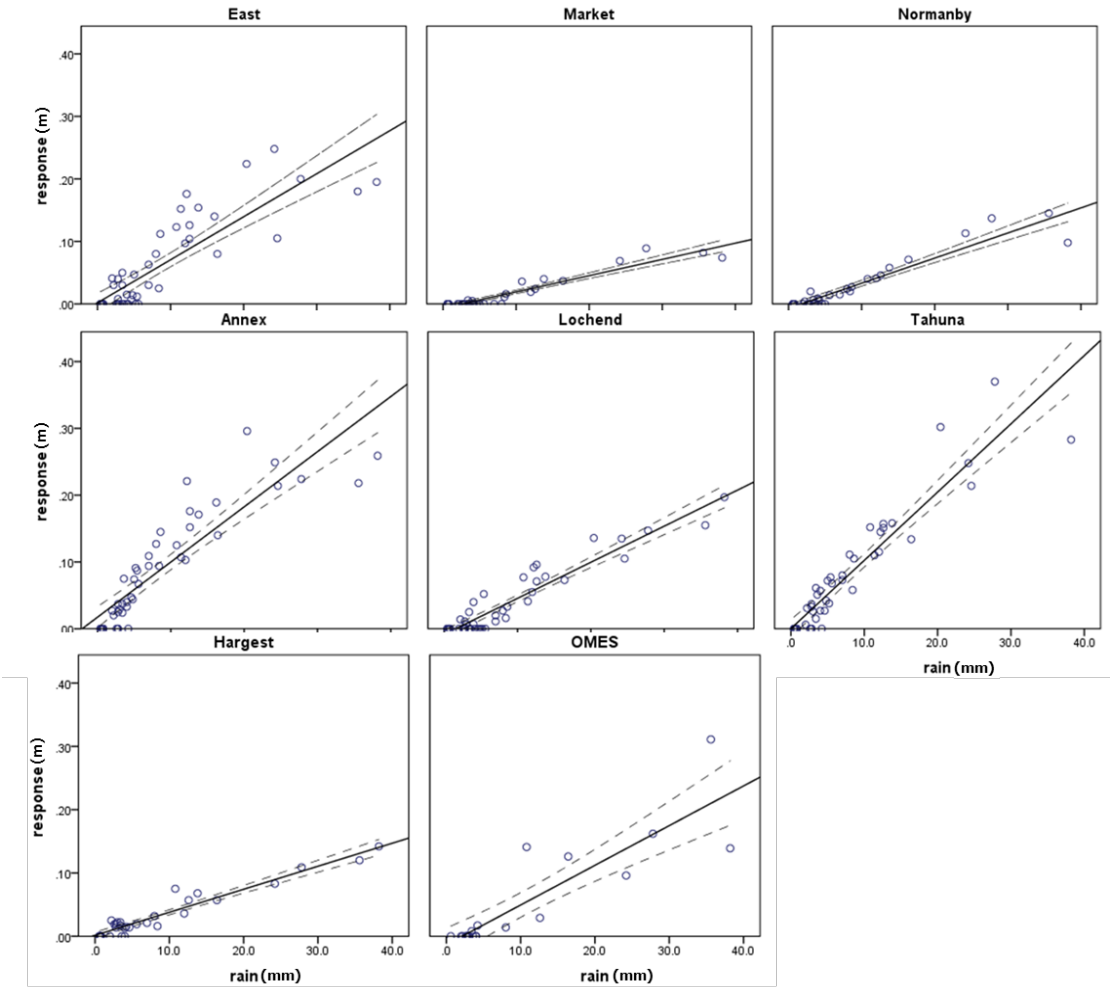


Figure 5.13 : Plots of rainfall depth (mm) and water table response (m) with 95% confidence intervals for South Dunedin groundwater monitoring sites.

Table 5.5 : Table showing regression equation and R^2 value for South Dunedin sites describing the relationship between rainfall depth (mm) and water table response (m)

site	R^2 value	equation of line
OMES	0.77	y = 0.0063x - 0.0133
Hargest	0.92	y = 0.0036x + 0.0015
Lochend	0.90	y = 0.0054x - 0.0084
Annex	0.79	y = 0.0083x + 0.0173
Tahuna	0.88	y = 0.0102x + 0.0003
Market	0.91	y = 0.0026x - 0.0067
East	0.73	y = 0.0069x + 0.0019
Normanby	0.90	y = 0.004x - 0.0069

It is noted that there are differences between the regression considering water table responses in terms of metres per hour (figure 5.12) compared to response in metres (figure 5.13). While Hargest and OMES display rapid responses they do not have the largest magnitude response. Annex St has a rapid and large response, Tahuna Rd displays the largest magnitude response but this is reached via a slow lagged response. This may be related to differences in infiltration and drainage away from the water table between sites. For the regression considering magnitude of response (m) the R^2 values are considerable higher, the minimum R^2 value being 0.73 for East St.

To explore the distribution of factors influencing the response of the water table a hierarchical cluster analysis was performed (figure 5.14). Ward's method was used to group sites based on hydraulic conductivity, response to rainfall, number of distinct layers of substrate, and the mean clay, sand and silt content of the substrate. The cluster analysis identified two main groups, clearly separating Hargest Cr and OMES from the other sites. There is a further division of Market St and East St from the remaining sites (Normanby Ave, Tahuna Rd, Annex St, Lochend St).

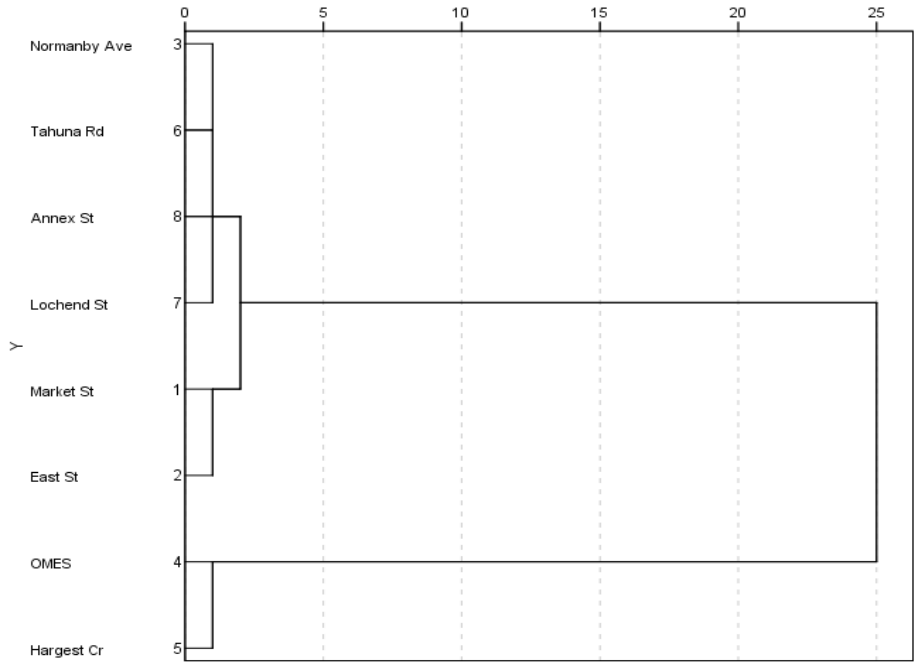


Figure 5.14: Cluster analysis results for South Dunedin groundwater monitoring sites

When these groupings of sites are examined on a map of South Dunedin it becomes clear that the groups identified by the cluster analysis form three areas of South Dunedin (figure 5.15). Hargest Cr and OMES are closest to the ocean on the eastern side of South Dunedin. These are the sites characterised by sand dominated substrate, high hydraulic conductivity values and a rapid, short-lived response to rainfall. East St and Market St form a group in the centre of South Dunedin. These sites are characterised by silt dominated substrate, very low hydraulic conductivity values, and a lagged, prolonged response to rainfall. This is also the area of the highest water table elevations. The third group of sites occurs to the western side of South Dunedin, and consists of Annex St, Normanby Ave, Lochend St and Tahuna Rd. Borelogs at these sites tended to display alternating layers of sand and silt. Where sand occurred above silt, responses to rainfall were rapid and prolonged for example, Tahuna Rd. Overall the responses observed within this group were mixed but represented a middle ground between the rapid responses of the sand dominated sites and the lagged responses of the silt dominated sites.

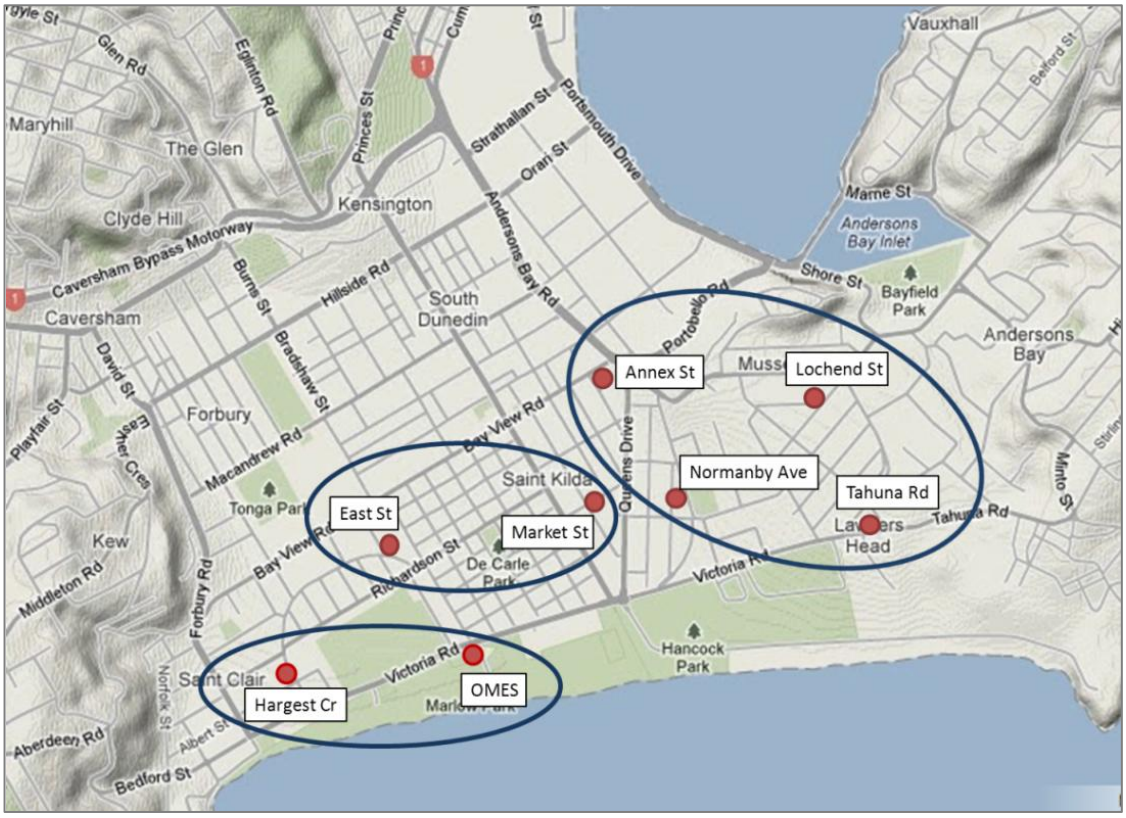


Figure 5.15: Cluster analysis results plotted on a map of South Dunedin showing grouping of sites.

Projecting water table responses to extreme events

The results thus far describe the variations in the position of the water table observed during the 6 month monitoring period. By establishing a relationship between rainfall and the water table response the possibility of considering the water table elevation under different rainfall scenarios becomes possible. NIWA's High Intensity Rainfall Design System (HIRDS) provides estimates of rainfall in mm depth for heavy rainfall events with average return intervals (ARI) ranging from 2 to 100 years, and event durations from 10 minutes to 72 hours, for New Zealand sites. This tool was used to provide 48hr rainfall event estimates for South Dunedin. Table 5.6 presents the rainfall depth estimated for 48 hour rainfall events with average return intervals of 2 to 50 years.

Table 5.6: Table showing estimates of rainfall depth (mm) for rainfall event with return intervals of 2 to 50 years and standard error of rainfall estimates

average return interval (years)	rainfall depth (mm) for 48 hour event	Standard error (mm) of rainfall estimates
2	67.5	2
5	85.7	2.7
10	100.4	3.7
50	142.3	9.1

In table 5.7 a linear relationship between rainfall and the water table response (m) is used to extrapolate the position of the water table for future rainfall event scenarios. The water table response projected due to heavy rainfall events is then added to the mean water table position (without recent rainfall) to consider the potential for groundwater to rise to the surface and cause flooding (cells highlighted in blue in table 5.7 indicate groundwater flooding). As rainfall increases the water table response increases, based on the linear relationship. While this pattern is common to all sites there are differences between sites in terms of their responses and in terms of the locations that are expected to experience groundwater flooding associated with heavy rainfall events. Tahuna St, Annex St, and East St experience the greatest incidences of groundwater flooding. It is noted that East St already has a particularly shallow water table (0.5m below the ground surface) so it takes little groundwater response to bring the water table to the surface. For Tahuna St and Annex St, it is the strong response to rainfall that is a more important factor leading to groundwater flooding. While OMES has a strong response to rainfall the mean water table level is 0.75m below the ground surface. Consequently, it is only for a 1 in 50 year event that the water table is projected to reach the surface.

The heterogeneity of the South Dunedin aquifer, in terms of sediment profile, hydraulic conductivity and, consequently, water table response to rainfall, has been summarised by cluster analysis as sites falling into three main groups. The projected mean water table responses for these main groups (labelled by dominant sediment type) are shown in table 5.8. The silt dominated sites exhibit the smallest water table responses to hypothetical future rainfall events, sand dominated sites also display a comparatively small response, while the sites with layers of sand and silt display the largest responses.

Table 5.7 : Table showing the water table response (with 95% confidence intervals) projected due to heavy rainfall events with average return intervals of 2 to 50 years, when the projected water table response would result in groundwater levels reaching the ground

Silt dominated sites		East		Market	
ARI (years)	rainfall depth (mm)	water table response (m)	95% CI	water table response (m)	95% CI
2	67.5	0.47	0.45, 0.48	0.17	0.17, 0.17
5	85.7	0.59	0.58, 0.60	0.22	0.21, 0.22
10	100.4	0.69	0.68, 0.70	0.25	0.25, 0.26
50	142.3	0.98	0.97, 0.99	0.36	0.36, 0.37

sand dominated sites		Hargest		OMES	
ARI (years)	rainfall depth (mm)	water table response (m)	95% CI	water table response (m)	95% CI
2	67.5	0.25	0.24, 0.25	0.41	0.39, 0.43
5	85.7	0.31	0.31, 0.32	0.52	0.51, 0.54
10	100.4	0.37	0.36, 0.37	0.62	0.60, 0.64
50	142.3	0.52	0.52, 0.52	0.88	0.86, 0.90

sites with sand and silt		Normanby		Tahuna		Annex		Lochend	
ARI (years)	rainfall depth (mm)	water table response (m)	95% CI	water table response (m)	95% CI	water table response (m)	95% CI	water table response (m)	95% CI
2	67.5	0.26	0.26, 0.27	0.66	0.65, 0.67	0.58	0.56, 0.59	0.36	0.35, 0.36
5	85.7	0.34	0.33, 0.34	0.84	0.83, 0.85	0.73	0.71, 0.74	0.46	0.45, 0.46
10	100.4	0.40	0.39, 0.40	0.98	0.97, 0.99	0.85	0.84, 0.86	0.53	0.53, 0.54
50	142.3	0.56	0.56, 0.56	1.39	1.38, 1.40	1.19	1.18, 1.20	0.76	0.76, 0.77

Table 5.8: Table showing the mean water table response estimated for silt sites, sand sites, sites with layers of sand and silt, and across all sites in response to 48 hour rainfall events with return periods of 2 to 50 years.

average return interval (years)	rainfall depth (mm) for 48 hr event	mean response (m) for sand dominated sites	mean response (m) for silt dominated sites	mean response (m) for sites with silt and sand layers	mean water table (m) response across all sites
2	**67.5**	0.329	0.317	0.464	0.393
5	**85.7**	0.419	0.403	0.589	0.5
10	**100.4**	0.492	0.473	0.69	0.586
50	**142.3**	0.699	0.671	0.977	0.831

Previous ORC research considering scenarios of sea level rise and how the water table may respond, concluded that changes in sea level would force equivalent rises in groundwater levels. Table 5.9 presents the results of considering the effect of extreme rainfall events combined with the effect of sea level rise on groundwater elevations. This is expressed as the percentage of sites where the water table is projected to reach the surface, causing flooding. The projected response of the water table to extreme rainfall events is added to a mean water table position with sea level rise scenarios of 0.1m, 0.28m and 0.4m of sea level rise by 2100. The mean water table position at each site is based on 0.9cm groundwater rise per 1cm rise in sea level (Rekker, 2012).

Table 5.9: Table showing the percentage of South Dunedin sites projected to experience groundwater flooding in response to 48 hour rainfall event scenarios under present sea level conditions and with sea level rise scenarios.

Average return interval (years)	Rainfall depth (mm) for 48 hour event	rainfall alone, no sea level rise	0.1m sea level rise	0.28m sea level rise	0.4m sea level rise
(no rainfall, sea level rise alone)			0%	0%	0%
2	67.5	0%	38%	50%	75%
5	85.7	38%	50%	63%	75%
10	100.4	50%	50%	75%	88%
50	142.3	63%	63%	88%	100%

These scenarios of sea level rise presented here are the same as those considered in the ORC modelling of groundwater levels in South Dunedin in response to sea level rise. The general pattern observed is that the larger the rainfall event average return interval, the higher the proportion of sites expected to experience groundwater flooding. When increases in mean groundwater levels due to sea level rise are included, the proportion of sites expected to experience flooding in response to rainfall events if further increased. The higher the sea level rise considered, the greater the proportion of sites projected to experience groundwater flooding. It is noted that considering sea level rise alone results in 0% of sites experiencing groundwater flooding, this is true for all the sea level rise scenarios.

5.7 Groundwater interactions with wastewater pipes

In South Dunedin the shallow groundwater conditions result in interactions between groundwater and below-ground urban infrastructure, most notably the wastewater and stormwater pipe networks. In the stormwater system for South Dunedin there is a baseflow volume of 430m^3/day discharged at Portobello. This baseflow discharge occurs even in the absence of recent rainfall and consequently has been attributed to groundwater infiltration into the stormwater pipe system (Rekker, 2012). Little is understood about the interaction between groundwater and wastewater/stormwater pipes in South Dunedin. As an initial step to investigate this phenomenon, pipe flow volumes were monitored to detect groundwater inflow. The stormwater pipe network is expected to receive higher flow volumes after rainfall, as surface runoff is directed towards pipes. On the other hand, the wastewater pipe network is not expected to display higher flows due to rainfall. Therefore, increases in flow in the wastewater network after rainfall could indicate inflow of groundwater.

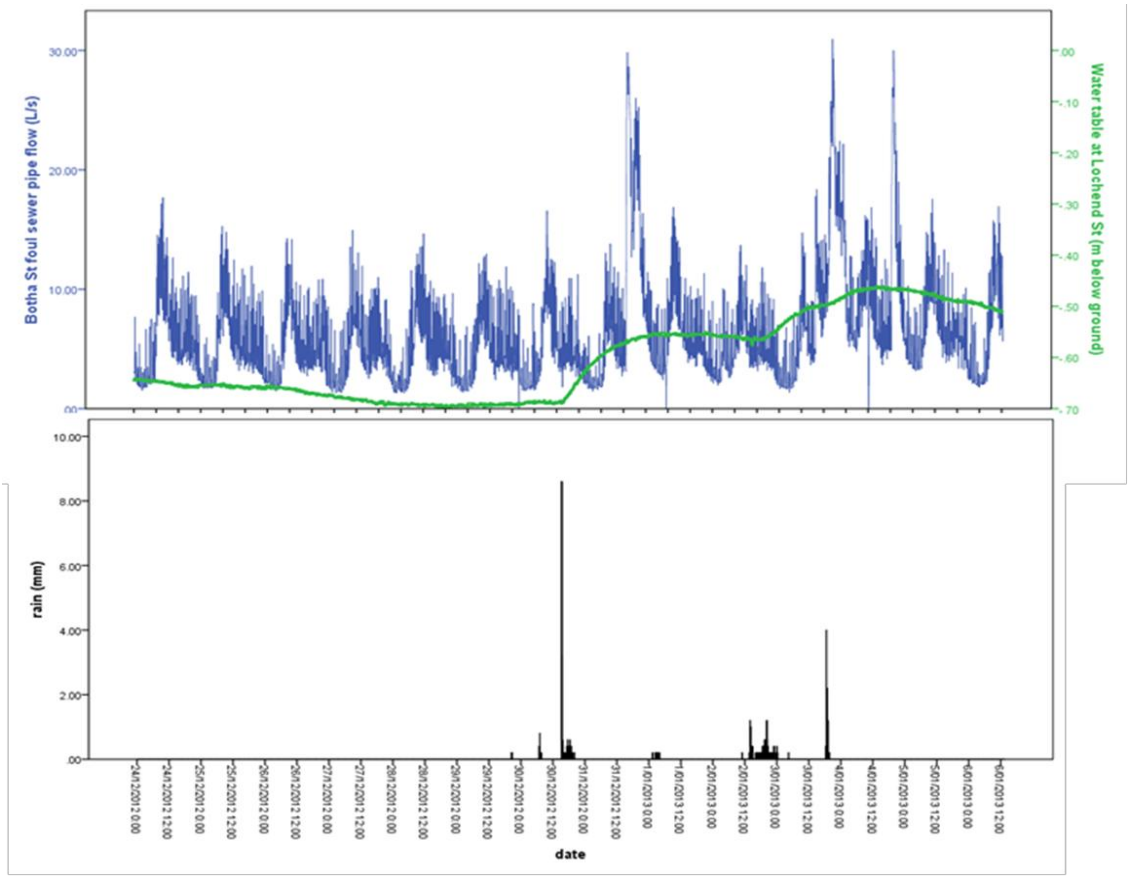


Figure 5.16 Graph of wastewater pipe flow volume at Botha Street in blue (manhole ID of site: FSM13669) and water table elevation at Lochend Street in green and rainfall between 24/12/12 and 06/01/13

Figure 5.16 shows flow volume in wastewater pipes at Botha Street (manhole ID of flow monitor site: FSM13669) and the water table elevation at Lochend Street (located approximately 2 blocks from the pipe flow monitoring site) compared to rainfall over two weeks. A typical diurnal cycle in wastewater pipe flow is observed during the period without rainfall, and then 3 main peaks in wastewater pipe flow occur after three main rainfall events. However, the peaks in wastewater flow appear to coincide more closely with the water table elevation than rainfall itself. After rainfall on 30/12/12 the water table begins to rise, there is a lag time of approximately a day and a half before the water table reaches its peak elevation and it is at this point that an increase in wastewater flow is observed. A similar pattern occurs with the rainfall occurring on 02/01/13 and 03/01/13 with the peaks in wastewater flow occurring after peak water table elevation is attained. This suggests the variations in wastewater flow are linked to the water table height and may be a result of the increased pressure experienced when the water table becomes elevated. The possibility that the peak in pipe flow is related to

stormwater inflow into the wastewater network remains. However, if this was the case, a smaller lag time between rainfall and peaks in pipe flow could be expected. The pattern observed suggests it is the elevation of the water table, rather than rainfall, which is more closely linked to increases in wastewater pipe flow volumes. However, an unexplained aspect of this pattern of flow is that the wastewater flow volumes return towards initial levels while the water table remains elevated.

Graph of wastewater pipe flow volume at East Avenue in blue (manhole ID of site: FSM12908) and water table elevation at East Avenue in green and rainfall between 24/12/12 and 06/01/13As a comparison Figure 5.17 shows sewage pipe flow volumes and water table elevation at East Avenue (manhole ID of flow monitor site: FSM12908) with no significant response in wastewater flow volumes as the water table rises. Both East Avenue and Botha Street were identified as areas of interest due to the presence of a prolonged response of the water table to rainfall events, yet a corresponding signal in the wastewater pipe network was only found at Botha Street.

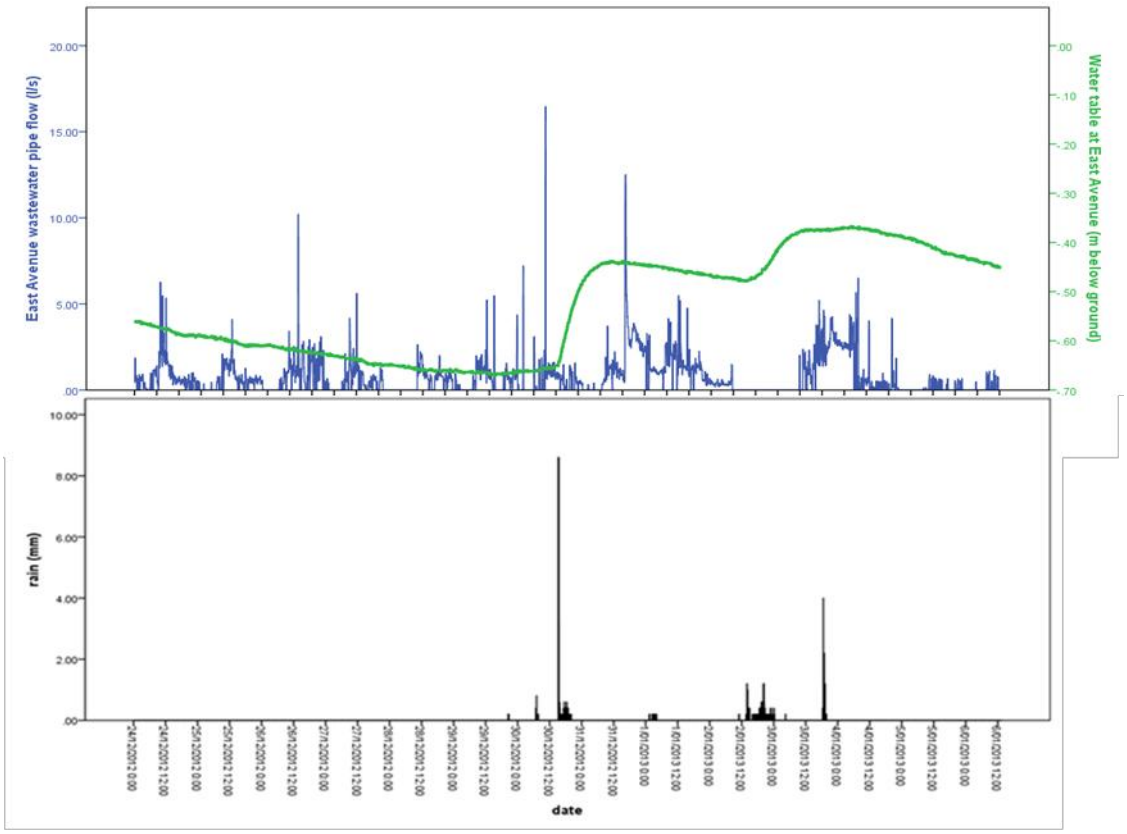


Figure 5.17 :Graph of wastewater pipe flow volume at East Avenue in blue (manhole ID of site: FSM12908) and water table elevation at East Avenue in green and rainfall between 24/12/12 and 06/01/13

6 Discussion

This chapter discusses variability in groundwater levels in response to rainfall events for a shallow coastal aquifer, using the South Dunedin aquifer as a case study. This information is of practical applicability as the aquifer is situated beneath an urban area. Due to this urban setting, movements of the already shallow water table may interact with below ground infrastructure and pose a risk of groundwater flooding, particularly when considered in combination with projected effects of future sea level rise. The chapter is divided into seven sections. In the first section hydrogeological characteristics of the South Dunedin aquifer are discussed, including spatial variation across the aquifer. In the following section temporal variation of the position of the water table is discussed. In the third section the implications of groundwater movements for the South Dunedin urban area are considered, including groundwater flooding and impacts to urban infrastructure. The fourth section discusses the wider implications of the findings of this research for management of shallow groundwater in coastal urban aquifers. Sections five and six discuss the limitations of the research and directions for future research respectively.

6.1 South Dunedin Aquifer

Hydrogeology

The first piece of information this study sought to gain about the South Dunedin aquifer was the position of the water table across the aquifer. Based on the monitoring sites established in this study, a more detailed picture of the groundwater level has been built up. Overall, this revealed an extremely shallow water table. This was strongly suggested from anecdotal evidence across South Dunedin. However, previously, the only measurements of groundwater levels available were from three ORC boreholes along the western edge of the aquifer and from the Tahuna Wastewater Plant. This study extended monitoring of groundwater levels to provide wider coverage of the South Dunedin area.

The sites sampled in this study indicate there is a mounding up of groundwater around the Saint Kilda area of South Dunedin; this is broadly in the centre of the South Dunedin Aquifer (slightly to the west). There were also two smaller pockets of slightly elevated groundwater levels in Tainui and Musselburgh. The mounding up of groundwater in the centre of South Dunedin coincides with the area with the most extensive silt layer, the lowest estimates of hydraulic conductivity, and a lagged, prolonged response to rainfall events. When viewed together, these pieces of information all support a picture of the water table in South Dunedin as influenced by the presence of a layer of silt that is most prominent around the central Saint Kilda area.

Interestingly this central silt dominated area, with a high water table, coincides with the highest density of earthquake damage claims resulting from the 1974 Dunedin earthquake (figure 6.1). The presence of silt and saturated conditions are known factor contributing to liquefaction risk (McCahon, 1993). The central part of South Dunedin is also found to contain the most saline groundwater, which is probably a relict from the area's history as a tidal salt marsh. The low elevation above sea level and the virtual lack of any gradient across South Dunedin means there is not a strong flow of freshwater towards the coast that could flush out this relict saline groundwater. The process of land reclamation may have altered the position of the fresh/saltwater transition zone, particularly on the Otago Harbour side, shifting it further into the harbour, but some pockets of salinity may remain and the system has not fully adjusted to the new shoreline (Guo and Jaio, 2007). However, saline intrusion is also a possibility, particularly due to the suspected drainage effect the pipe network may be having. The removal of groundwater from the system via the pipe network may be drawing saline groundwater from the coast further inland into the aquifer (PDP, 2011).

Early in this study the two sites closest to the ocean (OMES and Holiday Park) were identified as displaying water table movements that deviated from the pattern observed at other sites. These two sites are the closest to the ocean and, as such, a strong tidal influence and the highest salinity values were expected; however, neither were observed. Instead, they displayed the lowest salinity values, comparable to fresh water, and no tidal fluctuation. The two sites are located on old sand dunes and the groundwater encountered appears to be a perched water table of fresh water held in the sand dunes.

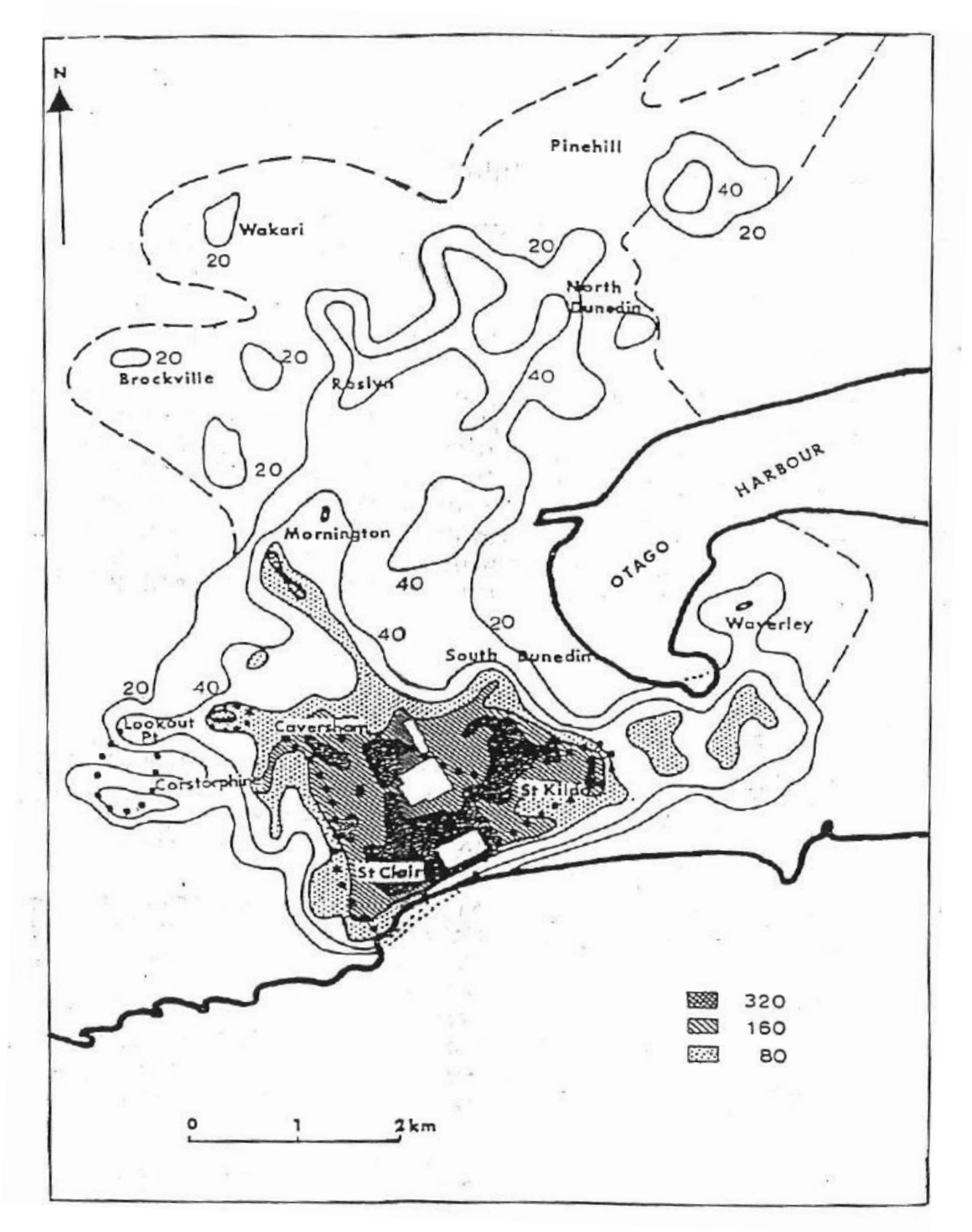


Figure 6.1: Map of density of damage claims resulting from the 1974 Dunedin earthquake, numbers indicate claims per km2 (source: McCahon, 1993)

Perched water tables in sand dunes have been observed in other locations such as around Saudi Arabia, Perth, and Morton Island, Australia (Australia, 2012; Harari, 1996). In this situation rainfall infiltrates into the dunes, but does not continue to reach the main underlying aquifer. As such the groundwater is not hydraulically connected to the main aquifer. In this study data from OMES and Holiday Park have not been included in representations of the position of the water table of the South Dunedin Aquifer. These sites have, however, been included in estimates of hydraulic conductivity and the response of groundwater to rainfall as they are examples of sites in sand dominated sediment.

The sediment encountered in the South Dunedin Aquifer in this study, and indicated in historic borelog records, reveals a complex stratigraphy at shallow depths. Of the groundwater monitoring sites established for the study there are three sites where sand is the dominant substrate (Hargest Cr, OMES, Holiday Park), two sites where silt is the dominant sediment (East St, Market St), and four sites where there are distinct differences along the vertical profile resulting in layers of sand and silt (Annex St, Lochend St, Tahuna Rd, Normanby Ave). The general vertical pattern indicated is a shallow silt layer, with underlying sand. The general horizontal pattern is the deepest extent of silt occurring around the centre of South Dunedin (around St Kilda). Along the eastern and western edges of the aquifer the silt layer does not appear to be as deep, with sand being encountered below the silt layer. This roughly mirrors the shape of the aquifer itself. LIDAR data provides an estimate of a depth of 60m to bedrock; a deeper area, interpreted as a stream channel, heading from North to South through the aquifer is also indicated. This may have been a path taken by what is now the Waters of Leith during a stage of the Dunedin area's history when sea level was lower (Rekker, 2012).

The silt encountered when establishing boreholes in this study was noted as being blue/grey and in some cases contained shell fragments. A blue/grey colour is characteristic of sediments that are saturated resulting in anaerobic conditions (Timms et al., 2001). It is suggested that the blue/grey silt is indicative of the area's history as a tidal swamp marsh. The shell fragments are of marine origin and when the area was a marshland silt and clay sized sediment would have been trapped and deposited. In historic records two lagoons located in South Dunedin are noted around the central South Dunedin area and tidal marshland around the Otago Harbour as seen in figure 6.2 (Rekker, 2012).



Figure 6.2: Painting depicting view of Otago Harbour from Anderson's Bay in 1869 showing tidal marshland of South Dunedin before reclamation (source: Hocken Library Collection)

Excavations in this study were limited to the depths able to be reached with a hand auger (approximately 3m in this case). However, borelogs sourced from a previous study by the EQC on earthquake risk in Dunedin have been used to build up a more detailed picture of the aquifer. An unfortunate discovery during this research was the loss of historic borelog records for South Dunedin. It appears that during restructuring of the Ministry of Works in the 1980s files containing records of borelogs collected for Dunedin were shifted and have been misplaced (pers. comm. Osborne, 2012). An index of borelog locations remains, but the borelogs themselves have vanished. However the EQC report provides an indirect source of some of these records.

While the silt encountered is described as a 'layer' throughout this study, it may be simplistic to describe the South Dunedin aquifer as being composed of a single layer of silt with underlying sand. This study suggests it may be more appropriate to consider the aquifer as composed of alternating layers of silt and sand near the surface, becoming dominated by sand below.

The deepest extent of silt indicated in borelogs reaches approximately 18m depth (recorded at King Edward St, Saint Kilda), and two other sites in the Saint Kilda area indicate silt encountered until 8 and 10m below the surface, all with underlying sand.

At present, the picture of the South Dunedin Aquifer is still incomplete and the full extent of the silt layer in South Dunedin remains an unknown. However, previously the aquifer was simply described as sand deposits (Glassey, et al. 2003; Bishop & Turnbull, 1996; Rekker 2012). Sand may be an accurate description of the dominant sediment type for the aquifer as a whole, but this study has highlighted the presence of a shallow silt layer that was previously unacknowledged. The presence of silt at shallow depths is less important for previous studies on long-term, head driven groundwater processes. But when considering how the water table responds to rainfall, the substrate encountered near the ground surface (and its hydraulic conductivity) are very important as they will influence how quickly the water table responds. Thus the presence of a shallow layer of silt becomes important.

The relationship between particle size and hydraulic conductivity, and consequently the movement of fluids is well established (Cherry and Freeze, 1999). Here the sites with the larger particle sizes (sand) were expected to return the highest hydraulic conductivity from slug tests. The hydraulic conductivity values estimated range from 0.0015m/day to 10m/day. Overall, the sites with the highest hydraulic conductivity did correspond to the sites with sand dominated sediments. The sites with the lowest hydraulic conductivity values corresponded to the sites with the silt dominated sediments around the centre of South Dunedin.

The complexity of the sediment profile is important when interpreting hydraulic conductivity in this study. For example, the site with the lowest estimated hydraulic conductivity is East St with 0.0015m/day; the sediment sampled in the lower section of the East St borehole had a silt content of 83%. However, the site with the highest silt content is Tahuna Rd (91%); if sediment type controls hydraulic conductivity this site could be expected to display the lowest hydraulic conductivity value. Yet this was not the case; the hydraulic conductivity estimated at Tahuna Rd is 0.0047m/day. The deviation from expected results may be a result of the complexity of the sediment profiles. For the East St site, silt is the dominant sediment throughout the entire borehole profile. Tahuna Rd, on the other hand, has a layer of sand dominated sediment overlying the silt. The presence of sand above silt at Tahuna Rd may allow faster infiltration and groundwater movement than if the sediment profile consisted of silt dominated sediment from top to bottom.

The highest hydraulic conductivity value recorded was 10m/day, estimated for the OMES site, falls within values expected for fine sands (the site is located on sand dunes). Yet, this is far less than the estimated hydraulic conductivity previously suggested for the aquifer by the ORC, of 22m per day, based on the tidal fluctuation method, as estimated by the ORC. It is important to note that the tidal method gives a value for the aquifer as a whole, while slug tests are site specific. Differences in hydraulic conductivity estimates for an aquifer ranging over orders of magnitude due to different methods are not uncommon (Rovey and Cherkauer, 1995; Schulze-Makuch et al., 1999; Sobieraj et al., 2004). This is attributed to a scale dependence issue with hydraulic conductivity estimates. In heterogeneous materials the smaller the scale of testing the lower the hydraulic conductivity estimate. This results in a tendency for methods testing hydraulic conductivity on smaller spatial scales, such as slug tests, to return lower estimates when compared to methods that provide estimates for hydraulic conductivity on larger spatial scales, such as pump tests (Schulz-Makuch et al., 1999). It is also noted that the ORC constructed a model of the South Dunedin aquifer in MODFLOW and during calibration and parameter optimisation the hydraulic conductivity estimate was adjusted from 22m/day to 3.6m/day (Rekker, 2012).

Water balance

The water balance presented in section 5.4 reflects the forces influencing groundwater fluxes in South Dunedin. A generalised groundwater balance equation (such as equation 5.2) can provide a starting point, but needs to be modified to take into account the urban and coastal aspects of the South Dunedin aquifer. This has led to the following water balance equation for South Dunedin:

$$R_r + R_p - D_o - I = \Delta S \qquad (6.1)$$

where R_r is rainfall recharge, R_p is recharge from leaking water supply pipes, D_o is discharge to the ocean and I is infiltration of groundwater into sewer and wastewater pipes.

The value of a water balance equation such as this is that it provides a tool to conceptualise movements of groundwater (figure 6.3). It allows the systematic consideration of all the potential pathways water may take and is able to give a snapshot of overall fluxes of groundwater for the system as a whole (Mitchell et al., 2001). However, there is significant uncertainty involved, particularly as the values used in this study are in the most part the product of calibration of a groundwater model of the South Dunedin aquifer with limited data inputs. Nevertheless, there is value in considering how fluxes of groundwater may be distributed (Xu and Singh, 1998; Zhang et al., 2002).

This approach has highlighted that while recharge from rainfall is likely the dominant source of recharge, leaking of water into the aquifer from water supply pipes could contribute a significant amount to total aquifer recharge (Vázquez-Suñé et al., 2005). While water supply leakage rates are difficult to quantify due to the diffuse nature of leakage, rates of 20-25% are considered common. A rate of 26% is reported for Gotborg, Sweden and 15-30% has been estimated for Tomsk, Russia (Lerner, 2002). Recharge from leaking water pipes is an aspect of the water balance that is unique to urban catchments, this highlights the need to consider the effects of urbanisation when investigating urban aquifers (Bhaskar and Welty, 2012)

Similarly, infiltration of groundwater into stormwater and wastewater pipes may be a significant factor removing groundwater from the South Dunedin Aquifer providing an unintended drainage function. Due to the high water table conditions in South Dunedin much of the wastewater and stormwater pipe networks are situated below the water table. As a result, groundwater may infiltrate into the pipe network through cracks and weaknesses. Work to reduce this groundwater infiltration is planned in South Dunedin through rehabilitation of pipes, targeting the oldest pipes as a priority. A potential indirect effect of this rehabilitation may be the removal of the drainage function currently provided by the pipe network. A further potential consequence is that higher groundwater levels may result (PDP, 2011).

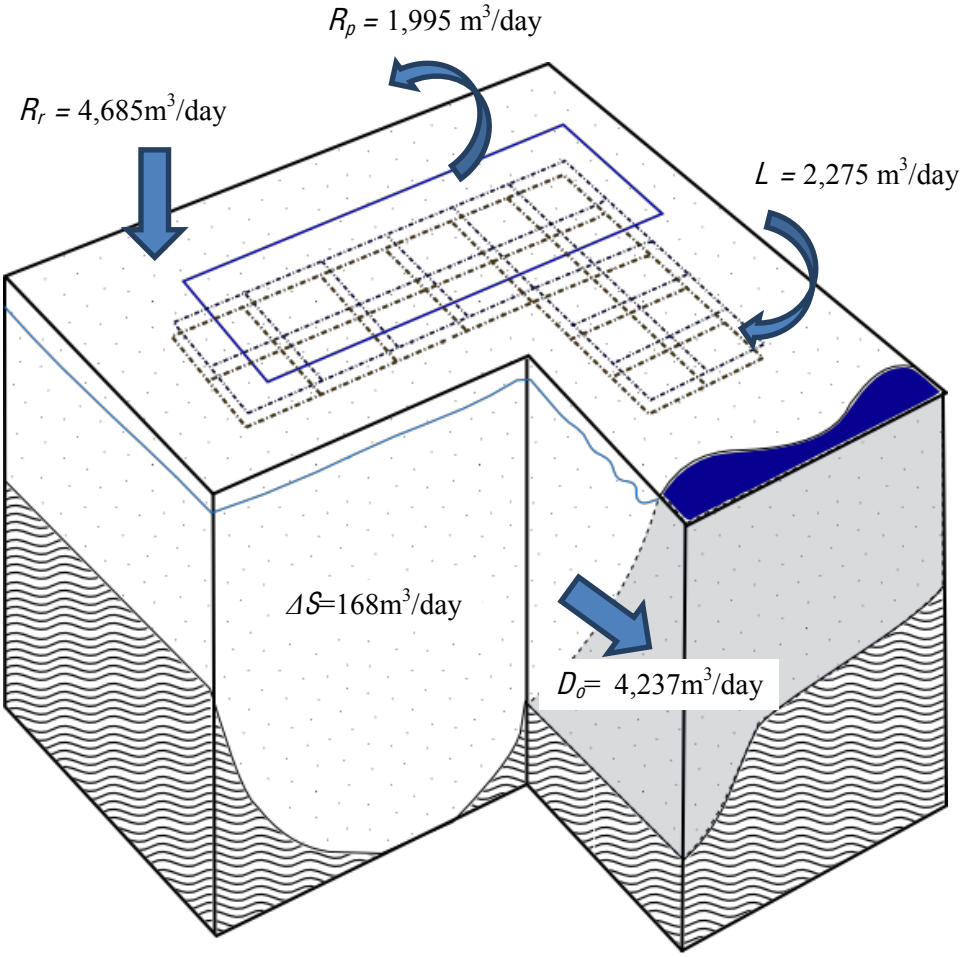


Figure 6.3: Conceptual hydrological model of the South Dunedin Aquifer showing groundwater fluxes

6.2 Movements of the water table

The position of the water table at a point in time will be an expression of the interaction between forces contributing groundwater to, or removing groundwater from, the aquifer. Any changes in the volume of groundwater stored will manifest as movements of the water table (Sophocleous, 2004). Identifying the mean water table position is a good first step to developing a better understanding of groundwater in South Dunedin (figure 5.1). However, a key aspect of this research is developing an appreciation of the variability in the position of the water table over time.

The two main factors investigated as influencing the position of the water table in this study are: tidal movements at the ocean boundary, and recharge from rainfall. It is also possible that some of the movements of the water table observed in this study may be related to inflow of water from leaking water supply pipes, or the outflow of groundwater as it infiltrates into the stormwater and wastewater network.

Tidal fluctuations

Tidal fluctuations of the water table have been previously observed in South Dunedin. In this study classical decomposition was used to isolate movements due to tidal forcing. This showed that the amplitude of tidal fluctuations was significantly smaller than those previously recorded by the ORC. However, when interpreted in light of the layer of silt sediment, and consequently lower hydraulic conductivity, encountered, dampened tidal fluctuations could be expected as the tidal signal would not transmitted through silt sediments as readily as through sand.

A tidal fluctuation of the water table indicates the groundwater body is hydraulically connected to the ocean (Nuttle and Portnay, 1992. As a result, movements of the ocean level (for example due to tides, waves, and storm surges), can cause loading and unloading at the ocean boundary (Neilsen, 1990; Horn, 2006; Turner et al., 1996). The resultant pressure wave propagates through the aquifer as seen in figure 6.4. The amplitude will dissipate with distance from the coast and there will be a time lag between movements in the ocean and of groundwater. The decrease in amplitude and lag with distance will be moderated by the hydraulic conductivity of the aquifer (Turner et al., 1996; van der Kamp, 2001).

The dampened tidal fluctuations observed are considered to be a result of interactions with the layer of silt, as this can impede the transmission of a tidal signal. A tidal signal would be transmitted through sand dominated sediment more easily (compared to silt dominated sediment) resulting in a larger amplitude of fluctuation being observed. The boreholes established in this study tend to be located within the shallow layer of silt covering much of South Dunedin, whereas the ORC boreholes extend through the silt layer to reach underlying sand.

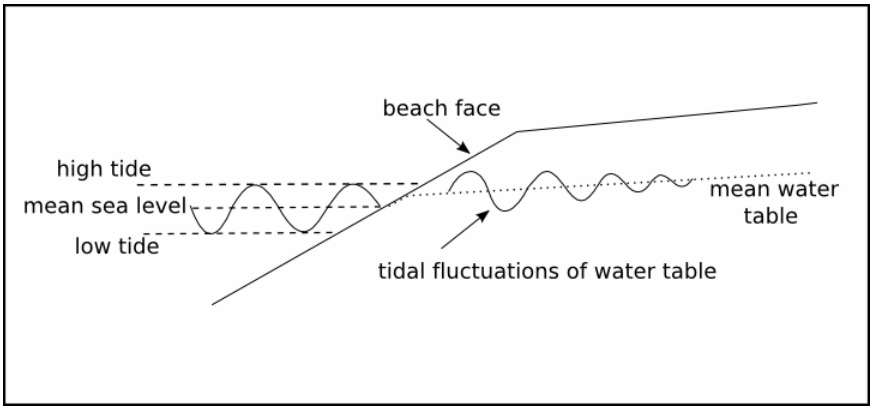


Figure 6.4: Diagram showing tidal fluctuations of groundwater in response to tidal movements at the ocean boundary

The dampened tidal fluctuations observed in this study are considered to be a result of the lower hydraulic conductivity and therefore supressed groundwater movement in this area. However, the possibility of the borehole design and construction having an effect remains. This possibility was investigated by comparing the groundwater movements in two boreholes at the East St site, one with a PVC pipe inserted and one without. The bare hole and the hole with the PVC pipe produced comparable hydrographs. This suggests that the PVC pipe design does not impeded groundwater movements and that the dampened tidal fluctuations are a feature of the environment rather than the equipment. There is some indication in the literature that the process of excavating a borehole can smear sediments along the walls of the hole leading to a reduced hydraulic conductivity, and that, to some extent, any method of excavating a borehole will disturb the aquifer material (Keller et al., 1989). In this sense some disruption is unavoidable. Nevertheless, in this study these factors are considered to be minimal and the results are considered to reflect the movements of the water table rather than occurring due to any effect of the borehole.

Response to rainfall

The influence of rainfall events is a major factor driving movements of the water table in South Dunedin. Groundwater hydrographs of water table elevation reflect the dynamic responses of the the aquifer to such climatic influences (Timms et al., 2001). The response to an individual rainfall event will appear as a temporary peak punctuating any longer-term trends in groundwater levels. The characteristics of the

peaks visible in hydrographs can provide insight into how the water table responds to rainfall (Winter et al., 2000).

This study found variation between sites in terms of their responses to rainfall. For example, the Tahuna Rd site exhibits a rapid response to rainfall, with the water table quickly reaching a peak after the onset of rainfall followed by a relatively rapid recession limb. In contrast, East St displays a slower, more prolonged response to rainfall. There is a larger lag between the onset of rainfall and the peak of the water table response, and the water table takes longer to recede. The differences between sites are considered to be driven by the differences in hydraulic conductivity of different sediments encountered at different sites. This has been observed in previous research such as de Marsily et al. (2005), Winter et al. (2000), and Fiori and Russo (2007), all of which reported differences in hydrographs over small spatial scales due to differences in geology and topography. Small scale spatial variation in hydraulic conductivity is considered to lead to small scale spatial variation in recharge and discharge as described by Cherry and Freeze (1999).

The observed differences in water table response between sites are considered to be driven by differences in hydraulic conductivity of sediments. Other factors that may influence how groundwater responds to rainfall include vegetation cover, evapotranspiration, and antecedent conditions. The characteristics of the rainfall (intensity, duration, depth) can also influence water table response. Differences between sites are visible when comparing the shape of groundwater hydrographs between sites and are confirmed further by the use of linear regression to characterise sites' reponses to rainfall. In this study, the responses of the different sites can be grouped into three main types of responses: rapid but short-lived responses (OMES and Hargest Cr); lagged and prolonged responses (East St and Market St); and reasonably rapid variable responses (Tahuna Rd, Annex St, Lochend St, Normanby Ave). Cluster analysis highlighted these groupings and it is noted that the rapid responses occur at the sand dominated sites, the lagged responses occur at the silt dominated sites and the sites with layers of sand and silt display variable responses. When plotted on a map the groups identified by cluster analysis form three zones in South Dunedin: rapid response in sand dominated sites close to the ocean, lagged response in silt dominated sites in the centre of South Dunedin, and, further away from the centre of South Dunedin, sites with layers of silt and sand with variable responses.

Sites with sand dominated sediment such as Hargest Cr and OMES display a rapid response. Where the water table responds quickly, water may also drain away from the water table quickly. If groundwater drains at a similar rate as the input from rainfall this could appear as no response at all. This may be an important factor controlling the threshold value for a water table response at sand dominated sites and may contribute to the smaller magnitude water table responses observed at sand dominated sites compared to silt dominated sites. For example, at East St, while the rate of water table rise is slow and lagged, the low hydraulic conductivity of the silt sediments may mean water does not drain away from the water table quickly, thus rainfall received is retained leading to a cumulative effect on the water table position. Conversely, it is also worth considering that the low hydraulic conductivity of these sites may also impede rainfall infiltration, as a result more overland flow may occur at these sites when rainfall arrives at the surface at a greater rate than infiltration allows. Sites with both sand and silt layers such as Annex St and Tahuna Rd exhibit the largest magnitude responses. It appears that, where there is a layer of sand above silt, the sand layer may promote infiltration of rainfall, while the silt layer ensures the received rainfall is retained.

A further difference in water table responses due to sediment is the threshold value, or the amount of rainfall required to elicit a response of the water table. Sand tends to retain less moisture than silt so in sand dominated sediments there may be more available pore spaces than need to be filled with water before saturation occurs and a water table response is observed. The shallower the water table before rainfall the smaller the distance infiltrating rainfall needs to travel before reaching the water table. This may mean that sites where the water table is closer to the surface have a smaller threshold value and the response may occur quicker. Where infiltrating rainfall has a greater distance to travel it may be lost to interception and storage in the unsaturated zone (figure 6.5).

It is worth noting that the Tahuna Road site has a particularly strong response. At this site sediment with a high sand content occurs above a silt layer, allowing rainfall to reach the water table quickly. In comparison, Lochend Street has a high sand layer under a silt layer. Since the arriving water would need to move through the silt layer before reaching the more permeable sand it does not display a response as strong as Tahuna Road.

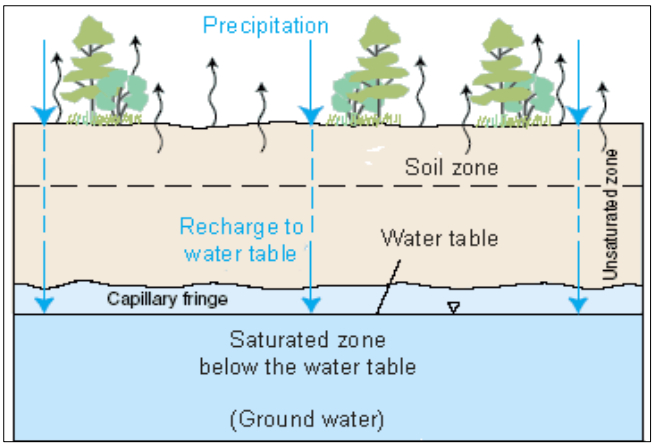


Figure 6.5: Diagram showing potential paths for water above and below the water table (source: USGS)

The silt layer means that when rainfall arrives at the surface it takes longer for water to percolate down through the substrate to the water table. Furthermore, once the water table becomes elevated it takes longer for the groundwater to drain away. The silt layer may be acting as an aquiclude and hence behaving differently to the lower levels of the aquifer. East Avenue takes the longest to return to initial water table level, followed by Market Street and Annex Street. All these sites have well developed silt layers. In contrast, OMES, followed by Hargest Crescent, are sites in sandy sediments and display the most rapid response and recovery.

Linear regression was used to characterise the relationship between rainfall and the water table response. This approach is described in the literature as a common approach in studies of water table responses to rainfall (Armstrong, 1988; Novakowski and Gillham, 1988; Park and Parker, 2008; van Gaalen et al., 2012; Viswanathan, 1983; Wu et al., 1996; Youngs et al., 1989). Linear trend lines are considered to represent the relationship between rainfall and the water table responses reasonably well, based on R^2 values ranging from 0.73 to 0.92 for the sites considered in this study. The variance that is not explained by fitted line may be related to factors such as antecedent conditions and differences in rainfall event characteristics data that contribute to deviation from a linear relationship.

The effect of antecedent conditions and differences in rainfall characteristics may lead to variation from the expected relationship (van Gaalen et al., 2012; Viswanathan, 1983). Differences in rainfall intensity are not considered in this study but are

acknowledged as having the potential to influence the shape of groundwater hydrographs. The same volume of rainfall arriving as a low intensity rainfall event over a long time period would be expected to produce a different table response than a high intensity event over a shorter time period. While low intensity events may produce a small water table response as rainfall may be lost to storage en route to the water table, high intensity events may lead to rainfall exceeding the infitration capacity of the soil and rainfall contributing to overland flow rather than reaching the water table. Medium intensity events could be expected to result in the largest water table rise. Over longer time periods, other factors influencing water table levels such as drainage and evapotranspiration may lead to complexity in water table responses (Healy and Cook, 2002; Ferdowsian et al., 2001). For this study other factors are assumed to be constant and the response of the water table attributed to rainfall.

Another example of the potential effect of antecedent conditions is high soil moisture: previous, recent rainfall may mean that the subsurface is already close to saturation and only a small input of rainfall is required to elicit a water table response (Jaber et al., 2006; O'Brien, 1982; Khaled et al., 2011). The importance of antecedent conditions is demonstrated in a study by Novakowski & Gillham (1988) which considers the role of the capillary fringe in water table responses. Novakowski & Gillham (1988) found that, where the capillary fringe extended from the water table to the surface, a small input of rainfall can result in a large rise in the water table. Soils that are able to retain moisture in pore spaces may exhibit a stronger response to rainfall as the soil is already closer to saturation. A further possibility is that soils that regularly become saturated may have higher moisture content than soils that only rarely find themselves below the water table. As a result, the response of the water table to rainfall may slow down as the water table approaches the surface. In this situation a linear trend line would not be appropriate. There is some evidence in the groundwater hydrographs of smaller responses occurring when the water table is already elevated. However a longer time series would be needed to tease out these effects. A study by van Gaalen et al. (2012) found that forecasting water table response to rainfall events could be significantly improved by considering antecedent water table level. The study also considered rainfall event size and duration.

A further factor that could result in a slowing down of the water table response to rainfall nearer to the surface is that groundwater flow patterns could change as the

water table rises. For example, as the water table becomes elevated, groundwater may be drawn towards drainage features that do not influence groundwater when the water table is lower. Thus further rainfall input may lead to an increase in discharge rather than a continuation of water table rise.

6.3 Implications for South Dunedin urban area

In South Dunedin, the response of the water table to rainfall is of interest mainly due to the shallow groundwater conditions in the area, which impart a vulnerability to groundwater flooding for the overlying urban area. This section considers, firstly, how the water table may respond to future heavy rainfall scenarios as an indication of the upper limits of the range of water table elevations that may be observed in South Dunedin over a long time scale (50 years). These responses of the water table to rainfall events are then considered in the context of changes in mean groundwater levels due to sea level rise. The importance of understanding water table dynamics in South Dunedin is emphasised by considering the potential for interactions between groundwater and the wastewater and stormwater pipe network.

Risk of groundwater flooding

Flooding is not a new risk for South Dunedin; for example in 1923 Dunedin received 22.9cm of rain in 24 hours (return period of over 150 years). Water was described as being waist deep, with the St Kilda area being worst affected (figure 6.6). The water then took many days to recede, which is probably a consequence of the low, flat topography of the area (ODT, 1923).

To consider the consequences of heavy rainfall events for South Dunedin, projected water table responses were added to the mean water table position at each site. This exercise sought to identify where the water table response to rainfall would result in groundwater reaching the surface causing groundwater flooding. For a 48 hour event of approximately 100mm of rain, which is considered a 1 in 10 year event, the water table is estimated to become elevated to the extent that it reaches the ground surface at 4 out of the 8 sites considered. The results of this study highlight the risk of groundwater

flooding, which is a topic that recent literature has drawn attention to as an underappreciated hazard (Kidmose et al., 2013; Hughes et al., 2011; Bjerklie et al., 2012; Rotzoll & Fletcher, 2012; Pinault et al., 2005). Locations with shallow groundwater conditions, flat topography and urban land uses are considered particularly vulnerable to groundwater level rise and flooding problems (Macdonald et al., 2012; Chebud & Melesse, 2011; Upton and Jackson, 2011; Kreibich et al., 2009).



Figure 6.6: Picture of Normanby St from 23/04/1923 showing flooding after 22.9cm of rain fell over 24 hours (source: ODT, 1923)

When considering where groundwater flooding may occur there are two main factors that need to be considered: the starting position of the water table and the magnitude of water table response to rainfall. For sites where the water table is particularly shallow, i.e. around the centre of South Dunedin, even a small response to rainfall can bring the water table to the surface. For example, East St, a silt dominated site where the water table is shallowest, is projected to experience groundwater flooding for rainfall events with a 5 year return period or more. The other sites projected to experience similarly high incidences of groundwater flooding are Tahuna Rd and Annex St. For these sites the initial water table level is further below the surface than at East St, but their

particularly strong responses to rainfall, due to sand overlying silt, are responsible for bringing the water table to the surface.

The complexity and spatial variability in the water table response to rainfall in South Dunedin makes it difficult to generalise how the water table may respond in the future. When attempting to project water table positions for future scenarios aquifer heterogeneity needs to be considered. In this study three broad groups were identified to characterise aquifer heterogeneity. These groups could be used to describe the risk of groundwater flooding in response to rainfall in the different parts of South Dunedin. Alternatively, if the sediment profile at a site is known the likely response to rainfall could be estimated. The mean water table responses for each group are presented in table 5.8, which allows an approximate water table response to rainfall to be estimated based on knowledge of the substrate alone. However, there is significant uncertainty involved, including uncertainty in the rainfall/response relationship and uncertainty arising through the grouping of sites. Assumptions that are of particular note in these results are that the water table response is added to the mean water table position, thus the possibility of the water table being already elevated due to recent rainfall is not included. A further assumption is the linear relationship between rainfall and the water table response. Considering that there are a number of factors that may contribute to the water table responding differently closer to the surface, which have been discussed in section 2.2, this assumption may not be accurate. Overall, some assumptions are necessary and the results are considered to give a good indication of how the water table may respond to future events. However, the reader is directed to the 95% confidence intervals provided in table 5.7 for a representation of the uncertainty involved.

The emphasis in this research is on understanding the range of groundwater levels that may be observed in South Dunedin; this is a response to a perceived gap in knowledge. When considering the risk of groundwater flooding occurring in South Dunedin it is not necessarily when the mean water table elevation is estimated to reach the surface that is the most important information for decision makers involved in planning for the South Dunedin urban area. This is because there is significant temporal variability around the mean groundwater level, in response to climatic factors such as rainfall. Therefore, how the likelihood of groundwater flooding changes as the mean water table position becomes elevated may be a useful way of conveying information about the risk of

groundwater flooding for South Dunedin. This necessitates an understanding of temporary, short-term variability in the groundwater system as well as an understanding of long term gradual changes in mean groundwater levels.

Few studies have characterised the variability in groundwater levels when considering the impacts of climate change on groundwater. Usually, it is the mean groundwater position that is represented (Rekker, 2012; Rotzol & Fletcher, 2012; Oude Essink et al., 2010; Rotzell & Wong, 2010). This thesis is differentiated from these studies by the consideration of the variability of groundwater levels. A further example of the relevance of variability of groundwater levels is provided by a study by Kidmose et al., (2013), which attempts to estimate extremes of groundwater levels under climate change scenarios by applying the concept of extreme value analysis. This approach requires a long data set, and therefore was not an option for the current study, as monitoring of South Dunedin groundwater levels is a relatively recent development. However, it is interesting to note attempts to forecast the maximum groundwater levels in response to rainfall events. This acknowledges variability of groundwater levels, the risk of groundwater flooding and the need to consider how climate change may increase such flooding occurrences in the future.

For South Dunedin the ORC has provided information about the projected response of the mean water table position due to gradual forcing from sea level rise up to 2100. When both sea level rise and the impact of rainfall events are considered together the two factors combine leading to a higher proportion of sites being expected to experience groundwater flooding than if either sea level rise or rainfall events were considered alone. Under current climate conditions a one in five year rainfall event is estimated to result in groundwater flooding occurring at some South Dunedin sites (38% of monitoring sites). When the effect of a 0.1m rise in sea level is included, a one in two year rainfall event is estimated to result in the same proportion of sites experiencing groundwater flooding. Thus an effect of sea level rise for South Dunedin is an increase in the probability of groundwater flooding occurring in response to rainfall events. Elevated groundwater levels due to sea level rise would augment the effects of natural variability in groundwater levels on the overlying urban area. The pattern here is that when the effects of sea level rise are considered in combination with the effects of rainfall events, the average return interval for rainfall events required to

elicit groundwater flooding is lower than if these factors are considered in isolation. Their interaction exacerbates the problems they pose for the urban area above.

While studies considering potential interactions between climate change pathways are rare, a good example is a study by Bjerklie et al, (2012) which considers the impact of sea level and changes in groundwater recharge driven by increases in rainfall. They concluded that groundwater levels in New Haven, Connecticut, could be expected to rise due to sea level rise and may rise higher if groundwater recharge also increases. Similarly, Bouraoui et al., (1999) considers both rainfall and potential evapotranspiration as important variables for groundwater recharge and applied a CO2 doubling scenario to a local weather generator to consider how these variables, and therefore, groundwater recharge, could be affected by climate change.

When considering how the water table in South Dunedin may respond to future rainfall events it is noted that the temporal distribution of heavy rainfall events is expected to change in the future due to climate change. By considering how the water table may respond to 2-50 average return interval rainfall events this study aims to represent the upper limits of the range of groundwater levels that may occur under current climate conditions. However one of the most consistent predictions of impacts associated with climate change is that the frequency and intensity of extreme events may increase (Dore, 2005; IPCC, 2007; IPCC, 2013). HIRDS is able to provide an indication of the rainfall depths estimated under various climate change scenarios for South Dunedin. A 1 in 10 year rainfall event is currently estimated as approximately 100mm of rain over a 48 hour period. Under a climate change scenario of 2 ^{o}C of warming by 2090 a 1 in 10 year rainfall event could become 113mm of rain over 48 hours. Any increase in rainfall depth could be expected to lead to an increase in the water table response. Thus, there may be further interactions between climate change impacts to consider that are not considered in the results of this thesis. Other avenues of potential climate change impacts include changes in recharge due to changes in evapotranspiration, changes in seasonal timing of rainfall, and changes in total rainfall received. Studies indicate it can be timing of rainfall that influences recharge more than amount (Stoll et al., 2011; Green et al., 2011). Sea level rise may also influence saline intrusion and groundwater discharge to the coast as well as the position of the water table (Nuttle & Portnoy, 1992; Werner and Simmons, 2009; Melloul & Collin 2006; Masterson & Garabedian, 2007; Shrivastava, 1998; Rozell and Wong, 2010).

A final consideration relating to the risk of groundwater flooding for South Dunedin is that the presence of a silt layer, which can impede infiltration of rainfall, may lead to surface ponding before the impact of rising groundwater levels causes flooding. When rainfall occurs at faster rate than infiltration can occur, surface ponding may result. In most catchments this produces surface runoff. However, due to the low-lying, flat nature of South Dunedin, water may instead remain in small depressions. For example Bathgate Park and Tonga Park are prone to surface ponding after heavy prolonged rainfall. Figure 6.7 is an image taken at Bathgate Park on 16th August 2012 after 73.8mm of rain fell over a 4 day period. This surface ponding this does not necessarily demonstrate groundwater flooding as a result of rainfall but perhaps rather a lack of infiltration or runoff. Thus surface flooding may not occur due to groundwater flooding alone; other processes may interact with groundwater flooding, exacerbating surface flooding.



Figure 6.7: Photo of Bathgate Park taken 16/08/12 demonstrating surface ponding after heavy prolonged rainfall

Interactions with wastewater and stormwater pipes

As the water table in South Dunedin sits within a metre of the ground surface both the stormwater and wastewater pipe networks (which are buried below 1m, with wastewater pipes sitting below stormwater pipes) will be interacting with groundwater. Where groundwater surrounds pipes there is the potential for groundwater to infiltrate or enter the pipe network through broken or porous pipes and joints (Mein and Apostolidis, 1992). As the pipe systems age, infiltration becomes more likely (Heywood, 1997).

At the Botha St site there is an indication that groundwater may be infiltrating into the wastewater pipe network and that this occurs at an increased rate after rainfall events. Elevated flows are observed after rainfall events but the increase in wastewater flow does not occur immediately after rainfall; rather it takes approximately 2 days to occur, which coincides with the time it takes for the water table to reach peak elevation after the rainfall event. The timing of the response to rainfall observed in the wastewater pipes appears to be more closely linked to groundwater elevations than to rainfall, indicating the increased loads may be the result of groundwater infiltration. There may be other pathways for rainfall to reach the wastewater pipe network such as incorrect joins between stormwater and wastewater pipe networks but this could be expected to display a response more closely aligned to the timing of the rainfall event. However, the flow volumes in the wastewater pipes return near normal levels while the groundwater level remains elevated.

It is interesting to note the ages of pipes around these monitoring sites. At Botha Street the pipes were installed between 1921 and 1940 and the pipes in the surrounding blocks are of the same age, apart from Lochend Street which has pipes dating from between 1901 and 1920. At East Avenue pipes were installed 1941-1960 at the South end, and 1961-1980 at the North end of the street. In the surrounding area pipes were installed 1961-2010, apart from Hargest Crescent where they were installed 1901-1920 (URS, 2011). The pipe material used is a further factor; older pipes may consist of short lengths of earthenware pipes for which there are known issues at joints. Joints may have been sealed, when pipes were laid, with products including concrete, coal tar, rubber, or with nothing at all. Over time these sealants can erode away and off-sets and leaks may develop.

While it is difficult to quantify the amount of infiltration occurring into both the stormwater and wastewater pipe network, the presence of flow in the stormwater pipe network when there has been no recent rainfall can be used as an indication. The Portobello Road Pumping Station discharges stormwater from South Dunedin to the Otago Harbour and has a baseline discharge of approximately 430m^3/day. Modelling of the South Dunedin aquifer by the ORC came to a value of 2275m^3/day of groundwater drained from the aquifer via the pipe network. This could be used as an indication of the amount of groundwater currently infiltrating into the stormwater pipe network. Groundwater infiltration is inherently difficult to quantify. The volume of infiltration will be related to the length and depth of pipes as well as hydrological characteristics of the soil, pipe materials, age, and corrosion (Karpf and Krebs, 2004). It can occur anywhere along the length of the pipe, although particularly at joins, and without direct observation it is difficult to know the nature and location of infiltration (Semandeni-Davis, 2004). A study by Ellis (2001) reported infiltration ranging from between 0.01 to 1m^3/day/mm pipe diameter/km length and increasing proportionally to the age of the wastewater pipes.

Previous studies have represented infiltration as a fixed component of total discharge (Mein & Apostolidis, 1992); however, this does not include consideration of how movements of the water table could result in variable rates of infiltration rather than a constant rate. Hernebring (1998) and Semandeni-Davis (1998) related infiltration to groundwater recharge and soil moisture respectively to try to include this. A study by Ellis (2001) emphasises the importance of increased infiltration occurring after rainfall; this is described as rainfall induced infiltration to differentiate from constant background rates of infiltration. This emphasises that basing estimates of infiltration based on dry weather conditions may not capture the full extent of infiltration occurring.

An important consequence of groundwater infiltration into the wastewater pipe network is that it will contribute to the load that needs to be processed by the Tahuna Wastewater Treatment Plant. At present a planned upgrade to secondary treatment is hindered by influxes of saline water in the wastewater pipe system. Infiltrating groundwater is considered a potential source of saline water and pipe repairs targeting the oldest pipes first are planned for South Dunedin. If all aged pipes were repaired the volume of groundwater currently removed from the aquifer would remain in storage,

potentially resulting in a higher groundwater level. In Dresden, Germany, the sewer and wastewater networks are considered to serve a drainage function, particularly during and after rainfall events. This drainage is shown to diminish the problems of rising groundwater levels, and after a flood event the drainage provided by pipe networks can contribute to lowering high groundwater levels that remain after flooding (Karpf & Krebs, 2004). Understanding the drainage effect of pipe networks on groundwater during and after rainfall events may be important when planning pipe repairs and rehabilitation in South Dunedin so that the indirect consequences, such as higher groundwater levels, are taken into account.

6.4 Wider implications

This thesis explores the South Dunedin aquifer as a case study of a shallow coastal aquifer with an overlying urban area. As well as having implication for South Dunedin, the insights gained in this research have a wider applicability. Firstly, other coastal cities with low, flat topography and shallow groundwater conditions may face similar challenges as South Dunedin (McGranahan et al., 2007). Extensive areas of the Netherlands and Belgium are situated below sea level and may be some of the first areas to experience impacts due to sea level rise (Vandenbohede et al., 2008; Oude Essink et al., 2010). River deltas may also experience similar issues as another example of a shallow groundwater environment, here changes in river flows, sea levels and groundwater levels may all interact (Barlow, 2003; Bjerklie, 2012; Bondesan, 2000) But, in a broader sense, there are implications for the way shallow groundwater systems are investigated, particularly when considering how the system may respond to climate change. Urban environments present further complexity and changes in hydrological systems can have important implications for planning (Olsson et al., 2009; Willems, et al., 2012). This section discusses the wider implications of this research which relate to the representation of variability, both spatial and temporal, and the potential for interactions between different parts of a groundwater system. A key focus is that an understanding of the inherent variability of a system is essential when considering how the system may respond to future stressors such as climate change.

Aquifer heterogeneity

The scale on which hydraulic conductivity is measured and represented can have a significant influence on the results of groundwater studies (de Marsily et al., 2005). Considering hydraulic conductivity on large spatial scales can overlook important heterogeneity that may be valuable in the interpretation of results (Woolhiser et al., 1996). The geology of an area is an important factor controlling the sensitivity of water levels to changes in climatic variables, such as rainfall (Winter et al., 2000). As a consequence areas of different geological make up can be expected to display differing responses (Weider, 2011). Thus including enough detail about heterogeneity of aquifer geology is important when attempting to understand groundwater movements (Fiori and Russo, 2007). For South Dunedin, the aquifer geology has been previously presented as sand deposits, but for this research, it is only in light of the presence of a layer of silt that differences between sites, in terms of their response to rainfall, can be understood. A study by van Roosmalen et al., (2007) has stressed the role of geology in controlling the magnitude of groundwater response to climate change. They found that an unconfined aquifer with sandy top soils displayed higher groundwater levels in response to a climate change scenario involving an increase in recharge, due to an increase in rainfall. Conversely, an aquifer with low permeability soils near the surface displayed only minor changes in groundwater levels under the same scenario (van Roosmalen et al., 2007). However, it is neither reasonable, nor feasible, to sample to the extent required to represent an aquifer exactly. What is needed is enough detail to allow the interpretation of groundwater movements. Thus the spatial scale that is appropriate will be governed by the scale at which the processes of interest operate (Mitchell et al., 2001; Seyfried and Wilcox, 1995).

Considering interactions

Climate change will not affect each component of the water balance in isolation, thus studying isolated aspects of a system may miss important interactions (Scibek and Allen, 2006). There are multiple pathways by which climate change may influence groundwater levels; for example, sea level rise, changes in evapotranspiration, and changes in rainfall patterns (Earman and Dettinger, 2011; Taylor et al., 2013; Oude

Essink et al., 2010). The effects of these multiple pathways may interact and combine, producing exacerbated impacts to groundwater (Willems et al., 2012; Holman, 2006).

The position of the water table at any point in time represents the interactions of different processes. When projecting how the water table may respond to climate change the potential for interactions between different stimuli needs to be taken into account. The example highlighted in this research is that the effects of sea level rise may be compounded by the effects of rainfall events. This is also acknowledged in a study by Rotzoll & Fletcher (2012) which focuses on the risk of groundwater flooding in response to sea level rise. They note that flooding would start sporadically and be especially intense seasonally when high tide coincides with rainfall events. However, the results of this study, along with most studies projecting the response of the water table under climate change scenarios, are presented in terms of changes in the position of the mean groundwater level. By representing the expected variability around a mean groundwater level, instead of simply a mean value, a more detailed picture of the risk of flooding could be provided.

A further consideration is that changes induced by climate change may occur in parallel with societal changes (Willems et al., 2012). Holman (2012) emphasises the role of policy, societal values and economic processes in shaping landscapes above aquifers. This becomes particularly important when changes in groundwater levels can interact with people. Where groundwater is used as a source of drinking or irrigation water there may be complex interactions between climate change and demand for groundwater. Any reduction in groundwater recharge may impact people relying on groundwater sources. Even where groundwater is not currently utilised (or heavily utilised) as a source of water, if climate change reduces surface water flow volumes there may be an increased reliance on groundwater resources in the future (Taylor et al., 2012). These societal factors may have important implications and should be taken into consideration when modelling the effects of climate change on groundwater. This calls for a multi-disciplinary approach to understanding groundwater and climate change.

In this research, the interactions between rising groundwater levels and urban infrastructure have been considered. This acknowledges that climate change could impact not just the natural environment but the built environment too. The IPCC has identified the vulnerability of human systems to climate change as a priority area where

research is needed (IPCC, 2007). A warmer climate has serious implications for urban drainage. Interactions between groundwater, and urban infrastructure such as water supply pipes, and sewer and wastewater pipe networks are poorly understood (Semandeni-Davis, 2004; Mitchell et al., 2001). Rising groundwater levels may have implications for stormwater management practices which promote directing collected stormwater to the ground. This practice has expanded recently and is promoted as a low-impact stormwater design aimed at slowing runoff by directing it towards soakways where infiltration can occur. A study by Randall et al. (2013) modelled the combined impact of increased recharge due to climate change and widespread instalment of stormwater infiltration infrastructure finding that stormwater infiltration practices can amplify problems associated with climate change. This study is unusual of its examination of potential interactions between management practices and changes in climate. While groundwater research focused on one particular process can be valuable by improving our understanding of that process, there is also a need to consider potential interactions with society and climate through integrated studies.

Understanding inherent variability of groundwater levels

Shallow aquifers are particularly dynamic groundwater systems, displaying considerable and constant fluctuations of the water table in response to climatic stimuli. High frequency water level data is required to capture this variability. However, this is rarely prioritised in groundwater monitoring. In general, groundwater levels are represented as mean levels, some seasonal trends may be captured with infrequent water level monitoring but the movements of the water table in response to individual rainfall events would not be appreciated. Where there are potenital interactions with an overlying urban area, the variability of groundwater levels may be an important aspect of groundwater behaviour with implications for groundwater flooding and interactions with underground infrastructure.

Given the importance of both spatial and temporal variability, the choice of scale is critical for both. In terms of temporal scale, Sophocleous (2012) suggests that the response time of an aquifer to a stimulus could guide the time scale considered. Response times, or time taken to adjust to a new equilibrium, can range from seconds to millions of years for groundwater (Sophocleous, 2012). This is an important concept for groundwater management as it is important to have an idea of when the impacts of a

change may become visible (and measurable). Due to the long residence time of groundwater there can be a long lag between a change and a response. For example a change in land use may alter the perviousness of a catchment, which may reduce recharge; however, this may not express itself as a reduction in discharge and lower groundwater levels for many years (Sophocleous, 2012).

Identifying an appropriate temporal scale may be straightforward when one type of stimulus or process is considered, but when the potential for interactions between different stimuli is considered there can be multiple time scales involved. For example, when considering the effect of sea level rise, sea level rise itself will occur gradually, and then the water table may take years to adjust to a new base level. At the same time as gradual adjustments to a new base level there will be short term variation of the water table in response to rainfall. It is important to consider how this variability may interact with changes in mean groundwater levels.

When attempting to capture the inherent variability of groundwater levels it is not simply the aquifer response time that needs to be considered. The longer the time period considered the more variation that can be captured. This relates to the probability distribution of extreme events. By considering the variability in groundwater levels over longer and longer time periods we can expect to encounter events with lower probabilities of i.e. more extreme events. In this study extreme rainfall events are considered as they can indicate the maximum groundwater levels that could occur. By considering rainfall events with longer return intervals e.g. 50 year and 100 year events it provides an indication of the variation in groundwater levels that may occur over longer and longer time scales even though the aquifer response to each rainfall event occurs over a period of days.

There can be short term variability embedded within longer term variability. For example, variation in groundwater levels has been linked to cyclic climate patterns such as the Pacific Decadal Oscillation, North American Monsoon and El Nino Southern Oscillation (Hanson et al., 2006; Weider, 2011). This variability can occur in parallel with trends representing more permanent changes in mean water table positions, for example, in response to a rise in sea level. Research considering how groundwater may be affected by climate change tends to fall into the category of considering long-term, gradual and permanent trends. However, when considering a long term trends in mean

groundwater level, an appreciation of the variability that will occur around this mean due to temporary fluctuations of the water table is also important. Particularly in situations where groundwater flooding is a possibility, information for decision makers about trends in mean groundwater levels could be enhanced by representing potential variability around the mean (Reichert and Borsuk, 2005). This recognises that groundwater levels are not static, but rather are in a constant state of flux (Shamsudduha et al., 2009; Kumar and Ahmed, 2003). As with any system expressing variation due to climatic stimuli, there will be different ranges of variation over different time scales and extreme events can be considered to represent the limits of variability (Hanson et al., 2006). For groundwater systems displaying responses to rainfall events, a consideration of potential responses to extreme rainfall events can provide information about the occurrence of extreme groundwater levels (Bichler and Furst, 2012). Extreme value analysis is regularly applied to rainfall and river flow data, but has not been widely used in groundwater hydrology. For areas where groundwater flooding is a risk, extreme value analysis could provide a tool for investigating the probability of groundwater flooding in response to rainfall events (Bichler and Furst, 2012; Kidmose et al., 2013).

For climate change impact assessment studies on hydrological systems a representation of the natural variability that occurs is often overlooked, predicted effects of climate change are presented as changes in mean conditions (Arnell, 2003). Yet the natural variability of hydrological systems may have important implications. Furthermore, when looking to observe impacts of climate change, we need to be able to separate natural variability in order to identify and correctly attribute any trends to climate change (Liu et al., 2013; Hulme et al., 1999). In the future, climate change impact studies could benefit from a greater appreciation of the natural variability of hydrological systems.

6.5 Limitations

When considering the results presented here an awareness of the limitations of the research is required. These limitations relate to data shortages, assumptions made, and sources of error, all contributing to uncertainty. There is still much to discover about the South Dunedin Aquifer. At present, estimates of hydraulic conductivity for the

aquifer vary significantly. Previously, the tidal method was used by the ORC to estimate hydraulic conductivity for the South Dunedin aquifer. For this study slug tests were used to provide hydraulic conductivity estimates. The estimates from these different methods vary by orders of magnitude; which may be related to the different methods used, and the different scale that the estimates relate to. A key aspect of the results is the spatial distribution with lower hydraulic conductivity estimates associated with silt dominated sediments, compared to higher estimates associated with sand dominated sediments.

The groundwater monitoring network established for this research was designed for short term use. Establishing permanent boreholes such as those installed by the ORC was neither possible nor suitable for this research. By establishing boreholes by hand more sites, covering a greater area of South Dunedin, could be included in this study. However, the use of a hand auger, rather than a drilling rig, limited the depth of boreholes to approximately 3m. This presented difficulties comparing results with ORC data which was from deeper boreholes reaching a depth of 6m. Information from historic borelogs have been used to supplement information about the South Dunedin Aquifer, but overall there is a shortage of borelog data, partly due to the loss of historic borelog records.

The possibility of the method of pipe construction influencing the water table elevation data was explored by comparing data from a borehole with a PVC pipe inserted to data from a hole with no pipe; the results suggested the influence of the pipe was negligible. It is also possible for the pipe and mesh covering to become clotted with fine sediment over time and lose responsiveness; however, there does not appear to be a trend of dampening in water table response over time in the data. At two sites (Richardson Rd and Cavell St) unusual signals were noted occurring part way through the monitoring period. These sites are considered compromised, possibly due to the pipe becoming blocked, and data has been excluded from analysis. Instrumentation error should also be acknowledged; this is indicated by the ‘noise’ in the water level signal as identified by classical decomposition of groundwater level movements.

A focus of this study has been capturing the variability in the position of the water table. While a year, or multiple years, of monitoring would be preferable, the timeframe available in this study was limited. A 6 month monitoring period from July 2012 to

January 2013 has provided the data used in this thesis. Although a 6 month period does not cover all four seasons that characterise Dunedin city's annual climate cycle, it should be noted that the city does not have a distinct seasonal pattern of rainfall. The 6 months included in this study are considered to represent the variability occurring within a year reasonably well. In 2012, over a full 12 months, there were 46 rainfall events (48 hour) with rainfall depths of 5mm or more. Of these, 22 were captured within the monitoring period, and of the four largest rainfall events, two occurred within the monitoring period. Whether 2012 is representative of a longer time period is a more complex question. The longer the time scale considered, the more variability that may be captured, as indicated by the maximum rainfall events estimated for a 5 year return interval, compared to a 50 year return interval.

This research study relies on extrapolation based on the relationship between rainfall and the water table response established from the 6 month monitoring period. The assumption involved in this scaling up is that the same processes operate, and groundwater will behave in a similar fashion, in response to each millimetre of rainfall that arrives at the surface. In reality this may not be the case; there are complexities in the rainfall/water table response relationship that are likely to lead to deviations from a linear relationship. The behaviour of the water table as it approaches the surface is not well understood and the influence of antecedent conditions may alter how the water table responds to rainfall.

The response when the water table is already elevated tends to be smaller compared to a response when the water table has recovered back to its initial level. This may be related to the presence of a capillary fringe, an area above the water table where water is held in pores through tension. This means that pore spaces are already partially filled with water and thus it requires a smaller contribution of water to become saturated. Also pores in the subsurface that periodically become saturated may retain water. In general water content in the subsurface decreases with distance above the water table. This may result in a greater contribution of water infiltrating from rainfall being required to lift the water table as it approaches the surface. In this case a linear relationship could overestimate the water table rise as the water table nears the surface.

Another assumption involved in the relationship between rainfall and the water table response is that other factors influencing the position of the water table are negligible.

Over short time scales, such as those involved in responses to rainfall events, this is generally considered reasonable and the role of tidal fluctuations has been accounted for. Thus this assumption is considered appropriate for this study. However the drainage role of the stormwater and wastewater pipe network is poorly understood, in particular during and after rainfall events.

There is uncertainty introduced by the use of estimates of future rainfall events and the response of the water table, to both rainfall and sea level rise. This study combines estimates of groundwater response to sea level rise (as presented by the ORC), with rainfall estimates from NIWA's HIRDS and with the relationship between rainfall and water table response established in this study. Each of these carries uncertainty with it. Projections of rainfall are highly uncertain and this uncertainty is augmented when rainfall extremes are considered because the properties of low probability events do not follow those of average rainfall events. Uncertainty associated with the response of the water table to rainfall is even larger when a mean water table response is presented, as is the case in this study, when considering the combined effect of both sea level rise and rainfall events. As there is significant uncertainty involved, this research cannot provide definitive forecasts of water table levels. The combination of the effects of sea level rise and rainfall is undertaken with the intention of demonstrating the capacity for interactions in the groundwater system.

6.6 Future research directions

As is the case with many studies, this research effort towards understanding the South Dunedin aquifer raises more questions than answers. The South Dunedin Aquifer requires further investigation to improve current knowledge of groundwater dynamics. Further modelling of the South Dunedin aquifer with greater data inputs could help clarify groundwater dynamics. For this study, time limitations have restricted the range of the objectives to a general investigation of the aquifer. Further groundwater modelling would be a useful way to consider how the aquifer may respond to future scenarios. Hydraulic conductivity is a crucial variable when modelling groundwater flow; at present, different methods have produced varying estimates. A pump test could be used to constrain estimates for the South Dunedin Aquifer.

Current understanding of the nature of the relationship between rainfall and groundwater levels in South Dunedin is limited. Long-term groundwater level data would help reduce the uncertainty involved in the rainfall/water table response relationship presented in this thesis. There is also the potential to consider the role of antecedent conditions and rainfall intensity in water table responses to provide further insight into the relationship between rainfall and groundwater levels. This thesis also presents an initial investigation into wastewater/stormwater and groundwater interactions but further research would help clarify interactions between groundwater and the pipe networks in South Dunedin. Further monitoring could help identify areas where infiltration of groundwater is occurring and how the elevation of the water table influences this. As a starting point areas of South Dunedin with the highest water table and prolonged responses to rainfall, coinciding with areas where the pipe network is oldest, could be considered.

Future research could also consider how the distribution of extreme rainfall events may be impacted by climate change and how this may impact groundwater levels. An increase in the frequency and severity of extreme events is widely projected as an impact associated with a warmer climate (IPCC, 2007; IPCC, 2013; Willems et al., 2012). Any increase in rainfall could be expected to lead to an increase in the water table response, thus there may be further interactions between climate change impacts to consider. This is not considered in the results of this thesis, however this could be a next step in considering how climate change may affect groundwater in South Dunedin. Likewise changes in mean rainfall and evaporation may occur with climate change and could be included in a broader view of the potential impacts of climate change on groundwater in South Dunedin.

7 Conclusions

Shallow, coastal aquifers are dynamic systems influenced by both terrestrial and marine processes. For these groundwater systems, there can be significant temporal variability in the position of the water table, particularly in response to rainfall events. This may have consequences where shallow aquifers are situated beneath urban areas, as groundwater may interact with the built environment, especially underground infrastructure. This research explores variability in the position of the water table beneath the South Dunedin urban area as a case study of a shallow, coastal aquifer.

This research involved groundwater monitoring at 10 sites across South Dunedin over 6 months in 2012. High frequency groundwater monitoring has provided not only a picture of mean groundwater levels across South Dunedin aquifer, but also of the temporal variability in the position of the water table. Rainfall events exert a major influence on groundwater levels. By establishing a relationship between rainfall and water table responses, the influence of rainfall events on groundwater levels can be characterised for sites in South Dunedin.

The water table response to rainfall displays spatial variability across the South Dunedin aquifer. This variability has been linked to differences in sediment encountered between sites, and consequently differences in hydraulic conductivity. A shallow layer of silt was found across South Dunedin with the deepest extent occurring around the centre of South Dunedin. Slug tests estimate low hydraulic conductivity values (0.0015 - 0.0059m/day) at sites with silt dominated sediment, around the centre of South Dunedin, where the silt layer is deepest. Whereas sites with sand dominated sediments, on sand dunes along the coast and around Saint Clair, obtained higher hydraulic conductivity estimates (2.2 - 10m/day). At silt dominated sites the water table response to rainfall can be characterised as lagged and prolonged. In contrast, at sand dominated sites the water table both responds and recovers quickly after rainfall. Sites where there is sand overlying silt display particularly strong and rapid responses to rainfall. It is suggested that the layer of silt impedes groundwater movements, the infiltration of rainfall towards the water table, and drainage of groundwater after rainfall.

To explore a wider range of groundwater levels that may occur, responses to extreme rainfall events with return periods of 2, 5, 10 and 50 years are extrapolated based on a linear regression relationship between rainfall and the water table response. This indicates that there is the potential for groundwater flooding to occur for rainfall events with 5 year return periods and more. The sites that are at greatest risk are sites where the water table is already within 0.5m of the ground surface, and sites where there are layers of sand overlying silt resulting in a rapid and strong response to rainfall. When the response to extreme rainfall events is considered in combination with projections of elevated groundwater levels due to sea level rise the risk of groundwater flooding in South Dunedin is exacerbated.

Under current climate conditions a one in five year rainfall event is estimated to result in groundwater flooding occurring at some South Dunedin sites (38% of monitoring sites). When the effect of a 0.1m rise in sea level is included, a one in two year rainfall event is estimated to result in the same proportion of sites experiencing groundwater flooding. Thus an effect of sea level rise for South Dunedin is an increase in the probability of groundwater flooding occurring in response to rainfall events. Elevated groundwater levels due to sea level rise would augment the effects of natural variability in groundwater levels on the overlying urban area. The pattern here is that when the effects of sea level rise are considered in combination with the effects of rainfall events, the average return interval for rainfall events required to elicit groundwater flooding is lower than if these factors are considered in isolation. Their interaction exacerbates the problems they pose for the urban area above. For coastal areas with shallow groundwater conditions, sea level rise alone may take many years to cause groundwater flooding, but before the mean groundwater level reaches the surface the area may experience more and more frequent groundwater flooding as the water table reaches the surface more often in response to rainfall events.

In addition to the risk of groundwater flooding the behaviour of the water table is of interest as groundwater in South Dunedin, and other similarly situated cities, can interact with the wastewater pipe network potentially infiltrating into the pipe network through weaknesses such as broken or porous pipes and joins. The position of the water table may influence the amount of infiltration occurring as a higher water table could exert greater pressure around pipes thus forcing greater infiltration. Flow monitoring indicates sewage pipe flow volumes are correlated with water table elevations,

indicating groundwater may be infiltrating into the pipe network, and doing so at an increased rate when the water table is elevated in response to rainfall. To some extent it is an intuitive idea that rainfall events can lead to elevated groundwater levels and that this may become more problematic for shallow urban aquifers where climate change impacts also lead to elevated groundwater levels. However this thesis presents a quantification of the potential interactions between factors showing their combined effects.

This research is an example of the important role that variability can play in groundwater studies. By presenting water table elevations as a mean level, the natural variability in groundwater levels is masked. Both spatial and temporal variability of groundwater levels can be important to represent. Climate change impact studies often present effects on groundwater levels due to climate change as gradual changes in mean levels. This research shows that natural variability may interact with trends due to climate change. For example, in South Dunedin sea level rise may lead to an elevation of mean groundwater levels, and when the effects of rainfall events is superimposed on top of this, the risk of flooding is augmented. Thus potential interactions between different processes influencing groundwater levels are important to consider in groundwater studies, as is the capacity for groundwater to interact with society and the built environment in urban settings.

Appendix A

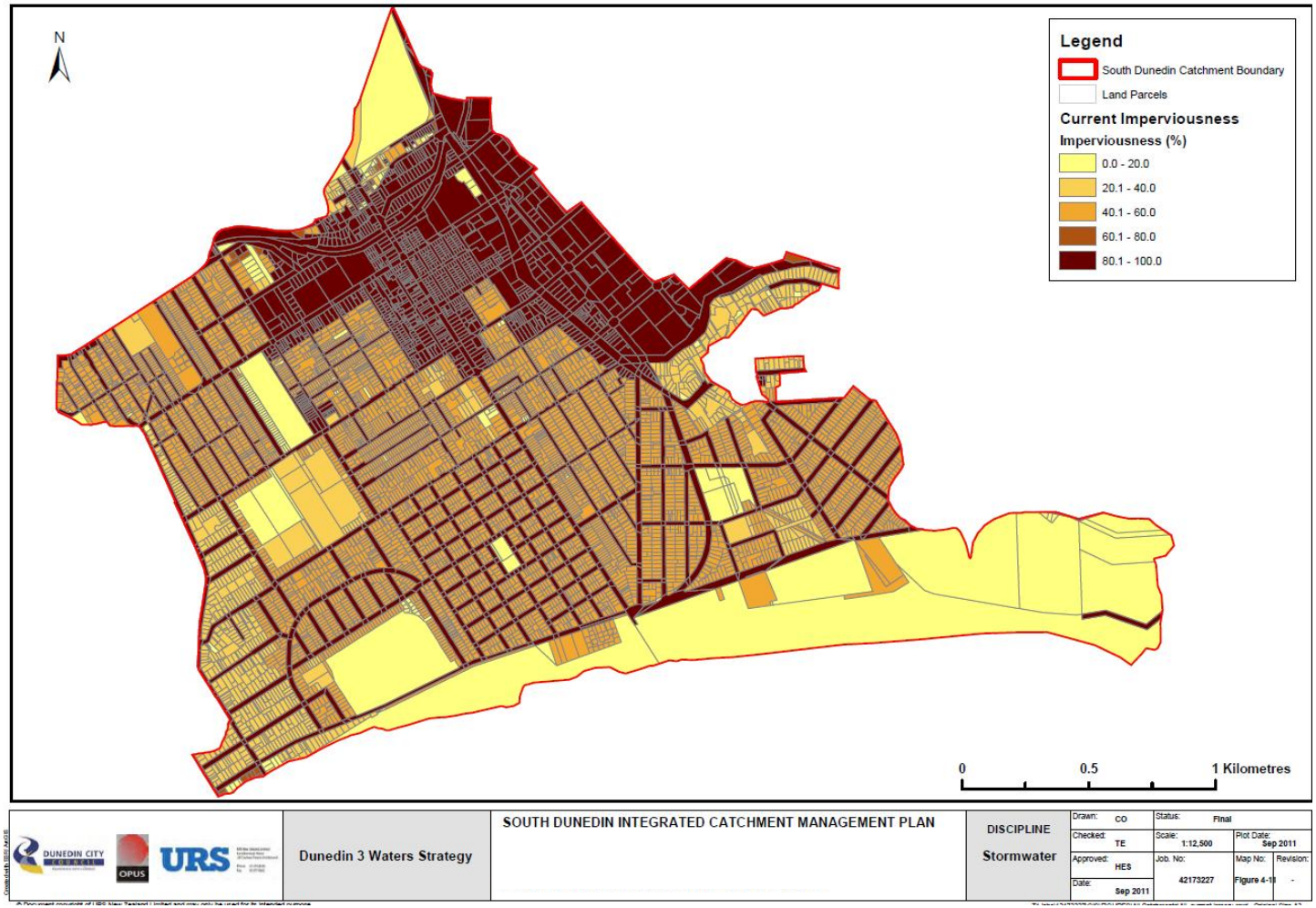


Figure A.1 South Dunedin Catchment Imperviousness, source (DCC, 2011)

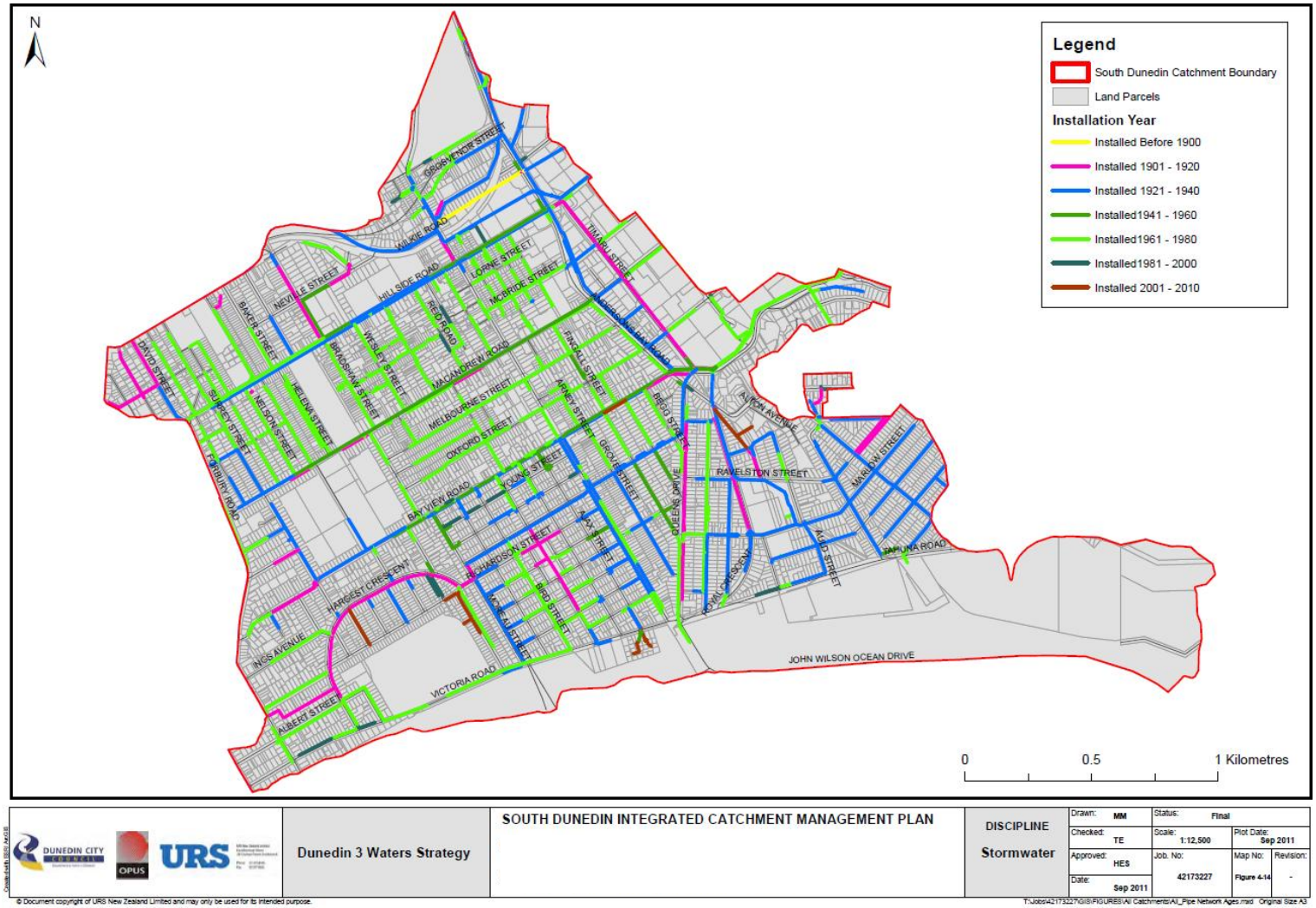
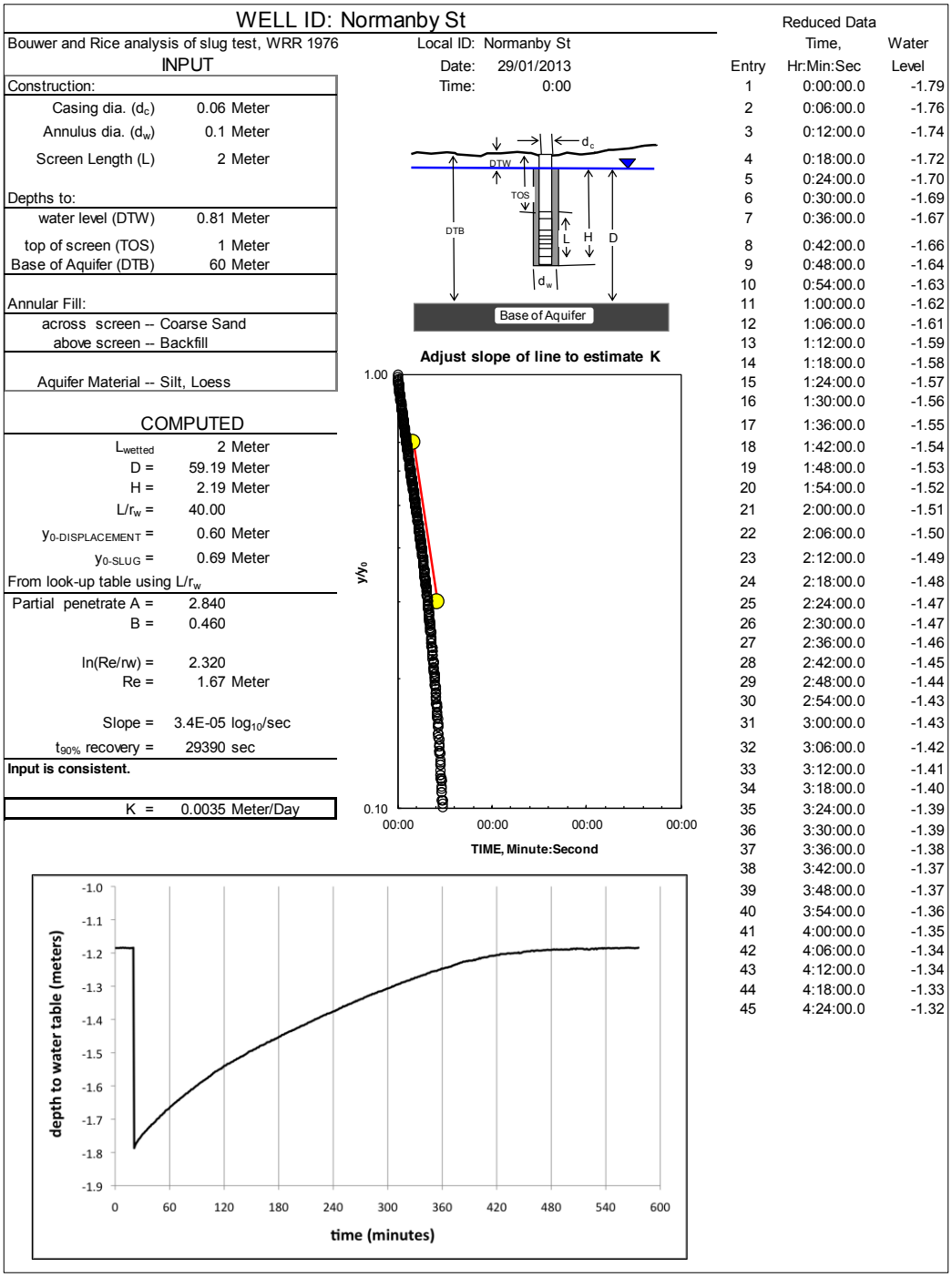


Figure A.2: South Dunedin catchment pipe network ages (source: DCC, 2011)

Table A.1 : Locations of groudnwater monitoring boreholes

Monitoring site address	GPS coordinates	Notes
5 Tahuna Road, Tainui	S 45.90335º E 170.52063 º	Site in back garden against back fence
86 Cavell Street, Tainui	S 45.90107 º E 170.52029 º	Site in front garden Abrupt shift in water level movements observed, pipe may have become blocked, site use discontinued due to compromised data
45 Lochend Street, Musselburgh	S 45.89878 º E 170.51993 º	Site against fence at back of property Used for slug tests
17 Normanby Street, St Kilda	S 45.90259 º E 170.51245 º	Site in front garden Used for slug tests
14A Market Street, St Kilda	S 45.90252 º E 170.50845 º	Site in side vegetable garden Used for slug tests
7 Annex Street, St Kilda	S 45.89810 º E 170.50897 º	Site in front garden Used for slug tests
Otago Model Engineering Society, 1 John Wilson Ocean Dr, St Kilda	S 45.90693 º E 170.50952 º	Site in bushes beside railway station Used for slug tests Site on sand dunes, freshwater observed, groundwater not connected to main aquifer, data considered seperate
Dunedin Holiday Park, 41 Victoria Road, St Kilda	S 45.90602 º E 170.51511 º	Site behind tourist flat #8 Site on sand dunes, freshwater observed, groundwater not connected to main aquifer, data considered seperate
18 Richardson Road, St Kilda	S 45.90240 º E 170.50406 º	Site in back garden Unusual drop in water level observed, site use discontinued due to compromised data
15 Plunket Street, St Kilda	S 45.90572 º E 170.49918 º	Site in front garden
27 East Avenue, St Kilda	S 45.90413 º E 170.49741 º	Site in front garden Used to trial pipe design Used for slug tests
110 Hargest Crescent, St Clair	S 45.90867 º E 170.49200 º	Site in side garden Used to trial hole excavation technique Used for slug tests
193 Macandrew Road, South Dunedin	S 45. 89928 º E 170.49417 º	Site in front garden

Appendix B



Entry	Time, Hr:Min:Sec	Water Level
1	0:00:00.0	-1.79
2	0:06:00.0	-1.76
3	0:12:00.0	-1.74
4	0:18:00.0	-1.72
5	0:24:00.0	-1.70
6	0:30:00.0	-1.69
7	0:36:00.0	-1.67
8	0:42:00.0	-1.66
9	0:48:00.0	-1.64
10	0:54:00.0	-1.63
11	1:00:00.0	-1.62
12	1:06:00.0	-1.61
13	1:12:00.0	-1.59
14	1:18:00.0	-1.58
15	1:24:00.0	-1.57
16	1:30:00.0	-1.56
17	1:36:00.0	-1.55
18	1:42:00.0	-1.54
19	1:48:00.0	-1.53
20	1:54:00.0	-1.52
21	2:00:00.0	-1.51
22	2:06:00.0	-1.50
23	2:12:00.0	-1.49
24	2:18:00.0	-1.48
25	2:24:00.0	-1.47
26	2:30:00.0	-1.47
27	2:36:00.0	-1.46
28	2:42:00.0	-1.45
29	2:48:00.0	-1.44
30	2:54:00.0	-1.43
31	3:00:00.0	-1.43
32	3:06:00.0	-1.42
33	3:12:00.0	-1.41
34	3:18:00.0	-1.40
35	3:24:00.0	-1.39
36	3:30:00.0	-1.39
37	3:36:00.0	-1.38
38	3:42:00.0	-1.37
39	3:48:00.0	-1.37
40	3:54:00.0	-1.36
41	4:00:00.0	-1.35
42	4:06:00.0	-1.34
43	4:12:00.0	-1.34
44	4:18:00.0	-1.33
45	4:24:00.0	-1.32

Figure B.1: Example of slug test data and calculation of hydraulic conductivity from Normanby St based on USGS provided spreadsheet.

Table B.1 : Slug test results from South Dunedin sites using rising head slug test method.

site	time interval	water level displacement	K (m/day)	mean K (m/day)	substrate (expected based on K)
Market St	10 sec	0.561	0.0059	0.0059	silt, loess
East St	1 min	0.774	0.001		
	1 min	0.62	0.0019	0.0015	silt, loess
Normanby Ave	1 min	0.673	0.0066		
	1 min	0.5	0.005		
	1 min	0.638	0.0035	0.005	silt, loess
OMES	1 sec	1.101	11.4		
	1 sec	0.569	10.2		
	1 sec	0.914	8.9		
	1 sec	1.003	9.5	10	medium sand
Hargest Cr	1 sec	0.989	2.25		
	1 sec	0.357	2.15	2.2	fine sand or sand/silt
Tahuna Rd	10 sec	0.762	0.0047	0.0047	silt, loess
Lochend St	10 sec	0.835	0.0066	0.0066	fine sand/silt
Annex St	10 sec	0.667	0.0078		
	10 sec	0.649	0.005	0.0064	silt, loess

Appendix C

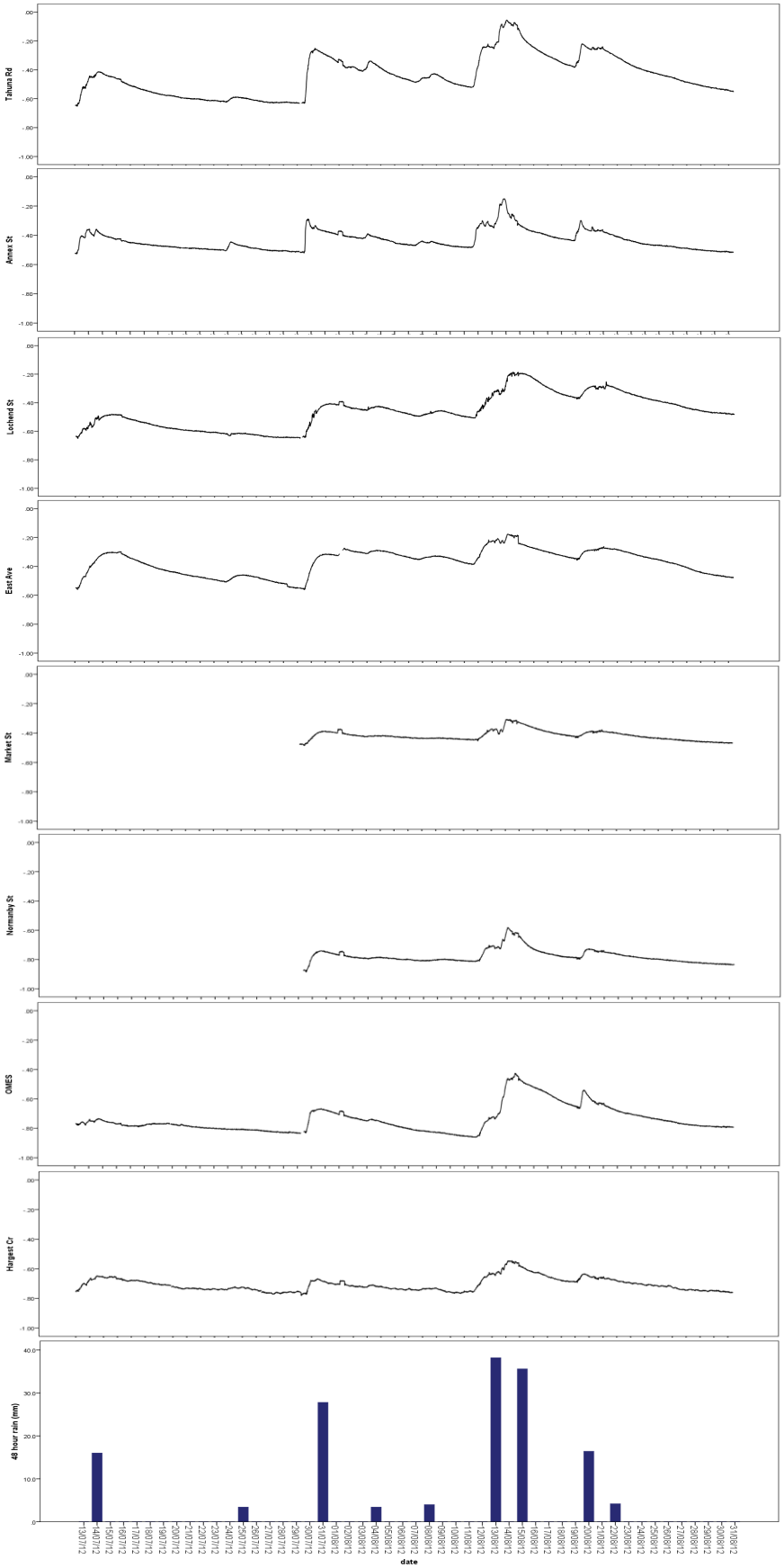


Figure C.1 : Water table hydrographs and rainfall at South Dunedin sites

Appendix D

Table D.1: HIRDS extreme rainfall assessment output for South Dunedin

Extreme rainfall assessment											
		Duration									
ARI (y)	**aep**	**10m**	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
1.58	0.633	3.7	5.2	6.5	9.2	13.4	24.3	35.3	51.3	62.4	70
2	0.5	4.1	5.8	7.2	10.3	14.8	26.6	38.4	55.5	67.5	75.7
5	0.2	5.6	8	9.9	14.1	20	34.9	49.6	70.5	85.7	96.2
10	0.1	6.9	9.9	12.2	17.4	24.5	41.9	58.8	82.6	100.4	112.7
20	0.05	8.4	12.1	14.9	21.3	29.6	49.9	69.2	96.1	116.9	131.1
30	0.033	9.5	13.6	16.7	24	33.1	55.1	76	104.9	127.6	143.1
40	0.025	10.3	14.7	18.2	26	35.8	59.1	81.2	111.6	135.7	152.2
50	0.02	10.9	15.7	19.4	27.7	38	62.5	85.5	117	142.3	159.6
60	0.017	11.5	16.5	20.4	29.2	39.9	65.3	89.1	121.6	148	166
80	0.012	12.5	17.9	22.1	31.7	43.1	70	95.2	129.3	157.3	176.4
100	0.01	13.3	19.1	23.6	33.8	45.7	73.9	100.1	135.6	164.9	185

Coefficients							
c1	**c2**	**c3**	**d1**	**d2**	**d3**	**e**	**f**
0.0007	-0.022	-1E-4	0.5164	0.539	0.283	0.2815	2.2247

Standard errors (mm)											
		Duration									
ARI (y)	**aep**	**10m**	**20m**	**30m**	**60m**	**2h**	**6h**	**12h**	**24h**	**48h**	**72h**
1.58	0.633	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.8	1.9	2
2	0.5	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.9	2	2.2
5	0.2	1.6	1.6	1.6	1.7	1.7	1.8	2	2.4	2.7	2.9
10	0.1	1.6	1.7	1.7	1.8	1.7	2	2.4	3.2	3.7	4.1
20	0.05	1.7	1.8	1.8	2	1.9	2.4	3.1	4.6	5.5	6.1
30	0.033	1.7	1.9	2	2.3	2	2.8	3.7	5.7	6.9	7.7
40	0.025	1.8	2	2.1	2.6	2.2	3.1	4.2	6.7	8.1	9
50	0.02	1.9	2.1	2.3	2.9	2.3	3.4	4.7	7.5	9.1	10.1
60	0.017	1.9	2.2	2.5	3.1	2.4	3.7	5.1	8.3	10	11.2
80	0.012	2	2.4	2.7	3.6	2.7	4.1	5.8	9.6	11.6	12.9
100	0.01	2.1	2.6	3	4	2.9	4.5	6.4	10.7	13	14.5

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