REVIEW OF INTERNATIONAL CASE STUDIES

Protection Options for Managing Rising Groundwater in South Dunedin

Submitted to:
Dunedin City Council
Otago Regional Council

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Executive Summary

South Dunedin has similarities with several other cities in the world with low lying areas and high groundwater levels that affect buildings and infrastructure through water ponding and drainage issues. Groundwater levels in South Dunedin are expected to rise as a consequence of sea level rise, exacerbating existing water ponding and drainage issues.

Dunedin City Council (DCC) and Otago Regional Council (ORC) are seeking to learn from overseas experiences of controlling groundwater levels and have engaged Golder Associates (NZ) Limited (Golder) and Deltares Ltd (Deltares) to identify and review overseas examples relevant to South Dunedin. This report presents fifteen case studies from throughout the world that provide useful information to inform the development of protection options in South Dunedin.

None of the case studies documented are exactly the same as the situation in South Dunedin. However, each offers clear similarities in the issues that authorities face in dealing with rising groundwater levels and they present multiple protection options that may also be feasible in South Dunedin.

In urban areas where groundwater levels are relatively close to the surface several issues may arise, such as surface water ponding, damage to infrastructure and buildings, and increased risks of liquefaction during earthquakes. These issues can be severe and widespread unless appropriate adaptive or management measures have been put in place. Factors such as sea level rise, increased weather extremes and land subsidence all influence the potential change in susceptibility.

The adverse effects of high and rising groundwater levels can be mitigated through careful planning, designing and maintaining adaptive mitigation measures. There are many different technical measures that can be implemented to control groundwater levels. The success of these systems depends heavily on the ability to install them in optimal locations, and the ongoing appropriate operation and maintenance of the systems.

Mitigation options include horizontal and vertical drainage, pumped open canals, ground improvement, seepage canals and cut-off walls. Horizontal subsurface drainage is the most widely used method for high groundwater level mitigation, as it can be retrofitted in existing urban areas. Subsurface drainage systems with infiltration capacities have been used to maintain a relatively flat groundwater table in some areas. The creation of open water bodies or canals with water levels managed through pumping can be an effective measure to control groundwater levels and provide added benefits in terms of stormwater management and amenity values.

A good understanding of local conditions (hydrology, hydrogeology and geology) and effective engagement of residents has been found to be critical in successful implementation and operation of technical measures. Successful case studies also have one or more key governmental authorities taking the initiative to drive the development of the mitigation approach.

To control rising groundwater levels in South Dunedin there are options to combine multiple protection measures. Protection options can be introduced slowly in a progressive manner rather than as a one-off operation and can be focussed initially to protect sensitive areas and buildings. There is potential to develop new recreational surface water bodies and features and look for windows of opportunity to maximise the benefits from constructional costs when retrofitting groundwater drainage systems. South Dunedin’s stormwater and wastewater networks are up for renewal in the near future. This may provide opportunity for implementing some measures to manage groundwater levels.
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APPENDICES
APPENDIX A
Report Limitations
1.0 INTRODUCTION

1.1 The Project

Like many coastal cities around the world, Dunedin has low lying areas with high groundwater levels that affect buildings and infrastructure through water ponding and drainage issues. Of particular concern is the South Dunedin area, a low lying urban area bounded by both the ocean and the harbour (Figure 1).

![Figure 1: South Dunedin, Dunedin Port and Otago Peninsula (source: Glassey et al 2002).](image)

Groundwater levels are strongly influenced by the sea in South Dunedin and sea level rise over the past century has increased groundwater levels there (ORC 2012 and ORC 2016). With sea levels expected to further increase in response to climate change, groundwater levels in South Dunedin are projected to continue to rise. This rise will increase South Dunedin’s susceptibility to water ponding and drainage issues.

These problems are not unique to South Dunedin. Cities throughout the world have built environments in low lying areas with high groundwater levels causing similar problems. Many of these cities have taken action to control groundwater levels or otherwise deal with the associated issues. Dunedin City Council (DCC) and Otago Regional Council (ORC) are seeking to learn from these overseas experiences.

DCC and ORC have requested Golder Associates (NZ) Limited (Golder) and Deltares Ltd (Deltares) to undertake an international review of case studies where protection options have been implemented, or are being implemented, to manage rising groundwater. This report describes fifteen case studies from throughout the world that can provide useful information for the development of solutions for South Dunedin’s high groundwater levels.

1.2 Objectives

The objective of this study is to provide an overview of available techniques to control groundwater levels in different types of urban environment, by reviewing international case studies. The factors that made these techniques a potentially viable options for groundwater level management are also presented. These factors include technical arguments as well as governance issues such as scale (population), environmental and social setting, funding arrangements, precedent, public preferences, as well as the ability to retrofit these systems in an existing urban area. Not all case studies are about success. Failures have also been presented to show pitfalls in the implementation of mitigation measures.
These matters will help DCC and ORC to gain better understanding of possible protection options in the context of the particular social, economic and environmental setting of South Dunedin. The intended use of this study is to provide information to inform consultation with community and stakeholders on the range of potential options available for addressing the high groundwater level issues in South Dunedin. This study does not provide recommendations as to which protection options are viable for South Dunedin.

1.3 Approach

Fifteen towns and cities throughout the world were selected as useful case studies, based on their relevance to the South Dunedin situation and the availability of information. Their locations are shown in Figure 2. In a desktop study and through literature search, these case studies have been systematically reviewed and categorised in terms of environment, socio-economics and governance, for easy comparison with South Dunedin’s circumstances. Where relevant and sufficient information is available, the following matters are described:

1) Characteristics, scale and size of the groundwater level rise issues.
2) Protection measures implemented or proposed (whether protection is part of a suite of measures).
3) Efficacy of the protection measures in achieving the intended goals (whether the protection component has provided the expected levels of service and whether residual risks have been created).
4) Limitations and constrains of implementing the protection measures imposed by technical factors or socio-economic factors (including the effectiveness of measures being limited to a finite period).
5) Community acceptance and the potential for ‘windows of opportunity’.
6) Indication of whole life costs of protection measures, including cost to implement, operate and maintain during the expected life time of the measures.

There are many other towns and cities throughout the world that are affected by high and rising groundwater levels in the urban environment that are not presented in this report. The study case studies presented in this report have been selected based on the information available on the protection options utilised. Some case studies have been studied for many years and mitigation measures have already been implemented. For others investigations are still underway. This means that the available information varies across the case studies and not all are described to the same level of detail. Many of the case studies are from the Netherlands, where a long and diverse track record of dealing with high groundwater levels has been established over decades.

Some case studies have similar issues or similar measures are implemented or considered. These case studies have been clustered to help provide a better overview of mitigation strategies and approaches.

The case studies presented in this report are all towns and cities with high groundwater level issues in existing urban areas. This means that mitigation measures, such as subsurface drainage, would have to be ‘retrofitted’ into an existing urban environment. There are constrains as to what mitigation measures can be implemented in existing urban areas. For example, options involving wholesale ground improvement and raising ground levels that are sometimes applied in new developments are often not feasible in existing urban areas. The focus in the selected case studies is on retrofitting systems in existing urban areas, which is most relevant to South Dunedin’s circumstances.
1.4 South Dunedin Setting

For the purposes of this report, the area referred to as South Dunedin comprises a low-lying dense urban environment of 600 ha which is less than 3 m above mean sea level. South Dunedin is located south of the Dunedin city central business district, between the Otago Harbour Basin and the Pacific Ocean. It includes the suburbs of South Dunedin, Tainui, St Kilda, Forbury, St Clair and Kensington. South Dunedin is mainly a residential area with medium density housing (ORC 2012). Approximately 10,000 people live in about 4,800 dwellings in this area. The population is mainly older, has a lower income and the residents are less likely to own their homes than residents in average suburbs in New Zealand (ORC 2016 and ORC 2012).

Groundwater levels in South Dunedin are high and generally less than 1 m below ground level. Near Tonga Park in the centre of the area, groundwater levels are generally less than 0.5 m below ground level. Current high groundwater issues mainly affect the suburbs Forbury, St Kilda West and Tainui and, to lesser extent, the suburb of South Dunedin (Figure 3).

The area is an ancient river valley partly filled with alluvial gravels and sands that has been buried in soft sediments (sand, silts and clays) forming a land bridge between the surrounding hills as sea levels rose after the last ice age (ORC 2012, ORC 2016 and Fordyce 2013). In recent times before European settlement the area comprised salt marshes, lagoons, dunes and intertidal mudflats. South Dunedin was developed into a predominantly residential and commercial / retail area from the 1800’s onward, following land reclamation and land filling. Land filling was often poorly compacted and some residual land settlement is still occurring (ORC 2016).
Coastal protection from inundation for South Dunedin is provided by seawalls along the harbour side to the northeast, and by dunes to the south. The groundwater issues arise in part from the fact that there are limited locations for surface water in the area to naturally drain.

The annual mean rainfall is approximately 800 mm/year and is more or less evenly distributed throughout the year (ORC 2016). However, extended periods of moderate to heavy rainfall and concentrated heavy rainfall events occur and can lead to surface flooding. With impervious surfaces (hardstand, roads or roofs) covering 60% of South Dunedin and locally up to 100%, the stormwater network has to cope with a significant amount of runoff in a short timeframe. In addition to direct rainfall, the area receives runoff from the surrounding hills through direct flow and through the stormwater network. There are no natural outlets and open water courses on the South Dunedin plains. The lowest part of the area is in the southeast near Tainui. At Portobello Rd the collected stormwater is discharged to the harbour through a pump station. Wastewater is collected in the Musselburgh pump station and then pumped to the Tahuna wastewater treatment plant.

South Dunedin has long faced stormwater management challenges. The area is flat and the stormwater network is constrained by the small differences in elevation. The most recent widespread flooding occurred in June 2015 (ORC 2016). During this event heavy rainfall and runoff, and the corresponding rise in groundwater levels, caused flooding especially in the central and western part of South Dunedin.

The current shallow groundwater levels are unintentionally mitigated to some extent by cracks and leaks in the existing aging sewage and stormwater networks. Replacement of these systems with non-leaking infrastructure may therefore lead to new groundwater issues in areas where they are currently not present.
There are also indications of locally higher groundwater levels resulting from infiltration at some locations, (ORC 2012, Fordyce 2013).

A study from ORC (2012) has confirmed the increased vulnerability of South Dunedin to high groundwater levels as a result of projected sea level rises. This study concluded that the area will be significantly impacted on an area-wide scale and extensive measures would be required to satisfactorily mitigate the adverse effects of rising groundwater levels. Capital costs and on-going operation and maintenance costs of measures to manage these effects have been estimated to be significant.

### 2.0 MITIGATION OPTIONS FOR HIGH GROUNDWATER IN URBAN AREAS

#### 2.1 Introduction

In the case studies presented in the following sections several mitigation measures and strategies have been considered and in some cases successfully implemented. This section gives a high-level overview of some general high groundwater level mitigation measures for urban areas. The measures presented below can often be applied in combination, to solve multiple groundwater problems. It is noted that liquefaction may severely affect subsurface infrastructure including many of the systems described below.

#### 2.2 Ground Improvement and Raising the Land

Low-lying areas prone to flooding and the effects of high groundwater levels can be raised using engineered fill to reduce their susceptibility (Figure 4). Ground improvement can be implemented to mitigate liquefaction risks and potential consolidation or heave.

![Figure 4: Ground improvement and raising the land.](image)

These measures are usually considered when rural land is being developed into urban functions (often referred to as ‘greenfield development’). They are sometimes applied in existing urban areas, but typically require demolition and re-building. Alternatively, partial raising of existing levels or excavation filling may be applied to create a permeable layer or trench to enhance groundwater drainage (Figure 5). Excavation filling entails the excavation of clay soils under roads and building sites and backfilling with sand. A subsurface drain is installed in the sand to control the groundwater levels.
2.3 Open Land Drain or Canal

An effective way to reduce groundwater levels is to install open drains or canals. This measure is often used in urban areas, either in combination with subsurface drainage or separately. The canals in Amsterdam, The Netherlands, are a well-known example. The Netherlands canals are often located below sea level and pumped to manage water levels to prevent flooding. Therefore canals and surface water features do not necessarily need a natural outflow.

The loss of land for development can deter developers from introducing open surface water drainage features into new urban areas. However, surface water can provide added benefits for stormwater management and also form a recreational and ecological amenity to the community. In addition, the value of properties located next to water may be higher. Waterproofed buildings reduce the loss of land for development (e.g., floating houses or pile houses, see Figure 7). In existing urban areas the establishment of open land drains may require purchase of property and the removal of dwellings.
Buildings can be made less susceptible to the effects of high groundwater levels, for example by raising floor levels, waterproofing basements or installing pumped drainage systems around basements. The property owners are usually responsible for implementing these measures.

Infrastructural networks and objects can also be made less susceptible to the effects of high groundwater levels, for example by using alternative construction materials, elevated construction levels or alternative methods for construction and maintenance. Public authorities and utility companies are usually responsible for implementing mitigation measures for these networks.

**Figure 7: Examples of waterproof buildings (left: pile house; right: floating house).**

### 2.4 Horizontal Subsurface Drainage

The best-known and widely applied measure to control groundwater levels is the installation of horizontal subsurface drains, typically known as “French drains” in New Zealand. These subsurface drains incorporate slotted pipes, either wrapped in a non-woven geotextile or placed in a gravel bed. These pipes are installed below the groundwater table to capture and divert the groundwater, thereby reducing nearby groundwater levels (Figure 8). If properly designed and installed, and soil permeability is favourable, subsurface drainage systems can be targeted and effective in controlling high groundwater levels.

**Figure 8: Horizontal subsurface drainage.**

Subsurface drainage is often effectively applied in urban areas, if well designed, operated and maintained. Planned stormwater or wastewater network upgrades that involve trenching in roads can provide an opportunity to install horizontal subsurface drainage measures.

The potential for clogging is an important consideration when designing these systems. Iron-rich groundwater can lead to iron oxides precipitating, which clog the systems over time. Clogging risks are generally small if the drainage system remains permanently submerged in groundwater and the drainage
material and native soil are geotechnically compatible. Tree roots are however also attracted to the presence of both water and air in a non-submerged subsurface drain. Provisions for discharging the drained groundwater are always required. Subsurface drainage systems can accelerate land subsidence if consolidation prone soils are present.

Subsurface drains can be installed on public land as well as on private land. Road maintenance authorities install subsurface drainage beneath roads to ensure sufficient drainage and this can help solve drainage problems on nearby properties. However, a low soil permeability may require additional subsurface drains to be installed on private land to avoid high groundwater levels under houses, buildings and gardens.

2.5 Vertical Drainage (Wells)

Wells can also be installed as mitigation against high groundwater levels. Pumping from the wells will lower the groundwater table in a radial area around the well (Figure 9). Multiple wells can be installed to drain a larger area.

![Figure 9: Vertical drainage (wells).](image)

Vertical drainage through wells is less targeted than horizontal drainage as the largest groundwater drawdown occurs near the well. Land subsidence and in particular differential settlement can be significant if consolidation prone soils are present. A disproportionate amount of groundwater would need to be pumped to be as effective as horizontal drainage, although the installation and operation of multiple wells may enhance the efficacy. The advantage of vertical drainage through wells is that no trenching is required and they are easier to fit into an existing urban environment. This technique may also be more effective than horizontal drainage systems in areas with low permeability top soils.

2.6 Combined Stormwater and Groundwater Drainage Systems

In many cases low-lying areas with high groundwater levels are characterised by soils that are prone to consolidation, which causes land subsidence when groundwater levels are lowered. Lowered groundwater levels can accelerate land subsidence and affect urban functions as much as high groundwater levels. These areas benefit from a groundwater table that is kept “flat” or fluctuates within a narrow band. This can be achieved by systems that will infiltrate water when groundwater levels are too low and drain water when groundwater levels are too high. This twinned function can be achieved by combining a stormwater system with subsurface drainage (Figure 10).

In most cases only a portion of the locally collected stormwater can be infiltrated. Whilst this may be sufficient to raise the groundwater table to a desired level, most stormwater will still need to be diverted and discharged. The potential for clogging is an important consideration when designing these systems. The groundwater quality may be very different from the stormwater quality and physical, chemical or biological processes can lead to clogging of the systems over time. As with horizontal subsurface drainage, these combined systems need to be installed in trenches and the best opportunity for installation is when stormwater and wastewater network upgrades are planned.
2.7 Seepage Drain or Canal

This is a similar concept as an open land drain (see above), but is installed specifically near a water body (river, lake or sea) that may in part be the cause of the high groundwater levels (Figure 11).

As with land drains, a seepage drain requires land to be surrendered that could otherwise be developed. However, seepage drains can have the same added benefits as open land drains for stormwater management and enhancing ecological, landscape and recreational values (see above). When installed near the sea, the water in the seepage drain will become saline over time.

2.8 Cut-Off Wall

A cut-off wall can be installed near a water body (river, lake or sea) that may in part be the cause of the high groundwater levels (Figure 12). Cut-off walls alone often have little value for mitigating high groundwater levels as installation to significant depth is often required to reduce the seepage beneath the wall satisfactorily. Additional measures such as subsurface drainage is usually required to make cut-off walls effective for groundwater management. There may be geotechnical constraints for installing cut off walls.

2.9 Managed Retreat

In some cases communities may choose to retreat from a certain area, or a part of it. Managed retreat entails the rezoning of affected areas to a non-urban function, which means building consents will no longer be issued and services no longer maintained. Buildings are vacated and this is usually followed by demolition and site clearing (Figure 13). In the context of coastal protection, managed retreat may also include the removal of coastal protection and allowing an area to become flooded.
The red zoning of large parts of Christchurch, including buying out property owners following the Canterbury Earthquake Sequence (CES), is an example of managed retreat.

Examples of managed retreat from urban areas specifically caused by groundwater flooding were not encountered in this investigation (although their existence cannot be excluded). Managed retreat from a part of the urban area did occur in Odense, Denmark (Case Study 11), but this was only indirectly instigated by high groundwater issues.

3.0 CASE STUDIES

3.1 Overview

There are multiple reasons for rising groundwater levels and although the cause of rising groundwater levels in many of the case studies are different to South Dunedin the lessons learnt in developing protection options can potentially be applied.

Some of the main causes of high and rising groundwater levels are:

- Tidal fluctuations and sea level rise raising groundwater levels.
- High water levels in rivers and streams raising nearby groundwater levels.
- Cessation of pumping from large municipal or industrial groundwater abstractions.
- Land subsidence.
- Upgrading leaking stormwater and sewage pipes and connections.
- Urban development effects on groundwater recharge and drainage.

Fifteen case studies from around the world are documented in this section. The case studies have been selected based on the amount of information available on the utilised protection options. Examples of various protection measures and suites of measures are presented.

Table 1 provides a ranking of the case studies and protection options with respect to their relevance to South Dunedin. None of the case studies is exactly the same as South Dunedin. Like all presented case studies, South Dunedin is unique in some ways. A good understanding of local circumstances is required for the successful implementation of protection strategies. Nonetheless, there are similarities between each of the case studies and South Dunedin. Protection options applied in the case studies are potentially viable in South Dunedin and lessons learnt from the case studies can be applied to South Dunedin.
South Dunedin has options to potentially combine multiple protection measures, as also documented in many of the case studies, in order to:

- Introduce measures in a progressive manner
- Combine stormwater and groundwater drainage measures
- Protect sensitive areas and buildings
- Develop new surface water recreational areas and features
- Identify windows of opportunity to minimise constructional costs of installing drainage.

As authorities and the community work through their preferred options for South Dunedin, the learnings from these case studies can be used to develop a solutions package of preferred measures.

The most comparable case study that has a similar coastal/urban setting to South Dunedin is Den Helder. It is a port town, surrounded by sea on three sides. It has high groundwater level issues and existing canals attracting saline groundwater. It has an on-going sewage replacement programme in which authorities are installing combined drainage/transportation stormwater sewage pipes (Gemeente Den Helder 2012). However, all case studies have relevance to South Dunedin and can be considered in the development of protection options.

### Table 1: Case studies - relevance to South Dunedin.

<table>
<thead>
<tr>
<th>Protection Options:</th>
<th>Case Studies:</th>
<th>Characteristics</th>
<th>Protection measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal drainage</td>
<td>Haarlem</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Haarlemmermeer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mitigating Tidal Influence and Sea Level Rise</td>
<td>Den Helder</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Perkpolder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined Horizontal Drainage and Infiltration</td>
<td>Amsterdam</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>New Orleans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Selective Groundwater Drainage</td>
<td>Hoogeveen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dresden</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Retrofitting Open Canals</td>
<td>Ooststellingwerf</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Drainage (wells)</td>
<td>Delft</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Eindhoven</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Buenos Aires</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Odense</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk-based Groundwater Management</td>
<td>Enschede</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquefaction and Managed Retreat</td>
<td>Christchurch</td>
<td></td>
<td><strong>Not a protection measure</strong></td>
</tr>
</tbody>
</table>

**Ranking key for relevance to South Dunedin Table 1:**

- **Most relevant**
- **Least relevant**
3.2 Horizontal Drainage

3.2.1 Introduction

Over several decades, the installation of horizontal drainage alongside sewage pipes has become widespread as part of building site preparation, sewer replacement and road (re)construction projects throughout The Netherlands. The efficacy of these systems is highly dependent on the quality of the design and subsequent implementation and maintenance. This section includes a ‘good practice’ example (Haarlem) and ‘lessons learned’ example (Haarlemmermeer).

3.2.2 Case Study 1: Haarlem (The Netherlands)

Characteristics

In the 1980s, the late 19th/early 20th century Leidsebuurt district (area of 34 ha) in Haarlem was one of the first locations in the Netherlands experiencing groundwater rise after sewer replacement.

Protection measures and mitigation approach

In response, the city of Haarlem financed and installed a horizontal subsurface drainage system in public land in 1989. To minimise clogging by iron oxides and damage by root growth, the system was installed in a gravel-filled trench below the (expected) lowest groundwater level. The drainage level can be changed with adjustable weirs in (dry) catch pits. Too low groundwater levels can affect foundations in this area and the ability to adjust drainage levels is important. The lowest groundwater level acceptable for these foundations may vary significantly over a short distance. The groundwater collected in the catch pits is discharged to nearby surface water through pumping, as the surface water level is higher than the drainage levels.

The drainage pipes are cleaned by medium pressure flushing every one or two years. After 26 years, the state of the subsurface drains was investigated. There was no clogging or root growth, and the coating material was hardly worn. As a result, the lifetime expectation of the drainage system was increased by another 60 years. Groundwater levels mostly remain within the imposed drainage levels and have not shown any upward trend since 2002, which often indicates clogging over time (Figure 14). The good performance of the system is considered largely to be owing to its permanent submergence in the groundwater.

Figure 14: Groundwater levels in one of 12 observation wells near the subsurface drainage system in Haarlem. Source: Wareco / City of Haarlem.
3.2.3 Case Study 2: Haarlemmermeer (The Netherlands)

**Characteristics**

The Haarlemmermeer is a reclaimed former lake in between the cities of Amsterdam, Haarlem and Leiden, and hosts the Schiphol International Airport and urban areas like Hoofddorp and Nieuw Vennep. In the 1990s, the district/city council initiated several large urban development schemes to relieve the regional housing shortage.

Because of its low elevation (i.e., some 4 m below mean sea level), groundwater seepage is significant in this area. The area has no natural outlet and has to be pumped continuously for drainage. New urban developments are equipped with mandatory groundwater drainage systems. Nonetheless, the district/city council received many complaints about groundwater in crawl spaces beneath houses after the completion of the ‘Getsewoud’ development between 2000 and 2005 (approximately 200 ha).

**Protection measures and mitigation approach**

Investigations by the district/city council revealed the following causes of the high groundwater problems:

1) The drainage design was not optimal. There were too few discharge points to surface water, which made the system vulnerable to issues when some sections clogged.

2) The maintenance was insufficient. Many drainage pipes clogged over time by iron-oxides precipitation.

3) Building block drainage was initially installed on private property, but many property owners had not been made aware of the drainage location and maintenance requirements. Many systems were not maintained, became clogged and sometimes became inaccessible after paving.

The district/city council followed a ‘quick win’ approach by adding discharge points and resuming regular maintenance of systems to solve immediate problems. Furthermore, the district/city council commenced monitoring of groundwater levels and drainage performance, started a maintenance programme for the drains in public land and raised public awareness of the drainage systems on private land. The latter was carried out by means of an extensive communication programme, comprising public meetings, newsletters, a website, and appointing stakeholder representatives within the district/city council (Witteveen+Bos / Municipality of Haarlemmermeer 2012).

3.2.4 Summary and relevance to South Dunedin

A general overview and relevance of case studies 1 and 2 to South Dunedin is provided in Table 2.
Table 2: Horizontal drainage – summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Haarlem and Haarlemmermeer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Rising groundwater table after replacement of leaking sewage pipes which were acting as drainage.</td>
<td></td>
</tr>
<tr>
<td><strong>Protection measures implemented or proposed</strong></td>
<td></td>
</tr>
<tr>
<td>Subsurface drainage installed during sewage replacement.</td>
<td></td>
</tr>
<tr>
<td>Not part of a suite of measures</td>
<td></td>
</tr>
<tr>
<td><strong>Efficacy of the protection measures</strong></td>
<td></td>
</tr>
<tr>
<td>Haarlem- example of subsurface drainage operating successfully for 26 years, life expectancy up to 60 years.</td>
<td></td>
</tr>
<tr>
<td>Haarlemmermeer – example of drainage not performing as expected due to design errors and lack of maintenance (residual risk).</td>
<td></td>
</tr>
<tr>
<td><strong>Limitations and constraints</strong></td>
<td></td>
</tr>
<tr>
<td>Haarlemmermeer is in a ‘polder’ with no natural outlet. Continuous pumping for drainage is required.</td>
<td></td>
</tr>
<tr>
<td><strong>Community acceptance and windows of opportunity</strong></td>
<td></td>
</tr>
<tr>
<td>Subsurface drains were installed during sewage replacement projects.</td>
<td></td>
</tr>
<tr>
<td><strong>Indication of whole life costs</strong></td>
<td></td>
</tr>
<tr>
<td>Indicative costs for installing subsurface drainage in roads in The Netherlands ranges from € 30 per metre to € 250 per metre.</td>
<td></td>
</tr>
<tr>
<td><strong>Relevance to South Dunedin</strong></td>
<td></td>
</tr>
<tr>
<td>South Dunedin's sewage pipes are also leaking and the same may occur if replaced.</td>
<td></td>
</tr>
<tr>
<td>Subsurface drainage may provide a long-term solution for (parts of) South Dunedin.</td>
<td></td>
</tr>
<tr>
<td>Like the Haarlemmermeer, South Dunedin has no natural outlet.</td>
<td></td>
</tr>
<tr>
<td>Future sewage network replacement in South Dunedin could provide a window of opportunity.</td>
<td></td>
</tr>
</tbody>
</table>

3.3 Mitigating Tidal Influence and Sea Level Rise

3.3.1 Introduction

Groundwater levels in areas close to the sea can rise at high tide as a result of seepage beneath coastal protection measures such as sea walls, stop banks or dikes. A similar situation may occur near a river at high flows. Whilst sea walls or stop banks may protect against flooding, the seepage can cause high groundwater levels issues. Mitigation against this seepage is implemented in the case study presented in this section.

3.3.2 Case Study 3: Den Helder

Characteristics

Den Helder is a port city in the northwest of the Netherlands, which is bounded by the sea on three sides (Figure 15). The city has a population of some 56,000 and is protected from sea water inundation by dunes in the west and seawalls along the northern and eastern boundaries (Figure 16). A network of canals was constructed in historical times for transportation and defence purposes and serves as a discharge point for stormwater (Figure 17). The pumped canals are flushed with nutrient-enriched surface water from rural catchments south of the urban area, but also receive seepage of fresh groundwater from the western dune.
area and saline groundwater from the sea. Therefore, the water quality varies and some part of the canals are brackish.

Although the canals assist in managing groundwater levels, Den Helder has high groundwater level issues in the urban environment. The main causes are considered to be a lack of drainage systems and relatively high water levels in the canals (Gemeente Den Helder, HHNK and Grontmij 2005). Groundwater issues have reportedly increased following the replacement of leaking sewage pipes (Gemeente Den Helder 2012).
Protection measures and mitigation approach

Since 2008 all city and district councils in The Netherlands, including Den Helder, are responsible for investigating groundwater issues in urban areas and taking appropriate measures in public spaces where there are structural and persistent groundwater issues (Section 4.5). Den Helder City Council has acknowledged groundwater issues and has implemented some measures. However, further internal policy for managing urban groundwater issues has yet to be adopted (Gemeente Den Helder 2012).

As part of an on-going sewage and stormwater network upgrade programme, the stormwater pipes are being partially replaced with ‘drainage and transportation’ stormwater pipes (Gemeente Den Helder, HHNK and Gronitmij 2005; Gemeente Den Helder 2012). These pipes provide sufficient storage and diversion capacity to manage stormwater, but also have a drainage and infiltration function to manage groundwater levels (Figure 18).

Costs and Finance

Costs for the implementation of high groundwater mitigation measures were projected to be €360,000 in the 2013 – 2017 management period.
3.3.3 Case Study 4: Perkpolder (Netherlands)

Characteristics
Near the Perkpolder, in the southwest of the Netherlands, 75 ha of agricultural land was returned to the sea to restore tidal salt marshes and associated environmental values along the Westerschelde (estuary of the North Sea). As such, this case study represents a form of managed retreat (Section 4.5).

It also meant that the sea would come much closer to the adjacent farmland than was previously the case. This would cause saltwater seepage beneath the stop bank and the subsequent rise of groundwater levels as well as saline intrusion behind the stop bank. Agriculture in this area depends on a freshwater lens which is used for irrigation and would be adversely affected.

Protection measures and mitigation approach
To counteract an increase of hydraulic heads associated with high sea tides, a seepage collection system was installed on the land side behind the stop bank, under the supervision of and financed by the national water authority ('Rijkswaterstaat'). The system consists of a seepage canal and 61 vertical seepage wells with 5 m to 10 m long screens (Figure 19). The wells were installed over a length of about 1 km at 12 m to 17 m depth, in an aquifer that mainly comprises fine sands. Monitoring results showed that the system would be effective even after the expected sea level rise has taken effect in this area (De Louw et al., 2016).

![Seepage system Perkpolder](image19.jpg)

Figure 19: Seepage system Perkpolder.

Costs and finance
Installation costs of the system were an estimated € 800,000. Returning fertile agricultural land to the sea remains controversial in this area, but the seepage system gives the farmers confidence that crops and freshwater resources for irrigation of the remaining farmland are safeguarded.

3.3.4 Summary and relevance to South Dunedin
A general overview and relevance of case studies 3 and 4 to South Dunedin is provided in Table 3.

---

Table 3: Mitigating tidal influence and sea level rise - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Den Helder and Perkpolder</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristics</strong></td>
<td>Saltwater intrusion and high groundwater levels affect nearby farmland (in the Perkpolder case) or urban areas (in the Den Helder case).</td>
</tr>
<tr>
<td><strong>Protection measures implemented or proposed</strong></td>
<td>For Perkpolder a seepage canal and wells are installed along coastal protection to capture saltwater intrusion and control groundwater levels.</td>
</tr>
<tr>
<td><strong>Part of suite of measures?</strong></td>
<td>In Den Helder, canals for water management and seepage control were historically constructed when the city was built. Recent groundwater issues are mitigated by drainage / transportation stormwater pipes.</td>
</tr>
<tr>
<td></td>
<td>Both cases involve a combination of measures.</td>
</tr>
<tr>
<td><strong>Efficacy of the protection measures</strong></td>
<td>Initial results show the system in Perkpolder would be effective even after the expected sea level rise takes effect. Therefore, it has provided the expected level of service. Residual risks are not documented.</td>
</tr>
<tr>
<td><strong>Has protection provided expected level of service?</strong></td>
<td>Den Helder involves installing new protection measures and results are not yet documented.</td>
</tr>
<tr>
<td><strong>Any residual risks?</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Limitations and constraints</strong></td>
<td>Neither Den Helder nor Perkpolder has a natural outlet.</td>
</tr>
<tr>
<td><strong>Community acceptance and windows of opportunity</strong></td>
<td>Use of drainage / transportation stormwater pipes, to be installed with sewage network upgrades in Den Helder. For Perkpolder, the solution ensured productivity of the adjacent farmland.</td>
</tr>
<tr>
<td><strong>Indication of whole life costs</strong></td>
<td>In Den Helder costs were projected to be € 360,000</td>
</tr>
<tr>
<td></td>
<td>Estimated installation costs of the system in Perkpolder were € 800,000</td>
</tr>
<tr>
<td><strong>Relevance to South Dunedin</strong></td>
<td>The groundwater level issues have occurred due to similar processes as in South Dunedin.</td>
</tr>
<tr>
<td></td>
<td>South Dunedin has no natural surface water outlet either.</td>
</tr>
<tr>
<td></td>
<td>A seepage canal with horizontal drainage like that used in Perkpolder may be applicable to South Dunedin.</td>
</tr>
<tr>
<td></td>
<td>Combined drainage / transportation stormwater pipes may be of use in South Dunedin.</td>
</tr>
</tbody>
</table>
3.4 Combined Horizontal Drainage and Infiltration

3.4.1 Introduction

Horizontal subsurface drainage can also be used for infiltration of (a portion of the) collected stormwater, or of surface water. This combined function can be used to draw the groundwater table almost flat, ensuring groundwater levels are neither too high nor too low. In areas with poorly permeable soils or high groundwater levels, the portion of collected stormwater that can be infiltrated through such system will be relatively small and has only limited relevance for stormwater disposal.

3.4.2 Case Study 5: Amsterdam (The Netherlands)

Characteristics

In the Vondelpark in Amsterdam, a combined drainage-infiltration system was designed to buffer groundwater fluctuation. The Vondelpark is lower than the surrounding residential properties and groundwater levels in the park were close to the surface (Figure 20). This posed a risk to fully-matured monumental trees in the park, which could degrade and even tumble. Wooden foundation piles of nearby historic residential buildings were originally installed below the groundwater table, which was common practice in historic times. These piles will rot if exposed to air after lowering the groundwater table, which potentially severely affects the buildings. Land subsidence as a result of groundwater drainage, could also affect nearby buildings.

Protection measures and mitigation approach

A combined subsurface drainage and infiltration system was installed to manage groundwater levels in an area of approximately 3 ha. The subsurface drainage system is connected to nearby surface water at ‘boezem level’ which allows infiltration from the surface water. Before infiltration, suspended sediment is trapped and the water is further filtered by passage through a lavastone bedding (i.e., a form of stormwater treatment facility). The activation of the surface water inlet is controlled by the groundwater level. A subsurface sheet pile wall prevents the residential area from excessive drainage into the park. The system performs as designed and ensures groundwater levels remain within acceptable levels, as shown in Figure 21.

Costs and Finance

After the first maintenance round in 2015, the system appeared to show no decline in performance. The drainage-infiltration system was part of an integrated renovation of the park, including also restoration of buildings, gates and statues. The total cost of the renovation was 29 million euros, largely due to the complexity of construction activities in narrow, historic streets in the centre of the city, and were financed by the Amsterdam metropolitan council, the district/city council, and several other governmental bodies. The district/city council took initiatives to acquire additional funding by selling ‘Vondelpark’ merchandise to the public, such as T-shirts, balloons, caps and umbrellas, and facilitating adoption of patches of the Vondelpark by companies.

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1 Many drainage systems in the Netherlands are divided in ‘polders’ and the ‘boezem’. Most boezem levels are within 1 m below sea level, while polder levels can be down to 6 m below sea level. Polders discharge their water to the boezem using pumps, through which the water is diverted via sluices to the sea or a nearby river.


Figure 20: Canals and restoration construction being undertaken, Vondel Park (Amsterdam).

Figure 21: Groundwater levels observed in a residential area near Vondelpark, Amsterdam, before and after implementation of a combined subsurface drainage and infiltration system in Vondelpark. Source: Waternet.
3.4.3 Case Study 6: New Orleans (USA)

**Characteristics**
Groundwater levels in Greater New Orleans have declined over the years, causing substantial land subsidence in an area possibly as large as 200 km$^2$. Land subsidence causes differential settlement, damages structures and infrastructure, and increases vulnerability to floods originating from the sea, river or Lake Pontchartrain. A major cause of declining groundwater levels and subsequent land subsidence is the abstraction of deep groundwater, but the drainage of shallow groundwater by leaky stormwater drainage and wastewater pipes and deep (freeboards in the) drainage canals has exacerbated the land subsidence (Figure 22).

**Protection measures and mitigation approach**
The repair or replacement of the stormwater drainage system is now considered, including installing a combined drainage–infiltration system to minimise land subsidence, as was implemented in the Vondelpark in Amsterdam (see above). This would raise average groundwater levels, and buffer large fluctuations caused by excessive rainfall events and prolonged drought (Figure 23).

![Figure 22: Land subsidence in New Orleans - land has subsided but not the floor level.](image-url)
Figure 23: Schematic representation of a groundwater table managed by a combined drainage - infiltration system.

**Costs and Finance**

New Orleans lacks complete information on the groundwater system which limits the ability to design efficient and effective measures tuned to local conditions. In addition, little is known about the propagation of water level fluctuations of the Mississippi River and Lake Pontchartrain into the groundwater system (Deltares, 2013). Groundwater level and land subsidence issues have only recently gained attention in the city’s first Urban Water Plan, and currently no entity is responsible for groundwater management (Waggonner and Ball, 2013).

Managing groundwater and land subsidence, is only a fraction of the integrated Greater New Orleans Urban Water Plan. Total implementation of the plan would cost an estimated $US 6.2 billion but generate a total economic benefit of an estimated $US 22.3 billion over a 50-year period. Despite the allocated budgets, the proposed large-scale (ground) water management will require a creative approach and multiple avenues of funding (Waggonner & Ball, 2013). Likewise, integrated water management will increase the number of stakeholders involved, including a multitude of public bodies but possibly also new collaborations between the public and private sector (Waggonner & Ball, 2013).

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Deltares
Golder Associates
3.4.4 Summary and Relevance to South Dunedin

A general overview and relevance of case studies 5 and 6 to South Dunedin is provided in Table 4.

Table 4: Combined horizontal drainage and infiltration – summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Amsterdam and New Orleans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Both high and low groundwater levels can have adverse effects in these areas.</td>
</tr>
<tr>
<td>Protection measures implemented or proposed</td>
<td>A combined horizontal drainage and infiltration system ensures the groundwater level is optimal.</td>
</tr>
<tr>
<td>Part of suite of measures?</td>
<td>If groundwater levels decline too much it can accelerate land subsidence and affect wooden pile foundations (exposure to air). Therefore levels are controlled and stabilised.</td>
</tr>
<tr>
<td></td>
<td>The Amsterdam case study involves a suite of measures; subsurface drainage, sheet piling, groundwater treatment and discharge to a surface water body.</td>
</tr>
<tr>
<td>Efficacy of the protection measures</td>
<td>System in operation in Amsterdam since 2015 and is reported as functioning well without residual risks.</td>
</tr>
<tr>
<td></td>
<td>New Orleans system is still in proposal phase.</td>
</tr>
<tr>
<td>Limitations and constraints</td>
<td>System design, operation and maintenance can be complex.</td>
</tr>
<tr>
<td>Community acceptance and windows of opportunity</td>
<td>Systems implementation forms part of urban renewal project.</td>
</tr>
<tr>
<td>Indication of whole life costs</td>
<td>$US 6.2 billion for full plan, however, much larger area than South Dunedin and costs reflect this.</td>
</tr>
<tr>
<td>Relevance to South Dunedin</td>
<td>High groundwater levels are the concern in South Dunedin.</td>
</tr>
<tr>
<td></td>
<td>Some areas may be prone to land settlement. Saline intrusion may be accelerated if drainage levels are set too low.</td>
</tr>
<tr>
<td></td>
<td>Urban renewal projects could also provide a window of opportunity for implementing protection options in South Dunedin.</td>
</tr>
</tbody>
</table>

3.5 Selective Groundwater Drainage

3.5.1 Introduction

The response of the authorities in these case studies was to progressively improve groundwater drainage under public buildings/spaces and communicate responsibility of private property owners to improve drainage within their own properties. Priority areas for protection measures have been determined through planning mechanisms.

The Hoogeveen case study serves as an example of the implementation of the legal framework for managing groundwater issues in urban areas in The Netherlands (Section 4.5). The city council has
implemented drainage in public spaces and facilitated measures taken by private property owners, for example by offering connections for groundwater discharge from private properties to the public stormwater system. The Dresden case study describes a situation in which a large urban area is affected by high groundwater levels following significant flows in a major river nearby. The dynamics of high river flows and subsequent groundwater level rise are different from sea level fluctuation effects on nearby groundwater levels but the adverse effects can be similar.

3.5.2 Case Study 7: Hoogeveen (The Netherlands)

Characteristics
Hoogeveen is a city in the north of The Netherlands that has widespread and locally persistent high groundwater issues, despite being located at relatively high ground. The main cause is the presence of a (nearly) impermeable glacial clay layer at shallow depth, and a loamy topsoil, both of which restrict proper drainage and cause high groundwater levels. The city has a population of 40,000 and the urban area covers approximately 20 km².

Protection measures and mitigation approach
Until 2008, little action was taken to tackle the problem, much to the frustration to the residents who did not know whom to address their issues. The establishment of the Dutch national legal framework on managing groundwater in urban areas (Section 4.5), prompted the district/city council to develop internal policy catered to local conditions. Three closely related key elements of this policy are as follows:

1) Establishment of an extensive groundwater monitoring network;
2) Development of a groundwater plan (Gemeente Hoogeveen & Wareco Ingenieurs 2012); and
3) Development of a communication strategy including an on-line water portal.

Initially, past experiences and monitoring data were used to delineate priority areas. Residents in those areas were interviewed in 2012 about their experiences with high groundwater on or near their property. The outcomes were then used to refine the district management plan. The district management plan states where the district/city council will take action, what type of action, and when. It combines several of district/city council’s responsibilities and by including groundwater management the potential for windows of opportunities (Section 4.5) were identified.

The groundwater plan states that when high groundwater level issues are regarded ‘structurally and persistently’, the district council has responsibility to implement mitigation measures, provided that they are cost effective. In this case the number of specific high groundwater complaints and the length of period that the depth to groundwater is less 0.8 m below ground level in the public space are used as criteria. A clear division of responsibilities between the public and private sector for addressing urban groundwater issues is formalised in the groundwater plan.

Hoogeveen city council aims to reduce present and future structural and persistent high groundwater issues, by taking cost-efficient measures on public land. The district/city council will also facilitate measures taken by private property owners, for example by offering connections for groundwater discharge from private properties to the public stormwater system.

Based on an evaluation of a pilot drainage project, it is expected that measures on private property are in many cases necessary, given the generally low permeability of the loamy topsoil. The following ranking in preferred measures to be taken by the district/city council in both new and existing urban areas applies:

1) Raise ground level (with sufficient addition of sand)
2) Ground improvement of the top soil
3) Create (additional) surface water
4) Install groundwater measures such as subsurface drainage
Furthermore, it was decided that design and construction standards are adopted or developed, so as to ensure sufficient and constant quality, and durability of all measures taken.

All relevant plans, projects and monitoring results are communicated through the water portal in a way that is understandable for the general public. The district/city council’s motto is ‘communicate what you do and do what you communicate’.

**Costs and finance**

For the period 2012-2014, the total costs of groundwater management were budgeted at circa € 835,000. Of this total € 725,000 are one-off costs (groundwater plan, district-scale groundwater plans, drainage projects), and € 110,000 are annual costs for groundwater monitoring, operation of the water portal, and maintenance of existing drainage.

The annual time investment for the responsible council officer amounts to 0.2 of a full time equivalent. All costs are financed from the sewage tax, which forms part of the council rates. Since the introduction of the national legal framework for managing groundwater issues in urban areas in 2008, many municipalities have extended the existing sewage tax to encompass groundwater management.

**3.5.3 Case Study 8: Dresden (Germany)**

**Characteristics**

Dresden is a city in the southeast of Germany and has a population of approximately 540,000. The Elbe River flows through the city centre. In 2002, unprecedented high flows in the river Elbe not only caused direct flooding of parts of the city of, but also raised groundwater levels in other parts of the city. This caused widespread damage to structures throughout the city.

**Protection measures and mitigation approach**

After the 2002 flooding Dresden City Council took initiative to mitigate the effects of future high river flows and subsequent groundwater level rise. This was done in cooperation with other authorities among others the Saxony Regional Council.

The city council developed a flood protection plan (Landeshauptstadt Dresden, 2011) in which a clear distinction between responsibilities was made:

- Mitigation measures aimed at controlling Elbe river stages, such as flood protection walls and upstream retention basins, are the responsibility of public authorities. These measures are not explicitly related to groundwater, but indirectly contribute to mitigating of groundwater rise.

- Local groundwater drainage systems dedicated to public buildings were installed (and financed) by the city council.

- The city council also implemented an extensive groundwater monitoring system (Figure 24), covering an estimated 20 % of the total city area.

- Private property owners are in principle responsible for taking measures against high groundwater levels. This means that private property owners are responsible for implementing groundwater mitigation measures (on their property), which may be required in those areas not benefiting from the measures related to Elbe river stages.

In 2013 another significant flood event occurred in the Elbe River, ranked second in history after the 2002 event. In a subsequent evaluation, it was concluded that Dresden coped well with the consequences of the 2013 event because of the efforts made since 2002 (Landeshauptstadt Dresden, 2013). This includes the effectiveness of technical measures taken, a better flood protection organisation, and a better organised self-reliance of residents in flood-prone areas. The self-reliance is seen as an important part of the mitigation strategy, because technical measures may not be sufficient to fully avoid flooding.
The groundwater monitoring network from the city council was upgraded into a real-time municipal groundwater monitoring network with web based access since 2013. The real-time data presented on the website enables residents to take timely measures against the effects of high groundwater levels.

Figure 24: On-line portal to groundwater monitoring network in Dresden with real-time display of measurements. Source: Landeshauptstadt Dresden, Umweltamt.

Costs and finance

The cost of local groundwater drainage systems dedicated to public buildings had mounted to €2.86 million by 2011. The costs of the groundwater monitoring system were €450,000 installation and an additional €30,000 per year for operation and maintenance.

3.5.4 Summary and relevance to South Dunedin

A general overview and relevance of case studies 7 and 8 to South Dunedin is provided in Table 5.

---

### Table 5: Selective Groundwater Drainage - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Dresden and Hoogeveen</th>
</tr>
</thead>
</table>
| **Characteristics**                          | ■ In Hoogeveen, poor drainage capacity of the soils result in high groundwater issues. Initially, property owners considered they had nowhere to turn to resolve these.  
■ In Dresden, increase in river flows as a result of more extreme weather has made the city more flood prone and increased urban groundwater issues. |
| **Protection measures implemented or proposed** | ■ Authorities developed policies and management plans with clear division of responsibilities of the council and those of property owners.  
■ Local groundwater drainage systems installed near council buildings and structures. However, private property owners remain responsible for drainage issues on their properties.  
■ Part of a suite of measures. |
| **Efficacy of the protection measures**      | ■ In Dresden, protection has provided the expected level of service as significant high river flow events occurred after implementation and effects of high groundwater levels were significantly less. Residual risks are communicated to the property owners.  
■ Hoogeveen involves the progressive installation of protection measures as individual sites are deemed to be affected through planning mechanisms. |
| **Limitations and constraints**              | ■ Protection measures installed by authorities under public buildings and public spaces.                                                                |
| **Community acceptance and windows of opportunity** | ■ The division of responsibilities and information sharing is formally outlined in policies and plans to provide transparency. |
| **Indication of whole life costs**           | ■ Dresden installation costs:  
Groundwater drainage system: €2.86 M.  
Groundwater monitoring network: €450,000 and O&M €30,000/y.  
■ Hoogeveen costs for plan changes and installation were € 725,000, ongoing monitoring and management € 110,000 per year. |
| **Relevance to South Dunedin**              | ■ A gradual increase of urban groundwater level issues as a result of climate change is also expected in South Dunedin.  
■ The separation of protection measures between authorities and property owners could be a relevant consideration for the South Dunedin situation. |
3.6 Retrofitting Open Canals

3.6.1 Introduction

Planned development or re-development in or near urban areas affected by high groundwater levels can provide a window of opportunity to cost-effectively implement large-scale and robust mitigation measures against the effects of high groundwater levels. The case study Ooststellingwerf in The Netherlands provides an example of the benefits of retrofitting open canals.

3.6.2 Case Study 9: Ooststellingwerf (The Netherlands)

Characteristics

The town of Oosterwolde in the municipality of Ooststellingwerf is located in the north of The Netherlands close to Hoogeveen (Section 3.5.2). It is set in a similar geological environment, with (nearly) impermeable glacial clays and loamy top soils characterising the subsurface. The town has a population of approximately 10,000. Stormwater flooding and high groundwater issues were persistent in the low-lying neighbourhood of Oosterwolde-Zuid in the south of the town, which covers an area of some 1 km².

This neighbourhood was developed during the post-WWII rapid urbanisation period, prompted by huge demand for housing. The quality of houses, roads and amenities of the neighbourhood deteriorated over time exacerbated by the stormwater and groundwater issues.

Protection measures and mitigation approach

In 2000, the district/city council, the water board (i.e., a local water management authority), two housing corporations and a residential interest group agreed on an integrated renovation of the housing stock, the public space, and the water system (STOWA / Deltares / Rijkswaterstaat, 2009; www.oosterwoldezuid.nl).

A major feature of the renovation was the creation of a central open canal in the neighbourhood, enabling storage for rain water and drainage of groundwater (Figure 25). A new stormwater network was installed as well as a subsurface drainage system that both discharged to the canal. The canal discharges into a nearby regional water course. A number of houses had to be demolished to develop the canal, but the canal provided clear added benefits to the overall quality of the neighbourhood by providing a recreational amenity. In addition, water houses were built partially into the water, as such utilising the apparent loss of land surface for the creation of open water.

The district/city council clearly communicated to stakeholders that the council would only install drainage systems on public land. Private property owners would have to implement measures on their own land if still required. However, the council made provisions so property owners could discharge the drained groundwater from their property. This division of responsibilities is an example of the implementation of the Dutch national legal framework on managing groundwater issues in urban areas, operative since 2008 (Section 4.5).

The district/city council played a crucial role in handling delicate issues such as the demolition of existing houses to make way for the open canal. The early and continuous involvement of the district/city council is considered a major success factor.
Costs and Finance

The renovation was financed by the housing corporation (€ 25 million) and the municipality (€ 7.5 million) and completed in 2007. Overall, the subsurface drainage system installed on public land still performs well after 10 years. Technical matters requiring attention are as follows:

1) Management of the inflow of iron-rich compounds, which may cause clogging, and
2) Informing newcomers about existing drainages and about their responsibilities with respect to managing groundwater on their properties (pers. comm., Municipality of Ooststellingwerf).
3.6.3 Summary and relevance to South Dunedin

A general overview and relevance of case study 9 to South Dunedin is provided in Table 6.

Table 6: Retrofitting open canals - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Ooststellingwerf</th>
</tr>
</thead>
</table>
| **Characteristics**                               | ■ Rapidly developed suburb in low-lying area. Groundwater issues arise from poor drainage.  
                                              | ■ Deterioration of houses, roads and amenities was exacerbated by stormwater and groundwater issues.                                             |
| **Protection measures implemented or proposed**   | ■ Urban renewal project involved the construction of open water (canal) as well as stormwater network renewal and groundwater drainage systems.   |
| **Part of suite of measures?**                    | ■ Part of a suite of measures.                                                                                                                      |
| **Efficacy of the protection measures**           | ■ Open water in combination with subsurface drainage provides both groundwater (drainage) and stormwater (storage) benefits. The system still works well after 10 years and is considered to be providing the expected level of service.   |
| Has protection provided expected level of service? | ■ Open water provides amenity values to the community.                                                                                             |
| Any residual risks?                               | ■ Residual risks not documented.                                                                                                                    |
| **Limitations and constraints**                   | ■ The implementation required removal of houses.                                                                                                    |
| **Community acceptance and windows of opportunity** | ■ Early community engagement and council involvement was crucial.  
                                              | ■ The urban renewal project provided multiple benefits and the outcome is widely accepted.                                                          |
| **Indication of whole life costs**                | ■ Housing corporation € 25 million.  
                                              | ■ Municipality € 7.5 million.                                                                                                                       |
| **Relevance to South Dunedin**                    | ■ Similar shallow groundwater in low lying area.  
                                              | ■ South Dunedin currently has no open water courses.                                                                                               |
|                                                   | ■ Creating open water may have similar constraints and benefits in South Dunedin.                                                                 |
|                                                   | ■ Urban renewal projects could also provide a window of opportunity for implementing protection options.                                              |
3.7 Vertical Drainage (wells)

3.7.1 Introduction

The effects of reducing pumping from production wells can cause rising groundwater levels under urban areas. The slow rise in groundwater level can be related to South Dunedin’s situation, even though the cause of rising groundwater level is different. Lessons learnt regarding pumping from deep wells to protect urban areas can be used to assess potential issues with vertical pumping as a protection measure. Some case studies found that pumping costs can be significant without a beneficial use for the abstracted water.

Many cities across the globe face the effects of abandoned large-scale groundwater abstractions, the cities of Delft and Eindhoven have taken initiative to take over the groundwater abstractions before they were closed, in an effort to mitigate against the effects of rising groundwater levels.

3.7.2 Case Study 10: Delft

General

The city of Delft is located in the west of the Netherlands and has a population of approximately 100,000. The city is located in an area with peat meadows, characteristic of the western and northern part of The Netherlands. Peat soils are prone to shrinkage which can cause land subsidence.

In Delft, the industrial groundwater abstraction ‘Delft Noord’ significantly reduced groundwater levels across the city (Figure 26), which also caused land subsidence over time. Cessation of pumping would raise groundwater levels in areas that had subsided and would cause widespread high groundwater issues.

Figure 26: Current drawdown of hydraulic head below Delft exceeds 10 meters, conditioned by pumping station Delft-Noord.
Protection measures and mitigation approach

The city council therefore decided to take over the groundwater abstraction, initially in cooperation with the regional council. The groundwater abstraction was maintained and the associated investments and annual operational costs amount to several million of euros. The city council would prefer to transfer the groundwater abstraction to a new user, but has so far not been able to find one, partly because the pumped groundwater is brackish and of little use to potential users.

Meanwhile, the city council proposed a stepwise reduction of pumping, in combination with close monitoring of groundwater level responses and implementation of additional horizontal subsurface drainage where needed. Priority areas for this subsurface drainage have been identified following a risk-based approach on the basis of monitoring results of an extensive groundwater monitoring network (160 shallow observation wells distributed over circa 24 km² municipality area), groundwater modelling of various future scenarios, and an assessment of objects that are vulnerable to groundwater rise.

High groundwater level issues are already common throughout the city, but are unrelated to the reduction of the large-scale groundwater abstraction. This often complicates communication with residents about the issue.

3.7.3 Case Study 11: Eindhoven

General

The city of Eindhoven is located in the south of the Netherlands and has a population of 200,000. The area has a sandy soil and subsurface and is less prone to land subsidence than Delft. In this case two large-scale groundwater abstractions were encroached by expanding urban areas. The cessation of pumping would cause groundwater levels to rise and local buildings and other urban functions do not have sufficient groundwater drainage provisions. The groundwater abstractions comprise of an industrial abstraction that became redundant, and a drinking water supply abstraction affected by groundwater contamination.

Protection measures and mitigation approach

The city of Eindhoven managed to establish a sustainable coalition with regional partners to continue pumping. This coalition maintains the industrial abstraction to avoid widespread groundwater flooding issues. The contaminated drinking water well was abandoned and the abstraction moved to a nearby area unaffected by the groundwater contamination. Furthermore, a reconfiguration of pumping regimes across three drinking water abstractions in the area was established, which had multiple benefits, such as drought relieve to environmental conservation areas, a reduction of salinization risks, and the prevention of high groundwater issues in the city of Eindhoven. Whilst groundwater levels did rise, this was maintained within acceptable limits for the local buildings and urban features in the area.

Cost and Finance

The costs of the described operations are jointly carried by the city of Eindhoven, the water authority, and the drinking water company. The city council’s contribution was € 750,000 (Gemeente Eindhoven, 2003).

3.7.4 Case Study 12: Buenos Aires

General

Buenos Aires is the capital and most populous city of Argentina, with a population of approximately 2.9 million. The city is located in the north east of Argentina near the coast.

Following growing concern about groundwater pollution, the main water supply authority was required to improve the quality of the supplied water to WHO potable standards. With groundwater no longer an option large volumes of treated surface water were imported to the city. However, widespread and persistent groundwater drainage problems occurred in the city as a consequence of the reduction in groundwater abstraction from the underlying aquifer.


**Protection measures and mitigation approach**

It was recognised that the generally low permeability of the shallow subsurface would render horizontal subsurface drainage inefficient. The most effective solution was to (partly) restore pumping from the underlying aquifer, preferably combined with some form of utilisation of the abstracted groundwater. In 2002, it was recognised that establishing an alliance of public authorities and representatives of the urban population would be crucial. A ‘revolving fund’ was proposed to finance the required efforts, which was to be recovered from urban rates and water charges (World Bank / GW MATE, 2002).

By 2007, several projects to control the groundwater table in specific areas of Buenos Aires were in the design phase. The plan proposed that pumped water was to be discharged into the stormwater drainage system (HIDROAR / Ciudad de Buenos Aires, 2007). The discharge of the pumped groundwater was a constraint on the system as leakage from the stormwater drainage network could lead to renewed recharge of the aquifer. The limited capacity of the stormwater drainage network during high rainfall was an additional concern. The cost of installing 37 wells with pumping equipment in the Puelche and Paraná aquifers was estimated at $US 3.2 million (HIDROAR, 2009). The installation of the wells was implemented in the framework of an integrated water management project in the Matanza – Riachuelo basin (2,240 km²).

No information was found on the actual implementation of the proposed measures, and their efficacy.

### 3.7.5 Case Study 13: Odense

**General**

Odense is located on the middle of Denmark on the island of Funen. The city’s groundwater abstraction history is similar to that of Buenos Aires (Laursen & Mielby, 2016). Groundwater abstraction gradually increased from 1870 onwards and reached its peak after 1950. Due to deterioration in water quality and a desire for a more sustainable abstraction, pumping has been reduced dramatically in the last decade. Pumping is now almost back at the same rate as during the first half of the 20th century.

During the same period the city has grown considerably from 11,000 inhabitants in an area of 2.5 km² in the 1850’s to more than 172,000 inhabitants living across 78 km² in 2014. Urban areas that were developed in the period of maximum groundwater drawdown are becoming increasingly waterlogged, as groundwater abstraction is reduced. This is a concern for the inhabitants. In addition, annual mean precipitation has increased by around 100 mm since measurements started in 1876, which exacerbates the groundwater issues.

**Protection measures and mitigation approach**

The local water / waste water service company (VCS) prefers to minimize the amount of groundwater entering the sewage system and would rather groundwater is discharged on site. In addition, the city of Odense has the ambition to manage stormwater locally as much as possible. Therefore, attempts are by the authorities to persuade private property owners to establish seepage systems and swales on their property. Those who do can get a reduction in council rates paid for sewage connection.

High groundwater levels interfere with the stormwater infiltration initiatives and localised managed retreat was implemented by VCS, to cope with reoccurring flooding in an Odense suburb. Seven property owners were bought out, their houses were removed and the resulting area was turned into a local park which included a rain water storage area (Figure 27). This measure was not designed to solve high groundwater issues, but rather to address stormwater issues that in part were the result of high groundwater levels.

Danish law rules that a party that abstracts groundwater is liable for any damages caused on buildings or structures by lowering the groundwater table. However, parties hold no liability for damages if groundwater levels are returned to the original level (i.e., after pumping is stopped). No measures have yet been implemented against the effects of high groundwater level and no major groundwater monitoring program or detailed groundwater modelling has been undertaken.
3.7.6 Summary and relevance to South Dunedin

A general overview and relevance of case studies 10 to 13 to South Dunedin is provided in Table 7.
### Table 7: Vertical Drainage (Wells) - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Delft, Eindhoven, Buenos Aires and Odense</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Characteristics</strong></td>
<td>■ Cessation of large groundwater abstractions can cause a significant rise in groundwater levels on a large scale, affecting extensive urban areas that do not have (sufficient) groundwater drainage infrastructure.</td>
</tr>
<tr>
<td><strong>Protection measures implemented or proposed</strong></td>
<td>■ Implementation of an area-wide solution would be too costly. Prioritisation of drainage issues has been made based on monitoring and scenario modelling.</td>
</tr>
<tr>
<td><strong>Part of suite of measures?</strong></td>
<td>■ Continuation of well abstractions and new use of abstracted water has been explored.</td>
</tr>
<tr>
<td></td>
<td>■ Alliances between authorities and stakeholders have been formed to address the issues (Delft, Eindhoven).</td>
</tr>
<tr>
<td></td>
<td>■ Suites of measures such as selective removal of properties, raising ground level and creation of storage for stormwater management, have been combined with groundwater level control (Odense).</td>
</tr>
<tr>
<td><strong>Efficacy of the protection measures</strong></td>
<td>■ Large scale abstraction from wells was effective in lowering groundwater levels.</td>
</tr>
<tr>
<td><strong>Has protection provided expected level of service?</strong></td>
<td>■ Continued large scale abstractions from wells can be expensive if there is no beneficial use for the abstracted water.</td>
</tr>
<tr>
<td><strong>Any residual risks?</strong></td>
<td>■ Drainage and stormwater storage solutions are being instigated to deal with the risks of rising groundwater level.</td>
</tr>
<tr>
<td><strong>Limitations and constraints</strong></td>
<td>■ Drainage water may be of poor quality and limits the possibilities for discharge (Buenos Aires).</td>
</tr>
<tr>
<td><strong>Community acceptance and windows of opportunity</strong></td>
<td>■ Authorities are looking at uses and disposal locations for the abstracted water.</td>
</tr>
<tr>
<td><strong>Indication of whole life costs</strong></td>
<td>■ Eindhoven involved split cost between city authorities, water authority, and drinking water company. City council’s contribution € 750,000.</td>
</tr>
<tr>
<td></td>
<td>■ Buenos Aires: Cost of installing 37 wells with pumping equipment in the Puelche and Paraná aquifers was estimated at $US 3.2 million.</td>
</tr>
<tr>
<td><strong>Relevance to South Dunedin</strong></td>
<td>■ The groundwater level rise in South Dunedin has a different cause, but the wide-spread effects and potential protection options are similar.</td>
</tr>
<tr>
<td></td>
<td>■ Any vertical pumping protection measure for South Dunedin would require careful consideration of discharge options and costs of pumping.</td>
</tr>
</tbody>
</table>
3.8 Risk-Based Groundwater Management

3.8.1 Introduction

This section includes a case study in which the authorities determined the responsibilities for managing high groundwater levels in urban areas by following a risk-based approach.

3.8.2 Case Study 14: Enschede (Netherlands)

Characteristics

The municipality of Enschede (approx. 158,000 inhabitants in 140 km²) faces groundwater level rise after reduction and closure of pumping stations, in this case mainly conditioned by the rise and fall of the textile industry during the 20th century.

Protection measures and mitigation approach

In response to groundwater level rises occurring throughout the city, the city council developed internal policy in recognition of the Dutch legal framework on managing urban groundwater issues (Section 4.5).

The city’s groundwater management policy comprises a risk-based approach to groundwater problems on private properties. Different categories of adverse effects of high groundwater are ranked according to their severity (health and safety issues ranking highest) and assigned a maximum acceptable risk threshold, based on frequency of occurrence (Figure 28). If the risk threshold is exceeded, action by the city is required provided that measures are cost-effective.

![Risk matrix as guidance for deciding upon measures against high groundwater.](image)

Figure 28: Risk matrix as guidance for deciding upon measures against high groundwater. VL=very low to EH = extremely high. Note: risk threshold may vary for different municipalities (policy choice). Adjusted after original by City of Enschede.

In the absence of a clear definition of cost-effectiveness in the national legal framework, the city council has adopted the (provisional) rule that the cost of measures in the public space should not exceed 80% of the cost of measures on private grounds. The city does not take responsibility for groundwater leakage or
flooding in basements as this is considered to be a responsibility of the property owner. Buildings younger than 1992 are excluded from this approach, as laws require them to have a damp-proof ground floor. Therefore, groundwater flooding in the crawl space under the new houses should not cause problems in the living spaces of the houses if installed correctly.

So far, the risk-based approach has been implemented in one case in Enschede. The outcome was that the city was considered responsible to take measures, which was welcomed by the residents. The city expects less positive reception in cases were no measures by the city council are required (i.e., when none of the risk thresholds are exceeded), even if the community has been made fully aware of the approach. Conversely, risk thresholds are expected to be exceeded in areas with large-scale effects on health, prompting measures by the city (pers. comm., City of Enschede). Currently, seven areas are prioritised for additional investigations, with areas estimated at 5 to 20 ha each (Gemeente Enschede, 2016).

### 3.8.3 Summary and relevance to South Dunedin

A general overview and relevance of case study 14 to South Dunedin is provided in Table 7.

#### Table 8: Risk-based groundwater management - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Enschede</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Cessation of large groundwater abstractions caused a significant rise in groundwater levels on a large scale, affecting extensive urban areas without sufficient groundwater drainage infrastructure.</td>
</tr>
<tr>
<td>Protection measures implemented or proposed</td>
<td>Groundwater management policy comprises a risk-based approach (ranking according to effects severity, based on frequency of occurrence) to groundwater problems on private properties.</td>
</tr>
<tr>
<td>Efficacy of the protection measures</td>
<td>Implemented in one area so far where the authorities carried out protection measures.</td>
</tr>
<tr>
<td>Has protection provided expected level of service?</td>
<td>Has allowed prioritisation of resources by the city council.</td>
</tr>
<tr>
<td>Any residual risks?</td>
<td>Residual risks to those considered low priority.</td>
</tr>
<tr>
<td>Limitations and constraints</td>
<td>In some cases the risk matrix may lead to the authorities deeming the responsibility for protection measures is the responsibility of the property owners.</td>
</tr>
<tr>
<td>Community acceptance and windows of opportunity</td>
<td>Accepted by those who gain from the results of the risk assessment.</td>
</tr>
<tr>
<td>Indication of whole life costs</td>
<td>No detail available for costs to determine the risk matrix. Costs to city will depend on extent of areas requiring protection measures.</td>
</tr>
<tr>
<td>Relevance to South Dunedin</td>
<td>The groundwater level rise in South Dunedin has a different cause, but the wide-spread effects and potential protection options are similar.</td>
</tr>
<tr>
<td></td>
<td>A risk-based approach provides a practical and transparent method to separate responsibilities between authorities and property owners.</td>
</tr>
</tbody>
</table>
3.9 Liquefaction and Managed Retreat

3.9.1 Introduction

Liquefaction of soils occurs when saturated or partially saturated cohesion-less soil substantially loses strength and stiffness in response to earthquake shaking, causing it to behave like a liquid. This can result in substantial damage to buildings and infrastructure. Liquefaction after a significant earthquake can be widespread in areas with a shallow groundwater table in combination with susceptible silty or sandy soils. The Christchurch case study presented in this section is an example of the widespread damaging effects of liquefaction following significant earthquakes.

3.9.2 Case Study 15: Christchurch (New Zealand)

Characteristics

Christchurch is located on the east coast of New Zealand’s South Island and has a population of approximately 350,000. Most of the city resides upon late Quaternary alluvial sediments, with alluvial gravels dominating the west of the city and coastal dunes and estuarine/tidal wetland sediments dominating the east. There are finer alluvial overbank deposits from the Avon and Heathcote Rivers superimposed on these accumulations (Brown and Weeber 1992). Groundwater is more than 5 m below the surface west of Christchurch City, but less than 2 m deep beneath much of the city (GNS 2014).

Urban expansion in the late 1800’s included widespread drainage works to allow for the development of the land. Separate stormwater and wastewater networks were installed, which over time developed leaks and consequently drains groundwater. Drainage into both the stormwater and wastewater networks has contributed to land subsidence (Hughes et al 2015).

Christchurch was struck by four major earthquakes on 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011 and a large number of significant aftershocks, which severely damaged much of the central business district and surrounding residential areas. Widespread soil liquefaction occurred predominantly in saturated, unconsolidated alluvial and marine fine sediments in east Christchurch, affecting roads, subsurface infrastructure and buildings (Figure 29). High groundwater levels in susceptible soils significantly increases the vulnerability to liquefaction. Urban rivers and streams were affected by liquefaction induced lateral spreading of the river banks, and sedimentation, which narrowed and shallowed the streams. The liquefaction and tectonic movement caused land subsidence in excess of 0.5 to 1 m along tidal stretches of the two main urban rivers (i.e. Avon and Heathcote). This greatly enhancing the spatial extent and severity of inundation hazards posed by 100-year floods, storm surges, and sea-level rise (Hughes et al 2015).

The land subsidence from drainage works, leaking sewage systems and, more recently, earthquakes have caused groundwater levels to be closer to the ground surface, which increased the areas susceptibility to high groundwater issues. However, reports of high groundwater level effects such as water ponding and damp or wet basements, being widespread and perceived as a significant issue throughout Christchurch could not be found. Christchurch has a long history in dealing with drainage issues and between 1875 and 1989 the now defunct Christchurch Drainage Board installed and maintained a network of open channels and drains to manage groundwater. That a separate body, with sole responsibility for drainage, was thought necessary for Christchurch from an early date is an indication of the difficulties the city’s site posed for drainage and sewage (CDB, 1989). CDB's responsibilities and assets were transferred to Christchurch City Council in 1989. Currently, high groundwater level concerns from the Christchurch City Council (CCC) and Canterbury Regional Council (CRC) are more related to the increased susceptibility to liquefaction of certain urban areas.
Protection measures and mitigation approach

A large part of Christchurch’s eastern suburbs has been ‘Red Zoned’ following the 2011 earthquakes. The Red Zone is an area defined by the Government as unsuitable for continued residential occupation at the present time. Generally this area encompasses the most severely damaged land in Canterbury (GNS 2014). This includes areas that were severely affected by liquefaction and for which the susceptibility for flooding increased. This can be considered a form of managed retreat.

Structural solutions to building foundations and ground improvement solutions are usually considered for reducing the susceptibility of a property to liquefaction. Although the relationship between high groundwater levels and liquefaction is acknowledged (GNS 2014, Hughes 2015), measures to control groundwater levels are not usually part of the design philosophy.

Drainage measures are considered for dealing with water ponding and wet/damp conditions in existing urban areas. CCC has issued drainage guidelines (CCC 2006) to be used during development or re-development of urban areas. It includes a description of design consideration for open drainage channels and subsurface drainage systems. These guidelines recommend that subsurface drainage should only be used to remedy surface water ponding in existing urban areas. The guideline also recommends that subsurface drainage is installed so that it is submerged at all times to avoid clogging. Furthermore, sufficient access points for maintenance are recommended. Ground levels should be appropriately raised in new developments and locally low-lying (wet) area should not be developed, but included as wetlands or open water within the development.

Private property owners are responsible for stormwater that falls on their own property and to install and maintain groundwater drainage measures on their property. CCC will provide a point of discharge for the property.

CCC does not have a communication strategy in relation to high groundwater level issues or a designated groundwater monitoring network for the shallow groundwater table to assess these issues. However, many shallow groundwater monitoring wells have been installed for geotechnical investigations. Shallow
groundwater investigations are mainly undertaken in the context of geotechnical investigations in relation to liquefaction susceptibility (GNS 2014).

3.9.3 Summary and relevance to South Dunedin
A general overview and relevance to South Dunedin is provided in Table 9.

Table 9: Liquefaction and managed retreat as adaption to seismic hazard - summary and relevance.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Christchurch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristics</td>
<td>Soil conditions and high groundwater levels in Christchurch's eastern suburbs makes the area prone to the effects of liquefaction during earthquakes, as occurred in the 2011 Canterbury Earthquake Sequence.</td>
</tr>
<tr>
<td>Protection measures implemented or proposed</td>
<td>Christchurch Residential Red Zone represents a form of managed retreat.</td>
</tr>
<tr>
<td>Part of suite of measures?</td>
<td>Ground improvement is usually applied when properties are (re)developed to reduce the liquefaction susceptibility.</td>
</tr>
<tr>
<td></td>
<td>Suite of measures includes retreat and land improvement.</td>
</tr>
<tr>
<td>Efficacy of the protection measures</td>
<td>Managed retreat rather than a protection measure against the effects of high groundwater levels.</td>
</tr>
<tr>
<td>Has protection provided expected level of service?</td>
<td></td>
</tr>
<tr>
<td>Any residual risks?</td>
<td></td>
</tr>
<tr>
<td>Limitations and constraints</td>
<td>Not a protection measure.</td>
</tr>
<tr>
<td>Community acceptance and windows of opportunity</td>
<td>High impact on communities.</td>
</tr>
<tr>
<td>Indication of whole life costs</td>
<td>Not a protection measure. Significant costs for loss of property.</td>
</tr>
<tr>
<td>Relevance to South Dunedin</td>
<td>South Dunedin has similar soil conditions and high groundwater levels.</td>
</tr>
<tr>
<td></td>
<td>The effects of liquefaction and the relationship with high groundwater levels could be taken into consideration when developing protection strategies for South Dunedin.</td>
</tr>
</tbody>
</table>
4.0 DISCUSSION

4.1 Introduction

This section provides a description of causes and effects of high groundwater issues in urban areas derived from the selected case studies and other relevant examples. Many of the case studies are from The Netherlands which is very low lying and has relied on protection measures such as pumped open canals for groundwater level and flood protection for many years (Figure 30).

The success of protection options depends heavily on the ability to install them in optimal locations, and the ability to properly operate and maintain the systems. The case studies highlight that other matters to consider when protection options are considered are ownership of land, financial means for installation, and clearly defined responsibilities for operation and maintenance. High groundwater levels are often only one of the issues that low-lying urban areas face, as these areas typically also have stormwater management challenges and can be prone to inundation from the sea.

4.2 Causes of High Groundwater in Urban Areas

High groundwater levels typically occur in flat, low lying areas with low permeability soils after periods of prolonged rainfall. These are usually areas close to rivers, lakes or the sea. If natural drainage is poor and urban water management systems are not sufficient to cope with these conditions, groundwater levels can rise significantly. Several different causes for groundwater level rise are identified within the case studies. The learnings from how authorities decided to respond to the situation and the protection options used can be considered when investigating potential options for South Dunedin.

Figure 30: Pumped open canal in Hoorn, The Netherlands.
4.3 Consequences of High Urban Groundwater Levels

In urban areas where groundwater levels are relatively close to the surface (less than 1 m on average) several issues may arise, including surface water ponding, damage to infrastructure and buildings, and increased risks of liquefaction during earthquakes (MFE 2015). There are several ways that these issues affect urban areas:

- Flooding involving stormwater ponding on the surface associated with high groundwater levels. The high groundwater levels mean flooding can persist for a long time after significant rainfall events. Flooding generates a wide range of secondary effects, with the severity of many of these effects linked to the duration of the flooding.

- Buildings can be affected by wet conditions in basements and crawl spaces. Continually damp conditions are ideal for growth of fungus, affecting building materials such as timber framing and cladding, and causing respiratory diseases in humans.

- Fluctuations in groundwater levels can result in differential deformation of structures such as roads and houses due to soil swelling and shrinkage. Building floors can bulge as a result of buoyancy. Some soils may swell when wet or saturated, causing surface heave. Other soils are prone to collapse, resulting in subsidence and settlement. Problems may also arise for the installation and maintenance of subsurface infrastructure.

- In combination with certain types of soil and earthquake ground motions, high groundwater levels contribute to vulnerability of the built environment to damage caused by liquefaction and lateral spreading, affecting buildings, roads, subsurface infrastructure and waterways.

- The infiltration and storage capacity of soils for stormwater can be reduced affecting the soils stormwater detention potential.

High groundwater levels in urban areas can affect the whole community, including private property owners, businesses and district/city councils.

Authorities in The Netherlands use minimum drainage depth guideline values for various urban functions as listed in Table 10 (SBR 2007) to evaluate if urban areas are potentially affected by the consequences of high groundwater levels. Issues described above often arise when the required drainage depth cannot be longer maintained.

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Drainage depth (depth the groundwater in m below surface level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Houses, buildings, structures</td>
<td>0.70</td>
</tr>
<tr>
<td>Primary roads</td>
<td>1.00</td>
</tr>
<tr>
<td>Secondary roads</td>
<td>0.70</td>
</tr>
<tr>
<td>Cables and pipes</td>
<td>0.60 – 1.20</td>
</tr>
<tr>
<td>Gardens and parks</td>
<td>0.50</td>
</tr>
<tr>
<td>Sports fields</td>
<td>0.50</td>
</tr>
<tr>
<td>Graveyards</td>
<td>0.30 below coffin</td>
</tr>
</tbody>
</table>

As a consequence of pumping to manage groundwater levels, saline intrusion can occur. Saline intrusion is the movement of saline water (e.g., sea water) into an aquifer formerly occupied by fresh water as a result of human activity (Fetter 1994). Fresh groundwater, which is of lower density than seawater, will float on top of the saline groundwater. Saline intrusion risk needs to be considered when designing protection options for
South Dunedin. Saline water can affect water quality of coastal streams and wetlands, but also buildings and infrastructure (salinity can affect concrete piles and riprap).

### 4.4 High urban groundwater in New Zealand

Most major urban centres in New Zealand are located close to the sea and include areas that are low-lying and potentially affected by inundation from the sea. These areas typically also have high groundwater levels. MFE (2015) has assessed which coastal urban areas in New Zealand lie close to the average spring tide sea levels. Christchurch and Dunedin are the cities with the largest urban areas and the most buildings and infrastructure in areas less than 1 m above the spring tide levels (Table 11).

**Table 11: Low-lying homes, businesses and roads in the four major cities of New Zealand (after MFE 2015)**

<table>
<thead>
<tr>
<th></th>
<th>0 – 0.5 m</th>
<th>0.5 – 1 m</th>
<th>Total (0 – 1 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dunedin</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homes (number)</td>
<td>2,683</td>
<td>604</td>
<td>3,287</td>
</tr>
<tr>
<td>Businesses (number)</td>
<td>116</td>
<td>29</td>
<td>145</td>
</tr>
<tr>
<td>Roads (km)</td>
<td>35</td>
<td>17</td>
<td>52</td>
</tr>
<tr>
<td><strong>Christchurch</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homes (number)</td>
<td>901</td>
<td>3,629</td>
<td>4,530</td>
</tr>
<tr>
<td>Businesses (number)</td>
<td>5</td>
<td>58</td>
<td>63</td>
</tr>
<tr>
<td>Roads (km)</td>
<td>40</td>
<td>77</td>
<td>117</td>
</tr>
<tr>
<td><strong>Wellington</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homes (number)</td>
<td>103</td>
<td>1,920</td>
<td>2,023</td>
</tr>
<tr>
<td>Businesses (number)</td>
<td>1</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>Roads (km)</td>
<td>2</td>
<td>21</td>
<td>23</td>
</tr>
<tr>
<td><strong>Auckland</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Homes (number)</td>
<td>108</td>
<td>457</td>
<td>565</td>
</tr>
<tr>
<td>Businesses (number)</td>
<td>4</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td>Roads (km)</td>
<td>9</td>
<td>18</td>
<td>27</td>
</tr>
</tbody>
</table>

### 4.5 Management and Governance Considerations

Experience in The Netherlands has shown that the development and implementation of mitigation measures against the effects of high groundwater levels in urban areas can be cumbersome and costly. The nature of the issues may change over time with an increasingly larger area being affected. It may be unclear to what extent the land or property owner is responsible for addressing the issues or whether authorities are best placed to take the initiative. There may be uncertainty about the ways to finance mitigation approaches.

In this section several management considerations arising from the collective case studies are described that have been found to be critical as part of investigations and discussions during the development of mitigation strategies. This section also provides background information with respect to some of the case studies that can support an understanding of how the protection measures were implemented.
Formalising responsibilities

High groundwater levels affect privately owned properties, businesses and council land. This leads to multiple stakeholders dealing with the consequences of high groundwater levels. In many cases the issues cannot be effectively addressed on a single property and collaboration between stakeholders and proper coordination is essential.

A starting point could be to formally define the responsibilities of different stakeholders. An example of this is the way high groundwater issues in urban areas have been embedded within a legal framework in the Netherlands since 2008. The law in the Netherlands now requires municipalities (i.e., district or city councils) to take measures on public land to minimise structural and persistent adverse effects of high groundwater levels on council land and land adjacent to it. Measures are only required when they can be implemented cost-effectively and provided that they do not fall under another authorities’ jurisdictions. Property owners are responsible for installing measures themselves on their own property if needed, such as a subsurface drainage system. However, the district/city council is required to provide a means to discharge the drainage water. This could be a connection point to the nearby stormwater system. The district/city councils are the ‘first port of call’ for stakeholders to raise issues and concerns. The councils are required to carry out monitoring, investigate issues and are responsible for appropriate communication and stakeholder engagement.

Communication strategy

Communication and stakeholder engagement is a key element of any mitigation strategy, as its success often depends on stakeholder ‘buy in’. On-line media can help provide timely, transparent and targeted communication to stakeholders.

Communication can include the provision of information about the groundwater issues, their causes and results from monitoring. On-line publications and web-based presentation of real-time groundwater monitoring data may inform residents and businesses about short-term and long-term risks of rising groundwater levels, as described in the Hoogeveen case study (Section 3.5.2).

Monitoring

Continuous monitoring of groundwater levels helps to create awareness for groundwater amongst residents and public authorities. The monitoring results allow for evaluation of the groundwater conditions and of the performance of any groundwater management system. Clogging, blockages and other problems can be signalled from the monitoring. Groundwater levels can be visualised for residents and for educational purposes by making observation wells visible.

Financial arrangements

The case studies show that embedding the district/city council’s responsibility for urban groundwater management into a legal framework works best if sufficient funding is available for the responsible authority to inform stakeholders and implement measures. This means the district/city council needs sufficient staff resources and funding for implementing, operating and maintaining measures. In the Netherlands the broadening of the district/city council’s water management responsibilities to include urban groundwater management, allowed district/city councils to increase rates within reason. Rates increases can potentially be offset for landowners as property values increase while the urban environment improves (Figure 31).

Stakeholder alliances

In the case studies, alliances between different authorities were often established or expanded to jointly undertake necessary investigations or the development and implementation of effective mitigation measures. This collaborative approach has led to financial benefits to authorities and stakeholders.

Utilising windows of opportunities

Windows of opportunities arise when certain large-scale developments occur in or near an urban area that is susceptible to the effects of high groundwater levels. If utilised, these windows of opportunity have provided
significant financial benefit to communities in their endeavour to tackle urban groundwater issues. The following windows of opportunity are worth considering:

- Planned road or sewage network maintenance programmes: one of the best opportunities to implement high groundwater mitigation measures is when roads are excavated in their entirety for stormwater, wastewater or water main renewal or upgrade. Similar opportunities occur when parts of the water supply network or the power network are being replaced.

- Building permitting processes: specific requirements for groundwater management measures can be included on building permits or consents when new urban areas are being developed or existing urban areas are re-developed.

![Urban open canal in Hoorn, The Netherlands](image)

Figure 31: Urban open canal in Hoorn, The Netherlands

**Integrated solution packages**

Low lying urban areas are usually subject to multiple hazards such as severe weather, flooding, earthquakes and tsunamis, together with geotechnical issues that exacerbate the effects of those hazards. Experience indicates that an integrated approach to resolving these collective issues is important because:

- Considering approaches and solutions collectively may enable multiple hazards to be mitigated at the same time, improving the cost effectiveness of the measures instigated.

- The risk of mitigation measures resolving one issue but simultaneously exacerbating other issues is reduced (e.g., groundwater drainage can also lead to acceleration of on-going land settlement).

The Miami region in the USA serves as an example how multiple hazards can expose urban assets and populations on a large scale. This region is susceptible to inundation from the sea, which has increased as a result of sea level rise (Anderson et al 2016). Saltwater seepage underneath sea walls through porous limestone also affects groundwater quality through saline intrusion (WRI 2014). The Miami stormwater system is locally designed to drain to the sea and experiences reduced effectiveness as sea levels rise or during extreme high tide periods, increasing flood risks.
5.0 SYNTHESIS FROM CASE STUDIES

5.1 Introduction

This section summarises the findings from the case studies in relation to South Dunedin, based on the six factors listed in Section 1.3. It gives a synthesis of the commonalities between case studies but also their uniqueness in relation the urban high groundwater issues. The different characteristics of the case studies are compared to the South Dunedin situation.

5.2 Characteristics, Scale and Size

The most common effects of high groundwater levels in urban areas are damp or even wet basements and crawl spaces beneath buildings, and the associated adverse effects on the building’s climate and construction as well as the occupant’s health. Also reported was damage to trees, bulging floors as a result of buoyancy or heave, and saline intrusion affecting groundwater quality, foundations and septic tanks.

The issue of liquefaction presented in the Christchurch case study is an issue specific to earthquake prone areas with silty and sandy soil types, which is relevant to South Dunedin’s situation.

South Dunedin’s issues cover multiple neighbourhoods. All but one of the presented case studies are on the scale of a neighbourhood, multiple neighbourhoods, a whole city, or a full metropolitan region. Several case studies of the successful implementation of mitigation strategies relate to an area of a similar size to South Dunedin. The scale of South Dunedin’s groundwater issue is therefore not considered to fundamentally restrict the development and implementation of a successful mitigation approach.

5.3 Protection Measures and their Efficacy

The successful application of technical measures is often more dependent on proper design, implementation and on-going maintenance than the nature of the measures. Often a suite of methods have been applied in the case studies rather than one protection measure alone.

Successful systems are designed to be robust and allow for sufficient options for maintenance and repair. Adequate supervision during installation and testing has been shown to be crucial. A proper understanding of local conditions (mainly hydrology, hydrogeology and geology) and effective engagement of residents is always required.

Relevant insights from the case studies include:

- Horizontal subsurface drainage is the most widely used method for high groundwater level mitigation as it can be retrofitted in existing urban areas. In most cases these systems better target the problem areas and require less water to be abstracted than vertical drainage systems.

- Vertical drainage through pumping wells is more feasible if the abstracted water can be used or other benefits can be achieved (case study Eindhoven).

- Horizontal subsurface drainage is best installed below the expected lowest groundwater level to ensure it is always saturated. This minimizes the risk of clogging and excessive maintenance (case studies Haarlemmermeer and Haarlem).

- Measures taken on private property should be properly documented and new property owners need to be made aware of their responsibilities. If not, systems may gradually degrade because of poor maintenance and lack of repair (case studies Haarlemmermeer and Oosterwolde).

- The use of subsurface drainage systems with infiltration capacities is feasible, if designed properly. They can be effective in maintaining a relatively flat groundwater table, which minimises land subsidence as well as high groundwater issues (case studies Haarlem and Amsterdam). The infiltration capacity can be obtained by linking the subsurface drainage with stormwater systems or nearby open water.
The creation of open water through the problem area or an open seepage canal along the water body that is contributing to the problem (i.e., a major river such as in the Dresden case study or the sea in the Den Helder and Perkpolder case studies), can be an effective measure that provides added benefits in terms of stormwater management and amenity values.

Successful case studies generally have one or more key authorities taking the initiative to drive the development of a mitigation approach. A key element for the successful implementation is the separation of responsibilities between authorities and private property owners. The risk-based approach to provide practical guidance to defining responsibilities in groundwater management as implemented in the Enschede case study can make decisions more transparent to the community.

Prioritising problem areas may also be an important consideration to accommodate budget constraints. This requires a good understanding of current and future issues through surveys, field investigations, on-going monitoring and modelling studies.

Planned large-scale developments or renovation programmes provide good opportunities to install technical measures at lower costs. Financial means for implementing mitigation strategies and their on-going costs are often gained from increasing sewage rates.

5.4 Limitations and Constraints

In the development of mitigation strategies for high groundwater issues in urban areas the following limitations and constraints will often arise and need consideration:

- The abstracted groundwater will need to be discharged and measures will need to be designed in view of the stormwater management and hydrology of the area. The capacity of existing pump stations may need to be increased, although the abstracted groundwater volumes are generally less than stormwater runoff generated during a peak storm event. The water quality of the pumped water potentially may limit the possibilities for discharging to open water. It is better not to discharge the abstracted groundwater into a combined sewer system (i.e., stormwater and wastewater) as that will dilute the wastewater and reduces wastewater treatment efficiency.

- The range and effectiveness of mitigation measures is heavily dependent on the hydrogeological characteristics of the area. Low permeability top soils and large distances between drainage measures restrict their effectiveness. The ability to implement measures at optimal distance may be limited in densely built urban areas. In many cases the implementation of measures on public land is not sufficient and additional measures on private properties is required.

- Technical measures against high groundwater levels require maintenance and residents need to be aware of systems on their properties and their responsibilities. It may be challenging to get buy in from tenants of rental properties and issues may arise sooner in areas with substantial numbers of rental properties.

- Certain groundwater drainage measures may inadvertently accelerate land subsidence processes increasing the areas susceptibility to the effects of high groundwater levels. This should be taken into consideration in the design of urban drainage systems.

5.5 Community Acceptance and Windows of Opportunity

Most of the successful case studies have implemented a proper groundwater monitoring programme and a well-developed communication strategy. On-line access to information about the reasons of the groundwater issues, how certain technical measures operate, the separation of responsibilities, and real-time groundwater level data, all help to create buy in from the community. Real-time groundwater monitoring accessible on-line, can provide added value as an early warning to residents who can take precautionary
measures on their properties. The groundwater monitoring network requires sufficient coverage to achieve this (see case studies Dresden and Hoogeveen).

Large-scale urban development or renovation programmes (of roads or stormwater and wastewater networks) provide good windows of opportunity for also mitigating high groundwater level issues. Mitigation measures taken in a large-scale development or renovation context may have a much broader scope and hence larger impact (e.g. added benefits to the community with the establishment of open water, such as in the case study Oosterwolde). Multi-purpose mitigation strategies can have added benefits over measures that only address the groundwater rise issue. This may also reduce the actual costs for mitigating high groundwater issues.

5.6 Costs and Finance

The programmes of measures identified in the case studies range in costs from approximately 1 million to tens of millions of euros. The scale of implementation and the complexity of the projects seem to have the most influence on the costs.

6.0 CONCLUSIONS

There are many case studies throughout the world that have similar causes and effects of high groundwater levels in urban areas such as South Dunedin. Whilst there are differences and each case is in some way unique, much can be learned from case studies that are well developed and where measures have been successfully implemented. South Dunedin’s issues cover multiple neighbourhoods and several case studies with successful implementation of mitigation strategies have issues affecting an area of a similar size.

The causes of high groundwater levels in urban areas vary considerably throughout the presented case studies. The effects are more similar, with damp or even wet basements and crawl spaces beneath buildings, the associated adverse effects on the building as well as the occupant’s health, and stability issues affecting roads and subsurface infrastructure being the most common. The issue of liquefaction presented in the Christchurch case study is an issue specific to earthquake prone areas with silty and sandy soil types, which are also present in South Dunedin.

Horizontal subsurface drainage is the most widely used method for high groundwater level mitigation as it can be retrofitted in existing urban areas. In most cases, these systems better target the problem areas and require less water to be abstracted than vertical drainage systems. Vertical drainage through pumping wells is more feasible if the abstracted water can be used or other benefits can be achieved. Horizontal subsurface drainage is best installed below the expected lowest groundwater level to ensure it is always saturated.

The use of subsurface drainage systems with infiltration capacities is feasible, if designed properly. They can be effective in maintaining a relatively flat groundwater table, which minimises land subsidence as well as high groundwater issues. The infiltration capacity can be obtained by linking the subsurface drainage with stormwater systems or nearby open water. The creation of pumped open water bodies or open seepage canals can be effective measures that provide added benefits in terms of stormwater management and amenity values.

Whether certain technical measures will be successful depends on proper design, implementation and ongoing maintenance. A proper understanding of local conditions (mainly hydrology, hydrogeology and geology) and effective engagement of residents is needed. Successful case studies would appear to have one or more key authorities taking the initiative to drive the development of a mitigation approach. A key element for the successful implementation is the separation of responsibilities between authorities and private property owners. Financial means for implementing mitigation strategies and their on-going costs are often gained from increasing council rates for storm drainage and sewage services.
Large-scale urban development or renovation programmes (of roads or stormwater and wastewater networks) provide good windows of opportunity for also mitigating high groundwater issues at lower costs. Mitigation measures taken in a large-scale development or renovation context may have a much broader scope and hence larger impact.

To control rising groundwater levels in South Dunedin there are options to combine multiple protection measures. Protection options can be introduced slowly in a progressive manner rather than as a one off operation and can be focussed initially to protect sensitive areas and building. There is potential to develop new recreational surface water bodies and features and look for windows of opportunity to maximise the benefits from constructional costs when retrofitting groundwater drainage systems.

7.0 REPORT LIMITATIONS

Your attention is drawn to the document, "Report Limitations", as attached in Appendix A. The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

8.0 REFERENCES


Ministry of Environment (MfE), 2015, Preparing New Zealand for rising seas: Certainty and Uncertainty.


APPENDIX A

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