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Groundwater REPORT

LDRP45: IMPACTS OF EARTHQUAKES AND SEA LEVEL RISE ON SHALLOW GROUNDWATER LEVELS

PREPARED FOR
Christchurch City Council

C17054

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PURPOSE

The LDRP45 study is a high level strategic study developed to inform Council's flood plain management work. The purpose of the study is to help Council understand the hazard that future groundwater level changes may have on the city. It has been developed to accommodate various objectives including the establishment of trigger levels to define serviceability limits for shallow groundwater flooding, and updating the previous analysis of shallow groundwater flooding risk under Christchurch, as well as assessing the impacts of sea level rise and earthquake subsidence on groundwater levels. The purpose was not to accurately define the shallow groundwater hazard at a local scale, but rather to provide a high-level assessment at the city-wide scale. This is referred to in the project objectives with specific requirements that relate to modelling as follows:

- Objective 6: "…establish the scale and extent of areas that exceed trigger levels for elevated groundwater now, and in the future (10 years, 25 years, 50 years and 100 years) with sea level rise…".
- Objective 7: "Apply the case study management options across the city to understand the potential future magnitude of groundwater management at the city wide scale and to inform production of city-wide GIS surfaces and future investigations and design work".

Regardless, small case study areas have been used to improve understanding of sea level rise effects on groundwater and have been extrapolated across the city. A full assessment has not been completed for all suburbs. The study assesses, at a high level, the impacts on residential areas and does not consider broader community or economic effects. The study is not sufficiently detailed to identify individual property risks and onsite investigations would be required to assess any property-level impacts. There are inherent uncertainties with groundwater modelling, and hence with the reported findings. The study was based on the best available information at the time. More information will become available in the future and a reassessment may be required.

While groundwater trigger levels were developed for the purposes of the study, these do not reflect current or future Council policy, but are used to provide a guide as to areas most likely to be affected by shallow groundwater.

The report is not intended as a means of communicating information to the public. It does not attempt to convey technical information to a wider audience. The report has been reviewed by an external peer review panel, for suitability to inform the Land Drainage Recovery Programme study which intends to assesses of the impacts of multiple hazards on floodplain management.

EXECUTIVE SUMMARY

Shallow groundwater is an existing problem for many locations across Christchurch. Post-earthquake, issues have worsened in some areas due to subsidence of the land surface caused by liquefaction. Over time, climate change is expected to increase sea level and also impact groundwater levels, further increasing the extent of the areas affected. Added to this, any future seismic events could result in further liquefaction and additional land subsidence.

Christchurch City Council (CCC) engaged Aqualinc Research Ltd (Aqualinc), together with Beca and Seequent (previously ARANZGeo), to model the changes in groundwater levels over time, and identify possible options for mitigating high groundwater. After peer review by a CCC-appointed panel, the main focus of the work was changed to be more focussed on shallow groundwater hazard, rather than mitigation options, and the purpose was changed to identify the extent of the risk of shallow groundwater, including sensitivity testing and development of an approach to test the confidence in the modelled groundwater surface and associated outcomes.

Measured depth to shallow groundwater was interpolated across the city using a geostatistical approach and data from over 700 shallow EQC monitoring bores, as well as CCC and ECan shallow wells. The trigger level at which groundwater was considered to become a problem was debated at length, and based on previous Dutch work, together with discussions with various CCC members of staff, a depth of 0.35 m for the 85th percentile water table was agreed (see Section 11). Given this, the areas of Christchurch where depths to groundwater were expected to be shallower than 0.35 m for 15% or more of the time were identified.

The long term impacts of the Canterbury Earthquake Sequence on shallow groundwater was assessed using data from long term monitoring wells. In addition, the long term climate drivers on shallow groundwater were assessed. Furthermore, using recent high resolution data (10 minute intervals) from 250 instrumented EQC holes, the short-term drivers (such as rainfall and tides) were also assessed.

A list of options for mitigating the effects of high groundwater levels was identified, and these were then reduced to a short list of two potentially feasible options, as follows:

- Subsoil drainage; and
- Shallow wells

Due to the change in direction of the project (to a hazards study), the mitigation options were not explored further.

There are number of uncertainties and technical risks associated with the high level approach to this study, as discussed in Section 15. However, It is recommended that:

- Council consider using this study to inform discussion about current and future groundwater levels and possible options for responding;
- This study is not used to identify specific projects or areas requiring groundwater mitigation, or to set budgets for groundwater mitigation projects or programmes;
- Trigger levels for groundwater mitigation are further considered;
- Where groundwater mitigation may be required, site specific investigations (desktop and field), options assessment and design are undertaken; and
- To better understand the likely performance of potential groundwater mitigation measures, pilot studies are considered; this is particularly relevant for shallow wells, which have not been widely used for permanent groundwater mitigation in Christchurch.

1 INTRODUCTION

1.1 Project Context

The key hazard of focus in the present study is shallow groundwater level, and this will be used to inform flood risk assessments and flood plain management decisions. The project falls under the Land Drainage Recovery Programme (LDRP). The LDRP was established to assess and mitigate, where feasible, adverse changes in flood risk resulting from the Canterbury Earthquake Sequence. . This project focusses on the impacts of the earthquakes on shallow groundwater levels, and the potential for further changes as a result of future earthquakes and/or sea level rise.

The original project objectives were to:

- Interview authors of earlier studies, collate previous reports and analyse gaps in the existing knowledge on groundwater levels and propose locations for ongoing monitoring of groundwater levels.
- Establish criteria and trigger levels for implementation of groundwater management for residential and public spaces (i.e. what are 'tolerable' durations and depths of elevated groundwater beneath roads, in parks, in back yards and beneath homes), including an assessment of increased salinity in tidal areas and potential impacts to vegetation (either due to salinity or 'drowning').
- Compare earlier analyses of groundwater data for newly collected data, confirm earlier assessments of change in groundwater behaviour from the Canterbury Earthquake Sequence (CES) and if required update the earlier analyses, and predict climate change and future EQ impacts in four case study areas of known or forecast groundwater issues.
- Develop the case studies to understand the issues associated with existing conditions and develop and quantify the range of sustainable, adaptable and resilient groundwater management options and the impacts of the 'do nothing' and 'do minimum' across these areas
- Understand in depth the relationship between shallow groundwater levels and climate (rainfall response and long term patterns) through the analysis of long term records to highlight event, seasonal, inter-annual and inter-decadal variance (highlighting correlations and causality between groundwater levels and meteorological data, development state, groundwater takes and other data).
- Utilise GIS analysis to establish the scale and extent of areas that exceed trigger levels for elevated groundwater now, and in the future (10 years, 25 years, 50 years and 100 years) with sea level rise and future development with reporting of this at a property level.
- Apply the case study management options across the city to understand the potential future magnitude of groundwater management at the city wide scale and to inform production of city-wide GIS surfaces and future investigations and design work.
- Establish the residual long-term risks associated with the options (at both the case study and city wide levels) and how options could be adapted in the future to manage future risks.

CCC engaged a Multi-hazards Panel, to undertake review of this project. This panel considered that the study should be framed as a Groundwater Hazard Assessment, rather than the original Impacts and Options assessment. As a result, the original report has been modified to reflect this.

The analyses are not suitable for local-scale predictions. Rather, the intent was a first-pass assessment that highlighted areas that were clearly affected, areas that were clearly not affected, and areas that would require further investigation to refine the assessment at a more local scale and provide an indication of potential groundwater hazard.

To reduce modelling uncertainties (which are inherent in any model), we chose to develop the best possible "baseline" surface (85th percentile) based on a rigorous geostatistical analysis of measured data (independent of the groundwater model), which was carried out by Seequent (Section 8 and Appendix D). The changes in SLR were then modelled, and these changes were added to the measured baseline surface (Section 9). This substantially reduces the influence of groundwater modelling uncertainties. However, uncertainties still remain with the approach adopted, which are discussed in Section 13.

1.2 Background to this Report

Aqualinc Research Ltd analysed and developed the groundwater level data to be used in the spatial interpolation to develop the 85th percentile surface used in this investigation. They were also responsible for modelling the sea level rise scenarios, assessing likely trigger levels, and applying the results of the modelling and interpolation to assess numbers of properties affected.

Seequent were responsible for the geostatistical approach to interpolation of the groundwater surface (Appendix D).

Beca Ltd (Beca, 2018) were responsible for:

- Modelling of the land surface change due to future earthquakes;
- Assessment of mitigation options, and risks and resilience of these; and
- Assessment of the regulatory controls.

1.3 Area of Interest

The area of interest was defined at the start of the project. Given the available data, and the focus on residential areas, the area of interest was defined as shown in Figure 1. This was subsequently extended to include the Sumner area, which was modelled separately and the results added to the main area of interest.

Figure 1. Area of interest

1.4 Key Groundwater Issues

The location of the groundwater table relative to ground surface is key in controlling soil saturation and areas where groundwater rises to the ground surface. This can have an impact in terms of groundwater flooding, but also will affect antecedent conditions in surface flood models. Shallow groundwater can also have impacts on human health, infrastructure and roads.

A key issue to be addressed was to determine what drivers control the depth to water, which can include:

- Rainfall recharge
  - Normal seasonal patterns of recharge
  - Changes due to climate change, including effects of interdecadal oscillations
- River recharge
- Tides
- Evapotranspiration
- Earthquakes
  - Subsidence due to ground settlement
  - Dynamic water table response to earthquakes
  - Long term changes in groundwater level
- Sea level rise

In addition, recent survey work by the University of Otago (Unpublished Technical memo, provided by CCC) suggests the coastal elevation has been declining along parts of the Christchurch coast over the past 3.5 years. Any decline in land surface elevation may cause additional issues in areas where groundwater is shallow.

The key issues and needs were therefore to:

- Develop better understanding of the current hydrogeological situation, including an assessment as to whether conclusions drawn from earlier work were still valid (van Ballegooy et al., 2014)
- Predict shallow groundwater levels for different future scenarios, including the effects of sea level rise and land surface subsidence from future earthquakes
- Identify what groundwater management approaches could work, and where they would be applicable.

1.5 Existing and Future Scenarios

A baseline surface was developed to inform the current situation. The future scenarios that were required to be assessed were land subsidence as a result of potential future earthquakes and liquefaction, and the effects of sea level rise.

Geotechnical analysis of earthquake performance of the land was completed for the three earthquake scenarios with annual exceedance probability of 1/250, 1/500 and 1/2500. The settlement was subtracted from the land surface to estimate the new ground surface elevations under each scenario.

The Canterbury groundwater model, developed by Aqualinc, was used to model potential changes in groundwater level due to sea level change, based on the predicted 0.19m, 0.4m, 1m, 1.88m and 2.40m SLR scenarios. The modelled differences were added to the baseline surface to generate the potential groundwater surfaces under different sea level rise scenarios.

1.6 Background and Existing Studies

The sequence of earthquakes In Canterbury during 2010 and 2011 caused substantial changes to land and groundwater in Christchurch City and surrounding areas. The effects on land included widespread uplift and subsidence, liquefaction, ground surface deformation and lateral spreading. The effects on groundwater included changes in piezometric level and potential changes in aquifer permeability and leakage (Rutter et al, 2016). The result of liquefaction-induced settlement was to bring the water table closer to ground surface in many areas.

Maps of the median and 85th percentile water table (elevations and depths) below ground were derived for Christchurch City and surrounding area, for the period since the 4 September 2010 M_w7.1 Darfield Earthquake (van Ballegooy et al., 2014). The work relied on 55 long term monitoring wells (ECan and CCC), and around 750 short-term EQC piezometers. The limitations of this work were that there were 3 years' or less data for the EQC piezometers, and in some cases, data from 9 months or less was used to represent the long-term median and 85th percentile. Although this study used additional data that had been collected after the 2014 study, the dynamic nature of groundwater level responses (see Section 5.5), means there are still residual uncertainties, in terms of the variability between data points and lack of spatial correlation (Section 8.5).

A comparison of pre- and post-Darfield Earthquake data from 55 wells with extended (decadal) records indicates that the water table was in most places unaffected by the earthquakes, other than short-term fluctuations. In four wells, van Ballegooy et al. (2014) identified that the median water table elevation was lowered by 0.5–1.0 m to new base levels, independent of whether there was ground uplift or subsidence. This work included an assessment as to whether such post-earthquake effects had persisted. Groundwater levels fluctuate naturally and between 1990 and 2010 there were inter-annual variations (around 2 m in the west and 1.2 m in the east) that were twice the scale of seasonal variations (around 1 m in the west, 0.5 m in the east) in the water table.

For the LDRP45 project, the statistics for existing groundwater levels were updated with the additional four years' of data (see Section 7.3).

1.7 Requirements of the District Plan

The Christchurch District Plan was prepared under the Canterbury Earthquake (Christchurch Replacement District Plan) Order in Council 2014 in conjunction with the community. It sets a framework for development and the management of resources in the Christchurch district in a manner that meets the goal of sustainable management of those resources. It includes objectives, policies and rules to manage the environmental effects of land use and subdivision activities.

The District Plan includes a requirement to take into account natural hazards. Natural hazards are defined in the Resource Management Act 1991 as:

- *Any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, or flooding) the action of which adversely affects or may adversely affect human life, property, or other aspects of the environment.*

The District Plan states that, in locations where the risk from natural hazards is considered to be unacceptable, new activities in those areas are generally to be avoided. In all other areas natural hazard risk is sought to be managed in a way that reduces the risk to acceptable levels. Flood hazards have already been modelled and are shown on the Council's planning maps. However, the contribution of groundwater has not been included in this assessment of hazard.

1.8 Other Ongoing CCC Projects

The Canterbury earthquakes increased flood risk in some parts of the city by changing the topography and damaging land drainage infrastructure. The Land Drainage Recovery Programme (LDRP) was established by Council in 2012 to understand the consequences of the earthquakes on the land drainage network within the city limits. The projects that are linked with the LDRP 45 project include the following.

1.8.1 LDRP97 Multi-Hazard Assessment

The aim of LDRP97 is to develop flood management plans for the study area, taking into account other hazards e.g. climate changes and land surface change. The focus is on the impacts of other hazards on flood plain management, including cascading effects (for example tsunamis, storms, etc) that affect flood plain management. They need to be able to develop an approach to making good decisions with respect to land use planning and development.

1.8.2 Liquefaction Project

Following the 2010-2011 Canterbury earthquakes, there have been significant improvements in the scientific understanding of the liquefaction hazard in Christchurch. CCC wished to collate this updated knowledge into a form which was useful to broaden public awareness of liquefaction hazard and inform land use planning. The methodology adopted was to combine subsurface ground testing data from across the city with observations of the location and severity of liquefaction effects that occurred during the Canterbury earthquakes. This involved a manual "calibration" process to align predictions of future performance with observations of past performance. The analysis will be used to map liquefaction vulnerability categories in accordance with the 2017 MBIE/MfE document "Planning and engineering guidance for potentially liquefaction-prone land". Maps will also be prepared showing the possible range of liquefaction-induced damage in various scenarios (e.g. different earthquakes and groundwater levels).

The liquefaction project will use the following information from LDRP projects as part of the analysis:

- Groundwater surfaces for current day and future sea level conditions
- Ground settlement predictions for the multihazard case study areas for various scenarios

The liquefaction project will provide ground settlement predictions across the Christchurch urban area for various scenarios to be incorporated into the LDRP45 project.

1.8.3 Climate Change Strategy and Action Plans

Council are developing a Climate Change Strategy and Action Plans for mitigation and adaptation. These documents will support the city's 2050 zero carbon target. The project is currently in its establishment phase and will provide District wide direction to more localised adaptation plans that will be prioritised based on vulnerability/risk.

2 CHRISTCHURCH CITY HYDROGEOLOGY

The Canterbury Plains were progressively built through coalesced deposition of outwash fans associated with the emergence of eastward-flowing braided rivers from the foothills of the uplifting Southern Alps. In the Christchurch City area, outwash fans, particularly from the Waimakariri River, were deposited during cold and warming climatic periods during the last half million years or more. During this period, low cold climatic sea levels (up to 125 m below present sea level) alternated with high, warm climatic sea levels (close to today's sea level). The coastline in the area varied in position from around 50 km to the east of its present position during cold periods, to approximately 10 to 15 km west of its present position during warm periods. The result of deposition during these climatic cycles is a sequence of at least 430 m of gravel-dominated strata. These form a heterogeneous sequence of gravels, sands and silts that (vertically) are reasonably interconnected in the west, but interbedded with a series of fine marine, marginal marine, swamp and distal alluvial intervals in the east (Suggate, 1958; Brown & Weeber, 1992; Weeber, 2008; Forsyth et al., 2008). The fine-grained marine/estuarine sediments are found up to 15 km inland from the present-day shoreline. The Port Hills and Banks Peninsula are a Late Miocene volcanic complex that became extinct c. 6 million years ago, and stand to the south of the city.

The upper sediments are the Springston and Christchurch Formations. The Springston Formation predominantly occurs to the west of the city, while the Christchurch Formation is exposed in the east of the city. The relationship between the formations is not simple, and complex interfingering of both the Christchurch and Springston formations occurs beneath Christchurch City (White, 2007a; White et al., 2007). These are not homogeneous deposits.

Table 1 summarises the key geological strata underlying the Christchurch City and surrounding area at depth, including the numbering system that Weeber (2008) adopted for the aquifers. Only strata within the upper 100 m are listed in Table 1. However, a further sequence of interbedded gravel and fine-grained strata exists at greater depths (Weeber, 2008).

Table 1: Summary of the principal geological units near and beneath Christchurch City and surrounding area.

Stratigraphic unit (with aquifer number if applicable)	Description
Christchurch Formation	Estuarine/marine fine sediments
Springston Formation (Aquifer 0)	Alluvial gravel, sand, silt
Riccarton Gravel (Aquifer 1)	Alluvial gravel, sand, silt
Bromley Formation	Estuarine/marine fine sediments
Linwood Gravel (Aquifer 2)	Alluvial gravel, sand, silt
Heathcote Formation	Estuarine/marine fine sediments
Burwood Gravel (Aquifer 3)	Alluvial gravel, sand, silt

Even within the Springston Formation, there is considerable variability. The formation's alluvial deposits can be divided into river flood channels that contain alluvial gravel as the main component, plus overbank deposits of sand and silt. In some areas, for example, the suburb of Marshland, peat deposits formed. This results in significant variability in the vertical profile across the area. In general, there is a sequence of alternating sand, silt, gravel, clayey silt and sometimes peat beds. The proportion of gravel beds is higher in the west, decreasing to the east. The meandering streambeds of the Heathcote and Avon/Otakaro rivers and their tributaries also incise and rework the surficial sediments creating local meander loop, channel and overbank deposits of sand, silt and peat/organics. There are also man-made deposits including landfills (e.g. Bexley Tip), reclaimed tidal areas (e.g. Bromley) and fill on existing land. Kerrs Reach on the Avon/Otakaro River and the Woolston Cut on the Heathcote River are manmade cut offs of meander loops. Thus, although the Springston Formation is generally thought of as an aquifer, it also acts as an aquitard, particularly in the east of the city.

The Christchurch Formation includes beach, estuarine, lagoonal, dune and coastal swamp (inter-dune) deposits (these latter areas are often largely reclaimed with fill). Brown et al (1995) suggest that under the study area, they are predominantly dune sands, with some areas of sand, silt and peat from drained lagoons and estuaries. The Springston Formation is dominantly represented by overbank sand and silt deposits. There are also mapped alluvial channels with gravels.

Weeber (2008) showed that there was no precise boundary line between the inland recharge zone and the coastal discharge zone, with the transition area situated west of Christchurch City. The change is gradual and is related to the geological complexity of the subsurface layers spatially (e.g. White, 2009) and temporal variations in recharge/discharge. While not precise, van Ballegooy et al (2014) found that there appeared to be different responses in shallow wells in the western (inland) zone compared to the eastern (coastal) zone.

The water table sits within the uppermost sediments, typically less than 10 m deep, throughout the area. These sediments include Christchurch Formation in the east and Springston Formation gravels in the west. Fine-grained deposits of both the Christchurch and Springston formations act as confining layers for deeper aquifers with artesian pressure. In some areas, such as Hoon Hay and Riccarton, wells in gravels with artesian pressures are present at depths of a few metres, and these wells were excluded from the water table data set.

Springs naturally emerge on the Canterbury Plains, either in depressions where alluvial fan complexes coalesce, e.g. along the Selwyn and Ashley rivers, or across the plains broadly along the transition from unconfined and semi-confined aquifers to the confined aquifers (Figure A.3 in Appendix A). Springs in near-surface channels provide base flow of the Avon/Otakaro, Styx, Heathcote, and Halswell rivers (Cameron, 1993; Earl, 1998; White, 2009). Prior to the 4 September 2010 Darfield Earthquake, relatively few springs emerged through the Christchurch City confined aquifers in the south and east of the city (White et al., 2007), but immediately following the earthquake a series of new springs began to flow in this area. Other springs developed at the margin of the Canterbury Plains along lower slopes of the Port Hills (Rutter, 2010; Cox et al., 2012; Rutter et al., 2012).

The water table slopes coastward from greater than 10 m elevation (relative to mean sea level) west of Christchurch City to less than 1 m elevation in the eastern suburbs, being a subtle reflection of the ground surface elevation. The water table surface is generally more than 5 m below ground west of Christchurch City, but less than 2 m deep beneath much of the city. The piezometric gradient is overall northwest to southeast, but is likely to differ significantly on a local scale due to the heterogeneous and anisotropic nature of the sediments.

3 EXISTING GROUNDWATER LEVEL DATA

There are several data sets of groundwater levels in Christchurch, with different record lengths and frequency of sampling. The approach used was to obtain a statistical summary of each site, decide on the appropriate statistic to use, and map that. However, in deriving a representative statistic for each site, considerable analysis of the data was required.

This document explains the correlation method used to develop summary data, and compares it to more-simplistic approaches of summary statistics.

The data used were:

- EQC GWL dip data from the NZGD[1], from 2011 onwards (dips are manual water level measurements taken by lowering a sounding probe into a well)
- Long term CCC shallow wells data, dipped mainly on a fortnightly basis and collected by NIWA
- Long term ECan shallow wells, dipped mainly on a monthly basis and collected by ECan
- Other short-term data from construction work
- Automated Piezometer Project (APP) piezometers

The data are described in Table 2.

All depths to water level were converted to elevation above mean sea level (Lyttelton datum) in metres for the purpose of interpolation of the water table surfaces.

During 2016, 249 piezometers were instrumented by EQC with transducers, measuring water levels at 10 minute intervals. It should be noted that 50 of these were new and do not have any record in the NZGD. These APP holes had data for one year, from September 2016 to September 2017, and the data were made available by T&T during the project. The data were not used in developing the median and 85 centiles for interpolation, as they were not available until the latter half of the project, and only represented a short time frame. They do, however, provide a very valuable data set to assess the drivers of water level variability, as described in Section 5. Initial indications are that some piezometers are showing almost identical patterns to others in close proximity, and the data could be very easily rationalised to give as good data with a smaller network.

[1] New Zealand Geodatabase: this was a successor to the Canterbury Geotechnical Database that was developed as a repository for geotechnical data collected in the aftermath of the Canterbury EQs

Table 2: Summary of data sources used

Dataset	Resolution	Comments
EQC shallow water table points		723 in total used from an initial dataset of 971. Data dipped on a monthly basis, over variable time periods between 2011 and 2017. Some of the EQC bores had very few dips, and the last dipped date was variable, some with only one dip in 2011, whilst others appeared to have been dipped monthly from 2011 to the start of 2017. It may be that this is due to holes being 'lost' due to construction or infrastructure work. Data were excluded (242 points) due to not achieving criteria as explained in Section 7.1. Many of these are in close proximity to other data points. 233 are within 500m of another bore with data; 161 are within 200m. Apart from two, the remaining 9 are not in areas where there is shallow water and low confidence in the interpolation. These two are not in areas that CCC has expressed a concern about.
CCC/ECan long term bores		55 shallow bores. Combination of CCC and ECan data. Dipped weekly to monthly. CCC shallow wells data, dipped and collected by NIWA; occasionally provided to ECan for inclusion in their database.
Short term data		Other short-term data from construction work
APP bores		249 bores in total. 21 do not coincide with the location of EQC bores (from full dataset – 43 do not coincide with the location of bores in the final dataset)

Considerable effort was involved in collating the data for various reasons:

- The data were collected in different formats and did not all reference the same datum.
- There are numerous naming conventions for both the EQC bores and the CCC ones. For example, for the CCC bores, the council have a 3 figure reference number (e.g. "ABI"), ECan have another reference number (e.g. M35/2345), and NIWA have a 7 digit ID. The EQC bores started with a format such as CPT-CBD-001, then the APP bores were given an APP number, and had to be cross-referenced. Additionally, it appears that there were 50 replacement holes, where the high resolution data could not be stitched together with the older dips.

If the data were made more accessible and the different datasets combined into one, simple system, the data would be very much more useable, and would certainly be used in many ways that are not even yet evident. There would be huge benefits to the CCC Land Drainage Recovery Programme, Natural Environment and District Plan teams. EQC have commissioned a project to collate the data, and present a case for rationalising the network, and propose a case for ongoing monitoring. It is expected that CCC will be a key part of this process.

3.1 Existing Data

Maps showing median and 85th percentile depth to water (below ground level) are shown in Figure 2 and Figure 3. Other maps (including maxima and minima levels) are shown in Appendix A. Whilst there is spatial coverage that is unique in terms of shallow groundwater monitoring, there are also areas where there is limited or no monitoring. The impact of the spatial distribution of the data on the derivation of the water table surface is discussed in Section 7.4).

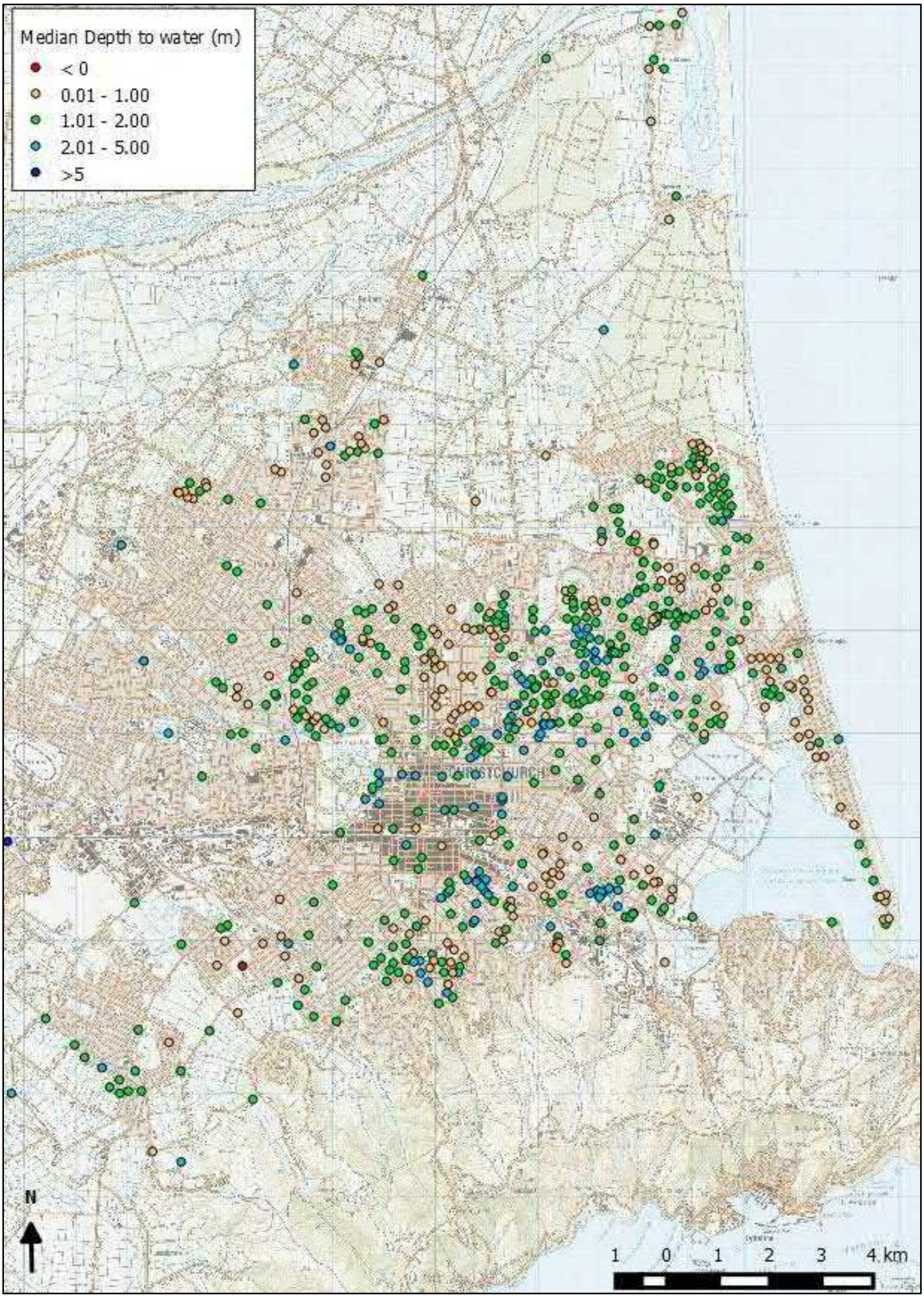


Figure 2. Median depth to groundwater (refer to Section 7 for details on the derivation of the median)

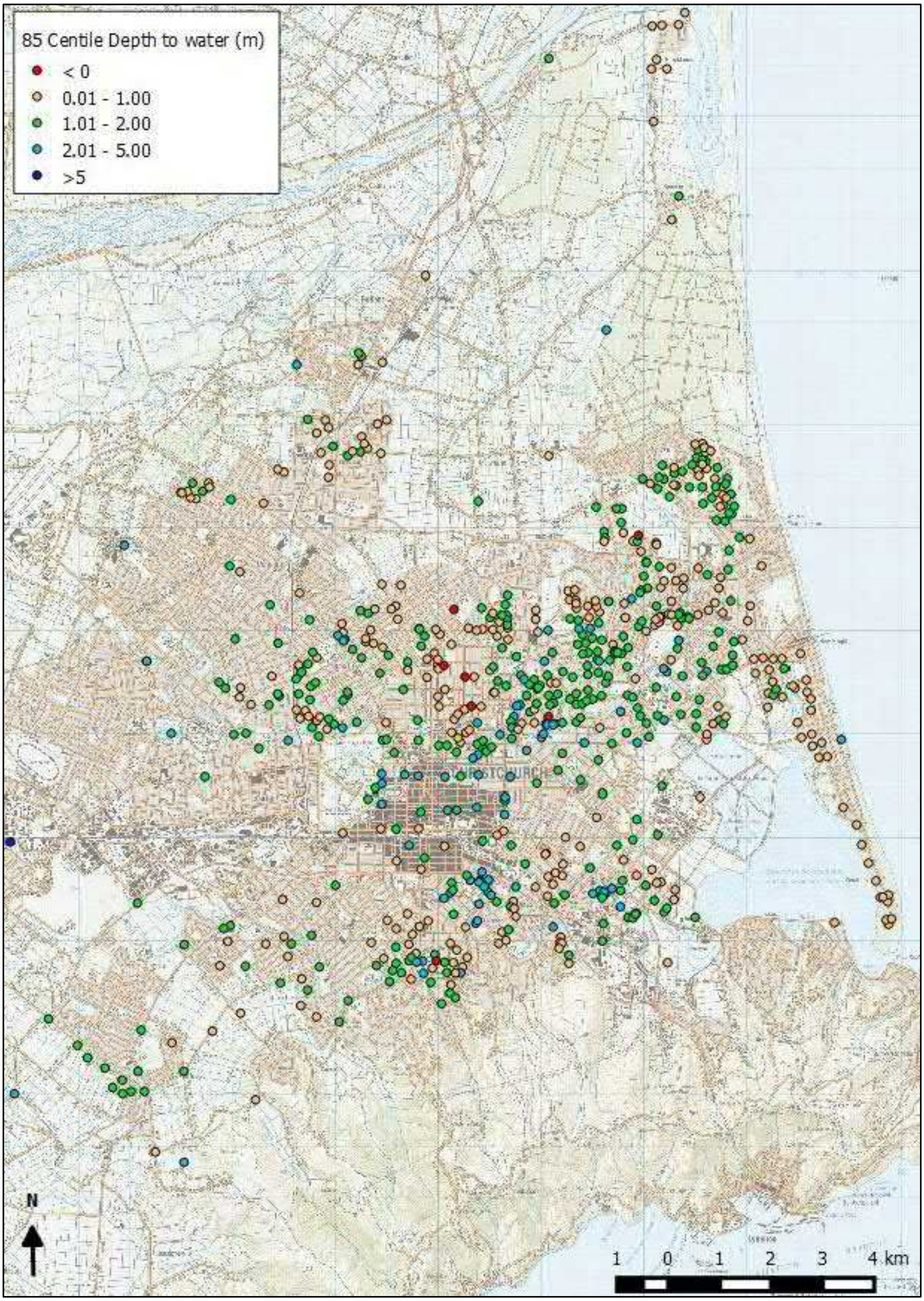


Figure 3. 85th percentile depth to groundwater (refer to Section 7 for details on the derivation of the 85th percentile)

4 CASE STUDY AREAS

One of the initial tasks was to define case study areas, these being areas that could be used to assess the impacts of land settlement and sea level rise in terms of depth to groundwater, and where mitigation options could be assessed. Although there was no requirement to consider mitigation options as a result of feedback from the MHP, we have still included the outcomes from the assessment of the case study areas in terms of impacts of shallow groundwater and SLR.

There was extensive discussion regarding the location of the case study areas. These needed to represent a variety of conditions across the city. Key questions to consider were:

- What is the effect of sea level rise on groundwater along coastal margins, and how does the effect of sea level rise on groundwater change as distance from coast increases?
- How does the groundwater response along the spit vary from the other coastal margins with a single margin?
- What are the most vulnerable locations in Christchurch with respect to rising groundwater with sea level rise? Or with land settlement?
- How do underlying aquifers influence groundwater and saline interfaces?
- How can the effects of groundwater change be reduced or controlled?
- What are the economic, environmental and social influences of engineering intervention?
- What are the costs and risks?

An MCA process was carried out on nine initial potential sites, in order to provide some rigour to the assessment. This scored sites based on:

- Case study size (4 = less than 60ha, to 1 = less than 300ha)
- Existing shallow groundwater (4 = less than 0.35m to median depth to water, 3 = less than 0.5m, 2 = less than 0.75m and 1 = less than 1m)
- Understanding areas where depth to groundwater might change due to variables changing
    - Land surface change due to EQs (4 = greater than 75% liquefaction after the February EQ, 3 = greater than 50%, 2 = greater than 25%)
    - Climate change leading to sea level rise (4 = within 1km of coast of tidal river, 2 = within 2 km of coast or tidal river)
    - Future land development (not intended in any of the proposed case study areas)
- Table 4 summarises the sites, with their score, as well as a description of the geomorphological environments and lithostratigraphy.

The potential sites are shown in Figure 4. The four that ranked highest in the scoring were taken to represent a range of conditions and were selected as the sites for the LDRP45 project.

Table 3: MCA scores for the potential case study sites

		Potential changes				
Area_Name	**Area**	**Area 60 to 90 ha**	**GWLs already exceed trigger levels**	**Land surface**	**Sea level rise**	**Score**
Steam Wharf Stream/St Johns	97.1	3	2	4	4	3.25
Avondale Green Zone	90.2	3	2	4	4	3.25
Flockton Basin	50.1	4	4	4	0	3.00
Southshore/South New Brighton	99.6	3	2	2	4	2.75
Knights Drain	90.2	3	1	3	4	2.75
Eastgate/McGregors	114.0	2	2	3	2	2.25
HoonHay	234.4	1	3	2	0	1.50
Owaka Basin	91.5	3	1	1	0	1.25
Redwood Springs	151.3	2	2	1	0	1.25

Table 4: Summary of potential case study sites

Area_Name	Area	Score	Geomorphological environment	Lithostratigraphical description	Comments
Steam Wharf Stream/St Johns	97.1	3.25	Fluvial - swamp and channel and coastal mud flat	Near surface sediments dominated by 2-4m of silts and sands, with peat of the Springston Formation overlying sands of Christchurch Formation.	Similar to Avondale though Avondale is likely to be more affected by river levels and St Johns by the estuary. May be similar to Eastgate, but St Johns probably has worse ground conditions, and scores more highly due to being closer to the coast,
Avondale	90.2	3.25	Fluvial - river plain	Near surface sediments dominated by 3-4m of silts and sands of the Springston Formation overlying sands of Christchurch Formation.	Large area affected by liquefaction
Flockton Basin	50.1	3.00	Fluvial - swamp and channel	Near surface sediments dominated by 3-4m of silts and sands of the Springston Formation overlying sands of Christchurch Formation.	Away from tidal reaches of the river, and GWLs may already be a problem
Southshore/South New Brighton	99.6	2.75	Coastal - dune	Christchurch Formation Sands from the Surface	
Knights Drain	90.2	2.75	Coastal - dune	Christchurch formation sands overlain with silts.	Similar to Southshore/South New Brighton.
Eastgate/McGregors	114.0	2.25	Fluvial swamp and coastal dune	Near surface sediments dominated by 2-4m of silts and sands of the Springston Formation overlying sands of Christchurch Formation.	Similar to St John's, but is further away from tidal reaches of the rivers, so less affected by rising sea levels
Hoon Hay	234.4	1.50	Fluvial - swamp and channel; edge of confining layer	Springston Formation over bank deposits (silts sands)	Probably not particularly representative of the city – the springs here are associated with the thinning confining layer, are limited to a relatively small area of the city.
Owaka Basin	91.5	1.25	Fluvial	Springston Formation over bank deposits (silts sands)	
Redwood Springs	151.3	1.25	Fluvial	Springston Formation over bank deposits (silts sands)	There are springs but they are well contained within the river channel.

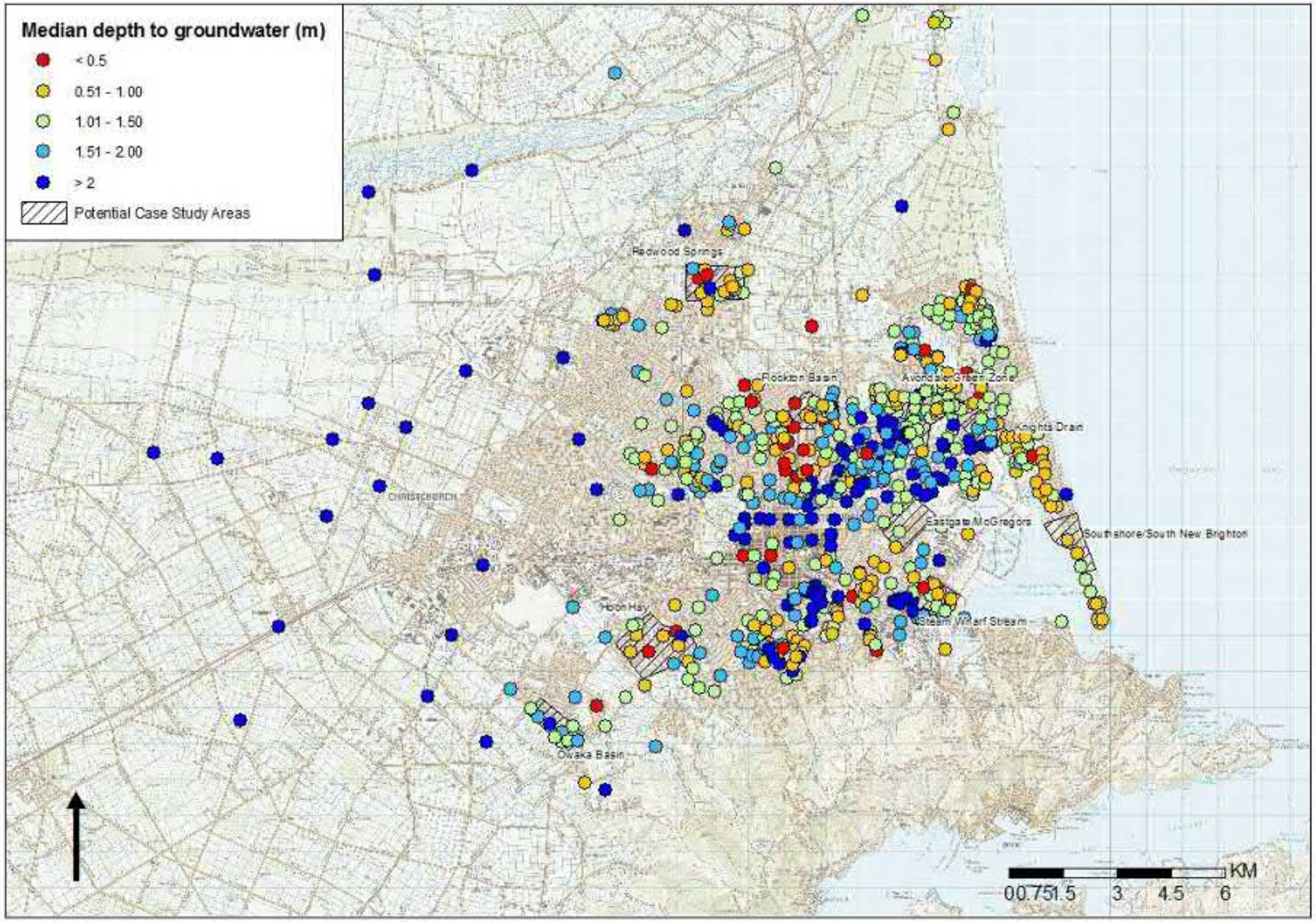


Figure 4. Potential case study sites

5 DRIVERS OF GROUNDWATER LEVEL CHANGE

5.1 Aims

The purpose of this work was to understand in depth the relationship between shallow groundwater levels and climate (rainfall response and long term patterns) through the analysis of long term records. The aim was to assess event, seasonal, inter-annual and inter-decadal variance, highlighting correlations and causality between groundwater levels and meteorological data, and other data. The methodology used follows that of a peer reviewed investigation of the water table response to rainfall events in central Florida (van Gaalen et al., 2013).

There were two main approaches. The first was using the long term data (CCC/ECan) to assess the groundwater level response to long term climate cycles. The second approach was to use the recently acquired high resolution data from the EQC APP piezometer network to assess the dynamic response to rainfall, tides and other drivers.

5.2 Impact of Climate Cycles

The terms “weather” and “climate”, have very different meanings. The difference between weather and climate is a measure of time. “Weather” is the condition of the atmosphere over a short period of time, and “climate” is how the atmosphere "behaves" over relatively long periods of time (decades). Weather can change from minute-to-minute, hour-to-hour, day-to-day, and season-to-season. In contrast climate encompasses all these continual changes (i.e. variability) including the highs, lows, and extreme events. MetService provide short term (hours and days) *weather* predictions, while NIWA provide medium term (months) *weather* predictions. Neither of these predictions directly relate to *climate*. For example the drought of 2014/15, the El Nino event in 2015/16, and the very low groundwater levels of 2016 are all examples of individual weather events, because the scale of events is days to months.

An analysis of a long historic period is necessary to separate trends from multi-decadal cycles, and from random variability (see Figure 5).

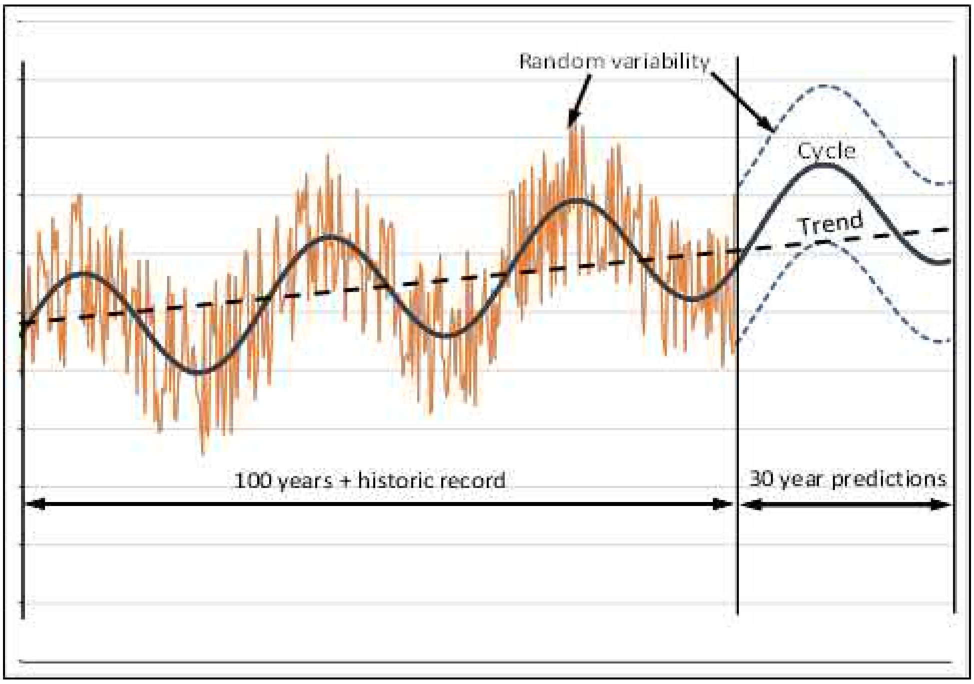


Figure 5: Schematic illustrating trends, cycles and random variability

Some of the variation in climate may be attributable to different large scale climate cycles. Relationships between observed groundwater levels and three different climate characteristics were assessed. These climate characteristics were:

1. El Niño - Southern Oscillation (ENSO),
2. Interdecadal Pacific Oscillation (IPO),
3. Southern Annular Mode (SAM)

A description of each climate characteristic is provided in Appendix B.

5.3 Correlation of Christchurch Rainfall With Climate Indices

Previous work did not suggest there is a strong relationship between climate indices and Christchurch (or Canterbury) rainfall (Griffiths, 2011; Brown *et al*, 2016). Griffiths (2013) also assess whether there was any change in rainfall trends over the 1962 to 2011 period, but could not find any statistically significant trend in the Christchurch data.

ENSO and Christchurch rainfall is available in a series of maps on the NIWA website (https://www.niwa.co.nz/gallery/chance-of-above-normal-rainfall-patterns-for-el-ni%C3%B1o-and-la-ni%C3%B1a-in-new-zealand). These suggest that, based on the ten strongest El Nino/La Nina events between 1960 and 2007, Christchurch rainfall is unlikely (i.e. 20-30%) to have above normal rainfall in summer under El Nino nor in winter, spring and summer for La Nina conditions.

Griffiths (2011) investigated the drivers of extreme daily rainfalls in New Zealand. She describes the correlations between Christchurch seasonal extreme daily rain with an ENSO index. The strongest correlation was a negative one (-0.21) during the December to February season, which had a p value of 0.12, i.e there is a 12 % chance the same result could be obtained from random. The negative relationship indicates there is a weak tendency for the extreme rainfall to reduce under El Nino conditions and increase under La Nina conditions.

For the Southern Annual Mode, the Christchurch March – May extreme daily rain was found to be negatively correlated at the $p < 0.05$ level, but no other season had a correlation at a $p < 0.15$ level.

Based on analyses for the Selwyn District (Brown *et al*, 2016), there was no statistically significant change in average or extreme rainfall events in response to the one degree change in temperature over the past 100 years. This work also assessed the annual frequency of high rainfall against ENSO and SAM indices and could not demonstrate any relationship between annual days with rain greater than the 95th percentile and average annual climate indices. The difference between the annual frequencies of high rainfall days for different IPO phases could not be shown to be different from zero. The lack of a relationship between rainfall data and the long term climate trend or climate cycles does not necessarily mean that a relationship does not exist. The natural climate is highly variable and it may be that the relationship cannot be detected amongst the high variation in rainfall from one year to the next.

5.4 Response of Groundwater Levels to Climate Cycles

To assess the potential impact of climate cycles, 6 long term sites at widespread locations across the Christchurch area were selected (see Figure 6). The annual maximum groundwater level was extracted for each year. For each climate cycle, the normalised annual average was calculated. Scatter plots of the annual maximum ground water level against ENSO, IPO and SAM indices are shown in Figure 7. These scatter plots indicate no relationship between any of the sites' annual maximum groundwater level and the climate indices.

This result is not surprising given the lack of a relationship between rainfall and climate indices described in Section 5.2. Previous work (Brown et al, 2016) concluded that groundwater level variations in shallow and deep wells across the Plains were primarily due to the year to year variability in rainfall, with the next biggest influence being existing irrigators pumping from groundwater. Climate trends (climate change) resulted in a minor change in groundwater levels. The impact of inter-decadal cycles was undetectable.

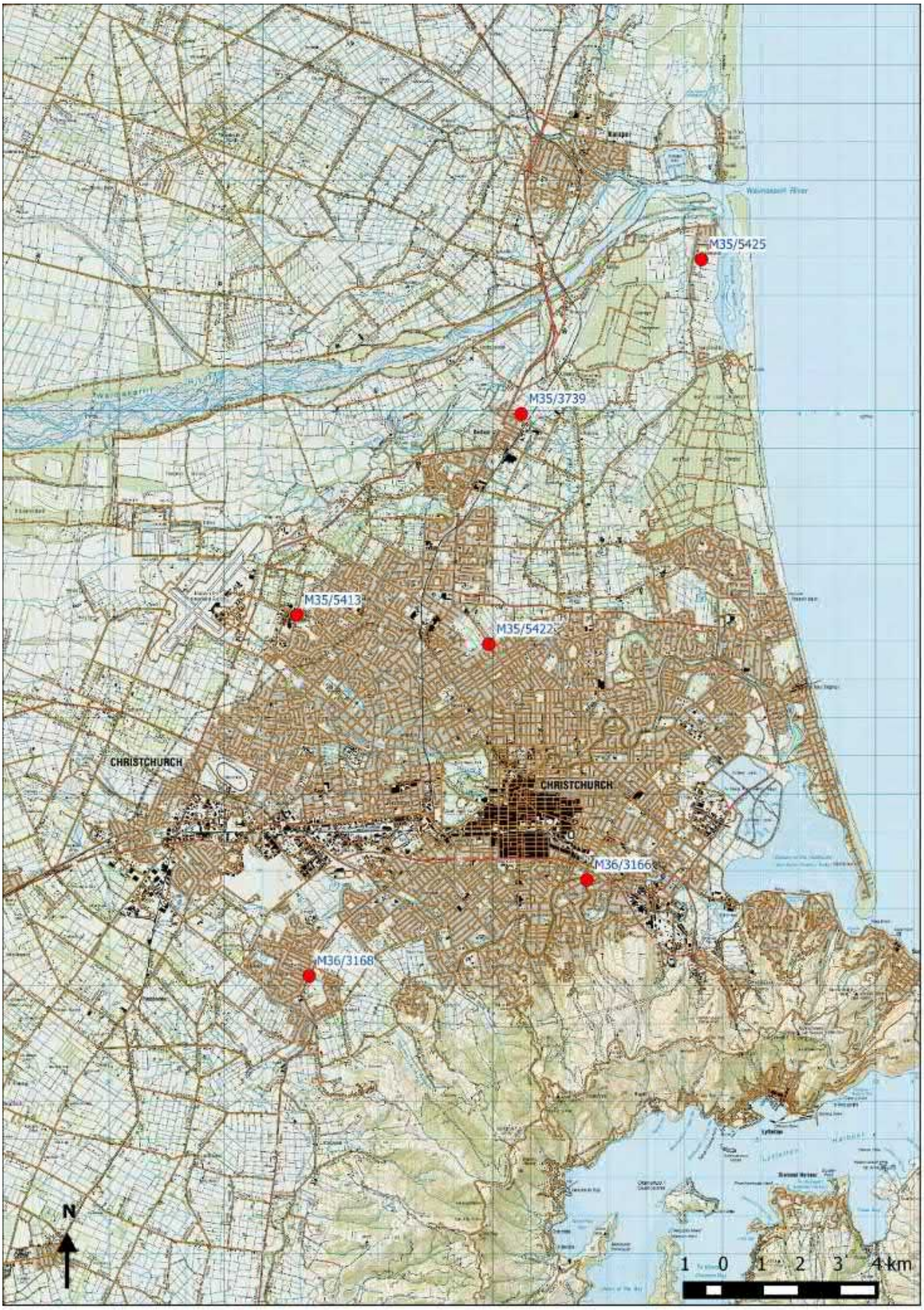


Figure 6. Long term wells used for the assessment of climate cycles on shallow groundwater levels

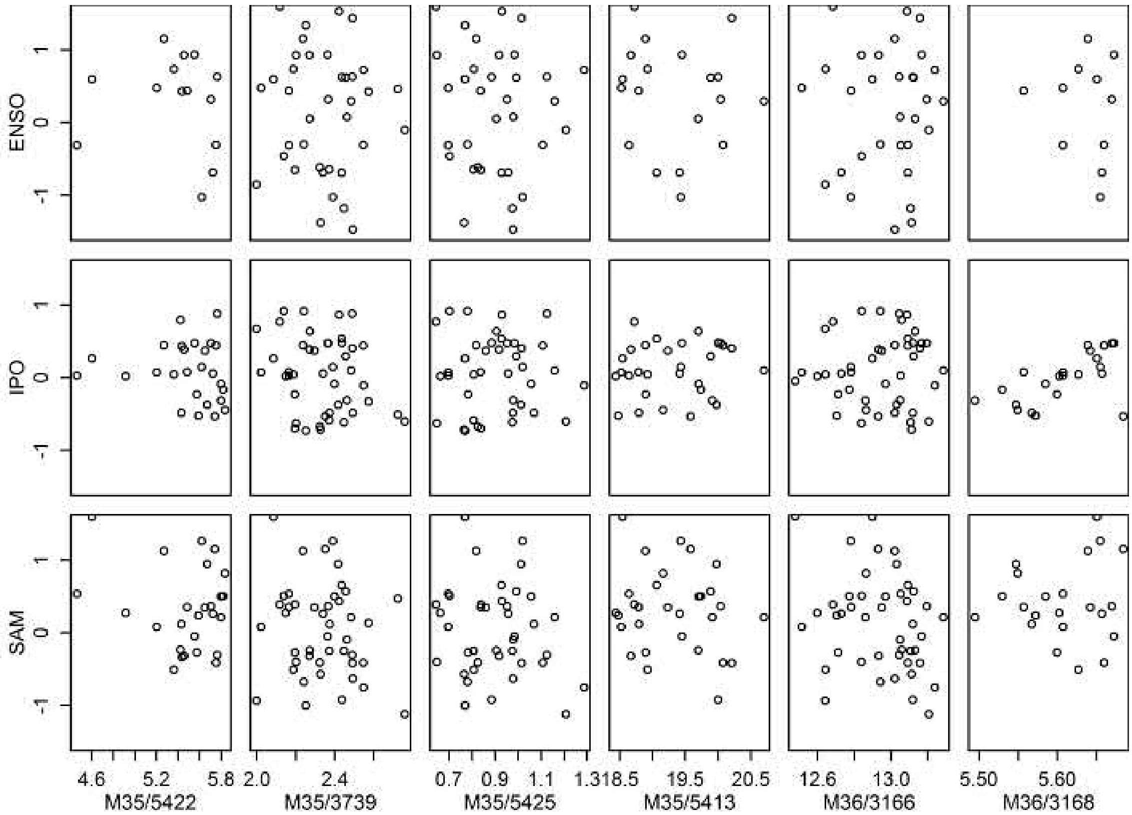


Figure 7. Scatter plots of annual maximum groundwater level versus average annual climate indices

5.5 Dynamic Response of Shallow Groundwater

The ability to assess the dynamic effects of recharge, tides and evapotranspiration is controlled by the availability of high resolution data, which was not available until towards the end of the project. This data has, however, given us a new insight into the dynamics of the shallow water table and suggests that even moderate rainfall events can cause a significant groundwater level rise. This is of considerable importance as during storm events, there will be less unsaturated soil to absorb water.

The dynamic response of shallow groundwater to rainfall was assessed for all wells for which high resolution groundwater level data were available, that is the 244 EQC APP piezometers for which we had data. There is a maximum of a year's data available for these, but it is sufficient to provide an insight into the response of the shallow water table over a range of groundwater levels and recharge conditions. The site locations were provided are shown in Figure 8. The groundwater data were provided as depth below ground level, and compensated for barometric pressure.

5.5.1 Response of Shallow Groundwater Levels to Rainfall

The response of the high resolution data to rainfall was assessed. High temporal resolution (15 minute) rainfall data were obtained for the Christchurch Airport automatic rain gauge from the NIWA Climate Database (Site agent number 4843 in cliflo.niwa.co.nz).

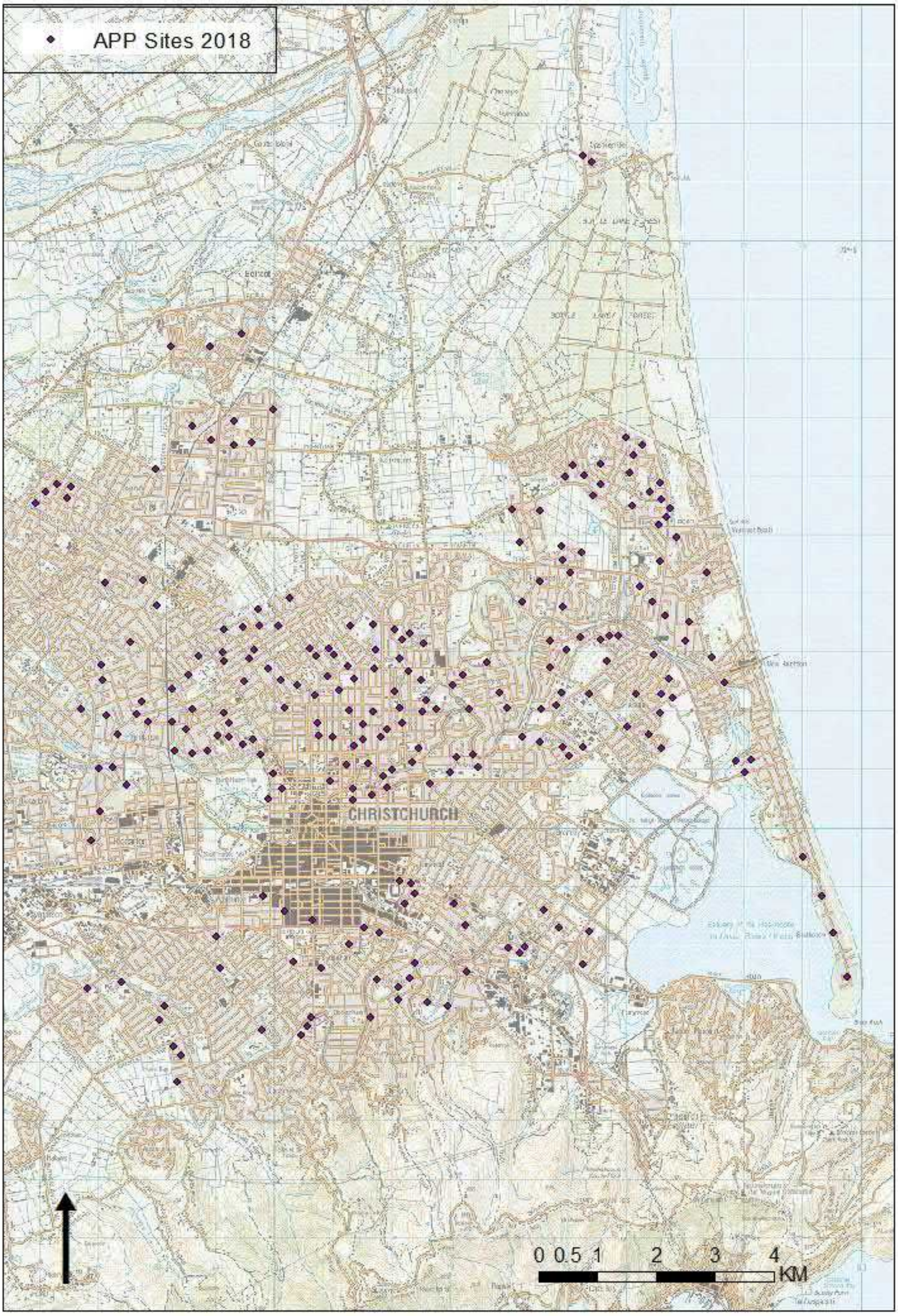


Figure 8. APP site locations

5.5.1.1 Noise Reduction

The data often exhibited high frequency signal variation that was considered to be unrelated to rainfall events. An example of the raw data from well CCC-POD02-BH004, (from 1/14 Moa Place in the Central City, about 300 m from the Avon River, just south of Bealey Ave and east of Madras St) is shown as the black line in Figure 9. This “noise” needed to be removed to enable identification of peaks in the groundwater signal.

The data was filtered by taking a fast Fourier transform of the data and then windowing the frequency domain to exclude the high frequencies. A Blackman Window was used to transition from the allowed frequencies to the excluded frequencies. By trial and error, the highest frequency that was unaffected was 0.38 hour-1 and the lowest frequency that was completely excluded was 1 hr-1. The red line in Figure 9 is the result of applying the filter.

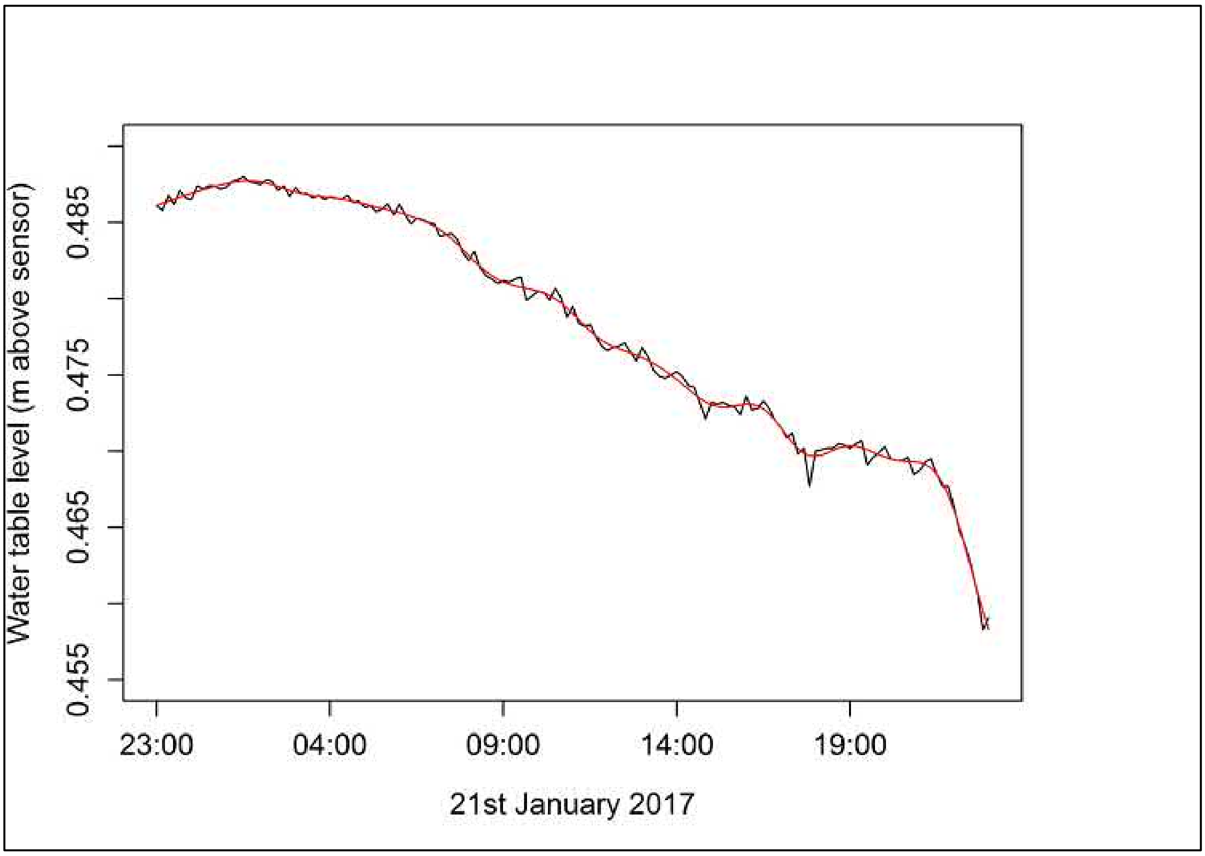


Figure 9. Example of high frequency noise in the groundwater level data. Black line is the raw data. Red line is the filtered data

Summer groundwater level data also frequently exhibited a diurnal fluctuation, likely to be associated with evapotranspiration (see Figure 10), and this was smoothed by taking a 24 hour running average. This filtering greatly improved the ability to identify groundwater peaks associated with a rainfall event, as it removed smaller peaks caused by noise or evapotranspiration that were unrelated to rainfall.

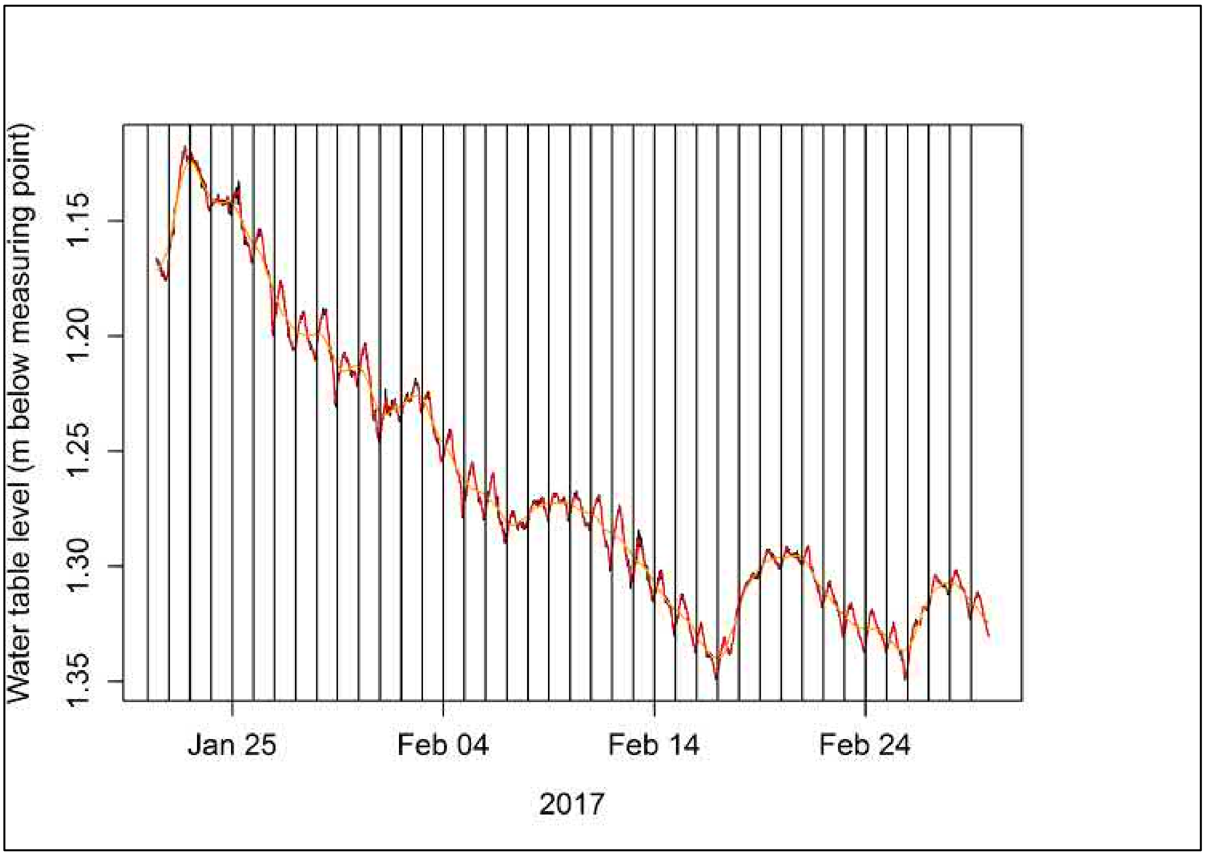


Figure 10. Example plot of the summertime diurnal fluctuation in the groundwater levels. Each vertical line is a different day. The red line is the low-pass filtered measurements. The orange line is a 24 hour centred running average. These data are from groundwater site reference AP114, also known as BIS-POD01-BH001, located in Bishopdale

5.5.1.2 Data Processing

Rainfall data were obtained for the period that the water level measurements were available. These rainfall data were divided into rainfall events, where an event was considered to be any period of time for which rain was measured within 24 hours of the previous measurement, that is, if there was no rainfall for 24 hours, then any new rainfall would be considered a new event. For each rainfall event the total rainfall was calculated.

At each groundwater measurement site, the groundwater level was found at the beginning of the rainfall event, and at the next groundwater level peak. The difference between the groundwater level at the rainfall event onset time and the first subsequent groundwater peak was considered the groundwater response. In some instances, the first groundwater peak following a rainfall event was lower than the groundwater level prior to the rainfall event. These events were discarded. Very small rainfall events that were unlikely to affect the groundwater response (with magnitudes less than 2.5 mm) were also discarded.

An example of rainfall events and associated groundwater peaks is shown in Figure 11.

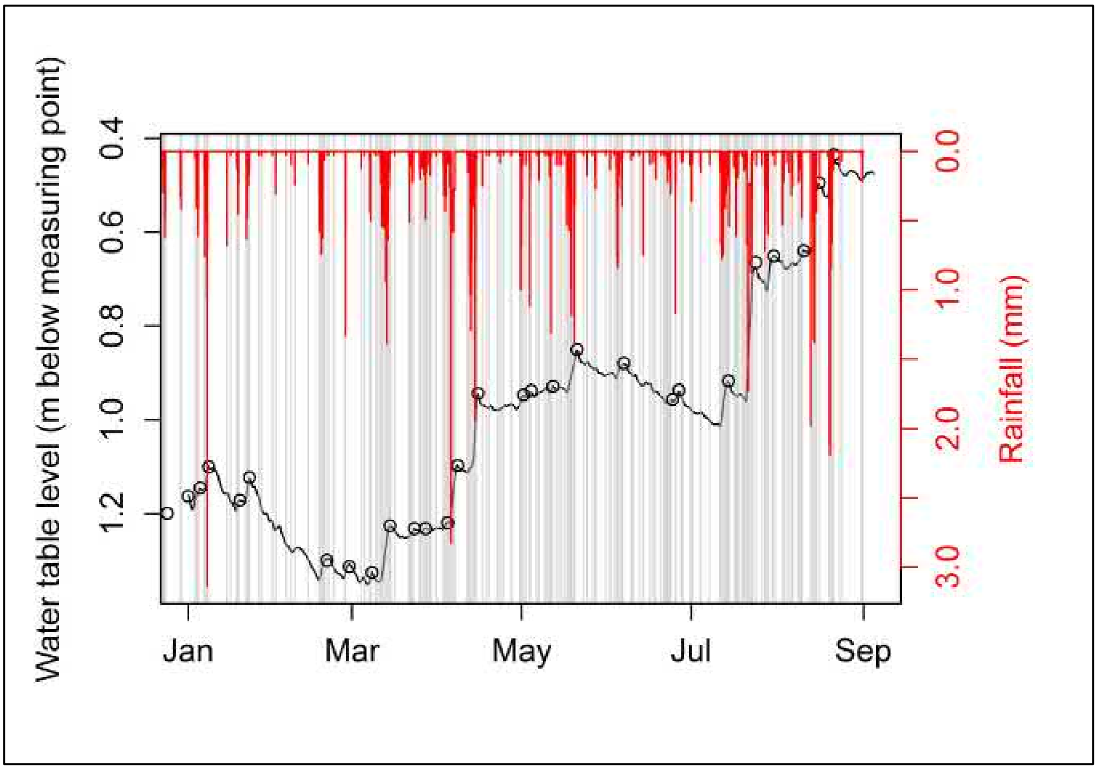


Figure 11. Example plot of rainfall events and subsequent groundwater peaks. Rainfall (red vertical lines) is associated with the right axis. Rainfall events are represented by the grey shaded bars. The groundwater level (black line) is associated with the left axis. Groundwater peaks detected as being associated with a rainfall event greater than 2.5 mm are designated with circles. These data are from groundwater site reference AP114, also known as BIS-POD01-BH001, located in Bishopdale, and rainfall data from Christchurch Airport.

For each site, the correlation (r^2 statistic) between the groundwater response and the rainfall event magnitude was determined. This was carried out for all data for the winter (April to September inclusive) and for the summer (October to March inclusive). (26 piezometers did not have data after March 2017, and could not be included in the analysis of winter responses).

An example plot of the groundwater response against rainfall event magnitude is shown in Figure 12.

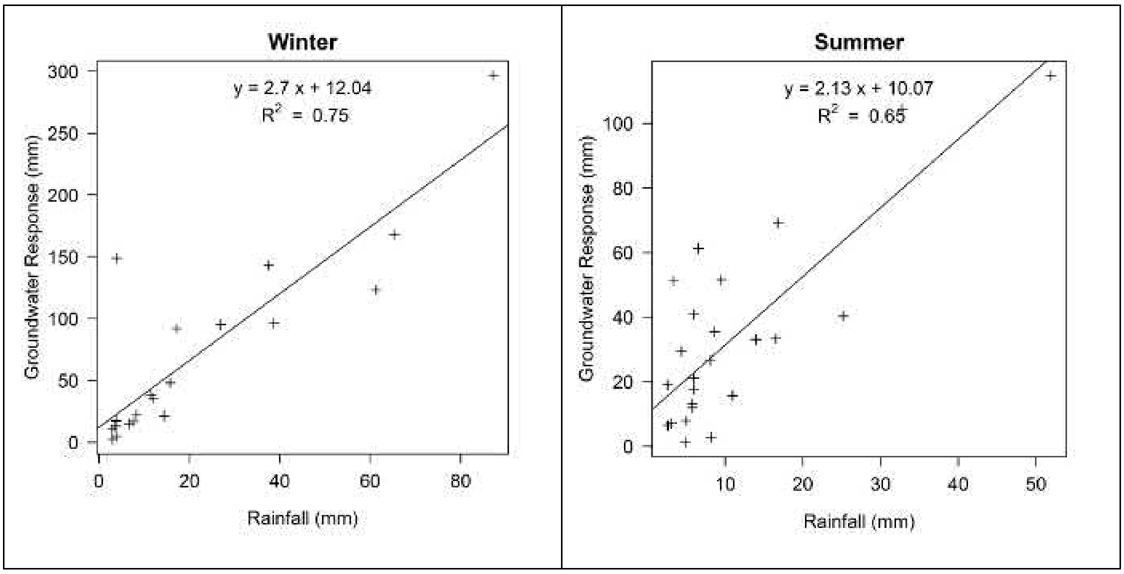


Figure 12. Example plot of groundwater level response against rainfall event magnitude for the winter and summer seasons. These data are from groundwater site reference AP114, also known as BIS-POD01-BH001, located in Bishopdale, and rainfall data from Christchurch Airport. The formula is for the linear line of best fit.

The likelihood that the correlation might occur by chance (p-value) was also determined for each site.

For those wells that were unlikely to have a correlation as a result of chance (less than 1 % likelihood, p-value < 0.01), the ratio of the groundwater response to the rainfall event magnitude was found and mapped (see Figure 17, Figure 18 and Figure 19). This is the slope of the linear best-fit line for the plotted groundwater response vs rainfall event magnitudes. 161 out of the 204 sites had a p-value less than 0.01 (and 180 had a p-value less than 0.05), showing there was a statistically significant relationship between rainfall and groundwater level response for the majority of sites. When split into winter and summer months, there is an obvious reduction in the ratio of groundwater level response to rainfall during summer months, and also fewer wells that provided a statistically significant correlation. This is likely to be explained by the fact that, in summer, there is a soil moisture deficit that needs to be replenished before recharge can occur, together with the fact that groundwater levels decline during the summer months, which may have complicated the analysis.

However, the response to rainfall events is not simple, as can be seen by the lack of a consistent pattern in these figures. This reflects the high degree of variability between hydrographs, with some showing a 'flashy' stream-flow type response, and others showing a more damped, groundwater-type response. The difference between manually-dipped data and the high resolution data available from the instrumented APP holes is illustrated in Figure 13. Some examples of the different types of hydrograph from the APP holes are shown in Figure 14 to Figure 16. From these limited examples, it can be seen that the range of hydrograph responses is extreme, and is likely controlled not only by rainfall, but tides, river flow, infrastructure, local hydrogeological conditions, infrastructure, and other unknown influences. Ultimately, the different response types will be important in terms of hazard, as the magnitude, duration and timing of exceedances (of any trigger level) will vary across the city. Within the scope of this project, it was not possible to investigate the drivers of different responses.

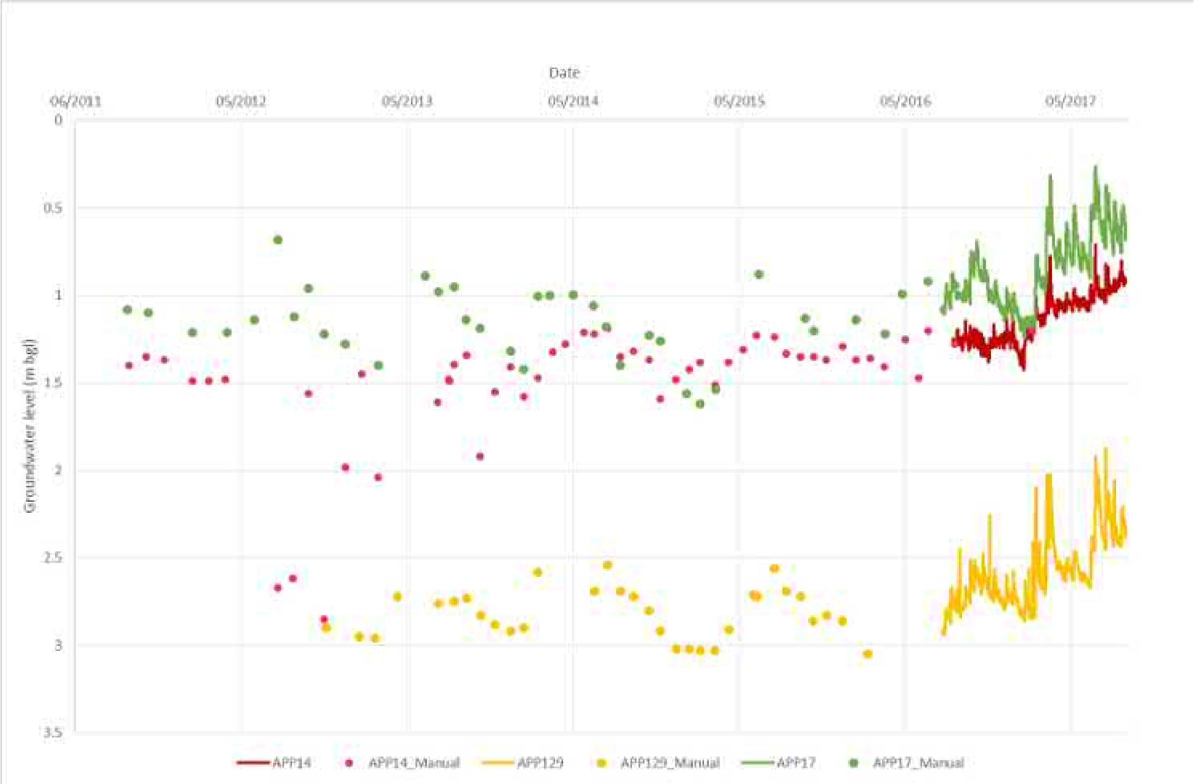


Figure 13. Comparison of manually dipped water levels and high resolution data

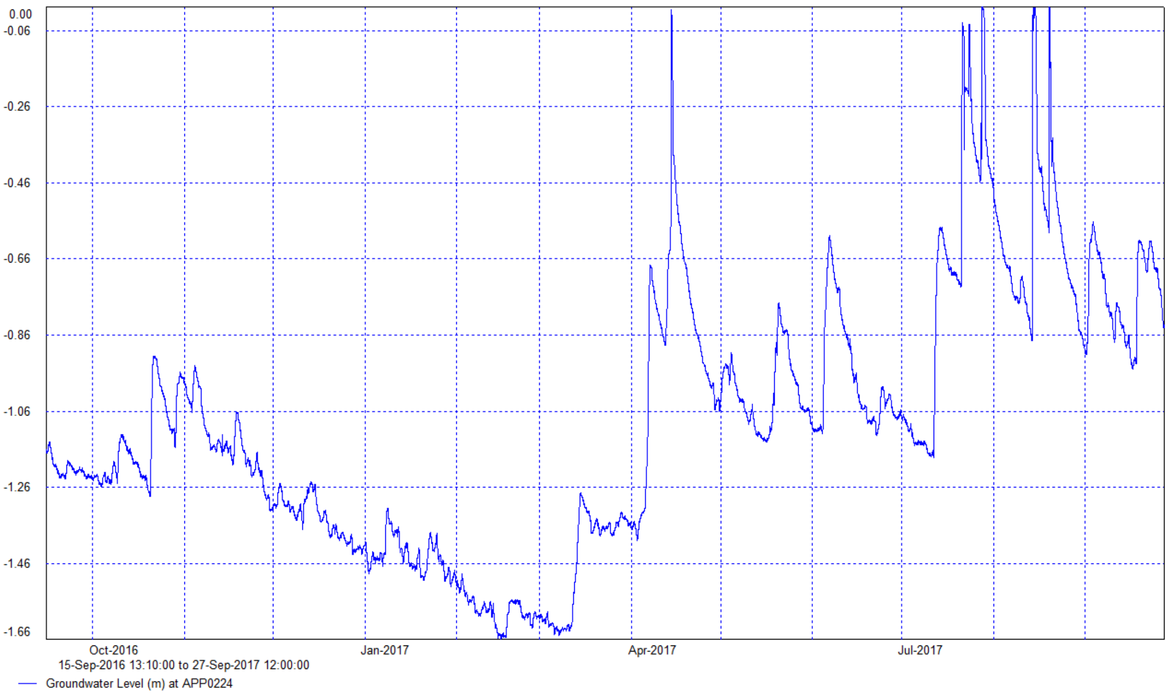


Figure 14. Example of a "groundwater"-type hydrograph APP224

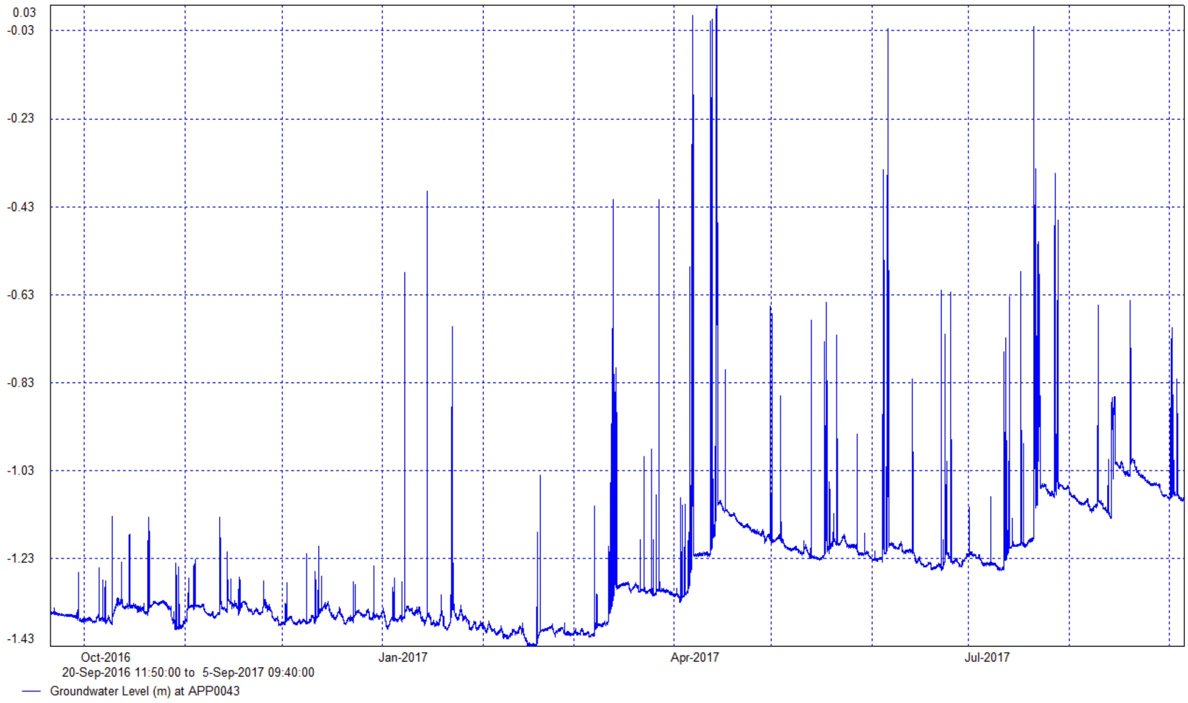


Figure 15. Example of a "streamflow"-type hydrograph: APP043

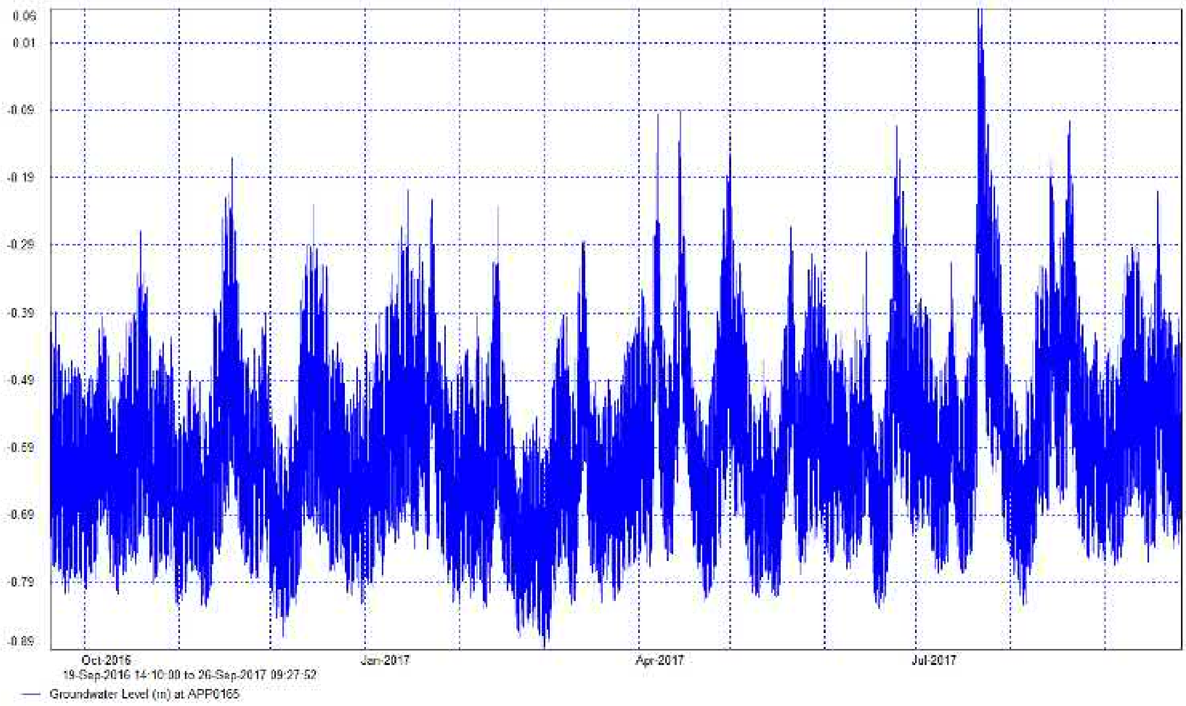


Figure 16. Example of a tidally influenced hydrograph

The greatest groundwater response to rainfall was 8.4 times the rainfall magnitude. This occurred at site reference FND-POD08-BH022 (APP68) near Christchurch Boys' High School in Fendalton. The hydrograph shows a baseflow, similar to a stream baseflow, with peaks in response to most rainfall events. The response here suggests a strong hydraulic connection with a surface water course (the piezometer is approximately 50 m from Ilam Stream) with peaks occurring rapidly, followed by a streamflow-type recession (Figure 20). It is very noticeable that the major peaks occur during winter, when groundwater 'baseflow' levels are also at their highest.

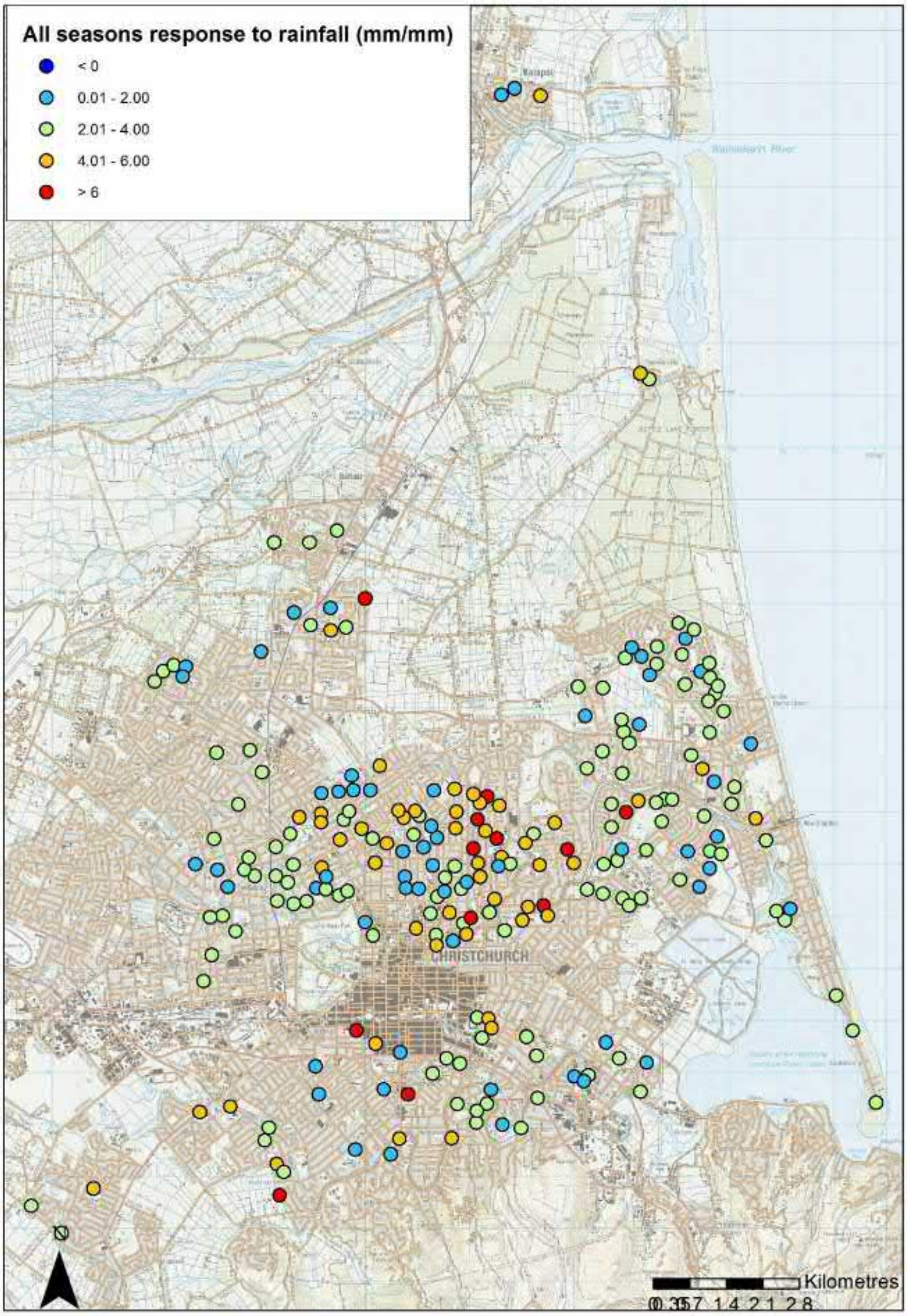


Figure 17. Groundwater response to rainfall event magnitude ratio (mm/mm), with data to late 2017. Only rainfall events greater than 2.5 mm were considered, where an event is determined by a minimum gap of one day between registered rainfall. Higher values are the most sensitive to rainfall.

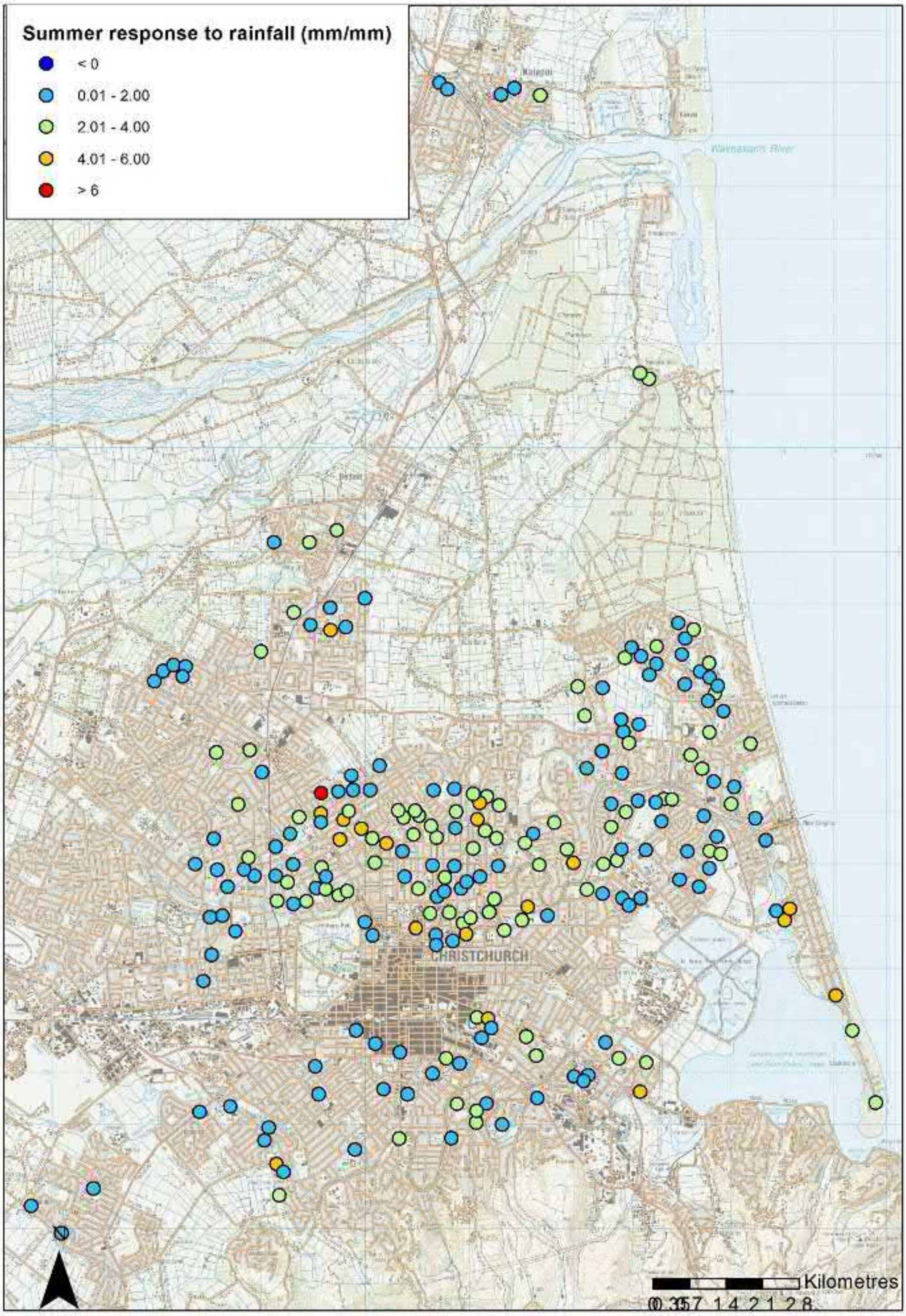


Figure 18 Groundwater response to rainfall event magnitude ratio (mm/mm), for summer data (October to March). Only rainfall events greater than 2.5 mm were considered, and an event is determined by a minimum gap of one day between registered rainfall. Higher values are the most sensitive to rainfall.

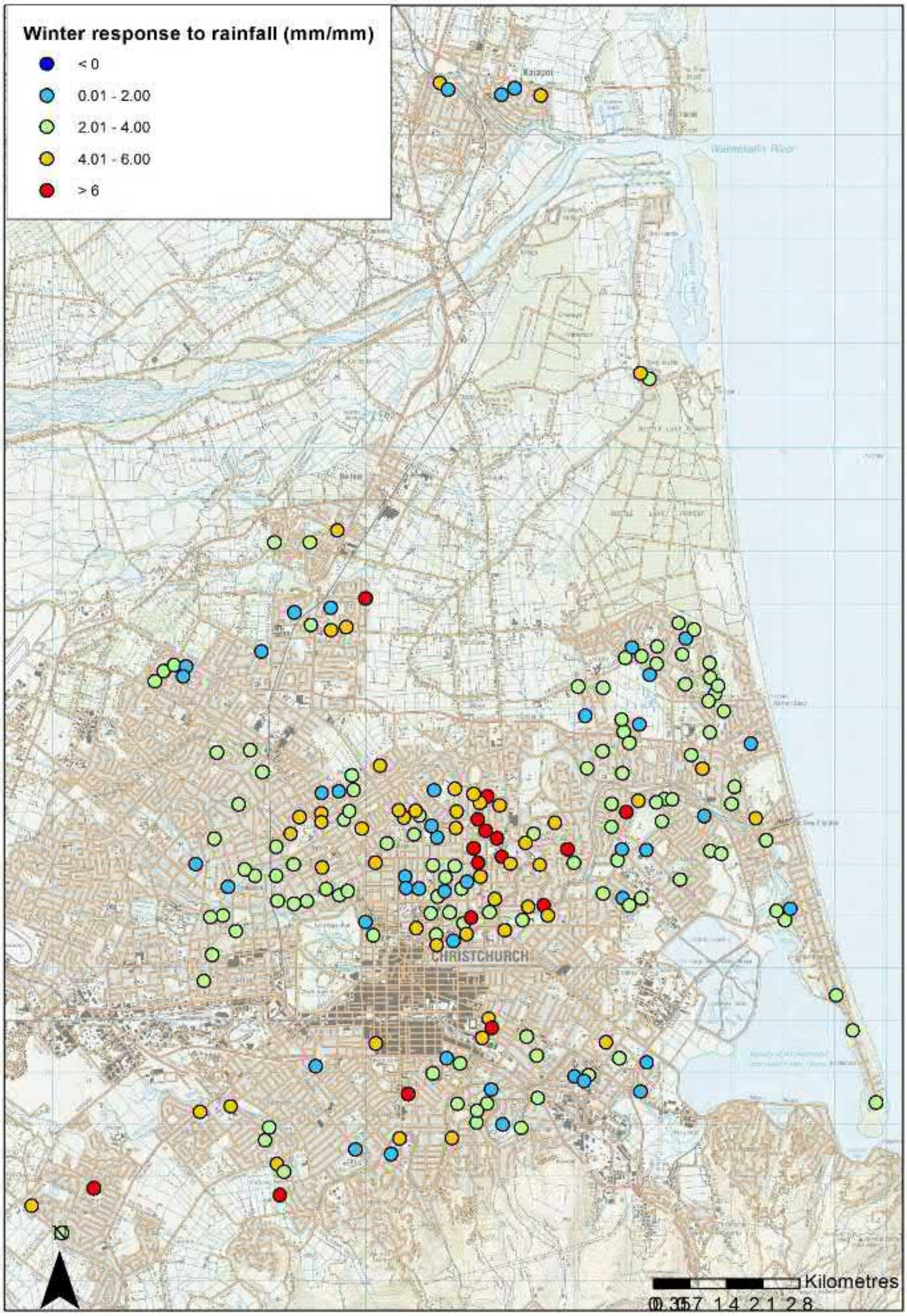


Figure 19 Groundwater response to rainfall event magnitude ratio (mm/mm), for Winter data (April to September). Only rainfall events greater than 2.5 mm were considered, where an event is determined by a minimum gap of one day between registered rainfall. Higher values are the most sensitive to rainfall.

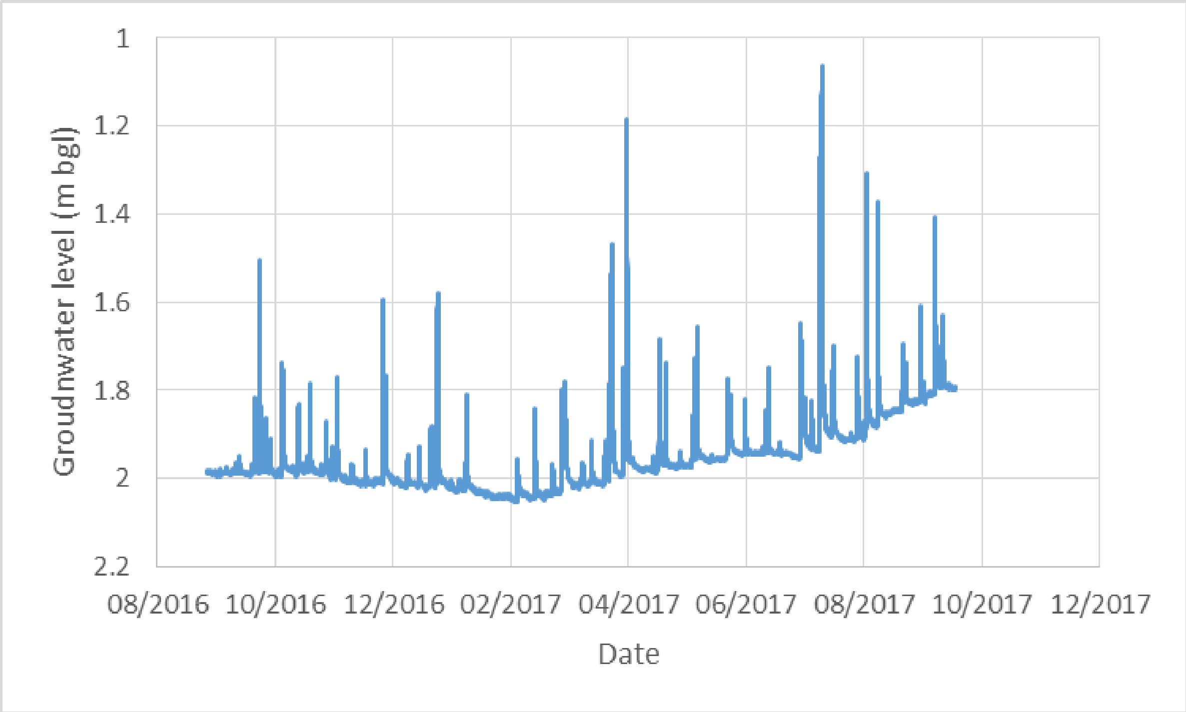


Figure 20. Groundwater hydrograph for APP68 APP224

In contrast, the least sensitive site had a rainfall response of 0.9 times the rainfall magnitude. This occurred at site reference APP235 in St Albans. The hydrograph is very noisy, with many small peaks rather than few, major peaks. The hydrograph is more similar to what would be expected from a groundwater hydrograph, with a summer recession, followed by a recovery to higher groundwater levels in the autumn and winter.

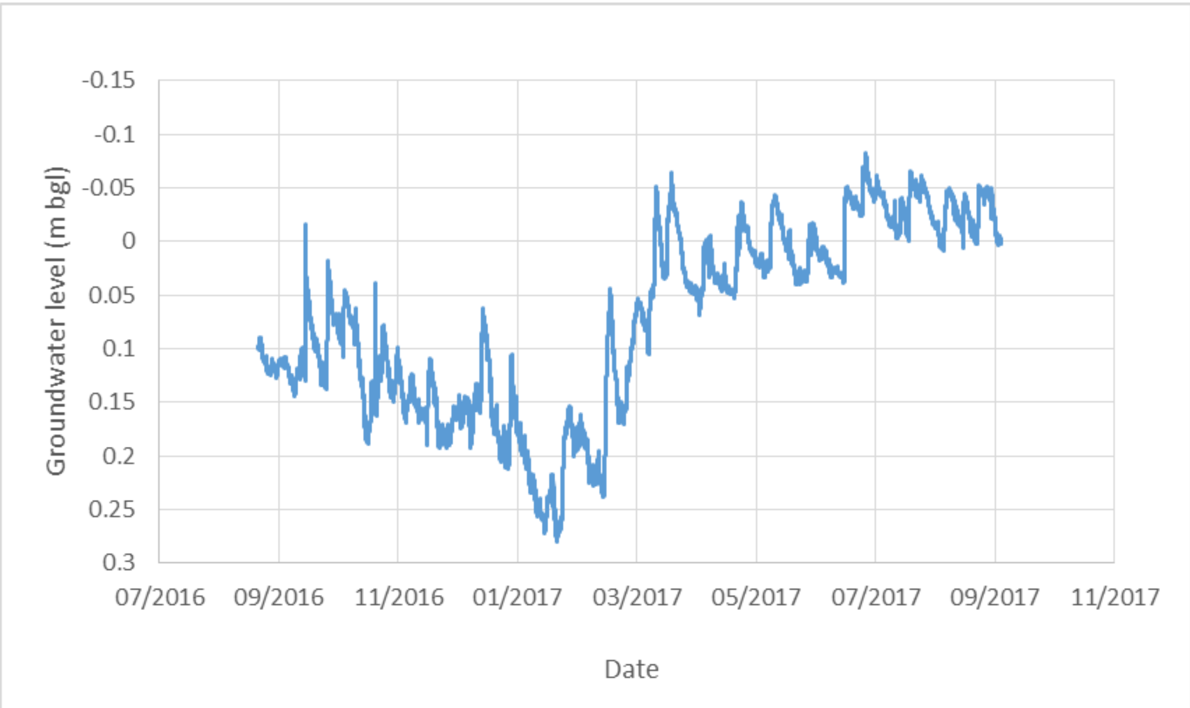


Figure 21. Groundwater hydrograph for APP235

When the magnitude of groundwater level response was compared with the major rainfall events that occurred during the period of record, fairly consistently, it was the same rainfall events that caused the biggest responses in groundwater levels across the city.

5.6 Response to Other Drivers

5.6.1 Streamflow

The apparent response of shallow groundwater to rainfall is complicated by the fact that rainfall also drives river flow. Figure 22 shows the response of the shallow piezometer APP132 and the Avon River at Gloucester Street. Whilst the Avon River data is only daily, both time series can be seen to be responding to similar rainfall events. It is currently not possible to separate out the effects of rainfall and river flow on groundwater levels, but it is likely to be a combination of both drivers, particularly close to streams/rivers, that results in the groundwater level response.

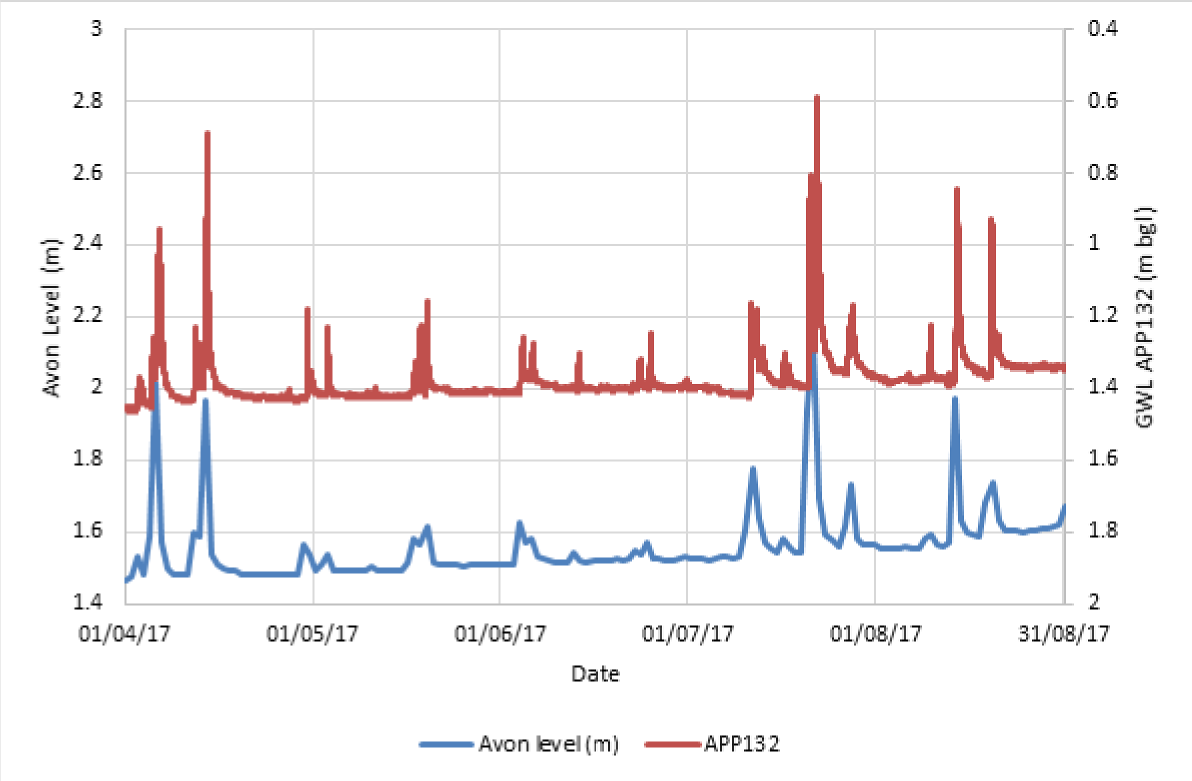


Figure 22. Avon River levels at Gloucester Street and groundwater levels for APP132 (close to University of Canterbury)

5.6.2 Tides

The impacts of tides were assessed by examining individual sites which were close to the coast or tidal sections of rivers. Previous work by Steinhage et al (2014) had suggested that the tidal signal propagated through the shallow groundwater to less than a kilometre from tidal sections of the Avon. They carried out a survey across four transects (Figure 23), and plotted the tidal range (maximum to minimum level during a tidal cycle). This suggested that even at short distances (around 50 m) from the channel, the tidal signal had reduced by 60%. It was difficult to identify a tidal signal at distances of greater than 200 m from the channel. The tidal range versus distance from the river is shown in Figure 24.

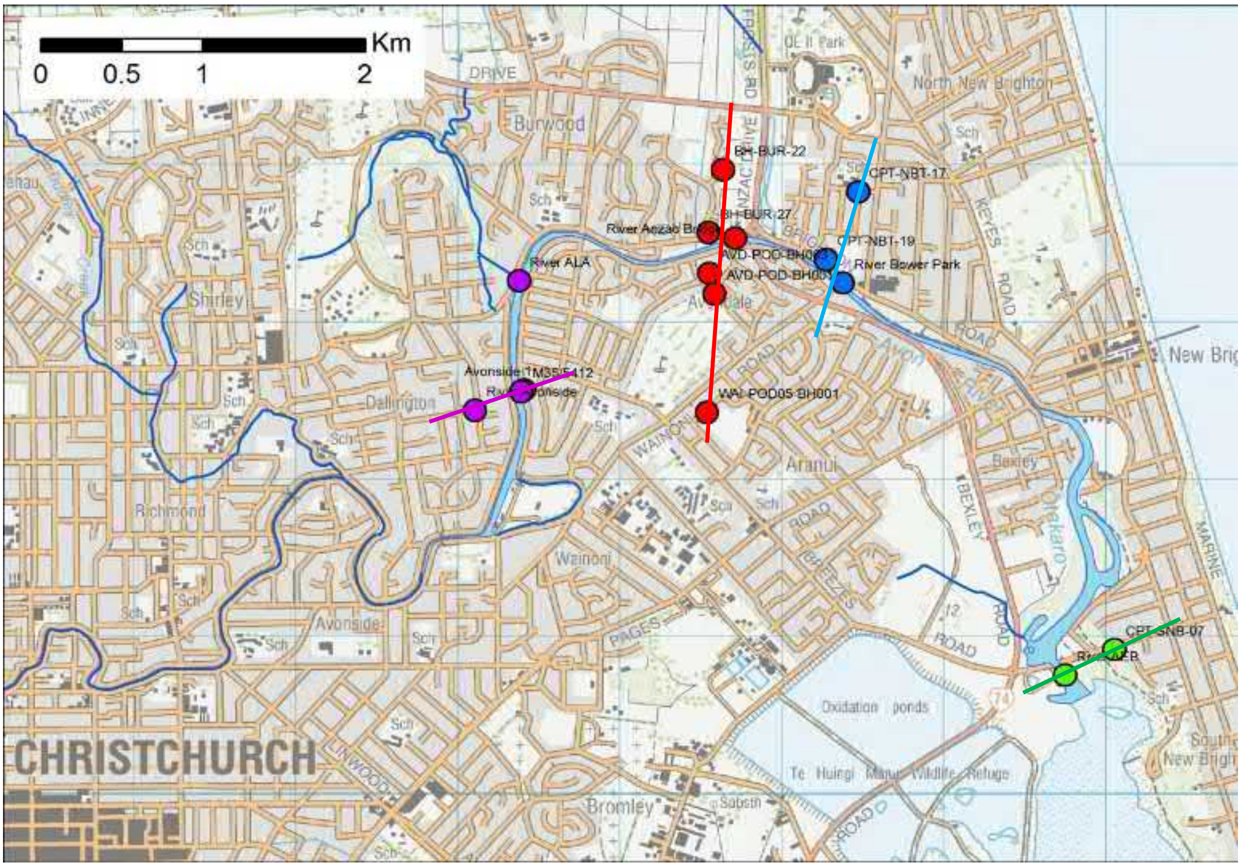


Figure 23. Location of transects (Steinhage et al., 2014)

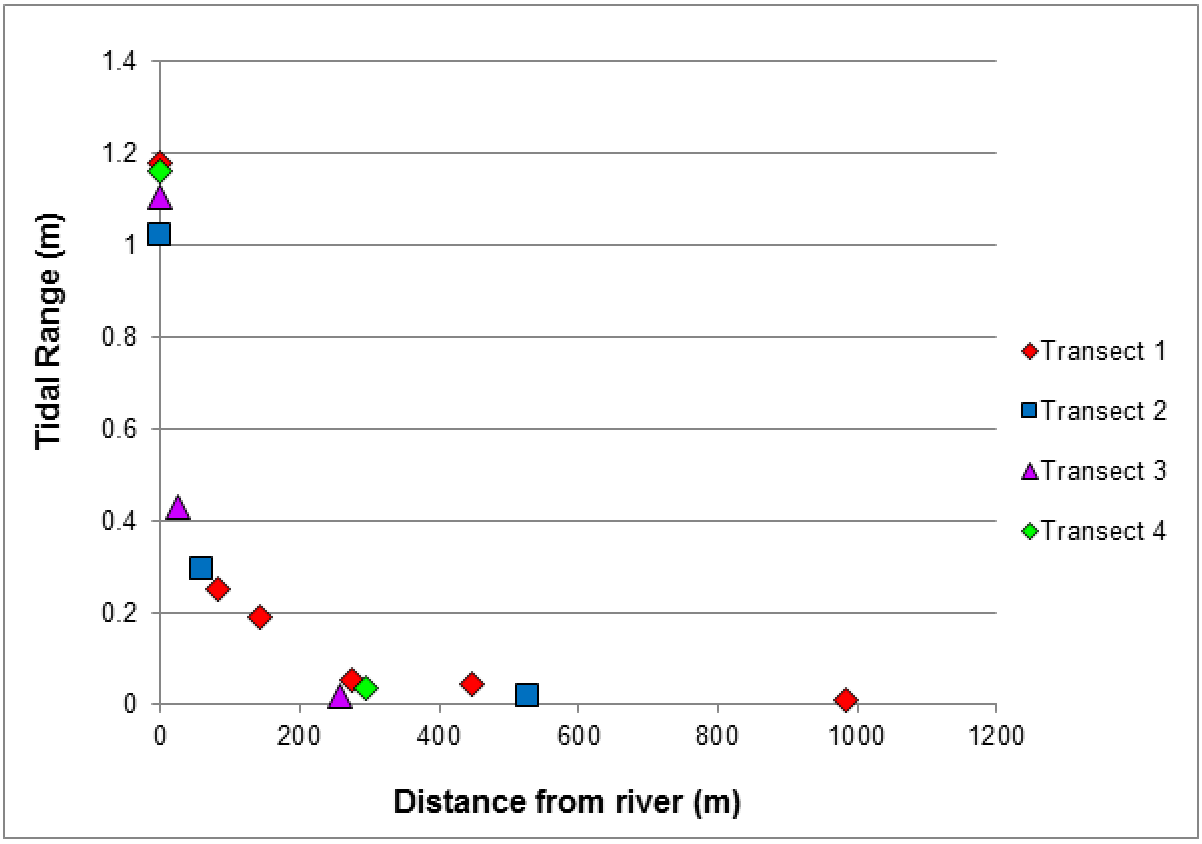


Figure 24. Tidal range (from Steinhage et al, 2014)

A similar approach was taken to analyse the APP data, using 10 piezometers identified within 300 m of the coast or a tidal channel (see Figure 25 and Table 5). The tidal range is plotted in Figure 26. The results confirm the earlier work by Steinhage et al (2014) and show that the short-term tidal signal does not significantly propagate distances further than 200m away from the coast or channel.

The high resolution APP data does provide additional insight into shallow groundwater behaviour under the Brighton Spit. Although APP165 has a dominant tidal signal, when plotted with APP66 and APP167 which do not show a tidal response, the impacts of recharge events can clearly be seen (Figure 27). In areas with a strong tidal response, the additional effects of recharge on top of the tidal response, may result in groundwater levels approaching ground level for significant periods of time.

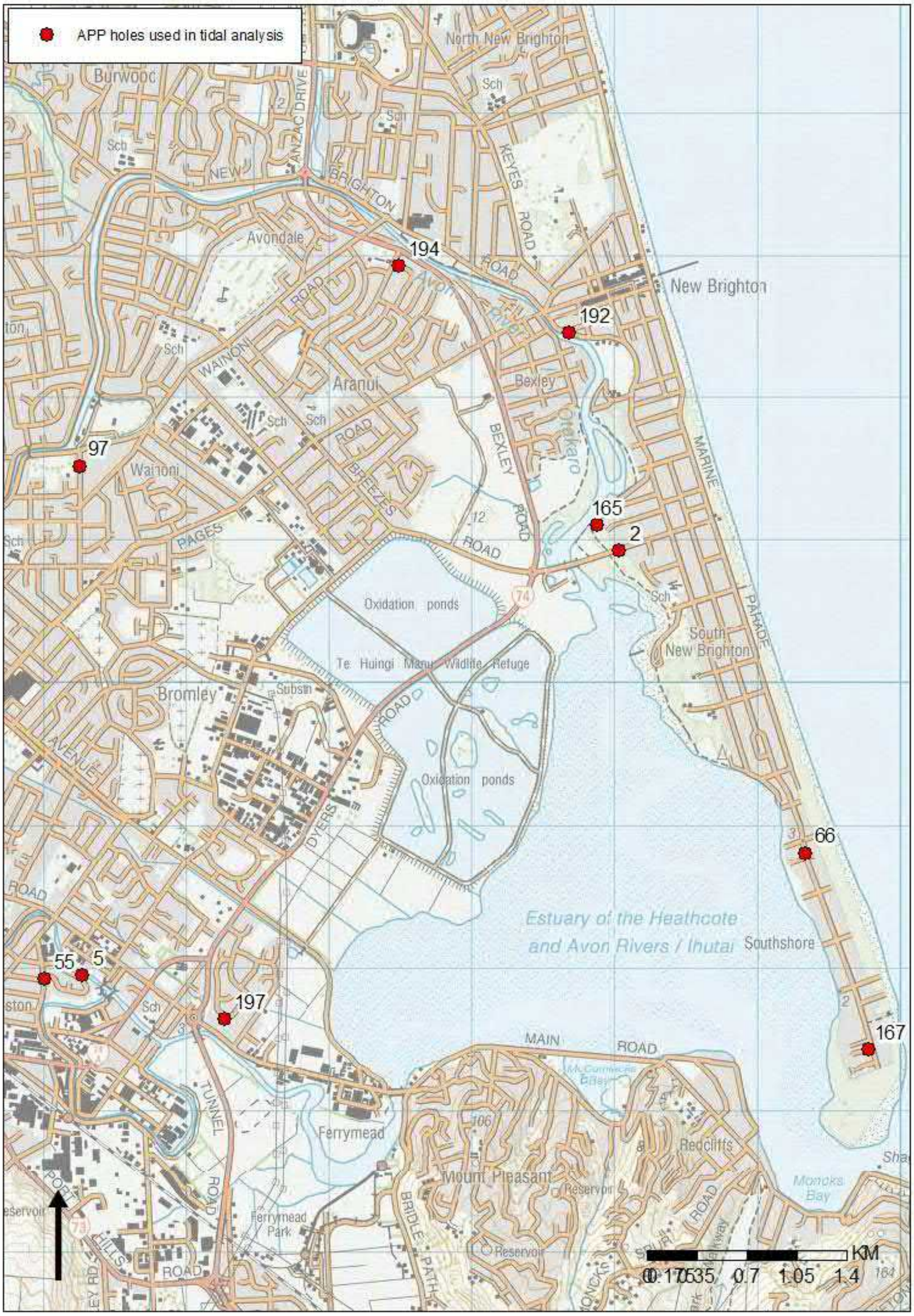


Figure 25. APP piezometers used for tidal analysis

Table 5: Tidal range of APP piezometers

APP number	Distance from Coast	Distance from	Average tidal range (m)
66	155	Estuary	0
197	125	Heathcote	0.07
192	25	Avon	0.3
97	150	Avon	0.11
194	135	Avon	0.1
167	270	Coast	0
165	60	Estuary	0.44
55	210	Heathcote	0
5	25	Heathcote	0.06
2	210	Estuary	0.06

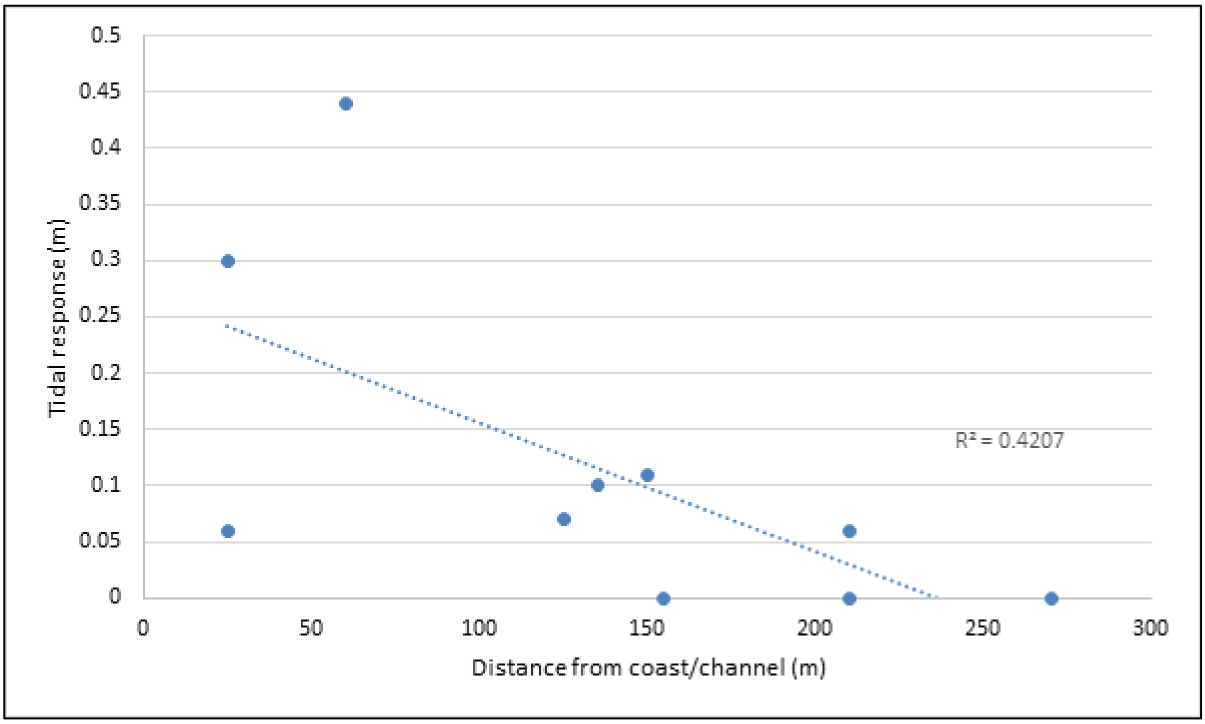


Figure 26: Tidal range observed in APP piezometers against distance from boundary

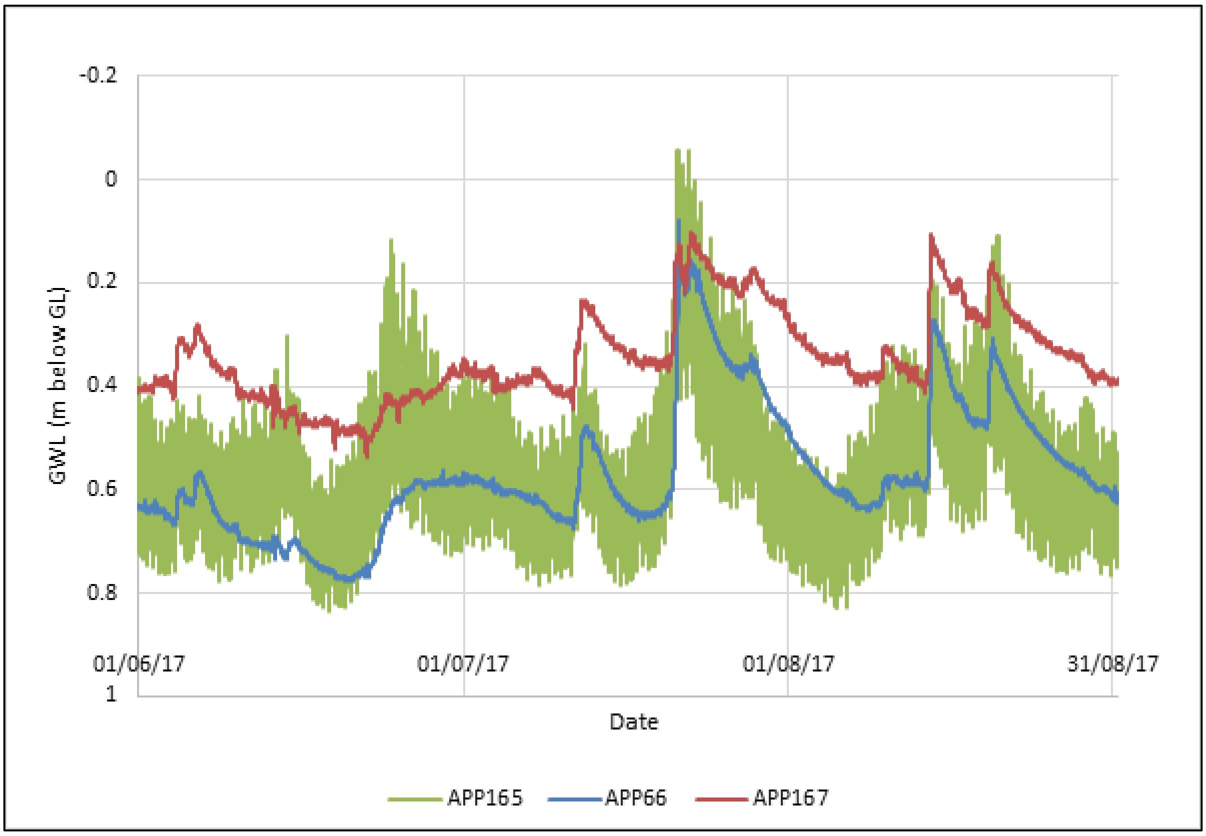


Figure 27. Comparison of hydrographs for three Brighton piezometers

5.6.3 Evapotranspiration

Evapotranspiration is assumed to be the main cause of the diurnal fluctuation in the groundwater signal during summer months (see Figure 10). This diurnal signal disappears in the winter months when evapotranspiration would be minimal. Although of interest, the fluctuations are only of the magnitude of 1-2 cm, and would occur when groundwater levels tend to be low anyway, and so are probably not an issue with regards to potential flooding.

5.7 Implications

Until these data were available, there was little or no understanding of the dynamic response of the shallow groundwater under Christchurch to rainfall and other drivers. The response of shallow groundwater to rainfall and river flow is significant. van Ballegooy et al (2014) identified that between 1990 and 2010 there were inter-annual variations of around 2 m in the west and 1.2 m in the east of Christchurch. With groundwater level changes of up to a metre in response to rainfall/streamflow, these short term responses may result in groundwater flooding or reduction in infiltration capacity over quite short time scales. Tidal responses, while limited to a short distance from the coast, may cause additional issues, but on a diurnal basis. This project has focussed on developing the long term median and 85th percentile surfaces, but it is important to understand that there is a highly dynamic short term response. The dynamic responses may be more important in areas with a high degree of dynamic response, than the longer-term base level.

It is also worthwhile reflecting on the fact that monthly dips are likely to represent a variety of groundwater conditions, from ‘base’ levels through to extreme peaks. This data on which the median and 85th percentile surfaces have been based, will represent a range of these hydrogeological conditions and may account for significant variability when using the summary data to develop a surface.

6.1.1 Spatial Distribution of Wells/Piezometers

For the purposes of this project, the principal gaps were gaps in the spatial distribution of the available water level data. The analysis to produce the water table surfaces relied on shallow piezometers and wells that were either part of the EQC network, or long term CCC or ECan wells. Some additional data were explored from site investigation work.

The analysis of the data, as well as the estimation and simulation processes carried out in the geostatistical analysis (see Appendix D), showed that the system is very “noisy” and that there was, in general, a great deal of uncertainty for water levels. The high nugget effect (reflecting a high degree of random behaviour in the data) showed that the expected water table could have up to a 20 to 30 cm uncertainty at the observation points. The conditional simulations highlighted that the uncertainty increased rapidly with relatively short distance from the data (<300m). The consequence is that in the areas with low sample density the water table is poorly defined.

From the surfaces developed, it was possible to extract areas where there is greatest uncertainty in the data, combined with, interpolated shallow depth to groundwater. Figure 28 shows areas where there is relatively shallow groundwater (median < 0.7m) and low confidence in the interpolation. These areas are not all equal in terms of requiring further monitoring: areas that will not be developed in the foreseeable future may not be a priority in terms of instigating further monitoring. Areas were identified, through discussion with CCC, which were higher priority, including Hendersons Road, Cranford Basin, Southshore/South New Brighton, Sumner, Redcliffs, and Riccarton. Within these areas, there may be existing wells/piezometers that could be dipped or instrumented.

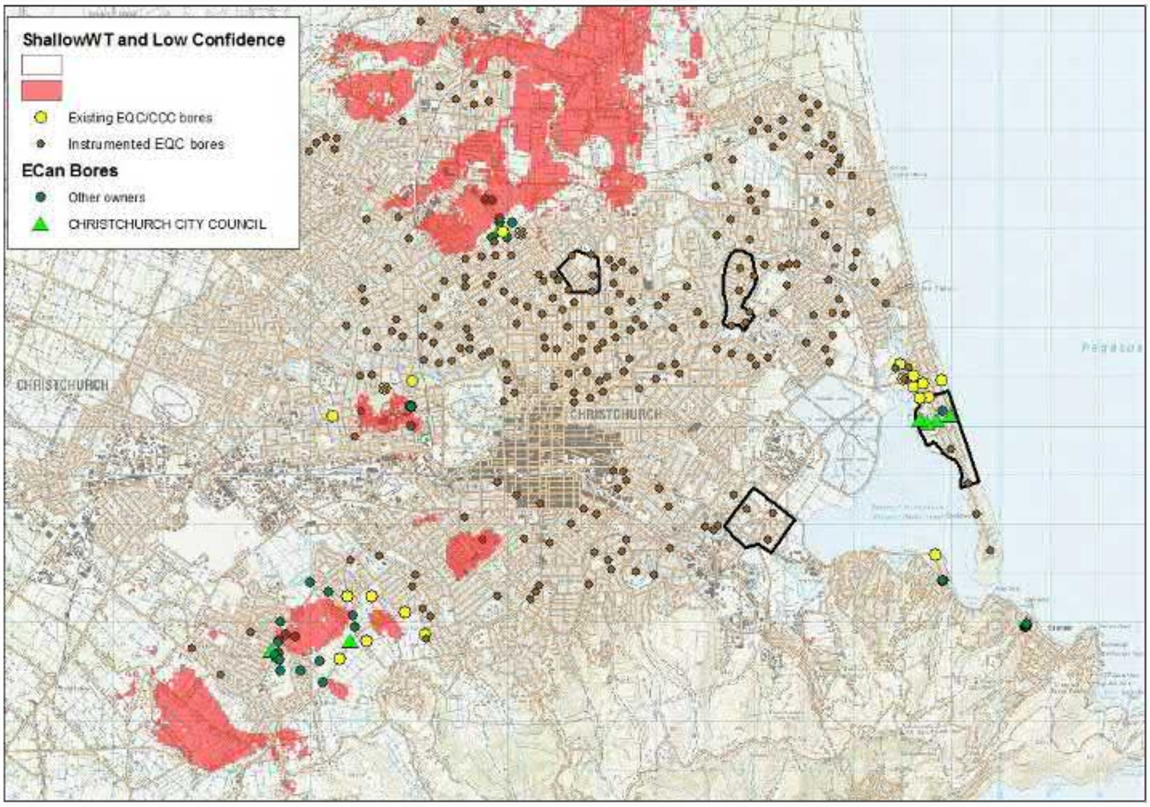


Figure 28. Areas with shallow median depth to groundwater and low confidence (red)

6.1.2 Temporal Availability of Data

Groundwater level data vary in all dimensions, including temporally, and part of the LDRP45 project had been to assess whether relatively short term datasets, that is the EQC data, could be used to represent the long term data. This is explored in Section 7.3. The results of this analysis suggested that the median and 85th percentile from the six years of EQC data were appropriate to use to represent the longer-term data from ECan and CCC monitoring wells.

New data that is collected would have no historical context, so if new piezometers are installed and instrumented in the future, there would need to be a period of data collection followed by an assessment of the data to determine median values or other statistics. In order to make more use of short term data, linear correlation can be determined with another piezometer, and the relationship used to extend the data series back in time. There are, however, drawbacks including:

- the uncertainty of the new median may be large
- a statistically significant correlation may not exist to a long term site
- additional complexity in data processing.

This approach had been tested when analysing the EQC data: linear regressions were prepared between every EQC bore and each of the 51 long-term sites. The regression with the highest r^2 (as long as the regression was significant) was found for each site: that is, the long terms bore that behaved most similarly to each EQC bore was identified. Of the 937 EQC sites, 216 sites could not have regressions calculated for them (usually due to a lack of data for the EQC site).

The r^2 values for the regressions that were significant has the distribution shown in Figure 29.

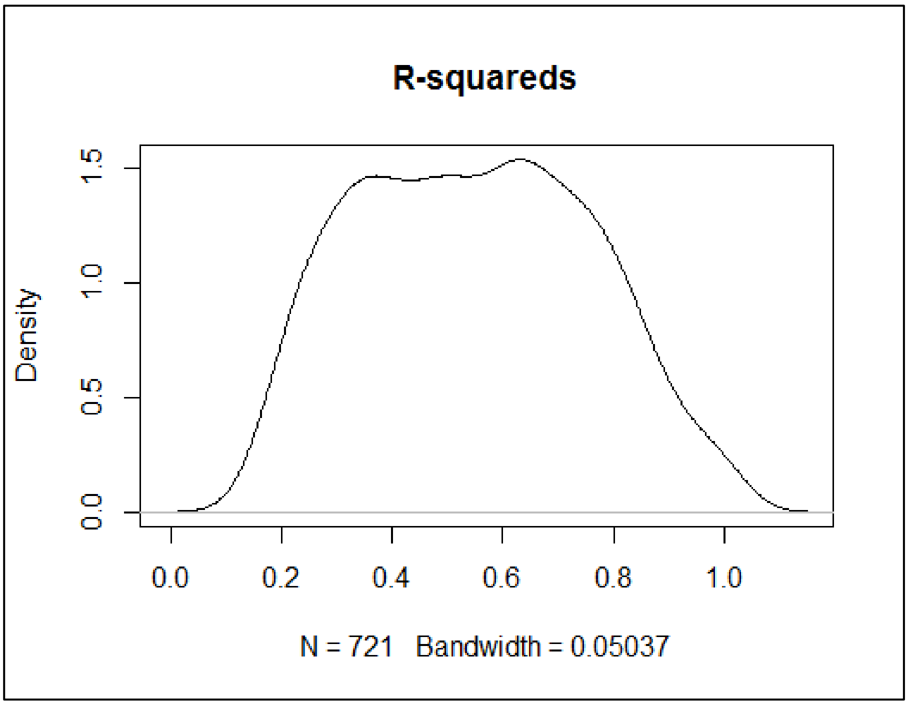


Figure 29. R^2 for regression between ECan/CC long term bores and EQC bores

The low value of the r^2 and the large number of sites that did not return statistically significant relationships suggests that time series extension through linear correlation was not always successful. This may be due to the dynamic response of the water table as described in Section 5.5. This may be because groundwater levels can be hugely variable, in response to drivers such as rainfall events, and that the comparisons can be very dependent on exactly when the data were collected.

As a result of the lack of correlation between long term water level data and the EQC data, there was no attempt to extrapolate the short-term data. Given the good relationship between the short-term medians (2011 to latest) and the long-term medians, this was considered to be acceptable.

6.1.3 Future Availability of Data

There are two issues to be considered: the spatial and temporal availability of data. In terms of the spatial distribution, because of the noisiness of the groundwater level data, once away from measurement points, the confidence in the interpolated groundwater surface declines. As a result, in areas where significant development is to occur, a monitoring plan should be instigated that has a relatively fine grid. Potentially, monitoring plans could be developed where comprehensive sampling over a short period, supports a more regular sampling at a smaller number of locations.

In terms of temporal data, the EQC network was put in place to inform land damage assessments. Of the original over 1000 piezometers, there were 971 datasets with some data, but only 723 had sufficient data to be analysed. Of this network, EQC instrumented around 200 holes with water level monitoring transducers, and drilled and instrumented a further 50, to provide a network of 249 instrumented holes (APP holes) across the city (see Figure 8). The remaining piezometers are no longer dipped, and the future of the APP holes was uncertain, but has now been taken on by CCC, together with some funding from ECan and EQC.

Initial characterisation of hydrograph responses was carried out as a part of an EQC project, and as a result of this, we consider that around 30 transducers could be re-deployed in other locations.

7 WATER LEVEL DATA ANALYSIS

In order to develop a "baseline" water table, on which to impose changes caused by earthquakes and/or SLR, we needed to carry out processing of the available water level data.

7.1 Data Pre-Processing

As described in Section 3, there were various sources of groundwater level data. Metadata were generated for each site, consisting of:

- Duration of the time series in days, including the start and end date of the time series;
- Average time step between observations;
- Number of observations;
- Maximum, minimum, average, median, and variance for each time series;
- Winter maximum and minimum; and
- Summer maximum and minimum.

The first step in the data pre-processing was QA to manually identify questionable data. Obvious outliers were identified and specific data points were removed from the dataset before processing.

Where there was more than one water level recorded within a month, the month's water levels were converted to a monthly mean; this generally only occurred for the CCC and ECan piezometers, some of which were dipped fortnightly, and others had daily data. These monthly values were then used for further processing.

Note that durations and time between observations have simply been taken for the entire monthly time series without correcting for gaps. That is, if a piezometer was dipped monthly, then not dipped for six months, and dipped monthly again, the average time step would be greater than a month.

Only those piezometers that had at least one observation for every month within the window were used. This prevented biases related to single observations, or summer only observations etc. Of the 971 sites, 816 had at least 1 observation for each month.

To maximise the amount of data used, but minimise the effect of any long term trends in the CCC/ECan bores, or from using data from different periods, the summary data was applied to a window of time, this being 1/1/2004 to 1/1/2014.

The 2004 - 2013 range was selected for a variety of reasons:

- to be recent, minimising land-use change effects and climate trends,
- to be long enough to include a variety of years,
- to avoid inclusion of the two recent very dry years so that the drought in 2015/2016 did not bias the result for the sites with shorter time series, particularly if there was only recent data available.

The drawback is that the ten years is too small to sample all parts of the Interdecadal Pacific Oscillation climate cycle. In order to test whether this might have an influence on the results, we assessed the impacts of IPO and other climate cycles, and concluded that the use of the past 10 years' data was justified (see Section 5.2).

Various statistics were derived from the data (see Table 6). Two approaches were taken to deriving median and mean values. As described earlier, for each bore, if there was more than one water level within a month, the mean water level was calculated for that month. Statistics were then derived based on these monthly values, including mean, median, 15^{th} and 85^{th} centiles. Additionally, means and medians of "month types" were calculated: that is, the means for all January's, February's, March's and so on, were found, then the mean or median of those 12 was found, to provide a statistic for the piezometer. There was found to be very little difference between the two approaches to calculating mean and median values for each bore, and the statistics from the monthly values were used for derivation of the water table surface, as had been done by van Ballegooy et al (2014). A description of the statistics derived in is Table 6.

The values (median and 85th percentile) were plotted spatially to make sure there were no obvious outliers.

Table 6: Summary of statistics generated

Attribute	Description	Comment
Durations.days.	The number of days from the start to the end of the data	Taken from the original data for the windowed period.
AverageTimeStep.Days.	The average time step in days	Taken from the original data for the windowed period. Was not corrected for any data gaps.
NoOfObs	The number of observations taken	Taken from the original data for the windowed period.
MaximumsOfMonthMeans.masl.	The maximum of the monthly values in metres above sea level. That is, the observations were converted to monthly averages, and then the maximum was found.	Taken from the time series of monthly means.
MinimumsOfMonthMeans.masl.	The minimum of the monthly values in metres above sea level	Taken from the time series of monthly means.
MediansOfMonthMeans.masl	The medians of the monthly values in metres above sea level	Taken from the time series of monthly means.
15thPercentilesOfMonthMeans.masl	The 15th centiles of the monthly values in metres above sea level	
85thPercentilesOfMonthMeans.masl	The 85th centiles of the monthly values in metres above sea level	
MeansOfMonthTypeMeans.masl.	The mean of the values for each month type. That is, the means for all Jan's, Feb's, Mar's etc. were found, then the averages of those 12 averages was found.	This is to avoid weighting to any month that has more observations than others.
MediansOfMonthTypeMeans.masl.	The medians of the values for each month type.	This is to avoid weighting to any month that has more observations than others.
Variance.masl.	The variance of the monthly values	This gives some measure of the variability of the seasonal signal.
SummerMaxOfMonthMeans.masl.	The maximum of monthly values for the February, March and April months.	
SummerMinOfMonthMeans.masl.	The minimum of monthly values for the February, March and April months.	
WinterMaxOfMonthMeans.masl.	The maximum of monthly values for the August, September and October months.	
WinterMinOfMonthMeans.masl.	The minimum of monthly values for the August, September and October months.	

7.2 Impacts of the Canterbury Earthquake Sequence on Long Term Groundwater Levels

The impacts of earthquakes can be both transient and permanent. A key issue in this project was to understand land settlement under various earthquake annual exceedance probabilities (AEPs), and to predict the changed depth to water. The previous work by van Ballegooy et al (2014) had shown that although there was frequently a dynamic response to the earthquakes, this rarely resulted in a permanent change in the depth to shallow groundwater. The wells that had been assessed as potentially having a permanent offset in median groundwater level were assessed again with the additional four years' data. It should be noted that the groundwater levels respond to numerous drivers, including rainfall, river flow, climate, and infrastructure works, as well as to the earthquakes. The winters of 2015 and 2016 had low recharge, and hence many areas of Canterbury show low groundwater levels during this period. However, the impacts of the low recharge winters are often hard to differentiate from the other drivers in the Christchurch area.

The summary findings from the analysis of van Ballegooy et al (2014) are shown in Table 7.

Table 7: Summary of earthquake-induced changes of water table elevation observed in shallow CCC and ECan monitoring wells in 2013.

Well_Nos	Observed Response	Number of wells
HLR, AWO, HGO, ABI	Persistent change to lower water table elevation, with or without short-term (transient) fluctuation	4
HHM, XRU, SDA, M35/7896, M35/8968	Distinct fluctuations or changes in variability, not always understood. Potentially explained by local pumping, temporary drainage changes, changes in local river flow or groundwater-surface water interaction (e.g. M35/8968), or well damage.	5
M35/0601, M35/0724, M35/6507	Unusually high water table elevation during winter 2012 (Kaiapoi region)	3
ARC, NK2, SF8, M36/5384, M36/5385	Short-term transient fluctuations ('spikes') then return to pre-earthquake elevation and variability	5
AAY, ACR, HHA, HSX, NDW, HHL, BIN, HHN, HCY, NHG, HSH, HCX, HHX, HFI, AP2, SF1, SBE, M35/1079, M35/1080, M35/1878, M35/3614, M35/5560, M35/0948, M35/1110, M35/1111, M35/1156, M35/1603, M35/1691, M36/0142, M36/0202, M36/2452, M35/6550, M35/7169, M35/6936, M36/4741, M35/5436, M35/8969, M35/4302	No statistically noticeable change – no short-term fluctuations, longer term departures in water table elevation, nor changes in variability	38

The four wells that showed a significant and definitive earthquake-related change were ABI, AWO, HGO and HLR, all located in the Eastern/Coastal Zone. The post-September 2010 water table elevation in these wells was mostly below pre- September 2010 elevation although record maximum, or near-maximum elevations were recorded at various times after the September 2010 earthquake. It is possible that maximum elevations have remained the same, even though the elevation of the median water table has fallen, and the range of groundwater fluctuations has increased in these four wells.

Ground elevation in the vicinity of ABI, AWO and HLR subsided through the earthquake sequence, changing in cumulative elevation by -0.5, -0.3 and -0.4 m respectively, whereas at HGO it was uplifted +0.2 m (see van Ballegooy et al, 2014). Importantly, decreases in water table elevation have occurred regardless of whether the land surface was uplifted or subsided. The decreases in median water table elevation (ABI -0.6 m; AWO -1.1 m; HGO -0.5 m; HLR -0.7 m) are almost twice the cumulative changes in ground elevation at each site.

The major change in ABI water table elevation occurred in September 2010 after the first Darfield Earthquake, whereas the decreases in AWO, HGO and HLR occurred after the February 2011 Christchurch Earthquake. ABI is situated in Dallington, approximately 250 m from the Avon/Otakaro River, where the September 2010 earthquake caused liquefaction and lateral spreading damage. The EQC monitoring wells in this area all appear to have water table elevation below sea level, and drainage and pumping stations along the river probably account for the level of the water table here (G. Harrington, pers. comm.). The new 'post-Darfield Earthquake' median water table elevation in AWO is at sea level, which is also the mean elevation of the Avon/Otakaro River nearby. At times there have been slightly negative values representing water table elevation below mean sea level. This could be explained by various factors including measurements made at low tide and/or post-earthquake drainage/dewatering work. For a period of time, the water table elevation in AWO was (anomalously) below mean sea level, which was caused by dewatering being performed for the nearby sewer repair work on Woodham Road between June 2011 and March 2012 (T. Borkus, SCIRT, pers. comm.). During 2017, there was a major recharge event with groundwater recovery to levels closer to pre-earthquake levels; with another year's data an assessment could be undertaken to determine whether this is temporary or not. AWO is situated in Linwood, around 700 m from the Avon/Otakaro River whereas HGO in Woolston and HLR in Opawa are both situated around 100 m from the Heathcote River.

The four wells showing persistent earthquake-related changes in water table elevation appear to decrease to new post- September 2010 median water table elevations that correspond to nearby base levels, being either sea level or a nearby river level. ABI, AWO, and HGO occur in areas where the ejection of liquefaction material was extensive. One possible explanation was considered to be that permeability and porosity of shallow soils at these sites was increased by the ejection of fine sand and silt to the surface, thereby providing a stronger hydrological connection between the monitoring well and the nearby river. An alternative is that cracking caused by shaking and lateral spreading could produce a similar effect. While the exact mechanism is not known, it does appear that the water table elevation has decreased at these four sites.

There were a number of wells where the water table fluctuations are less straightforward to interpret, where there are anomalous fluctuations that are not clearly coincident with the arrival time of earthquakes, but fluctuations may be indirectly related to earthquake events (or associated human activity). Some of these are:

- HLR. Following the original reduction in water level post-earthquake, there appears to be a persistent change to shallower GW RL from 2014 onwards, with or without short term (transient) fluctuations (Figure 30). Median water level post-earthquake increased from 2.31 (2011 – 2012) to 2.39 m RL (2011-2017). Recent data showed a rapid GWL recovery from January 2017 to a peak of 3.5m RL in September 2017. This peak was short-lived and recent data show GWLs are around 2.4 to 2.6 m RL (Figure 30).
- AWO. There appeared to be a persistent change to shallower GW RL in March 2013, with a period of stable water levels through to Feb 2017 when there was another shift to shallower water levels (Figure 31). Median GWL post-earthquake shifted from 1.042 to 1.347 m RL. Since January 2017, there was a very marked recovery and groundwater levels are currently over 2m m RL. With future data, we will be able to assess whether GWLs have returned to pre-earthquake levels, or whether this is temporary.
- HGO. This showed a marked decline in groundwater levels from February 2011. There has been a slight overall recovery in GWLS since 2011, with a marked response to recharge in early 2017, peaking in July 2017, but recessing again rapidly (Figure 32). GWLs are frequently below mean sea level, possibly due to the location adjacent to a tidal section of the Heathcote River.
- ACR. The trend in lower GW levels post-earthquake continued, but appears to be a linear reduction in GWLs over a long time period, and possibly not related to the earthquakes (Figure 33).
- SDA in Brooklands showed a decline in groundwater level post-September 2010, followed by a gradual increase in groundwater level through the following years (Figure 34). The low recharge winter of 2015 is reflected in limited recovery of groundwater levels through 2015, but if followed by a very abrupt increase in level of around 0.5m in May 2016. This was thought to possibly represent a change in measuring point, though this has since been discounted. It could be a result of the cessation of dewatering in the area.
- XRU initially showed significant post-Darfield Earthquake variability, with larger seasonal fluctuations than those experienced in the past decade. The monitoring point is very close to the oxidation ponds, that were known to have been severely damaged by the earthquakes, and this could possibly have accounted for some of the observed changes. Since 2016, the variability has decreased.

- M35/7896 had a lot of sediment in the well that was flushed in 3 May 2011. The water table dropped significantly to a new record low elevation, but since June 2015 is back at pre-earthquake levels.
- M35/8968 at McLeans Island near Waimakariri River is a 7.6 m deep well in which the water table has become progressively lower with time, reaching record low levels during Mar-May 2012, possibly due to local quarrying activities or effects of natural shifts in the position of Waimakariri river channels and/or groundwater flow. Due to the natural decline in groundwater levels from 2001 to 2010, it is difficult to know what the effects of the earthquakes were, but groundwater levels have been stable from 2010 to present, and within the same range as the 2009-2010 period.
- Three wells in the Kaiapoi region (M35/0601, M35/0724, M35/6507) recorded anomalously high water table elevation during August 2012.Water levels have since returned to be within the normal range.

Overall, the effects seen in HLR and HGO appear to have persisted through to current time, whilst groundwater levels at AWO may have recovered: this cannot be stated for certain until more data are available. The observations from 2013, together with current observations, are summarised in Appendix C.

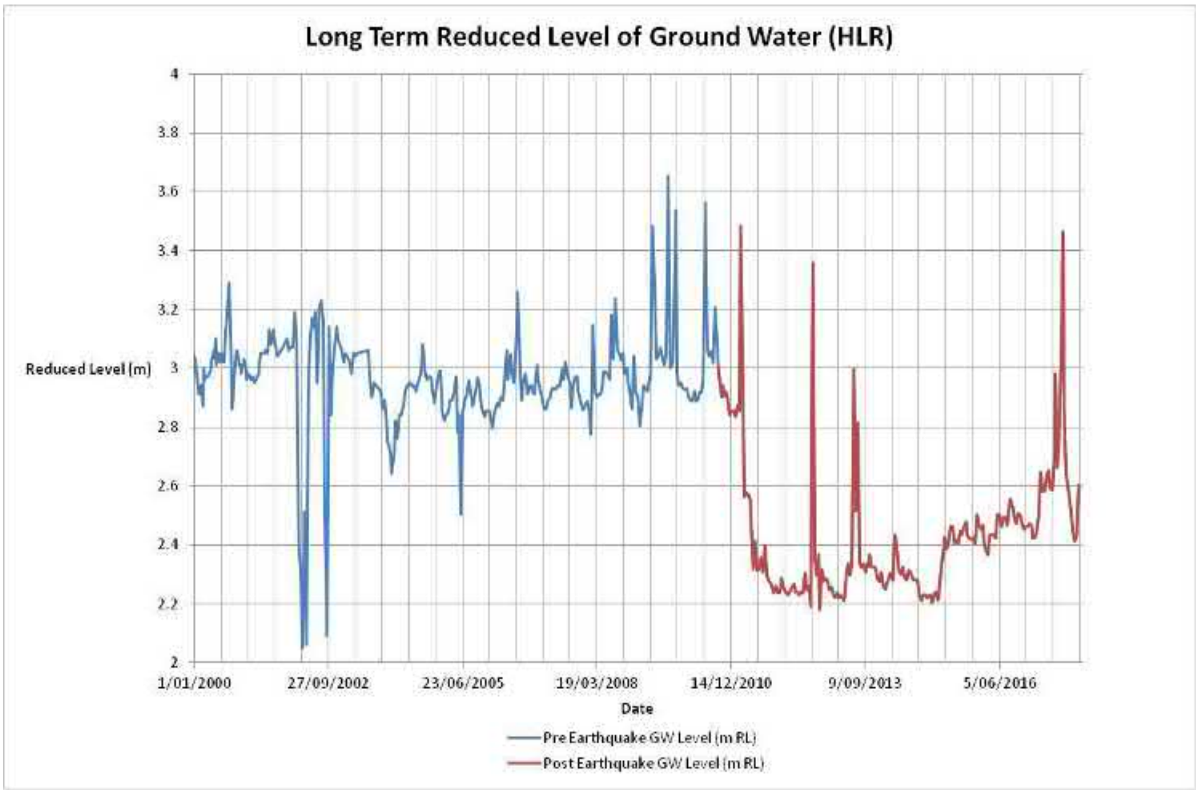


Figure 30. Pre- and post-earthquake groundwater levels - HLR

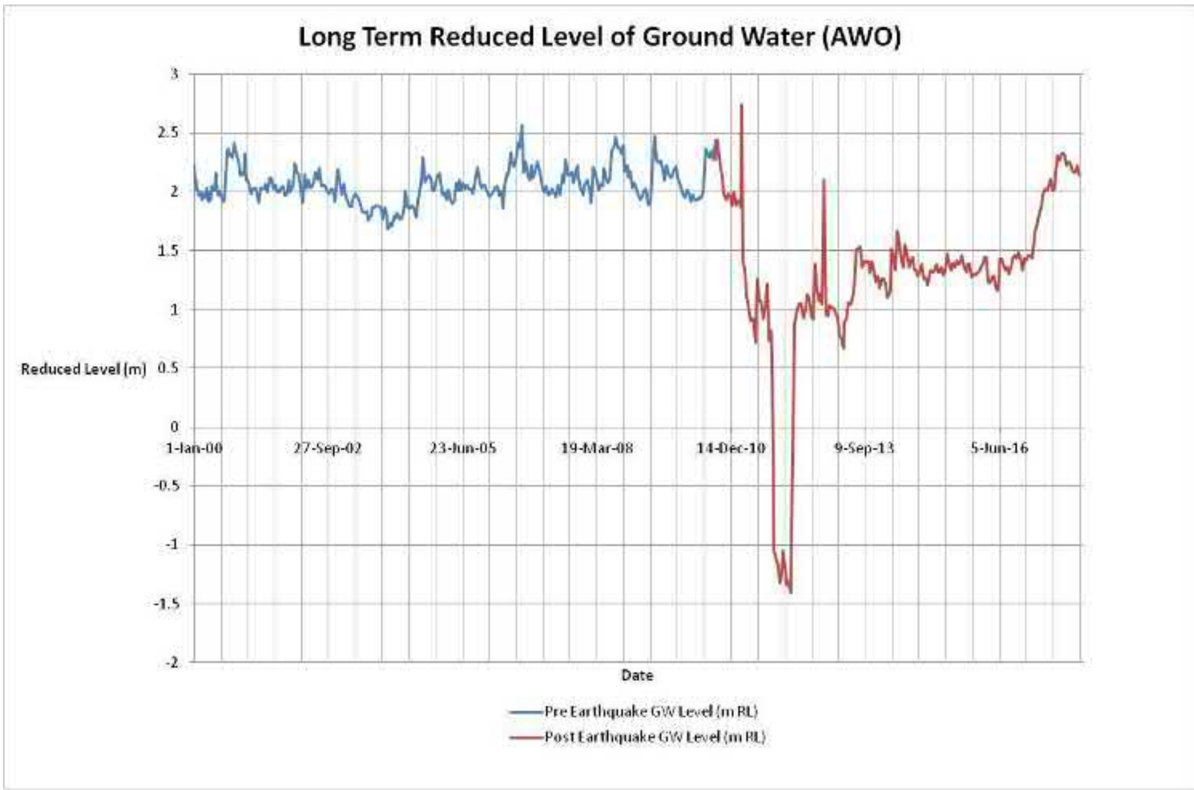


Figure 31. Pre- and post-earthquake groundwater levels - AWO

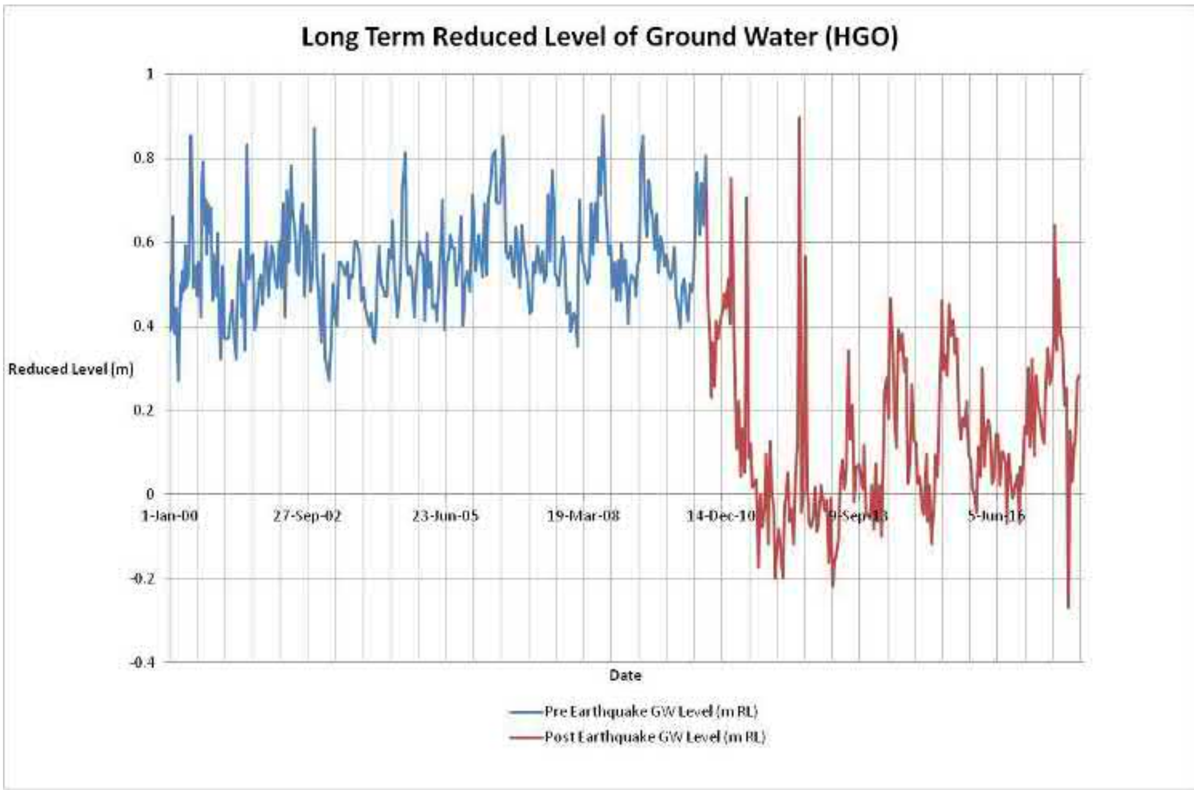


Figure 32. Pre- and post-earthquake groundwater levels - HGO

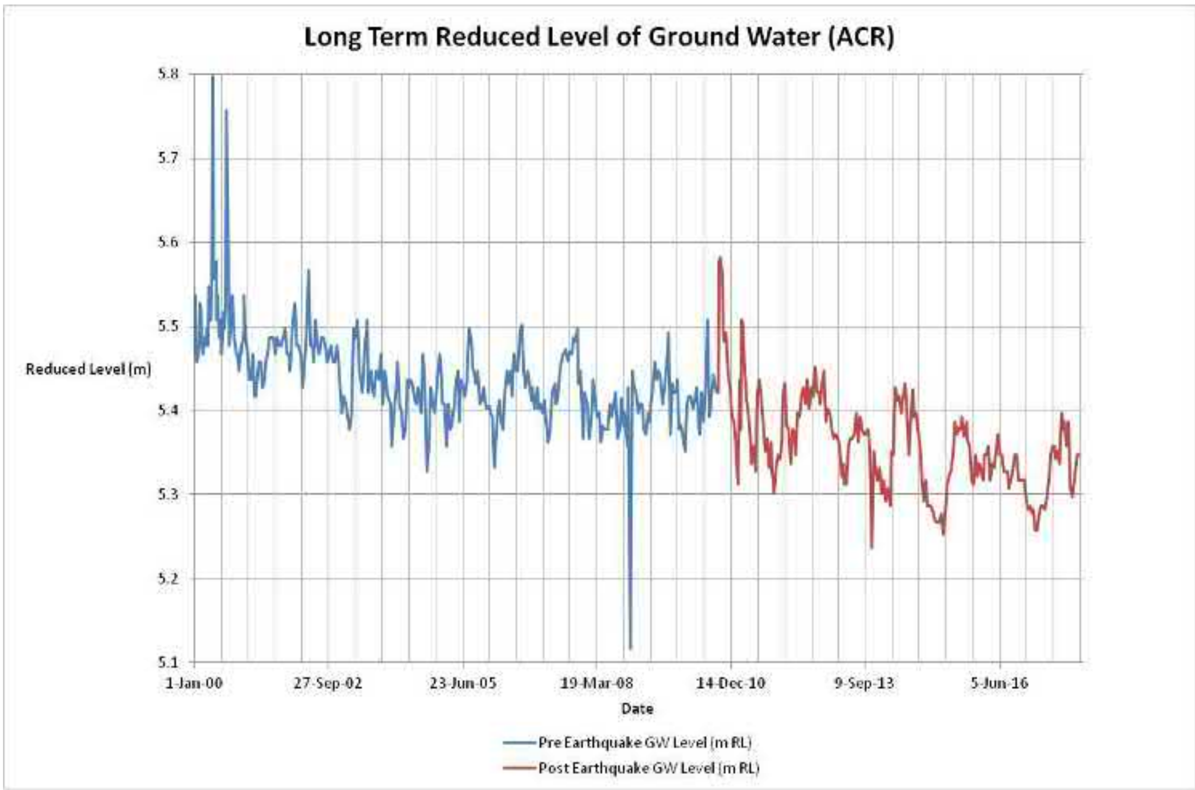


Figure 33. Pre- and post-earthquake groundwater levels - ACR

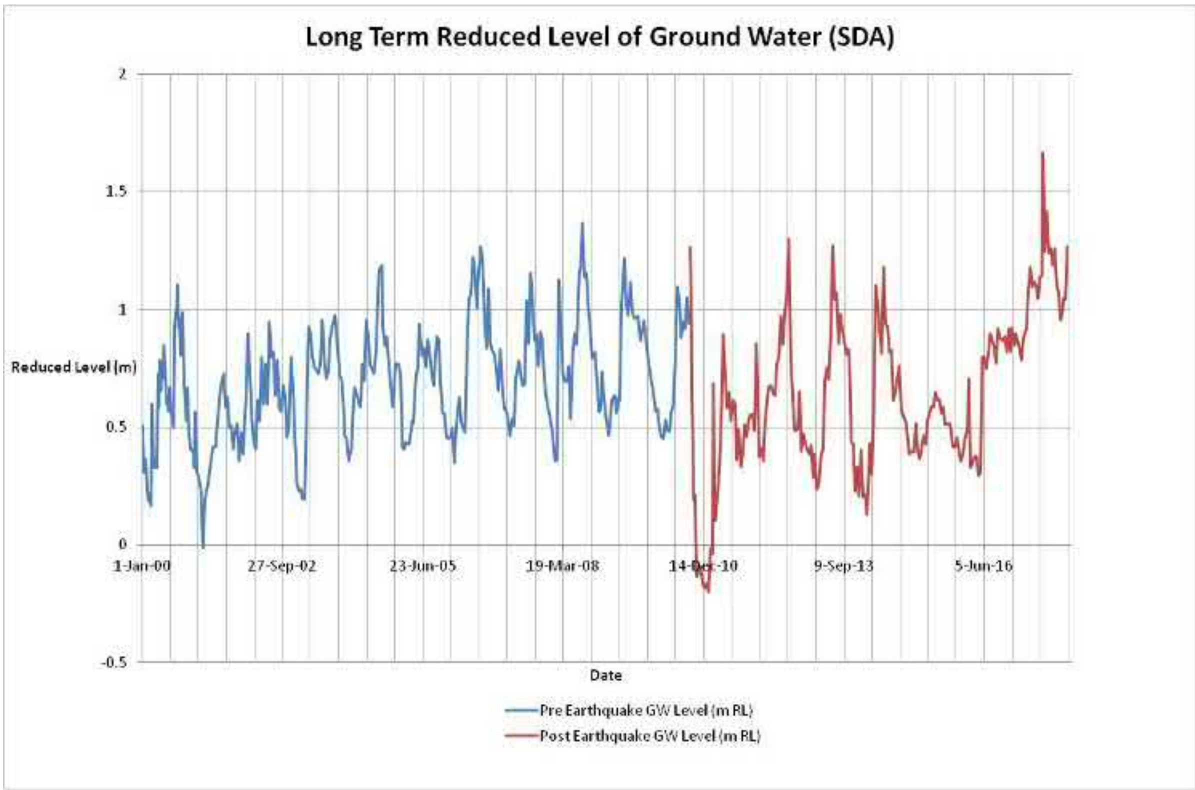


Figure 34. Pre- and post-earthquake groundwater levels - SDA

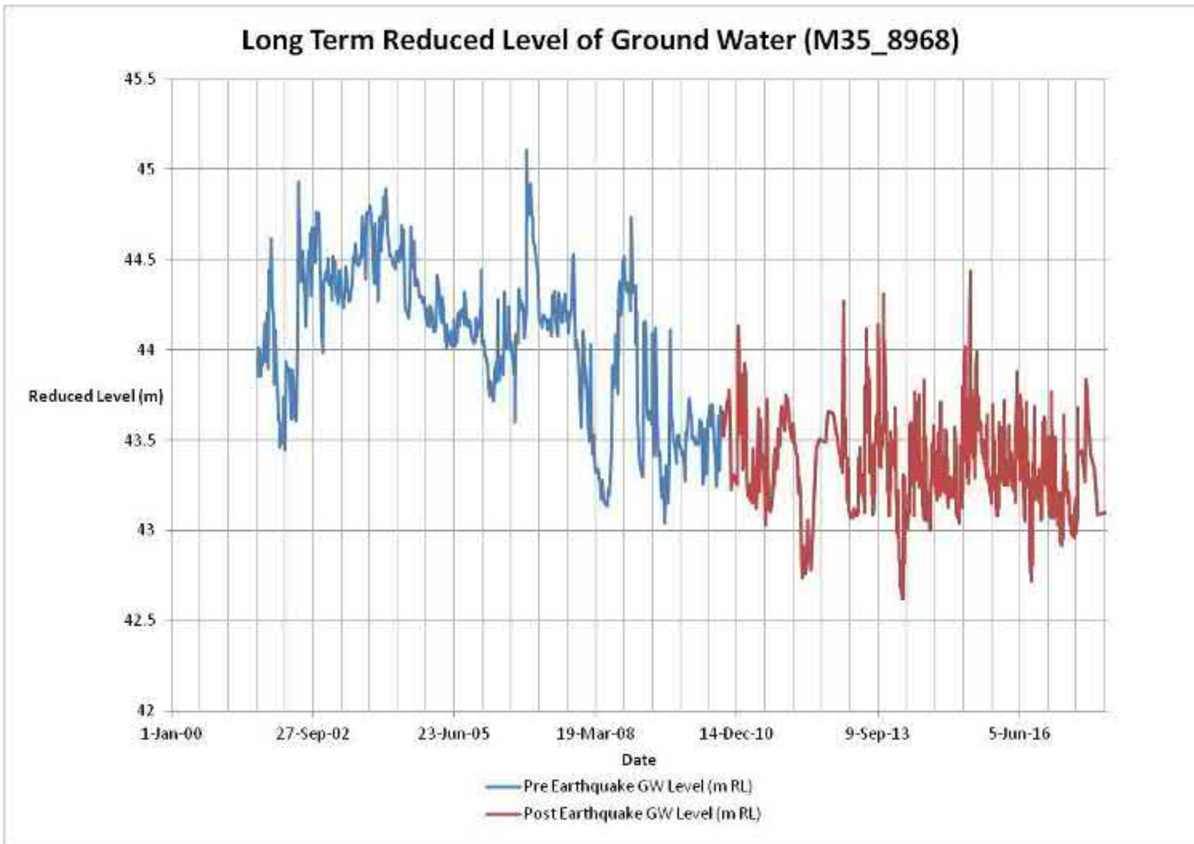


Figure 35. Pre- and post-earthquake groundwater levels – M35/8968

The conclusion from this analysis was that permanent effects were only conclusively observed in four wells, and the effect was a reduction in groundwater levels (that is, an increase in depth to water). It is possible that this effect would occur in other, similar, situations; that is, where groundwater is close to a discharge point, and where ground damage, as a result of earthquakes, might have resulted in increased permeability.

7.3 Comparison of Time Series Data

The earlier work (van Ballegooy et al., 2014) had used wells with as little as a year's data to interpolate the shallow water table, and one of the questions that needed to be answered was whether the additional 3 years data since the 2014 study changed the statistics. It was also important to assess whether the short-term EQC records adequately represented the long term groundwater levels.Therefore, for each EQC site we determined:

- The median for 2011 to November 2013 (ie the previous post-earthquake median).
- The median for 2011 to present.
- The difference between the two medians.
- The long term median and compared it with the short-term (2011-2017) one for 51 long term ECan/CCC bores.
- The 85th percentile and 15th centiles for the period from 2004 to 2014

We also used a correlation approach to extend the 2011 – 2016 data back in time. The results of this approach are described below.

7.3.1 Comparison of 2011-November 2013 and 2011-Present

The first test was to assess whether the data used in the initial derivation of the shallow water table (van Ballegooy et al (2014) were different to the longer term data that we now have available from the EQC network. The purpose of this was to better understand whether the previous data were representative of a longer term time series.

The median for each piezometer was determined for the time period from February 2011 to November 2013, and compared to the medians from February 2011 to the latest date (Figure 36). The plot of these medians against each other is shown below, and indicates that for only a few sites is there a large difference between the medians of the different time periods

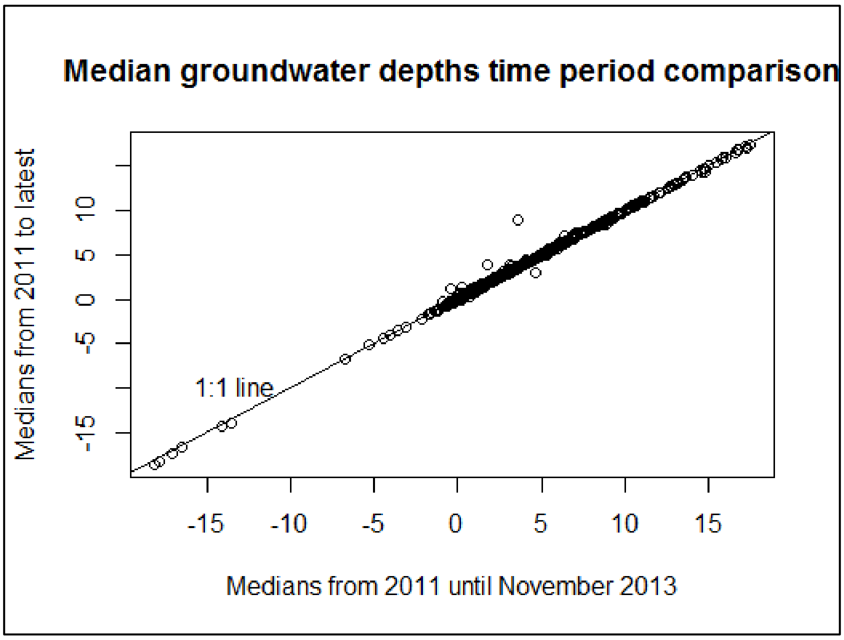


Figure 36. Comparison of median from February 2011 to November 2013 to the medians from February 2011 to the latest date

As a quality control exercise, the sites were ordered based on the size of the difference between these two medians. The ten sites with the largest difference (both absolute and relative to the site's inter-quartile range) between their 2011-2013 medians and their 2011 to latest were investigated for explanations. We found that for most of these sites, the difference was explained by the recent three years being dry, and/or a general trend in the data. The analysis didn't suggest that there was a major or systematic difference between the medians that had previously been calculated by van Ballegooy et al (2014), and the medians for the bores to 2016/17.

The locations of these sites are shown in Figure 37. There is no systematic spatial pattern to the location of the sites with the greatest difference in median values.

Figure 37. Groundwater depth observation sites. Yellow dots are those sites with the greatest shift in medians before and after November 2013

In terms of the time series of EQC data available, of the original 971 sites where data had been collected, 128 sites had data between February 2011 and November 2013, but not later: that is, dips were not continued at these sites after the 2014 investigation. 3 sites had data after November 2013 but not before.

7.3.2 Validity of a Six-Year Median From EQC Data

The time series collected at each site is not constant, but varies in duration and in some cases sampling frequency. At the time of this study the EQC bores only had a maximum of six years' data, whereas CCC and ECan datasets spanned a number of decades. These water level observations have both seasonal and inter-annual variability. One thing that had not been established in previous work was how representative medians were of the overall time series.

The EQC bores only had a maximum of six years' data, and care was required to ensure that the six years' data were representative of a long-term median. This was achieved through two approaches:

- Assessing whether the 2011-2017 period was representative of the longer term signal
- Ensuring that short-term records had data from every month of the year, such that they couldn't be biased towards summer lows or winter highs.

In terms of assessing if the recent years were representative of the long term median levels, the approach was to use the ECan/CCC sites to compare these two periods. An analysis of the ECan/CCC sites was carried out separately to assess if the pre- to post-earthquake changes that had been noted in van Ballegooy et al (2014) had persisted (see Section 7.2). 51 sites, with no significant pre- to post-EQ shift were then used for the purpose of comparing pre-EQ and post-EQ median levels.

The medians for the pre 2011 and post 2011 periods were calculated and plotted for the 51 long-term bores (Figure 38). This indicates that there is not a large difference between the post-2011 median and the median for the whole record for the CCC and ECan bores. This supported the use of the short-term EQC data as representative of the long term median.

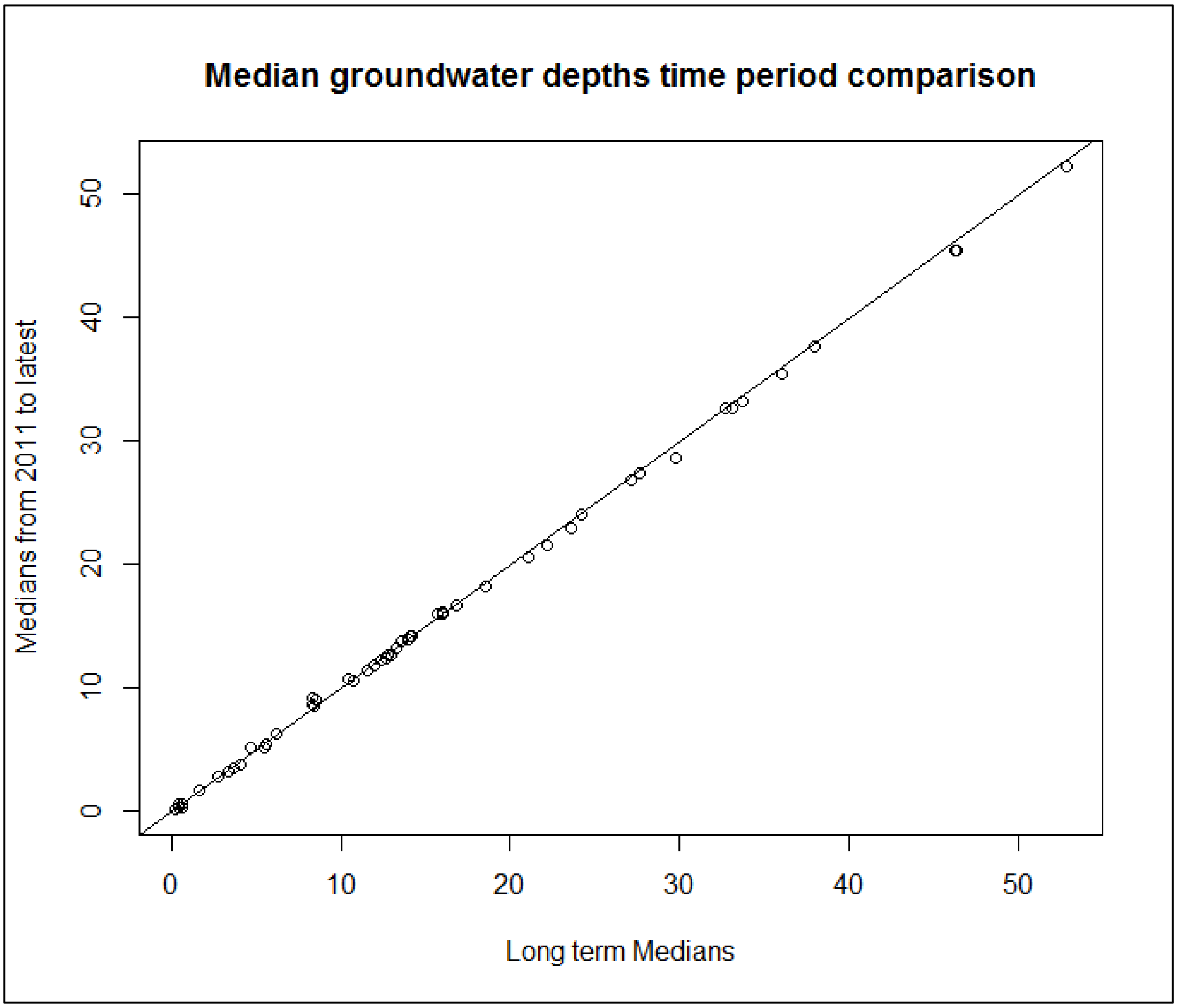


Figure 38. 2011- 2017 medians vs long term medians for the 51 long-term bores

8 DEVELOPMENT OF BASELINE SURFACE

The geospatial analysis to produce the median and 85th percentile water tables was carried out by Seequent. Their full report is attached in Appendix D, and is summarised here.

8.1 Data

A database was provided of median and 85th percentile water levels for wells, together with a rivers and coastal dataset. The elevation data for the rivers Avon and Heathcote were filtered to reduce the number of data points. This was to reduce potential bias in the estimation, since the data density was far higher spatially for surface water features than the groundwater monitoring network.

There were 16 points with a median water table elevation below sea level (see Figure 39). The majority of these points were in the Horseshoe Lake area, where groundwater levels are maintained below sea level due to pumping from the lake into the Avon River. There is also a small group in the Aranui area. In these areas, there are local pumping and drainage reducing groundwater levels.

Figure 39. Piezometers with median groundwater elevation below sea level

8.2 Median and 85th Percentile Surfaces

The initial work developed a median water table surface. After lengthy discussion about the appropriate water levels to use to develop the surface, the 85th percentile surface was subsequently developed (see Section 8.1). When the results of this surface were examined in detail, it was found that the interpolation of the water table elevation couldn't take into account small drains that were locally drawing the water table down in the Flockton and St Johns case study areas. In these areas, there appeared to be substantial groundwater inundation that wasn't occurring in reality. As a result, drain levels were extracted for a few points in these areas, and the surface re-interpolated taking these into account.

8.3 Estimation of the Water Table

Analysis of the data shows the water table elevation is broadly higher to the West and reduces down to approximately sea level at the eastern coast line. This is the direction of shortest continuity and perpendicular to this, approximately north-south the continuity is longest. With the available data, the area of interest can be divided into two areas. The well data in the East shows a flatter water table (smaller overall gradient) with significant local variability. The local variability in the East is clear from the larger nugget effect. The western part has a larger gradient. Based on these observations the dataset was divided into two areas for the estimation.

Though the data spacing varies and does not follow a particular grid, within the central zone between the Avon and Heathcote rivers, the well spacing is around 200 x 200m. The experimental variograms show a nugget effect, this is greater to the east (9%) than to the west (3%). A nugget is a representation of the uncertainty or variation close to the point of measurement.

The estimation of the water table (groundwater elevation) was undertaken by Ordinary Kriging into block sizes of 200 x 200 x 1m. The east and west were estimated separately with a soft boundary. In reality the boundary does not exist and it was therefore necessary to expand the sample selection beyond the boundary in order to smooth the transition between the two models when joining to create the water table surface. It was found that a soft boundary of 1500m was adequate.

Initial estimated surfaces indicated problems in the Styx river area where the well and river data were in conflict; the river data is significantly lower than ground water levels. Therefore the river data from the Styx were excluded from the estimate.

Various block sizes for the estimate were investigated. Using a block size of 200x200m, approximately the mean well spacing in the central area, provided an adequately smoothed surface.

In the east, it was found that a second search volume (search distances x 2) was necessary to improve the coverage of the kriged estimates, without which would have led to gaps.

Validation of the model, including visual and statistical checks and slice (swath) plots, was carried out and showed that, overall, the estimated water table correlated reasonably well with the data.

Residuals were symmetric (not skewed) and centred around zero (no bias).

8.4 Conditional Simulation to Estimate the Water Table

Conditional simulation is a process to estimate a surface that honours the spatial variability (variogram) seen in the data, and that also honours the data (within the accuracy of the nugget).

The simulations used the parent cell size of 200 x 200m which were divided into 5 in each direction, therefore the points were spaced at 40m. Ordinary kriging was used as the kriging method and a search strategy of where the data are relocated to grid nodes and a spiral search is used. The search distances used were 3 100m along the major axis and 3 000m for the minor axis. 50 simulations were found to be adequate for the mean and variance to stabilise. The simulations were back-transformed and selected simulations were checked that they honoured the original data. Both the histograms and variograms reasonably replicated the original raw data input.

8.5 Uncertainty in the Case Study Areas and Wider Area

It is clear from both the kriged water table and the conditional simulations that variance (uncertainty) in the water table increases rapidly away from the data, which is also seen in the variograms. This is a result of the degree of variability of the 85%ile and median data between adjacent datapoints, and the difficulty in producing the surfaces. It means that there will be limited confidence in the surfaces, with confidence rapidly declining with distance. Close to the datapoints, there will be increased confidence in the surface. This issue has been addressed in Section 11, in terms of assessing the hazard and identifying areas where we can have greater and lesser degrees of confidence that there is, or is not, likely to be an issue with shallow groundwater.

The conditional simulations provide a higher degree of detail with respect to areas of higher and lower confidence based on the variance and 15% and 85% likelihood levels. Figure 40 illustrates the four case study areas (in black) in relation to the conditional simulation variance for the area of interest. The blocks coloured red denote high risk/uncertainty areas. It is noted that the low variability associated with data does not extend more than approximately 300m. The blue lines classify areas of reasonable confidence.

Each of the case study areas are relatively well informed by data. Of the four, the Flockton case study area has a slightly higher variance. St. Johns and Avondale are within areas with the lowest variability, closely followed by Southshore/South New Brighton. The well spacing in St. Johns and Avondale are around 200 x 200m and at Southshore/South New Brighton it is coarser up to 1000m in the northern part. Flockton is in a slightly higher variance area. On the north and west flanks the well spacing is around 450-550m. Based on theoretical calculations of well spacing to 200 x 200m, the kriging variance can be expected to be reduced by around 40%. As a comparison, when looking at the conditional simulation variance in the water table (by comparing values in the different values) there is a potential reduction in variance from ~1.4 to ~0.03m2, which is substantially more. However, Flockton has higher water table elevations than the others, and the variance in general increases from east to west (following the higher density of data areas), therefore to reach the same level of low variance seen in the east it is likely the well spacing would have to be 200 x 200m at minimum.

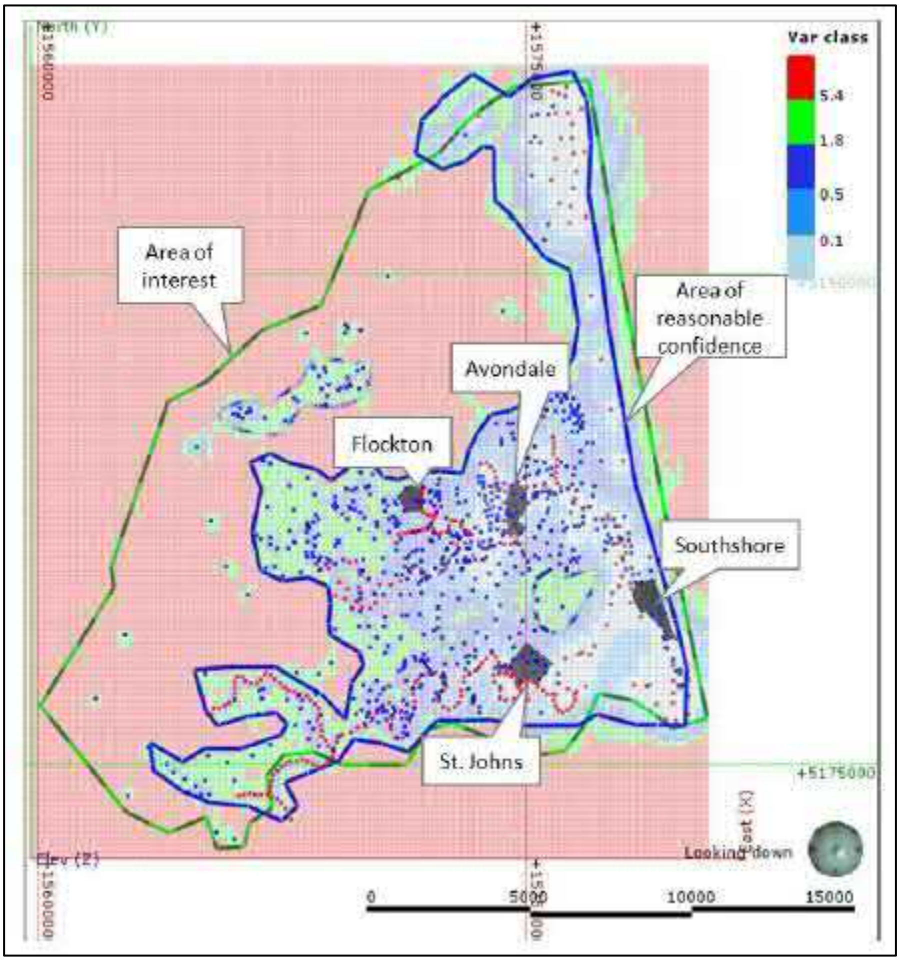


Figure 40. Water table variance with case study areas. Wells in blue, rivers and coast in red

9 IMPACTS OF SEA LEVEL RISE: GROUNDWATER MODELLING

9.1 Canterbury Groundwater Model

It is well documented that sea level rise will cause inundation of land and a rise in the groundwater table, particularly in coastal areas (Rotzoll & Fletcher, 2012). Sea level rise increases the groundwater level at the discharge point i.e. the coast. As a result, groundwater levels inland also will rise in order to maintain the hydraulic gradient. Such a groundwater rise in Christchurch is likely to present challenges in the future. Scenarios of sea level rise, and corresponding groundwater rise under Christchurch, have been modelled to determine locations most at risk of experiencing shallow groundwater issues.

Although the effects of sea level rise are expected to be greatest along the coastline and streams that are influenced by the sea, sea level rise affects the groundwater system beyond the coastal margins. It is not just a local phenomenon. Furthermore, there are multiple hydraulic features at the catchment scale influence how the effects of sea level rise develop and propagate inland (e.g. recharge sources; stream networks; etc.) . Therefore, it is important to ensure that any model used to predict sea level rise effects in groundwater accommodate the larger-scale aquifer system. This is further reinforced by the catchment-scale focus of the overall LDRP45 study. The Canterbury groundwater model (Weir, 2018) is a model that includes the catchment-scale mechanisms that cause and control the effects of sea level rise. It is therefore a suitable tool for this assessment and there is currently no better tool for this.

While local-scale models are helpful for developing mitigation measures at the local scale, they are inadequate to predict the overall scale of change that would likely occur (and therefore mitigated). For example, local scale models need to be constructed with specified boundary conditions that reflect the catchment-scale changes from sea level rise. If these larger-scale boundaries are not derived from realistic catchment-scale modelling, then the usefulness of a local scale model is hindered.

The Canterbury groundwater model was used to model the effects of rising sea level on the Christchurch shallow aquifer system. A brief description of this model follows, and a fuller explanation can be found in Weir (2018).

9.1.1 Description of the Model

The most recent version of the Canterbury groundwater model builds upon the following work previously completed by Aqualinc:

- The first version of the Canterbury groundwater model, initiated in 2001 by the Dunsandel Groundwater Users Association and the Ashburton Community Water Trust (ACWT). This initial work is documented in Aqualinc (2005). Some of the assumptions used in developing the hydrological components of the model were developed under the Canterbury Strategic Water Study (Morgan, *et al.,* 2002).
- Subsequent to the initial investigation, the model was updated in 2006 to reflect changes in understanding of the groundwater system and the inclusion of newer data. This work was primarily completed for the Rakaia-Selwyn consents hearing and is documented in Aqualinc (2006).
- After this, the model was re-engineered to address potential areas of improvements identified through the application and evaluation of the model over the preceding years. This work was primarily used for predicting the potential effects of the (then) proposed Central Plains Water Enhancement Scheme, and is documented in Aqualinc (2007).
- During 2013, the model was used to support Environment Canterbury's water quality and quantity limit setting process for the Selwyn-Waihora catchment. For this work, the model was

truncated approximately 5 km south of the Rakaia River. In addition, streambed parameters were adjusted to further improve the calibration of flows.

More recently, the model has been significantly re-engineered to align with new modelling techniques and expectations, to include new data, and to address potential areas of improvements identified through the application and evaluation of the model over the preceding years. A key component of the re-engineering is the conversion to the numerical code MODFLOW-NWT (Niswonger *et al.,* 2011). Model documentation is provided in Weir (2018).

Various software packages have been used to generate model inputs and process outputs. The numerical model has been built using the computer graphical user interface GMS (2017). It has been constructed as a MODFLOW-NWT model (Niswonger *et al.,* 2011), which is a three-dimensional, block-centred, finite difference groundwater flow model.

Irrigation demand and land surface recharge time series have been calculated using Aqualinc's crop-soil water balance model IRRICALC. Additional scripts, Microsoft Access databases and Excel spreadsheets were developed in-house and used to assist in the preparation of pumping and recharge data.

The model encompasses the aquifer system between the Waimakariri and Rakaia rivers (Figure 41) and simulates groundwater levels and stream flows over a 55.5-year period from 1 June 1960 through to 31 December 2015. The base of the alpine foothills forms the western (inland) boundary of the model, and the eastern boundary extends approximately 10 km beyond the coast to represent the off-shore discharge of the aquifer system.

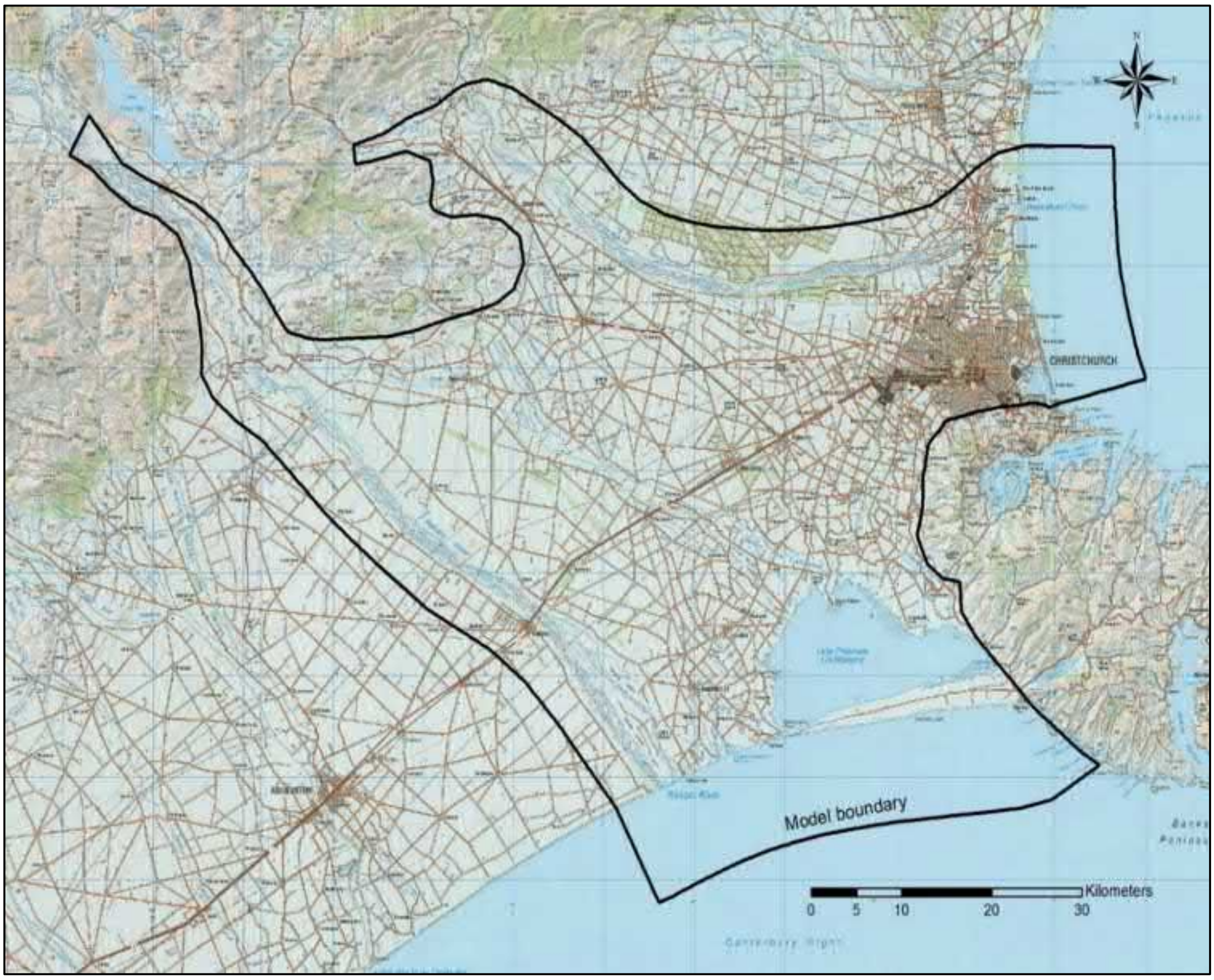


Figure 41: Canterbury groundwater model boundary

Land surface elevations were derived from a combination of LiDAR surveys, photogrammetry and topographic map contours (in order of preference). Various sources of geological information have been collated to describe the overall geological composition of the aquifer system, with the main data sources being surfaces of the interfaces between Christchurch formations supplied by GNS Science (Begg *et al.,* 2015) and geological data logged during well installation (as supplied by Environment Canterbury). The base of the alluvial gravels has been derived by University of Canterbury using geophysical techniques (Lee *et al.,* 2016). Aquifer tests results have also been used to inform hydraulic parameters.

In describing the alluvial deposits at a regional scale, it is the general and obvious water bearing layers and the separating aquitards that are of interest, and as such, the precise and accurate description of the geology is not necessary (from a hydrogeological point of view).

The ocean and estuary were modelled using constant head boundaries, as shown in Figure 42.

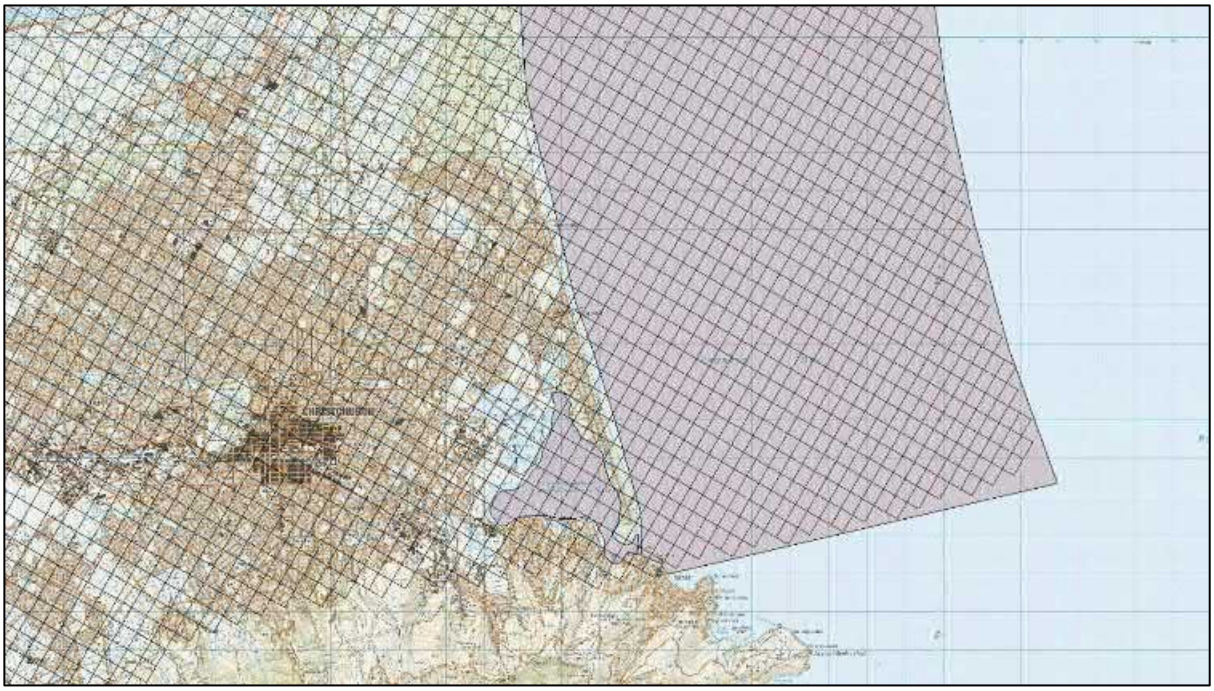


Figure 42. Canterbury groundwater model constant head boundaries

9.1.2 Time Varying Land Use

Time series of land use over the model domain has been generated primarily from Environment Canterbury's consents and wells databases. Gaps in these databases were filled and errors that were found were corrected as best as possible. This information was then processed to generate a time-series of irrigated area, which compares favourably to recent surveys. Time-series of groundwater abstraction and land surface drainage have been generated using this time varying land use information along with soil and climate data. These results compare favourably with measured abstraction and recharge data.

9.1.3 Time Varying River Flow Inputs

Measured flow time series for rivers and streams used as inputs to the model (i.e. the main rivers and streams flowing onto the plains from the alpine foothills) were obtained from NIWA and Environment Canterbury. Gaps in this data, and extensions of the data to cover the full simulation period, were synthesised using time series extension software developed by Aqualinc.

9.1.4 Model Input and Output Intervals

Model inputs have been generated at daily intervals. The computer model calculation time-steps are shorter than daily.

All output data reported has been derived from daily output intervals. Output values of groundwater levels are instantaneous values at 1-day intervals. Output values of river flows are daily-mean values for that day.

9.1.5 Model Calibration

The dynamic response of the aquifer system is dominated by climatic patterns via land surface recharge and small streams. However, recharge from the major rivers is significant in maintaining a relatively stable base groundwater level. The magnitude of the dynamic response is increased artificially by groundwater abstraction and land use.

Model calibration consists of adjusting model parameters (within realistic limits) until the simulated outputs agree with measured data as best as practical. This includes groundwater and stream flow responses from both natural and artificial drivers.

9.1.6 Groundwater Levels

Average (steady state) groundwater levels simulated by the model compare favourably with measured groundwater levels in 734 wells located throughout the study area. The normalised mean error in groundwater levels for the steady state model is approximately 0.3% and the normalised root means square error is approximately 1.2%. Errors are typically randomly distributed over the model domain implying that there is no significant model bias. Flow budget errors for the steady state model are very small (~0) indicating that the software has accounted for flows without noticeable numerical error.

Transient groundwater levels were calibrated against measurements in 178 wells. The dynamic response of measured groundwater levels is replicated well in the modelled outputs. The groundwater model follows the seasonal highs, lows and trends visible in the measured data.

9.1.7 Hydraulic Conductivity Distribution

The model's hydraulic conductivity has been derived initially from test results, where these were available (see Section 2.5 of Weir, 2018). Then, gaps between test results have been further adjusted through model calibration so that measured and modelled groundwater levels and river flows match as best as possible. This is a sound and readily accepted method of parameterising a groundwater model. The resulting (combined) hydraulic conductivity distribution is discussed in Section 5.9 of Weir (2018). This has been further adjusted for the LDRP45 project, as discussed below.

9.1.8 Development of the Model for the LDRP45 Project

The Canterbury groundwater model was developed further for the LDRP45 project. Additional model developments, include the following:

- Developing a finer model grid in the city area;
- Adding extra resolution into the Christchurch city main streams (stream locations, invert levels and cross sections);

- Adding much of CCC's shallow drainage network (in addition to the main streams discussed above); for simplicity, drain inverts were set to 1 m below ground level, which is the approximate median depth of the available drain invert measurements in a GIS coverage supplied by CCC;
- Raising the specified head boundary along the coastline by 0.5 m to allow for groundwater table over-height;
- Reduce the maximum hydraulic conductivity in the shallow Christchurch Formation to align better with the perception of tighter materials in this area (these changes made little difference to the model predictions); the resulting hydraulic conductivity field is shown in Figure 43; this is consistent with the range of hydraulic conductivity values reported by Freeze & Cherry (1979) for the typical materials forming Canterbury's water bearing layers (silty sands through to clean gravels, with a hydraulic conductivity range of approximately $1x10^{-2}$ m/day to $1x10^{4}$ m/day);
- Additional time calibrating the city area, with particular effort focussing on the shallow (uppermost) layer; this included history-matching to an additional 778 shallow groundwater level measurements in the greater city area (shown in Figure 44);
- Improvements to the calibration of the original 734 steady state calibration wells (shown in Figure 45); and
- Further matching of river flows, stage heights and backwater effects at key monitoring sites (discussed below).

A key focus of model refinement was the accuracy of river stage elevations, which is in part a function of the backwater effects from the costal boundary. The surface water component of the groundwater model does not accommodate these backwater effects. However, Quilter *et. al.* (2015) does, and although this is a model with its own uncertainties, it was recognised that this model likely represents river stage elevations adequately. Therefore, river invert levels in the groundwater model were adjusted until they matched (as best as practical) the long-term averages reported by Quilter *et al.* (2015) for a few locations in the Styx, Avon and Heathcote rivers. Good comparisons were achieved for both flows and stage elevations, as noted in Table 8 and Table 9 respectively. River cross sectional geometries were not changed; only invert elevations (and associated reach gradients).

Table 8: Comparison of modelled and measured average river flows

Comparison of river flow				
Location		Average river flow (m^3/s)		Difference (m^3/s)
River	Site	Measured	Modelled	
Styx River	Radcliffe Rd	1.47	1.49	0.02
Avon River	Gloucester St Bridge	1.87	1.58	-0.29
Heathcote River	Buxton Tce	1.03	0.85	-0.18

Table 9: Comparison of modelled and measured average river stage elevations

Comparison of river stage elevation			
Location		Average stage elevation (m a msl)	
River	Site	Measured	Modelled
Styx River	Harbour Rd	0.07	0.14
	Lower Styx Rd	0.62	0.46
Dudley Creek	Aylesford St	2.73	2.71
Avon River	Bridge St	0.33	0.33
	PS205	0.51	0.52
	Fitzgerald Ave	1.05	1.05

Heathcote	Ferniehurst	6.72	6.67
	Opawa Rd	0.52	0.56

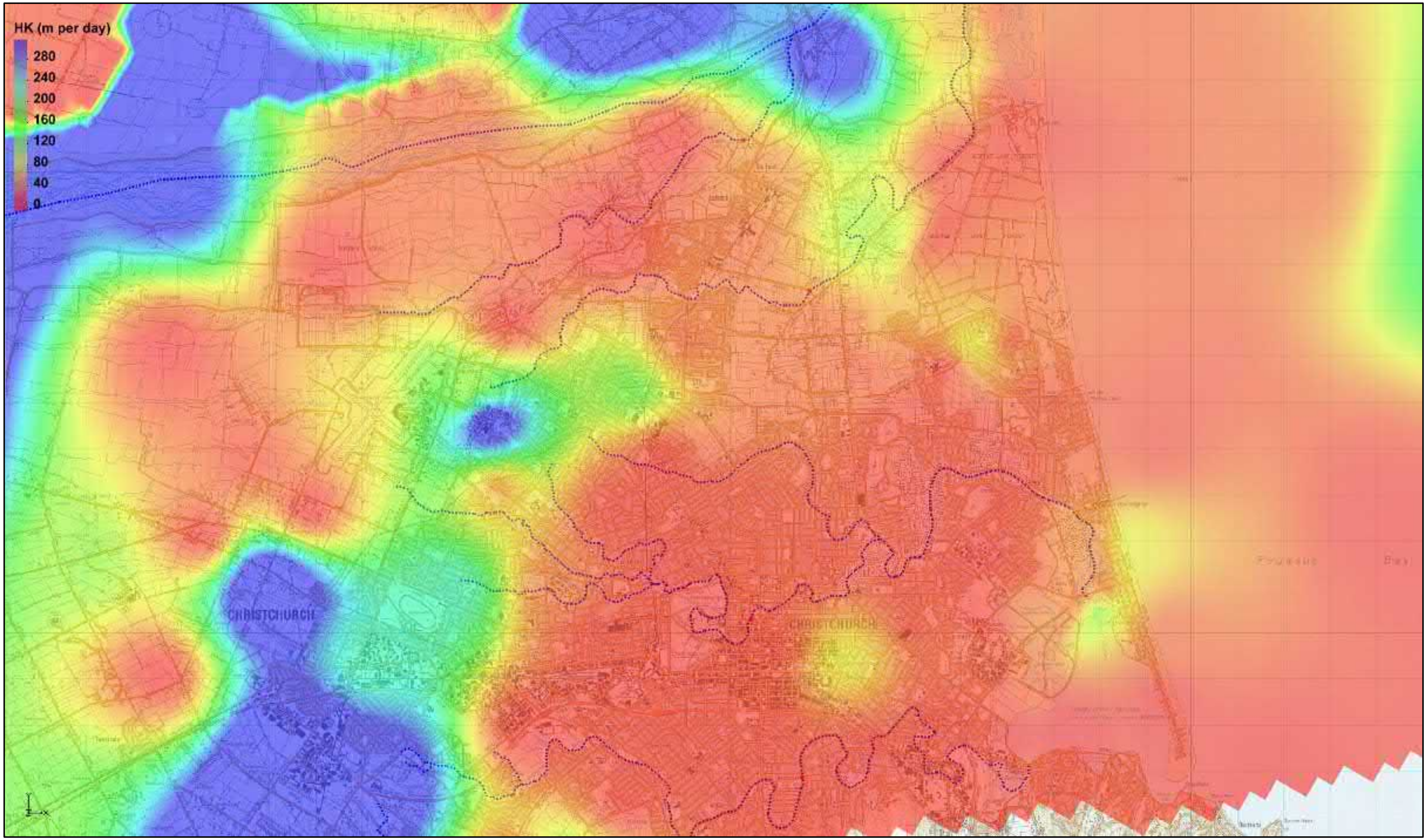


Figure 43. Updated Kh for the shallow aquifer

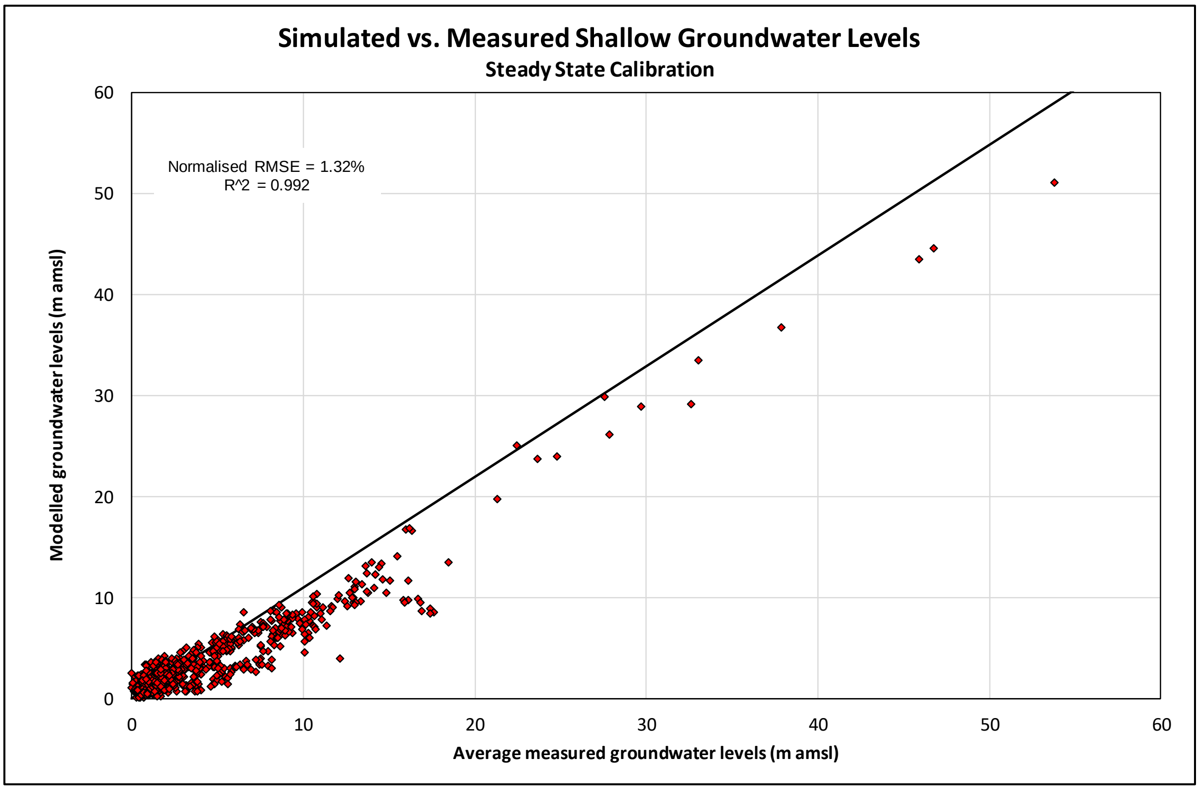


Figure 44. Measured versus modelled groundwater levels in additional Christchurch city shallow monitoring bores

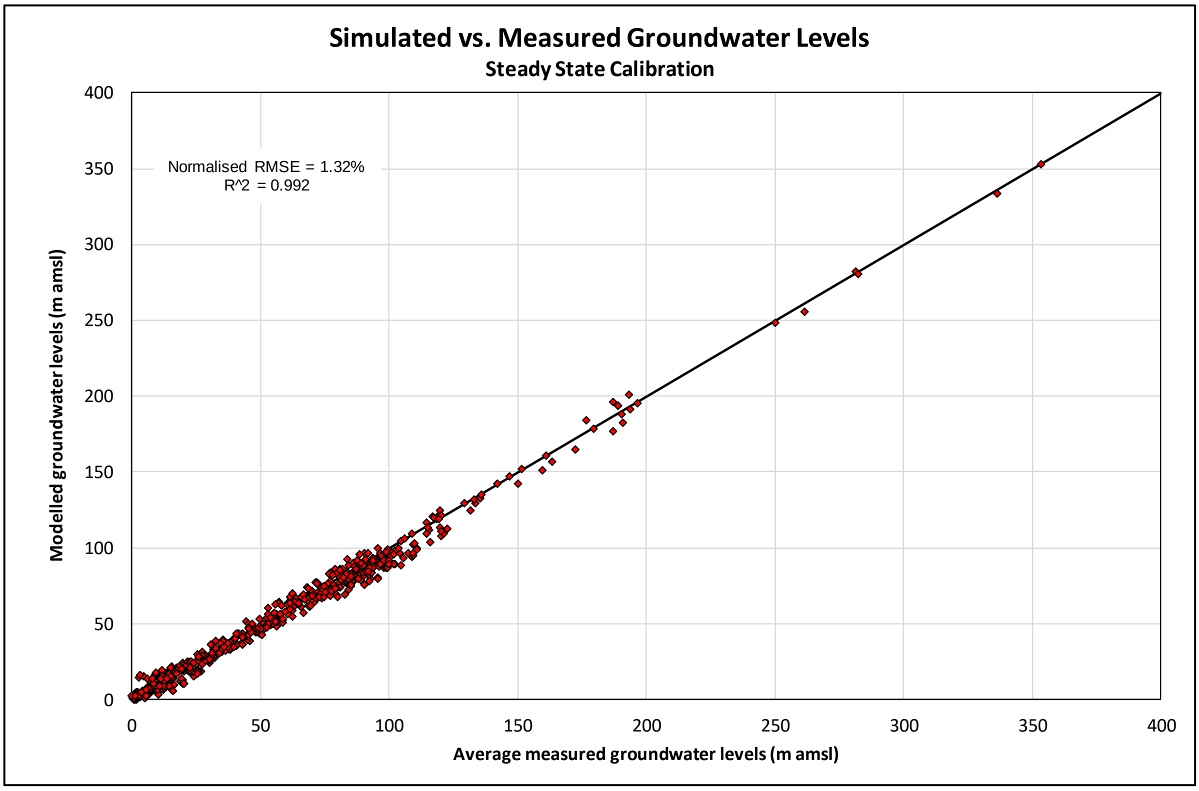


Figure 45. Measured versus modelled groundwater levels in original monitoring bores

In terms of future sea level rise, Quilter *et al.* (2015) reports the predicted surface water stage elevations (calculated with backwater effects), and then assumes that these represent groundwater levels by simple interpolating between the surface water sites. However:

- Groundwater levels do not follow a straight line between adjacent river levels;
- The river bed has a degree of clogging; this retards the hydraulic connection between surface water and groundwater; and
- Drains and infrastructure act as pressure relief valves that reduce the scale of the rise;

As such, river levels do not necessarily represent groundwater levels immediately adjacent to, or underlying, the rivers, and groundwater levels can be quite different to river stage, even at modest distances from the river. The groundwater model is therefore a better tool for predicting the response in groundwater. By adjusting the groundwater model's surface water results to match Quilter *et al.* (2015), and given the robust accommodation of groundwater processes by the groundwater model, the groundwater model provides the best possible prediction of sea level rise effects for Christchurch's groundwater system. A comparison between the Quilter and Aqualinc models for the predicted stage elevations under a 1 m SLR scenario are noted in Table 10.

Table 10: Comparison of modelled river stage elevations under a 1 m SLR scenario

Comparison of Groundwater Change Under 1 m SLR Scenario			
River	**Groundwater level change (m)**		**Difference (m)**
	Quilter	**Aqualinc**	
Styx	1.0	0.9	+0.1
	0.75	0.8	+0.05
	0.5	0.4	-0.1
	0.25	0.3	+0.05
	0	0.1	+0.1
Avon	1.0	1.0	0
	0.75	0.75	0
	0.5	0.5	0
	0.25	0.26	+0.01
	0	0.1	+0.1
Heathcote	1.0	1.2	+0.2
	0.75	0.7	-0.05
	0.5	0.5	0
	0.25	0.3	+0.05
	0	0	0

9.2 Sumner Groundwater Model

The Sumner area was not included in the original Canterbury groundwater model (Aqualinc, 2007) due to it being a relatively isolated aquifer system from the larger Plains system, with very limited data. Therefore, a simple local-scale groundwater model was constructed to predict the response in groundwater from sea level rise. The modelled area is shown in Figure 46.

The groundwater flow model was built using the computer graphical user interface GMS (2019). It has been constructed as a MODFLOW-NWT model (Niswonger *et al.,* 2011), which is a three-dimensional, block-centred, finite difference groundwater flow model. The model area comprises the entire Sumner valley floor (Figure 46), and extends approximately 500–800 m offshore. Model cell sizes were 50 m x 50 m.

There is limited information available on the geology of the Sumner valley. Bore logs (shown in Figure 46) indicate that the profile consists of sands and silts with no evidence of gravels. The deepest bore has a depth of 21.6 m and did not encounter volcanic basement rock or gravels. The valley is bounded by the volcanic formations of the Port Hills. Again there is little information to define this, and so it has been assumed that the model base is 20 m below sea level.

The locations of the drain and stream network was provided by CCC and were represented in the model using MODFLOW's drain (DRN) package. Local rainfall data was used to estimate long-term average land surface recharge. A general head boundary was used to represent the ocean.

A memo overviewing the Sumner model is provided in Appendix E.

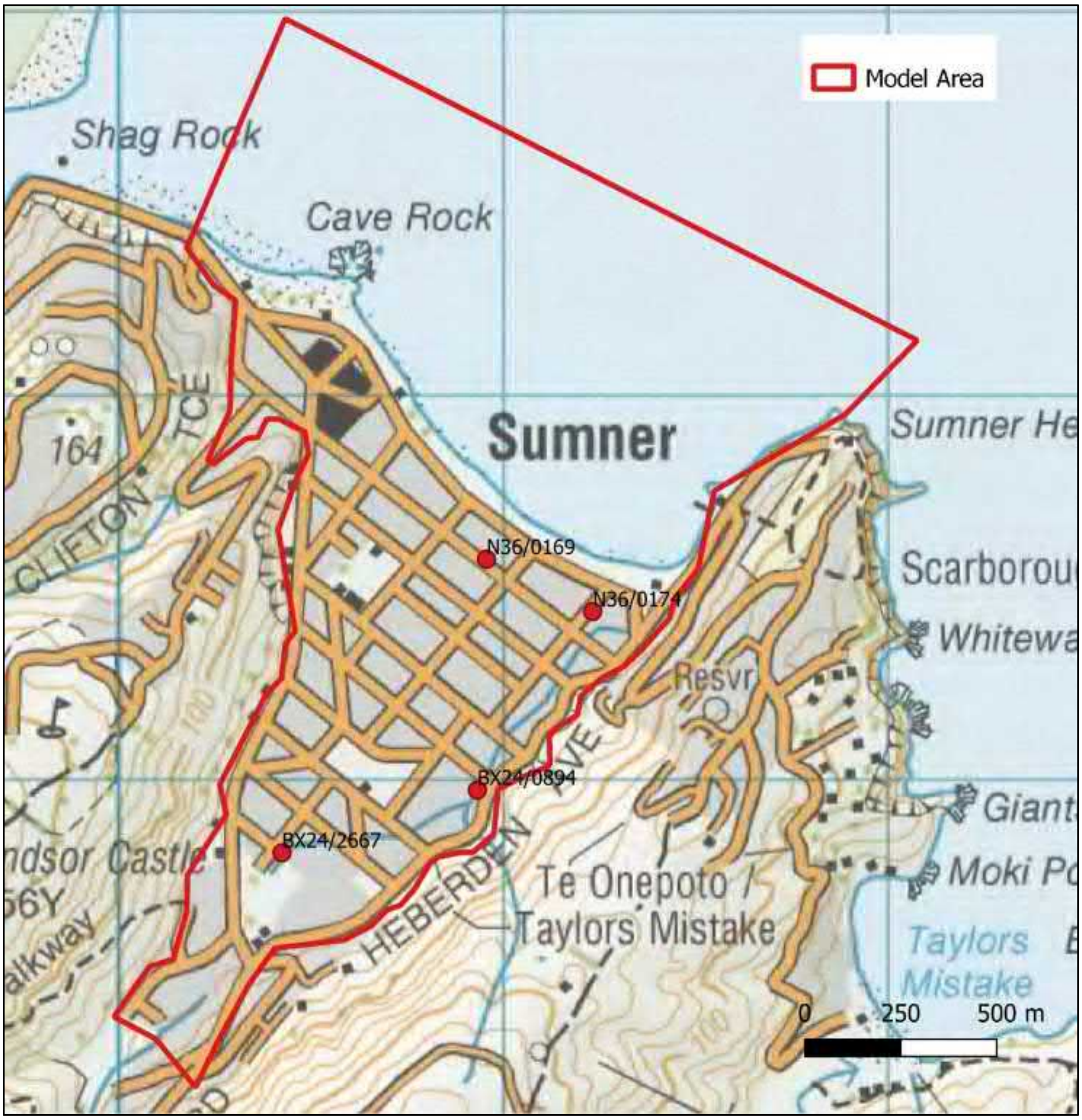


Figure 46. Sumner model domain and bore log locations

9.2.1 Calibration

Limited groundwater level measurements exist for the Sumner area, with no existing Canterbury Regional Council groundwater level monitoring bores. Sparse data has been collated from a short-term record in one bore, plus spot measurements from geotechnical investigations over the period 14/6/2012 to 1/2/2019.

The model was constructed as steady state and calibrated to the few groundwater levels available with focus on the higher June/July groundwater levels to approximate a higher 85th percentile groundwater level). However, an overall poor match to measured data was achieved, primarily attributed to the sparse groundwater levels that are distributed over a considerable time period. A comparison of measured and modelled groundwater levels is shown in Figure 47.

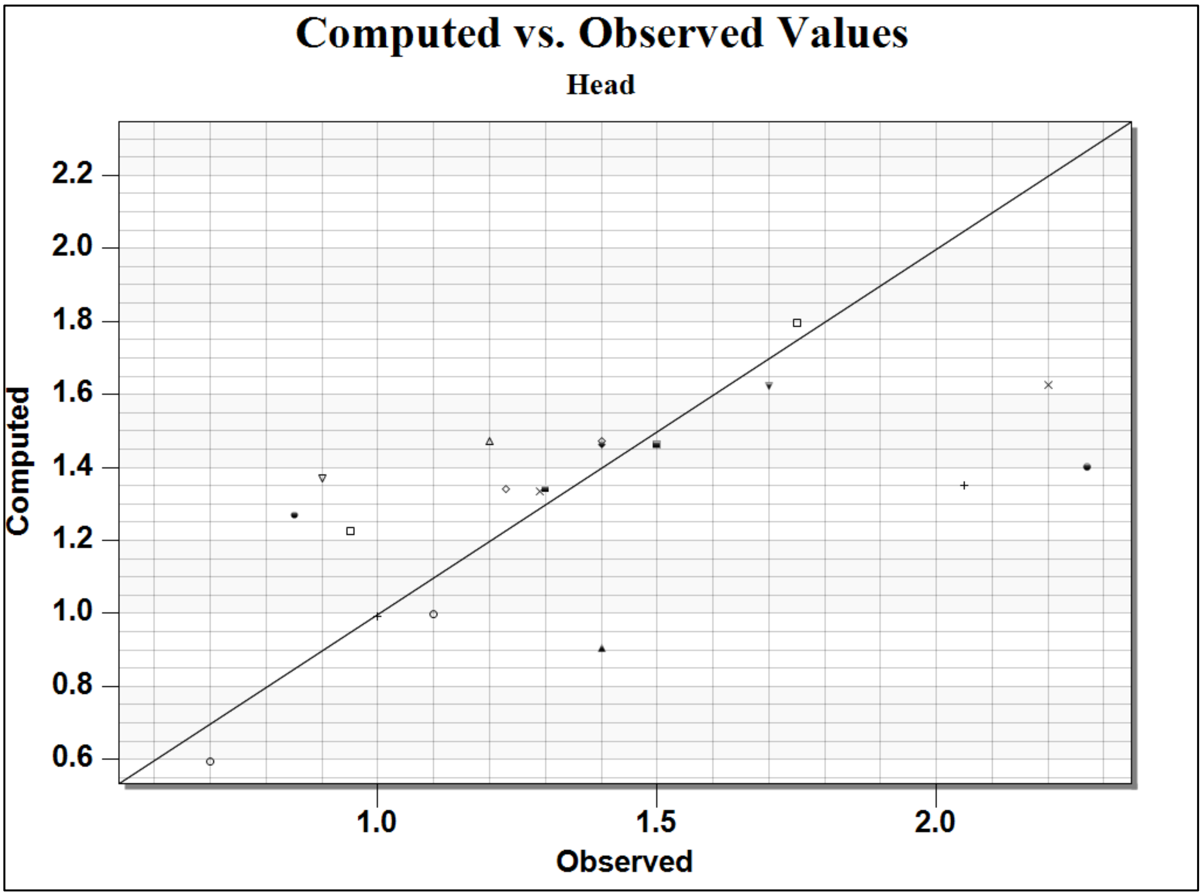


Figure 47. Sumner measured versus modelled groundwater levels

9.2.2 Model Outputs

Sea level rise scenario outputs from the Sumner model have been combined with outputs from the larger Canterbury groundwater model (discussed in Section 9.1). These combined results are presented in the following report sections.

9.3 Data Quality Assurance

Multiple data sets were collated and used to build both the Canterbury groundwater model (Weir, 2018) and the Sumner model (Section 9.2and Appendix E). These datasets include:

- Land surface elevations;
- Bore geological logs and interpreted formations;
- Groundwater level measurements (including reference datums);
- River flows and river stage elevations (including reference datums);
- River cross sections and invert elevations (including reference datums);
- Aquifer test results;
- Climate (rainfall and PET);
- Groundwater abstractions; and
- Outputs from other models (such as IrriCalc; Quilter; etc.).

These data sets have been used on the assumption that data quality assurance has been completed by the agencies supplying the data. Regardless, Aqualinc modellers have completed common sense checks and calculations on the data sets as they have been prepared and incorporated into the models. This ensures that the data is fit for purpose and that there are no known data quality problems that would affect the models' predictions of the response of groundwater from sea level rise.

9.4 Sea Level Rise Scenarios

The Canterbury and Sumner groundwater models were used to assess the effects of five sea level rise scenarios. Originally, three scenarios were requested by CCC; then an additional two were requested. The sea level rise scenarios were the mid-range projections from IPCC 2014 for RCP8.5 greenhouse gas emission scenario (status quo), and are the same as those in the Christchurch coastal hazards assessment (Table 6.1 of LDRP97 gap report). The sea level rise scenarios used in the assessment were 0.19m, 0.4m, 1m, 1.88m and 2.40m. Slightly different projections are used in the LDRP 97 project (0.41 m since 1995 by 2065, and 1.06 m since 1995 by 2120). The small differences were not remodelled, as the uncertainties involved, and the small magnitude of the difference, would have an immeasurable effect.

The scenarios were undertaken using a steady state version of the Canterbury groundwater model that used averaged values of groundwater levels, stream flow, recharge and groundwater abstraction. For each scenario, the level of the constant head boundaries for the estuary and ocean were set to the corresponding sea level. The model was run, and a new groundwater surface was produced. These surfaces were subtracted from the original steady state model surface to produce a change in groundwater level surface. In this way, the relative change in groundwater level was added to the baseline surface that had been generated through a rigorous geostatistical approach (described in Section 7.4). This was considered to be a more robust approach to producing the affected surface, rather than using the absolute levels from the model.

There were a number of assumptions made when producing these surfaces:

- No increase in sea and estuary area due to the rising sea level. This was justified by assessing the potential additional area inundated under the SLR scenarios. The additional area was found to be very limited.
- No difference in climate, affecting recharge, river flow, pumping and other factors during the scenario time periods, that is, it was sea level rise specifically that was assessed.
- No change in mitigation measures to prevent flooding
- No change in groundwater pumping during the scenario time period

The results are from the modelling are shown in Figure 48 through Figure 52. In general the contours are parallel with the coast except along the rivers. As expected, the larger the change in sea level the further the effects are seen inland.

Figure 48. Contours from a 0.19 m change in sea level

Figure 49. Contours from a 0.40 m change in sea level

Figure 50. Contours from a 1.00 m change in sea level

Figure 51. Contours from a 1.88 m change in sea level

Figure 52. Contours from a 2.40 m change in sea level

9.5 Sensitivity Analyses

Aqualinc was asked by CCC to undertake simple sensitivity analyses on the sea level rise (SLR) scenarios presented for the LDRP45 programme, in order to understand how changes in model parametrisation might affect the results generated. The sensitivity work comprised:

- Sensitivity of groundwater levels to horizontal hydraulic conductivity near the coast;
- Sensitivity of groundwater levels to land surface recharge; and

- Prediction of the time taken for groundwater levels to equilibrate after a change in sea level.

Results of these analyses are presented in Appendix F. Key findings from this work are as follows:

- Absolute groundwater levels vary under the first two sensitivity scenarios noted above, but subsequent predictions of the *change* in groundwater levels due to sea level rise is minimal. This is an important output of the sensitivity work as it is the change due to sea level rise that feeds into other components of the study, not the absolute groundwater level (absolute groundwater levels used elsewhere in the study are founded on measured data, not modelled). The groundwater model (and groundwater models in general) is best suited for predicting changes rather than absolute values (as has been applied in this study).
- Altering Kh in the coastal area or changing land surface recharge has little influence on the *change* in groundwater levels due to sea level rise.
- Areas of greatest influence on the *change* occur near streams and drains where the initial groundwater level is noticeably different from the original Kh state. For example, under the scenarios of higher Kh or lower recharge, absolute groundwater levels are generally lower than measured, and lower than the local drain invert in some areas. Therefore, with SLR, the groundwater level is able to rise more (compared to the original Kh scenario) before the stream is able to regulate the groundwater level. Conversely, under the scenario of lower Kh or higher recharge, groundwater levels are higher, and so streams regulate groundwater levels changes more effectively in some areas, reducing the capacity for change from sea level rise.
- Under scenarios of different Kh and land surface recharge, the model does not match measured groundwater levels as well as the original scenario (it is less calibrated). Therefore, the original Kh scenario provides the most realistic and accurate prediction of the effects of sea level rise.
- The hydraulic response of sea level rise is expected to largely equilibrate within 1-2 months of any change occurring. This is different to the transport response (say from sea water intrusion) which would take longer to reach a new equilibrium.

10 IMPACTS OF FUTURE EARTHQUAKES ON LAND SETTLEMENT: GEOTECHNICAL MODELLING

This section summarises potential land settlement from future earthquakes for the case study areas. It is described in more detail in Beca (2018)

The LDRP45 project study considered the effects of earthquake induced land settlement on groundwater, in the four case study areas (Figure 4)). Earthquake ground surfaces were generated for the 1/250 AEP, 1/500 AEP and 1/2500 AEP earthquake scenarios.

10.1 Ground Conditions

Brown & Weeber (1992) Geology of the Christchurch Urban Area 1:25000 scale geological map indicates variation in the geology across the four study areas. The study areas at Flockton Basin (Area 1), Avondale (Area 2) and Woolston (Area 3) are dominated by Springston Formation alluvial sand and silt overbank deposits of typical thickness of 3 to 6 m, overlying Christchurch Formation sands at depth (typically 3 to 6 m). The Southshore/New Brighton study area (Area 4) geology comprises Christchurch Formation dune and beach sands (Figure 53).

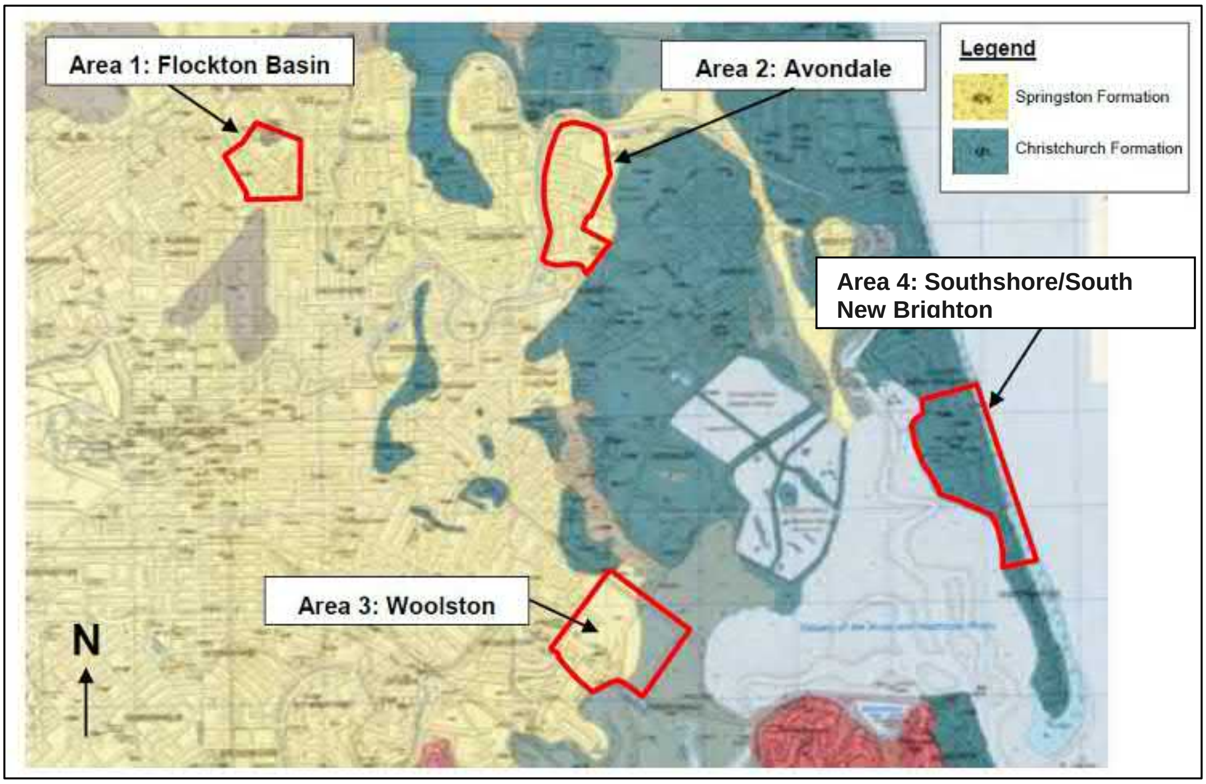


Figure 53. Geological map of the Christchurch Urban Area, with Case Study areas (Brown and Weeber, 1992)

10.2 Spatial Estimation of Earthquake Induced Ground Settlement

10.2.1 Ground Surface after Earthquakes

An assessment was performed to estimate the approximate vertical ground settlement associated with earthquake strong ground motion for theoretical earthquake scenarios. This assessment considered both free field post-liquefaction reconsolidation and the vertical component of lateral spread ground deformation. The assessment did not consider potential ground surface change associated with tectonic movement associated with near field earthquakes.

The assessment considered three probabilistic earthquake scenarios, these being:

- An earthquake with an annual exceedance probability (AEP) of 1/250, which corresponds to an earthquake with sufficient intensity to induce free field post-liquefaction reconsolidation settlement but limited lateral spread ground deformation.
- An earthquake with AEP of 1/500, which corresponds to an earthquake with sufficient intensity to induce free field post-liquefaction reconsolidation settlement and lateral spread ground deformation. This earthquake also corresponds to the Ultimate Limit State (ULS) earthquake event adopted for adjacent residential developments in accordance with the loadings code AS/NZS 1170.
- An earthquake with an AEP of 1/2500, which corresponds to a significant earthquake scenario that induces widespread liquefaction, ground deformation (post-liquefaction reconsolidation and lateral spread) and structural damage.

10.2.2 Geotechnical Investigation Data

Cone penetration test (CPT) data to a depth of 20m below ground level was used for the assessment of liquefaction triggering and earthquake induced ground settlement, with laboratory gradation testing results used to refine the assessment of fines content and gradation of the silty and sandy soils. The investigation data was sourced and collated from the New Zealand Geotechnical Database (NZGD).

10.2.3 Geotechnical Assessment of Future Post-earthquake Ground Surface

Geotechnical analysis of earthquake performance of the land was undertaken in order to spatially estimate seismic settlement for a range of earthquake events. This settlement estimate includes both free field post-liquefaction reconsolidation and lateral spread ground deformation. The median groundwater level from EQC monitoring piezometers was used for the liquefaction assessment.

For all empirical methods to assess seismic settlement associated with post-liquefaction reconsolidation, a 50% confidence has been considered to provide an average estimate. Assessment also considers estimated settlement within the upper 20m of the soil profile to remove bias from analysis of CPT of varying depths. The Avon River, Heathcote River, Dudley Creek, and Avon-Heathcote Estuary waterways act as potential free faces of varying height (1 to 5.5m) to which liquefied soils can laterally spread upon development of flow failure conditions resulting in triggering of extensive liquefaction through the upper 5 to 10m of the ground profile. The magnitude of lateral spread ground deformation was calculated in two dimensions by the method of Youd et al (2002) along with manual verification checks. This method uses earthquake, soil composition, and performance characteristics.

Experience at the Christchurch wastewater treatment plant oxidation pond embankment during the Canterbury earthquake sequence is that the vertical deformation associated with lateral spread ground deformation was typically approximately 25% to 50% of the lateral translation. Analysis provides a moderately conservative estimate of settlement associated with lateral spread by considering incremental lateral stretch and assuming that a constant volume is maintained. The theoretical earthquake surfaces generated for seismic settlement and lateral spread are smooth, not incorporating knowledge of change in ground conditions and geotechnical performance over short distances. Also the relatively low density and spacing of CPT investigation points will strongly influence predictions. To improve the level detail of spatial variation in study predictions of post-earthquake ground surface between assessed CPTs, observations from the 22 February 2011 Mw6.2 Christchurch Earthquake were used to improve the resolution of estimated settlements. The 22 February 2011 earthquake had an AEP in the order of 1/250 to 1/2500 across the study areas (with varying PGAs), and was assessed to generate a theoretical ground settlement. The results predicted theoretical change in ground surface compared against the LiDAR digital elevation model (DEM) interpreted ground settlements. Spatial variance in settlement was used to produce a variance ratio across the study areas that considered the variance between LiDAR predicted settlement to a smoothed settlement surface. Theoretical predictions of earthquake land settlement for the synthetic theoretical 1/250, 1/500, and 1/2500 AEP earthquakes were multiplied by the variance ratio to incorporate past observations of relative differences in seismic performance spatially into the estimates. Maps of expected spatial ground settlement induced by earthquake events are provided in Appendix 2 Beca (2018).

For each earthquake scenario, the 2015 LiDAR (provided by CCC) has been modified to create a synthetic approximate future post-earthquake ground surface, by reducing ground elevations by the estimated total ground settlement. This is the sum of the free field post-liquefaction reconsolidation and ground settlements induced through lateral spread incorporating definition form relative performance during the 2010-2011 Canterbury earthquake sequence. Maps of post-earthquake ground surface (MSL) are provided in Beca (2018).

11 HAZARD ASSESSMENT

11.1 Trigger Levels

A key issue to be resolved through the LDRP 45 project was what constituted a problem level in terms of groundwater level. These problems could be physical, chemical/quality, or even cultural.

The assessment of trigger levels was based on long term water table surfaces (median and 85th percentile). Ideally, we would also have taken into account the frequency and duration of exceedance of trigger levels. However, this was not achievable due to lack of long term, high resolution data. There were three shallow, long term ECan wells with high resolution data, but the results for each were very different, and it was not possible to extrapolate any results across the city. As covered in Section 3, high resolution data for around 250 shallow piezometers became available during the project, but the data were too limited in temporal extent to classify areas according to their dynamic groundwater response.

Previous work has identified that damage to urban areas from groundwater rise can include (Al-Sefry & Şen, 2006):

- Flooding of house basements
- Deterioration of roads and highways
- Damage to building foundations
- Soil contamination
- Offensive smell
- Breeding of mosquitoes

High groundwater levels can also results in chronic health complaints due to living under damp conditions (SBR, 2007).

Therefore, of great importance are the trigger levels, or the groundwater depths that are associated with negative impacts to people or land. A literature search revealed there are very few studies that actually define groundwater trigger levels for different land uses, at which damage occurs.

A study in the Netherlands defined minimum drainage depths for different urban functions (SBR, 2007). The work in the Netherlands highlights the fact that, when developing land with shallow groundwater, there is a need to focus on the costs for site preparation, and for whole of life operational costs: optimisation should be for the whole of life of the development, and not just for construction. There may be different depths required for site construction and habitation, and the approaches may be to mitigate shallow groundwater effects across the whole site, or just the parts of the site affected.

The Dutch work is used by some councils as a guide, and may be appropriate for using when modelling impacts of sea level rise in Christchurch (Table 11).

Table 11: Minimum drainage depths associated with various urban functions (SBR, 2007)

Land use type	Drainage depth (depth to groundwater in m below surface level)	CCC guidelines
Houses, buildings, structures	0.70	
Primary roads	1.00	0.65 (NZTA – 1.5m)
Secondary roads	0.70	0.65 (NZTA – 1.5m)
Cables and pipes	0.60 – 1.20	0.4 (UFB 0.3m)
Gardens and parks	0.50	1.0 (trees)
Sports fields	0.50	
Graveyards	0.30 below coffin	
Footpaths		0.4 (NZTA – 1m)

These depths are used as guidelines as to when the councils are required to put in mitigation to control groundwater levels. They are exceeded when groundwater is above these levels frequently or for extended periods of time.

A workshop was held to try to define suitable trigger levels for Christchurch. There appear to be no regulations that define what is acceptable in terms of depth to groundwater. Issues that were raised were:

- Under the building act, water shall not enter a building.
- CDHB produced a report on flooding and damp and health issues, though this was thought to be more to do with surface flooding.
- In terms of waste water, around 30% of flow in sewers is groundwater infiltration. Sewers are located 2m beneath roads, and therefore may be helping keep groundwater out of the sub base of many roads.
- Pressure and vacuum sewer systems that are being installed will not drain groundwater.
- With new subdivisions, the roads are designed to work as stormwater channels, so houses are elevated relative to roads.
- Some subdivisions have put in place groundwater drainage.
- For road construction, 0.4m is the accepted depth to keep groundwater out of.
- For road use, depth to water will affect the durability of the road; heavier traffic would require greater depth to water to prevent deterioration.
- Once deterioration has occurred, reducing groundwater levels would have no benefit.
- Hard surfaces in parks would possibly require a similar depth to water as roads, though they wouldn't have the same traffic.
- Due to the low permeability nature of Christchurch soils/sediments, land drainage effects may not propagate far – so drawing down groundwater under a road may have no impact on residential properties on either side of the road.
- Decisions to repair roads due to groundwater damage are done on a cost/benefit approach.
- For parks, the issue is really about when groundwater reaches the surface and causes ponding, or when it is close to surface such that rainfall can't infiltrate and ponds. The council is adaptable in terms of tree species.
- Groundwater is discharged into the stormwater network, but is not defined as groundwater or managed under the stormwater consent due to capacity issues.

A review of complaints to the Council was also carried out to assess if there were already issues being identified by house holders. It was found to be very difficult to assess from the complaints database which, if any, of the flooding issues were groundwater related.

For residential areas within the case study areas, sensitivity analysis suggested that a 0.35m 85th percentile level affected approximately the same number of properties as the 0.7m median. That is, using the 0.7m median depth to water as a trigger level was equivalent to a trigger level of 0.35m only being expected to be exceeded 15% of the time, in terms of the numbers of properties affected. After extensive discussion, it was decided that an 85th percentile surface with a trigger level of 0.35m was most appropriate to be used as a trigger level. For residential properties that had an average depth to water across the property that exceeded the trigger level, mitigation options were assessed (Section 10).

For new developments, CCC should consider whether new housing should be built in areas that are not within the acceptable depth to groundwater, or ensure that groundwater mitigation is part of the development strategy.

11.2 Hazard Assessment Approach

After determining what constituted a hazard in terms of depth to groundwater, it was possible to use the results of the previous modelling (SLR and ground settlement) and add these results to the baseline groundwater level surface, to predict the reduction in depth to groundwater, and understand how the hazard might increase under different scenarios. The results, however, depend not only on depth to groundwater, but are also affected by uncertainties in the data, particularly as a result of the fact that confidence in the interpolated surface decreased rapidly away from the datapoints (as outlined in Section 8).

The following approach to understanding confidence in the results was developed, creating one final output for selected sea level rise scenarios, which is a raster showing gradational colouring. The colouring would be as follows:

- White/clear: "Good confidence not affected"
- Light tone: "Low confidence in predictions" – we are not confident in the predictions, and it is not clear whether there is a problem or not
- Solid tone: "Good confidence of adverse effects"

The components of uncertainty that are considered are:

- Threshold - height above (or below) the shallow groundwater level threshold (0.35 m below ground level), based on the baseline surface.
- Measured GW levels - areas with good data (and interpolation) versus areas with little or no data;
- Model accuracy - confidence in the modelled rise in GW levels from sea level rise; and
- Drains - presence (or lack of) local-scale drains that have (or have not) been included in the model.

As a result of modifying the groundwater model to include drains, this final component was removed from the hazard assessment. For each of these categories, we applied a grade. Expert judgement was needed to define these classifications, and the descriptions below are the final grades, after testing out different approaches.

The assessment is founded on the initial coverage of threshold level. The remaining rasters were then used to scale this coverage. The aim was that, even if the threshold level was (for example) low, the confidence might be reduced due to lacking measured data in that area.

11.2.1 Threshold

The threshold is based on the baseline depth to groundwater surface. The results were categorised based on height above or below the 0.35m threshold depth to water. The larger the predicted height above (or below) the threshold, the more confidence there is that the threshold will be breached (or not breached).

Categories used were:

- -10 for < 0.35 m below threshold (i.e. deeper than 0.7 m below ground level).
- 0 for = threshold (i.e. = 0.35 m below GL)
- + 10 for > 0.35 m above threshold (i.e. equal to or greater than ground level)

Values between these categories were linearly interpolated. The result is shown in Figure 54. This became the baseline surface for adding further uncertainty.

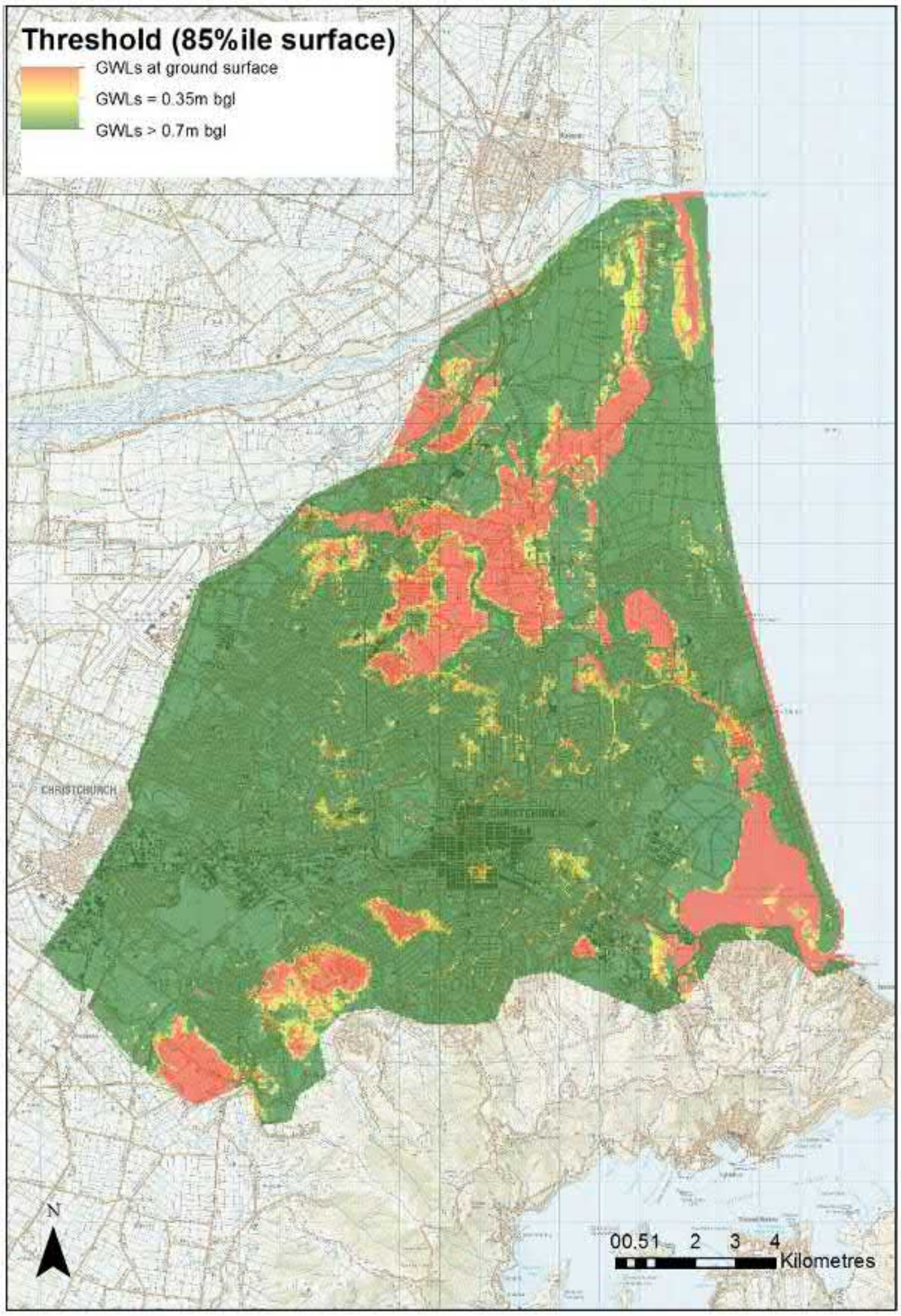


Figure 54: Threshold classification

11.2.2 Interpolation uncertainty

As discussed in Section 8.5, there was considerable uncertainty in the interpolated surface once away from the measured data points. Using Seequent's groundwater level interpolation uncertainty surface, a grading of 0.5 – 1 was assigned, where 0.5 is low confidence (no close data points to support the interpolation), and 1 is very confident of the baseline 85th percentile groundwater level (close to measured data points). The method assigned a value of 1 where the uncertainty surface had values less than 0.2m (very confident) through to a value of 0.5 for interpolation uncertainty values of 4m (very unconfident). These values were later multiplied with the base threshold category to provide a composite baseline / interpolation value. The resulting coverage is shown in Figure 55.

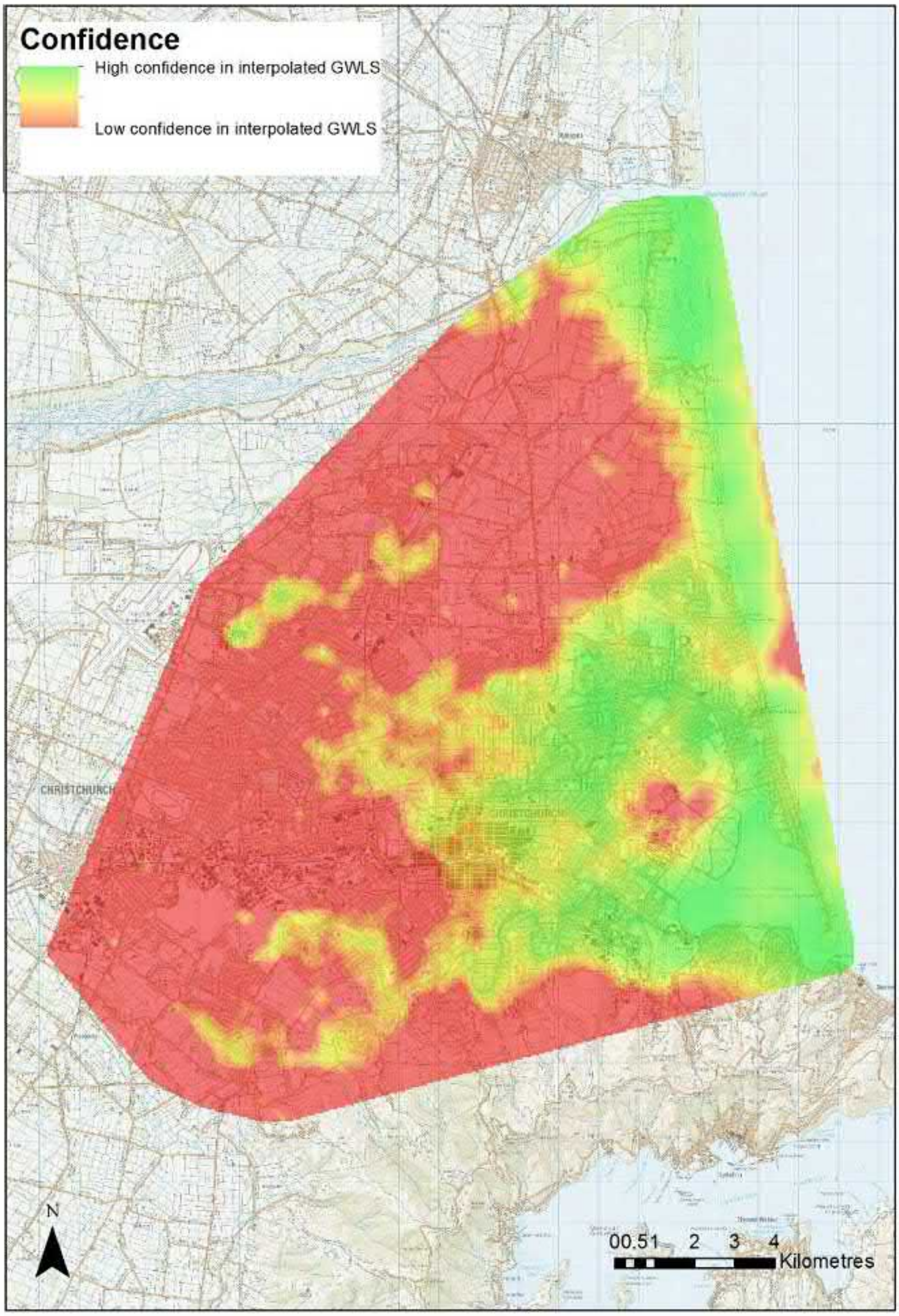


Figure 55: Interpolation confidence

11.2.3 Model Accuracy

The aim had been to use the results of the sensitivity of sea level rise predictions to model parameters (Kh, Kv) in the coastal zone to assign a grade of 0-1, 0 being for cells that changed markedly when K was varied, through to 1 for cells that did not change at all under different sensitivity results. Cells located well away from the coast that are unaffected would have a grade of 1. Cells near the coast that are directly driven by the sea level rise would also have a grade of 1. However, after carrying out sensitivity analyses, whilst absolute groundwater levels were sensitive to changes in these values, the predicted change due to sea level rise was relatively insensitive to these values. Therefore, model accuracy was removed from the uncertainty analysis.

11.2.4 Drains

It had been identified that some areas with shallow depth to groundwater were in areas that were drained by relatively small drains, ones that were not included in the modelling. In such areas, especially in areas with few datapoints, the drains could be exerting considerable control on groundwater levels that were not represented in the interpolation or model. The intent was to use the drains network to place highest confidence in areas where streams, rivers or drains exist and were included in the interpolation and groundwater model (e.g. near the Avon, Heathcote and Styx rivers), and lowest confidence in areas where smaller drains exist but were not included. This stage was removed after further model development was carried out to include the streams and drains within the numerical model.

11.2.5 Summary of Final Classification

Table 12 summarises the classifications applied to each category:

Data set	Value	Explanation
Threshold level	-10 - +10	Low (negative) values where GWLs are lower than 0.35m, high values where they are shallower than 0.35m
Interpolation uncertainty	0.5 - 1	High values where we have a lot of confidence; low values where we have little confidence.
Model sensitivity	N/A	Sea level rise predictions insensitive to model parameters.
Drains	N/A	Not carried out due to inclusion of drains and streams in numerical model

Table 12. Summary of final classification

The rasters were multiplied together to generate a composite grading in the range -10 to + 10. For example:

- A location with GWL more than 1.0 m below ground level (Threshold = -10), located close to a measurement point (Confidence = 1.0), value of (-10 x 1.0) = -10.00. The result is high confidence that there is not a problem.
- A location with GWL of 0.38 m below ground level (Threshold = -2, say), located in an area of good data (Confidence = 0.9 say), will have a value of (-2 x 0.9) = -1.80. The result is low confidence that there is not a problem.
- A location with GWL of 0.08 m below ground level (Threshold = +5, say), located in an area of poor data (Confidence = 0.5), will have a value of (+5 x 0.5) = +2.5. The result is low confidence that there is a problem.

- A location with GWL at ground level (Threshold = +10, say), located in an area of good data (Confidence = 0.9 say), will have a value of (+10 x 0.9) = +9.00. <u>The result is high confidence that there is a problem.</u>

The resulting coverage is presented in Figure 56.

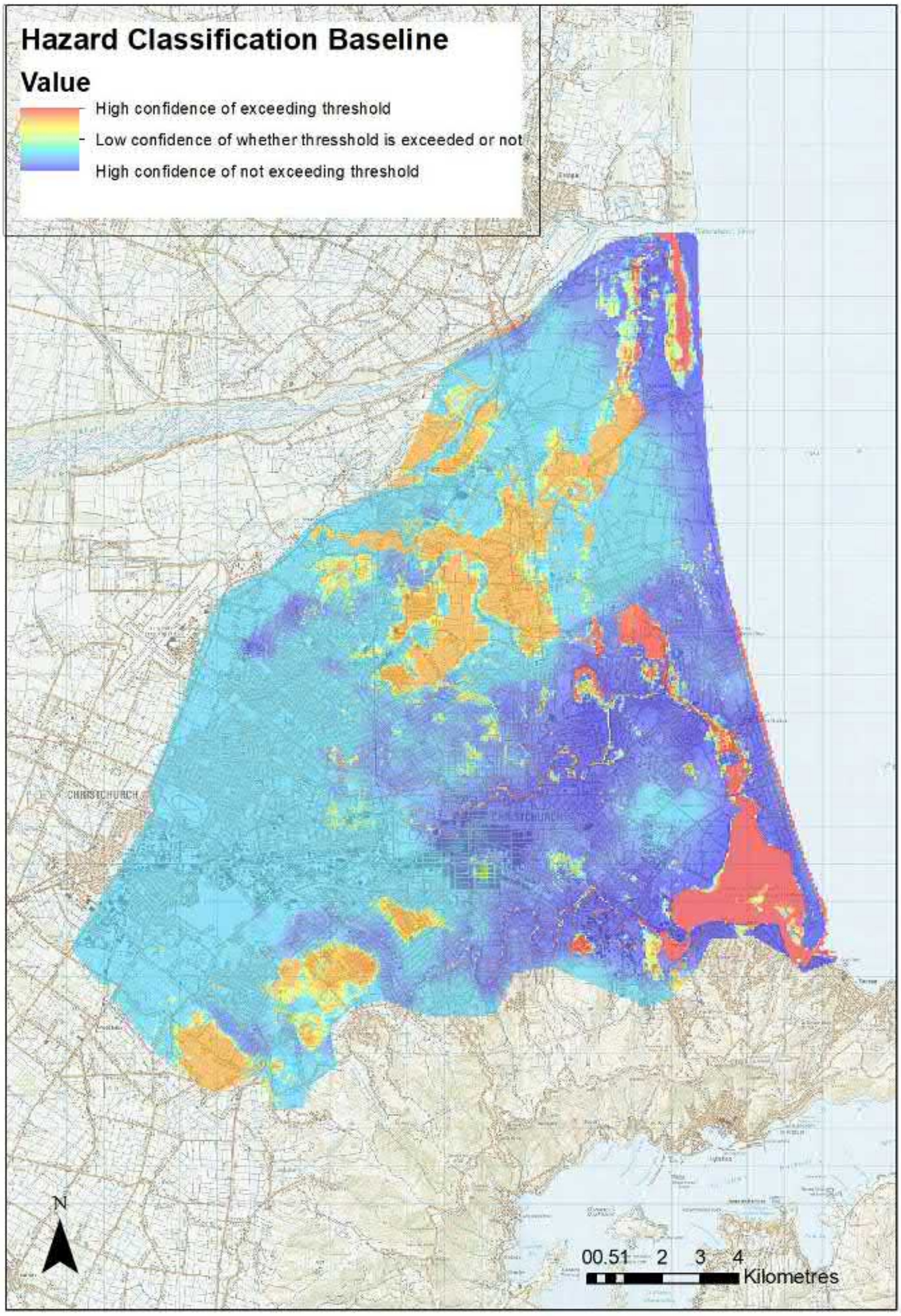


Figure 56. Hazard Classification for baseline surface

12.1 Case Study Areas

The number of properties affected by different SLR scenarios and the 1 in 2500 earthquake scenarios were calculated for the case study areas (Section 4). Residential properties were extracted from the District Plan, using the primary parcels (LINZ dataset) to identify the individual properties. It should be noted that Red Zone properties were excluded in this way.

	Area 1: Flockton		Area 2: Avondale	
	Area (m^2)	Number	Area (m^2)	Number
All properties	308,056	500	259,021	397
Existing Centile 85th	2,238	2	0	0
SLR- ~25yr / 0.19 m	2,238	2	0	0
SLR- ~50yr / 0.4 m	2,238	2	6,401	11
SLR- ~100yr / 1 m	2,238	2	88,761	144
SLR- 1.88 m	2,238	2	126,178	200
SLR- 2.40 m	2,973	3	139,535	220
Earthquake 1/2500 AEP	25,087	89	9,071	16
Earthquake 1/2500 AEP + SLR 100yr	27,402	99	124,615	200
	Area 3: St Johns		**Area 4: South New Brighton**	
	Area (m^2)	Number	Area (m^2)	Number
All properties	999,157	1296	404,400	611
Existing Centile 85th	0	0	0	0
SLR- ~25yr / 0.19 m	2,086	1	0	0
SLR- ~50yr / 0.4 m	2,345	2	0	0
SLR- ~100yr / 1 m	132,250	90	209,931	314
SLR - 1.88 m	410,439	449	349,884	533
SLR- 2.4 m	484,593	534	368,221	560
Earthquake 1/2500 AEP	50,051	21	0	0
Earthquake 1/2500 AEP + SLR 100yr	378,072	408	283,676	431

Table 13. Area and number of residential properties covered by properties in the case study areas

12.2 City Wide Maps

The baseline (85th percentile) surface, plus SLR scenarios were mapped in terms of the predicted depth to water, and also the hazard classification for each of the surfaces (as outlined in Section 11.2). These are shown in Figure 57 to Figure 68.

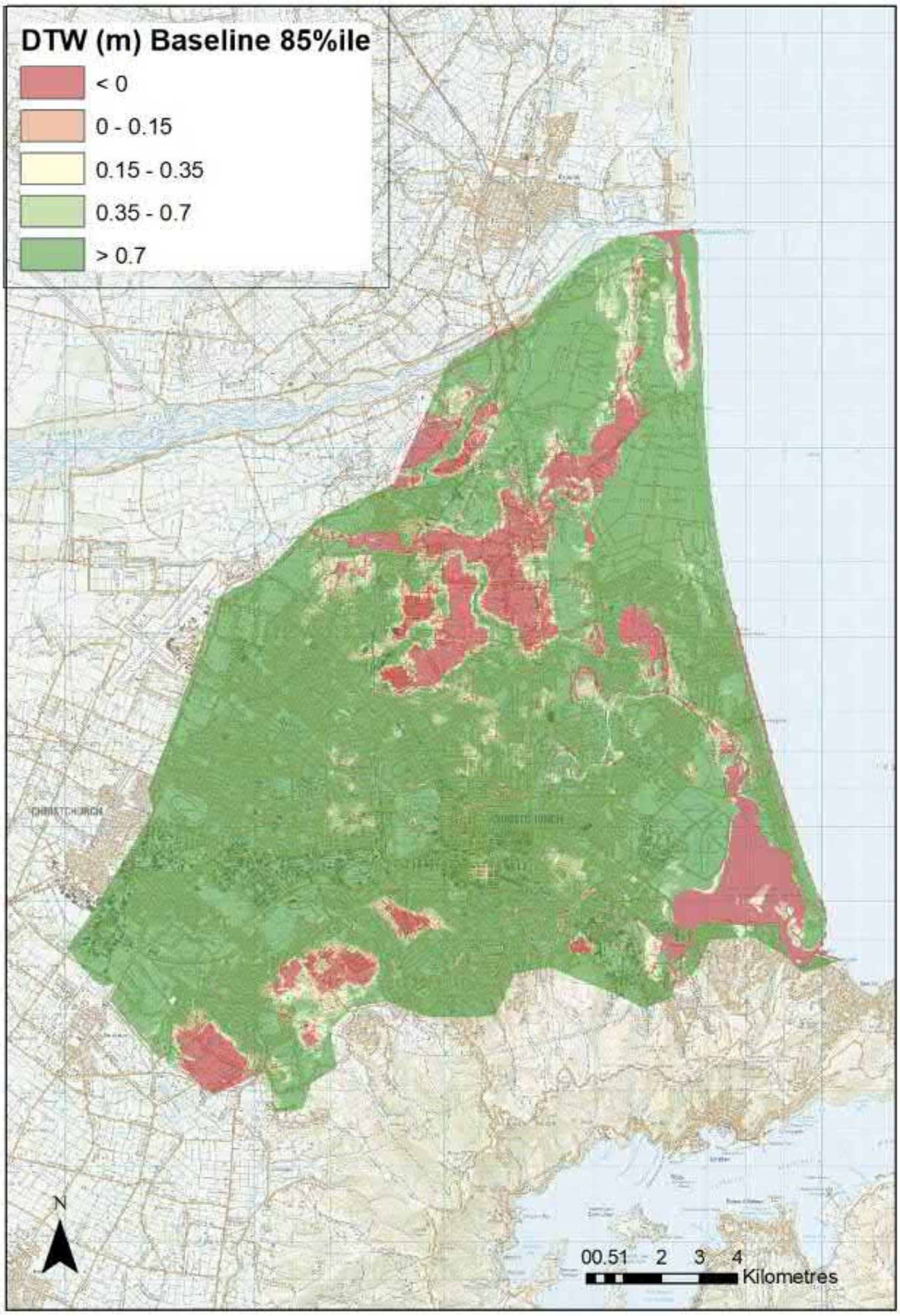


Figure 57. Depth to groundwater – baseline 85th percentile surface

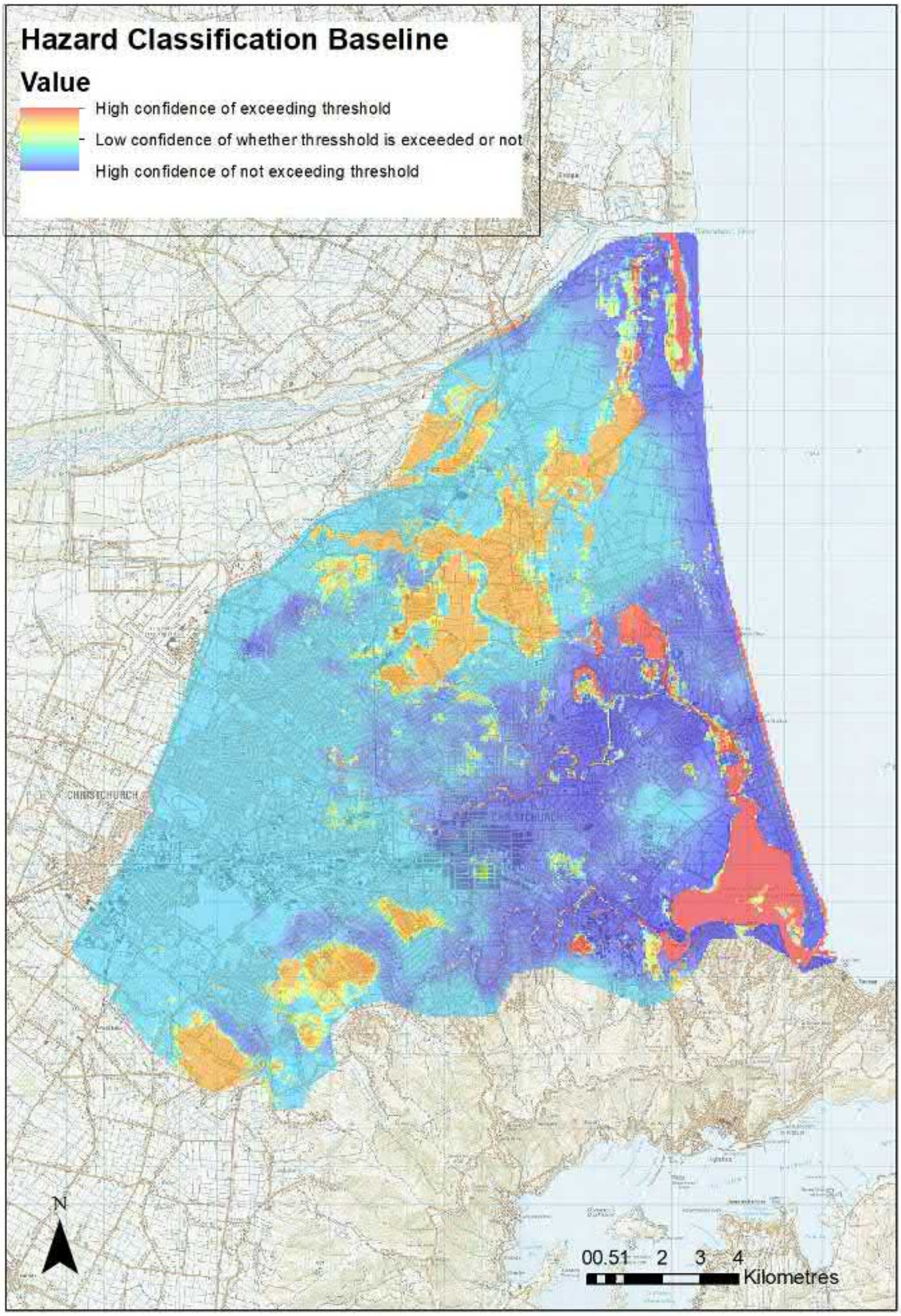


Figure 58. Hazard classification – baseline 85th percentile surface

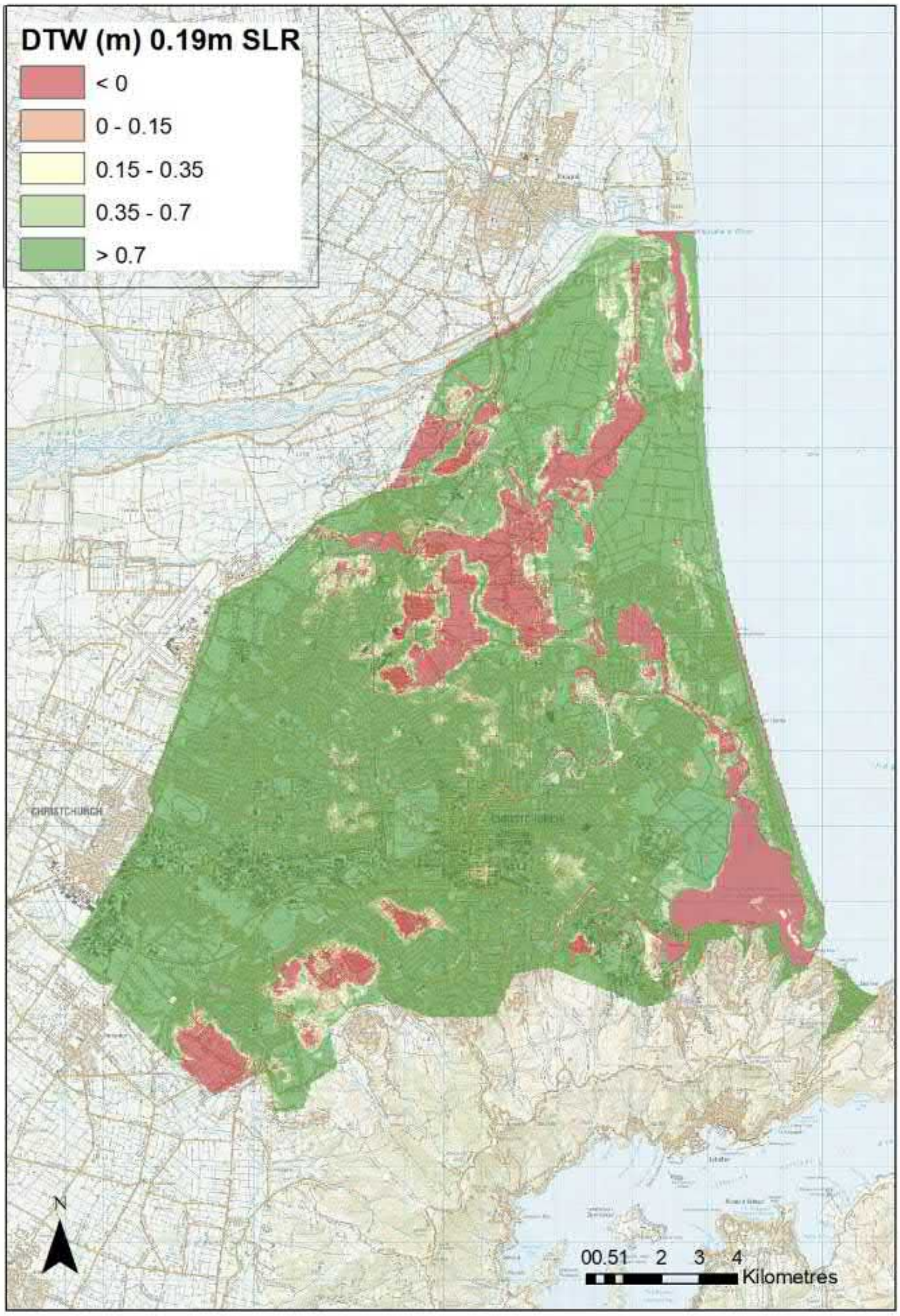


Figure 59. Depth to groundwater – 0.19m SLR scenario

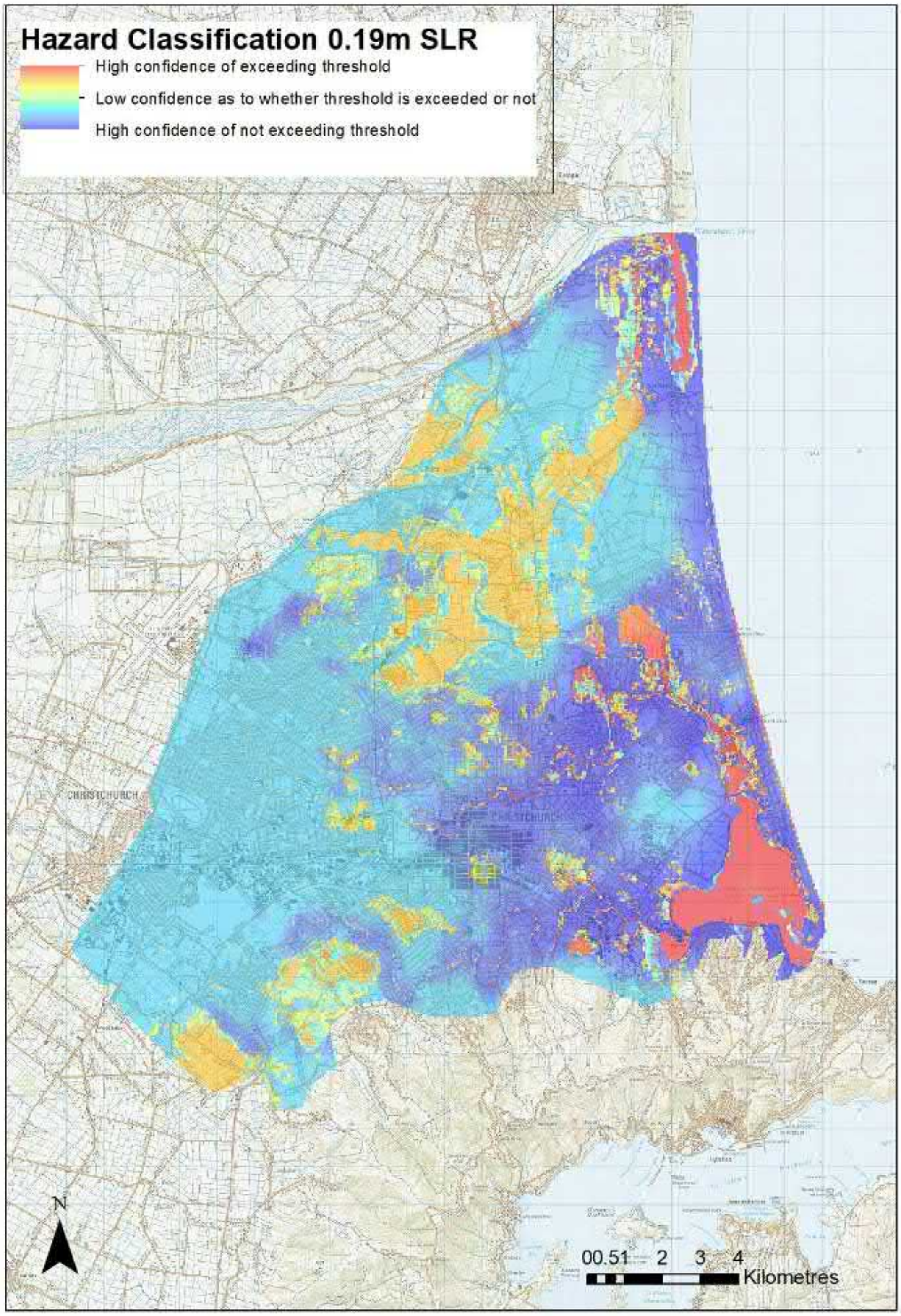


Figure 60. Hazard classification – 0.19m SLR scenario

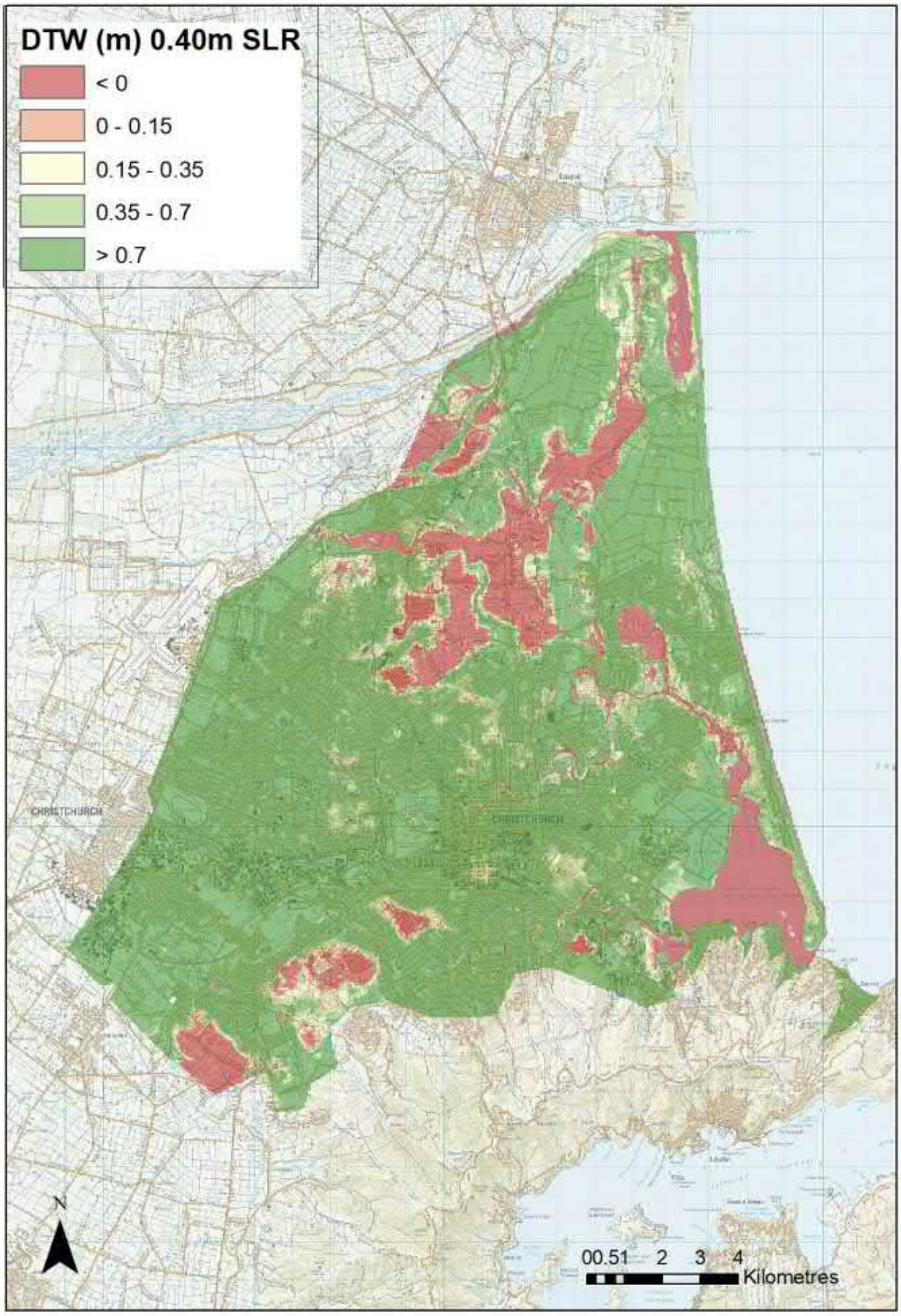


Figure 61. Depth to groundwater – 0.40m SLR scenario

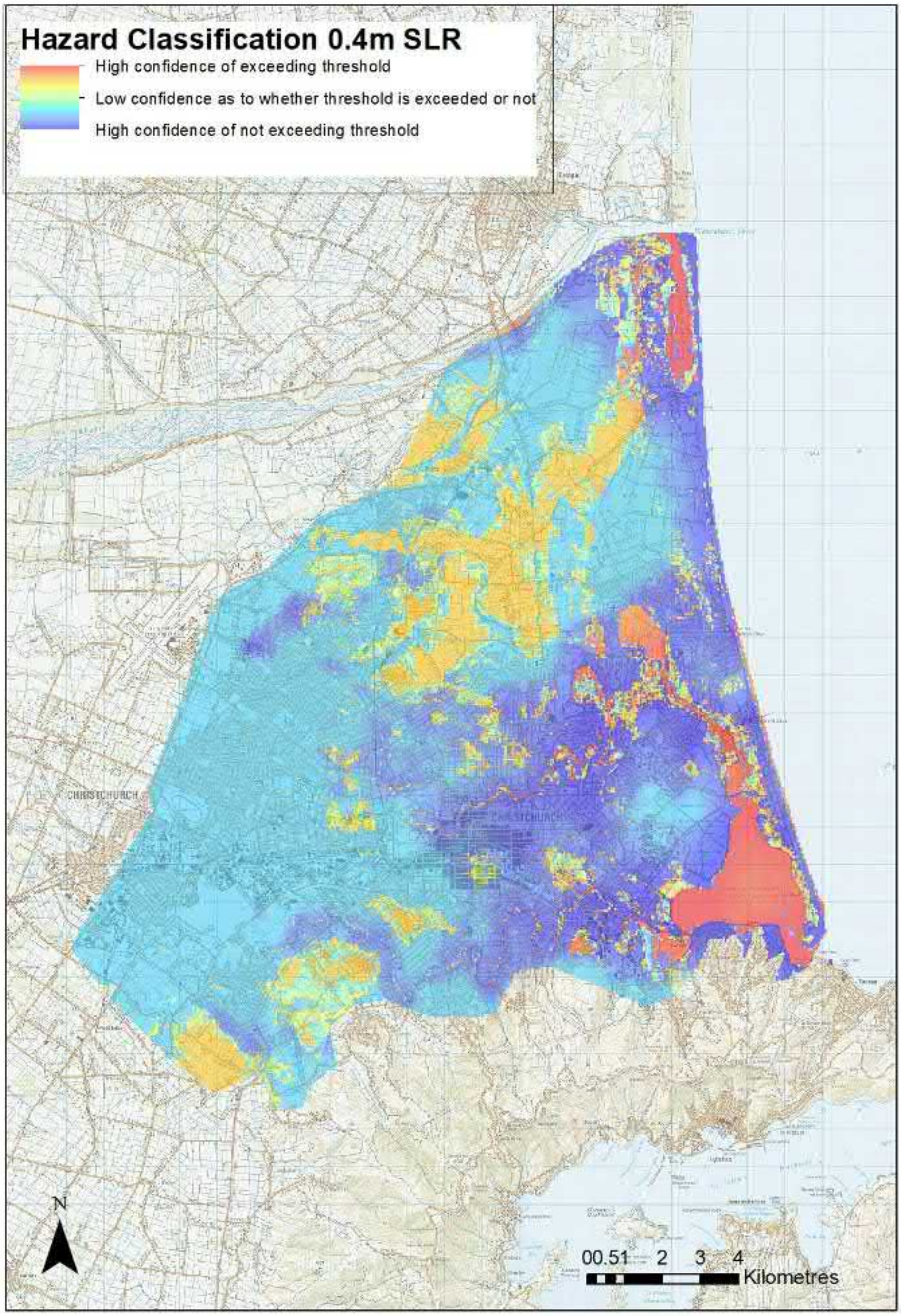


Figure 62. Hazard classification – 0.40m SLR scenario

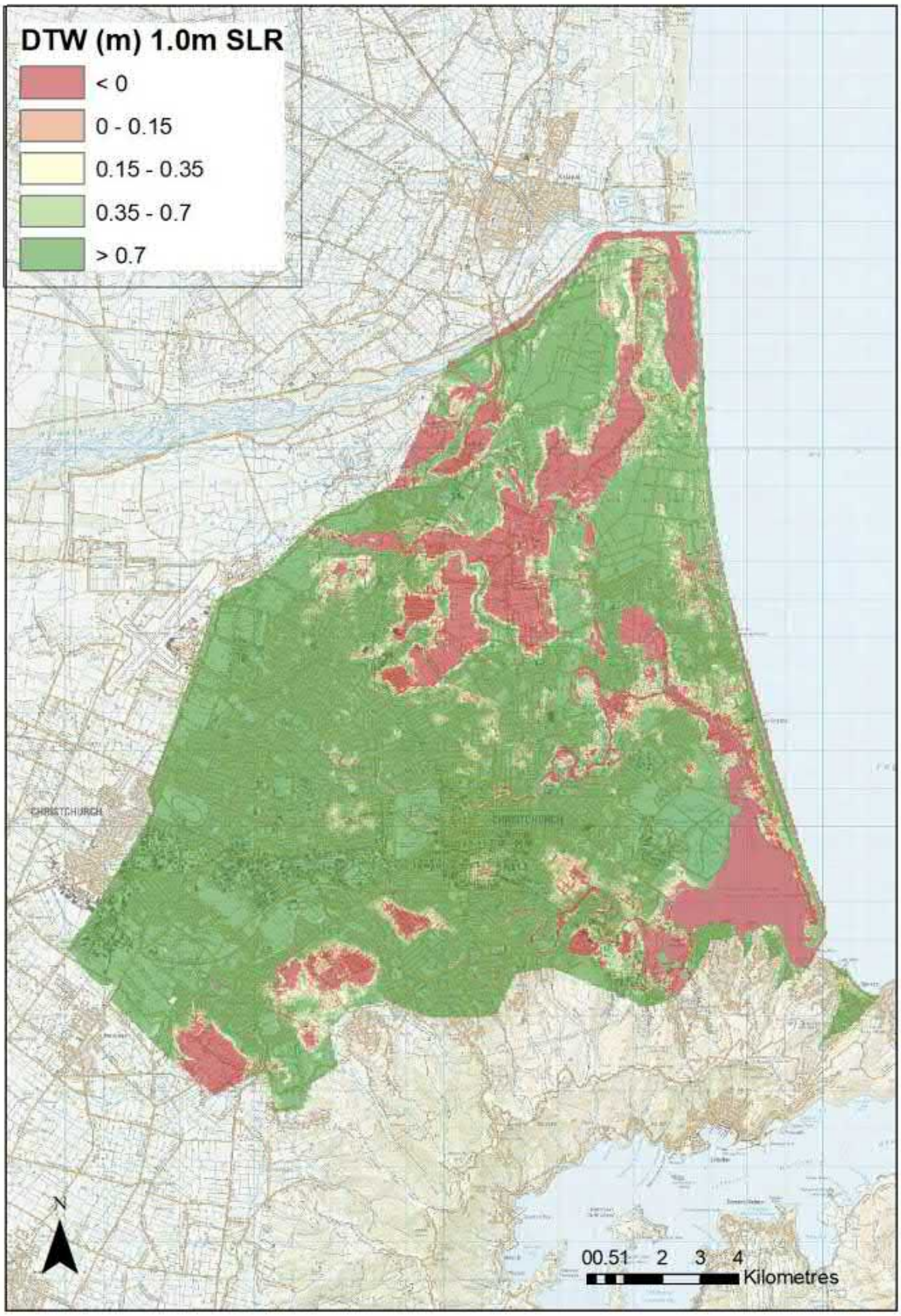


Figure 63. Depth to groundwater – 1.0m SLR scenario

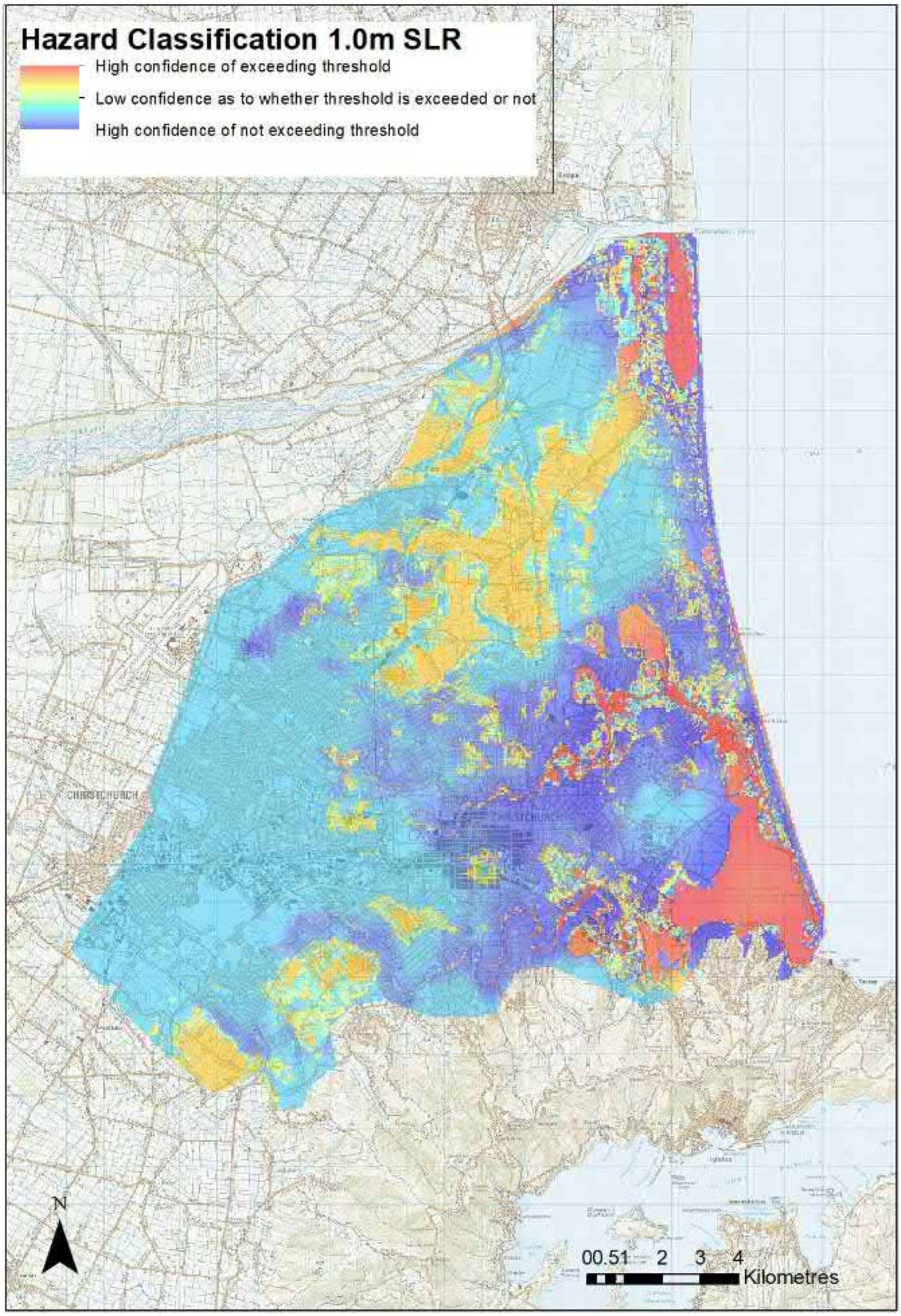


Figure 64. Hazard classification – 1.0m SLR scenario

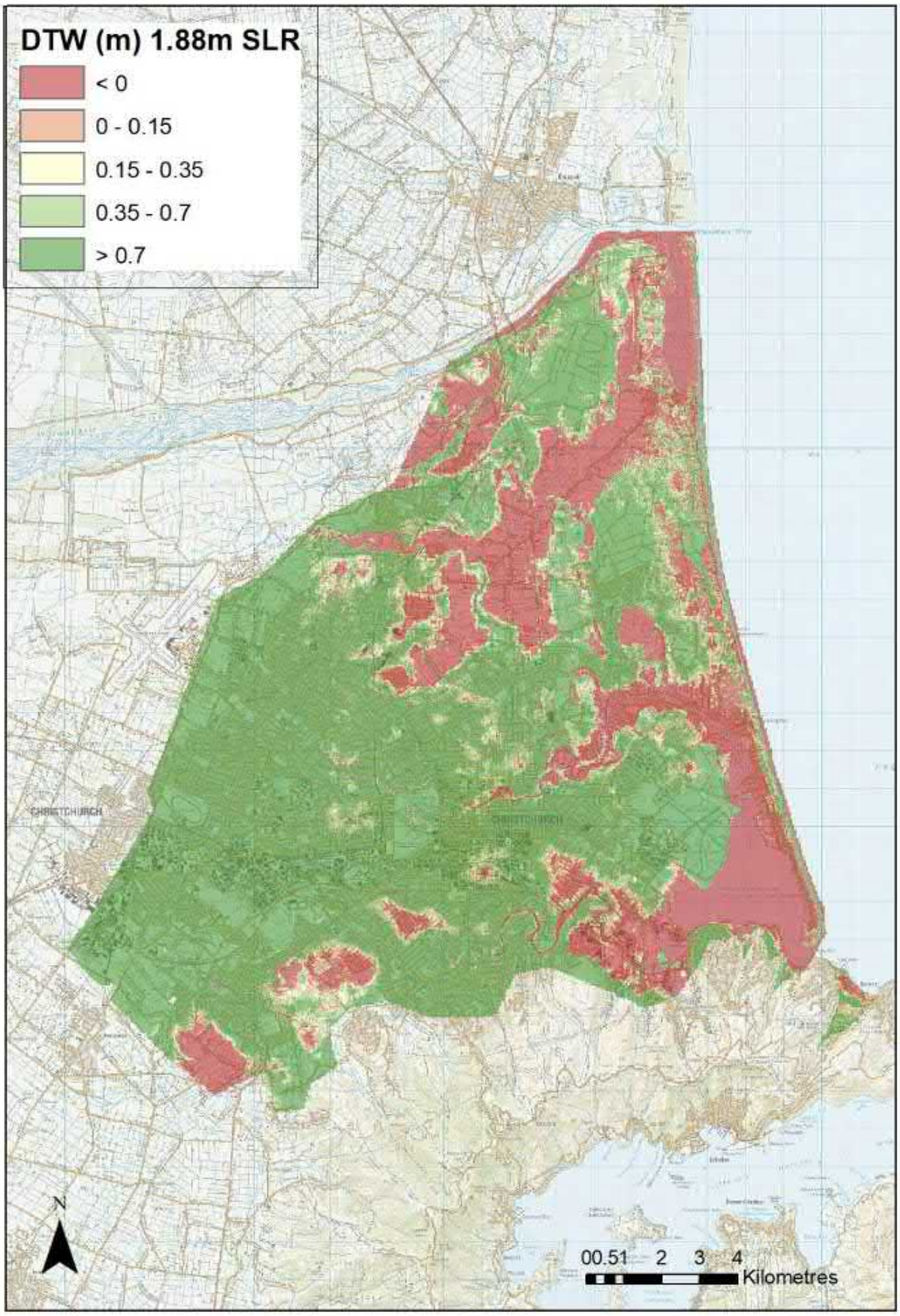


Figure 65. Depth to groundwater – 1.88m SLR scenario

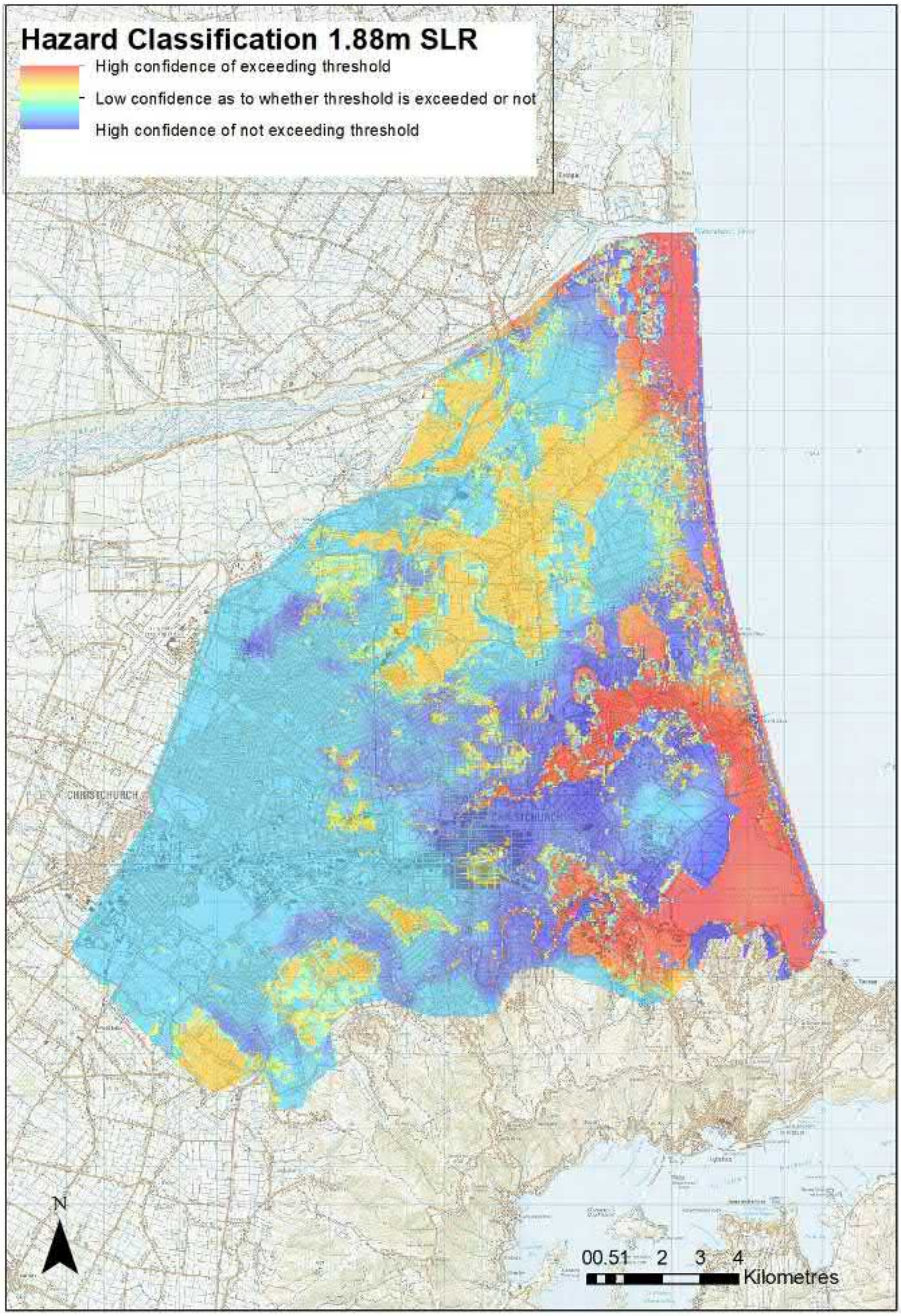


Figure 66. Hazard classification – 1.88m SLR scenario

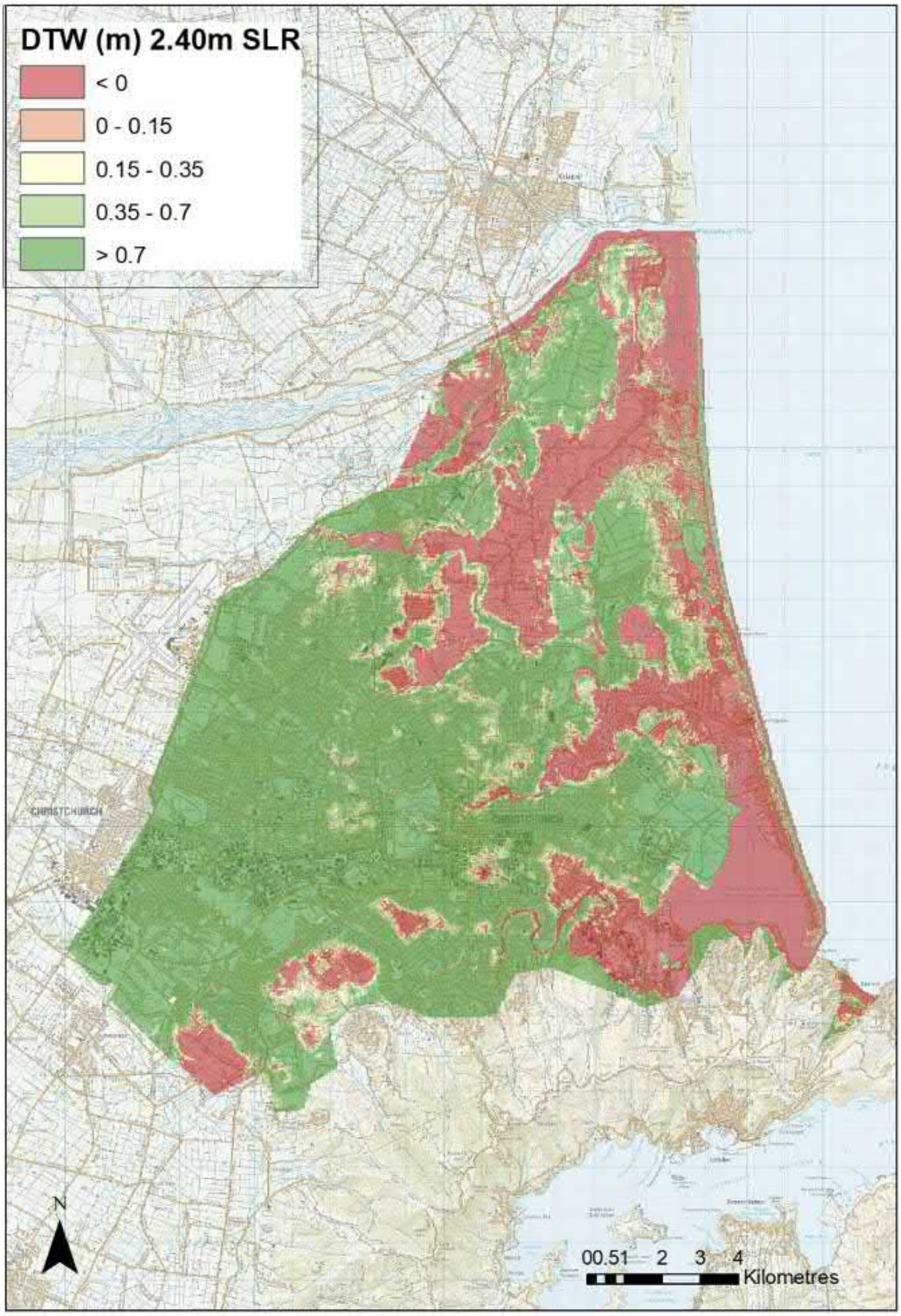


Figure 67. Depth to groundwater – 2.40m SLR scenario

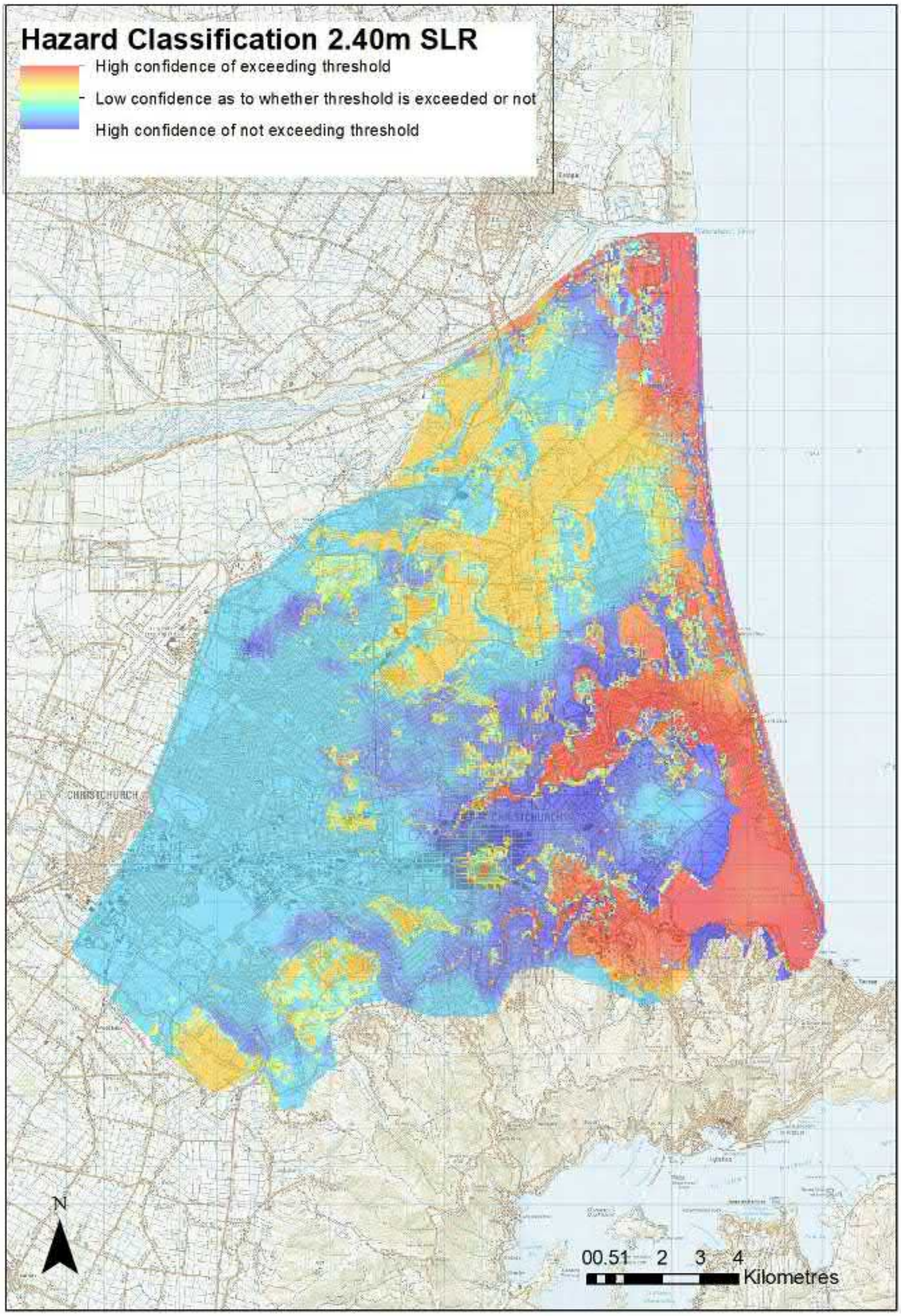


Figure 68. Hazard classification – 2.40m SLR scenario

13 LIMITATIONS, UNCERTAINTIES AND ASSUMPTIONS

There are numerous limitations and uncertainties associated with the results of this study, and the assumptions used in this study. There is a huge degree of variability within the natural strata through which the groundwater moves, and this cannot be measured or modelled accurately. In urban areas, horizontal infrastructure causes variable effects on groundwater levels and flow paths, as is well known in terms of infiltration into waste water pipes. The result is that the groundwater level data, upon which modelling is based, has a lot of variability, both in terms of the temporal response to climate and other drivers (see Section 5.5), and spatially (see Section 13.1.2)

The numerical groundwater model represents a gross approximation of the variability that occurs at the ground surface and beneath it, but provides a very precise numerical output, which can be mistakenly represented as a very accurate assessment. A realistic way of using the output from the model is to acknowledge that it is an approximation of reality, and accept the lack of accuracy to fully represent the groundwater flow system, then to present a range of possible outcomes and to indicate the level of certainty associated with those outcomes, which will vary spatially depending on the amount and accuracy of the information used to build the model. To account for this, the hazard assessment approach was used, which helps to understand the areas where greater or lesser certainty can be placed in the results.

Analyses are not, and have never been, suitable for local-scale predictions. Rather, the intent of this study was a first-pass assessment that highlighted areas that were clearly affected, areas that were clearly not affected, and areas that would require further investigation to refine the assessment at a more local scale.

13.1.1 Baseline Surface

To reduce modelling uncertainties (which are inherent in any model), the best possible "baseline" surface (85th percentile) was developed based on a rigorous geostatistical analysis of measured data (independent of the groundwater model), which was carried out by Seequent. The changes in sea level rise were then modelled, and these changes were added to the measured baseline surface. This substantially reduces the influence of the groundwater modelling uncertainties.

The analyses are not suitable for local-scale predictions. Rather, the intent of this project was a first-pass assessment that highlighted areas that were clearly affected, areas that were clearly not affected, and areas that would require further investigation to refine the assessment at a more local scale.

13.1.2 Data Uncertainties

The actual measured groundwater level data used to define the baseline demonstrates a high degree of variability in itself. For example, in the Avonside area, a group of five shallow piezometers, all within a 170 m radius, show a variability of up to 1.3 m in their median groundwater level elevations; two of these, which are only 40 m apart, show a difference of 0.56 m. This high degree of variability makes interpolation of the baseline surface itself challenging, and there is a resulting high degree of uncertainty in the surface at relatively short distances away from the measurement points. Ground surface elevations can also vary considerably over short distances, providing further interpolation uncertainties to the depth of groundwater.

In addition, the high resolution data illustrates the temporal variability of the shallow groundwater data. With the manual "dipped" data that was used to produce the baseline surface, it is inevitable that there will be variability due to the date and time of data collection, and potential for collecting data under different weather conditions: this may have added to the apparent spatial variability.

These types of uncertainties are measurement based, without the added uncertainty of modelling.

13.1.3 Modelling Uncertainties

No model can perfectly replicate real life. It is important to recognise that the purpose of the project was not to accurately define the shallow groundwater hazard at a local scale, but rather to provide a high-level assessment at the city-wide scale. Accordingly, the Canterbury model (Weir, 2018) was considered an appropriate tool to identify the scale and extent of areas likely to be affected at the city-wide scale. There are multiple and complex hydraulic processes that are needed to adequately predict the effects of sea level rise (SLR) in the Christchurch shallow groundwater system, such as:

- Streams and rivers (and associated water routing and groundwater interactions);
- Drains;
- Land surface recharge;
- Groundwater pumping;
- Anisotropy and heterogeneity (including multiple layers);
- Interfacing with the greater plains aquifer system;
- Artesian pressures; and
- Off-shore discharge.

The Canterbury model accommodates these processes, and they interact to rebalance any sea level rise at a new level of dynamic equilibrium.

The model is a well calibrated three-dimensional flow model that has been developed over many years, with recent specific refinements for Christchurch city. It is a deterministic representation of reality, whereby the hydraulic processes are represented as completely as possible. Alternative stochastic modelling methods would need to run a model many thousands of times to quantify model uncertainty, and to do this the model needs to run fast. Therefore, these models often need to be simple, with key processes often left out or simplified. In doing so, the model does not replicate reality as well as a more deterministic model, and the model uncertainty, although well explored, is larger than it could otherwise be. As the Aqualinc model replicates the hydraulic processes as closely as possible, we believe that it provides CCC with the best tool currently available for assessing the complex nature of future groundwater levels resulting from SLR.

To reduce modelling uncertainties (which are inherent in any model), we chose to develop the best possible "baseline" surface (85th percentile) based on a rigorous geostatistical analysis of measured data (independent of the groundwater model), which was carried out by ARANZGeo (now Seequent). The changes in SLR were then modelled, and these changes were added to the measured baseline surface. This substantially reduces the influence of groundwater modelling uncertainties.

13.1.4 Key Areas of Uncertainty

Key areas of uncertainty therefore include:

- City-wide groundwater modelling and the resulting depth to groundwater, and uncertainties associated with this, including:
    - Limited data availability in terms of spatial and temporal resolution and distribution
    - Uncertainties in the interpolated groundwater surfaces, due to the high degree of variability between datapoints

- Simplified high level categorisation of soil types and assumptions regarding hydraulic parameters which are input into the groundwater model
- Use of LiDAR data, and assumptions of the accuracy of the LiDAR data in urban areas, where buildings and other data have had to be filtered out.
- Uncertainties associated with assumed sea level rise horizons
- Uncertainties associated with the modelling of backwater effects
- Impacts of earthquakes
  - Future post-earthquake ground surface, based on theoretical future earthquakes
- Trigger levels used to trigger the need for mitigation. These were developed based on international work, but the need for mitigation will vary according to the problems needing to be resolved. That is, different trigger levels might be more appropriate for different issues.
- Cascading or cumulative effects, including the cumulative effects of several drivers acting at once to increase groundwater levels. This could include issues such as decommissioning sewers and the resulting effect on shallow groundwater levels (see Appendix G).

These need to be kept in mind when using the outcomes of this study.

While these uncertainties may be able to be reduced through site specific investigation, they are unlikely to be eliminated.

13.2 Residual Risk

It is not possible to accurately predict the area/s which will affected by groundwater in the future. Sea level rise and groundwater level rise will occur gradually over time, and there are inherent uncertainties in the approach taken by this project of estimating future groundwater levels.

In the event that groundwater mitigation systems are constructed, there will still be uncertainty about future groundwater level rise, including the future areas affected, future groundwater levels and timeframes.

14 RECOMMENDATIONS

It is recommended that:

- Council consider using this study to inform discussion about current and future groundwater levels and possible options for responding.
- This study should not be used to identify specific projects or areas requiring groundwater mitigation, or set budgets for groundwater mitigation projects or programmes.
- Appropriate trigger levels for groundwater mitigation are further considered.
- Where groundwater mitigation is required, site specific investigations (desktop and field), options assessment and design are undertaken.
- To better understand the likely performance of potential groundwater mitigation measures, pilot studies are considered. This is particularly relevant for shallow wells, which have not been widely used for groundwater mitigation in Christchurch.

15 CONCLUSIONS

This is a high level study to investigate the scale of the potential issues.

Using the trigger level adopted for this study (groundwater 0.35 m below ground surface), a number of properties are identified as potentially above this trigger level. With sea level rise, and with land subsidence from future earthquakes, the area and number of properties affected will increase significantly. The effects will be greatest in areas close to the coast or tidal reaches of river, with a reduced effect further away.

REFERENCES

Al-Sefry, S, and Z Sen (2006): *Groundwater rise problem and risk evaluation in major cities of arid lands—Jeddah case in Kingdom of Saudi Arabia.* Water Resour. Manage. 20 (1), 91–108.

Aqualinc (2005): *Canterbury Groundwater Model.* Prepared for the Dunsandel Groundwater Users Association and the Ashburton Community Water Trust. Report No L05007-8/1. April 2005.

Aqualinc (2006): *Rakaia-Selwyn Consents Hearing - Groundwater Model Simulations.* Prepared for various parties. Report No. L05037/1. March 2006.

Aqualinc (2007): *Canterbury Groundwater Model 2.* Report No. L07079/1. September 2007.

Beca (2018): *LDRP45 Earthquake Effects on Groundwater Levels.* Case Study Options Report.

Begg, JG.; Jones, KE and Barrell, DJA (2015): *Geology and geomorphology of urban Christchurch and eastern Canterbury.* GNS Science geological map 3. Lower Hutt, New Zealand. GNS Science.

Brown LJ, Weeber JH 1992. *'Geological Map: Geology of the Christchurch Urban Area. Scale 1:25,000.'* Institute of Geological and Nuclear Sciences. Boulanger and Idriss 2014

Brown P., Kerr T., Weir J., Kashima A (2016*): Impact of Climate Cycles and Trends on Selwyn District Water Assets.* Client report prepared for Selwyn District Council. Report Number C16049/1. Aqualinc Research Limited, Christchurch.

Cameron SG (993): *A hydrogeological study of the interaction between Avon River baseflow and shallow groundwater, Christchurch, New Zealand*. MSc thesis, University of Canterbury.

Cox, S.C.; Rutter, H.K.; Sims, A.; Manga, M.; Weir, J.J.; Ezzy, T.; White, P.A.; Horton, T.W.; Scott, D. (2012): *Hydrological Effects of the Mw7.1 Darfield (Canterbury) Earthquake, 4 September 2010, New Zealand.* New Zealand Journal of Geology and Geophysics, DOI: 10. 1080/00288306.2012.68474. Published 3 September 2012.

Earl P (1998): *Groundwater springs: a literature review of existing classification schemes and studies, and proposal for a Canterbury Spring Classification System*. Environment Canterbury Report U98/7. Griffiths, G 2011. Drivers of extreme daily rainfalls in New Zealand, Weather and Climate, 31, 24-49

Freeze, RA and Cherry, JA (1979): *Groundwater*. Published by Prentice Hall.

Griffiths, G (2013): *New Zealand six main centre extreme rainfall trends 1962-2011.* Weather and Climate, 33, 76---88

GMS (2017): *Groundwater Modelling System (version 10.2.6, 64-bit).* Software developed and supported by Aquaveo LLC (USA). (USA). Final build date 20 June 2017. Copyright 2017.

Lee, RL; Bradley, BA; Ghisetti, FG; Thomson, EM (2016): *Development of a 3D High-Resolution Velocity Model of the Canterbury, New Zealand Region.* Bulletin of the Seismological Society of America (submitted).

Morgan, M; Bidwell, V; Bright, J; McIndoe, I; Robb, C (2002): *Canterbury strategic water study.* Lincoln Environmental report No 4557/1. August 2002.

Niswonger, RG; Panday, S; Ibaraki, M (2011): *MODFLOW-NWT, A Newton formulation for MODFLOW-2005.* US Geological Survey Techniques and Methods 6-A37.

Quilter, PW; van Ballegooy, S; Russ, M. (2015): *The Effects of Sea Level Rise on Liquefaction Vulnerability.* 6th International Conference on Earthquake Geotechnical Engineering. Christchurch, New Zealand. 1-4 November 2015.

Rotzell, K and Fletcher, CH (2012): *Assessment of groundwater inundation as a consequence of sea-level rise. Nature Climate Change (Advance Online Publication)* www.nature.com/natureclimatechange

Rutter, HK (2010): *Impacts of the Christchurch earthquake on the Canterbury groundwater system.* Abstract, New Zealand Hydrological Society Conference, Dunedin, Dec 6-10, 2010.

Rutter, H; Cox, S; Weir, J; Palmer, K (2012): *Hydrological Responses to the Canterbury Earthquakes.* Korean Water Resources Association Conference, Jeongsun, South Korea, May 2012; pp 19-20.

Rutter, HK; Cox, S; Dudley Ward, HF; Weir, JJ (2016*). Aquifer permeability change caused by a near-field earthquake, Canterbury, New Zealand.* Water Resour. Res., 52, 8861–8878, doi:10.1002/2015WR018524.

SBR (2007): Ontwatering in stedelijk gebied (Dewatering in urban areas). SBR, Rotterdam. *In Dutch.*

Steinhage, F; Rutter, H; Cox, S (2014): *Surface water-groundwater interaction, lower Avon/Otakaro River, Christchurch, New Zealand.* Hydrological Society of New Zealand Conference, 2014.

Suggate RP (1958): *Late Quaternary deposits of the Christchurch metropolitan area*. New Zealand Journal of Geology and Geophysics 1: 103–122.

van Ballegooy, S; Cox, SC; Agnihotri, R; Reynolds, T; Thurlow, C; Rutter, HK; Scott, DM; Begg, JG; McCahon, I (2014): *Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake.* GNS Science Report 2013/01, 66 pages plus 8 appendices.

van Gaalen, JF; Kruse, S; Lafrenz, WB; Burroughs, SM (2013): *Predicting Water Table Response to Rainfall Events, Central Florida.* Groundwater 51, 350–362. doi:10.1111/j.1745-6584.2012.00970.x

Weeber JH (2008). *Christchurch groundwater protection: A hydrogeological basis for zone boundaries, Variation 6 to the Proposed Natural Resources Regional Plan*. Environment Canterbury. Report No.U08/21. ISBN 978-1-86937-802-8, 60 p. White PA 2007. 'Geological model of the Christchurch Formation and Springston Formation.' GNS Client report 2007/87 to Environment Canterbury. Environment Canterbury report U07/24. 99p.

Weir, JJ (2018): *Canterbury Groundwater Model 3. Model Documentation.* Prepared for MBIE Wheel of Water Research. Aqualinc report C1506611. 17 August 2018.

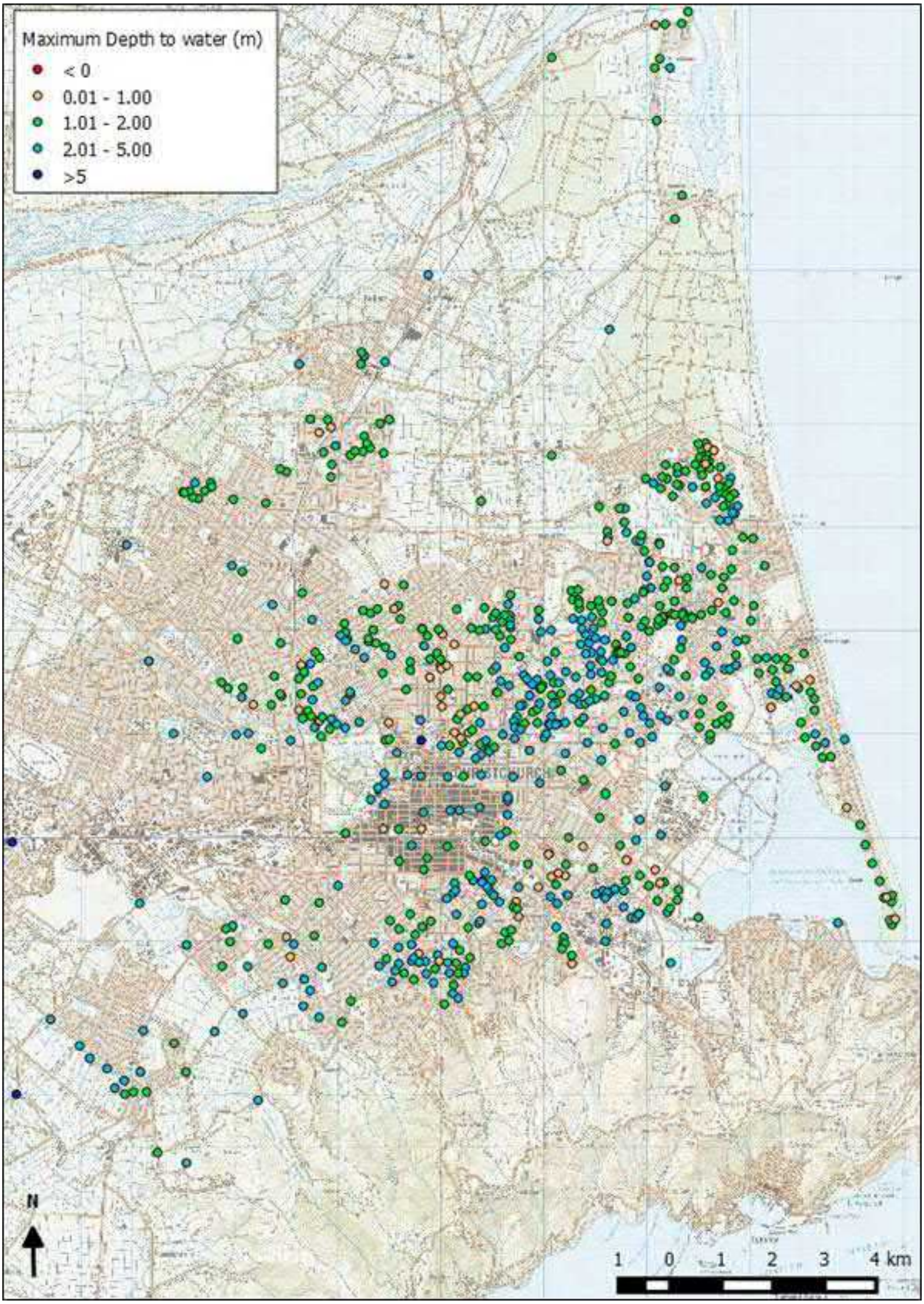
White PA (2009): *Avon River springs catchment, Christchurch City, New Zealand.* Australian Journal of Earth Sciences 56(1): 61-70.

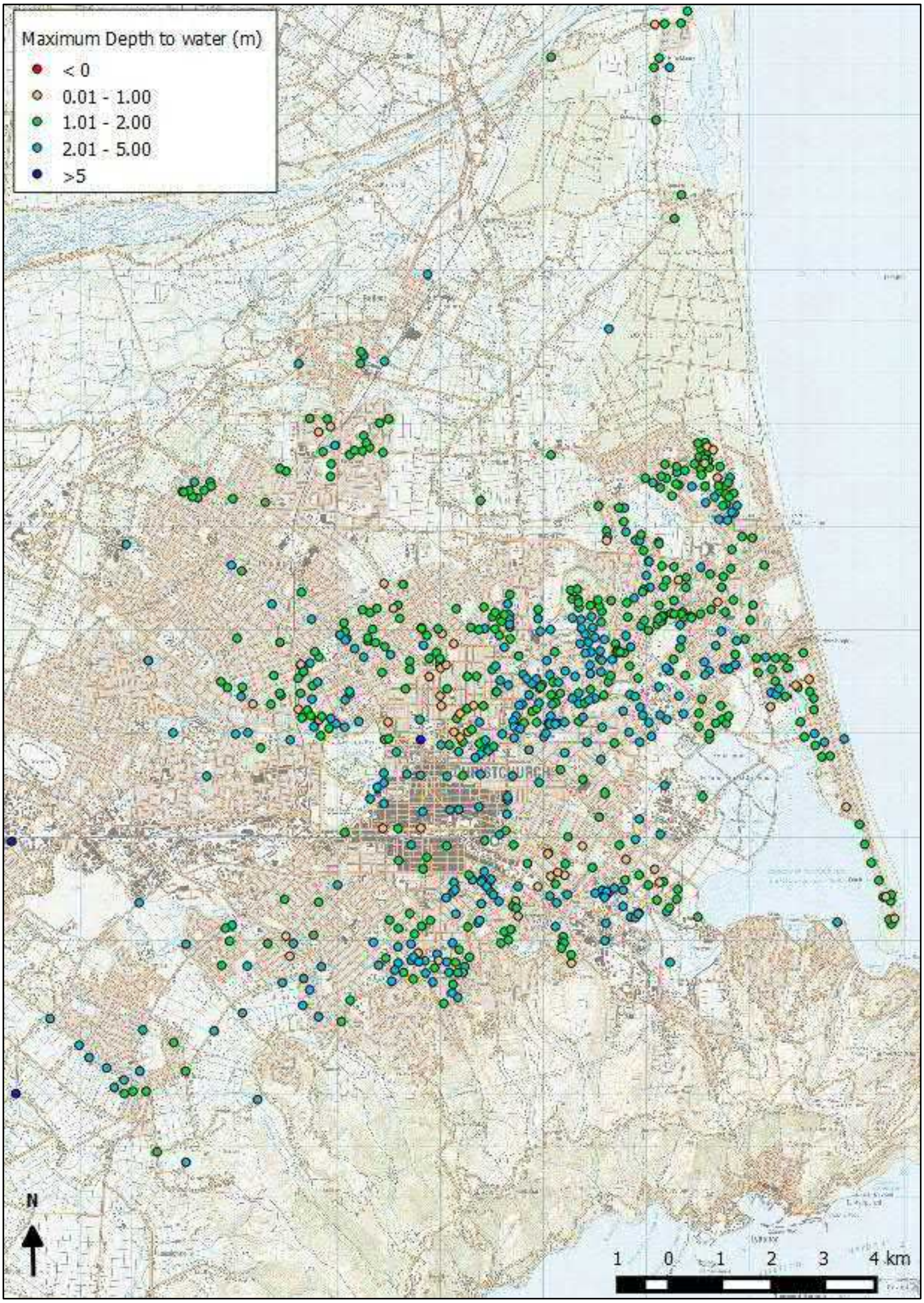
White PA; Goodrich K; Cave S; Minni, G (2007): *Waterways, swamps and vegetation of Christchurch in 1856 and baseflow discharge in Christchurch City streams.* GNS Client report 2007/103 to Environment Canterbury. Environment Canterbury report U07/39.

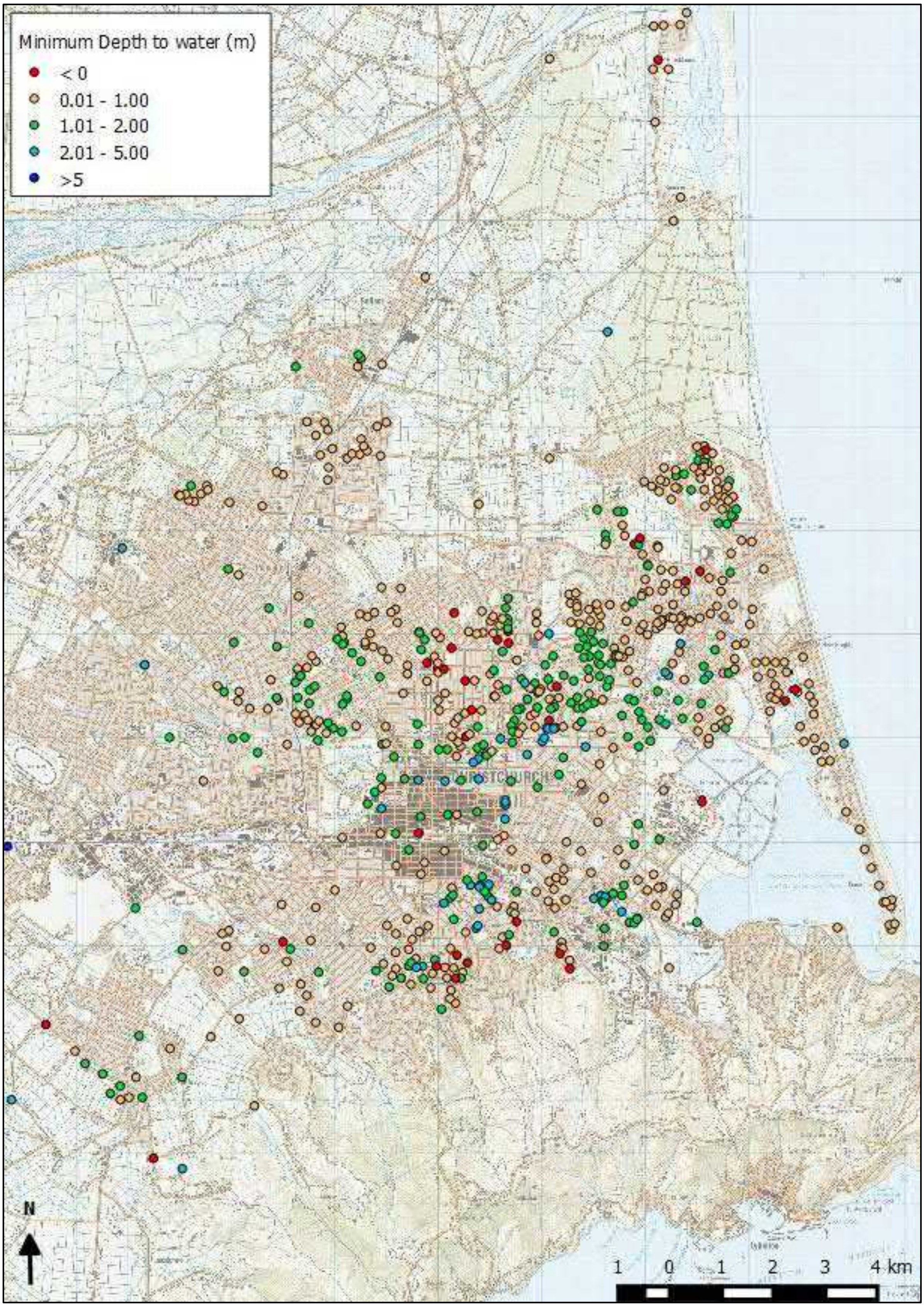
Youd, TL; Hansen, CM; Bartlett, S F (2002): *Revised multi-linear regression equations for prediction of lateral spread displacement.* J. Geotech. Geoenviron. Eng., 128 (12) 1007–1017.

Appendix A: Groundwater level plots

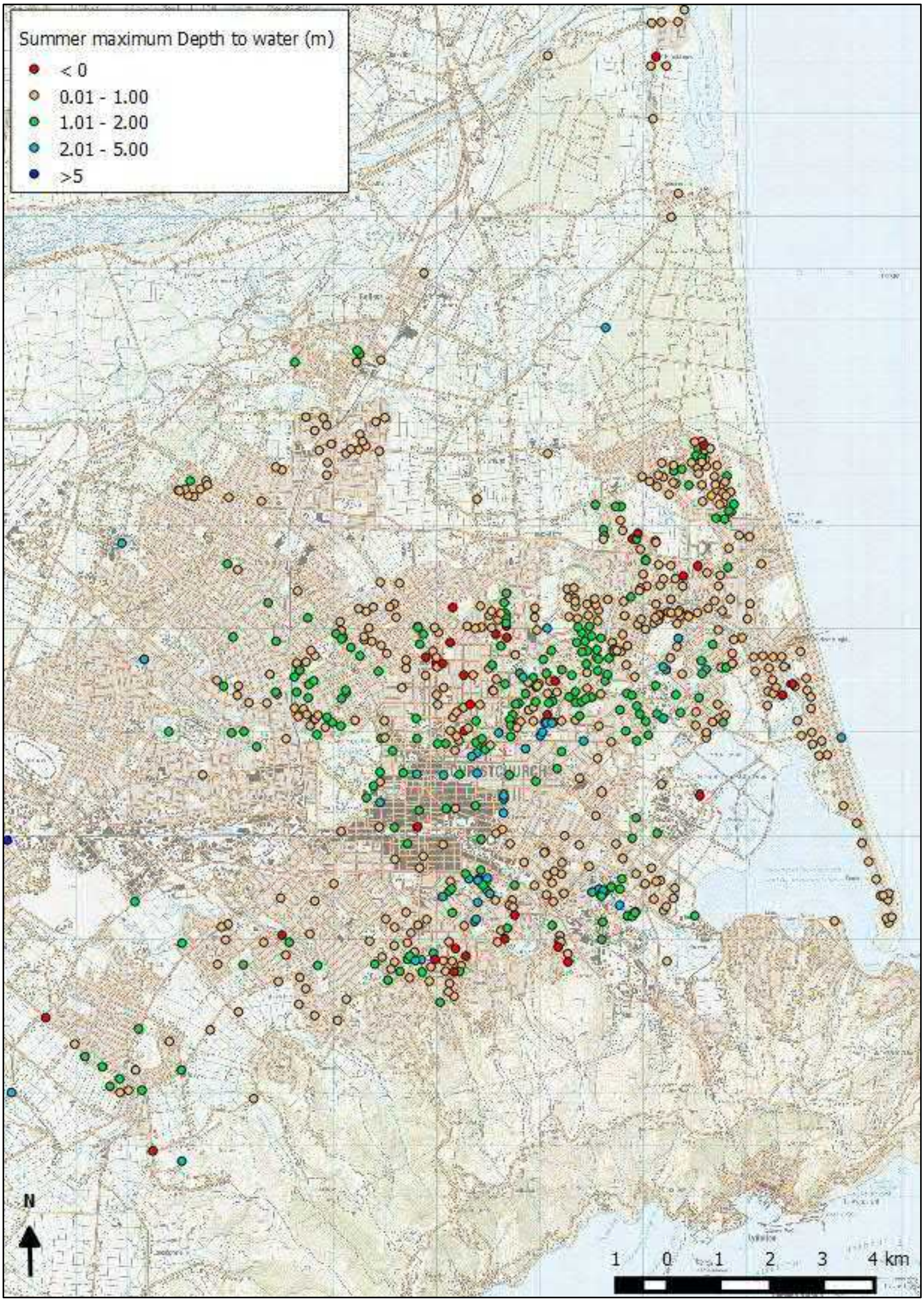
Groundwater data used to develop the following plots are described in Table 2. The plots show minimum and maximum depths to groundwater at the measurement points.

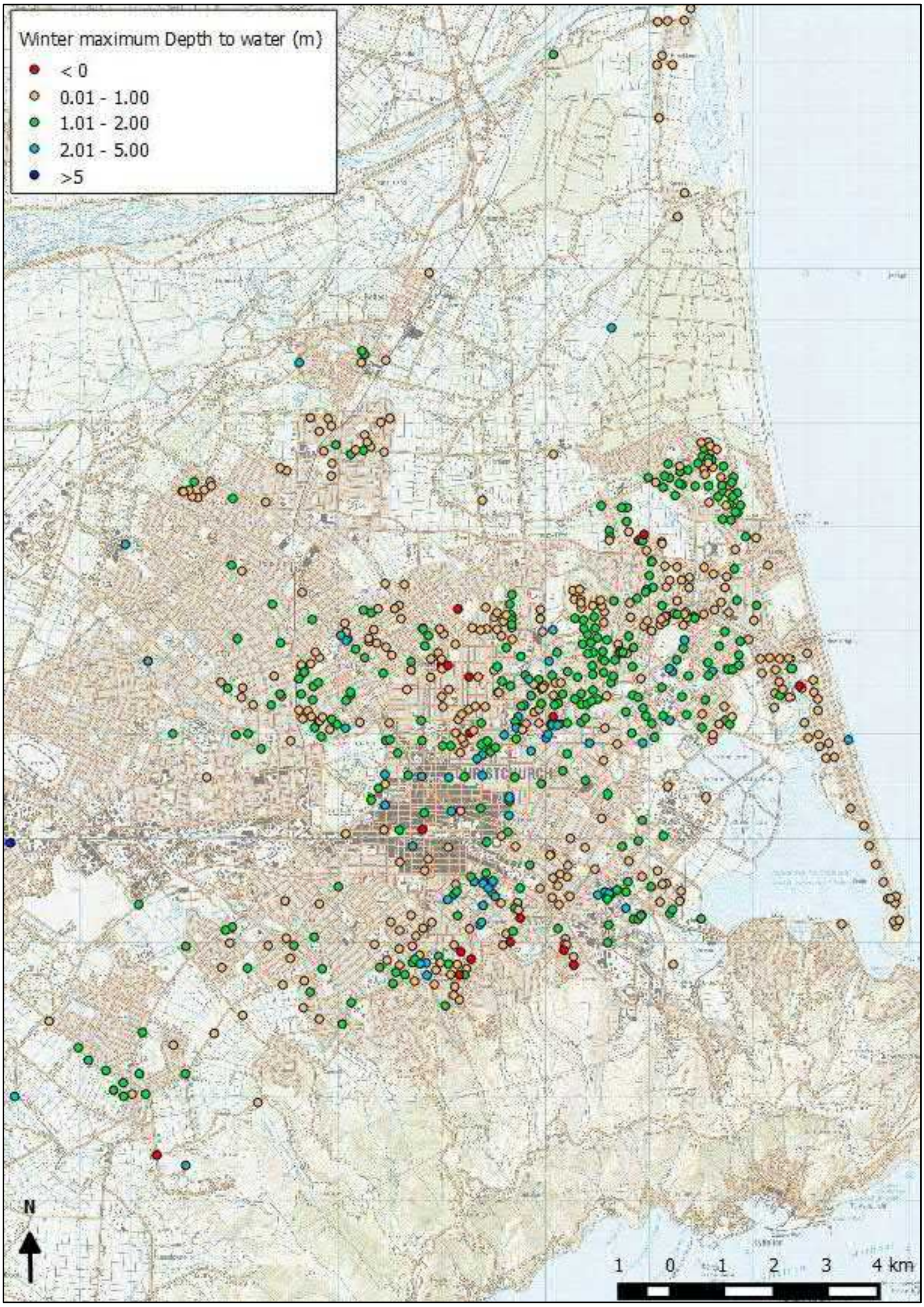

Maximum Depth to water (m)
< 0
0.01 - 1.00
1.01 - 2.00
2.01 - 5.00
>5
N
1 0 1 2 3 4 km


Maximum Depth to water (m)
< 0
0.01 - 1.00
1.01 - 2.00
2.01 - 5.00
>5
N
1 0 1 2 3 4 km



Minimum Depth to water (m)
< 0
0.01 - 1.00
1.01 - 2.00
2.01 - 5.00
>5
N
1 0 1 2 3 4 km


Summary maximum Depth to water (m)
< 0
0.01 - 1.00
1.01 - 2.00
2.01 - 5.00
>5
N
1 0 1 2 3 4 km


Winter maximum Depth to water (m)
< 0
0.01 - 1.00
1.01 - 2.00
2.01 - 5.00
>5
N
1 0 1 2 3 4 km

B.1 El Niño Southern Oscillation (ENSO)

ENSO is a climate characteristic related to the sea surface temperature in the eastern equatorial Pacific (commonly known as El Niño) and the atmospheric pressure difference across the equatorial Pacific (known as the Southern Oscillation). ENSO has been shown to relate to weather conditions throughout the world and has multi-month persistence that enables seasonal forecasting in some locations. The physical explanation for the variations are a subject of considerable research, with positive feedback of ocean-climate interactions playing a large part.

The strength of the El Niño, the Southern Oscillation, or a combination of the two may be measured in a variety of different ways. We have selected the Coupled ENSO Index (CEI) as our measure (Figure B.1) as it covers the time span that the data are available for, and combines the sea surface temperature and atmospheric pressure measurements that constitute the ENSO phenomena.

The variation in the CEI over time is shown in Figure B.1. For the CEI, a negative index indicates an El Niño event while a positive value indicates a La Niña event. The recent extreme El Niño years of 1982-83, 1997-98 and 2015-16 show as extreme low points with this index.

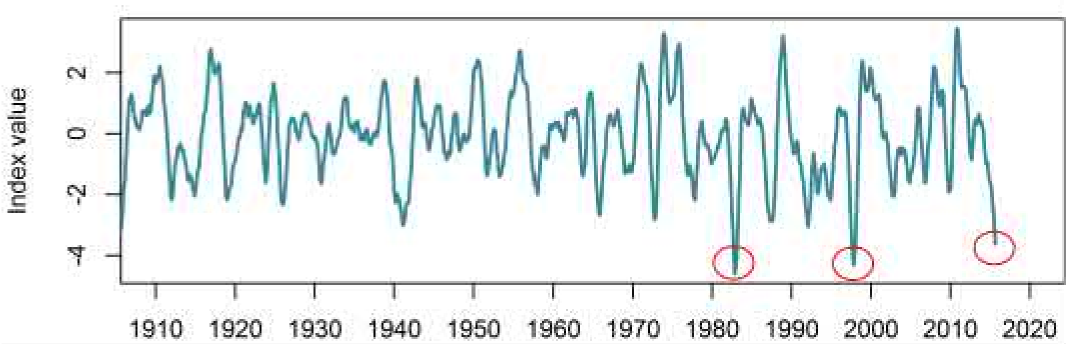


Figure B.1: ENSO variation represented by the Coupled ENSO Index (CEI).

B.2 Interdecadal Pacific Oscillation (IPO)

Pacific sea surface temperatures show variation on a multi-decadal timescale often referred to as the Interdecadal Pacific Oscillation (IPO). The multi-decadal variation has been observed in weather throughout the Pacific and in the strength of the ENSO oscillations. The physical explanation of the variation is not well understood. There are three different measures that may be used to describe this variation. It is common to consider these measures in terms of their “phase”, as in “the positive phase from the late 1970’s to early 2000’s”, rather than the actual values. A smoothed version of the three measures are shown in Figure B.2. Over the last century the measures are all positive from 1922 to 1944, negative from 1946 to 1977, positive from 1979 to 1998, and negative from 2000 to 2015.

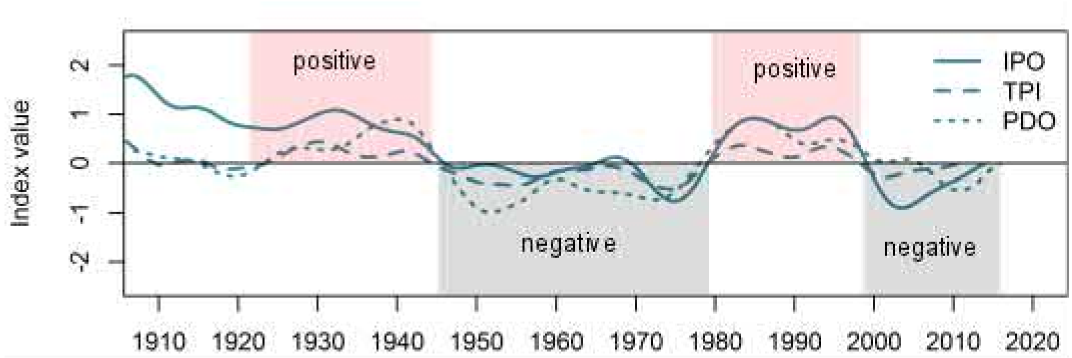


Figure B.2: 13 year filtered indices of Pacific sea surface temperature. IPO is the Interdecadal Pacific Oscillation index, TPI is the Tripole Index for the Interdecadal Pacific Oscillation, and PDO is the Pacific Decadal Oscillation index.

B.3 Southern Annular Mode (SAM)

The SAM is a description of the strength and position of the westerly winds around the mid-latitudes of the Southern Hemisphere. SAM is measured by the SAM Index. A positive SAM index indicates the westerly winds have moved closer to Antarctica. A negative SAM index indicates the westerly winds have moved closer to the equator.

Locally the SAM is expressed as the strength, frequency and location of the westerly winds across the South Island. The higher the SAM index, the weaker the westerly winds over the South Island.

The SAM index is shown in Figure B.3. SAM changes at a weekly timescale and can be used for short term forecasting. There is a long term trend in the SAM towards higher values indicating that climate change is leading to less frequent and weaker westerly winds over the South Island.

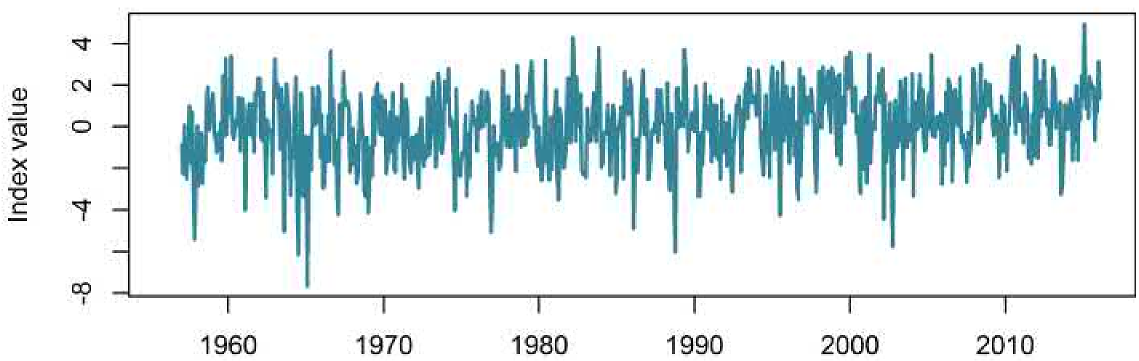


Figure B.3: Southern Annual Mode (SAM)

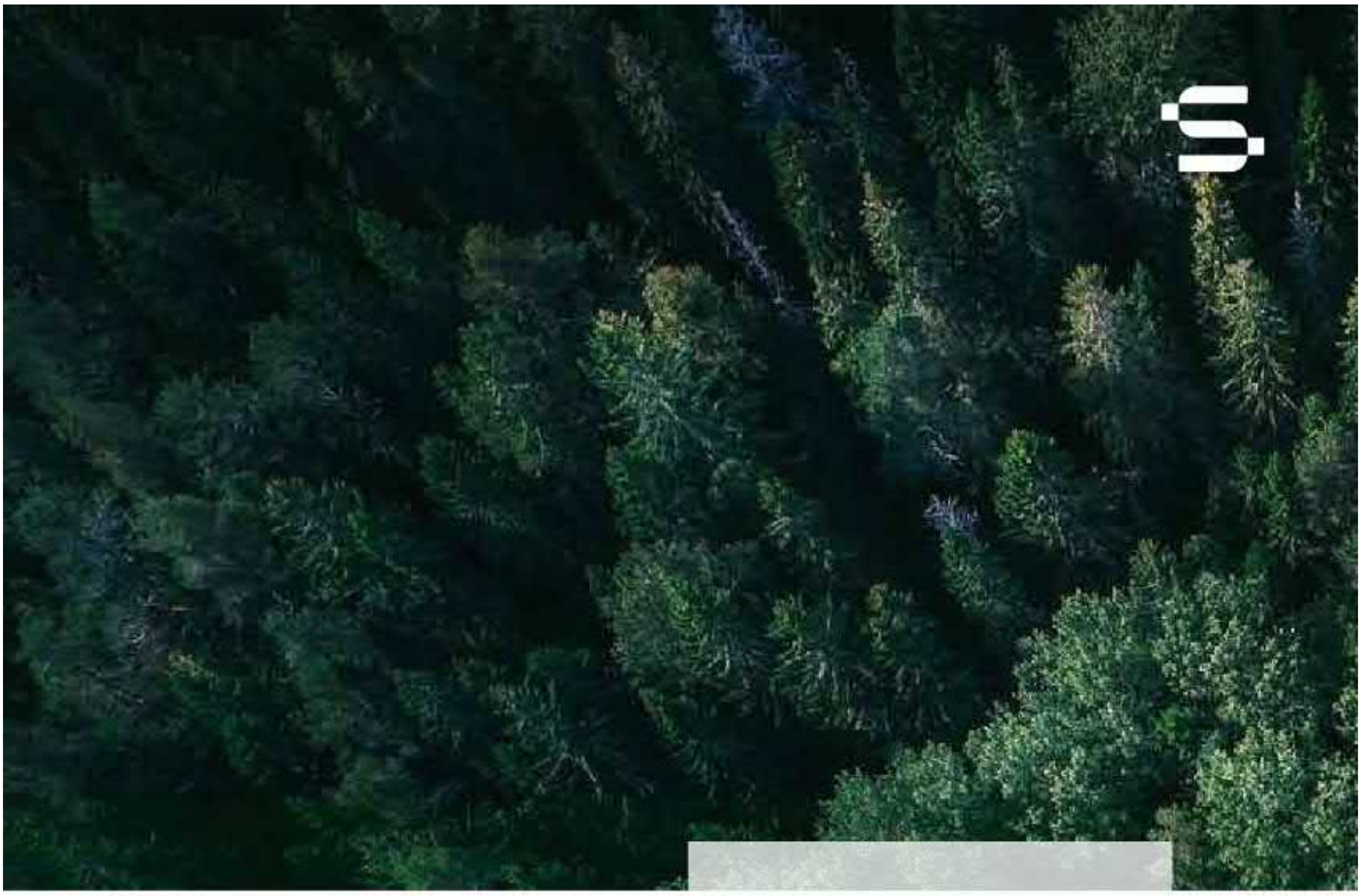
Appendix C: Summary of observations of long term earthquake impacts on shallow groundwater

Well numbers	2013 observations	2018 Observations
ABI, AWO, HLR	Persistent change to lower groundwater levels, with or without short-term (transient) fluctuation. Post_Earthquake 85th centilepercentile below pre-Darfield Earthquake 15th centilepercentile. Caused by a combination of both subsidence (decrease in ground/MP RL) and increased depth to water below MP. CLEARLY SIGNIFICANT EQ-induced lowering	HLR = Following the original reduction in water level post-earthquake, there appears to be a persistent change to shallower GW RL from 2014 onwards, with or without short term (transient) fluctuations. Median water level post-earthquake increased from 2.31 (2011 – 2012) to 2.39 m RL (2011-2017). Recent data showed a rapid GWL recovery from January 2017 to a peak of 3.5m RL in September 2017. This peak was short-lived and recent data show GWLs are around 2.4 to 2.6 m RL (Figure 30 of main report). Pre EQ Median = 3.002 m RL Post EQ Median (20/11/2012) = 2.310 m RL Post EQ Median (full data set) = 2.388 m RL ABI = no additional data Pre EQ Median (20/11/2012) = 0.667 m RL Post EQ Median = -0.023 AWO = There appears to be a persistent change to shallower GW RL in March 2013, with a period of stable water levels through to Feb 2017 when there was another shift to shallower water levels (Figure 31 of main report). Median GWL post-earthquake shifted from 1.042 to 1.347 m RL. Since January 2017, there was a very marked recovery and groundwater levels are currently over 2m m RL. With future data, we will be able to assess whether GWLs have returned to pre-earthquake levels, or whether this is temporary. Pre EQ Median = 2.087 m RL Post EQ Median (20/11/2012) = 1.042 m RL Post EQ Median (full data set) = 1.347 m RL
HGO	Persistent change to lower groundwater levels, with or without short-term (transient) fluctuation during earthquakes. Post-Darfield Earthquake median below pre-Darfield Earthquake 15th centilepercentile. Increased depth to water below MP despite uplift (increase in ground/MP/RL). POTENTIALLY SIGNIFICANT EQ-induced lowering	There has been a slight recovery in GWLS since 2011, with a marked response to recharge in early 2017, peaking in July 2017, but recessing again rapidly (Figure 32 of main report). GWLs are frequently below mean sea level, possibly due to the location adjacent to a tidal section of the Heathcote River. Pre EQ Median = 0.512 m RL Post EQ Median (20/11/2012) = 0.052 m RL Post EQ Median (full data set) = 0.072 m RL
ACR	Lowering of median groundwater due to subsidence (ground/MP elevation change). Post-Darfield Earthquake 85th centilepercentile below pre-Darfield Earthquake 15th centilepercentile. Depth to water appears constant.	The trend in lower GW levels post-earthquake has continued, but appears to be a linear reduction in GWLs over a long time period, and possibly not related to the earthquakes (Figure 33 of main report). The post-earthquake median GW level has reduced with the incorporation of the most recent data. Pre EQ Median = 5.467 m RL Post EQ Median (20/11/2012) = 5.402 m RL Post EQ Median (full data set) = 5.357 m RL

Well numbers	2013 observations	2018 Observations
	CLEARLY SIGNIFICANT EQ-induced lowering	
SDA	Apparent lowering of median groundwater level due to lowering of MP RL. Well card says GL=0, but upstand now visible above ground. Post-Darfield Earthquake median below pre-Darfield Earthquake 15th centilepercentile. Deoth to water appears constant. POTENTIALLY SIGNIFICANT EQ-induced lowering	There appears to have been a shift back to pre earthquake GW level RL in mid to late 2016 followed by a continual rise in water levels through 2017 and early 2018 (Figure 34 of main report). Offset of 0.5m in May 2017 looks suspicious and may be an offset in measurement point. The continual late rise in levels could alternatively be associated with the wet winter of 2017. Pre EQ Median = 0.667 m RL Post EQ Median (20/11/2012) = 0.530 m RL Post EQ Median (full data set) = 0.617 m RL
M35/0724	Post-Darfield Earthquake median groundwater levels higher than pre-earthquake median. MP/Ground elevation decreased relative to pre-earthquake. Particularly high during winter 2012 (Kaiapoi region). Gradual rise unrelated to earthquakes? CLEARLY SIGNIFICANT rise	There does not appear to be a significant shift in water levels post-earthquake other than short term water level fluctuations. Median GWL post-earthquake has decreased slightly from 0.21 to 0.20 m RL with the addition of the most recent data set. Pre EQ Median = 0.1 m RL Post EQ Median (20/11/2012) = 0.21 m RL Post EQ Median (full data set) = 0.20 m RL
M36/4741	Lowering of median groundwater level despite little change in ground/MP RL. Post-Darfield Earthquake 85th centilepercentile below pre-Darfield Earthquake 15th centilepercentile. Caused by increased depth of groundwater. CLEARLY SIGNIFICANT fall	There does not appear to be a significant shift in water levels post-earthquake other than short term water level fluctuations and a reduction in water levels between 2015 and 2016 which are likely to be associated with a period of drought. Median GWL post-earthquake has shifted from 10.94 m to 10.88 m with the addition of the most recent data set. Pre EQ Median = 10.95 m RL Post EQ Median (20/11/2012) = 10.94 m RL Post EQ Median (full data set) = 10.88 m RL
M35/8968	Lowering of median groundwater level due to both change in ground/MP RL and increased depth to groundwater. Site near Waimakariri River where river channel position may affect local groundwater recharge. CLEARLY SIGNIFICANT fall	There does not appear to be a significant shift in water levels post-earthquake other than short term water level fluctuations (Figure 35). Median GWL post-earthquake has shifted from 43.42 m to 43.30 m with the addition of the most recent data set. Pre EQ Median = 44.15 m RL Post EQ Median (20/11/2012) = 43.42 m RL Post EQ Median (full data set) = 43.30 m RL
M35/0948, M35/3614, M35/5436, M35/5560	Lowering median groundwater despite little change in ground/MP RL. Post-Darfield Earthquake median below pre-Darfield Earthquake 15th centilepercentile. Increased depth to groundwater might be explained by irrigation practices. POTENTIALLY SIGNIFICANT lowering	M35/0948 = There appears to be a gradual reduction in water levels post-earthquake with or without minor seasonal fluctuations. A reduction in post-earthquake median GWL has occurred with the inclusion of the most recent data from 37.64 m to 37.56 m RL. Pre EQ Median = 37.86 m RL Post EQ Median (20/11/2012) = 37.64 m RL Post EQ Median (full data set) = 37.56 m RL M35/3614 = There appears to be a shift in GWL post-earthquake with a reduction in water levels reaching a low point in May 2016. Water levels then recovered back to the previous post-earthquake median. The reduction in water levels in 2016 may be associated with very dry conditions experienced at the time. An overall reduction in median

Well numbers	2013 observations	2018 Observations
		water from 20.87 m to 20.49 m RL has occurred when incorporating all post-earthquake data. Pre EQ Median = 21.28 m RL Post EQ Median (19/12/2012) = 20.87 m RL Post EQ Median (full data set) = 20.49 m RL M35/5436 = The initial post-earthquake median was lower than the pre earthquake median. This reduction in levels appears to have been temporary as the levels have since returned to those pre earthquake. It should also be noted that areduction in water levels occurred between 2015 and 2016 associated with a period of drought. Post-earthquake median has increased from 13.67 m to 13.75 m RL after incorporation all the latest post-earthquake data. Pre EQ Median = 13.83 m RL Post EQ Median (10/12/2012) = 13.67 m RL Post EQ Median (full data set) = 13.75 m RL M35/5560 = There appears to be a gradual reduction in groundwater level post-earthquake with seasonal variability. Between 2014 and 2016 the seasonal variability was not as marked as other years. This may have been associated with an extended period of limited precipitation. Post-earthquake median groundwater level has reduced 13.09 m to 12.86 m RL when the most recent data are incorporated. Pre EQ Median = 13.23 m RL Post EQ Median (20/11/2012) = 13.09 m RL Post EQ Median (full data set) = 12.86 m RL
NDW	Rise of median water table despite little change in ground level/MP. Post-Darfield Earthquake median above pre-Darfield Earthquake 85th centilepercentile. Decreased depth to groundwater POTENTIALLY SIGNIFICANT rise	A shift back to approximately pre earthquake levels occurred between 2014 and 2016 which may be due to periods of low precipitation/drought. There was then a shift back to the original post-earthquake median in 2017 and early 2018. Pre EQ Median = 13.557 m RL Post EQ Median (20/11/2012) = 13.777 m RL Post EQ Median (full data set) = 13.727 m RL
ARC, SFB, M36/5384, M36/5385, (see also NK2, ABI, AWO, HGO, HLR, SDA	Short term transient fluctuations ('spikes') then return to pre-earthquake elevation and variability Transient EQ-induced	
AAY, AP2, BIN, HCX, HCY, HFI, HHL, HHM, HHN, HSH, M35/0601, M35/1079, M35/1080, M35/1110, M35/1111, M35/1156, M35/1691, M35/1878, M35/6507, M35/8969, M36/0142, M36/0202, M36/2452, NHG, SBE, SF1	No statistically noticeable change – no short-term fluctuations, no longer term departures in water table elevation, no changes in variability. NONE	

Appendix D: Seequent Report



SEEQUENT

Aqualinc Research Ltd.

Water table reliability analysis

19th November 2019

Authors: Thomas D. Krom & Carrie Nicholls

Reviewer: Ignacio Torresi

Executive Summary

Seequent were approached by Aqualinc Research Ltd (Aqualinc) initially in 2017 for the development of a water table exceedance map for Christchurch City Council (CCC). The purpose of this update to the median water table is to include the drain data made available.

Water level data from observation bores and surface water features has been analysed using geostatistical methods. These analyses were used in the development of the expected water table for Christchurch. Furthermore, conditional simulations were undertaken to determine the cumulative distributions for the expected water table across the city. These were used to map out the 15% and 85% confidence interval surfaces.

The analysis of the data as well as the estimation and simulation process have shown that the system is very "noisy" and that there is in general a great deal of uncertainty for water levels. The high nugget effect show that the expected water table has up to a 20 to 30 cm uncertainty at the observation points (autocorrelation). This observation of high uncertainty is reinforced by the results of the conditional simulation. The conditional simulations have highlighted that the uncertainty increases rapidly with relatively short distance from the data (<300m).

The consequence is that in the area with low sample density the water table is poorly defined, and furthermore the uncertainty "envelope" thicken rapidly away from observations.

A consequence is that in areas where significant development is to occur, one should instigate a monitoring plan that has a relatively fine grid. Potentially, one could develop monitoring plans where comprehensive sampling over a short period, supports a more regular sampling at a smaller number of locations.

Recommendations to reduce variance at the 3 study or focus areas are:

- Flockton: sampling spacing should be on the order of 200 x 200m minimum.
- Southshore: one well inserted to reduce the spacing to 500m in the north.
- St. Johns: one to two wells inserted in northern most tip.

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1. Introduction

Seequent was initially approached by Helen Rutter of Aqualinc Research Limited (ARL) for assistance in the development of a water table exceedance map for Christchurch City Council (CCC) in February 2017. The scope of the works at that point was to investigate the spatial reliability of the interpolated water table for the median expected surface from the data provided. The data comprised of 778 wells and a rivers and coastal dataset.

The work was repeated at the request of ARL for the 85 percentile surface, using the dataset provided and included additional data from drains. The purpose of including the drain data was for areas of particular interest in the Flockton basin and St. Johns.

This update to the median surface includes the drain data as it was not used in the original study and would be more comparable with the 85 percentile surface.

2. Data

2.1. Database

A database was provided of 778 wells with and a rivers and coastal dataset. The wells were provided as the Median Depth to Water Table measurement, whereas the river and coastal data was provided as water elevation. The well data was converted to the water table elevation for consistency.

ARL carried out initial data analysis; they provided statistical output that was used in the modelling of the groundwater table.

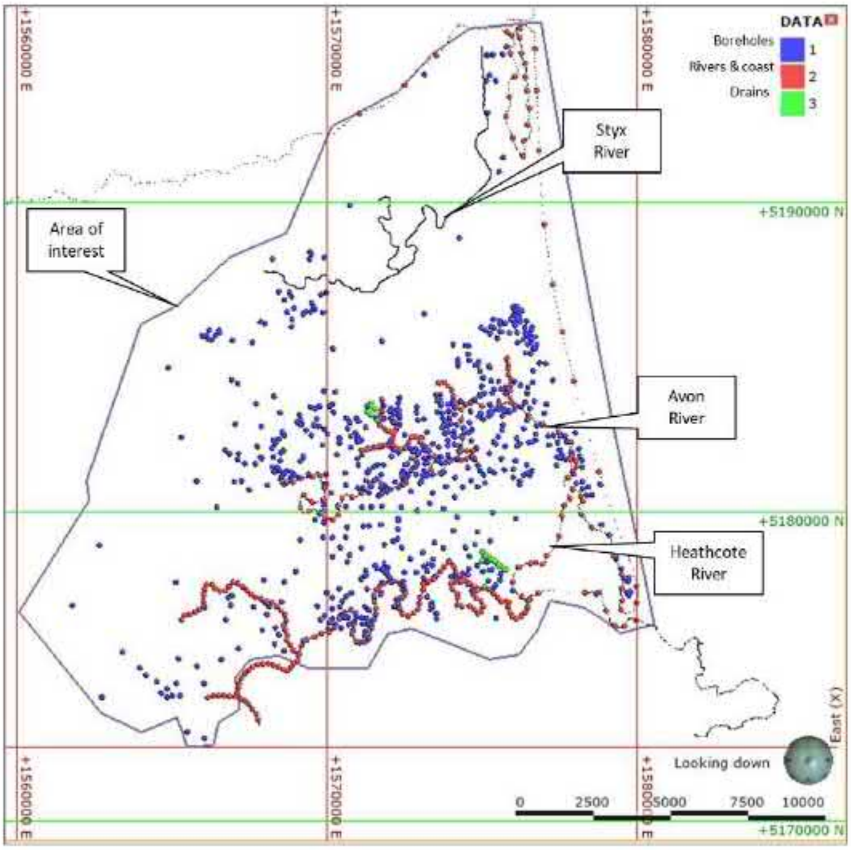


Figure 1 Map showing the location of the area of interest (outlined), and final dataset used where the rivers and coast were down sampled and Styx river data removed. The dataset includes well data locations (blue), rivers and coast (red) and drains (green).

2.1.1. Adjustments/exclusions

Well ID	Action	Reason
M35/4302	Excluded	Negative median depth to water table
M36/4741	Excluded	Negative median depth to water table
BH320	Corrected ground level elevation	Incorrect ground level elevation; was 0, corrected to 5.33m amsl

Table 1 Database corrections

The elevation data for the rivers Avon and Heathcote were filtered (down-sampled) to reduce the number of data points. This was to reduce potential bias in the estimation, since the data density was far higher spatially for surface water features than the groundwater monitoring network. The Styx river data was also removed after initial investigation in the estimation process – see section 4.2.

3. Exploratory Data Analysis

3.1. Basic statistics

Figure 2 shows a histogram of the water table elevation data as well as minimum, maximum, variance and mean for these information. This figure is for the data after it has been filtered along the rivers. As typical for environmental data it shows a log-normal type distribution. It is also interesting that there are significant number of data below mean sea level. Figure 3 shows a map of the water level data.

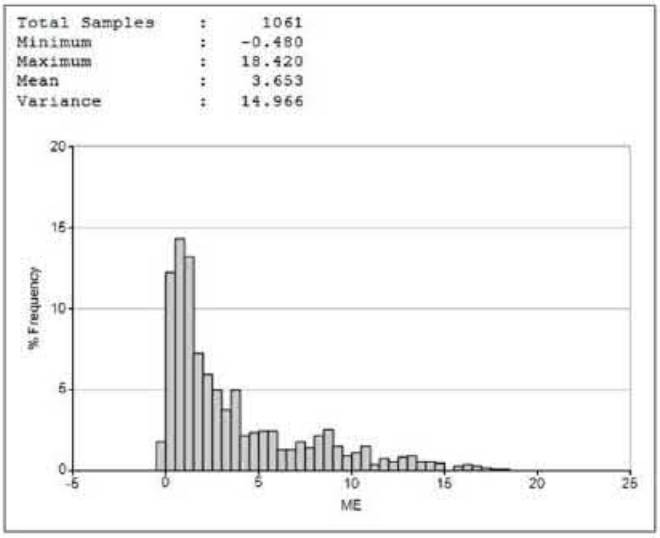


Figure 2. Histogram of the water table elevation data, as well as the range, mean and variance.

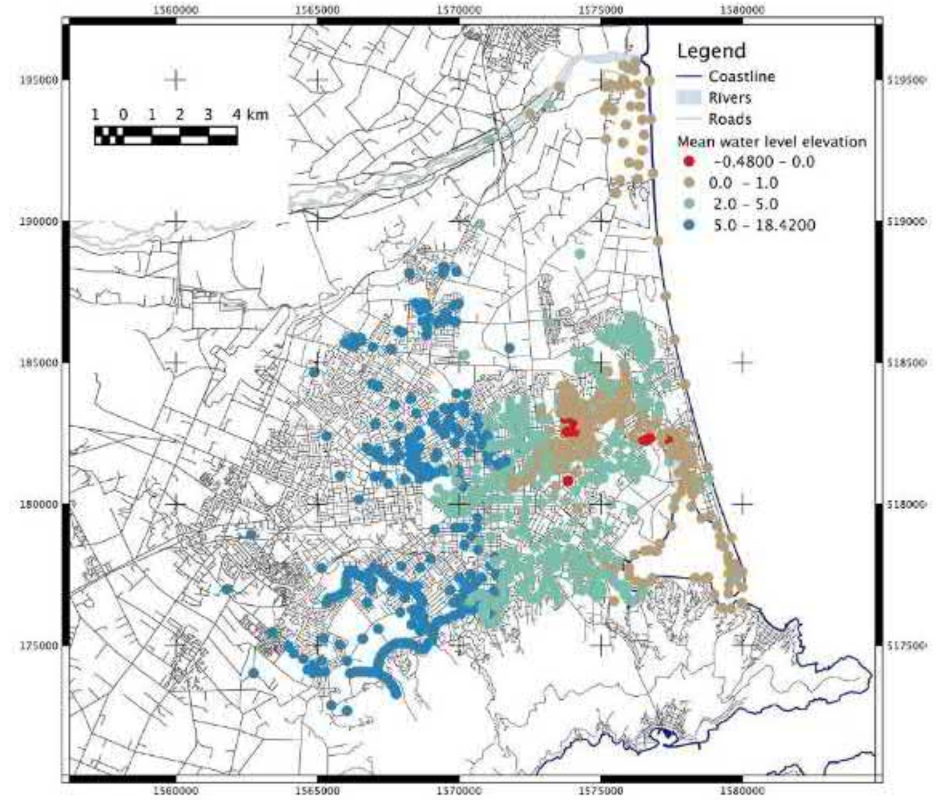


Figure 3 Map of the data showing water level elevation

4. Estimation of water table

4.1. Introduction

Analysis of the data shows the water table elevation is broadly higher to the west and reduces down to approximately sea level at the eastern coastline. This is the direction of shortest continuity and perpendicular to this, approximately north-south the continuity is longest.

With the available data, the area of interest can be divided into two areas. The well data in the east shows a flatter water table (smaller overall gradient) with significant local variability, whereas the western section has a steeper E-W gradient.

The variography also gives further insight into the local variability. Lags, the distance between pairs of samples to calculate the variability in the variogram calculation was based on the sample spacing. The well spacing does not follow a grid, though within the central zone between the Avon and Heathcote rivers, the spacing of the wells are around 200m. The variography was therefore carried out using lags of 200m, in the two datasets divided into the east and west. As expected the variography indicated that the continuity is lower in the east-west direction than the north-south direction. This is due to the general direction of groundwater flow towards the coast. The western part of the area displays longer ranges, hence higher continuity than the eastern model – supporting the observations.

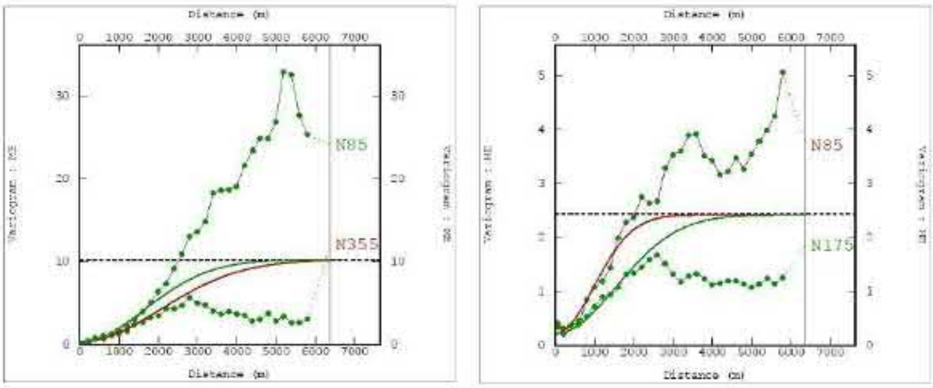
The local variability in the east is clear from the proportionally larger nugget effect as modelled from the variogram (Figure 4). The nugget effect is the inherent variability at very short distances. It cannot be measured directly but it is inferred by modelling the experimental variogram points where it crosses the axis at 0m. The higher the nugget effect, the higher the local variability. Based on these observations the dataset was divided into two areas for the estimation.

Exponential variogram models were used to fit the data and the models are summarised in the table below.

Area	C_0	C_1	Ranges (m)	
			Major (N-S)	Minor (E-W)
West	0.31 (3%)	9.90	5 029	4 052
East	0.22 (10%)	2.2	3 800	2 400

Table 2. Water table elevation variogram models, C_0 is the nugget and C_1 is the sill (total variance).

The variogram models show a nugget effect which is greater to the east (10%) than to the west (3%). A nugget is a representation of the uncertainty or variation close to the point of measurement.



(a) Water Elevation west variogram model

(b) Water Elevation east variogram model

Figure 4. Water table elevation variograms, note the vertical scale difference.

In order to produce a seamless as possible transition between the east and west zones, a soft boundary (data overlap) was used during the estimation process.

4.2. Estimation

The estimation of the mean (expected) water table (ground water elevation) was undertaken by Ordinary Kriging into block sizes of 200 x 200 m. The discretisation points used were 7 x 7. Estimates are calculated for each discretisation point in the block and then averaged, using a high number ensures a better representation of the block volume. The east and west were estimated separately with a soft boundary on the sample selection. In reality the boundary does not exist that was used to separate the data for the variogram (continuity) models. It was therefore necessary to expand the sample selection beyond the boundary in order to smooth the transition between the two models when joining to create the water table surface. It was found that a soft boundary of 1500m was adequate.

Investigations indicated problems in the Styx river area where the well and river data were in conflict; the river data is significantly lower than ground water levels. Therefore, the river data from the Styx were excluded from the estimate.

Various block sizes for the estimate were investigated. Block sizes smaller than the data spacing run the risk of having a high kriging variance and subsequent low confidence in the local estimate in poorly supported areas. Thus, block sizes of 50x50m and to a lesser extent 100x100m resulted in striations in the model that were not desirable. Using a block size of 200x200m, approximately the mean well spacing in the central area, provided an adequately smoothed surface.

In the east, it was found that a second search volume (search distances x 2) was necessary to improve the coverage of the kriged estimates, without which would have led to gaps (unestimated blocks or cells) in the kriged estimates. The reason is local data paucity, that is insufficient number of data within the search radius means that no estimate is determined.

The following parameters were used in the estimation:

Area	Search radii (m)		No. samples		2nd search volume
	North-south	**East-West**	**Min**	**Max**	
East	3 420	2 160	2	6	Yes: x2
West	4 526	3 646	2	6	No

Table 3. Search parameters for kriged water table

4.3. Estimation validation

The model validation process involves visual and statistical checks and slice (swath) plots. Highlighted in the figure below, a lack of data has led to kriging artefacts in the Styx river area (Figure 5). This results in an area of low confidence in the estimated model surface. Overall, Figures 5 and 6 shows that the estimated water table correlates reasonably well with the data. The higher degree of north-south continuity is clearly visible in the west compared to the east.

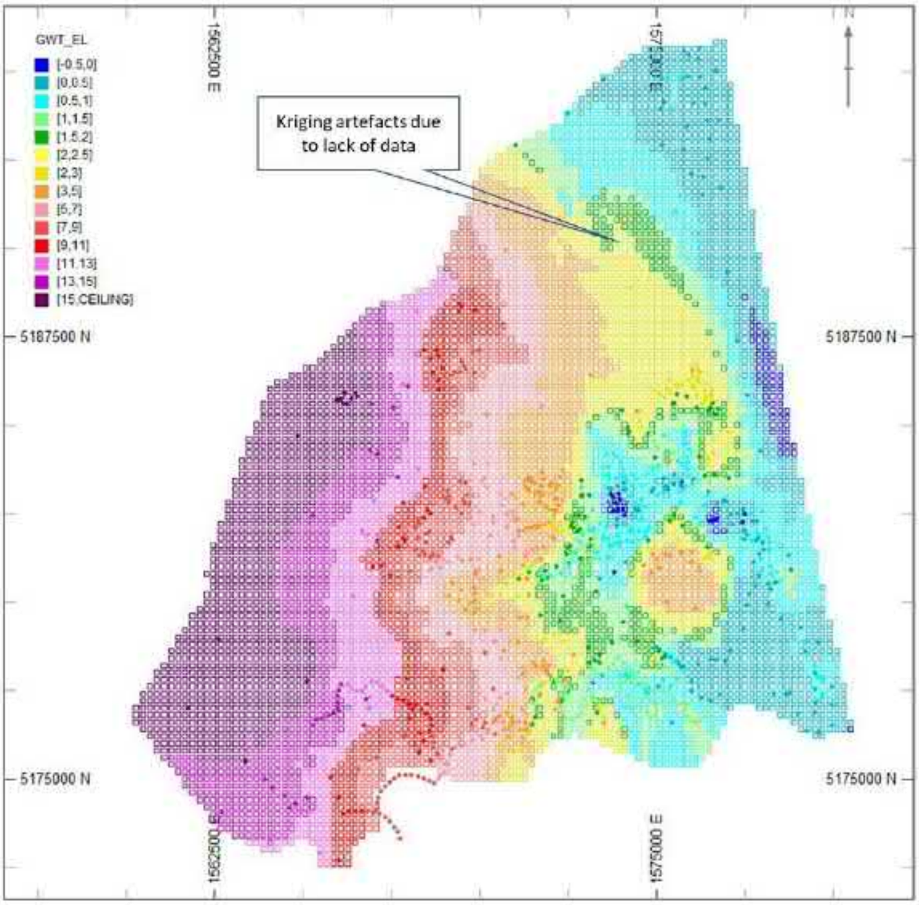


Figure 5 Validation of water table

Difference (residual) is defined as $(x_o - \hat{x})$, where the observation is x_o and the estimate is $\hat{x}$. Figure 6 shows PDF and CDF for the residuals, and these are symmetric (not skewed) and centred around zero (no bias). Figure 7 shows a map of the residuals and this seems to indicate that there is no major regional bias. However, a section of the Heathcote river is underestimated while the surrounding well data is over estimated.

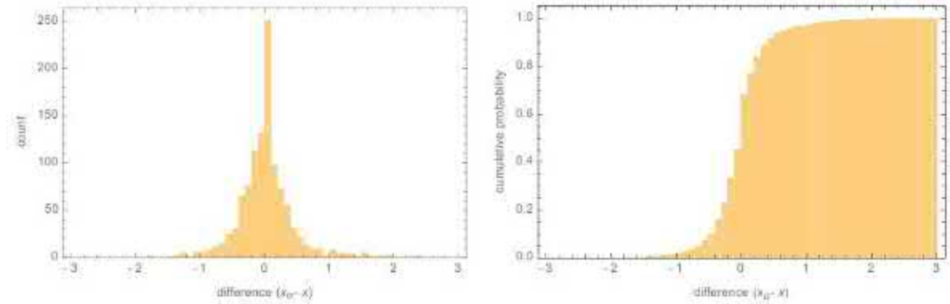


Figure 6. Histogram and cumulative histogram for the residuals between the gridded expected water table ($\hat{x}$) and the median observations (x_o).

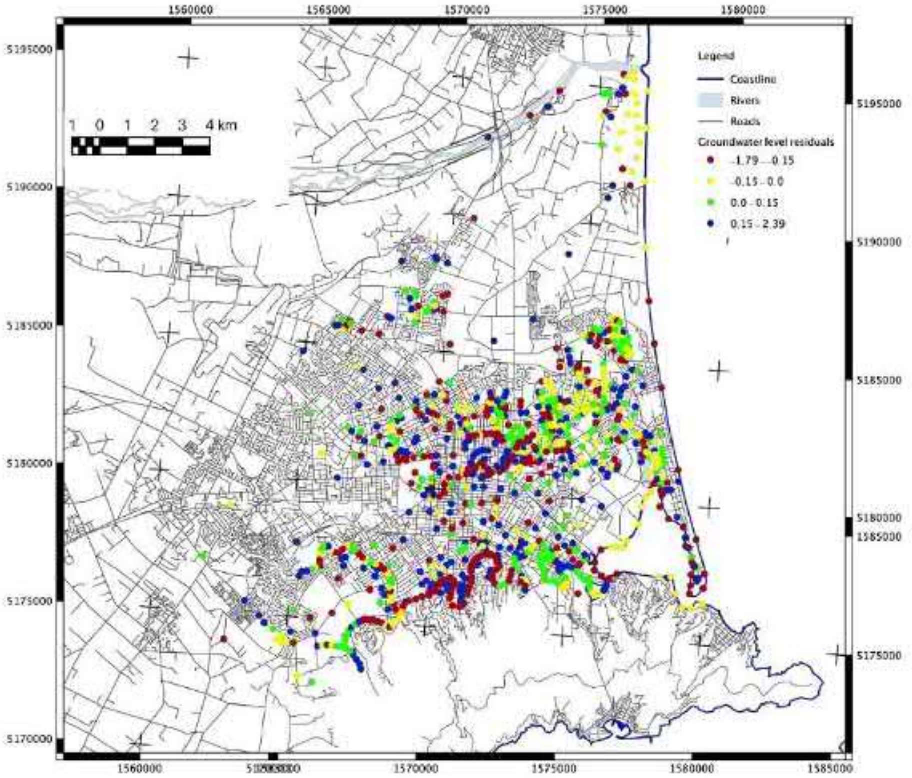


Figure 7 Map of residuals scaled by size and colour

The highest degree of continuity is along the north-south direction, therefore slice plots along the easting provide the most meaningful comparisons. In the figure below, it can be seen that the samples (S_MEAN) correlate well with the block means (M_MEAN). In the far west, the area has a low sample of numbers (<10 per slice), and in this area the correlation is not as good.

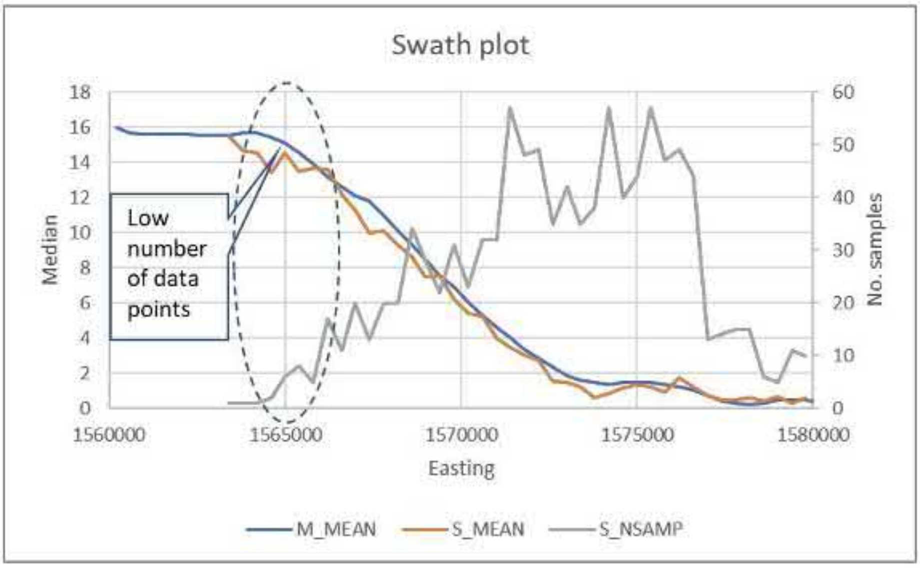


Figure 8. Easting slice plot for the sample (S_MEAN) and model (M_MEAN) means and no. of samples (S_NSAMP).

5. Conditional Simulation

5.1. Introduction

Conditional simulation is a process to estimate a surface that honors the spatial variability (variogram) seen in the data, and that also honors the data (within the accuracy of the nugget). Kriging (and other estimation techniques) do not reproduce the variogram.

The majority of steps for the conditional simulation were run in Datamine[1], with the variography carried out in Isatis[2]. The conditional simulations (Sequential Gaussian) were run in Datamine which utilises GSLIB[3] code (Geostatistical Software Library). Simulations were carried out in the same way as the estimation in terms of an east-west split domains (with a soft boundary). Ultimately it was decided the best approach was the conditional simulations on the dataset as a whole due to the differences in the variance between the two models. This allowed an assessment of the risk in the form of the variance in a coherent manner.

[1] Datamine; Datamine Software: http://www.dataminesoftware.com

[2] Isatis, Geovariances 2017: http://www.geovariances.com/en/software/isatis-geostatistics-software/

[3] Deutsch, C.V. and A.G. Journel (1992). GSLIB: Geostatistical Software Library and User's Guide. Oxford University Press.

5.2. Methodology

The steps undertaken in the conditional simulation process are as follows:

1. Normal score transformation of the data to normal space
2. Model the variogram
3. Conditional simulations
4. Back transform the conditional simulations from normal space
5. Post-processing the simulations results over each block in order to generate the statistics (cumulative distribution functions and moments) for each block.
6. Validate the results

The normal score transformation was carried out in Datamine. Table 4 and Figure 9 below are the summary statistics and histograms respectively of the raw and transformed data.

Description	Raw	Normal score
Total no. samples	1 061	1 061
Minimum	-0.48	-3.307
Maximum	18.42	3.307
Mean	3.65	0.0
Variance	14.97	0.999
Std Deviation	3.87	0.999

Table 4. Summary statistics for the input data.

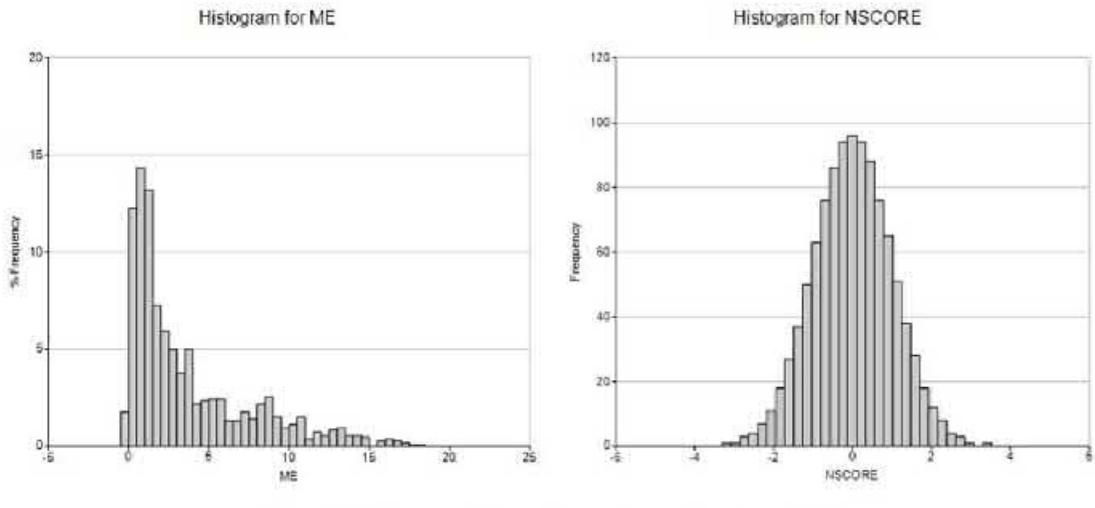


Figure 9. Histograms of raw and normal score transformed data

The variography was modelled separately for the east and west domains as was done for the kriging estimate. The initial approach was to do the simulations separately on each domain but after much consideration the conditional simulations were run on the whole dataset. For this the variogram modelled for the east zone was used (below), as the case studies and the majority of the data is in this area. The variogram model on the transformed data shows a similar nugget effect to the raw data at 10%.

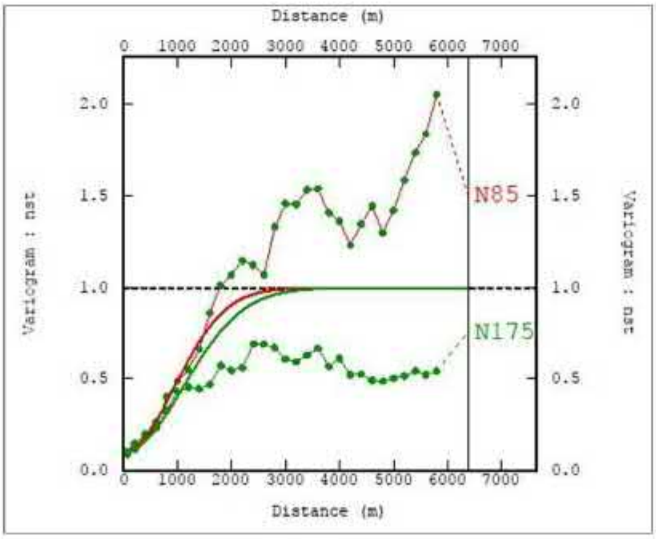


Figure 10. Variogram model on transformed data – east domain

C_0	C_1	Ranges (m)	
		Major (N-S)	Minor (E-W)
0.1	0.9	2 700	2 300

Table 5. East variogram model

The simulations used the parent cell size of 200 x 200m which were divided into 5 in each direction, therefore the points were spaced at 40m. Ordinary kriging was used as the kriging method and a search strategy of where the data are relocated to grid nodes and a spiral search is used. The search distances used were 3 100m along the major axis and 3 000m for the minor axis. 100 simulations were found to be adequate for the mean and variance to stabilise.

The simulations were back-transformed and selected simulations were checked that they honoured the original data. Both the histograms and variograms reasonably replicate the original raw data input. Examples of selected simulations of the histograms and variograms are in the figures below:

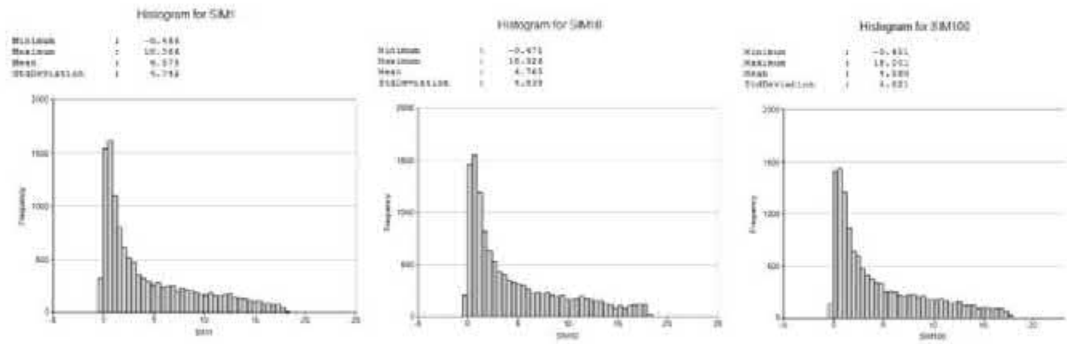


Figure 11. Histograms of 3 randomly selected back-transformed simulations

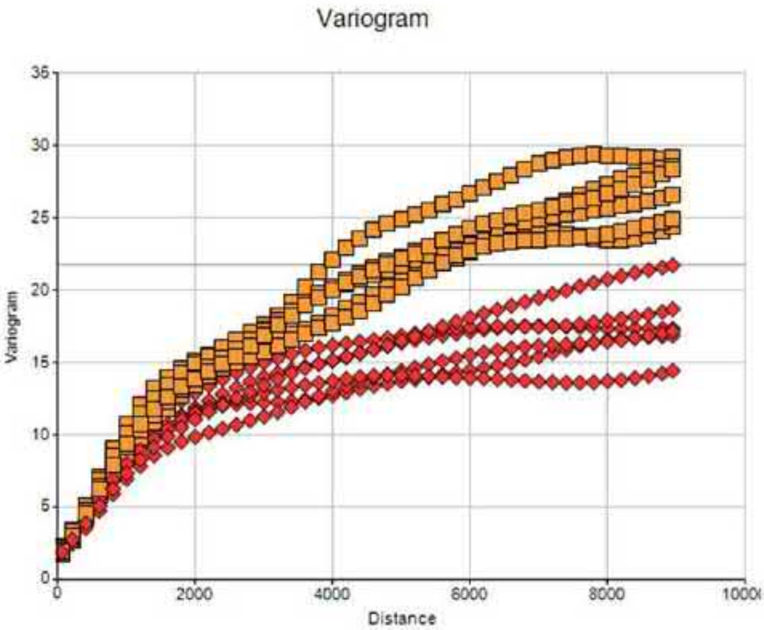


Figure 12. Back transformed experimental variograms from selected conditional simulations. Orange squares are the east-west direction and the red diamonds are the north south direction.

6. Uncertainty in the case study areas

It is clear from both the kriged water table and the conditional simulations that uncertainty in the water table increases rapidly away from the data, which is also seen in the experimental variograms. The conditional simulations provide a higher degree of detail with respect to areas of higher and lower confidence based on the variance and 15% and 85% likelihood levels.

Figure 13 below illustrates the four case study areas (in black) in relation to the conditional simulation variance for the area of interest. The blocks coloured red denote high risk/uncertainty areas. It is noted that the low variability areas associated with isolated data do not extend more than approximately 300m. Therefore, the blue lines define areas of reasonable confidence.

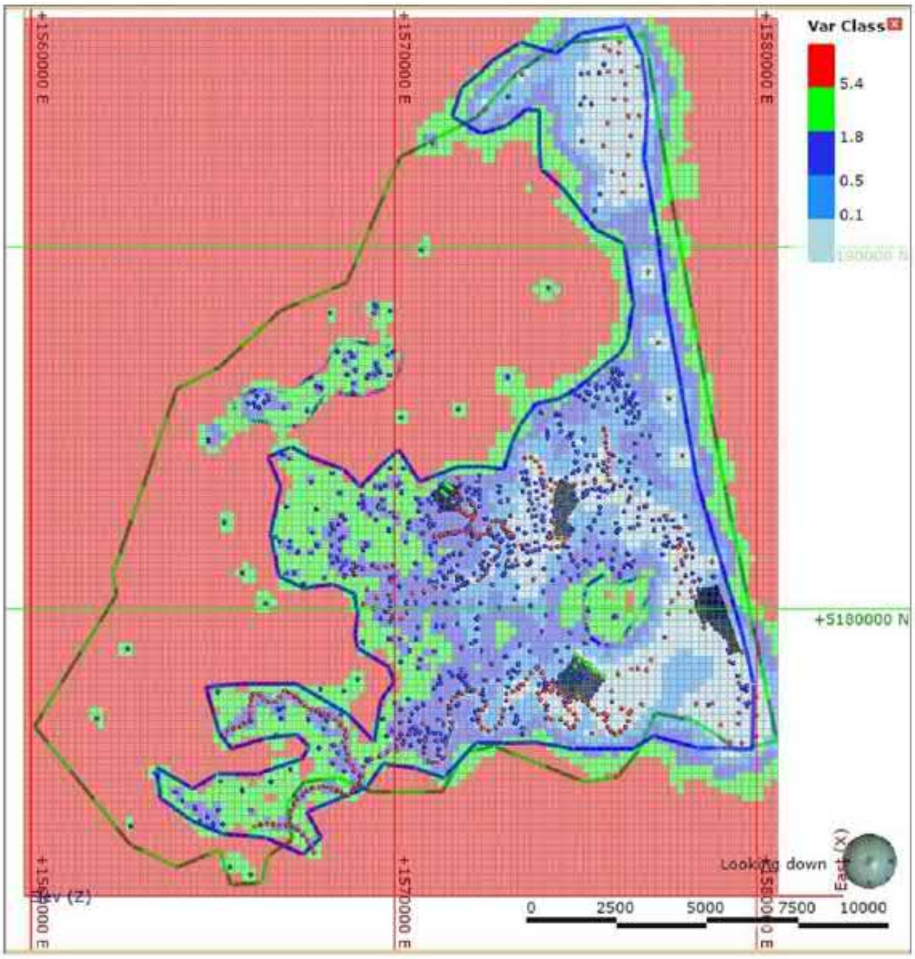


Figure 13. Water table variance with case study areas. Data points: wells in blue; river and coastal in red; drains in green

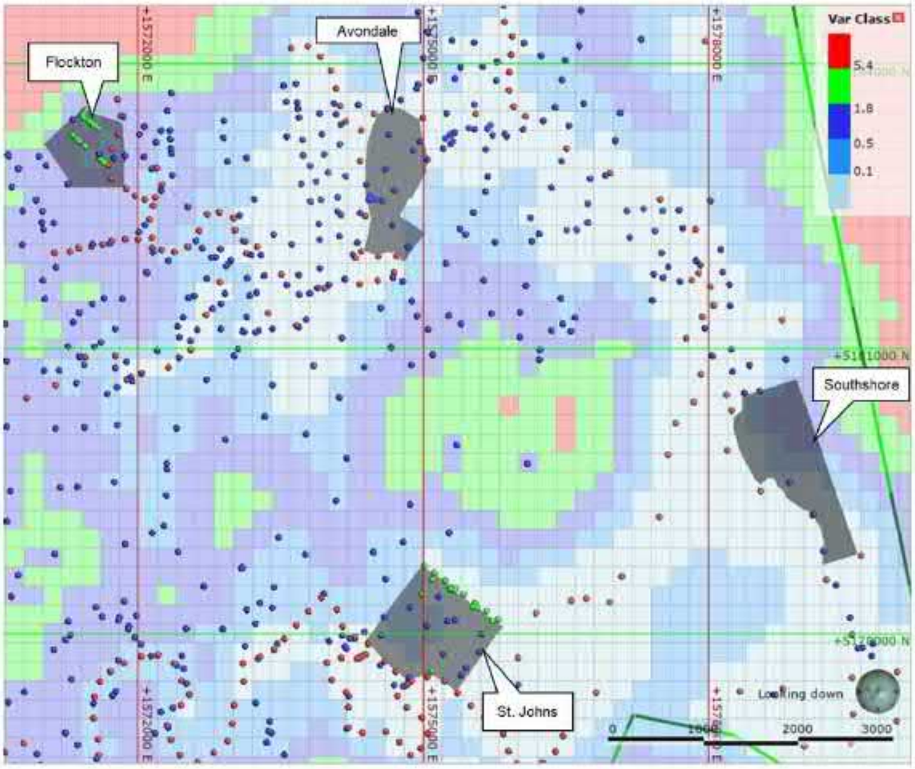


Figure 14. The four case study areas

To view the local variations in the variance, a zoomed in view of the four case study areas are in Figure 14:

- Each of the case study areas are relatively well informed by data and of the four; the Flockton case study area has a slightly higher variance.
- St. Johns and Avondale are within areas with the lowest variability, closely followed by Southshore. The well spacing in St. Johns and Avondale are around 200 x 200m and at Southshore it is coarser up to 1000m in the northern part.
- Flockton is in a slightly higher variance area. On the north and west flanks the well spacing is around 450-550m. Based on theoretical calculations of well spacing to 200 x 200m, the kriging variance can be expected to be reduced by around 40%. As a comparison, when looking at the conditional simulation variance in the water table (by comparing values in the different values) there is a potential reduction in variance from ~1.4 to ~0.03m^2, which is substantially more However, Flockton has higher water table elevations than the others, and the absolute variance in general increases from east to west (following the higher density of data areas), therefore to reach the same level of low variance seen in the east it is likely the well spacing would have to be 200 x 200m at minimum.

6.1. Cumulative distribution functions (non-normal distributions)

The reason why simulation is needed as opposed to using the Kriging variance can be seen from Figure 15 which shows the cumulative distribution function at three random points in the area. The output distribution is clearly non-linear and at least at two locations not normally distributed. In other words, if one used the Kriging variance which assumes a normal distribution alone as a measure of reliability, reliability will be falsely exaggerated.

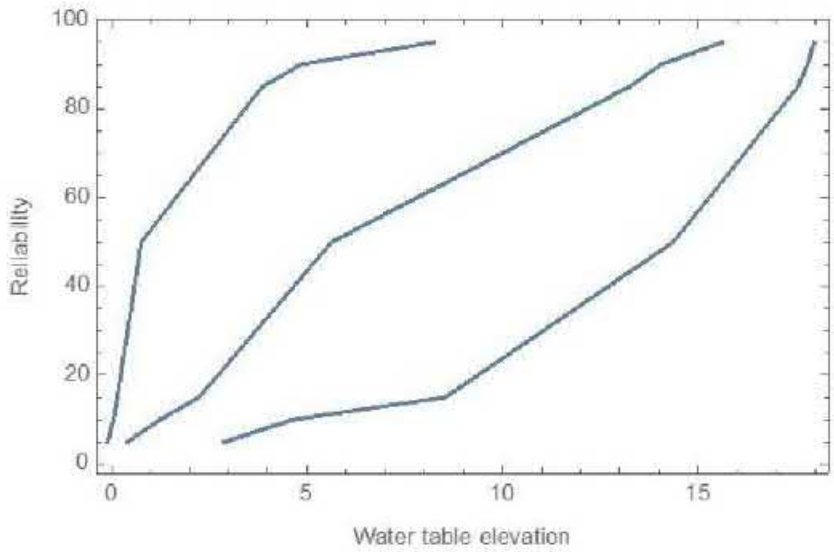


Figure 15 Cumulative distribution function at three points in the study area.

6.2. 85% confidence surface

An advantage from having executed conditional simulation is being able to quantify reliability at what elevation the ground water table lies. Figure 16 shows the elevation of the 85% surface; that is to say, there is 85% reliability that the water table is at or below this elevation. Or, there is a 15% chance the water table is higher. However, it is important to note that at some locations, this surface is at or above land surface. There must be either drainage in place or artesian conditions, the surface water features clearly must drain some of these areas (i.e. the Styx and Heathcote). Figure 17 shows the elevation of the water table where there is an 85% likelihood that the water table is higher.

The surface is also highly variable, this may be due to both local geological conditions as well as anthropogenic influences on the system (i.e. pumping, drains, et al.).

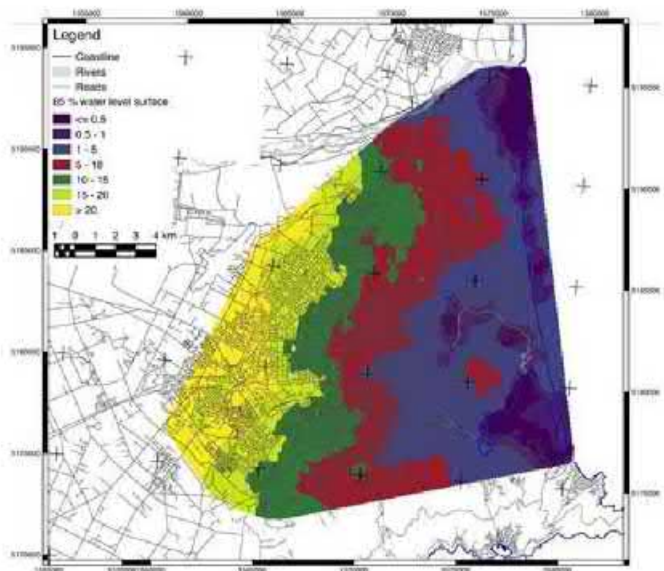


Figure 16. Map of the elevation of the water table at 85% confidence.

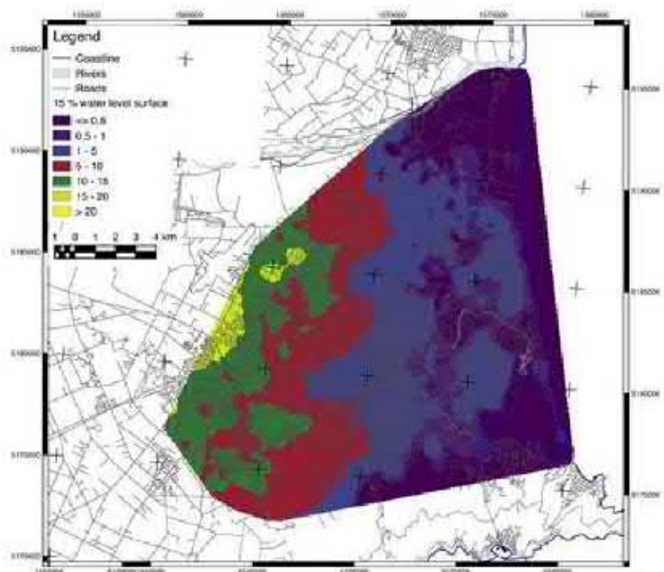


Figure 17. Map of the elevation of the water table at 15% confidence

7. Conclusions and Recommendations

The analysis of the data as well as the estimation and simulation process have shown that the system is very "noisy" and that there is in general a great deal of uncertainty for water levels. The high nugget effect or short scale variability, shows that the expected water table has up to a 20 to 30 cm uncertainty at the observation points (autocorrelation). This observation of high uncertainty is reinforced by the results of the conditional simulation. The conditional simulations have highlighted that the uncertainty increases rapidly with relatively short distance from the data (<300m).

The consequence is that in the area with low sample density the water table is poorly defined, and furthermore the uncertainty "envelope" thickens rapidly away from observations.

A consequence is that in areas where significant development is to occur, one should instigate a monitoring plan that has a relatively fine grid. Potentially, one could develop monitoring plans where comprehensive sampling over a short period, supports a more regular sampling at a smaller number of locations.

Recommendations to reduce variance at the 3 study or focus areas are:

- **Flockton**: sampling spacing should be on the order of 200 x 200m minimum
- **Southshore**: one well inserted to reduce the spacing to 500m in north.
- **St. Johns**: one to two wells inserted in northern most tip

8. References

Coombes, J. (2016). *I'D like to be OK with MIK, UC?* Coombes Capability.

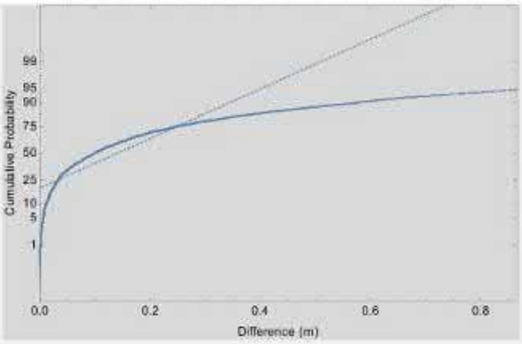
Krom, T. D., & Nicholls, C. (2017). *Water table reliabililty analysis.*

Krom, T. D., & Nicholls, C. (2017). *Water table reliability - 85 percentile surface.*

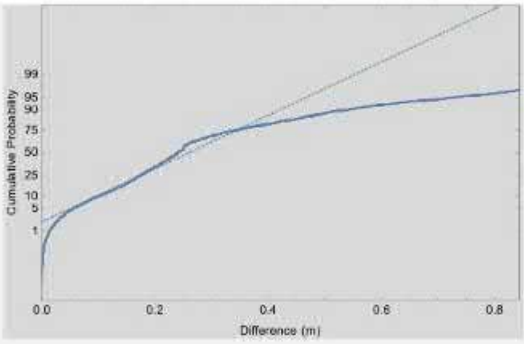
Appendix A: Note regarding estimated water tables

Seequent has delivered analyses for the uncertainty of the shallow water table around Christchurch for the water table that would not be exceeded 85% of the time as well as the median water table. These analyses are based upon data delivered by Aqualinc Research.

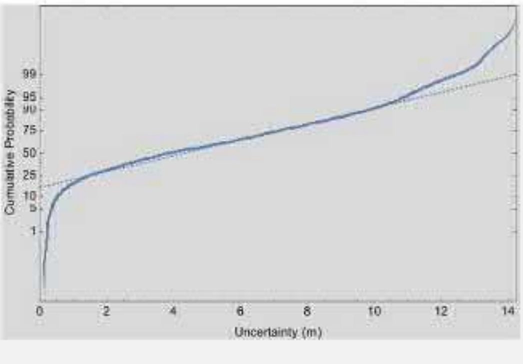
There are some locations where the Kriged water table for the median situation lies above the 85% water table. There seem to be two reasons that underly this and these are somewhat related to each other. It needs to be point out that the two water tables are very close to each other. As can be seen in the two cumulative histograms below for roughly 75% of the area these water tables are within 20 to 30 cm of each other. This can be compared to the uncertainty of the two surfaces, also presented below as a cumulative histogram. There we can see that say only 1 or 2 percent of the area has an uncertainty at the scale of 20 to 30 cm.



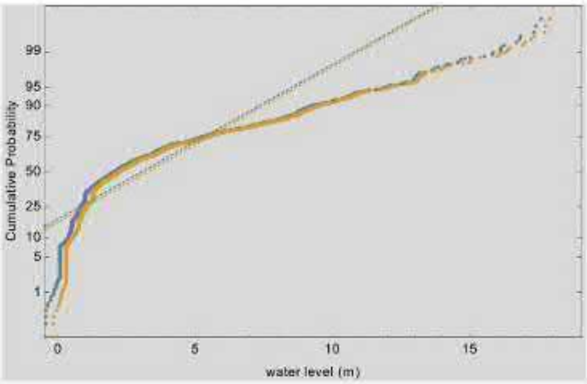
Difference between the expected median and expected 85% water tables where the median is above the 85% surface



Difference between the expected median and expected 85% water tables where the median below above the 85% surface

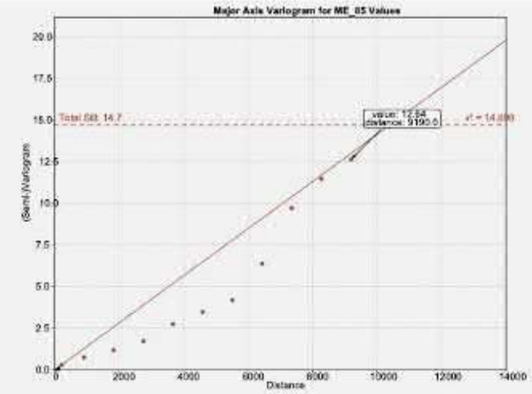


Cumulative histogram for the uncertainty (15-85%) of the median water table.

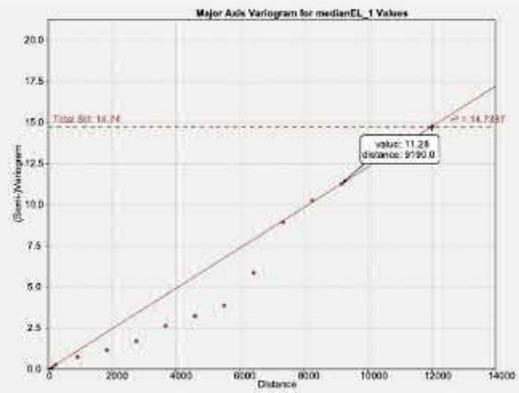


Cumulative histograms for the two sets of data: the median in blue and the 85% data in orange.

The data sets for the median water table and the 85% water table have different statistics. Their global variability (variance - histograms above) are different as are their spatial variance (variogram – see below). The median water table data has a greater range (correlation distance) than the 85% water table data at a lower variance (semi-variogram γ). The greater range for the median data results in a smoother surface. Complicating this is that while globally the two data sets have similar variance, this is not true if one looks at data close (<500 m) versus far from the river. At distances greater than 500 m from the river the median data is noisier (greater variance) while close to the river it is the other way around (the median data has a smaller variance compared to the 85% data). So, these data have different characteristics, and that is the fundamental reason one gets some water table crossings.



Major variogram for the data used for the 85% water table



Major variogram for the data used in the median water table

Another issue is that the statistical change applied to the river data between the 85% data and the median data seems to be rather uniform and greater at the coast than inland.

As an example of the water table crossings, below are two cross-sections zoomed into the area around the estuary. The locations of the cross-sections is shown in the Appendix. What one can see in these two figures is that the red median water table is smoother (broader highs and lows) and this results in the water tables crossing. If one inspects elsewhere for crossings, the same reason seems to be behind the crossings.

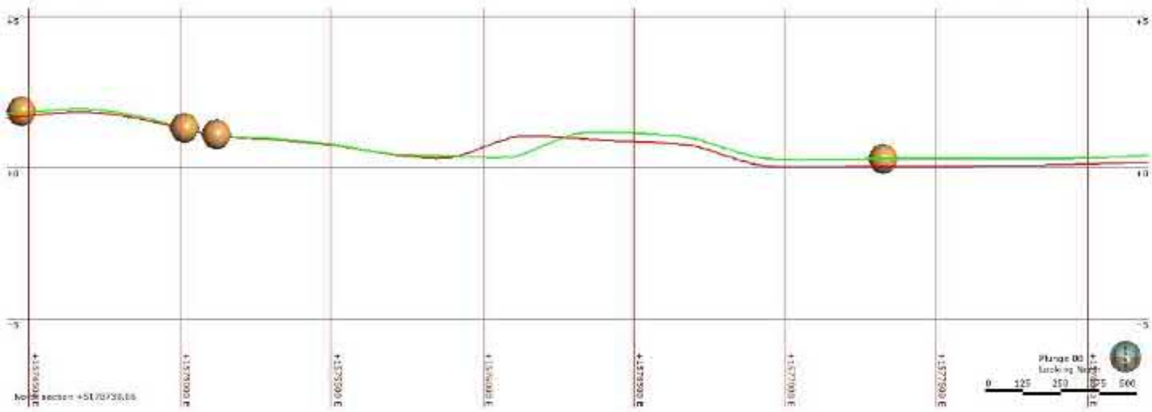
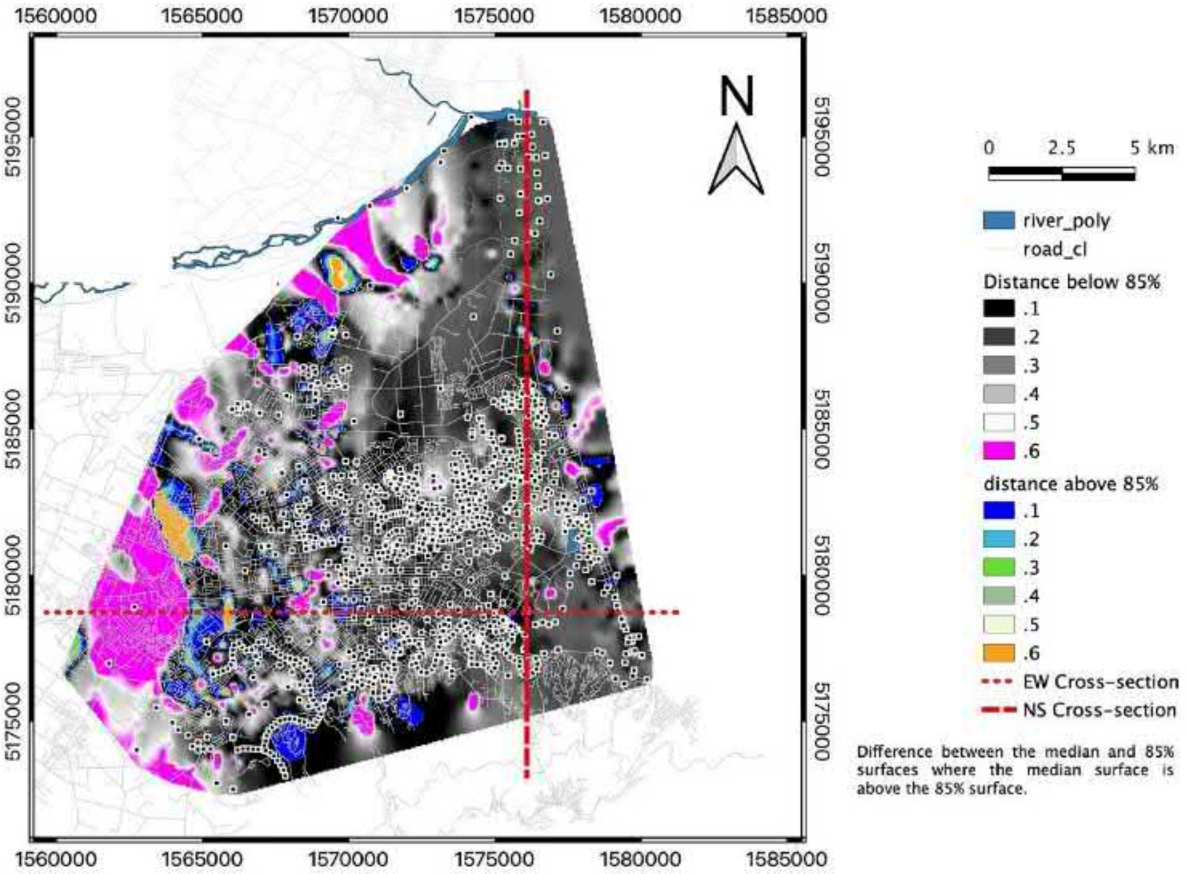


Figure 18. The expected median (red) and expected 85% (green) water tables zoomed in to near the estuary where they cross on an EW cross-section.

Figure 19. The expected median (red) and expected 85% (green) water tables zoomed in to near the estuary where they cross on an NS cross-section.

SEEQUENT



Difference between the median and 85% surfaces where the median surface is above the 85% surface.

Appendix B: Map Sheets

- Map of residuals for the mean water table surface
- Map of depth to water
- Map of the 85% confidence level surface
- Map of waste water nodes in relation to the mean water table surface

Appendix E: Sumner sea level rise modelling

E.1 Introduction

The work in this Appendix was undertaken for Christchurch City Council (CCC) and details the predicted response in groundwater levels in the shallow aquifer at Sumner, Christchurch, from rising sea levels. The Sumner area was not included in the previous Canterbury groundwater model (Weir, 2018) due to it being a relatively isolated aquifer system from the larger Plains system. A simple local-scale groundwater model was therefore constructed to assess sea level rise effects in this area. The modelled area is shown in Figure 1.

The outputs from the modelling include surfaces of the modelled change in groundwater levels (compared to the baseline 'calibrated' model). Furthermore, an assessment of hydraulic conductivity derived from tidal response analysis in a shallow bore is provided.

E.2 Data sources

Geology

There was limited information available on the geology of the Sumner valley. Bore logs indicate that the profile consists of sands and silts with no evidence of gravels. A selection of available bore logs are provided in Appendix A, and their locations are shown in Figure 1. The deepest bore has a depth of 21.6 m and did not encounter volcanic basement rock or gravels. The valley is bounded by the volcanic formations of the Port Hills. There is no information on the depth to the volcanics in this area; therefore it has been assumed that the angle of the underlying volcanics follows the topography of the surrounding hills. Therefore, the thickness of the valley floor aquifer system is thickest along the centre of the valley and thins towards the edges.

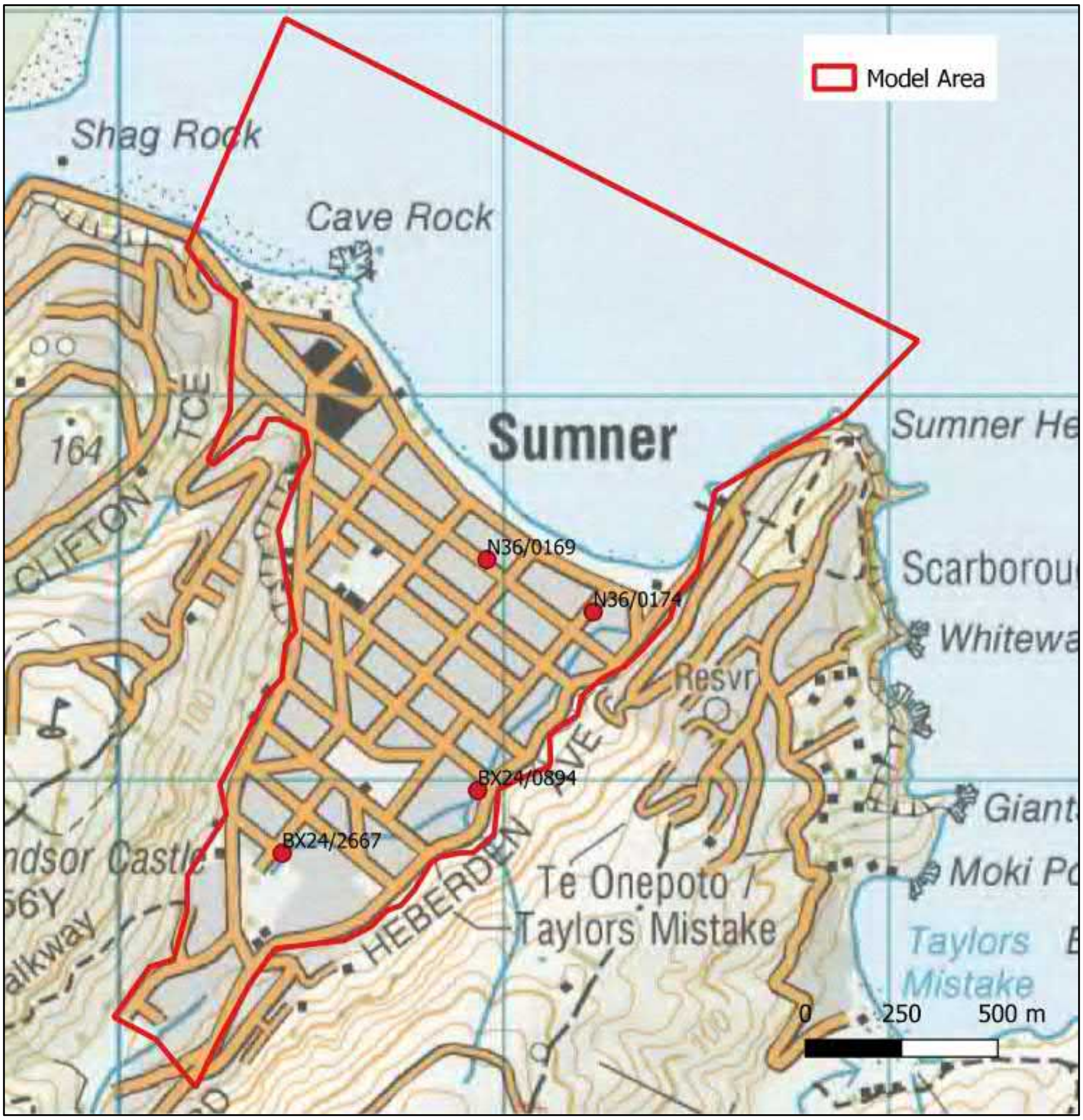


Figure 1: Model domain and bore log locations

Groundwater Level Data

Limited groundwater level measurements exist for the Sumner area, with no existing Canterbury Regional Council groundwater level monitoring bores. One bore with a time series of groundwater level data is N36/0044, and a short period of measurements exists in this bore from April 1969 through to April 1972 (Figure 2). This data shows a distinct seasonal pattern of higher groundwater levels in winter and lower levels in summer and autumn, as expected. This bore is located in the centre of Sumner Valley and may not fully represent levels in the whole area, especially closer to the coast.

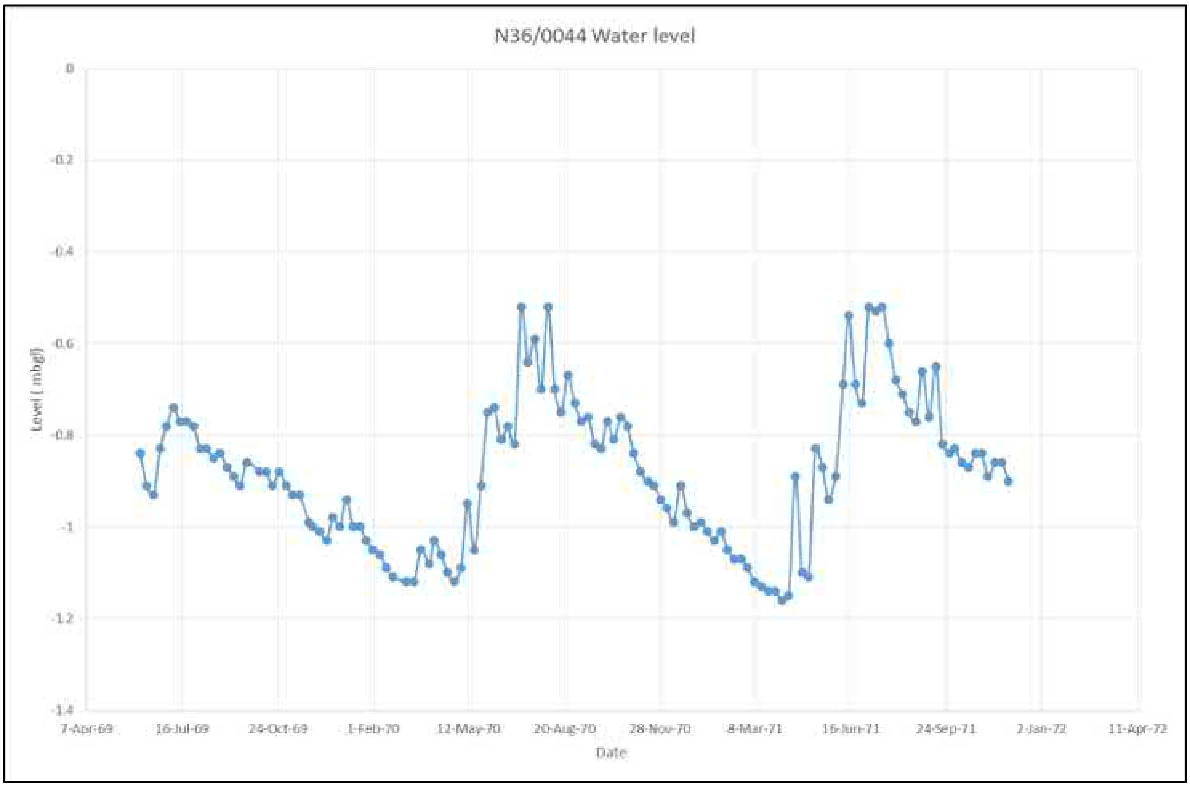


Figure 2: Groundwater level data for N36/0044

Additional single groundwater level measurements were obtained in Sumner during geotechnical investigations, primarily from cone penetration testing. These one-off values were measured over the period 14/6/2012 to 1/2/2019. These levels, relative to Lyttelton Vertical Datum 1937 (MSL), are shown in Figure 3. An attempt was made to correlate water levels from N36/0044 with other longer-term groundwater level records across Christchurch, in order to put this record, and the one-off measurements, into a larger time-scale perspective. However, there were no other records which could be adequately correlated. Instead, groundwater levels recorded in June and July were used to calibrate the model, and it was assumed that these represent a period of higher groundwater levels.

Figure 3: Groundwater levels above Lyttelton vertical datum (1937) from measurements over the period 2012-2019

Ground Surface Elevations

A Christchurch DEM 2015-2016 was used to specify elevations of the land surface. The ocean bed was arbitrarily graded from 0 m at the coast, to -10 m at the edge of the model off shore.

Drain and Stream Network

The locations of the drain and stream network was provided by CCC and were represented in the model. The elevation of the base of the drains were obtained from a digital elevation model (DEM), where available; otherwise they were estimated from the land surface elevations (Figure 4).

The drain elevations were altered during the scenarios to accommodate the hydraulic effects of sea level rise. If the drain elevations were below the new raised sea level, then the drains would not drain (they would be water logged, assuming they are not pumped). Hence, drain base elevations were increased to match this rise. This simulates the drains filling with water when sea level rises and thus them becoming less effective.

Figure 4: Sumner drain modelled drain network

Land Surface Recharge

Rainfall data was obtained from CCC's Van Asch Street rainfall site (Site 325711, located in Sumner). This data was compared to data from Christchurch Gardens to ascertain whether the previously calculated drainage from the Christchurch Gardens site could be used at Sumner; otherwise drainage would need to be re-calculated for the Sumner site. These two sites have similar rainfall record timing and magnitude. Figure 5 shows an example of the comparison of the two sites between 18/11/2010 and 1/4/2012. The average daily rainfall at the Christchurch Gardens site was 1.73 mm for the period 1/12/1967 to 31/12/2015, similar to the Van Asch Street site of 1.65 mm for the same period (95% of the Christchurch gardens site). Christchurch Gardens IrriCalc data was therefore used to assign dryland pasture drainage rates, and this was reduced by 5% to account for the differences in rainfall at the two sites. The calculated average dryland pasture drainage is 0.57 mm/day (1960-2015). The majority of Sumner has single story residential properties, and a runoff factor of 0.5 has been used to account for the reduced drainage as a result of impermeable area (Fetter, 2001). The average daily drainage to groundwater for the entire model was therefore 0.29 mm/day.

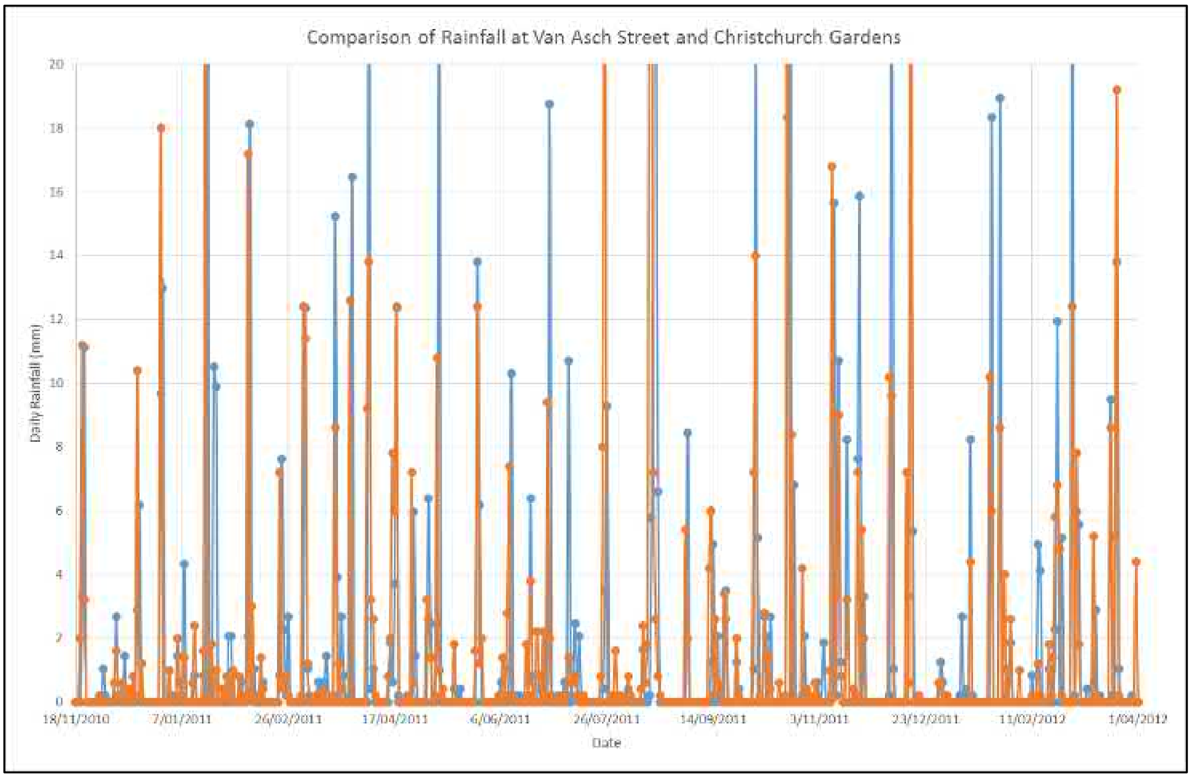


Figure 5: Comparison between daily rainfall at Van Asch Street and Christchurch Gardens

Sea Level

Sea level was set to the Lyttelton Vertical Datum 1937 (MSL) plus 0.064 m to account for sea level rise after the datum was set. The model does not allow for water table over height.

E.3 Numerical Groundwater Modelling

A numerical groundwater flow model has been built using the computer graphical user interface GMS (2019). It has been constructed as a MODFLOW-NWT model (Niswonger *et al.,* 2011), which is a three-dimensional, block-centred, finite difference groundwater flow model.

The model area comprises the entire Sumner valley floor (Figure 1), and extends approximately 500–800 m offshore. The model was constructed with a single layer extending from the ground surface to 20 m below the Lyttelton Vertical Datum 1937 (MSL). All elevation data used in the model is consistent with this datum. Model cell sizes were 50 m x 50 m. The ocean was modelled as a general head boundary with a conductance value controlling the hydraulic connection with groundwater. Drains and streams were modelled using MODFLOW's drain (DRN) package with a single conductance value for all reaches.

E.4 Calibration

The model was constructed as steady state and calibrated to the June/July groundwater levels. Pilot points were used to represent the spatially-variable aquifer horizontal hydraulic conductivity. Conductance values for the ocean and drains was also adjusted during calibration. A graph of modelled versus measured groundwater levels is shown in Figure 6. This shows a relatively poor match. The poor match can be attributed to the sparse groundwater levels that are distributed over a considerable time period.

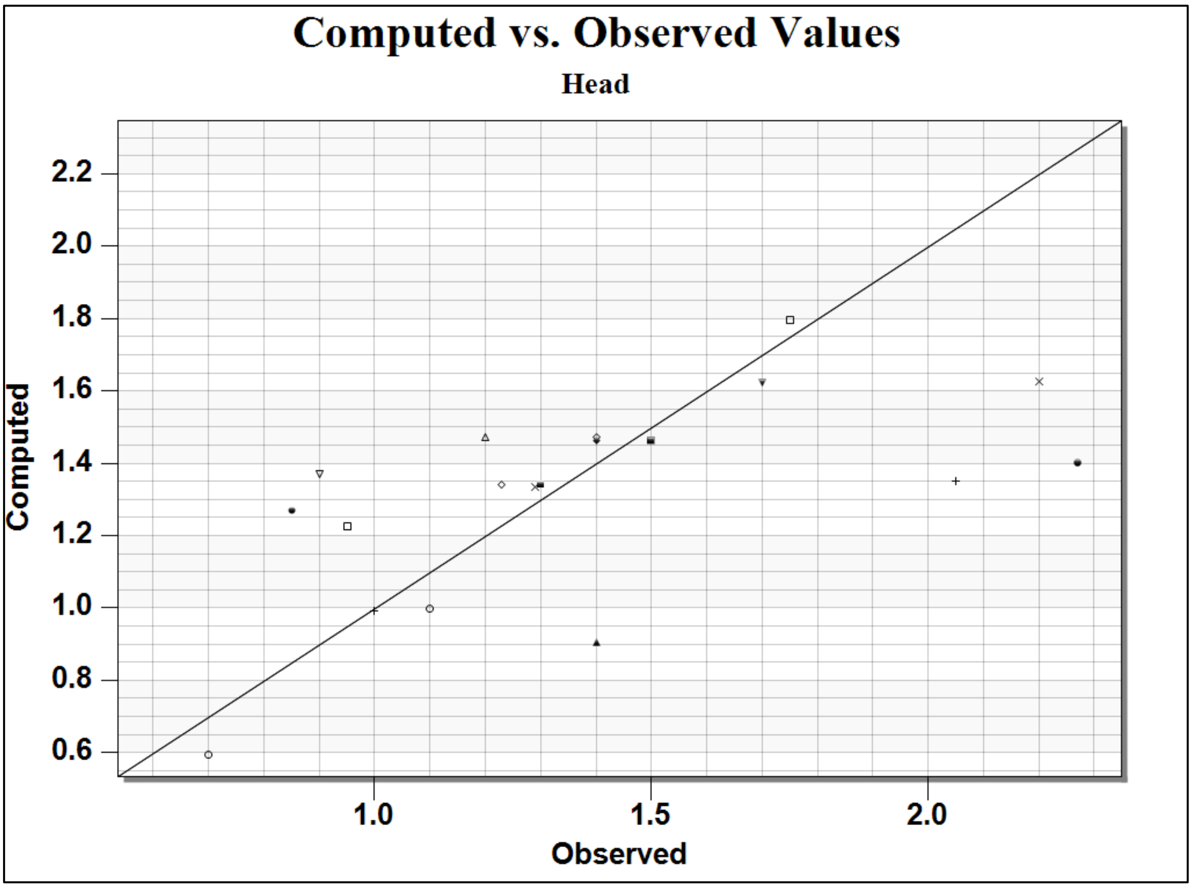


Figure 6: Modelled versus measured (observed) groundwater levels

Figure 7 shows the calibrated groundwater levels together with an indication of the match between modelled and observed for each bore. The largest differences occur in the two bores towards Sumner village. The cause of this is unknown but may be due to proximity to basement rock, weather patterns prior to when groundwater levels were measured, or local hydraulic effects in this area (such as leaky pipes).

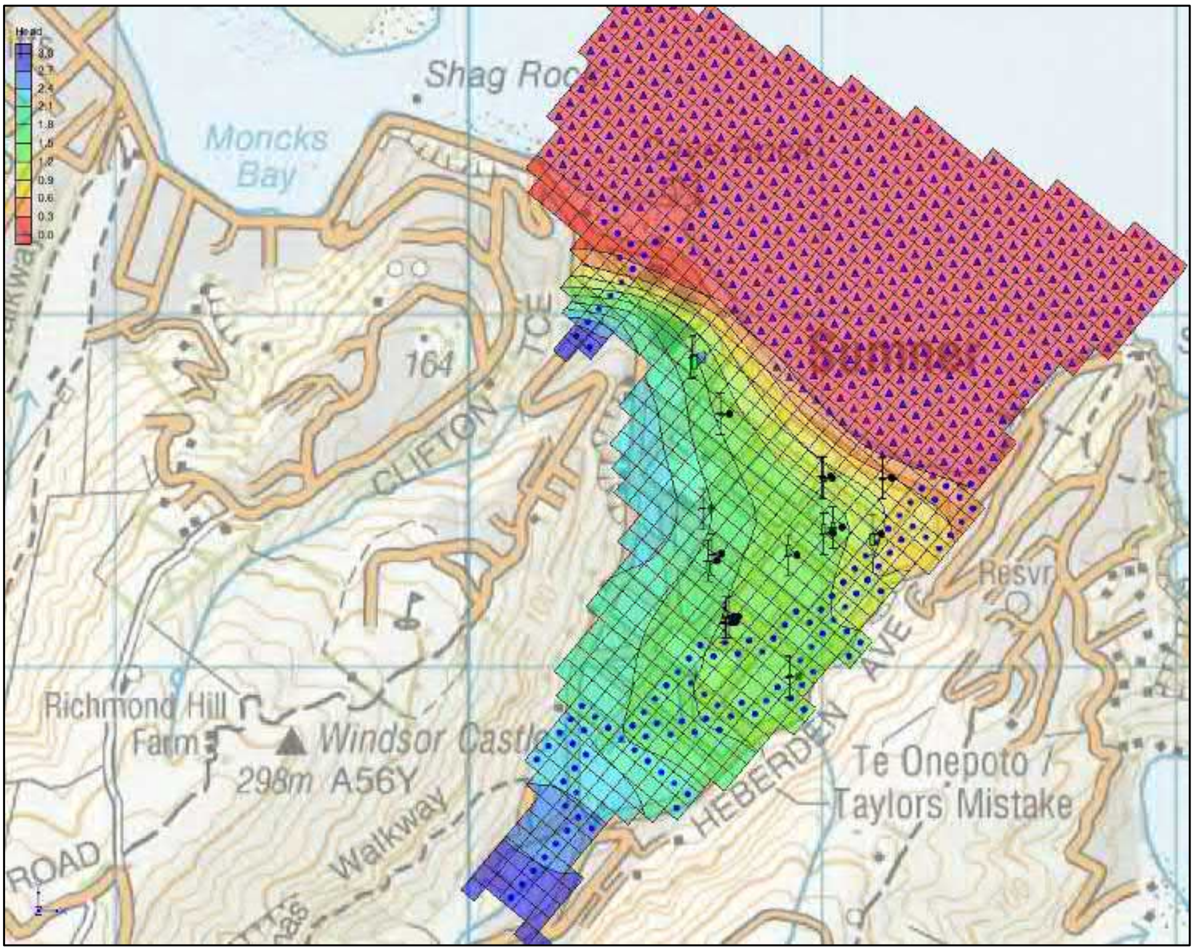


Figure 7: Modelled groundwater levels showing location of calibration bores, drain cells (blue circles) and offshore general head (blue triangles)

E.5 Results

The calibrated model was used to assess 4 sea level rise (SLR) scenarios as noted in Table 1.

Table 1: Sea level rise scenarios

Scenario	SLR (m)
1	0.19
2	0.40
3	1.00
4	1.88

The steady state model was used to predict the response of sea level rise scenarios on groundwater levels. For each scenario, the level of the constant head boundary for the ocean was increased by the corresponding value in Table 1. Drain inverts were also raised to simulate flooding by seawater. The model was run, and a new groundwater surface generated. These surfaces were subtracted from the original surface to produce the *change* in groundwater levels.

The results from the modelling are shown in Figures 8–11. These indicate that the drains and streams on the south east side of Sumner have a large controlling effect on groundwater levels in that area. This control decreases as the sea level rise increases and the drains are inundated.

Figure 8: Predicted increase in groundwater levels above present modelled surface as a result of a 0.19 m increase in mean sea level

Figure 9: Predicted increase in groundwater levels above present modelled surface as a result of a 0.40 m increase in mean sea level

Figure 10: Predicted increase in groundwater levels above present modelled surface as a result of a 1.00 m increase in mean sea level.

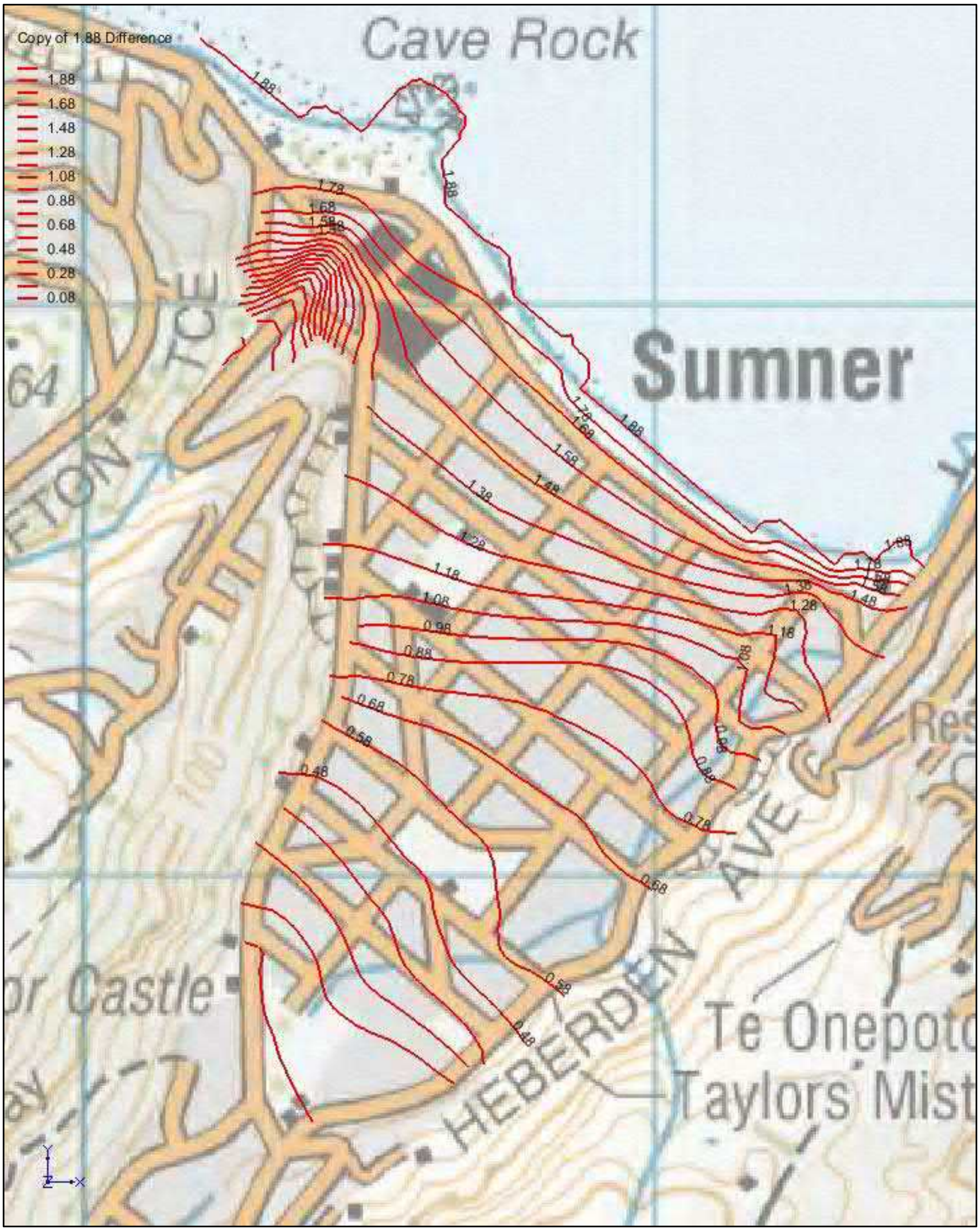


Figure 11: Predicted increase in groundwater levels above present modelled surface as a result of a 1.88 m increase in mean sea level

The modelling results have also been presented by area where a 100 mm change or greater is predicted. These are shown in Figures 12-15.

Figure 12: Predicted area with 100 mm or greater increase in groundwater levels above present modelled surface as a result of a 0.19 m increase in mean sea level

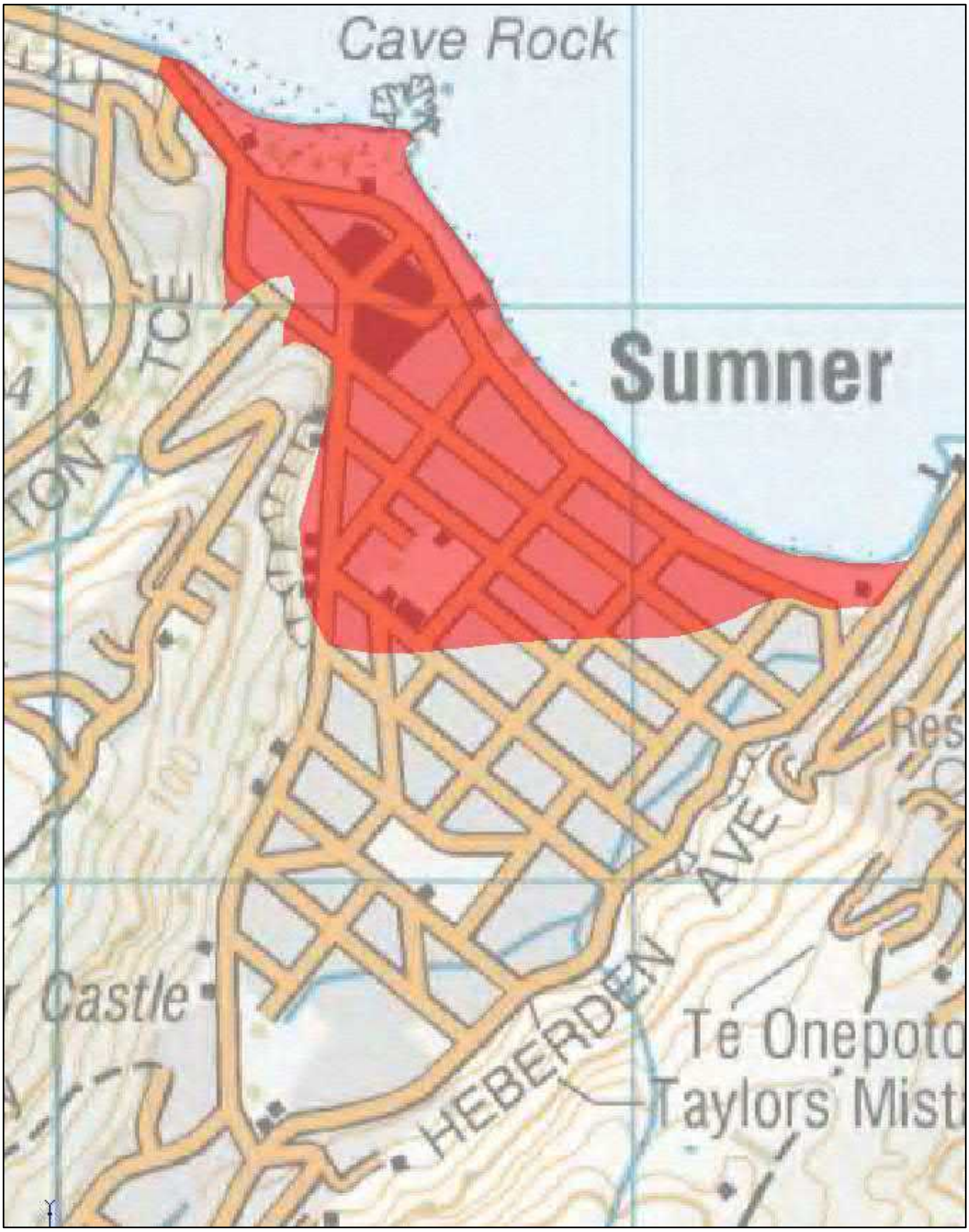


Figure 13: Predicted area with 100 mm or greater increase in groundwater levels above present modelled surface as a result of a 0.40 m increase in mean sea level.

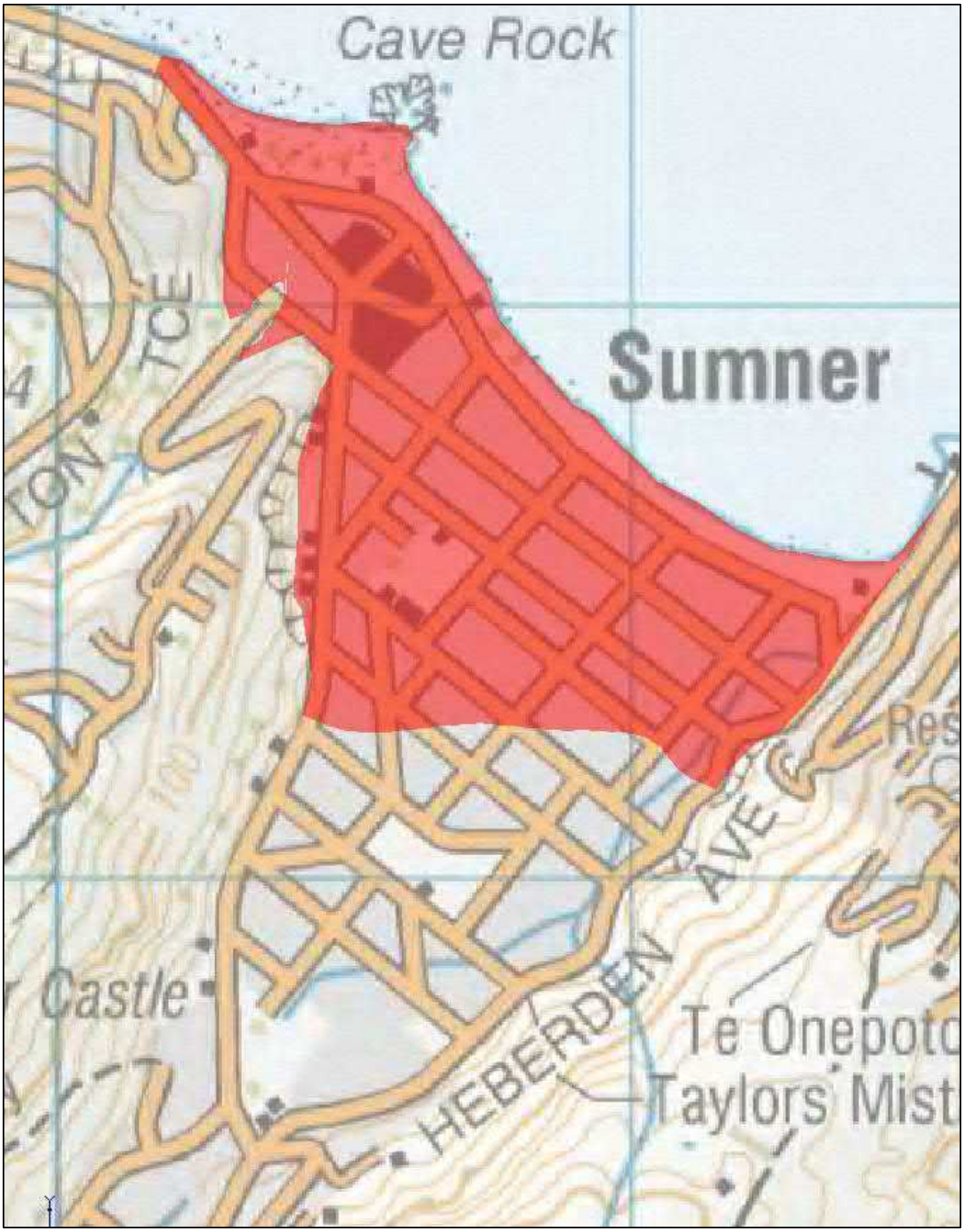


Figure 14: Predicted area with 100 mm or greater increase in groundwater levels above present modelled surface as a result of a 1.00 m increase in mean sea level.

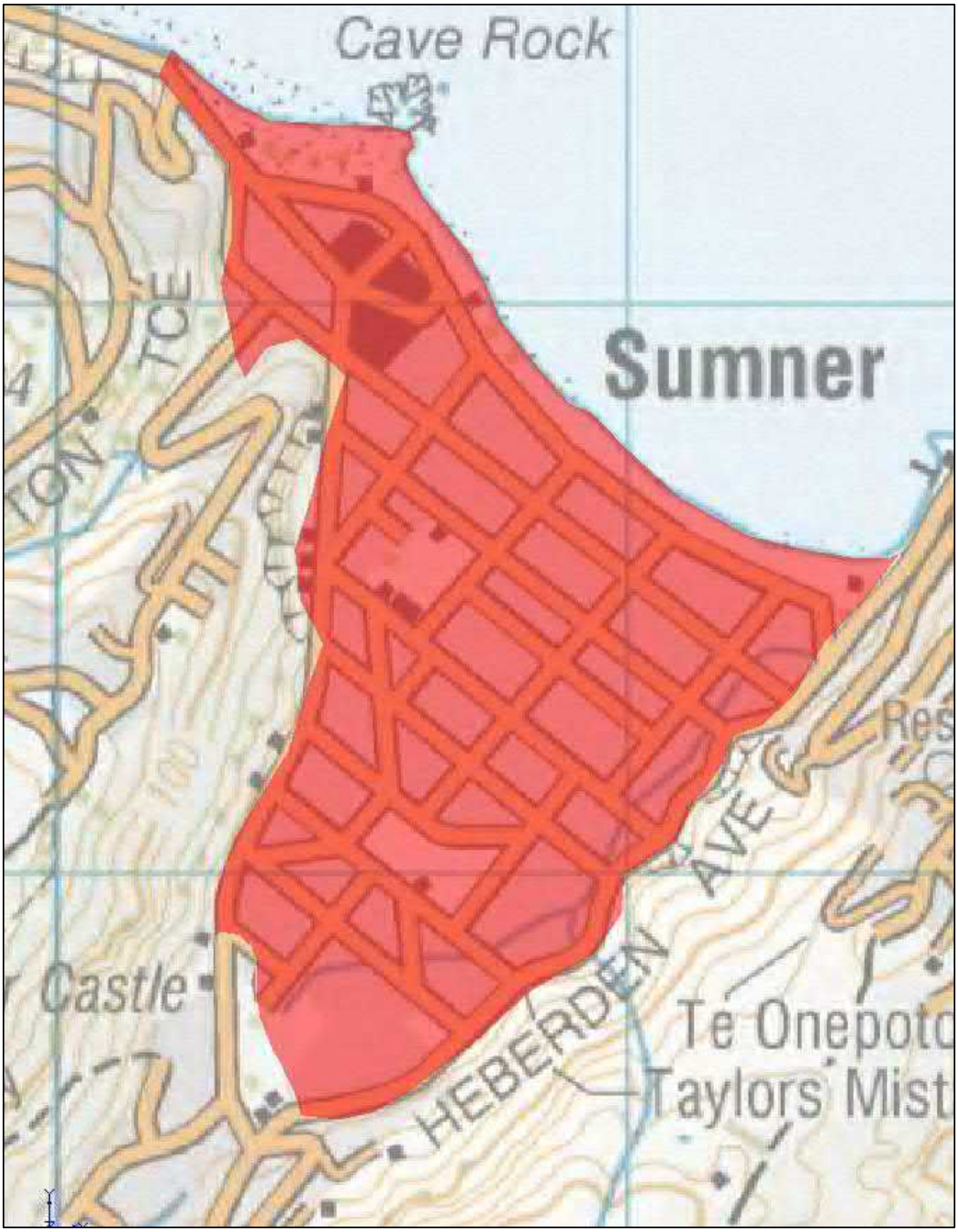


Figure 15: Predicted area with 100 mm or greater increase in groundwater levels above present modelled surface as a result of a 1.88 m increase in mean sea level.

E.6 Assumptions and data gaps

There were a number of assumptions and data gaps associated with developing this model. These are discussed below.

Assumptions include:

- The coastline position does not alter with rising sea level. This is a reasonable assumption given the seashore topography at Scarborough Beach, but may not be true at Sumner Beach. Ingress of water through the drainage system may also occur and has not been fully accounted for.
- The sea wall provides a physical barrier to over-topping, but the hydraulic response from an increase in sea level will propagate under the wall.
- No flow from outside the model area. There is likely to be only minor flow from streams into the model area from outside (such as the upper valley catchment). However, inflows from groundwater are unknown.
- No change in climate (recharge) during the scenario periods.
- No pumping introduced into the study area.
- No change in mitigation measures.

Data gaps include:

- The sparsity of groundwater levels.
- No drain conductance values and uncertain drain depths.
- Unknown ocean conductance values.
- No aquifer tests to constrain aquifer hydraulic conductivity, though this is discussed later.

E.7 Analysis of Tidal Response in N36/0247 to Estimate Kh

High frequency groundwater level monitoring data was supplied by CCC after the Sumner modelling was complete. This data was used to estimate horizontal hydraulic conductivity (Kh). The resulting Kh value was compared to the Kh distribution used in the model. No pumping tests have been undertaken in this area, so this is the only independent estimation of Kh available. As outlined above, Kh in the model was back calculated from groundwater level data as part of model calibration.

CCC supplied high resolution data from N36/0247 which is located in the Sumner shopping precinct, 250 m from the coastline, as shown in Figure 1. The bore log for N36/0247 is shown in Appendix A. N36/0247 is 3.1 m deep and screened between 0.5 m and 3.1 m. The bore is screened in fine to coarse sand, which is typical for bores in the Sumner area.

Figure 16: Location of N36/0247

Groundwater level data from N36/0247 is displayed in Figure 17. When plotted over a short time period (Figure 18), a distinct sinusoidal signal is present, with a period slightly greater than 12 hours. This is evidence of a tidal response. These groundwater level oscillations are a similar magnitude to those found at similar distances next to the tidal reaches of the Avon River (Steinhage 2014). Specific yield is high in unconfined aquifers, and therefore the amplitude of tidally-forced head oscillations will quickly reduce at increasing distances from the coast.

Figure 17: Groundwater level data for N36/0247

Figure 18: Groundwater levels and tide data used to estimate conductivity

Tidal data was obtained from the Sumner Head sea level site. This site has been recording data from 9/8/2011 to present and is the closest to the Sumner model site. Figure 18 also shows Sumner head tidal data with N36/0247 groundwater level data. The data is shown relative to the Christchurch Drainage Datum.

Tidal and groundwater responses were collected for a period in the GW level record that was relatively stable, to limit the effects of external influences on the response (such as rainfall). Table 2 summarises the groundwater level response to tide and the corresponding tidal maximum and minimum values. The differences between the maximum and minimum values are also shown. There is a lag in the bore response compared to the tidal response, which is to be expected given the distance of the bore from the coast. The tidal period is shown and has an average of 0.513 days. Tidal efficiency, defined as the ratio of amplitude of the water level fluctuation in a well and the corresponding amplitude of sea level fluctuation, is also shown.

The data in Table 2 was used to calculate hydraulic diffusivity (*T/S*), using the Jacob 1950 tidal dissipation model (after Jiao *et al*. 2019), as follows:

$$\frac{T}{S} = \frac{\pi}{t_0}\left[\frac{-x}{ln\left(\frac{h_x}{h_0}\right)}\right]^2 \qquad (1)$$

Where:

- T is transmissivity (m^2/d)
- S is Storativity
- t_0 is the ocean tidal period (d)
- x is the distance of the bore from the coast (m)
- h_x is the tidally induced groundwater fluctuation (m), and
- h_0 is the tidal fluctuation (m)

Table 2: Groundwater and tidal oscillation data

Groundwater date/time	GW level (m)	GW oscillation (m)	Tidal date/time	Tide (m)	Tidal cycle (d)	Tidal oscillation (m)	Tidal efficiency
9/02/2020 5:20	10.538		9/02/2020 4:23	10.42			
9/02/2020 12:40	10.52	0.018	9/02/2020 10:33	8.295		2.125	0.008
9/02/2020 18:45	10.539	0.019	9/02/2020 16:39	10.313	0.511	2.018	0.009
10/02/2020 0:40	10.514	0.025	9/02/2020 22:40	8.19		2.123	0.012
10/02/2020 5:45	10.534	0.02	10/02/2020 4:57	10.493	0.513	2.303	0.009
10/02/2020 13:35	10.517	0.017	10/02/2020 11:19	8.2		2.293	0.007
10/02/2020 19:15	10.538	0.021	10/02/2020 17:49	10.336	0.536	2.136	0.010
11/02/2020 1:45	10.521	0.017	10/02/2020 23:52	8.073		2.263	0.008
11/02/2020 7:35	10.539	0.018	11/02/2020 5:39	10.492	0.493	2.419	0.007
11/02/2020 14:20	10.519	0.02	11/02/2020 12:37	8.168		2.324	0.009
	Average	**0.019**			**0.513**	**2.223**	**0.009**

Equation 1 assumes the aquifer is confined, homogeneous, of a constant thickness, and that there are no effects from vertical groundwater flow or density differences. This equation has been shown to be valid for unconfined aquifers (which the shallow aquifer in Sumner is assumed to be) if there is no appreciable vertical flow and the saturated thickness is large compared to the measured fluctuations (Jiao *et al.* 2019).

The assumed thickness of the aquifer under Sumner is 25 m which is large compared to the measured fluctuations, and there is likely to be predominately horizontal flow. Therefore the equations assumptions are likely to be valid. A summary of the data used to calculate hydraulic diffusivity is shown in Table 3. Using these values, a hydraulic diffusivity of 17,037 m^2/d was calculated.

Table 3: Summary data

t_o	0.513 days
h_x	0.019 m
h_o	2.223 m
x	250 m
Aquifer thickness	25 m

Hydraulic diffusivity can be converted to transmissivity if specific yield is known, and then to Kh given an aquifer thickness. Text book specific yield values (Fetter, 2001) for unconfined, pure fine to coarse sand aquifers range from 0.1-0.35. The specific yield is not known accurately for this aquifer, but the aquifer is assumed to be semi-unconfined to unconfined. The bore is located in an urban area where there are compacted soils and artificial hard surfaces meaning it could be more semi-unconfined. Therefore smaller values than the textbook values were used (0.01-0.2) to calculate transmissivity. The aquifer thickness is also not known precisely; therefore, a range of values is given (5-25 m). Table 4 shows the range of conductivity values calculated.

Table 4: Range of conductivity (m/d)

Specific yield	Aquifer thickness (m)		
	5	10	25
0.2	681	341	136
0.1	341	170	68
0.05	170	85	34
0.01	34	17	7

The Kh values that were calculated in the model ranged from 0.001 to 28 m/d, as shown in Figure 19. These values correspond to the relatively confined and thick aquifer calculated in Table 4 (Sy=0.01 and thickness=25 m), but are generally lower than the other values in this table. The K value from this bore may be influenced by the proximity to the basement rock on the Sumner cliffs (a 'no-flow' boundary). If this location results in a thinner aquifer than assumed, or if the boundary amplifies the tidal response, then this would increase the calculated K value. The degree of confinement in this bore is also not known, but could be significant given its urban location.

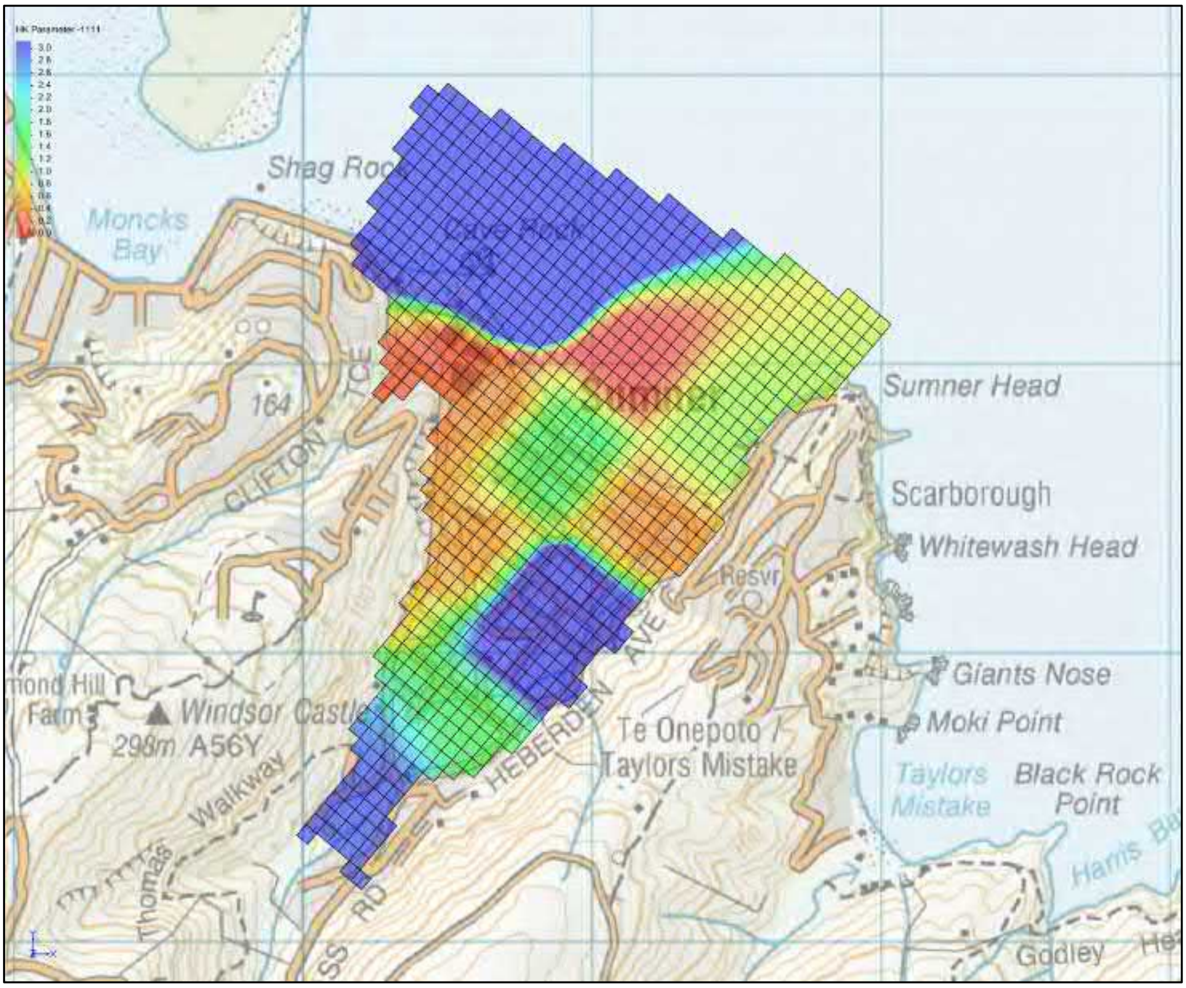


Figure 19: Conductivity distribution in Sumner model

Tidal Analysis Conclusions

A single bore was analysed for tidal response to estimate a Kh value for the Sumner aquifer. The value may not be representative of the aquifer as a whole, and the tidal response in this bore may have been influenced by the urban setting and the proximity to a no flow boundary. However, the results suggest that Kh values in this aquifer are greater than those used in the current model. If the current Sea level is higher than that in the model, then seabed conductance, aquifer Kh, or both, will need to increase to maintain the match to groundwater levels.

References

Fetter, CW (2001): *Applied Hydrogeology*. Prentice Hall Publishing

GMS (2019): *Groundwater Modelling System (version 10.4.4, 64-bit).* Software developed and supported by Aquaveo LLC (USA). (USA). Final build date 3 May 2019. Copyright 2019.

Jiao, J; Post, V (2019): *Coastal Hydrogeology*. Cambridge: Cambridge University Press.

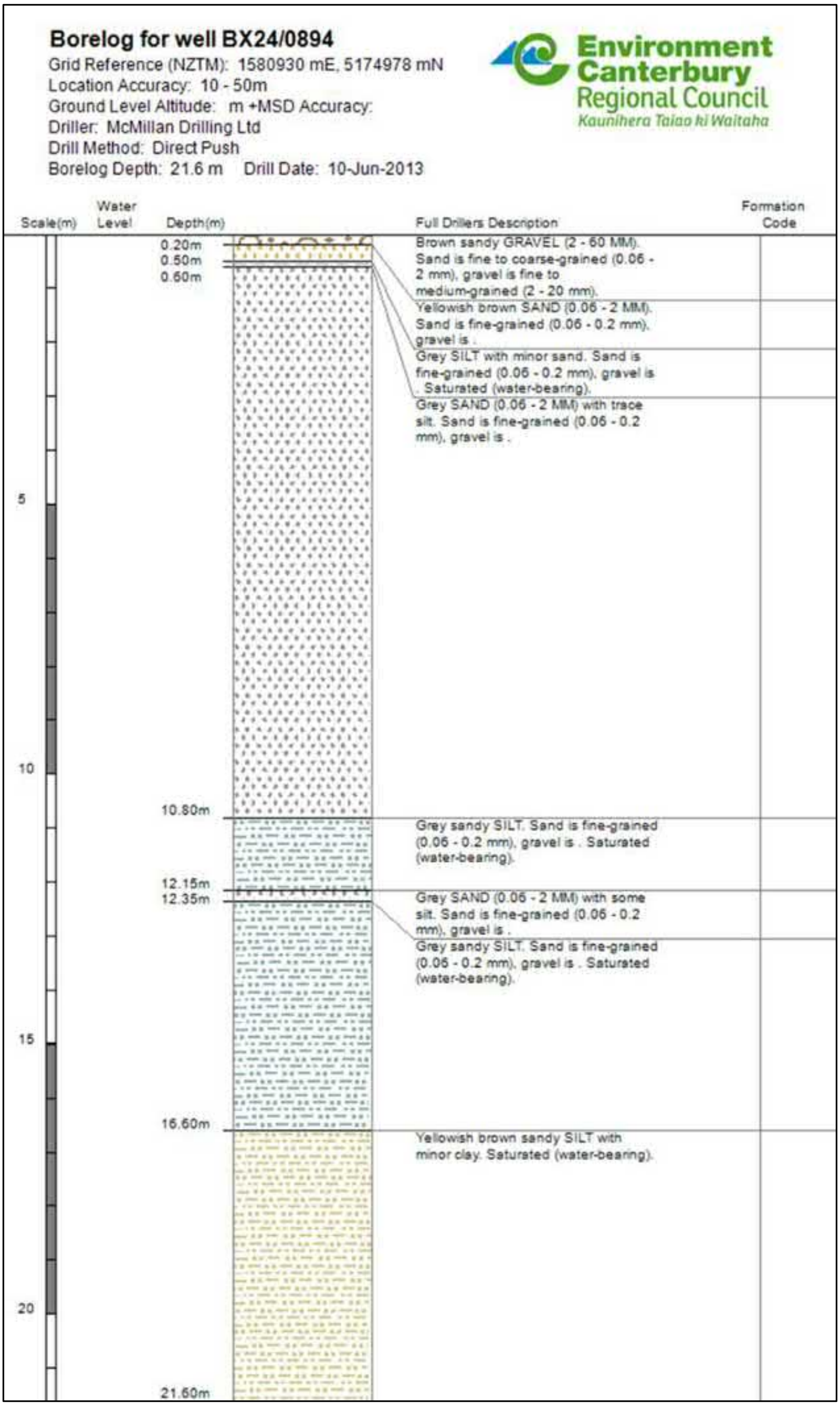
Niswonger, RG; Panday, S; Ibaraki, M (2011): *MODFLOW-NWT, A Newton formulation for MODFLOW-2005.* US Geological Survey Techniques and Methods 6-A37.

Steinhage, F; Rutter, H; Cox, S (2014): *Surface water-groundwater interaction, lower Avon/Otakaro River, Christchurch, New Zealand.* Hydrological Society of New Zealand Conference, 2014.

van Ballegooy, S; Cox, SC; Thurlow, C; Rutter, HK; Reynolds, T; Harrington, G; Fraser, J; Smith, T (2014): *Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake. Version 2*. Lower Hutt, N.Z.: GNS Science. GNS Science report 2014/18-*2005.*

Weir, JJ (2018): *Canterbury Groundwater Model 3. Model Documentation.* Prepared for MBIE Wheel of Water Research. Aqualinc report C1506611. 17 August 2018.

Appendix A: Bore Logs



Borelog for well BX24/2667

Grid Reference (NZTM): 1580421 mE, 5174814 mN
Location Accuracy: 10 - 50m
Ground Level Altitude: m +MSD Accuracy:
Driller: Pro Drill Diamond Drilling
Drill Method: Rotary Rig
Borelog Depth: 21.5 m Drill Date: 31-Oct-2013

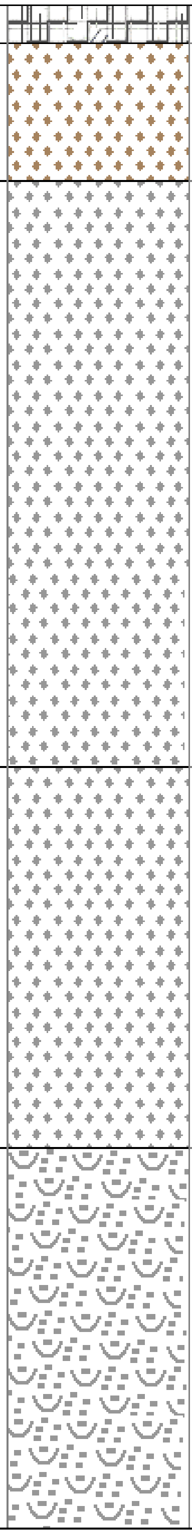
Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		1.40m	Brown sandy GREYWACKE with some silt. Sand is fine to coarse-grained (0.06 - 2 mm), gravel is fine to medium-grained (2 - 20 mm). Gravels are sub-rounded. Saturated (water-bearing).	
		2.00m	Brown silty SAND (0.06 - 2 MM). Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
		2.40m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
		3.60m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine to medium-grained (0.06 - 0.6 mm), gravel is . Saturated (water-bearing).	
		4.10m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine to medium-grained (0.06 - 0.6 mm), gravel is . Saturated (water-bearing).	
		4.30m	Dark grey silty SAND (0.06 - 2 MM). Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
5		5.90m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
		8.30m	Dark brown SAND (0.06 - 2 MM) with some silt. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
		8.80m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine to medium-grained (0.06 - 0.6 mm), gravel is . Unsaturated (dry or moist).	
10		11.10m	Dark grey SAND (0.06 - 2 MM) with trace silt. Sand is fine to coarse-grained (0.06 - 2 mm), gravel is . Saturated (water-bearing).	
		11.80m	Dark grey silty SAND (0.06 - 2 MM). Sand is fine to medium-grained (0.06 - 0.6 mm), gravel is . Saturated (water-bearing).	
		14.80m	Dark grey SAND (0.06 - 2 MM) with some silt, trace shells. Sand is fine to medium-grained (0.06 - 0.6 mm), gravel is . Saturated (water-bearing).	
15		15.70m	Grey silty SAND (0.06 - 2 MM). Sand is fine-grained (0.06 - 0.2 mm), gravel is . Unsaturated (dry or moist).	
		16.30m	Grey SAND (0.06 - 2 MM) with some silt. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	
		16.60m	Grey silty SAND (0.06 - 2 MM) with trace clay. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Unsaturated (dry or moist).	
		16.80m	Grey sandy SILT with some clay. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Unsaturated (dry or moist).	
		17.30m	Grey clayey SILT. Saturated (water-bearing).	
		18.35m	Brown SILT with some clay, trace shells. Unsaturated (dry or moist).	
20		21.45m	Grey clayey SILT with trace sand. Sand is fine-grained (0.06 - 0.2 mm), gravel is . Saturated (water-bearing).	

Borelog for well N36/0169

Grid Reference (NZTM): 1580954 mE, 5175577 mN
Location Accuracy: 10 - 50m
Ground Level Altitude: 3.0 m +MSD Accuracy: < 2.5 m
Driller:
Drill Method:
Borelog Depth: 6.0 m Drill Date: 02-Jul-1989

Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha

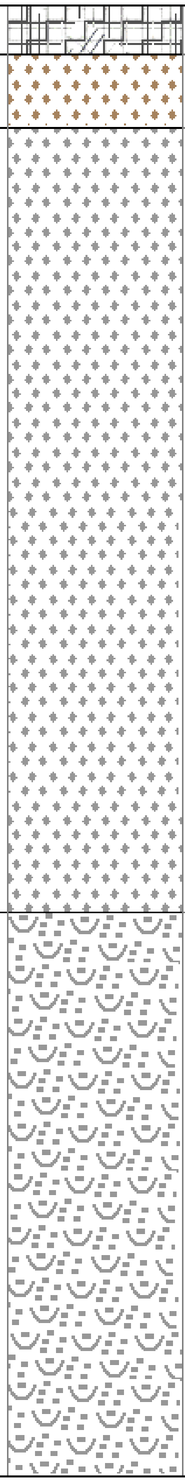


Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		0.15m	brown grey non-cohesive dry road metal	
		0.70m	light brown non-cohesive moist dune sand	
1, 2		3.00m	dark grey non-cohesive wet dune sand	
3, 4		4.50m	dark grey non-cohesive saturated dune sand	
5		6.00m	dark grey non-cohesive saturated dune sand and shells	

Borelog for well N36/0174

Grid Reference (NZTM): 1581229 mE, 5175441 mN
Location Accuracy: 10 - 50m
Ground Level Altitude: 3.0 m +MSD Accuracy: < 2.5 m
Driller:
Drill Method:
Borelog Depth: 6.0 m Drill Date: 02-Jul-1989

Environment Canterbury Regional Council
Kaunihera Taiao ki Waitaha



Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		0.20m	brown grey non-cohesive dry road metal	
		0.50m	light brown non-cohesive moist dune sand	
1, 2, 3		3.70m	grey non-cohesive wet saturated dune sand	
4, 5		6.00m	grey non-cohesive saturated dune sand with some shells	

Appendix 3: N36/0247 Bore log

URS New Zealand

BORE HOLE LOG

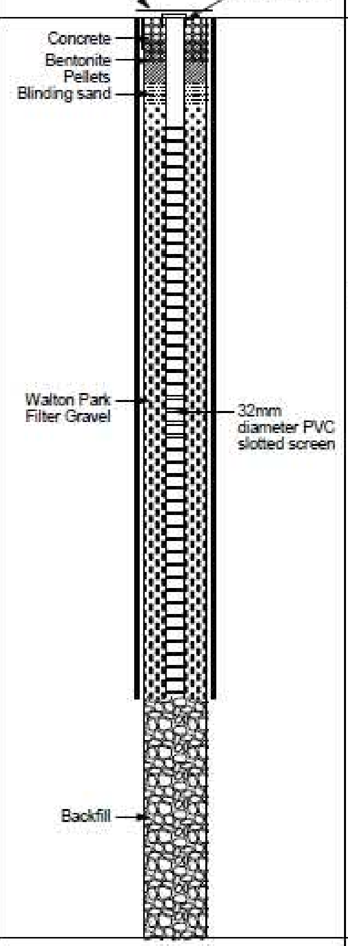
MW102

Sheet 1 of 1

URS New Zealand Limited 287 Durham Street, Christchurch	Phone: (03) 374 8500 Fax: (03) 377 0655	Project No.: 42763026	Project Name: Shell Ex-Marine Service Station
Drilling Contractor: McMillans		Survey Grid: Level Datum:	
Drill Type: Hollow Stem Auger	Logged By: TF Checked By: GO Date Started: 3-4-09 Date Finished: 3-4-09	Reduced Level: m Coordinates: 5737551.00 mN 2490542.00 mE	Client: Shell New Zealand Ltd
		Consent No: N36/0247	Location: Sumner, Christchurch

SOIL SAMPLE ID	SAMPLE DEPTH	ANALYSIS	PID (ppm)
MW102	0.5m	TPH, BTEX	7.9
MW102	1.2m		11.2
MW102	1.5m	TPH, BTEX	11.2
MW102	2.8m	TPH, BTEX	11.9
MW102	4.0m		

WELL CONSTRUCTION



DRILL WATER COMMENTS: water level at approx. 1.25 m

DEPTH (m)	DESCRIPTION OF STRATA	STAINING/ ODOURS AND COMMENTS	GUIDELINE CLASSIFICATION
0	ASPHALT (3cm)	No hydrocarbon odour or staining	
	Brown sandy gravel FILL, dry.	No hydrocarbon odour or staining	1
0.5	Borwn fine to Coarse SAND, dry.	No hydrocarbon odour or staining	1
1.2	grey fine to Coarse SAND, damp. (wet from 1.3 m)	No hydrocarbon odour or staining	1
1.8	Grey fine to medium SAND, wet.	No hydrocarbon odour or staining	1
3.0	Grey fine to medium SAND with some silt, wet, with some white shell fragments.	No hydrocarbon odour or staining	1
4.2	Bore terminated at 4.2 m at target depth		

REMARKS:

Well Monitoring Data Date/Time	Level	Comments

Monitoring Point: Top of PVC

MfE (1999) Guideline Classification

1. SAND, sandy loams, silty sands
2. SANDY SILT, silt, silty loams, clayey sands
3. SILT CLAY, clay loam (clayey silt), sandy clay
4. CLAY
5. Pumice
6. Peats and Highly Organic Soils
7. Gravels
8. Fractured Basalt

J:\JOBS\42763026\5 WORKS\SHELL MARINE BORE LOGS.GPJ   Print Date: 16/4/09

Appendix F: Sensitivity analyses

Aqualinc has been commissioned by Christchurch City Council (CCC) to undertake simple sensitivity analyses on the sea level rise (SLR) scenarios presented for the LDRP45 programme. The sensitivity work undertaken comprises:

- Sensitivity of groundwater levels to horizontal hydraulic conductivity near the coast;
- Sensitivity of groundwater levels to land surface recharge; and
- Prediction of the time taken for groundwater levels to equilibrate after a change in sea level.

Results of these analyses are presented below.

F.1 Sensitivity to Coastal Aquifer Parameters

The sensitivity of groundwater levels to horizontal hydraulic conductivity (Kh) in the coastal Christchurch area has been assessed by altering the values in the shallow (uppermost) model layers. The Kh values were altered in an area spanning from the off-shore model boundary to approximately 10 km inland from the coast, as shown in Figure 1.

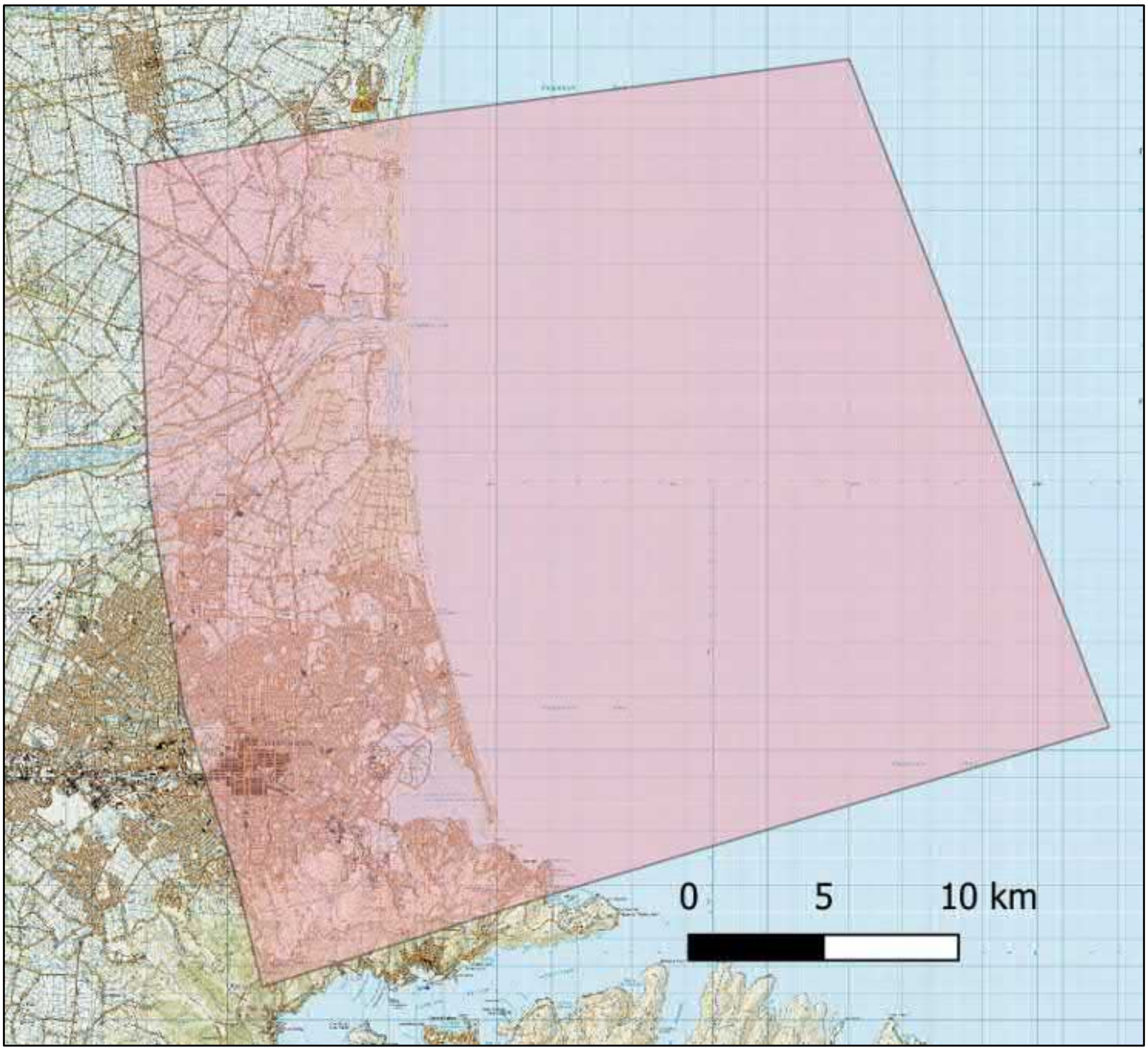


Figure 1: Area of change in Kh values

Both 0 m and 1 m SLR scenarios were then run to test the effects of changes in Kh on the prediction of SLR. Two scenarios were tested: 0.1 x initial Kh, and 10 x initial Kh. The results were subtracted from the original scenario values to derive the response in groundwater levels from these changes. The results are presented in Figures 2 to 6, as follows:

- Figure 2 presents the change in groundwater levels due to a 1 m increase in sea level under the base scenario (no change in Kh), for comparison.
- Figure 3 shows the change in groundwater levels as a result of a 1 m rise in sea level with a 10 x increase in horizontal hydraulic conductivity in the coastal area.
- Figure 4 shows the increase in groundwater levels as a result of a 1 m rise in sea level with a 10 x decrease in horizontal hydraulic conductivity in the coastal area.
- Figures 5 and 6 present the difference in these differences to demonstrate how sensitive the model predictions of SLR are to Kh values for use in other areas of the study.

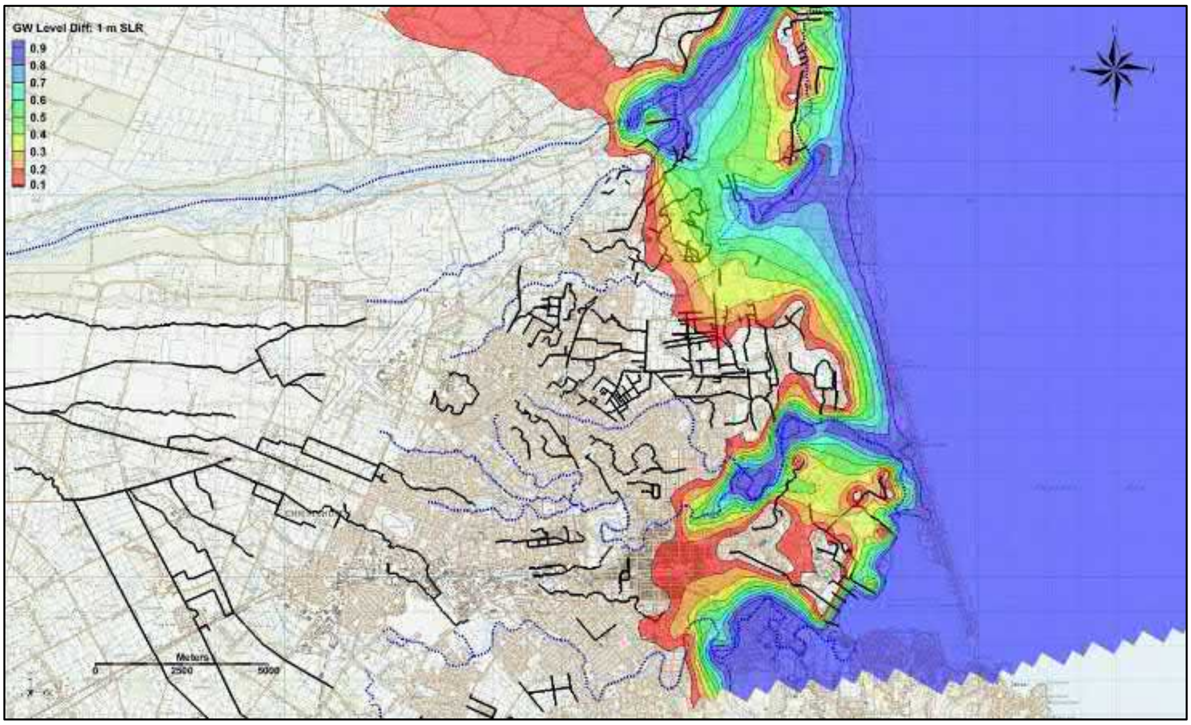


Figure 2: Difference between baseline and 1 m SLR scenarios: base scenario

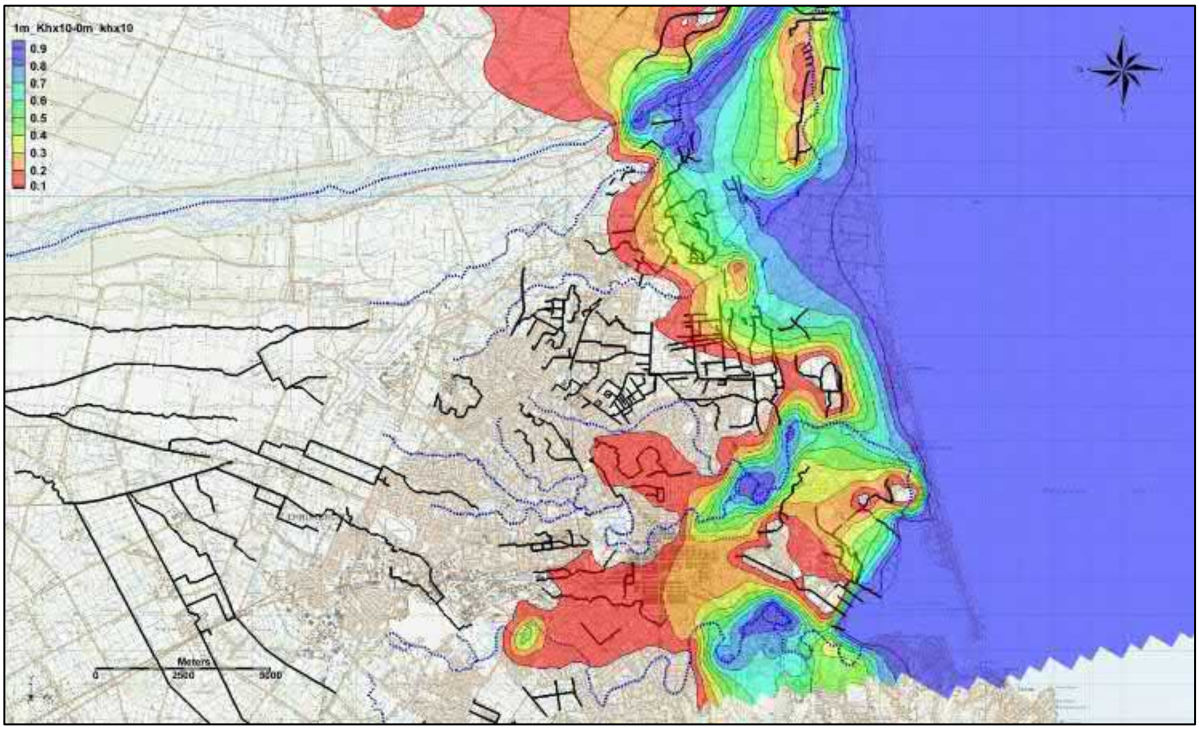


Figure 3: Difference between baseline and 1 m SLR scenarios: 10 x coastal Kh

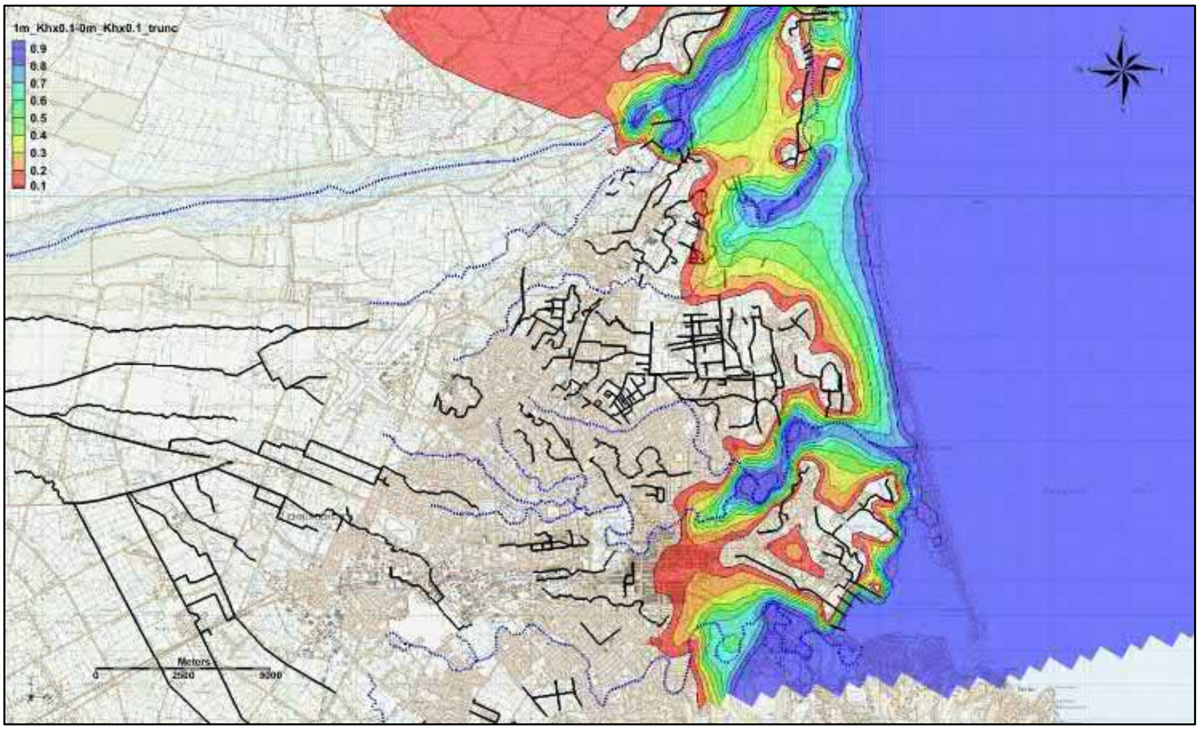


Figure 4: Difference between baseline and 1 m SLR scenarios: 0.1 x coastal Kh

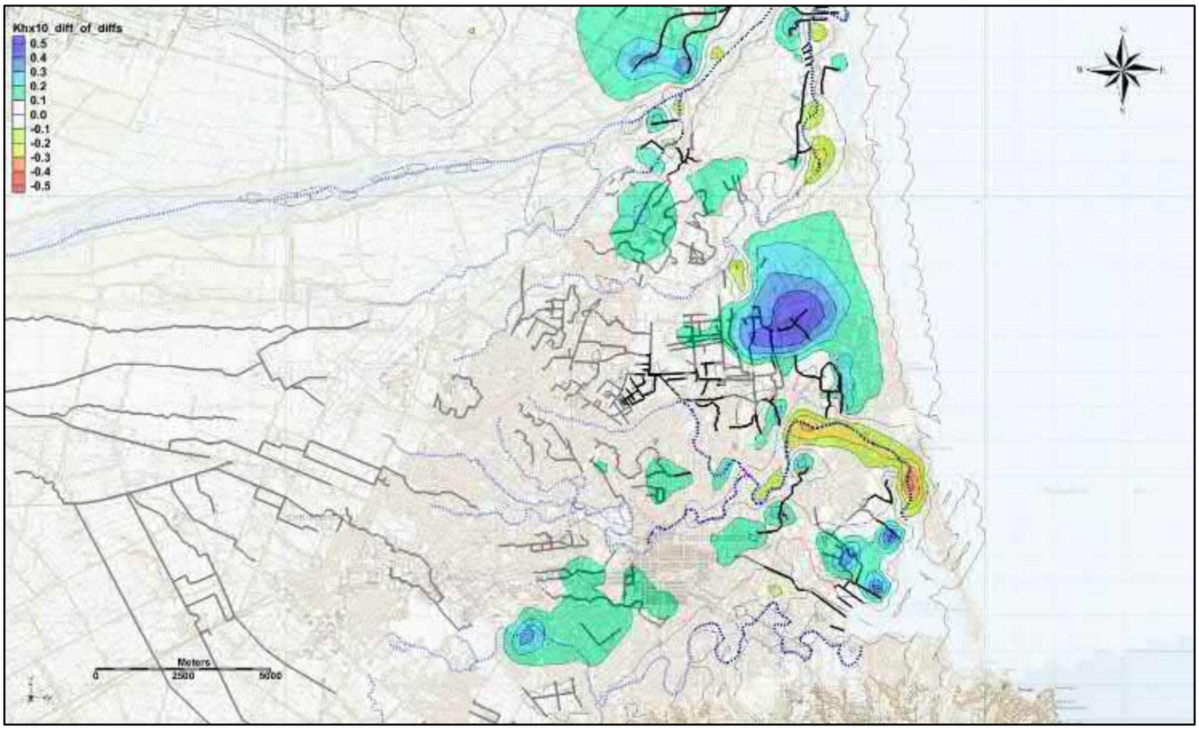


Figure 5: Difference between the 10 x Kh SLR prediction and the original Kh SLR prediction.

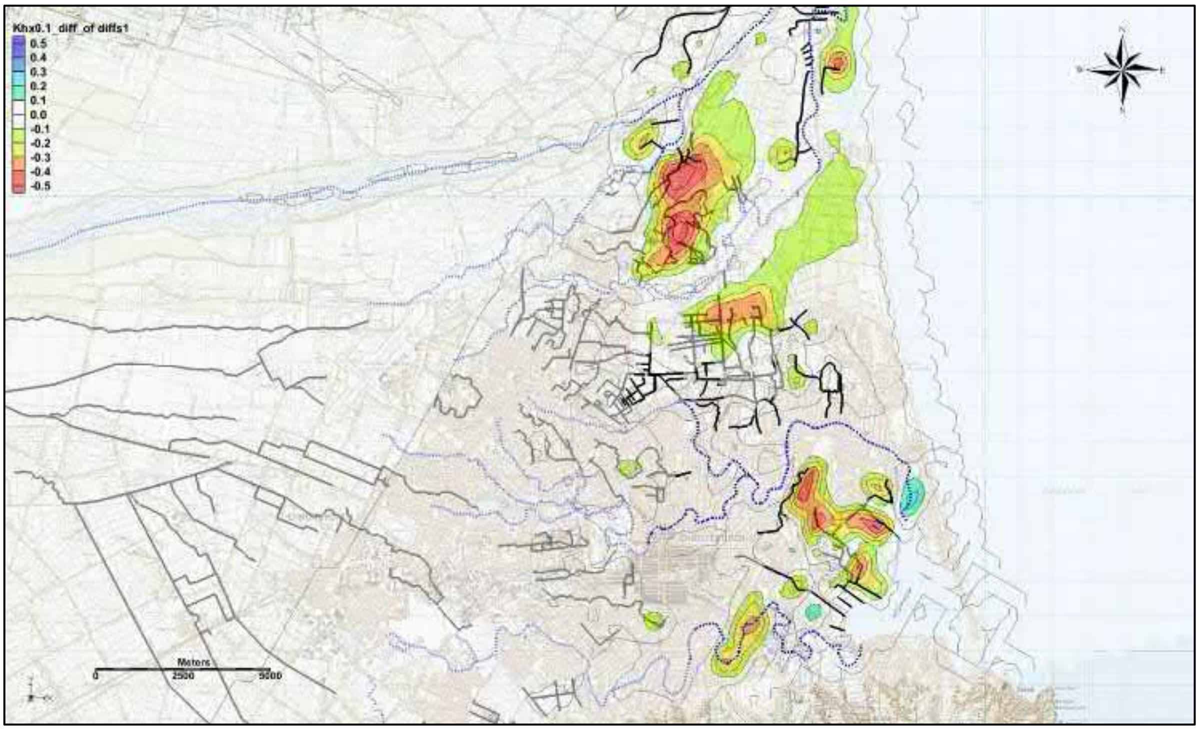


Figure 6: Difference between the 0.1 x Kh SLR prediction and the original Kh SLR prediction

From Figure 2-4, changing Kh in the coastal area results in minimal change in the predicted SLR for much of the city and eastern suburbs. The larger changes occur in areas of drains where the base groundwater level changes relative to the local stream invert. For example, under the scenario of higher Kh, absolute groundwater levels are generally lower than measured, and lower than the local drain invert in some areas. Therefore, with 1 m SLR, the groundwater level is able to rise more (compared to the original Kh scenario) before the stream is able to regulate the groundwater level.

Conversely, under the scenario of lower Kh, groundwater levels are higher, and so streams regulate groundwater levels changes more effectively in some areas, reducing the capacity for change from sea level rise. However, under scenarios of different Kh, the model does not match measured groundwater levels as well as the original Kh scenario (it is less calibrated). Therefore, the predicted *changes* due to sea level rise under altered Kh scenarios are not the best predictor of the response that is likely to occur.

The impact of model sensitivity to the overall LDRP45 project is indicated by the changes in predicted groundwater level *change,* as shown by Figures 5 and 6. The larger positive differences in Figure 5 tend to occur near the drains. As noted above, the starting elevation of the baseline groundwater levels relative to the drain inverts influence the potential rise. Hence, the larger rises due to SLR occur from a lower starting elevation. Similarly, the larger negative differences in Figure 6 result from a base level that is higher compared to the drain inverts (reduced Kh raises absolute groundwater levels in places), and so the change is negative compared to the baseline change. This again highlights the effect on shallow groundwater levels that the drains and streams impose.

F.2 Sensitivity to Land surface Recharge

To test the sensitivity of the model to land surface recharge (LSR), two scenarios were considered: a 20% reduction in LSR and a 20% increase in LSR. These changes were applied over the entire model domain. Both scenarios were run for the baseline and the 1 m SLR scenarios to derive the influence on the SLR change prediction. Changes due to SLR where then compared to the original baseline change to SLR to quantify the influence on the overall LDRP45 project. The results are presented in Figures 5 to 9, as follows:

- Figure 5 presents the reduction in groundwater levels as a result of 20% less LSR.
- Figure 6 shows the increase in groundwater levels as a result of 20% more LSR.
- Figures 7 and 8 present the change in groundwater levels due to a 1 m sea level rise prediction for the above two scenarios.
- Figure 9 and 10 show the differences between the above two SLR outputs above compared to the baseline SLR prediction, and demonstrate how sensitive the model predictions of SLR are to LSR for use in other areas of the LDRP45 study.

Figures 5 and 6 show similar patterns of change, except the 20% reduction scenario shows negative change whereas the 20 % increase shows positive. Again, there is reduced change around the river and coastal boundaries.

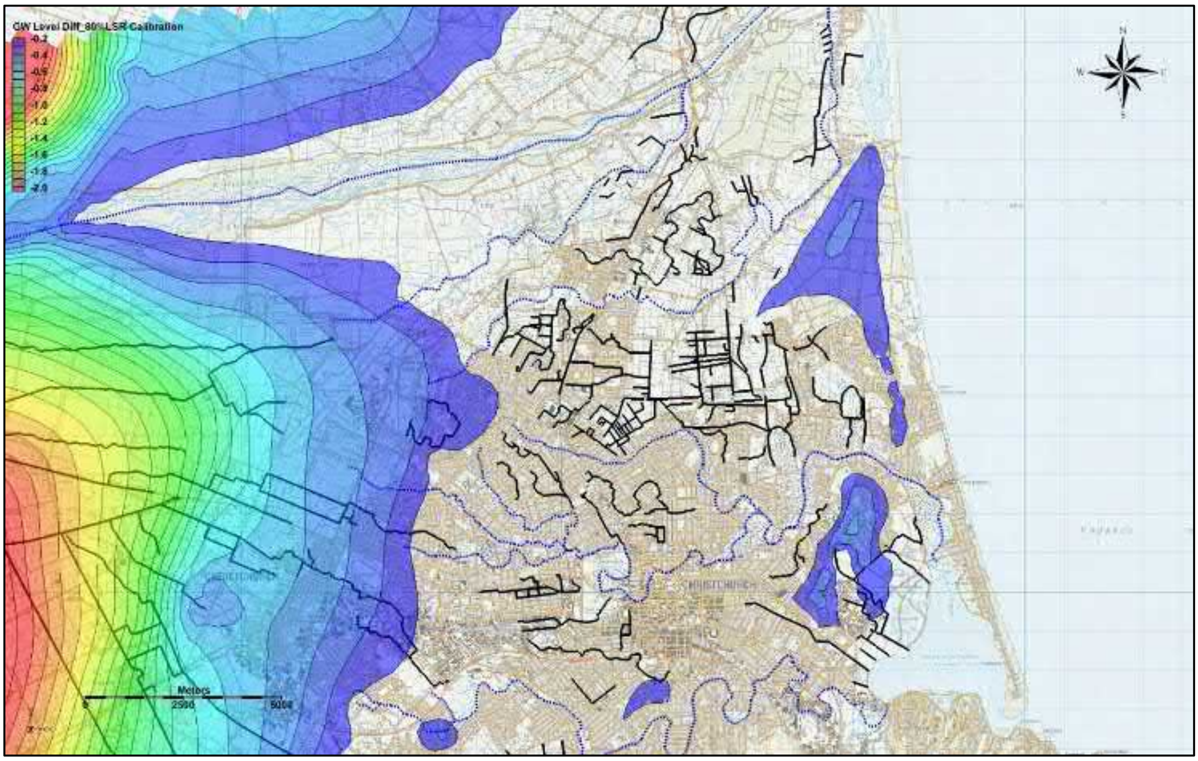


Figure 5: Difference in groundwater levels from a 20% reduction in LSR under the baseline scenario

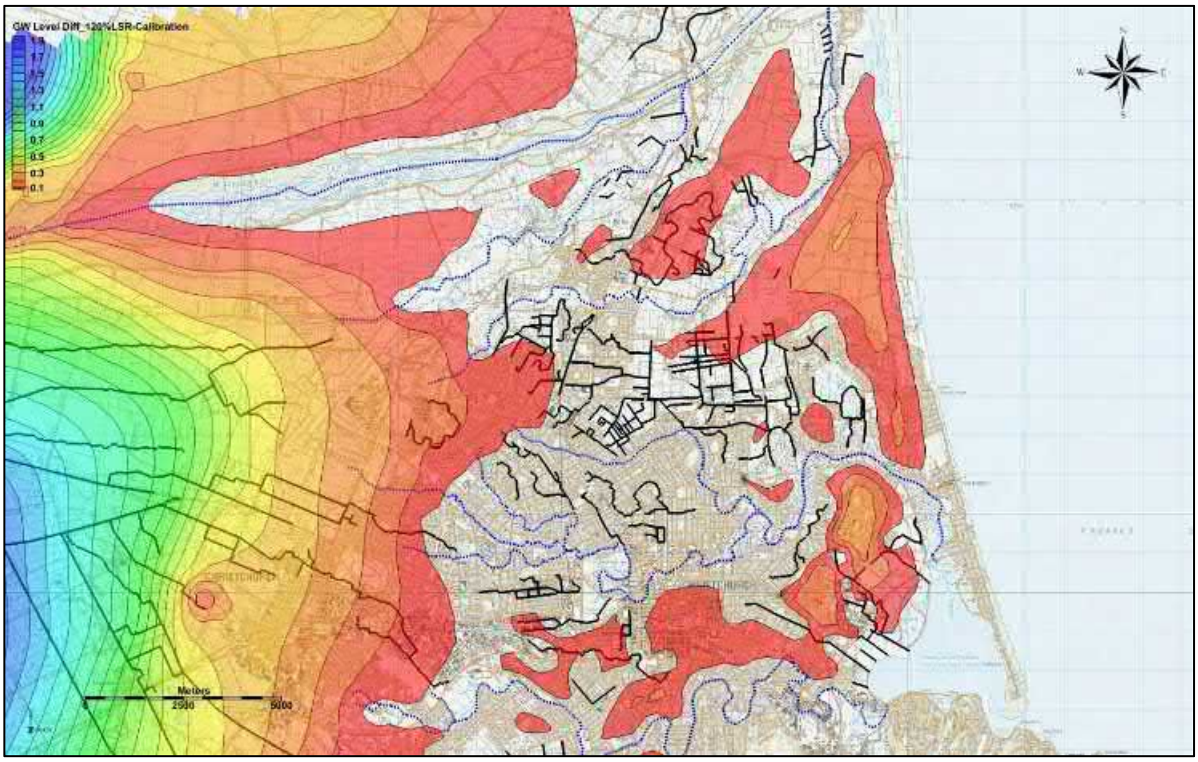


Figure 6: Difference in groundwater levels from a 20% increase in LSR under the baseline scenario

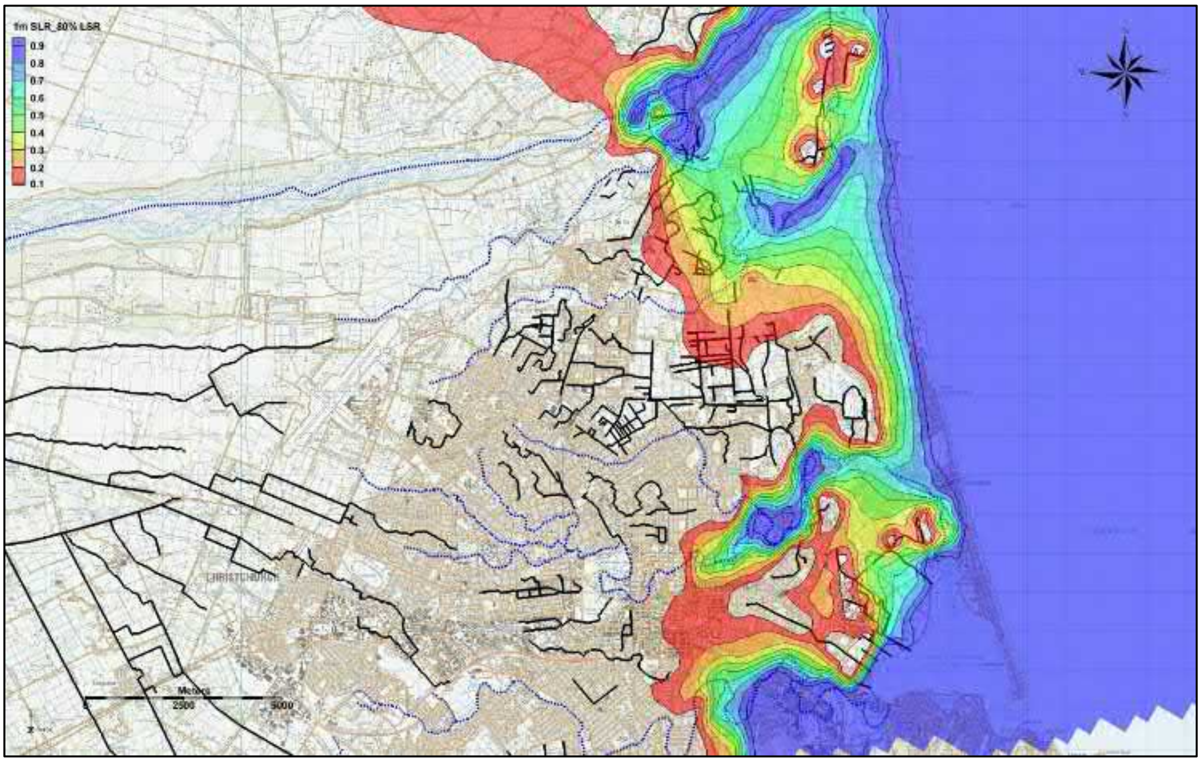


Figure 7: Difference between baseline and 1 m SLR scenarios: 20% less LSR

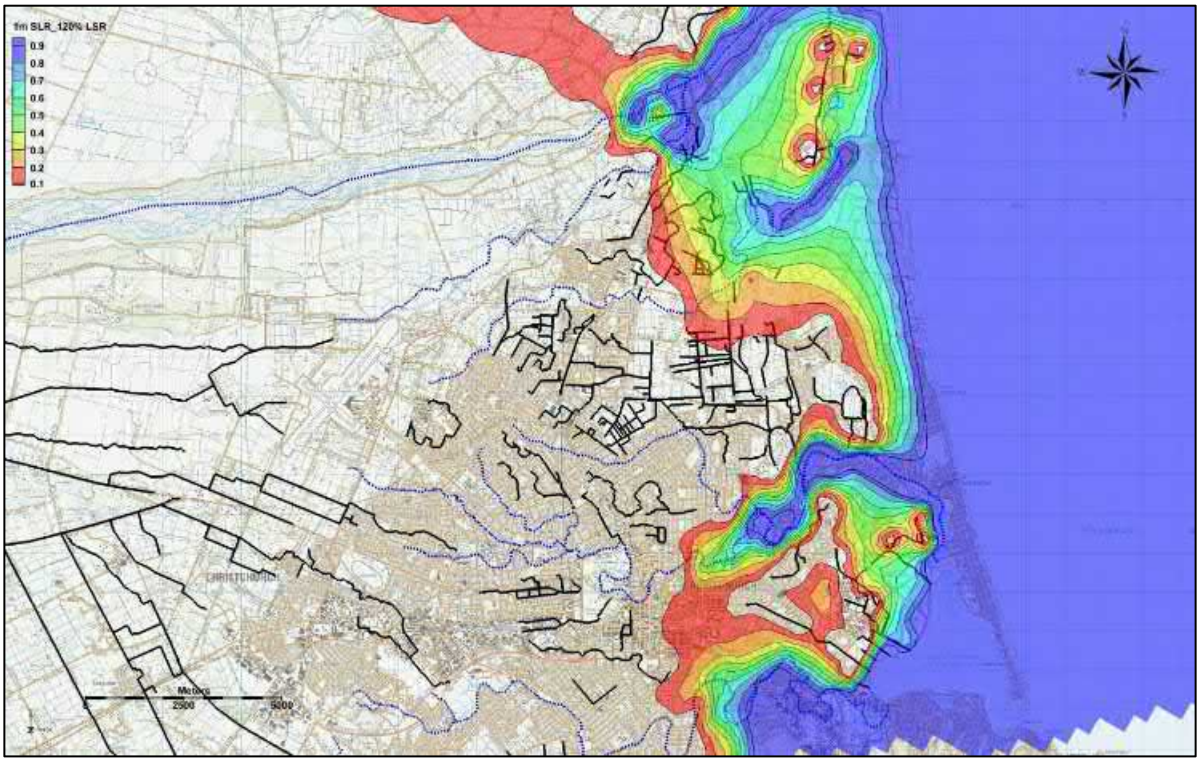


Figure 8: Difference between baseline and 1 m SLR scenarios: 20% more LSR

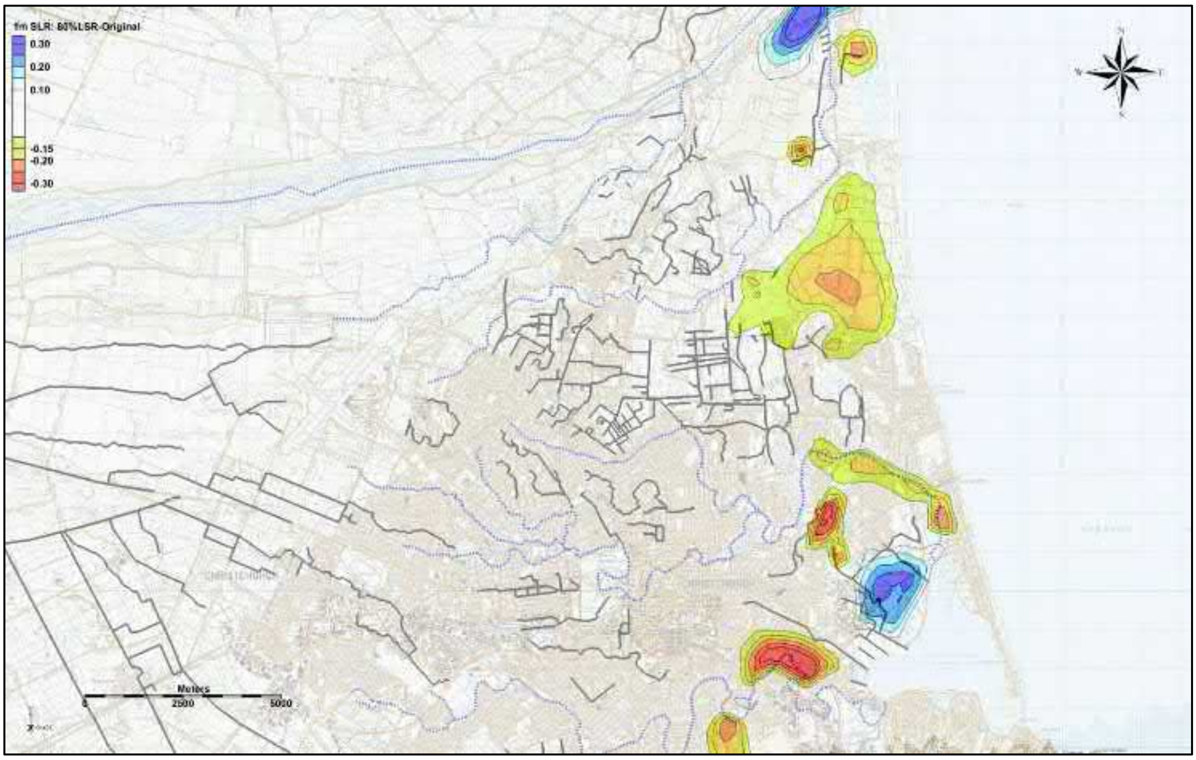


Figure 9: Difference between the 20%-less-LSR SLR prediction and the original SLR prediction

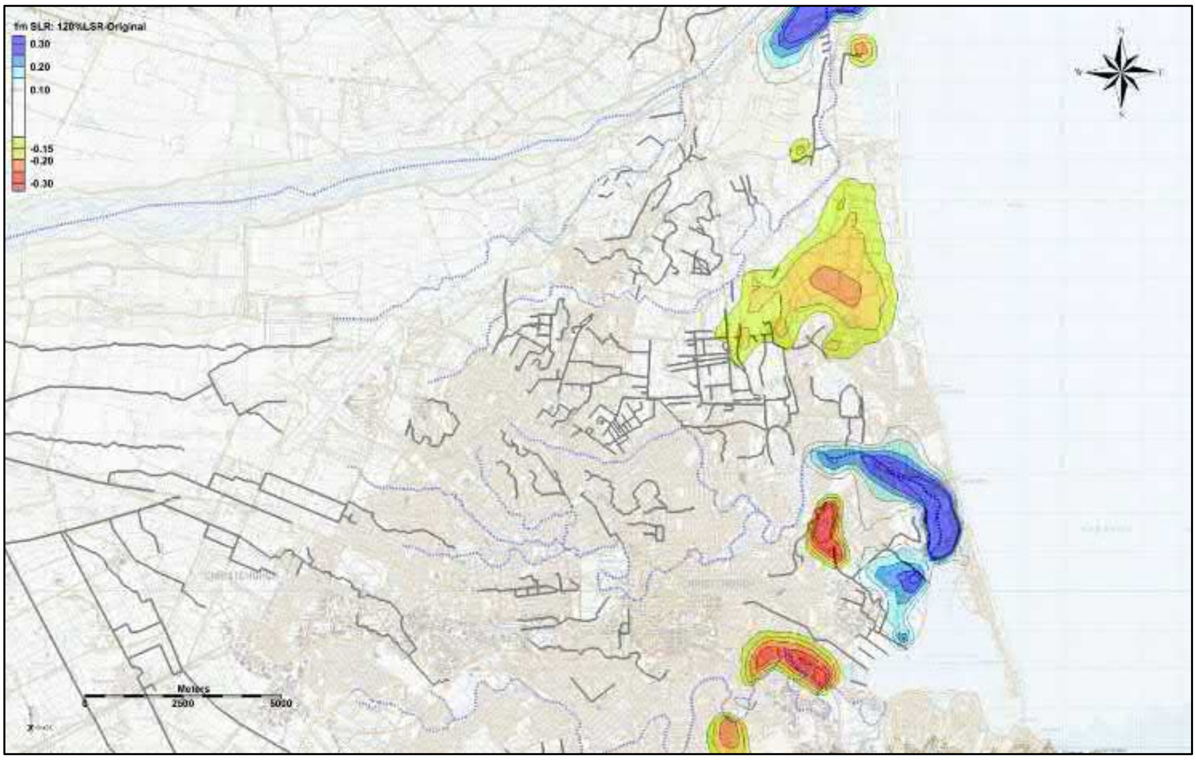


Figure 10: Difference between the 20%-more-LSR SLR prediction and the original SLR prediction

F.3 Test of Groundwater Equilibration Time

To predict the approximate length of time groundwater levels would take to equilibrate after SLR has occurred, a transient model with daily time steps has been run over a five-year duration. Modelled groundwater levels at 12 observation points located in the uppermost aquifer were extracted to assess how rapidly the model equilibrated to a step-change in sea level. Initial heads were set from the base scenario of 0 m sea level, and the model run for the first 10 days with no changes to sea level. Then, sea level was instantaneously raised to 1 m and the transient model left to continue. All other model inputs were set as steady state.

The locations of the 12 observation points are shown in Figure 11. Modelled groundwater levels at each location are shown in Figure 12. For clarity, only the first 100 days of the model run are presented.

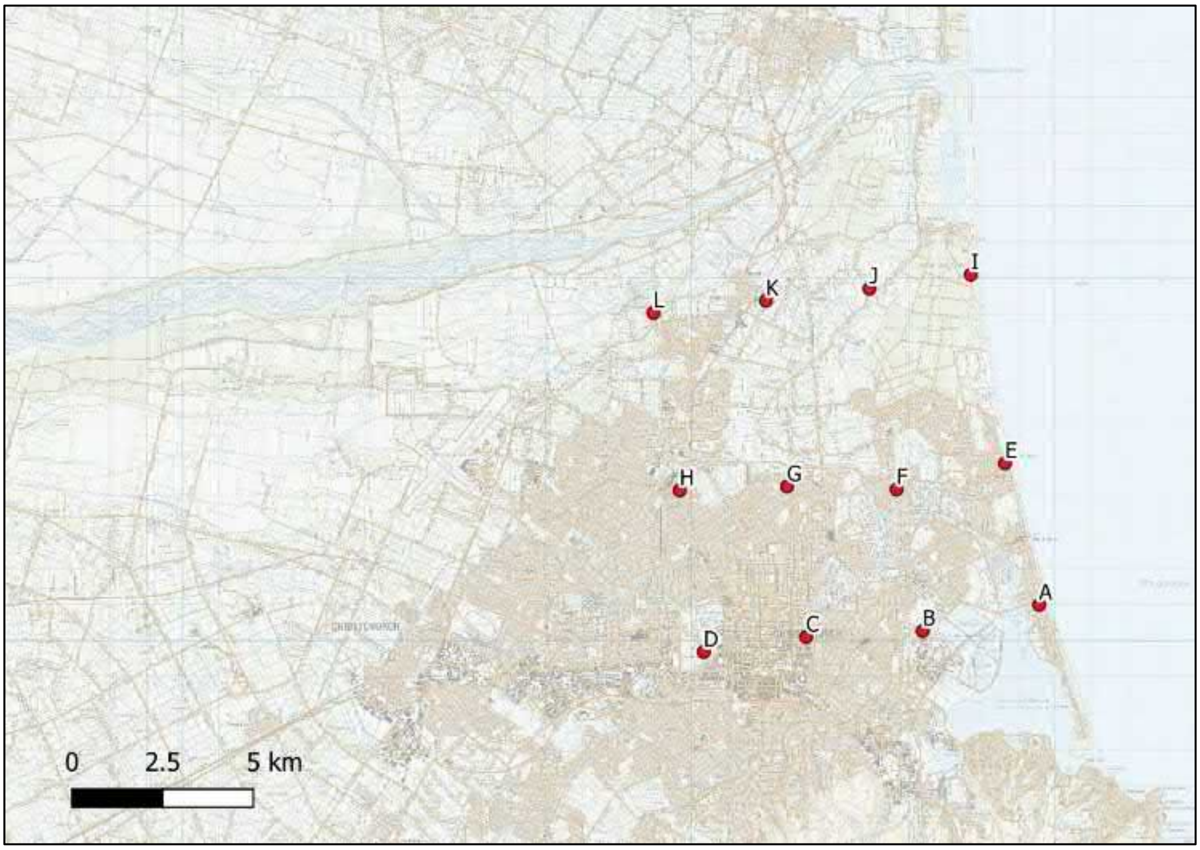


Figure 11: Location of transient groundwater level model outputs

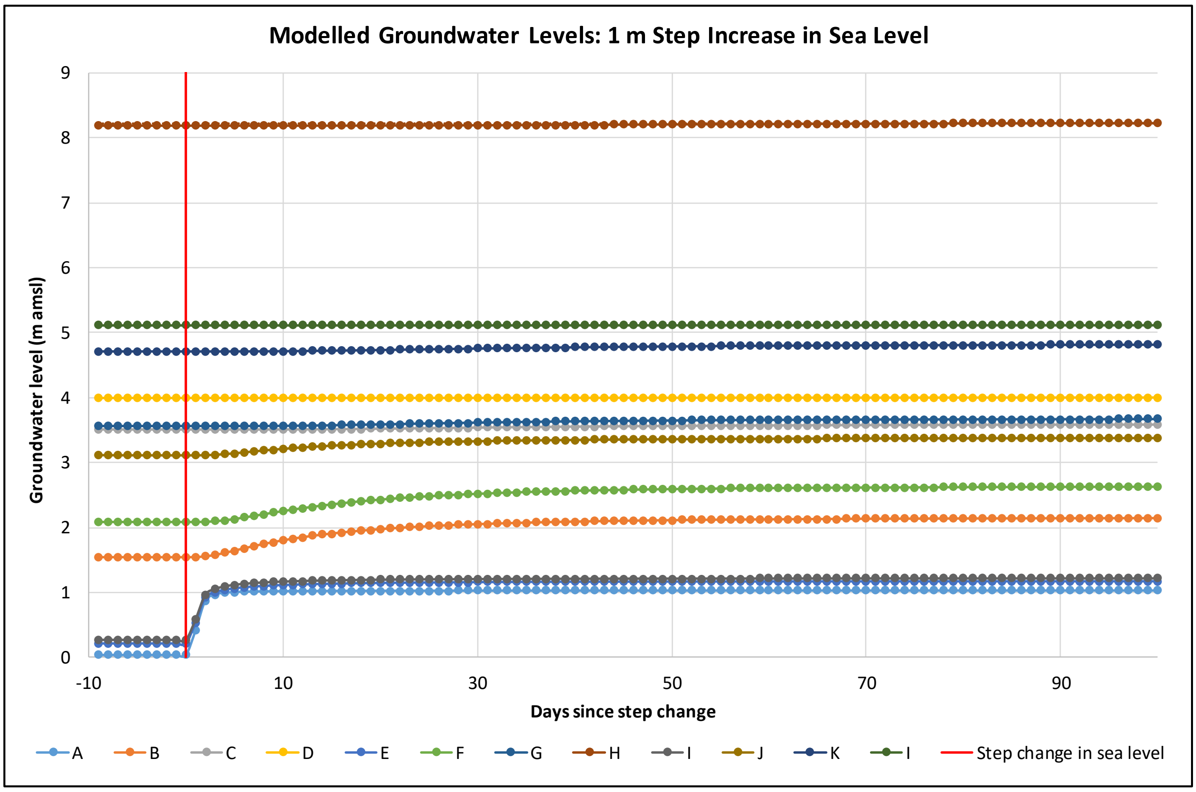


Figure 12: Modelled groundwater levels at designated locations showing a 1 m step sea level change

Figure 12 shows that the modelled 1 m change in sea level largely equilibrated within approximately 10 days after the change for the sites located nearer the coast (A, E, I). Locations further inland (B, F and J) took approximately 30-40 days to equilibrate. Other sites still further inland did not show a noticeable response as a result of the step change. After the initial rapid equilibration, groundwater levels in all locations slowly increase, with a maximum of 0.04 m in five years.

This indicates that the hydraulic response in groundwater levels after a 1 m sea level rise will largely equilibrate after approximately 40 days. This is different to the transport response (say from sea water intrusion) which would take longer to reach a new equilibrium.

A scenario with a step change in SLR is unrealistic. In reality, climate-driven SLR will occur gradually, over a long period of time, and unlikely as a result of a single event as modelled above. The gradual rise in sea level will correspond to a gradual rise in coastal groundwater levels, giving sufficient time to equilibrate.

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AQUALINC RESEARCH LIMITED

Memorandum

To:	Tom Parsons	CCC
From:	Helen Rutter	14/6/2018
Subject:	**Impacts of decommissioning the gravity driven sewer system in the Woolston area**	

Introduction

As an alternative to repairing the earthquake-damaged gravity network system, in various areas within Christchurch, CCC has installed pressure sewer systems and decommissioned the old gravity driven sewer system. As the damaged, gravity system provided a pathway for drainage of shallow groundwater, the impacts of decommissioning are potentially an increase in shallow groundwater levels.

Aqualinc were asked to assess the potential impacts of decommissioning the gravity sewer systems on groundwater in the Woolston area.

There are four piezometers local to areas of Woolston that may show the groundwater impacts of sewer decommissioning (Figure I.1). In Woolston North these are APP86 and APP82; the latter is in an area where the sewer decommissioning has only been partially completed. APP86 is located close to a sewer that has been decommissioned. In Woolston South, there are two piezometers: APP55 and APP80. Data were collected and corrected for barometric variations, then plotted together with the older data. There is a gap in the data due to downloading of the September 2017 to March 2018 data by Tonkin and Taylor: these data will be made available to us at some point in the future.

Shallow Hydrogeology

From the recent LDRP45 project, the area is considered to be characterised by around 4 m of silt, underlain by fine-grained sand, with horizontal permeabilities of 10^{-6} and 10^{-4} m/s respectively. It is anticipated that the old sewers were located in the upper 4m silt layer.

Impacts of sewer decommissioning

Sewer decommissioning started on 3-4th May in Woolston South, and was completed in Woolston North on 8th May. At 11 am on 7th May, a rapid rise in groundwater level started in the area of APP86, the rate of rise decreasing until around 15 hours later, at which time, groundwater levels had risen approximately 0.5m. Groundwater levels in the remaining three piezometers appear to show little impact of sewer decommissioning. The responses are discussed in more detail below.

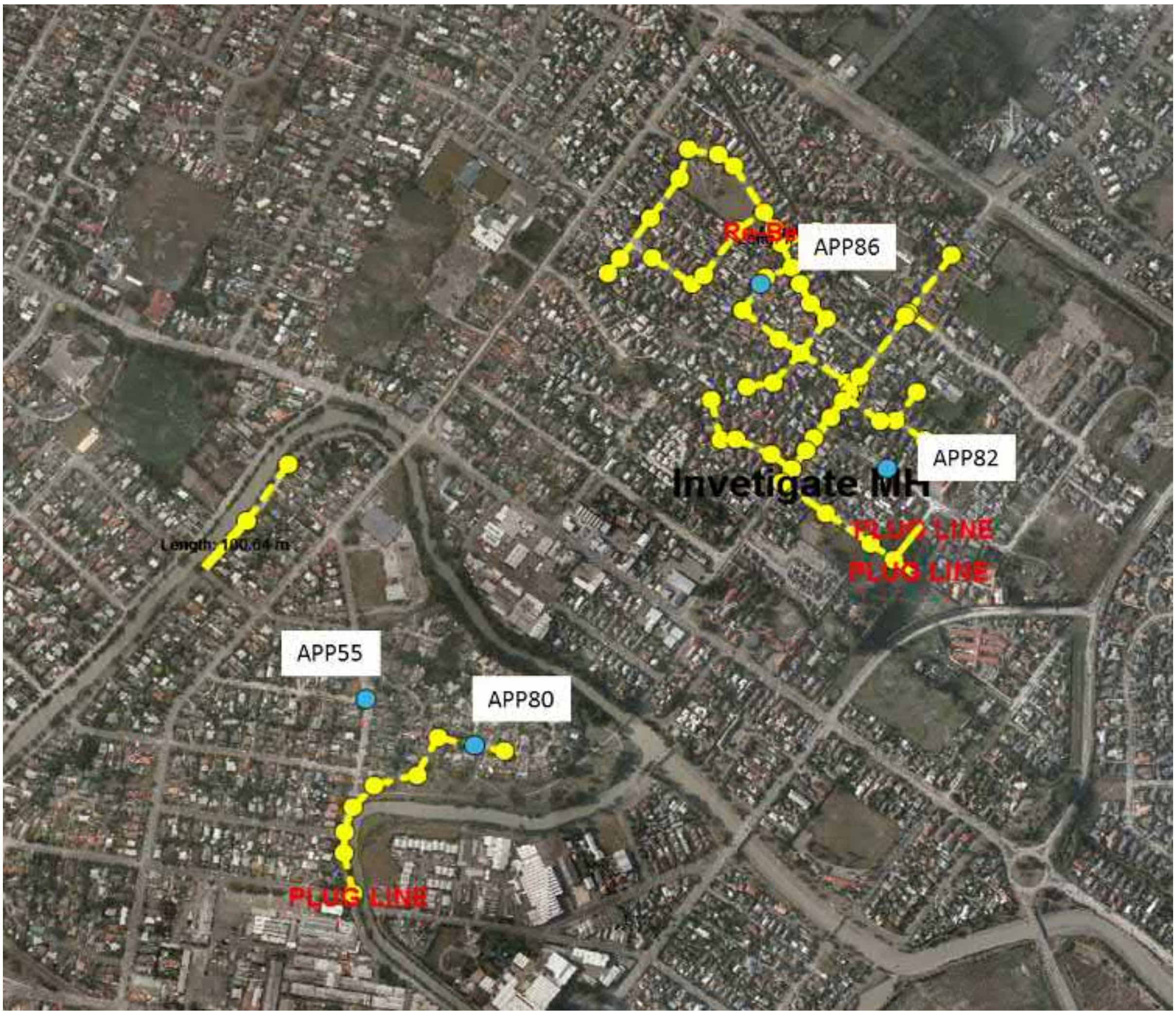

Figure G.1: Location of APP piezometers in the Woolston area, and sewer lines that are due to, or have been, decommissioned.

Woolston North

APP86

APP86 showed an immediate response to the effects of grouting the sewer system, with a groundwater level rise of around 0.5 m (Figure I.2). This appears to have resulted in a permanent offset in groundwater levels, with levels now above any previously recorded levels at the site (Figure I.3). Since the rise, groundwater levels have re-established at around 0.2 m below ground level, but in response to recent rainfall, levels peaked at 3 cm below ground level, indicating a groundwater level very close to surface in areas close to this piezometer. Given the fact that groundwater level peaks of 0.1 to 0.2 m frequently occur in response to rainfall, and that typical winter groundwater levels have been in the range of 0.4 to 0.8 m below ground level, it is quite likely that groundwater levels will rise to the surface on a semi-regular basis.

The effects of grouting the sewers are a simple offset in groundwater levels. Based on the historical data, with a 0.5 m rise in groundwater level, groundwater inundation at the surface will probably occur for one or two days at a time, and could occur several times a year. The actual frequency, magnitude and duration of groundwater inundation will vary depending on antecedent groundwater levels, antecedent soil moisture conditions, season, and magnitude of the rainfall event.

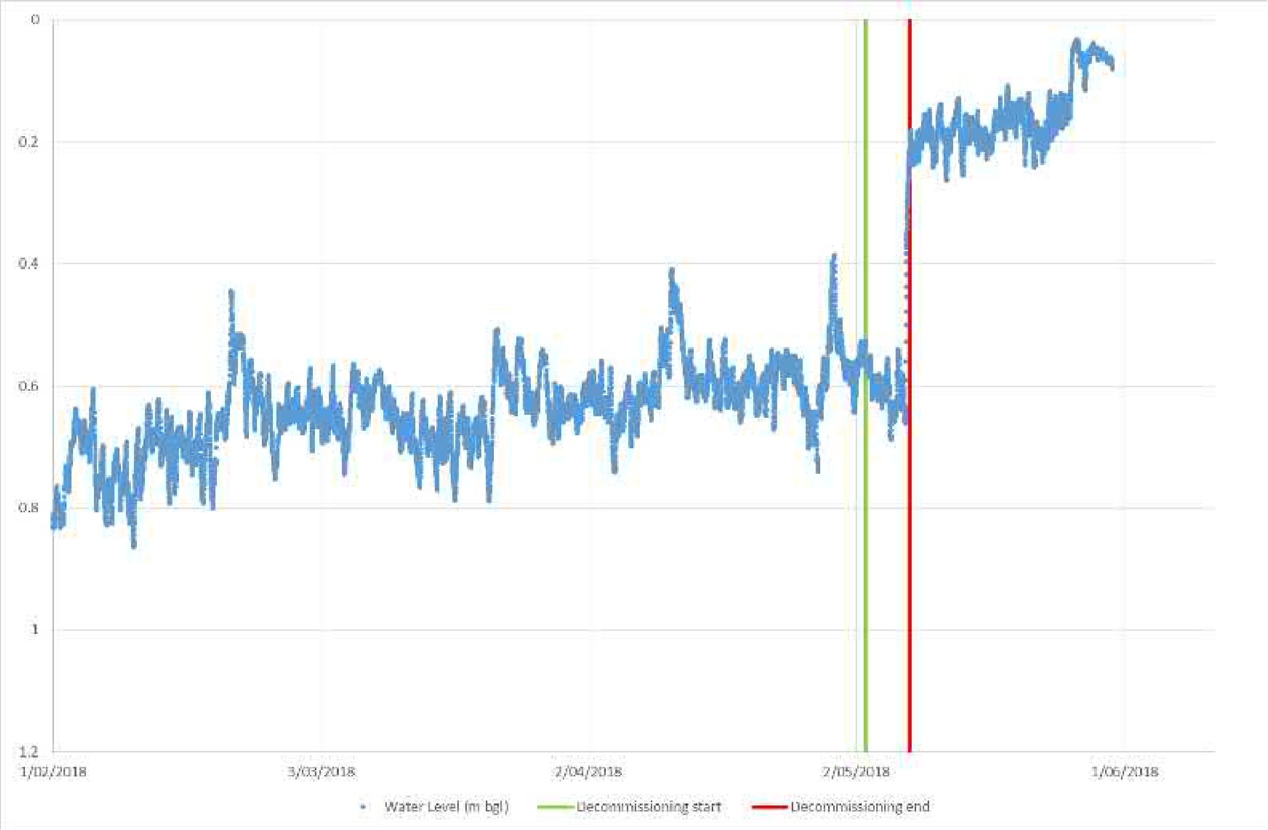

Figure G.2: Short-term groundwater levels in APP86

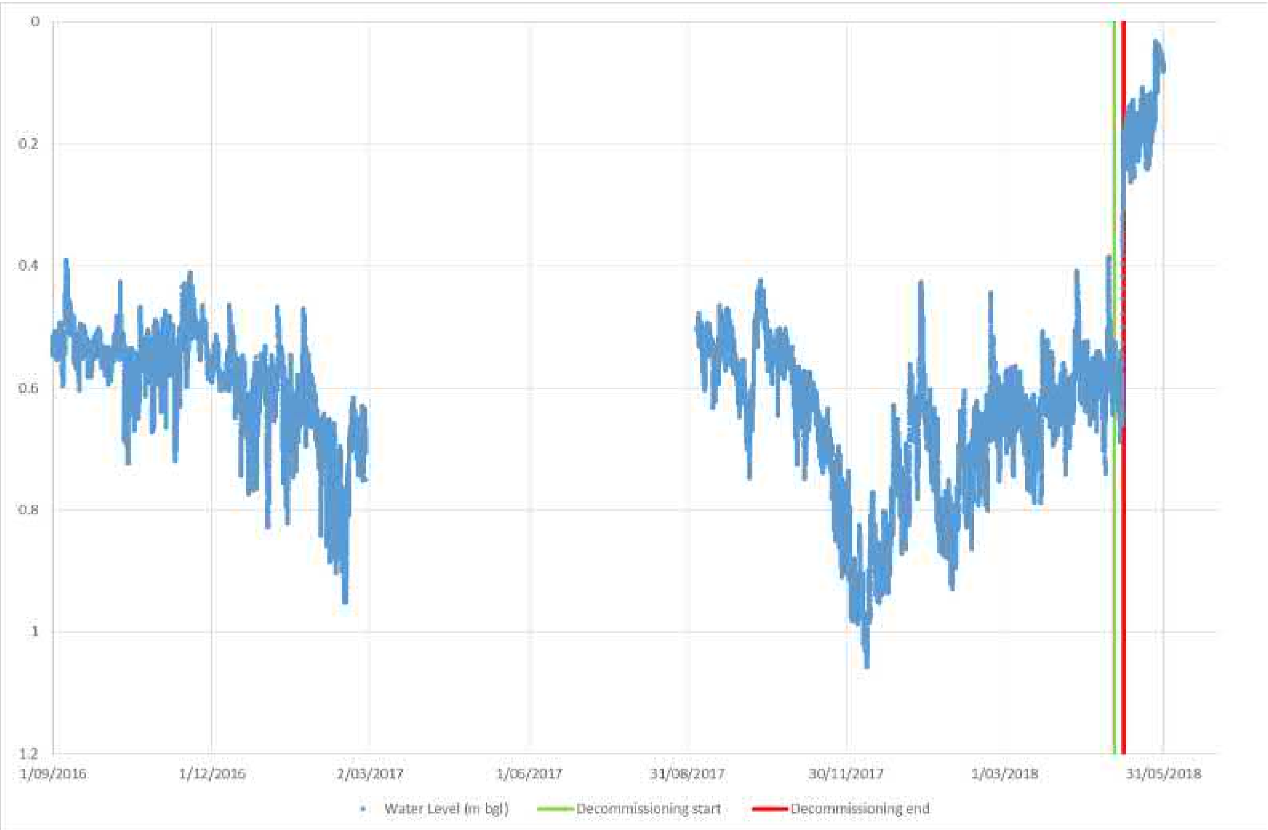

Figure G.3: Longer-term groundwater levels in APP86

APP82

In contrast, APP82 showed no visible response from sewer grouting, as shown in Figure I.4.

Figure G.4: Short-term groundwater levels in APP82

Although groundwater levels rose to the surface at the start of June, Figure I.5 shows that this has occurred on other occasions at this location. In summary, the high groundwater levels in June this year are likely to be a natural occurrence, and unlikely to be a result of grouting the sewer system. APP82 (on St Luke's Rd) is possibly not affected due to (1) the fact that grouting along Clinton Lane hasn't been finished (2) the distance from the grouted sewers (around 100 m). But over-riding this is the fact that the sewer along St Luke's Road (at 1.5 m depth) is not grouted and is still draining groundwater. This doesn't mean that the area is not affected – wherever the sewers have been grouted in this general area, given the response we see at APP86, and the shallow depth to groundwater in this area, it is likely that there would be a groundwater level response.

Figure I.6 compares APP86 and APP82, and clearly illustrates the similarity of the hydrographs, and the offset in groundwater levels at APP86 as a result of the grouting.

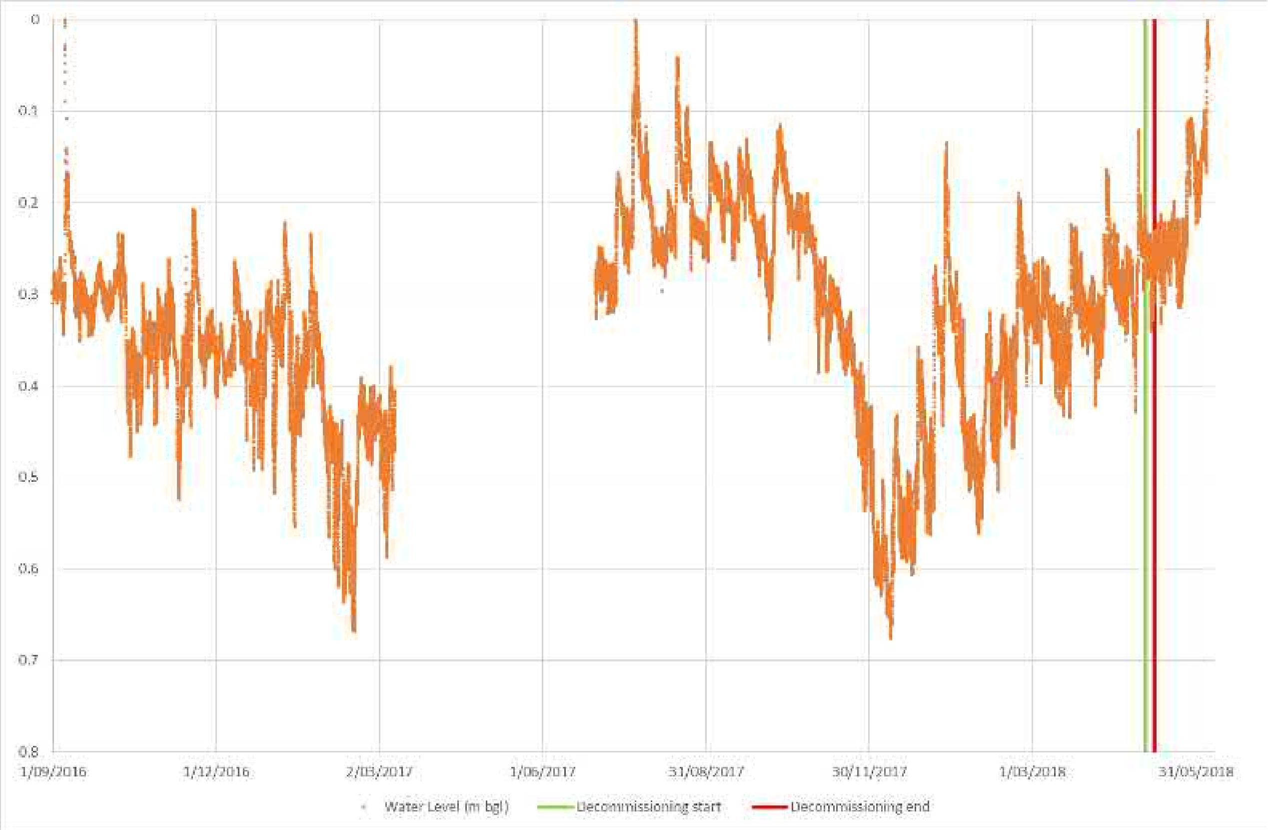

Figure G.5: Longer-term groundwater levels in APP82

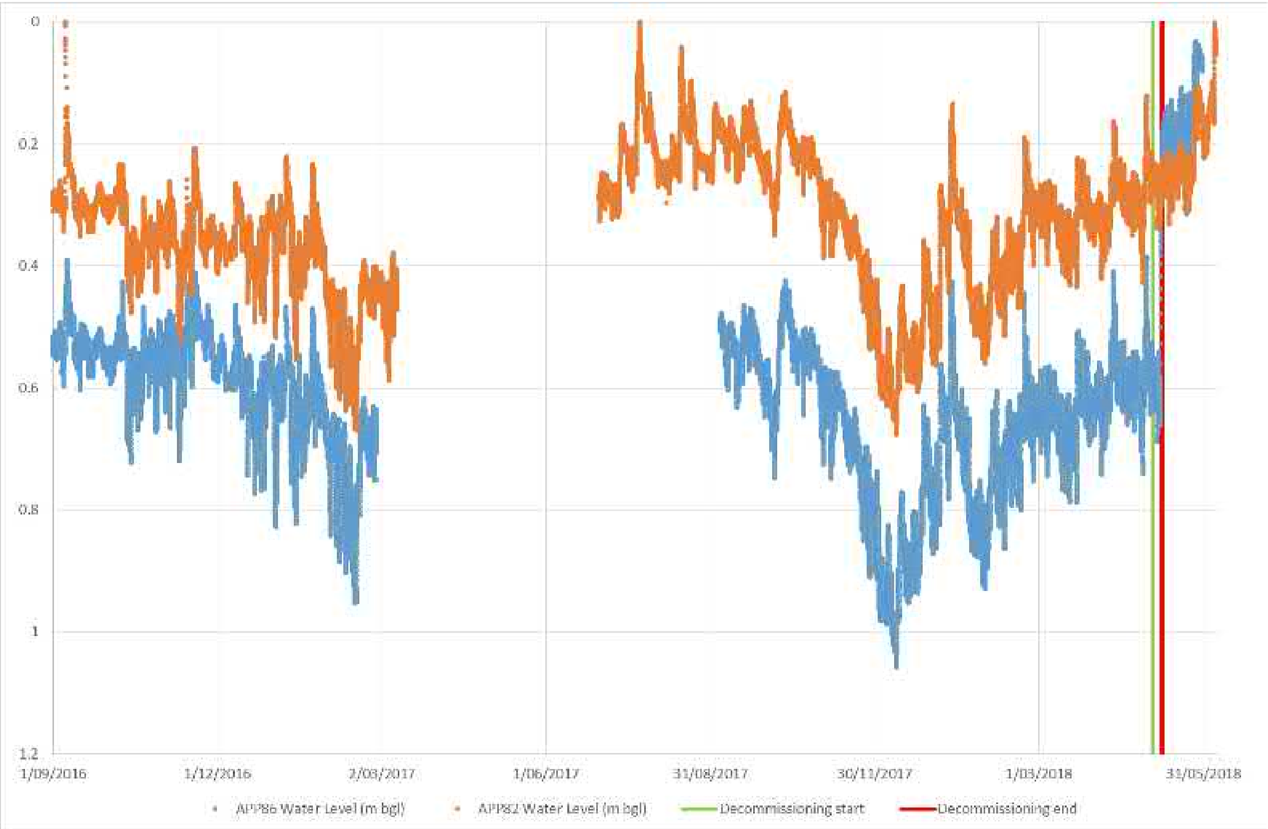

Figure G.6: Comparison of groundwater levels in APP86 and APP82

Woolston South

Groundwater levels in the Woolston South area were much lower, at depths of greater than 1.5 m. Recent groundwater levels in both APP80 and APP55 are much deeper than earlier recorded levels, though older dipped data suggests groundwater levels have previously been at lower levels than during the September 2016 to September 2017 period (Figure I.7). Until the missing data (from September 2017 to March 2018) are available, it is not possible to say whether this difference is due to a measurement technique (e.g. an offset caused possibly by moving the transducer in the piezometer), or whether it is an actual decline in groundwater levels (perhaps due to local dewatering). It is much more likely to be the latter, given that both piezometers show the same effect.

Neither of the piezometers showed any offset as a result of the sewer grouting (Figure I.8 and Figure I.9). Being closer to the area of decommissioning, APP80 might have been expected to show an effect, but in reality this piezometer suggests there is a gradual decline in groundwater levels from March 2018 to June 2018, and no observable instantaneous impact of grouting. However, the depth to groundwater here is greater than the depth to the gravity sewers, so in this area, the lack of response to grouting was simply that the sewer was not acting as a groundwater drain in the first place. The EQC piezometers in this area consistently show depths to water of around two metres or more, whereas the sewers are at depths of between 0.9 and 1.8 m in the area adjacent to APP80[2].

Figure G.7: Comparison of groundwater levels in APP80 and APP55

2 With the exception of a short length of sewer along Riley Crescent which has a depth of 2.9 m according to data on Webmaps.

Figure G.8: Comparison of groundwater levels in APP80 and APP55 with dipped data back to 2012

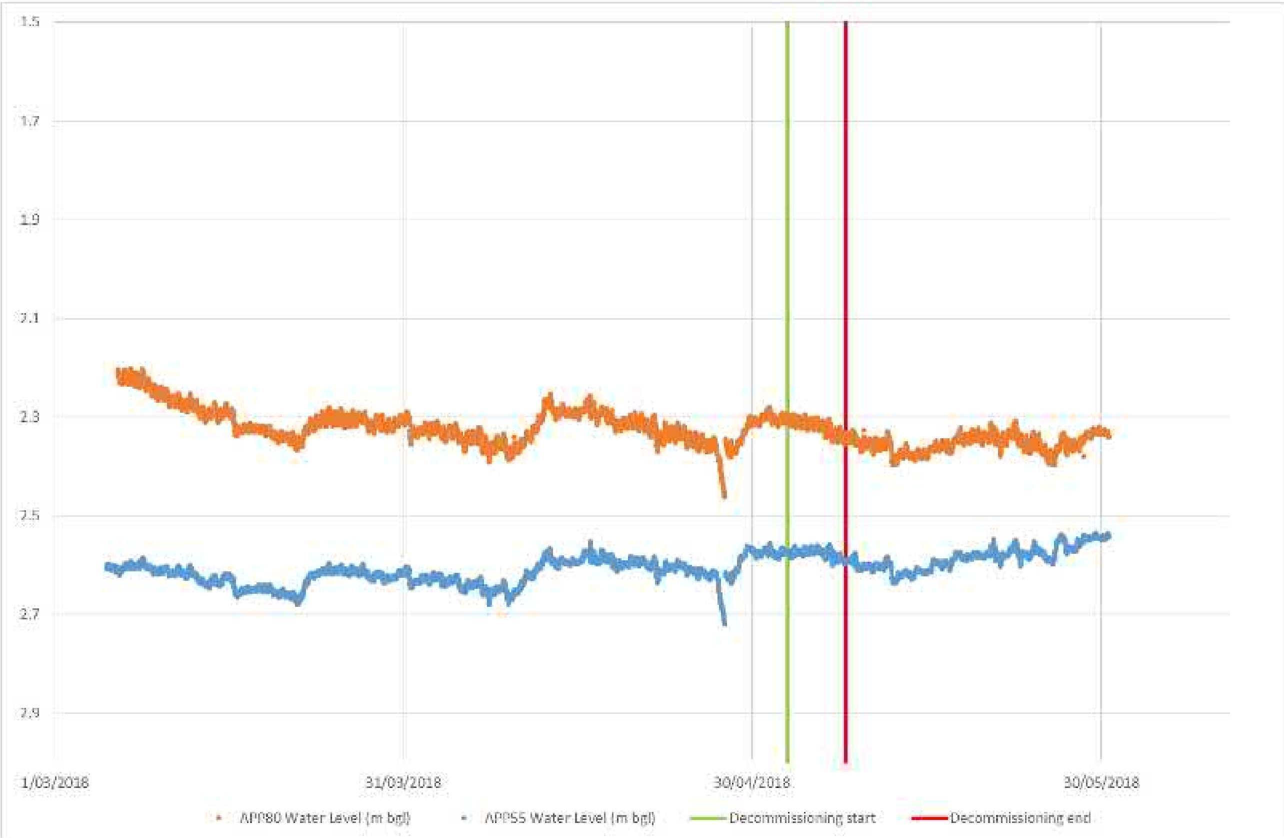

Figure G.9: Short-term comparison of groundwater levels in APP80 and APP55

Extent of influence of sewer decommissioning

There are a large number of unknowns when trying to estimate how far the impacts of grouting sewers could extend across an area. However, based on the assumed low permeability of the upper sediments in this area (the upper silts being around 10^{-6} m/s), the effects are unlikely to be measurable at distances of more than 20-30 m from the edge of the affected sewers.

This would fit with the observation that APP82 (located approximately 200m from the nearest area of decommissioning) shows no impact from the decommissioning.

Effects will only be observed in areas where depths to groundwater are less than the depth to the sewer. In some areas this will vary temporally. For example in Woolston South, although there was no immediate impact of sewer decommissioning due to the sewers being shallower than groundwater, it is likely that if groundwater levels rose to less than 1.8 m, as they have done in the record for APP80, there could be a delayed effect.

Conclusions

The only impacts from sewer decommissioning were observed at APP86, where groundwater levels rose 0.5 m in less than 24 hours following grouting. The data collected post-decommissioning suggest that groundwater has re-equilibrated at a new higher level in this bore. If this is the case, then it can be expected that groundwater levels will be sustained at less than 0.35 m below ground level for the majority of the time, and will likely inundate the ground surface after moderate to heavy rainfall events.

The extent of the effect is only estimated to extend a few tens of metres (approximately 20-30 m) from the edge of the area of sewer decommissioning. In reality, decommissioning the sewers has allowed groundwater levels to return to what would occur 'naturally'. In all likelihood, the effects of the sewers acting as groundwater drains would have extended only a few tens of metres from each of the sewers, beyond which 'natural' groundwater levels would not have been noticeably affected.

The lack of a response in APP80, and to a lesser extent in APP55, is likely to be a consequence of the sewers not acting as groundwater drains due to the depth to groundwater. However, at times of high groundwater level, it is possible that there will be an additional rise due to the lack of opportunity for groundwater to drain.