Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake
Version 2

S. van Ballegooy, S. C. Cox, C. Thurlow,
H. K. Rutter, T. Reynolds, G. Harrington,
J. Fraser, T. Smith

GNS Science Report 2014/18 **May 2014**

Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake

Version 2

S. van Ballegooy, S. C. Cox, C. Thurlow, H. K. Rutter,
T. Reynolds, G. Harrington, J. Fraser, T. Smith

GNS Science Report 2014/18 May 2014

The following report is an update of the median water table elevation report for Christchurch and surrounding areas released in March 2013 (GNS Report 2013/01). The revision encompasses an extension of the period of groundwater monitoring (4 September 2010 to 30 November 2013) and new surfaces for improved definition of water table fluctuation.

BIBLIOGRAPHIC REFERENCE

S. van Ballegooy, S. C. Cox, C. Thurlow, H. K. Rutter, T. Reynolds, G. Harrington, J. Fraser, T. Smith, 2014. Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2. GNS Science Report 2014/18, 79 pages plus 8 appendices.

Sjoerd van Ballegooy, Chris Thurlow, Tony Reynolds
Tonkin and Taylor Limited, P O Box 5271, Auckland

Simon Cox
GNS Science, Private Bag 1930, Dunedin

Helen Rutter
Aqualinc Research Ltd, PO Box 20-462, Christchurch

Graham Harrington
Christchurch City Council, PO Box 73014, Christchurch

Jeff Fraser
Golder Associates (NZ) Limited, PO Box 2281, Christchurch

Titus Smith
Riley Consultants Ltd, PO Box 4355, Christchurch

ISSN 1177-2425
ISBN 978-1-927278-41-3

PREFACE

It has been 3.5 years since the Mw7.1 Darfield earthquake struck the Canterbury region, nearly 1.5 years since the last major ground-damaging earthquake in the aftershock sequence, and the rebuilding of Christchurch is now well underway. The earthquakes resulted in extensive ground damage, principally due to liquefaction and lateral spreading processes that reflect a combination of both strong shaking and weak, saturated ground. One of the earliest issues for geotechnical engineering and land planning was a need for clear knowledge of the depth of shallow groundwater forming the water table, and how this may vary in space and time.

Version 1

In a move to fill such need an informal working group was set up in late 2012 comprising representatives of key organisations holding relevant data, knowledge and/or expertise. The group faced four principal challenges:

1. Prior to the earthquakes, groundwater monitoring was principally focussed on water supply and the deep (>20 m) aquifers, rather than shallow groundwater and the water table of importance for engineering. Existing shallow groundwater data (55 sites) included long-term (>20 year) information that provide records of the temporal variability, but these are widely spaced.

2. The elevation of the ground and wells changed during the earthquake sequence. In areas of extensive land-damage, some wells required restorative work, whilst others were damaged irreparably. Groundwater assessment needed to account for any changes in water level and well head elevations relative to sea level, and consider changes in the characteristics of flow between wells and surrounding ground/aquifers.

3. As part of earthquake recovery, EQC had set up an extensive network of piezometers for monitoring shallow groundwater. Vast quantities of new data had been collected, and were being collected, from sites across Christchurch City. The spatial density of “post-Darfield Earthquake” data were much improved, particularly in areas of land damage due to liquefaction. Available information included sites where groundwater had been measured for < 9 months, and whilst the observations did not necessarily represent the full range of seasonal fluctuations, data from each site had potential to be modelled to provide a surrogate median groundwater level and an indication of groundwater fluctuations throughout an entire year.

4. Whilst there was a marked improvement in the spatial distribution of post-Darfield Earthquake data, removing some of the uncertainty in lateral variations in the water table, the observations had to be placed in a temporal context. It needed to be established whether this short snap-shot of groundwater readings reflected the expected behaviour of the shallow groundwater in the long-term, and/or to what extent the earthquakes might have affected the status-quo.

After considerable debate over methodology, testing, data sourcing and checking, calculations, calibration and quality control, internal and external reviews, the working group's findings were published as a public science document "*Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake Version 1 – March 2013*" (van Ballegooy et al. 2013).

It was always envisaged the 2013 report should be updated, particularly as the collection of shallow groundwater data were continuing and more monitoring sites developed. In particular, the uncertainty as a result of seasonal fluctuation was expected to be reduced over time, especially as sites that previously had < 9 months of data extended into full annual records. With more sites, the spatial uncertainty would also be decreased, so long as short-term observations can be adjusted with surrogate (modelled) median values. As work to rebuild Christchurch advanced, an additional need to improve definition of the temporal variation of the water table has evolved.

Version 2

The informal working group re-convened in late 2013 to produce an update. In addition to recalculating the median water table position during the 'post-Darfield Earthquake' period (now three years, from September 2010-December 2013), their new challenge was to define 15th and 85th percentile water table positions below and above the median, respectively. That is, outline the spatial differences in the water table fluctuations that occurred during 2010 - 2013. This report "*Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake: Version 2 – March 2014*" provides such information. The method used for Version 2 follows that used in 2013 closely, although discriminates short-term sites where there was less than one year’s worth of data (12 months rather than < 9 months). For those who have already been using Version 1, the subtle difference between the median groundwater surface presented in Version 2 and the earlier surface is clearly illustrated.

In order for this contribution to be most effectively used, the limitations and qualities need to be understood and important caveats highlighted. Firstly, wherever possible, observations were processed so that the median surfaces represent the position at which water table was at or above 50% of the time, and at or below 50% of the time. Interpolation of median surfaces does, however, include sites with variable length data-records including many that do not cover the entire post-Darfield Earthquake period (September 2010-November 2013). The statistics of regular-period site data can provide an estimation of period the water table exceeded a particular elevation, for example, 85th percentile values of water table elevation indicate levels exceeded 15% of the time. To an extent the interpolated 15th and 85th surfaces also provide a similar estimation, but robust analysis of uncertainties is complicated and the temporal probabilities represented by the interpolated surfaces remain untested.

Regardless, the post-Darfield Earthquake median, 15th and 85th percentile surfaces only represent groundwater elevations during a relatively short period. They include seasonal fluctuations during the three years, but only one-half of the variation seen in long-term 1990-2010 monitoring was demonstrably seasonal. Groundwater levels beneath, and the flow rate of springs into, Christchurch City reflect a delicate balance between recharge from rainfall and river infiltration, versus outflow by discharge and abstraction. The earthquakes could have changed many of the controlling parameters, and others such as cumulative rainfall, vary over longer time-scales than three-years. The report makes no presumptions that non-parametric statistics of post-Darfield Earthquake monitoring reliably represent temporal probabilities in the future, and the usual elements of risk will apply when using the past to predict the future. However, the earthquakes have not affected the major input parameters of rainfall and river flow. Unless there are significant changes due to new infrastructure or earthquake ground damage, it seems likely the scale of variations in the future should be of a scale similar to those in the longer-term past (e.g. 1990-2010), although potentially varying about a different absolute median elevation. Of importance are some monitoring wells in areas of extensive land-damage that showed significant change following the earthquakes. It is yet to be fully established whether such changes are widespread across land-damage areas or merely local.

Finally, although questions remain as to the extent the post-Darfield Earthquake median, 15th and 85th percentile surfaces capture the temporal variability there is a great improvement in the confidence of the spatial distribution of water table fluctuations across Christchurch City and surrounding area. The median, 15th and 85th percentile water table maps are statistical surfaces representing a period of around 3 years that could deviate from the actual physical shape of the water table surface at any one point in time. It remains to be seen how much they deviate from a more-instantaneous measure of the potentiometric surface and whether they can be reliably used, for example, to calculate the gradient and direction of groundwater flow. It should be noted that the scale of post-earthquake water table monitoring network in Christchurch far exceeds anywhere else in New Zealand, and is likely to be amongst the most-extensive of any cities in the world.

EXECUTIVE SUMMARY

The sequence of Canterbury earthquakes during 2010 and 2011 caused substantial changes to land in Christchurch City and surrounding areas, including widespread uplift and subsidence, liquefaction, ground surface deformation and lateral spreading. Understanding the future liquefaction vulnerability is a major engineering consideration when determining how to rebuild on liquefaction prone land. The depth to the water table is a fundamental parameter when undertaking liquefaction vulnerability assessments that aim to determine the potential future damaging effects of liquefaction for the purposes of building foundation design.

Maps of the median water table elevation, percentile statistics of its fluctuation, and depth below ground were derived for Christchurch City and surrounding area, for the period from 4 September 2010 (M_w7.1 Darfield Earthquake) to 30 November 2013. The study includes data covering an area between Prebbleton in the southwest, Swannanoa in the northwest, and the coastline in the east, but is specifically intended for use in Christchurch residential land (zoned TC1, TC2, TC3, and Red Zone) within this area. Monitoring well, contour and grid data sets will be provided via the Canterbury Earthquake Recovery Authority (CERA) Canterbury Geotechnical Database (CGD) website. Map development necessitated a number of assumptions and interpretations, not immediately evident in the final product. This report provides documentation of the methodology, data sets, assumptions used to derive the water table maps, confidence levels and caveats, as well as new observations, results and recommendations for future work.

Data from 967 shallow monitoring wells were obtained from Christchurch City Council (CCC), Environment Canterbury (ECan) and geotechnical investigations carried out for the Earthquake Commission (EQC). 657 monitoring wells had records of twelve months or longer from which a representative median water table elevation was determined for each site. 310 wells had short-term records, from which surrogate medians were estimated by using longer-term data from nearby wells to account for seasonal variation. LiDAR Digital Elevation Models and physical survey data were used to correct the monitoring well measuring points for ground elevation changes caused by the earthquakes. River and coastline data help shape and position the water table contour maps at places of significant groundwater-surface water interaction.

The median 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, approximately coincident with the change in ground elevation. Groundwater is more than 5 m below the surface west of Christchurch City, but less than 2 m deep beneath much of the city. Differences between the (preferred) median water table derived from post-Darfield Earthquake longer-term data (≥ 12 month records), and a surface derived using surrogate medians derived from short-term (< 12 month) data, are subtle and in most places within ± 0.5 m. Surfaces of 15th and 85th percentile groundwater levels were developed to enable engineers and scientists to gain an appreciation for the groundwater fluctuations that have occurred in different areas of the city since the Darfield Earthquake.

A comparison of pre- and post-Darfield Earthquake groundwater data from 44 wells with extended (decadal) records continuous throughout the earthquake sequence indicates that the water table elevation was in most places unaffected by the earthquakes, other than short-term fluctuations. In six wells in the Eastern/Coastal Zone the median water table was lowered by 0.2–1.4 m, four of them independent of whether there was ground uplift or subsidence. 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. Natural fluctuations of groundwater occur at time-scales longer than post-Darfield Earthquake monitoring. Until such a time as more data become available, the pre-Darfield Earthquake variations during 1990-2010 provide the best proxy of the likely scales of future water table fluctuations.

KEYWORDS: water table, Christchurch, groundwater, earthquake, hydrogeology, monitoring wells, median, kriging, liquefaction assessment

CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX A: BACKGROUND FIGURES

APPENDIX B: MONITORING WELL DATA

APPENDIX C: LIDAR INFORMATION

LiDAR survey and benchmark comparisons

APPENDIX D: SENSITIVITY OF DATA SELECTION FOR MONITORING WELLS

APPENDIX E: RIVER LEVEL DATA

APPENDIX F: POST-DARFIELD EARTHQUAKE WATER TABLE SURFACES

APPENDIX G: POST-DARFIELD EARTHQUAKE WATER TABLE SURFACES, INCLUDING SURROGATE MEDIANS FROM SHORT-TERM DATA

APPENDIX H: WATER LEVEL FLUCTUATION

1.0 INTRODUCTION

The impact of the Canterbury earthquake series, including four major earthquakes in 2010 and 2011 that caused extensive damage related to liquefaction, has highlighted the need to better understand the elevation, spatial distribution and temporal variability of the water table in Christchurch City and its surrounding areas. This report aims to improve liquefaction hazard assessments in Christchurch City by mapping the water table surface over time since the 4 September 2010 M_w7.1 Darfield Earthquake. The maps aim to improve information that feeds into liquefaction hazard assessments for new subdivisions and for building developments on existing residential and commercial properties in Christchurch City. A secondary objective has been to observe and document any effects of the earthquake on the water table.

In addition, the maps developed in this report could also be useful for:
- managing Christchurch City underground water supply and wastewater collection pipe networks by better understanding infiltration and inflow; or managing the drainage network including the efficacy of the open channel network;
- geotechnical assessments which place individual or limited-period site observations of groundwater elevation into a more extensive spatial and longer-term context;
- understanding the hydrological effects of the earthquakes and tracing their impact on the flow of groundwater between aquifers.

However, users of this document need to be cognisant of its limitations (refer to Section 1.5) and ensure they have independently validated that the data presented in this report is appropriate for their particular application.

Maps developed in this report include: median water table elevation and depth; 15th and 85th percentile surfaces that aim to represent the variability of the water table over time.

1.1 Outline

This report has been written to accompany digital data sets that will be made available through the Canterbury Earthquake Recovery Authority (CERA) Canterbury Geotechnical Database (CGD) website[1]. Its purpose is to document the methodology, data sets, assumptions used to derive the water table maps, confidence levels and caveats, as well as highlight some new observations and results.

Section 2 of this report provides background information, including an overview of the groundwater regime in Christchurch City and the Canterbury earthquake sequence. Section 3 summarises the methodology adopted in order to maximise the amount of data and number of sites used in the calculation of the water table for the post-Darfield Earthquake period. Uncertainties have been reduced by incorporating as many observations as possible from shallow monitoring wells installed following the 2010 to 2011 earthquakes.

Sections 4 to 8 describe the sources of data and details of median water table calculations and

---

[1] https://canterburygeotechnicaldatabase.projectorbit.com

corrections at each site, as well as the procedures used to interpolate between measurement points. Corrections need to be applied to monitoring well data because there have been changes to ground elevation as a result of the earthquakes.

The principal results are presented in Section 9, which provides the preferred map of the median water table surface during the post-Darfield Earthquake period. Observed variations in groundwater levels are presented in the form of a 15th and 85th percentile[2] groundwater elevation surface to provide users with an appreciation for the spatial extent to which groundwater levels varied across Christchurch City.

Although a large number of monitoring wells have been installed following the Darfield Earthquake, improving the spatial accuracy of models, many of these monitoring wells have limited observation records. Section 10 presents a method for estimating a surrogate median water table elevation for wells where there are only single observations or short-term data records (< 12 months duration), in order to account for seasonal variation. The method utilises records of nearby wells in which there are longer periods of monitoring. The approach could be adapted by geotechnical engineers faced with limited groundwater measurements when undertaking site-specific investigations. Section 10 also provides comparison of median groundwater surfaces created using only longer-term data, those including < 12 month data, and the equivalent surfaces created in the 2013 Version 1 of this report (van Ballegooy et al., 2013).

Section 11 is an assessment of the historic (multi-decadal) fluctuations in the water table prior to the earthquakes as a proxy for potential future changes, as well as observations of direct effects caused by the earthquake sequence. Section 12 summarises the findings of the report and presents conclusions. References and a glossary are provided at the rear. Many diagrams and additional information have been placed in the appendices, which should also simplify and expedite downloading from the CGD website.

1.2 Study area

The water table maps developed in this report are specifically intended for use in urban residential areas where water tables are shallow and liquefaction has been observed, or is a significant risk, i.e., the land zoned Technical Category 2 (TC2), Technical Category 3 (TC3) and Residential Red Zone, excluding the Port Hills (Figure 1.1). Maps of the post-Darfield Earthquake water table surfaces (Appendices F & G) only cover these areas.

Development of these maps required an understanding of the wider groundwater system. Therefore, the study utilised data in an area bounded by Prebbleton (Wheatsheaf Corner) in the southwest, Swannanoa in the northwest, and the coastline in the east, as shown in Figure 1.1 (see also Appendix A). Observations and derivative data sets are limited to the region between NZTM (NZGD2000) co-ordinates: 1557000 – 1582000 east, 5174025 – 5198475

---

[2] The 15th percentile surface represents the elevation which groundwater is below for 15% of data records for each monitoring well, the median the elevation which groundwater is below for 50% of the data records, and the 85th percentile surface is the elevation which groundwater is below for 85% of data records.

north. Note that TC2 and TC3 land along the Halswell River in the Selwyn District (Figure C.2, Appendix C) are beyond the study area, and are not considered by this report.

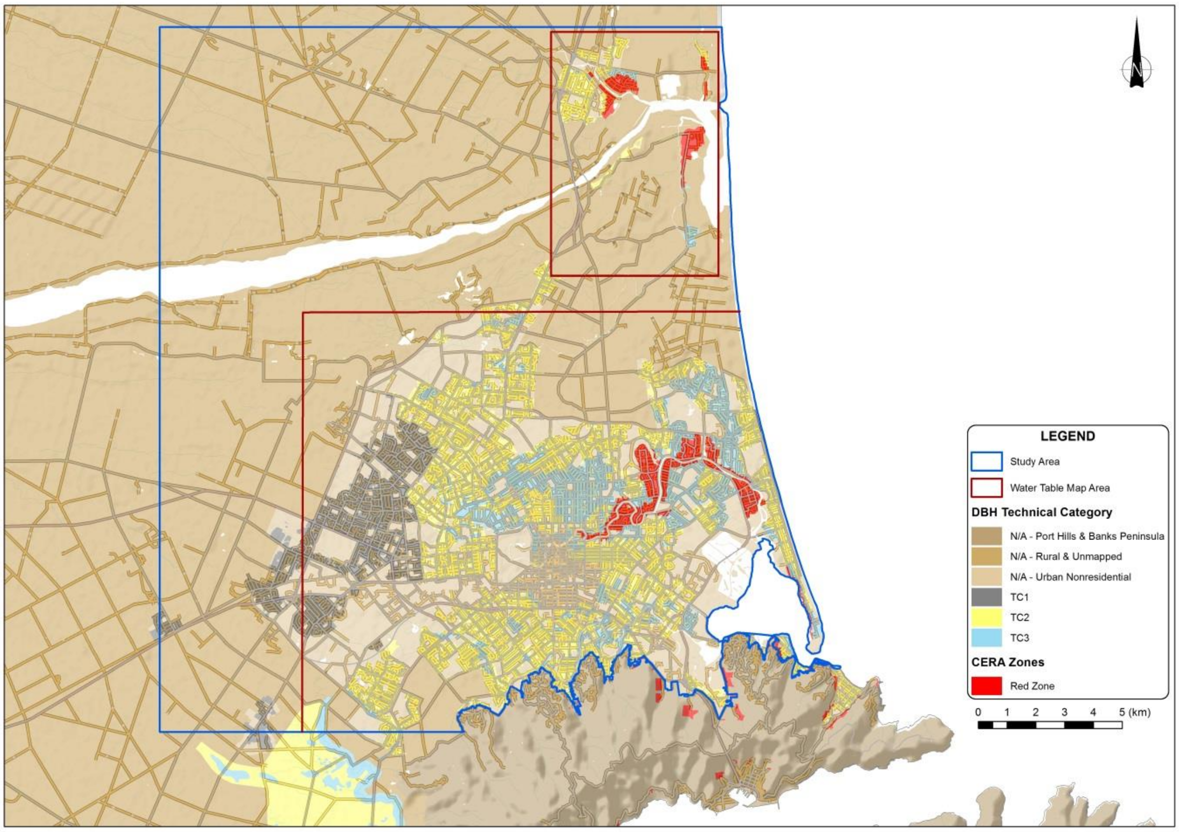


Figure 1.1 Location diagram, showing the area of water table maps (Appendices F & G) and location of the residential TC1, TC2, TC3,, & Red zones for which the report is specifically intended, as well as the wider study area from which groundwater data has been sourced.

1.3 Datum

This report uses Lyttelton Vertical Datum 1937 (LVD-37) that has a reduced level of +0.0 mRL. Spatial data sets are recorded in New Zealand Geodetic Datum NZGD2000, with maps and coordinates presented using the New Zealand Transverse Mercator Projection (NZTM). The following should also be noted:

- water table elevation data from monitoring wells has been calculated relative to LVD-37 (Section 4);
- river level data for the Avon/Otakaro, Heathcote and Styx Rivers, provided by Christchurch City Council, were reported relative to the Christchurch Drainage Datum (CDD) which is 9.043m lower than LVD-37. For the purpose of the water table assessment, these values were converted to LVD-37 (Section 7.2.1);
- river level data for Waimakariri River, provided by Environment Canterbury, were provided relative to LVD-37 (Section 7.2.2);
- mean sea level is taken as +0.064 mRL, i.e. 0.064 m higher than LVD-37 (Section 7.4). This is a datum correction;
- all figures presented in this report are relative to LVD-37.

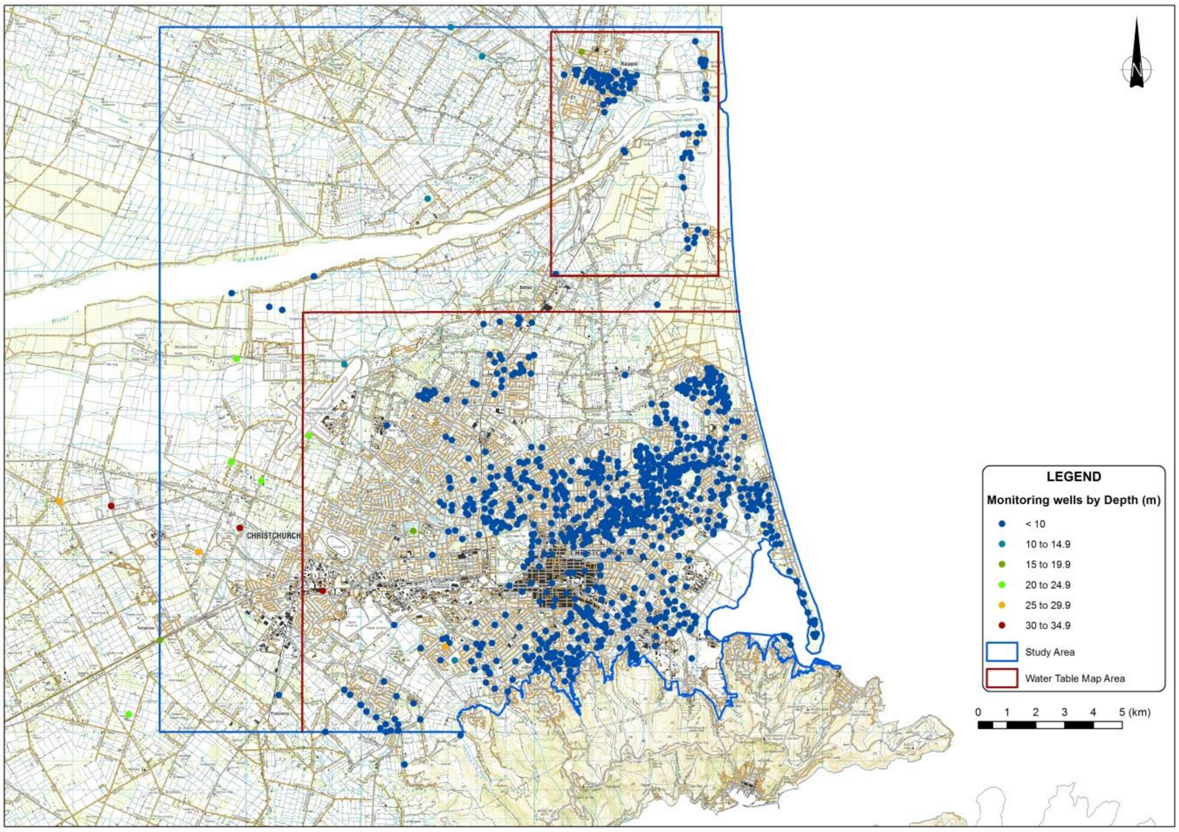


Figure 1.2 Map showing the location of monitoring wells coloured by depth (for greater detail see Figures B.1 and B.2, Appendix B), together with the water table map area (red line) and wider study area (blue line).

1.4 Water table and selection of well data

The water table, defined in the Glossary, has been derived from shallow groundwater observations in monitoring wells that are typically less than 10 m deep (Figure 1.2). Some observations in greater depth wells have been included from the western side of the study area where there is a near-total absence of shallow monitoring wells. Deeper wells were only included where: the drilling log suggests that the screened zone, or the base of the well casing, is measuring unconfined/semi-confined groundwater; vertical hydraulic gradients are calculated to be downwards; and the elevation of recorded groundwater is consistent with other nearby wells or surface water elevation. Monitoring wells screened in confined aquifers were excluded, as far as possible, from the data set. The term 'water table surface' is used throughout this report to specifically describe the calculated grid and contour dataset, being a mathematical representation of the water table throughout the study area.

1.5 Uncertainty, limitations and assumptions

While the water table surfaces presented in this report may be used for a variety of purposes, it is important that anyone using them understands the assumptions that have been made to develop the surfaces, and the limitations inherent in them. It is also important that users have independently validated that the data presented in this report is appropriate for their particular application.

There are two main areas of uncertainty:

1. Temporal fluctuations in groundwater levels and the duration of monitoring, including:
    - Short-duration post-Darfield earthquake data;
    - Seasonal and annual impacts of natural rainfall recharge;
    - Artificial influences, such as dewatering (short term) and abstraction (longer term);
    - Changes to elevation of ground and well heads due to earthquakes.

2. Spatial uncertainties and limitations associated with interpolation, including:
    - Distribution of data, and the low density of data points in areas outside the TC2/TC3/Red Zone;
    - Uncertainty in the absolute position of the well head, measuring point, and ground elevations;
    - Different depths of wells, and possible different pressures at these depths;
    - Degree of groundwater connection with rivers, estuaries and the sea.

At any location, there is a temporal uncertainty in the water table elevation. The water table fluctuates both inter-annually as well as seasonally because rainfall recharge (e.g., the difference between rainfall and evaporation) is one of the principal influences on groundwater level (Section 11). **Engineers and scientists using the median water table surface presented in this report will need to consider whether the use of a median water table derived from a three-year period is appropriate for their particular application.**

At any location there is spatial uncertainty in the water table elevation and depth resulting from interpolation of data across various data sets with differing distributions and accuracy. For example discrepancies may occur between water table and ground elevations where rapid changes in topography occur (e.g. near river banks). **Engineers and scientists using the water table elevation and depth maps will need to consider whether or not additional site-specific surveying or groundwater investigations are necessary, and whether such maps are appropriate for their particular design/analysis application.**

The groundwater elevation surface is much smoother and constant compared to the depth to groundwater maps which is affected by the rapidly varying surface topography. The accuracy of the depth to groundwater at any point in space will depend on the resolution of the digital ground surface terrain model. Depth to groundwater maps are presented in this report based on a 25 m resolution digital ground surface terrain model for the purpose of presenting an overview of the spatial pattern of depth to groundwater across Christchurch. **However if engineers and scientists need to obtain depth to groundwater information, we recommend using the groundwater elevation surfaces to obtain groundwater levels,**

which can then be subtracted from ground surface elevations at specific locations or based on different resolution digital ground surface terrain models depending on the level of spatial accuracy or spatial smoothing required.

Rainfall during 2011-2013 (Figure 1.3) was at, or slightly above, median values rather than towards the higher or lower limits of precipitation that have previously occurred. Section 11 provides some analysis of long-term (pre-earthquake) groundwater fluctuations to help place the post-Darfield Earthquake variability in a long-term context. Engineers and scientists can refer to the 15th and 85th percentile surfaces (Section 9.3), which were interpolated from statistical values below and above the medians, respectively, to help determine the likely range of groundwater levels that occurred at a particular location. These can then be checked against statistics from the 1990-2010 period (Section 11), to see whether additional variation should be planned for, or groundwater monitoring required.

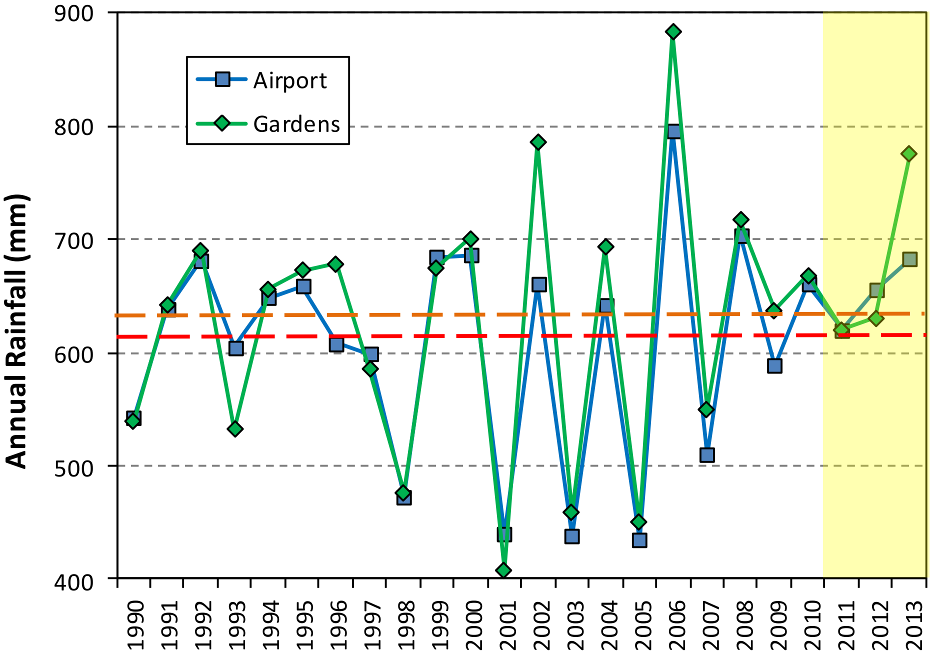


Figure 1.3 Graph of total annual rainfall at Christchurch Airport and Gardens between 1990 and 2013. Dashed red and orange lines are median values of 616 mm (red = Airport) and 638 mm (orange = Gardens), respectively. Rainfall during the post-Darfield Earthquake period, highlighted in yellow, appears to be at, or slightly above, median values rather than near high or low limits that occurred between 2001-2006 (Data from NIWA Cliflo database, network numbers H32451 and H32561 http://cliflo.niwa.co.nz/).

Civil infrastructure construction, such as associated with the rebuilding of Christchurch, is likely to have some impact on both past and future water table levels. Dewatering of excavations for new stormwater, wastewater and water mains can temporarily drawdown (i.e. lower) surrounding groundwater levels, resulting in potentially low readings (and potentially a lower liquefaction risk) (Section 11). Similarly, the repair of damaged storm water and sewerage network could either lower groundwater levels in surrounding piezometers (if water was leaking from the pipe network), or raise groundwater levels (if the cracked pipe network was previously acting as a drain and was then repaired). There are a number of sewers presently under conversion from a gravity draining system to a pressure pumped system, such that groundwater will in future not be able to drain into the sewer pipes and groundwater levels could increase. Short-term construction works should not have a significant influence on surfaces developed for this report, as typically they have only local influence and will have been of short-duration, but major infrastructure damage/repair could influence wider areas. **This report has not attempted to account for human-induced changes, nor does it specifically outline any predictions for the future.**

It is important to note that sea level rise has not been addressed but is likely to result in changes to groundwater in the low-lying coastal areas of Christchurch City in the future. Further study is recommended to quantify the expected changes to groundwater levels as a result of rising sea levels.

Maps have been developed with a focus of providing a measure of the most likely median water table elevation and depth. While this is useful for, and aimed directly at, geotechnical assessment purposes it creates a 'statistical' surface that incorporates a number of measurements over time that may deviate from the actual physical shape of the water table surface at any one point in time. Therefore, it may not be appropriate to use the median water table elevation map as a potentiometric surface to indicate the hydraulic gradient and direction of instantaneous groundwater flow – there could be subtle differences lost in the statistical treatment of data.

The report draws on observations made during the post-Darfield Earthquake period, being updated to September 2010 – November 2013 for this Version 2. The median, 15th and 85th percentile surfaces constrain the spatial variability of the water table elevation across Christchurch City and the surrounding area during this three year period. The density of the monitoring wells is a primary control on the level of confidence in the median water table surface (Section 10.5). Installation of a dense array of monitoring piezometers within the TC2/TC3/Red zones following the earthquakes has greatly reduced spatial uncertainty of the post-Darfield Earthquake observation period.

A significant source of spatial uncertainty is still the absolute elevation of well head measuring points (relative to sea level), and the extent to which these have changed during the earthquake sequence. Many wells have not been precisely surveyed, so changes in elevation have been based on successive Light Detection and Ranging (LiDAR) ground elevation surveys and an assumption that well head measuring points and ground level are the same. **Engineers and scientists using the water table elevation and depth maps will need to consider whether or not additional site-specific surveying or groundwater investigations are necessary, and whether such maps are appropriate for their particular design/analysis application.**

Groundwater/surface water relationships are also an important constraint. The difference in elevation between the median river level and the nearby water table is dependent on factors including riverbank topography and the hydraulic properties of the riverbank/streambed and shallow aquifer. In this study, we have assumed that the water table in a riverbank is in direct hydraulic contact with the surface water in the channel. However changes in the shape of the water table are likely to occur close to the rivers, with either ridges or troughs in the water table depending on the interrelationship between groundwater and river levels. It should also be noted that the levels of these rivers are also complicated by a variety of factors including the Christchurch drainage network, pumping, and tidal flows.

1.6 Previous assessments

Early liquefaction assessments presented water table contour maps for Christchurch City that were developed using 10 year data from 91 wells down to depths of 30 m (Beca, 2004, 2005). Differences of around 1 m were observed between the water table elevation in summer and winter (Beca, 2005). A more recent model of the water table across the Christchurch City area was developed by Begg & Scott for use in Brackley (compiler) 2012, using methods similar to those adopted for this study. The Begg & Scott model utilised pre-earthquake monitoring well data and provided a maximum water table (referred to as the UGS - unconfined groundwater surface), using 192 measurements in wells and 572 LiDAR-derived points for surface water, with collar elevations derived from a ground surface Digital Elevation Model (DEM). The report considered the model to be 'interim' and it was not presented separately. The report stated that ‘building a widely accepted, high-quality unconfined groundwater model for the project area would greatly enhance the reliability of liquefaction susceptibility assessment’.

1.7 Context

1.7.1 Version 1 (2013)

In a move to fill the need for understanding the water table in Christchurch, an informal working group gathered in late 2012 comprising representatives of key organisations holding relevant data, knowledge and/or expertise. After considerable debate over methodology, testing, data sourcing and checking, calculations, calibration and quality control, internal and external reviews, the working group's findings were published as a public science document "*Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake Version 1 – March 2013*" (van Ballegooy et al. 2013).

The study used data from 806 monitoring wells, many of which were installed following the 4 September 2010 M_w7.1 Darfield Earthquake. It accounted for changes in ground elevation because of the earthquakes. As collection of shallow groundwater data by EQC and other parties was continuing and more monitoring sites were being developed, it was always expected the report would be updated. In particular, the uncertainty as a result of seasonal fluctuation was expected to be reduced over time, as sites that previously had < 9 months of data extended into full annual records. With more sites, the spatial uncertainty would also decrease, so long as seasonal bias was removed from short-term observation records.

1.7.2 This (2014) Version 2

The informal working group re-convened in late-2013 to produce this update. As work to rebuild Christchurch had advanced, there was an additional need to improve definition of the temporal variation of the water table had evolved. In addition to recalculating the median water table position during the 'post-Darfield Earthquake' period (now three years, from September 2010-

December 2013), the new challenge was to define 15th and 85th percentile water table positions below and above the median, respectively. That is, outline the spatial differences in the water table fluctuations that occurred across Christchurch City and surrounding area during 2010 - 2013.

The water table surfaces and figures presented in this report are a revision of those originally published in March 2013 (van Ballegooy et al, 2013). Data from 967 monitoring wells have been utilised. Wherever possible the methodology was kept the same, but there are some key differences and improvements:

- The revised surfaces have been developed from groundwater data collected between 4 September 2010 and 30 November 2013 (39 month period). The original Version 1 surfaces used data from 4 September 2010 to 31 December 2012 (28 months).

- In Version 1, a nine month cut off was selected for determining whether data from an individual piezometer was sufficient to represent a full annual cycle of seasonal fluctuations. Surrogate median values were modelled for locations where there was < 9 months of data. Now that the period of available data is much longer, Version 2 used surrogate medians only for locations with < 12 monthly readings. Both versions present median water table surfaces developed both without (preferred) and including the short-term data records (refer to Section 10).

- River surface elevations for the Avon/Otakaro, Heathcote and Styx Rivers, used to help constrain the position of groundwater level in Version 1, were obtained by linear interpolation along the length of the river between gauging stations. For Version 2 these elevations were refined using data supplied by CCC, from surveyed profiles and cross-sections combined with flow modelling based on gauging station records.

- Where previously only the main river channels of the Avon/Otakaro, Heathcote and Styx Rivers were incorporated in the surface calculations, some extensions and additional tributaries were included in Version 2.

Overall, the above changes to the methodology have had little effect on the produced median surfaces. Observed differences between Version 2 and Version 1, reviewed in detail in Section 9.2, are typically within ± 0.5 m.

Version 2 provides new 15th and 85th percentile surfaces for the post-Darfield Earthquake period, based on interpolation of statistics at each site extended to the period between 4 September 2010 and 30 November 2013. The only outline of water table variation in Version 1 was based on the assessment of long-term monitoring from 1990-2010 (see Section 11 of Version 2). The post-Darfield Earthquake statistical analysis in Version 2 (Section 9.3) represents a shorter temporal period (3 vs 20 years) but has much higher spatial definition (657 vs 55 data sites), than analysis of longer-term pre-earthquake data (Section 11).

2.0 BACKGROUND

2.1 Christchurch City hydrogeology

The Canterbury Plains built progressively 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 and/or its predecessors, 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 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 occur up to 15 km inland from the present-day shoreline. The Port Hills and Banks Peninsula are part of a Late Miocene volcanic complex that became extinct c. 6 million years ago, and stand to the south of the city.

There is a significant groundwater resource in Canterbury that provides around 80% of the region's drinking supply and 50% of the water used for agriculture (Brown & Weeber, 1992). Fan and alluvial gravel sequences form aquifers, whereas the marine/estuarine sediments of silt, clay, peat, and shelly sand act for the most part as aquitards. In the coastal area, the alternating fine-grained and coarse-grained sediments form a multi-layered confined aquifer system. Further inland, the layered structure of the coastal confined aquifers is less obvious and groundwater occurs in semi-confined to unconfined aquifers.

Figure A.1 (Appendix A) is a surficial geological map of the Christchurch City area (Brown & Weeber, 1992). The Springston Formation predominantly occurs at the surface to the west of the city, while the Christchurch Formation occurs in the east of the city (Figure A.2, Appendix A). 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).

Table 2.1 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 2.1, however a further sequence of interbedded gravel and fine-grained strata exists at greater depths (Weeber, 2008). Some useful background information relating to the hydrogeology in the Christchurch City area can be found in: Wilson, 1976; Talbot et al.,1986; Brown & Weeber, 1992, 1994; Brown, 2001; White, 2007a, 2008, 2009; White et al., 2007; Brackley (Compiler), 2012.

Table 2.1 **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 may also act as an aquitard.

The Christchurch Formation includes beach, estuarine, lagoonal, dune and coastal swamp (inter-dune) deposits (these latter areas are often largely reclaimed with fill). Figure A.2 (Appendix A) is a schematic west-east geological cross-section along the upper part of the coastal Waimakariri River floodplain. The finer-grained deposits of the Springston and Christchurch formations are thickest near the coast and disappear as a coherent layer approximately 12 km inland. Near the coast they may be up to 45 m thick while near the inland extent of the area they are < 10 m thick.

Weeber (2008) proposed three broad, land surface, groundwater protection zones for the Christchurch-West Melton groundwater system. Between these zones, he defined boundaries using the following two criteria: 1) the presence/absence of near-surface fine-grained sediments > 3 m thickness, and 2) the presence/absence of upward or downward hydraulic gradients between the Riccarton Gravel and Springston Formation aquifers. Key characteristics differentiating the three zones are summarised in Table 2.2. While this study is not concerned with groundwater protection zones, the map of zones provided by Weeber (2008) (Figure A.3 in Appendix A) is useful because it indirectly outlines areas characterised by upward and downward hydraulic gradients, and where superficial fine-grained deposits that act as confining layers are thicker than 3 m.

Table 2.2 **Christchurch City groundwater protection zones (adapted from Weeber, 2008).**

Zone	Key Characteristics
1 Inland	• Consists of soils that are generally thin, meaning that the Aquifer 0 gravel layer is at or near the ground surface, and there is no obvious marker bed separating Aquifer 0 from Aquifer 1.
2 Transition	• Consists of a complex hydrogeological region and broadly encompasses the transition from unconfined conditions in the west to the confined conditions along the coast; • Aquifer 0 gravel lobes are interbedded within alluvial and marine fine sediments. In some places Aquifer 0 and Aquifer 1 gravels are in direct contact, especially towards the western side of Christchurch City; • The increasing presence of low permeability fine sediments in the Springston and Christchurch Formations restricts the vertical flow of groundwater between the aquifers. This coincides with a gradual transition from a downward pressure gradient in the west to an upward gradient in the east.
3 Eastern/Coastal	• Consists of at least five layers of relatively permeable water bearing gravel (aquifers) that are typically separated by much less permeable layers of fine sediment that confine the aquifers; • There are no interbedded gravels above confined Aquifer 1, and the zone is dominated by fine-grained marine and estuarine sediments with some alluvial silts and peat.

Weeber's work 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 related (i) spatially to the geological complexity of the subsurface layers (e.g. White, 2009) and (ii) temporally to variations in recharge/discharge. While not precise, the subdivision of Christchurch City hydrogeology into three zones (Table 2.2) has been useful and was adopted for this report. For example, the Eastern/Coastal Zone forms a background for figures in Appendix H.

The water table sits within the uppermost sediments, typically less than 10 m deep, throughout the area. These sediments include Christchurch Formation dune sands in the east, which are of primary interest when assessing liquefaction vulnerability, 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 care has been taken to exclude such wells 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, 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).

2.2 2010 – 2011 Canterbury earthquake sequence

On 4 September 2010, a series of faults beneath the Canterbury Plains ruptured in a complex sequence to produce the Greendale Fault trace (approximately 30 km long), accompanied by the M_w7.1 Darfield Earthquake (Beavan et al., 2010; Gledhill et al., 2011; Quigley et al., 2012). Greendale Fault (Figure A.4, Appendix A) is an east-west trending rupture through semi-confined inland aquifers of central Canterbury Plains. Fault motion was dominantly right-lateral strike-slip, with an average horizontal surface displacement of ~2.5 m and maximum vertical offset ~1.5 m (Quigley et al., 2012). Seismological and geodetic data indicate the rupture at ~10 km depth in basement rocks involved both NE-SW striking reverse faults and E-W striking right-lateral strike-slip faults (Beavan et al., 2010).

A sequence of major earthquakes and aftershocks (Figure A.4, Appendix A) ensued throughout the rest of 2010 and 2011, occurring mainly to the east of Greendale Fault on concealed faults below the Eastern/Coastal confined aquifer system, that did not result in any further surface ruptures. Aftershock distributions, earthquake focal mechanisms and modelling of ground deformation, define zones characterized by both E-W striking strike slip and NE-SW striking reverse slip. Table 2.3 summarises the more significant events in the Canterbury earthquake sequence. A major M_w6.2 earthquake on 22 February 2011 (the Christchurch 1 Earthquake) occurred on an oblique thrust fault beneath volcanic rocks of Banks Peninsula (Bannister et al., 2011; Beavan et al., 2011; Kaiser et al., 2012). It caused severe damage in Christchurch City, explained by its close proximity to the city, a shallow source and exceptionally strong vertical ground motions (e.g. Bradley & Cubrinovski, 2011; Fry et al., 2011). Other damaging earthquakes of note were the M_w5.6 and M_w6.0 on 13 June 2011; and the M_w5.8 and M_w5.9 on 23 December 2011.

The earthquakes were high stress-drop events that radiated anomalously high amounts of seismic energy relative to their magnitudes (Fry & Gersternberger, 2011; Fry et al., 2011; Gledhill et al., 2011; Kaiser et al., 2012; Reyners, 2011). While shaking has caused considerable structural damage to buildings, much residential property damage was caused by liquefaction causing ground surface deformation and lateral spreading (Tonkin & Taylor, 2013; Cubrinovski et al., 2011; Kaiser et al., 2012; Orense et al., 2011). These were unprecedented for New Zealand.

Table 2.3 Summary of major Canterbury earthquakes in the 2010-2011 sequence.

Event and general location	Date	Magnitude (M_w)	Depth and Location
Darfield Earthquake (Greendale)	04 Sept 2010	7.1	10 km deep, 35 km W of Christchurch City
Christchurch 1 Earthquake (Lyttelton)	22 Feb 2011	6.2	5 km deep, 10 km SE of Christchurch City
Christchurch 2 Earthquake (Sumner, 2 events)	13 June 2011	5.6 and 6.0	9 km deep, 10 km SE of Christchurch City; 6 km deep, 10 km SE of Christchurch City
Christchurch 3 Earthquake (New Brighton, 2 events)	23 Dec 2011	5.8 and 5.9	8 km deep, 20km E of Christchurch City; 6 km deep, 10km E of Christchurch City

3.0 METHODOLOGY FOR WATER TABLE CALCULATION

3.1 Median water table surface

The process of developing a median water table (Figure 3.1) has involved:

- selection of all relevant data, identifying the monitoring wells that measure water table depth, then separating them on the basis of the period of data record (Figure 3.1, Stage 1);
- deriving a ground surface DEM from LiDAR measurements (Figure 3.1, Stage 1; see also Appendix C);
- calculation of a water table elevation (i.e. ground surface minus water table depth, based on surveyed well head and/or LiDAR ground surface elevation) (Figure 3.1, Stage 1);
- calculation of a median of water table elevation at each well;
- calculation of the median river and stream levels (along the centre line of the rivers) and elevation of sea level at the coastal boundary (Figure 3.1, Stage 1). Rivers, streams and the coast are assumed to be connected to the water table aquifer, so their elevations are relevant to the water table maps;
- gridding and contouring median water table elevation and depth (Figure 3.1, Stages 2 and 3);

Further discussion of the method is provided in Sections 4 to 8.

3.2 15th and 85th percentile water table surfaces

The process for developing the percentile water table surfaces (Figure 3.2) has involved:

- at each of the wells used in the median water table model, calculation of the 15th and 85th percentile levels of the water table elevation (Figure 3.2, Stage 1);
- calculation of the relative difference between the 85th percentile-median, and the median-15th percentile for each well;
- calculation of the 15th and 85th percentile levels of surface water at river and stream gauges, and along the coast from tidal fluctuations; assign expected differences between 85th percentile-median and median-15th percentile for groundwater adjacent to rivers and the coast, based on observations of the surface water fluctuations and known limits of tidal flow in rivers (Figure 3.2, Stage 1 - see also Section 7.3);
- interpolation of grids of the difference between 85th percentile-median, and of the median-15th percentile (Figure 3.2, Stage 2);
- addition of the grid of 85th percentile-median difference to the grid of the median water table, to obtain of 85th percentile water table surface; subtract grid of median-15th percentile difference to the grid of the median water table, to obtain of 15th percentile water table surface;
- subtraction of the percentile elevations from LiDAR ground elevation to obtain depth to 15th and 85th percentile surfaces (Figure 3.2, Stage 2);

The rationale for using a median ± contoured difference value, rather than contouring actual percentile values, is that the 15th percentile, median and 85th percentile surfaces are near-parallel with very small vertical separations (0.2 m – 2 m) compared with the large horizontal distances between data points (100 m - 5,000 m). The value in having these three surfaces is so that they can be used together. The adopted approach avoids compounding uncertainties in absolute elevations and minimises differences in mathematical artefacts from one surface to another. Contouring the difference values and adding/subtracting these from the median ensures that the 85th percentile surface will always be above the median surface, which in turn will always be above the 15th percentile surface, even when interpolating across large distances. By following this methodology the relative shape and position of the 15th percentile, median and 85th percentile surfaces are consistent relative to each other, and the resulting solutions are more-robust. Further discussion of the method is provided in Section 9.3.

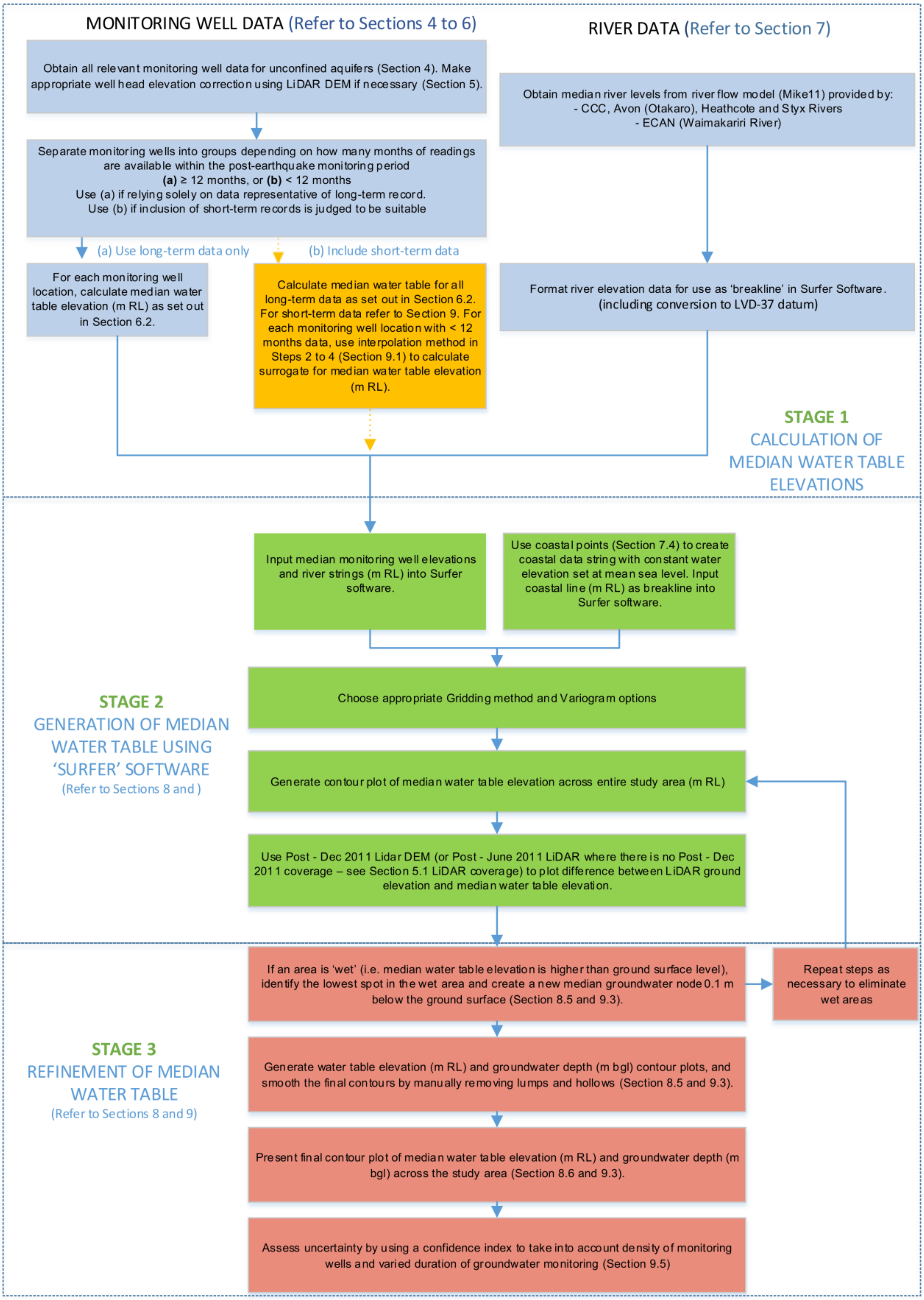
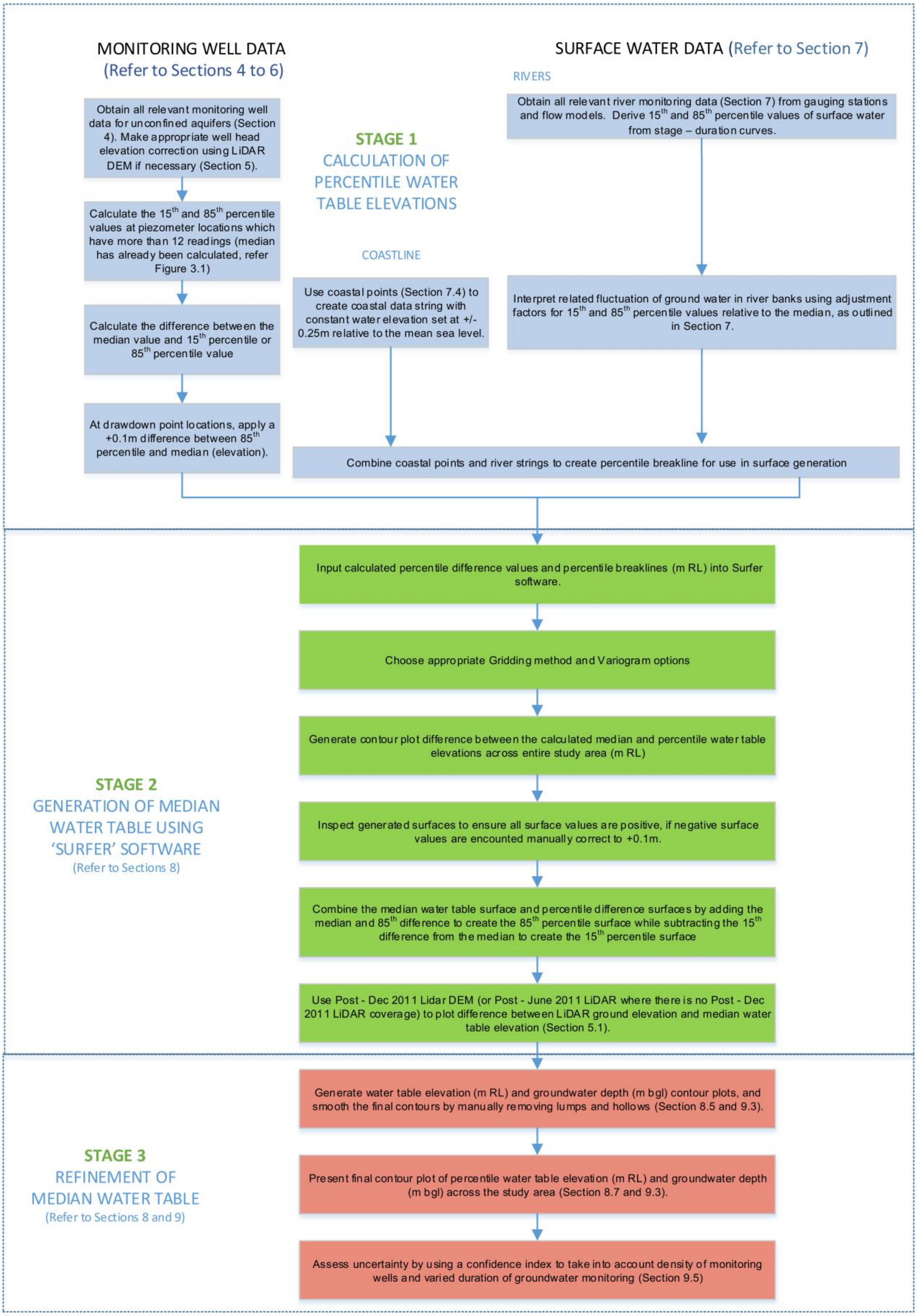


Figure 3.1 **Flowchart of adopted methodology for generating the median water table surface.**



Obtain all relevant monitoring well data for unconfined aquifers (Section 4). Make appropriate well head elevation correction using LiDAR DEM if necessary (Section 5).

Calculate the 15th and 85th percentile values at piezometer locations which have more than 12 readings (median has already been calculated, refer Figure 3.1)

Calculate the difference between the median value and 15th percentile or 85th percentile value

At drawdown point locations, apply a +0.1m difference between 85th percentile and median (elevation).

Obtain all relevant river monitoring data (Section 7) from gauging stations and flow models. Derive 15th and 85th percentile values of surface water from stage – duration curves.

Use coastal points (Section 7.4) to create coastal data string with constant water elevation set at +/- 0.25m relative to the mean sea level.

Interpret related fluctuation of ground water in river banks using adjustment factors for 15th and 85th percentile values relative to the median, as outlined in Section 7.

Combine coastal points and river strings to create percentile breakline for use in surface generation

Input calculated percentile difference values and percentile breaklines (m RL) into Surfer software.

Choose appropriate Gridding method and Variogram options

Generate contour plot difference between the calculated median and percentile water table elevations across entire study area (m RL)

Inspect generated surfaces to ensure all surface values are positive, if negative surface values are encountered manually correct to +0.1m.

Combine the median water table surface and percentile difference surfaces by adding the median and 85th difference to create the 85th percentile surface while subtracting the 15th difference from the median to create the 15th percentile surface

Use Post - Dec 2011 Lidar DEM (or Post - June 2011 LiDAR where there is no Post - Dec 2011 LiDAR coverage) to plot difference between LiDAR ground elevation and median water table elevation (Section 5.1).

Generate water table elevation (m RL) and groundwater depth (m bgl) contour plots, and smooth the final contours by manually removing lumps and hollows (Section 8.5 and 9.3).

Present final contour plot of percentile water table elevation (m RL) and groundwater depth (m bgl) across the study area (Section 8.7 and 9.3).

Assess uncertainty by using a confidence index to take into account density of monitoring wells and varied duration of groundwater monitoring (Section 9.5)

Figure 3.2 **Flowchart of adopted methodology for generating 15th and 85th percentile water table surfaces.**

4.0 MONITORING WELL DATA

4.1 General

Monitoring wells used in the calculation of the median and percentile water table elevations (Section 6) were selected as representative of the water table aquifer (as opposed to confined aquifers) through being either:

- shallow wells less than 10 m deep, that either penetrated the Springston Formation or the Christchurch Formation in the Eastern/Coastal or Transition zones, with groundwater elevation that is not anomalously high relative to local ground elevation, or groundwater in nearby monitoring wells; or,

- deeper wells (to 35 m) in unconfined/semi-confined aquifers on the western side of the study area. In this 'Inland zone' area, there is a distinct lack of shallow piezometers to record the water table surface. Weeber (2008) demonstrated weakly downwards hydraulic gradients and connectivity between Aquifer 0 and Aquifer 1, such that deeper wells have groundwater levels representative of the shallow water table.

Although well logs are notoriously variable in their reliability and quality, they were evaluated to check for the presence/absence of fine-grained sediment intercepted during drilling. Wells that appeared to be measuring confined groundwater pressures were excluded from the data set. Data were sourced from CCC, ECan and EQC monitoring (Table 4.1; Figure B.1, Appendix B) – discussed individually below. The depths of all monitoring wells used for water table calculations are shown in Figures 1.2 and B.2 (Appendix B).

4.2 Christchurch City Council monitoring wells

Christchurch City Council has installed monitoring wells for the purpose of observing depth of the water table below ground level. These are all shallow wells, between 1.7 and 10 m deep. CCC provided data for 27 monitoring wells within the study area. The duration of data were generally at least 13 years, with some well records extending back to 1959. Water table levels have typically been measured at weekly intervals, however in some cases they were monitored at fortnightly intervals. One bore (HHA – M36/7366) has an 11-year record of daily values. Wells are currently monitored on behalf of CCC by the National Institute of Water and Atmospheric Research (NIWA).

The CCC monitoring data includes the elevation of the well head (or measuring point ‘MP’ in mRL, relative to LVD-37) and the surrounding ground level (‘GL’ - in metres below the MP). An example CCC monitoring well record sheet (accessed via the Environment Canterbury website[3]), is presented in Figure B.3 (Appendix B). The elevation of 22 measuring points were re-surveyed in December 2012 (Section 5.2) and these wells were included in the calculation of the median water table and percentile surfaces (Figure B.1, Appendix B). Data from all 27

---

[3] http://ecan.govt.nz/services/online-services/tools-calculators/Pages/well-card.aspx

monitoring wells were used in the assessment of pre-Darfield Earthquake fluctuations in water table elevation (see Section 11).

Table 4.1 Water table readings available since September 2010, by monitoring well source.

Number of months within post-Darfield Earthquake period for which at least one monthly reading is available	No. of CCC wells	No. of ECan wells	No. of EQC Initial Phase wells	No. of EQC TC3 Phase wells	Use
1 - 3	-	-	49	9	See Section 10 for use of short-term data (< 12 months data)
4 - 6	-	-	27	23	
7 - 9	-	-	24	52	
10 - 11	-	-	24	102	
12 - 15	-	-	44	37	See Sections 5 to 9 for use of longer-term data (≥ 12 months data)
16 - 18	-	-	76		
19 - 20	-		105	-	
21 - 24	-	1	320	-	
25 - 27	-	-	28	-	
28 - 30	-	1	-	-	
31 - 32	-	2	-	-	
33 - 36	2	5	-	-	
37 - 39	20	16	-	-	
Total	**22**	**25**	**697**	**223**	

4.3 Environment Canterbury monitoring wells

Environment Canterbury (ECan) monitors groundwater in wells throughout Canterbury, including water table levels and piezometric pressures in deeper confined aquifers. ECan provided data from 320 monitoring wells within the study area. The length of the monitoring record and type of monitoring for each well varies. Much of the data are unsuitable for this study as ECan's objective has been to monitor groundwater level and quality parameters in the deep aquifers used for water supply. There are, however, some wells developed for specific projects or as part of regional groundwater surveys. Importantly, there are ECan wells beyond the Christchurch City boundary that define the position of the water table, and/or shallow unconfined/semi-confined groundwater, and some shallow wells within the city with long-term records.

ECan has some data records that extend as far back as 1894[4], and many with durations of 30 - 50 years. A number of other ECan wells were only monitored for short periods (i.e. weeks or months after completion of the well). The frequency of groundwater measurements in ECan monitoring wells range from once every 15 minutes to monthly. Quite a few of the ECan monitoring wells with pressure transducers have no records since 2010, as parts of the

---

[4] Canterbury Museum well M35/2564 in a confined aquifer.

monitoring network were damaged and became non-functional during the 2010 – 2011 Canterbury earthquake sequence (Environment Canterbury, 2011c).

Data provided by ECan includes the well head measuring point (MP) elevation and the surrounding ground level (GL). Elevations of a number of these measuring points were re-surveyed in August 2012 by RTK-GPS tied to Land Information New Zealand (LINZ) benchmarks. Figure B.4 (Appendix B) summarises the ECan conventions for MP and GL. An example ECan monitoring well record sheet and well log are presented in Figure B.5 (Appendix B).

A total of 25 ECan monitoring wells (Figure B.1, Appendix B) were selected to contribute to the map of the post-Darfield Earthquake median water table and percentile surfaces. Data from 28 ECan monitoring wells were used in the assessment of pre-Darfield Earthquake fluctuations in water table elevation (Section 11).

4.4 EQC geotechnical investigation monitoring wells

4.4.1 General

A large number of monitoring wells (Figure B.1, Appendix B) have been constructed and monitored as part of geotechnical investigations being carried out for EQC. The wells were constructed in two separate phases of work, including the Initial Phase and the TC3 phase, as outlined below. Well installation details are presented in Figures B.6 and B.7 (Appendix B). The ground elevation at the location of these wells was surveyed at the time of installation. However, there is no surveyed record of well head elevation, which is assumed to be at the ground surface.

At the time of writing, this investigation was practically complete and brought the total number of investigation points on the CGD to 14,000 CPTs and 1,400 machine augered boreholes. In some CPT and borehole locations, monitoring wells have been constructed to enable the water table to be measured at monthly intervals (e.g. Figure B.7, Appendix B).

4.4.2 Initial Phase (2010-2012)

Following the 4 September 2010 Darfield Earthquake, EQC commissioned geotechnical ground investigations in areas of Canterbury affected by consequential liquefaction. These investigations were largely completed when the Christchurch Earthquake occurred on 22 February 2011, and were primarily targeted for the government-funded ground improvement works along waterways to improve land and mitigate the potential for future lateral spreading (Tonkin & Taylor, 2010). The February and June 2011 earthquakes resulted in a larger area of land affected by consequential liquefaction, so a geotechnical investigation with a wider scope was commissioned by EQC. In addition, CCC commissioned a comprehensive geotechnical investigation over the central business district of Christchurch City (Tonkin & Taylor, 2011). The site investigations for both EQC and CCC comprised:

(a) cone penetration testing (CPT) with dynamic pore pressure measurement;

(b) borehole drilling with selected geotechnical testing;
(c) geophysical testing primarily comprising multi-channel analysis of surface waves (MASW); and,
(d) construction of monitoring wells for measurement of water table depths.

Wells have been installed in some of the drilled boreholes and CPT holes which were carried out for the geotechnical investigations. Example details of initial phase wells are provided in Figure B.6 (Appendix B). These wells have screens between 4 m and 7.5 m below ground level (bgl). Water table depths were observed at the time of installation and, for the most part, have been measured by manual dipping at monthly intervals since well completion. In some cases, monitoring wells were damaged by subsequent earthquakes and repair work to the damaged infrastructure and as a result recording of groundwater depths ceased.

Data from 697 initial investigation phase monitoring wells were examined for analysis of the post-Darfield Earthquake median water table and percentile surfaces. Monitoring of these wells commenced as early as June 2011. A total of 573 of the wells had groundwater monitoring readings for at least 12 months since September 2010 (Section 6). Only monitoring wells with ≥ 12 months data were used for calculation of the median water table (Sections 5 to 9 and Appendix F). A total of 124 initial phase wells had short-term or discontinuous groundwater monitoring data records (< 12 months) for which a surrogate of the median water table elevation was estimated (Section 10 and Appendix G).

4.4.3 TC3 Phase (2012 onwards)

Further geotechnical investigations at relatively closely spaced intervals were later carried out by EQC, private insurers and property owners, in areas of land identified by MBIE as requiring further geotechnical investigation for dwelling foundation design purposes. These areas of land are referred to as TC 3, (Department of Building and Housing, 2011; Figure C.2, Appendix C), and the associated investigations are referred to as the TC3 Phase in this report.

Installation of 223 TC3 Phase monitoring wells began in October 2012. The duration of groundwater records is more than one year (i.e. more than 12 readings) in only 37 wells and their median and percentile values have been incorporated in the development of the water table surfaces (Section 6). The remaining 186 wells have short-term monitoring records of less than one year (< 12 readings) and median water table depths are estimated for these wells (surrogate method - Section 10 and Appendix G).

5.0 GROUND ELEVATION FROM LIDAR SURVEYS

5.1 General

The ground elevation in Christchurch City and surrounding area is known to have changed locally, by subsidence or uplift, as a result of the seismic events (Section 2). Recordings by continuous GPS stations suggest significant coseismic changes in ground elevation occurred abruptly during the four major earthquakes (e.g. Beavan et al., 2011, 2012), rather than gradually in the interseismic periods between earthquakes, although work on this continues (e.g. Lashgary et al., 2012).

Airborne LiDAR surveys have been used to develop Digital Elevation Models (DEMs) and to assess the incremental ground elevation changes since 4 September 2010, and throughout 2011, as a result of the seismic events. Differences in elevation between LiDAR surveys are an effective method for measuring the incremental change in Christchurch City ground surface elevation, and surrounding areas, associated with the earthquake sequence. LiDAR was acquired by AAM Brisbane (AAM) and New Zealand Aerial Mapping (NZAM) following each of the significant earthquakes (Table 5.1). Figure C.1 (Appendix C) shows the cumulative ground level changes measured by LiDAR that have occurred as a result of the Canterbury earthquake sequence.

Table 5.1 Christchurch City LiDAR surveys, typically collected at least one month after each major earthquake.

Name of Digital Elevation Model	Source LiDAR	Water table monitoring period for which LiDAR survey data can be used as a reference of ground elevation
Pre-earthquake	AAM 6-9 Jul 2003 AAM 21-24 Jul 2005 AAM 6-11 Feb 2008	Before 4 Sep 2010
Post-Sept 2010	NZAM 5 Sep 2010	4 Sep 2010 – 21 Feb 2011
Post-Feb 2011	NZAM 8-10 Mar 2011 AAM 20-30 May 2011	22 Feb 2011 – 12 June 2011
Post-June 2011	NZAM 18 & 20 Jul, 11 Aug, 25-27 Aug, and 2-3 Sep 2011	13 June 2011 – 22 Dec 2011
Post-Dec 2011	NZAM 17-18 Feb 2012	23 Dec 2011 onwards

5.2 Precision and accuracy of the LiDAR surveys

Appendix C outlines the analysis to assess the accuracy of the LiDAR survey data that was completed by Tonkin & Taylor Ltd for EQC (CERA, 2014). The procedure compared survey levels for benchmarks with the adjacent LiDAR survey points. The following conclusions were drawn:

- the median error is close to zero for all of the LiDAR data sets, apart from the 'Post-June 2011' digital elevation model;
- the 'Post-June 2011' LiDAR survey points have an offset of approximately 50 mm (i.e. the median error is +50 mm) giving elevations that are too high relative to other digital elevation models, so needed to be adjusted downward by 50 mm;
- the standard deviation of each LiDAR survey point is approximately 160 mm for the 'Pre-Earthquake' LiDAR survey points, and approximately 60-70 mm for the subsequent data sets.

5.3 Ground elevation at monitoring well locations

Ground elevation at many monitoring well locations has changed because of the earthquakes, as measured by:

- LiDAR surveys (Section 5.1); and,
- re-surveys of some ECan monitoring well locations in August 2012 and CCC monitoring well locations in December 2012, by RTK-GPS tied to LINZ benchmarks

As a result the measuring point elevation at the top of the well head has also changed because of the earthquakes. Corrections were applied to the time-series of monitoring data values used to calculate the water table elevations. The correction process is summarised in Figure 5.1 and Table 5.2 and described further in the following sections.

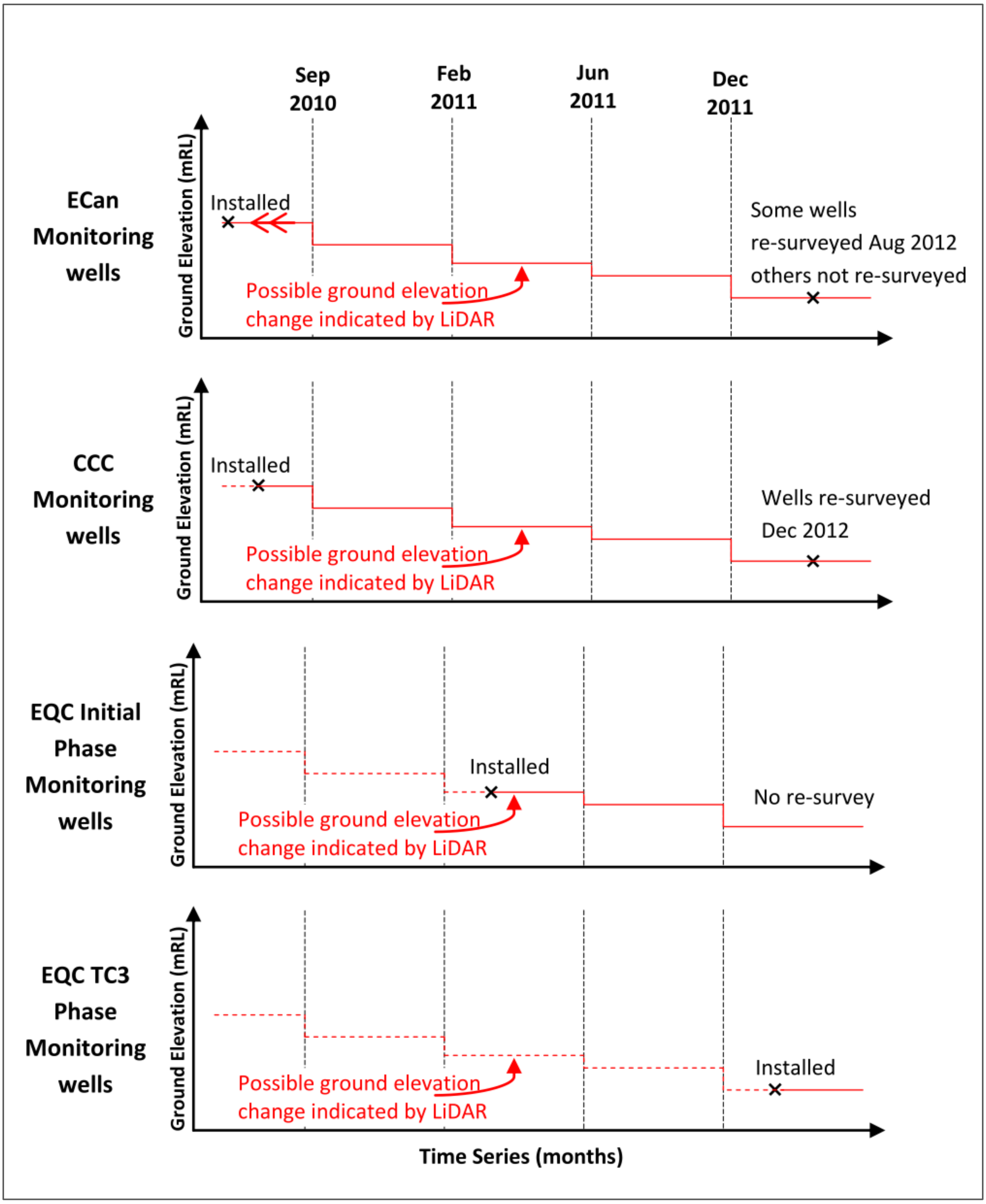
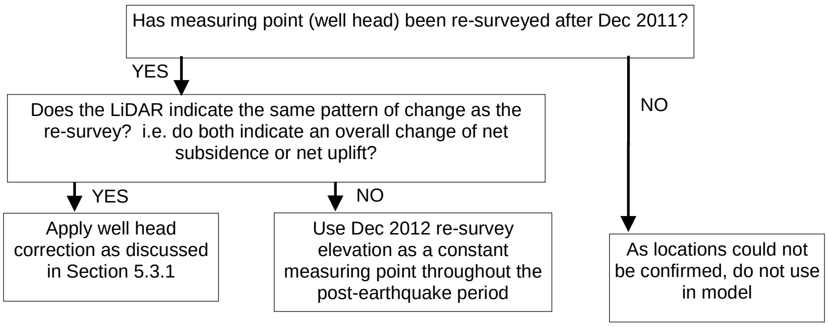
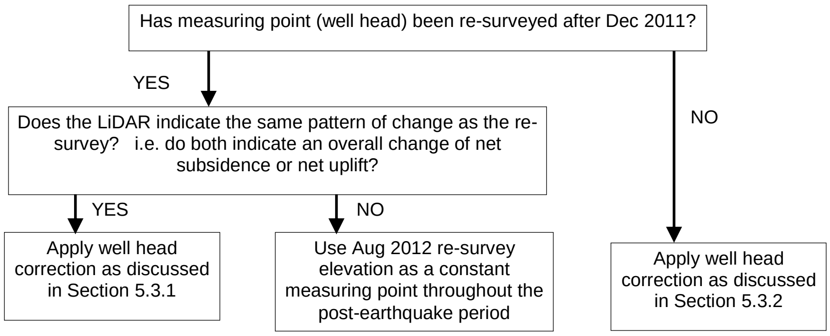


Figure 5.1 Examples of the different types of ground elevation data available for correcting the measuring point elevation of monitoring wells, depending on their source and time of installation.

Table 5.2 Procedures to correct for changes in well head elevation.

Well data source	Criterion for well head elevation correction based on LiDAR
CCC	All monitoring wells installed prior to the September 2010 seismic event. Elevation of measuring points (well head) re-surveyed in December 2012 
ECan	All monitoring wells installed prior to September 2010 seismic event. Some of the wells have been re-surveyed in August 2012, others show no record of being re-surveyed since installation. 
EQC Initial Phase	Monitoring wells generally installed from May 2011 onwards, so they have sustained up to 2 significant earthquakes: June 2011 and December 2011. No re-survey carried out after these events. Use LiDAR elevation (Post-June 2011 and Post-Dec 2011) as an indication of ground elevation change. Apply well head correction as discussed in Section 5.3.2.
EQC TC3 Phase	Monitoring wells installed from beginning of 2012 onwards, so they have sustained no major seismic events. Well head correction not necessary, so use surveyed ground elevation at time of well installation for entire period of water table monitoring.

5.3.1 Example well head elevation correction for CCC and ECan monitoring wells

The surveyed well head elevation is adjusted for each period between earthquakes in proportion to ground elevation changes measured in LiDAR surveys, but utilising absolute elevations of the well head from the survey data. In Figure 5.2, S_1 and S_2 are the original and final surveyed well head elevations, respectively. The correction procedure aims to account for step-wise changes in the LiDAR well head elevation (L_1 to L_5) due to major earthquakes.

In the example (Figure 5.2):

- $S_1 - S_2 = 100$ mm
- $L_1 - L_5 = 90$ mm
- $L_1 - L_3 = 40$ mm
- the well head elevation at L_3 after the 22 February 2011 earthquake, is adjusted so that it is 44 mm (i.e. 40/90 x 100 mm) less than the surveyed S_1 elevation.
- all water table readings for months between February 2011 and June 2011 are calculated using a well head elevation that is S_1 – 44 mm.
- the procedure is repeated for all other step-wise changes to the ground elevation indicated by the LiDAR surveys.

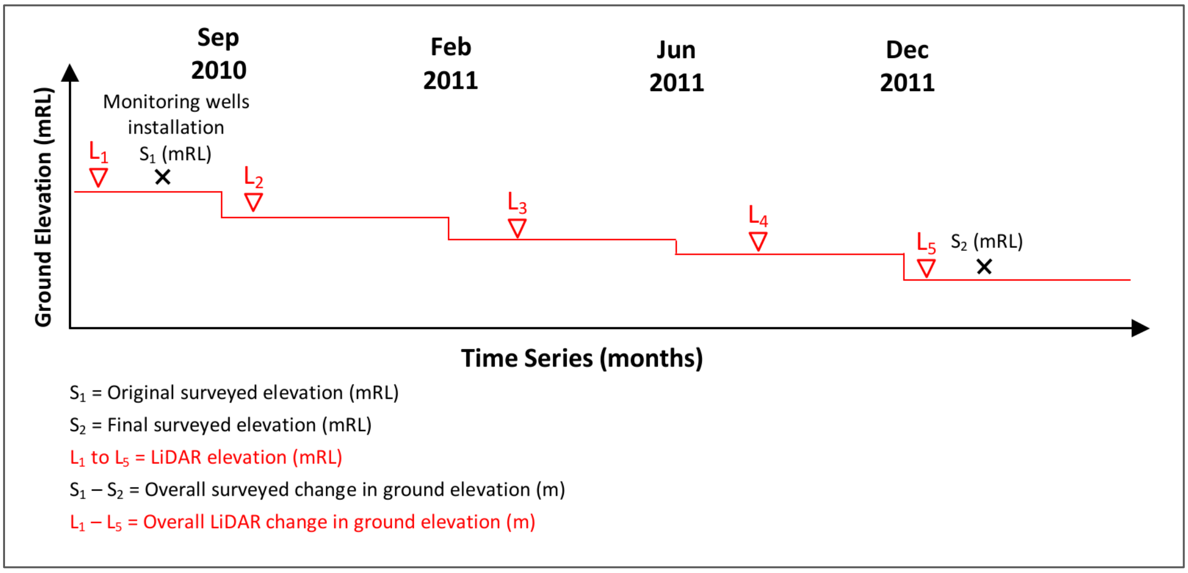


Figure 5.2 **Schematic changes in well head elevation, with data from re-surveys of CCC and ECan well head measuring points and/or LiDAR surveys.**

5.3.2 Example well head correction for EQC (Initial or TC3 Phase) monitoring wells

The surveyed well head elevation is adjusted for each period between earthquakes by the amount of ground elevation change measured by LiDAR surveys at the site. In Figure 5.3, S_1 is the original surveyed well head elevation and is expected to be a more precise measuring point elevation than the LiDAR ground elevation L_3. The correction procedure aims to account for step-wise changes in well head elevation (L_4 to L_5) due to uplift or subsidence caused by major earthquakes.

In the example (Figure 5.3):

- S_1 = 2.5 m RL
- $L_3 – L_4$ = 40 mm
- $L_3 – L_5$ = 50 mm
- the well head elevation at L_4 after the June 2011 event, is adjusted so that it is 40 mm less than the S_1 elevation. The well head elevation at L_5 after the December 2011 event is adjusted so that it is 50 mm less than the S1 elevation.
- for the particular well, all water table readings for months between June 2011 and December 2011 are calculated using a well head elevation that is S_1 – 40 mm, and all water table readings for months after December 2011 are calculated using a well head elevation that is S_1 – 50 mm.

In many instances L_3 and S_1 are different. Therefore the incremental changes to the well head elevation applied by the method (i.e. L_3 to L_5) are the best estimate of the local effects of the earthquakes.

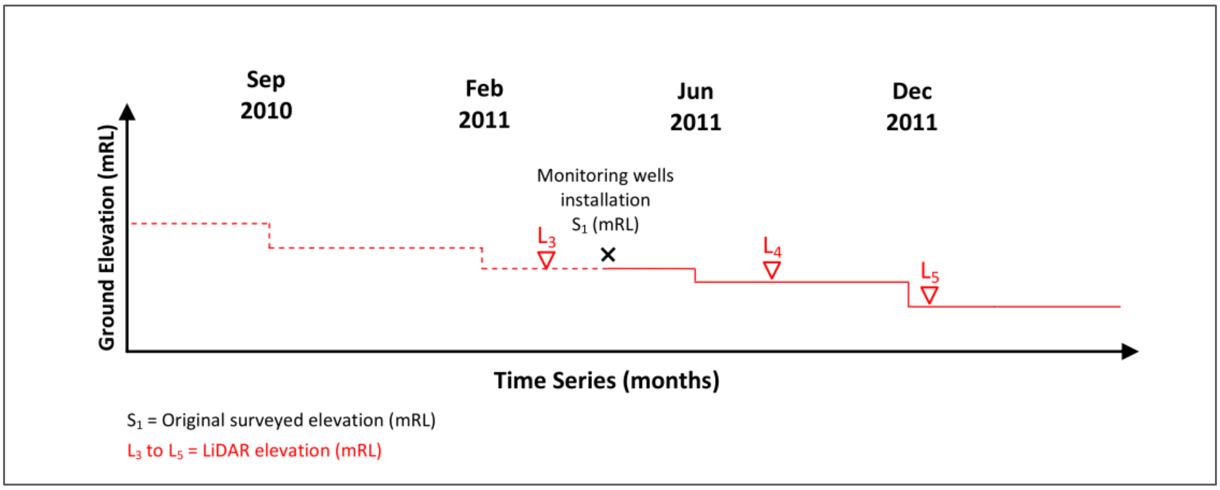


Figure 5.3 **Schematic changes in well head elevation, with data from LiDAR surveys.**

6.0 WATER TABLE ELEVATION FROM MONITORING WELL DATA

6.1 Selection of data

Stage 1 of the flowchart in Figure 3.1 summarises how data from the available monitoring well locations (CCC, ECan and EQC) have been used to calculate a median water table elevation for each particular well location using a data set from the post-Darfield Earthquake period (i.e. 4 September 2010 to 30 November 2013).

Median values (in mRL LVD-37) were calculated by using the available monthly data, based on only one reading per month. If there was more than one reading per month then the measurements a monthly median was calculated. Table 4.1 indicates the proportion of wells that had at least one monthly reading over the 39 month post-Darfield Earthquake period.

6.2 Median water table elevation from wells with longer-term data records (≥ 12 months)

A complete set of monthly readings within the post-Darfield Earthquake period is available for the CCC and ECan monitoring wells (Sections 4.2 and 4.3). These data have been used to carry out a sensitivity check on the effect of data duration. Figures D.1 and D.2 (Appendix D) show median estimates as a function of record duration. Notably, median estimates typically converge where 12 or more values are used in the calculation. Therefore, median estimates derived from a period that is greater than 12 months, but where the seasonal representation is uneven (e.g., 18 months of data collected during two summers and one winter), are likely to be a reasonable representation of the median water table at that site.

Median, 15th and 85th percentile values were calculated for each piezometer location using the full available data set where the monitoring record has more than 12 monthly readings. Unlike Version 1 of this report, no adjustments were made to ensure an equal number of seasons are included in the median and percentile calculations. Monitoring wells with short-term (< 12 months) data were judged unlikely to have sufficient readings for their median to be representative of the full range of seasonal cycles so were not included in the first calculations of the median water table (Sections 8 & 9) – but are discussed separately and used in Section 10.

7.0 CONSTRAINTS FROM SURFACE WATER

7.1 Rivers overview

Groundwater and surface waters are commonly in hydraulic contact such that their levels and fluctuations can be correlated. Within the study area, rivers are both losing to, and gaining from, groundwater (White et al., 2001). Outflow from the Waimakariri riverbed provides a major source of groundwater for Christchurch City (White et al., 2012). Much of this groundwater emerges in springs to feed the Styx, Avon/Otakaro and Heathcote rivers. Springs in Christchurch City were classified by Cameron (1993) into two distinct types:

- artesian springs emerging through fine-grained sediment overlying water-bearing gravels, the springs emerging through ‘vents’ in the fine-grained deposits;
- seepage through the stream bed where the stream channel intersected the water table.

Where rivers are in direct hydraulic contact with groundwater there is potential to use their levels as a proxy for the water table elevation immediately adjacent to the riverbank. There are situations, or scales of observation, where such an approach is invalid, or oversimplified when examined in detail. For example, where a riverbed is comprised of low permeability materials, the river may be perched above the water table, with an unsaturated zone beneath the base. Where there are substantive gains or losses in head between the river and groundwater, there could be a steep hydraulic gradient towards or away from the river. For rivers that discharge to groundwater, the water table will be below the water level in the river. An example is the Waimakariri River, which has an unconfined aquifer with groundwater which has been modelled with an average depth of 2 m below riverbed (White et al., 2001, 2012). The Avon/Otakaro, Heathcote and Styx rivers gain base flow from groundwater springs sourced in either the water table aquifer and/or confined aquifers. Where depicted on maps (e.g. Figure E.1, Appendix E) these spring-fed rivers are perennial with levels that are likely to be slightly lower than the water table due to the effects of streamflow and head loss through the hyporheic zone/streambed.

The difference in elevation between the median river level and the nearby water table is dependent on factors including riverbank topography and the hydraulic properties of the riverbank/streambed and shallow aquifer. Differences in the Avon/Otakaro, Heathcote, and Styx river elevation relative to the water table have not been studied in detail, however relevant observations can be found in Cameron’s (1993) MSc study of the Avon/Otakaro River and Cowan’s (1987) North Canterbury Catchment Board study of the Harewood-Styx area. There are numerous EQC monitoring wells along the banks of the Heathcote and Avon/Otakaro rivers, as these are places where much of the liquefaction and lateral spreading damage occurred. Based on an inspection of LiDAR ground elevation and nearby monitoring well levels along these rivers, our observations suggest the difference between groundwater and river levels are rarely more than ±1 m. This is a topic worthy of future work, although it should also be noted that the levels of these rivers are also complicated by a variety of factors including the Christchurch drainage network, pumping, and tidal flows.

In this study, we have assumed that the water table in a riverbank is in direct hydraulic contact with the surface water in the channel. Changes in the shape of the water table are likely to occur close to the rivers, with either ridges or troughs in the water table depending on the interrelationship between groundwater and river levels. We assume that the median water table level is the same as the median river level, as provided by CCC and ECan stage-duration curves.

The variability of surface water elevation will be much greater than the variability of groundwater levels at the river edge. In the absence of detailed data on riverbank groundwater elevation fluctuations, we calculated the 15th and 85th percentile values of surface water elevation from river stage-duration curves, then interpreted the likely groundwater fluctuation. Values of tidal efficiency near the coast or tidal-reaches of the rivers for this adjustment were derived from a short experiment at Avonside (H. Rutter pers. comm.) and observations in similar geological settings and materials elsewhere in New Zealand (e.g. Rekker, 2012; Fordyce, 2013).

Surface water elevations (median, 15th and 85th percentiles) were calculated from gauging and flow models of the Avon/Otakaro, Heathcote, Styx and Waimakariri rivers (Table 7.1). A map showing the extent of surface water bodies used in the surfaces and locations of river gauging stations is provided in Figure E.1 (Appendix E). The approach was to assign median values, and adjusted 15th and 85th percentile values, to data strings representing these rivers, then incorporate them into water table contouring through Surfer's breakline[5] function. River lines were not used to inform the Beca (2004, 2005) study, but were used by Begg & Scott in Brackley (Compiler) 2012.

Table 7.1 **Summary of river level monitoring stations.**

Main River Branch	Tributary	Data provider	River Gauging stations
Avon/Otakaro River	Dudley Creek Horse Shoe Lake Wairarapa Stream Waimairi Stream Broadhurst Creek	CCC	AEB ALA ALB AGL
Heathcote River	Jacksons Creek Heathcote Diversion	CCC	HFM HOP HBX HFE
Styx River	Kaputone Creek	CCC	SBL SBK SSP SRF
Waimakariri River	N/A	ECan	Old Highway Bridge (OHB)

---

[5] The gridding algorithm in Surfer allows searches and interpolation across a breakline, and uses breaklines to define changes in slope. Breaklines are distinct from 'faults', which act as an interpolation boundary. A fault cannot be crossed by the gridding algorithm search.

7.2 Calculation of median values

7.2.1 Avon/Otakaro, Heathcote and Styx rivers

Level data for the Avon/Otakaro, Heathcote and Styx rivers were provided by CCC, based on flow models developed using the MIKE 11[6] program. Critical inputs to the MIKE 11 model include: representation of the upstream and downstream hydraulic boundaries (water level and/or flow); cross sections (surveyed and estimated) along the river course; estimates of channel roughness using the Manning ‘n’ approach (e.g. Arcement & Schneider, 1989). The model uses these critical inputs (plus additional information) to resolve the kinematic, diffusive or fully dynamic, vertically integrated mass and momentum equations. These are also known as the “Saint Venant” equations, and they are resolved in the MIKE 11 model using an implicit finite difference scheme.

Median (and percentile) river levels were calculated at gauging stations that show little or no tidal effect (Table 7.2; Figures E.1 to E.4, Appendix E). These median flows were adopted as input to the MIKE 11 models, incorporating surveyed elevations and cross sections, in order to calculate/model a median flow elevation along the length of each river. The calculated water level was interpolated between cross sections and reported by CCC as a river string for use in the Surfer package.

7.2.2 Waimakariri River

On the Waimakariri River there is only one monitoring station within the study area - Old Highway Bridge (OHB). River level data were provided by ECan, in mRL relative to LVD-37, reported at six-hour intervals. Data are also collected at another station (Gorge) located outside the study area, approximately 60 km upstream from Old Highway Bridge station. While this was not directly useful for this study, ECan and other organisations use this site for flow modelling.

A set of modelled Waimakariri River median water elevation values were derived by ECan at 47 other locations within the study area where river cross-sections have been surveyed. The median water elevations were calculated by ECan as follows:

- a median discharge (flow rate) was calculated for the Waimakariri River at OHB, based on the calculated median water level from monitoring records at OHB as well as known river channel geometry at OHB (based on a channel survey);

- the calculated median discharge at OHB was assumed to occur at each of the other 47 cross-sections at various locations along the river. Based on the median discharge, and known river channel geometry at each cross-section location (based on channel surveys), a median water level was calculated for each of the cross-section locations (Figure E.5, Appendix E).

---

[6] DHI software http://www.mikebydhi.com/

7.3 Calculation of 15th and 85th percentile levels

The Avon/Otakaro, Heathcote, Styx and Waimakari rivers all have relatively low gradients near the coast and have reaches that can be classified (Figures E.1-5, Appendix E) as:

- tidal - where river levels rise and fall directly in relation to sea tides, with lesser influence by high-flow pulses from upstream;
- transitional - where the riverbed elevation is between high and low tide levels, such that the flow is influenced by high-tides in the lower sections of the river, but not low-tides;
- non-tidal (fluvial) - upstream reaches where the rise and fall of the river is principally related to precipitation and spring flow, unaffected by tides.

The approximate locations where tidal influences cease are:

- Avon/Otakaro River, between Barbadoes Street and Madras Street;
- Heathcote River, approximately 500 m – 1000 m downstream of the recorder site at Buxton Terrace;
- Styx River, approximately halfway between Radcliffe Rd and the recorder site at Lower Styx Road. (NB: The lower reaches of Styx river have flood control engineering);
- Waimakariri River, approximately at the State Highway 1 bridge.

At each river monitoring station, stage-duration curves were used to derive 15th and 85th percentile surface water fluctuations, then the differences below and above the median flow, respectively, were calculated in metres (Table 7.2). Such observations are site specific and there will be differences in the variation of stage along the river profile according to the shape of the channel cross-section. Corresponding fluctuations of groundwater levels in the riverbank/streambed were then assigned according to an adjusted proportion of the river fluctuations applied to the mean tide, based on observations of tidal influences at Avonside (H. Rutter pers. comm.) and measurement of tidal efficiency in similar hydrogeological settings (e.g. Rekker, 2012; Fordyce, 2013).

Table 7.2 **Relationship between observed surface water fluctuations at river monitoring stations or in tide models, and fluctuations assigned to river and coastal data strings to represent variation of local groundwater levels at different locations (see Figures E.2-E.4, Appendix E).**

River	**Observed fluctuations in stage duration curves and tide models.** **Values in metres.** **(Station name)** ***= influenced by tides**		**Adjustment factors (in metres) assigned to represent groundwater fluctuations in river and coastline strings**				
			85th percentile		**15th percentile**		
	85th percentile minus median (difference)	Median minus 15th percentile (difference)	Non-tidal	Tidal	Non-tidal	Transitional (linear adjustment)	Tidal
Avon	0.21 (AGL) 0.57 (AEB)*	0.04 m (AGL) 0.40 (AEB)*	0.25	0.25	-0.1	-0.1 to -0.25	-0.25
Heathcote	0.15 (HFE) 0.18 (HBX)*	0.06 (HFE) 0.08 (HBX)*	0.25	0.25	-0.1	-0.1 to -0.25	-0.25
Styx	0.26 (SRF)	0.24 (SRF)	0.25	0.25	-0.25	-0.25 to -0.25	-0.25
Waimakariri	0.34 (OHB)*	0.25(OHB)*	0.25	0.25	-0.25	-0.25 to -0.25	-0.25
Coastline	0.58*	0.58*	N/A	0.25	N/A	N/A	-0.25

Table 7.2 outlines the 85th percentile-median and median-15th percentile differences observed in non-tidal parts of the river, and the adjustment values assigned to tidal, transitional and non-tidal reaches of the river strings that have been selected to represent local groundwater fluctuations. Adjustment values (differences) were added (for 85th percentile) or subtracted (for 15th percentile) to/from the median river strings for surface calculation as follows:

- the 85th percentile water table surface used a breakline set +0.25 m above the median river string level for all tidal, transitional and non-tidal zones;
- the 15th percentile water table surface used breaklines set:
    - 0.1 m (below) the median in the non-tidal zone in the Avon/Otakaro and Heathcote rivers;
    - 0.25 m (below) the median in the non-tidal zone of the Styx and Waimakariri rivers;
    - 0.25 m (below) the median in the tidal zone in each river and at the coastline;
    - 0.1 m (below) the upstream end of the transitional zone and -0.25 m at the downstream end of the transitional zone in the Avon/Otakaro and Heathcote rivers, with the level varying linearly along the river string.

7.4 Coastline

7.4.1 Median values

The water table elevation is connected to, and influenced by, sea level at the coast including:

- the estuary of the Heathcote and Avon Rivers/Ihutai;
- Brooklands Lagoon;
- all other beaches and coastlines.

This study assumes the median groundwater level at the coast is equal to mean sea level, being +0.064 m RL (Section 1.3). Approximately 950 location points along the coastline were used in kriging interpolation of water table surfaces. The coastline used in the modelling was taken from LINZ 1:50,000 topographical maps.

Oceanic tides are not considered in the median water table calculations because they are regular and high-frequency, and are represented by 'mean sea level'.

7.4.2 Oceanic tides and the 15th and 85th percentile elevations

The tidal range in the Tasman Sea immediately offshore of the study area has an amplitude approximately ± 1.3 m, although the amplitude within any one tidal cycle is more typically ± 0.6 m[7]. Corresponding 15th and 85th percentiles are approximately ± 0.58 m relative to mean sea level, depending on length of period sampled.

Tidal oscillations also occur in groundwater near the coast, but with a much smaller magnitude than oceanic tides. In a coastal dune sand, tidal oscillations are almost completely damped within 200-400 m of the mid-tide line (e.g. Rekker, 2012). In lower permeability material the equivalent damping occurs much closer to the shoreline and/or river channel edge.

Wells M36/5385 and M36/5384, located 145 and 100 m from tidal water in the Avon-Heathcote estuary (Figure H.1, Appendix H), have water table fluctuations with tidal amplitude of ± 0.25 and ± 0.03m, respectively.

Without attempting to account for any variations in hydrogeology, a constant difference of +0.25 m has been adopted relative to the median to represent 85th percentile level of the groundwater at the coastline (i.e. 85th percentile = 0.314 m RL). A difference of -0.25m has been adopted relative to the median for the 15th percentile level has been adopted at the coastline (i.e. 15th percentile = -0.186 m RL) (Table 7.2). Based on data for non-tidally affected sites this approach is considered generally conservative.

---

[7] Tidal data and tide calculators are provided at www.niwa.co.nz

8.0 WATER TABLE SURFACE INTERPOLATION AND CONTOURING

This section outlines processes referred to in Stages 2 and 3 of the flowcharts in Figures 3.1 and 3.2 (Section 3). A software program called ‘Surfer 11’ (Golden Software, Inc.[8]), henceforth referred to as just ‘Surfer’, has been used to interpolate median and percentile water table grids and contours, based on the discrete values of water table elevation (mRL) calculated for monitoring wells, rivers and coastlines (as described in Sections 4 to 7).

8.1 Adopted gridding method: kriging

The differences between the various gridding methods in Surfer are in the mathematical algorithms used to compute the weights during grid node interpolation. Each method can result in a different representation of input data. Various gridding methods were considered for the purpose of creating the water table surfaces using the monitoring wells and river data. The strengths and limitations of these methods are summarised in Table 8.1 below, and ultimately the kriging method was chosen as the most appropriate for the purpose of creating a median and percentile water table surfaces for this analysis. Studies of groundwater elevation contouring approaches have commonly shown that kriging is generally considered a robust method, such that it has almost become the default approach for the last 30 years.

A key factor in determining which gridding methods were suitable was whether the particular method allowed for the inclusion of breaklines in the contoured surface. The median elevations of the rivers and coastlines have been used as soft breaklines, that is, the elevation values along the features are maintained at their location.

Kriging is a geostatistical method that is widely used in many scientific fields, as it is a very flexible gridding method and typically produces visually appealing maps from irregularly spaced data. Within Surfer, the kriging defaults can be used to produce an accurate grid based on the input data, or alternately kriging can be custom-fit to a data set by specifying the appropriate variogram model. Kriging can be either an exact or a smoothing interpolator depending on the user-specified parameters. For the current calculation of the water table surfaces, an exact interpolator method has been adopted. The overall accuracy of the final contours once the grid has been created is a function of the grid spacing used to plot the contours. A 25 m grid has been adopted for this study.

---

[8] www.goldensoftware.com/products/surfer

Table 8.1 **Summary of gridding methods (Surfer version 11).**

Gridding method	Strengths of this method, for creation of median water table	Limitations of this method, for creation of median water table
Inverse Distance to a Power	Can use breaklines to model rivers/coastline	Tends to produce bulls eye features Does not extrapolate beyond data range Produced contours appear jagged and steep
Kriging (ADOPTED)	Can use breaklines to model rivers/coastline Flexible Recommended by Surfer authors Can extrapolate beyond data range	May be relatively slow depending on the complexity of the data set and breaklines
Minimum Curvature	Can use breaklines to model rivers/coastline Fast Can extrapolate beyond data range	Over-predicts where data are scarce
Modified Shepard's Method	Can use smoothing functions to reduce bulls eye effects Can extrapolate beyond data range	Cannot use breaklines
Natural Neighbour	Works well when there is a combination of densely spaced and sparsely spaced data	Cannot use breaklines
Nearest Neighbour	Can use breaklines to model rivers/coastline	Produced contours that looked like suburb boundaries/zones Works for regularly spaced data, which this study doesn't have
Polynomial Regression	Fast Can extrapolate beyond data range	Cannot use breaklines Doesn't calculate known elevation of groundwater in monitoring wells accurately
Radial Basis Function	Can use breaklines to model rivers/coastline Similar to kriging	Very slow
Moving Average	Can use breaklines to model rivers/coastline Fast	Better suited to large data sets (1000+ points) Requires regularly spaced data
Local Polynomial	Can use breaklines to model rivers/coastline	Produced jagged contour lines

8.1.1 Suitability of co-kriging

Co-kriging, as with ordinary kriging, can be an exact interpolator using measured data points (depending on input parameters). In some cases, where the elevation of the water table tends to mimic the ground surface, kriging without considering ground surface elevation can lead to erroneous predictions of water table levels. The co-kriging method can improve the estimate of water table elevation by considering a bounding ground surface elevation as a second variable (Hoeksema et al., 1989).

Figure F.1 (Appendix F) presents a plot of median water table elevation for the monitoring wells (as calculated in Section 6) against LiDAR ground surface elevation. Co-kriging is generally seen as an appropriate method where there is a strong correlation (i.e. broadly linear relationship) between the median water table elevation and the ground surface elevation (Chung, 2007).

It can be seen in Figure F.1 that there is some spread between median water table elevation and ground surface elevation for the majority of monitoring wells (seen particularly clearly where ground surface elevation is less than 10 mRL). Also, there appears to be a break in the trend line for data points with ground elevation above 20 mRL, although above this level there is much less data available.

Given that there is not a unique relationship between the median water table elevation and ground surface elevation, the co-kriging method has not been used to create a contoured median water table in this version of the report. However, given the availability of precise DEMs from LiDAR surveys, it is an avenue worthy of further research.

8.1.2 Variogram options

The variogram is a three dimensional function which is a measure of how quickly levels of a surface change on average. Underlying this is the principle that two observations closer together are more similar than two observations further apart. The variogram is created by fitting a mathematical function to actual variance in a data set based on distance and orientation. Once created, the variogram model is directly used to determine interpolation weights which are applied to data points during grid node calculations.

The following two variogram options were considered for use in creating of the median and percentile water table contours:

- the default Surfer variogram (linear function);
- an operator defined variogram (exponential function).

A key consideration in selecting the appropriate variogram is that it should accurately predict known median water table elevation (already calculated in Section 6) at discrete monitoring well locations. Sensitivity tests carried out for this study found that both of the variogram options predicted the known water table elevation at well locations accurately, and visually the contours generated away from areas that contained data appeared reasonable. For this reason, the custom variogram option was not considered superior to the default option, and the default option was still considered appropriate for the purpose of creating the water table surfaces.

8.2 Unconstrained interpolation of water table surface

Co-ordinates and the calculated median water table elevation have been input into Surfer for: CCC, EQC and ECan monitoring wells (discrete locations); river and coastline breaklines. After carrying out the kriging analysis in Surfer using this input data, a plot was created that shows the water table (m RL) as a contour map across the study area. Figure F.2, F.5 and F.8 (Appendix F) are contour plans of the median and percentile water table (m RL) based only on monitoring well locations with 12 months or more of monitoring data and river level breaklines.

8.3 Manual checking and refinement

Mathematical interpolation of surfaces sometimes produces some unexpected and unrealistic results that reflect the distribution of data points rather than reality of the feature being modelled. In order to check and refine the surface generated to represent the median and percentile water table, it has been compared with the Dec 2011 LiDAR DEM over the extent of the study area. In some areas it was found that the estimated water table (m RL) is higher than the LiDAR DEM ground elevation (m RL), that would indicate that the area is ‘wet’, even though there is no surface water. For the most part this appears to be due to the relatively wide distribution of monitoring well sites, compared with the small scale changes in topography that are known in detail from LiDAR DEM’s.

Any apparent wet areas on the contour map that do not reflect actual known areas of surface water in Christchurch City, or areas where surface water collects, were refined using the iterative process summarised in Stage 3 of Figure 3.1 and 3.2 (Section 3). This included identifying the lowest spot in the wet areas and creating a new water table ‘drawdown point’ set at 0.1 m below the ground surface. Once remodelled in Surfer, this drawdown point (or control point) acts like a 'drain', creating a boundary condition to keep the water table just below ground.

Once this iterative process had refined the wet areas, the water table contours (m RL) were reviewed further and places which showed anomalies in the grid and contours (e.g. local spikes that were unreasonably steep, such as might be created by a single measurement error), were smoothed manually. This only removed any locally anomalous spikes or hollows in the water table that are less than 200 m across.

9.0 PRINCIPAL RESULTS

9.1 Median water table surface

The final contour plot of the median water table as an elevation (m RL) is presented in Figure 9.1, based on monitoring well locations with 12 months or more of data, median river level breaklines, and drawdown points.

A contour plot showing the depth to the median water table (m bgl) is presented in Figure 9.2, generated by taking the water table surface plotted in Figure 9.1 and subtracting these elevations from ground elevations defined by the LiDAR DEM (using Post-Dec 2011 where covered, Post-June 2011 elsewhere).

Generated using longer-term monitoring wells, Figures 9.1 and 9.2 are representations of the post-Darfield Earthquake median water table elevation and depth, and are the author's preferred models. The figures are reproduced in greater detail in Figures F.3 and F.4 (Appendix F) which also show the location of monitoring wells (circles) and drawdown points (black stars).

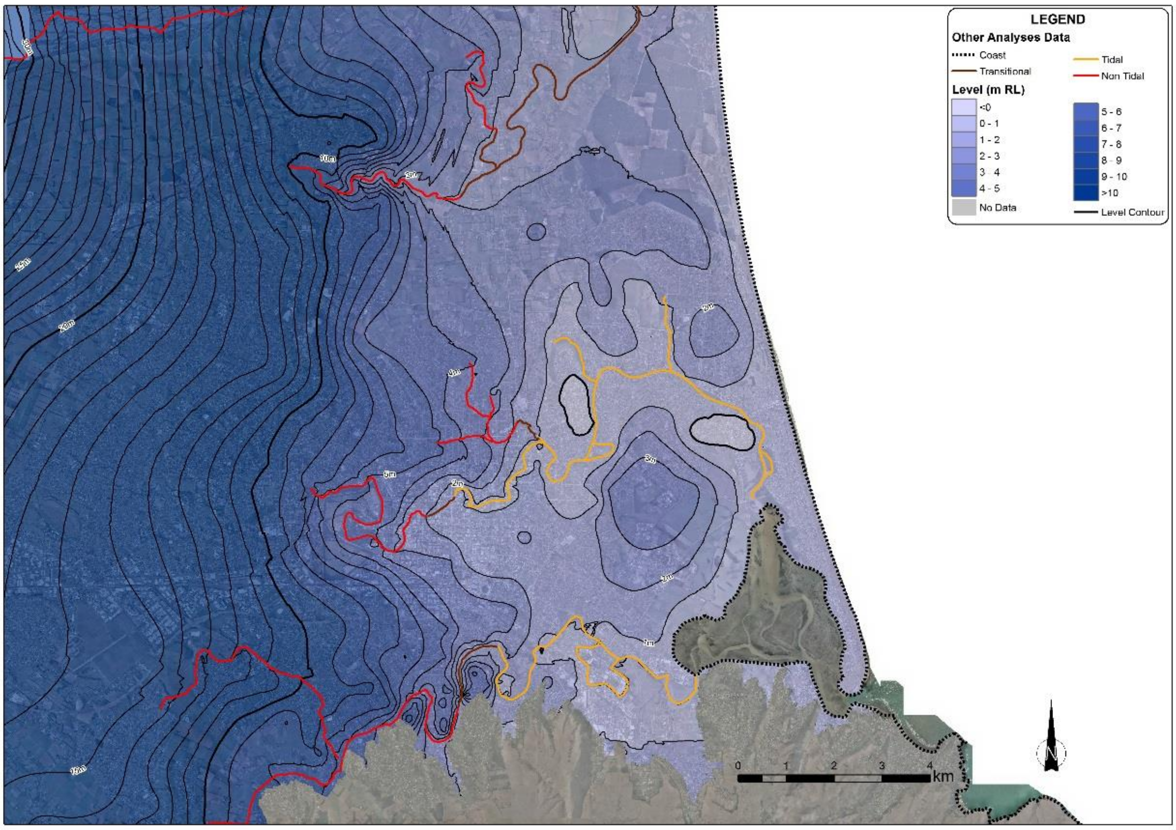


Figure 9.1 **Elevation of the post-Darfield Earthquake median water table (preferred model). A more detailed version of the map, showing monitoring wells with longer-term data (≥ 12 months) and drawdown points, is provided in Figure F.3 (Appendix F).**

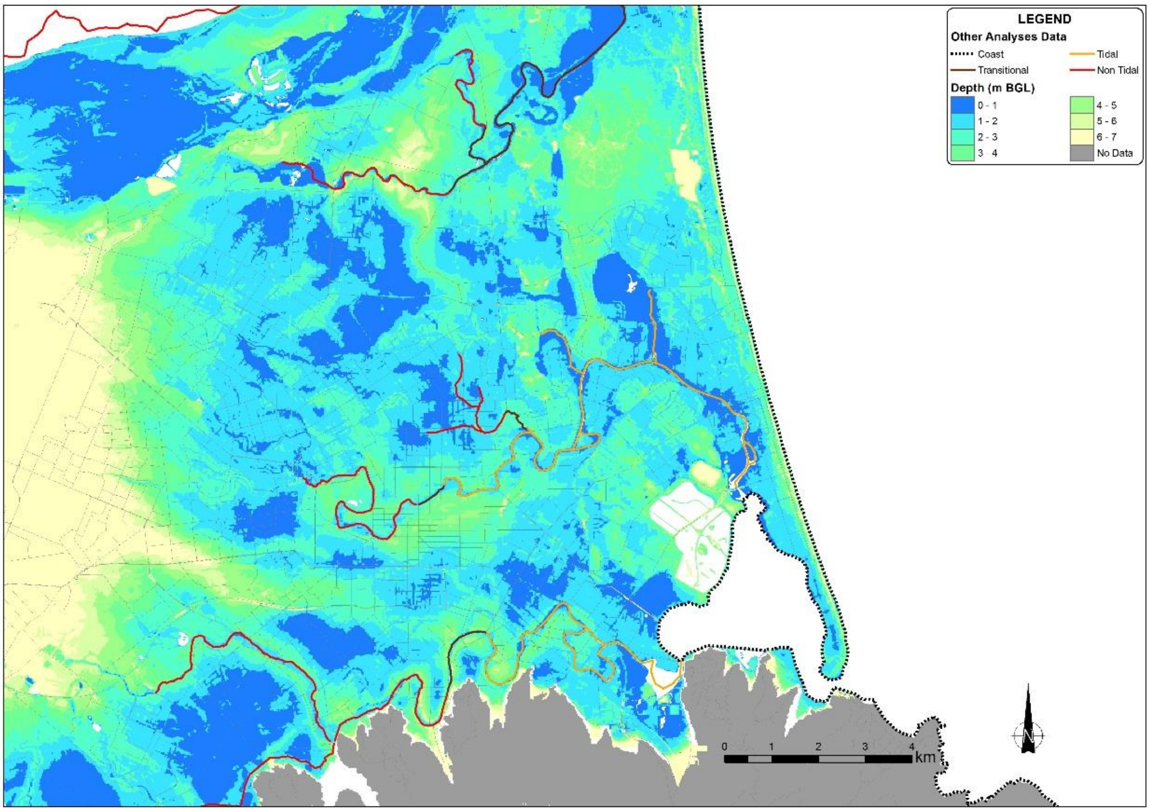


Figure 9.2 **Depth of the post-Darfield Earthquake median water table (preferred model). A more detailed version of the map, showing monitoring wells with longer-term data (≥ 12 months) and drawdown points, is provided in Figure F.4 (Appendix F).**

Some key observations of the median water table elevation and depth to the median water table maps are:

- The elevation of the median water table varies across the study area, with a general slope from > 10 m elevation in the west to < 1 m in the east. The water table is close to the slope of land, but is generally deeper below ground in the west (> 5 m deep) than in the east. The water table is less than 2 m below ground beneath much of Christchurch City. Exceptions can be found: (1) where the water table is very shallow in the southwest (Hillmorton-Halswell-Hoon Hay area) and in the northeast (Marshlands area), (< 2 m bgl); (2) where the water table is locally deep (> 6 m bgl) due to high ground in Bottle Lake Forest (landfill), northeast of the airport, and northeast of the oxidation ponds.

- There are local anomalies in the elevation of the median water table. Near Horseshoe Lake there is an area approximately 1 km x 1.5 km where the median water table is < 0 m, i.e. below sea level. Depression of the water table is thought to be the result of pumping and drainage in this area by CCC. An anomaly of similar dimension occurs in Aranui / Bexley, where the median water table is also below sea level.

- There is a broad median water table high, within an approximately 3 km x 3 km area between Aranui, Wainoni, Bromley and the Te Huingi Manu Wildlife Refuge/Oxidation Ponds where the water table is > 2 m above sea level. A similar, 1 km x 1 km water table high of > 2 m occurs in North New Brighton.

- The median water table appears to be noticeably undulating against the northern margin of the Port Hills. The Heathcote River and the monitoring wells immediately adjacent to the river have median water table elevations that are locally low. In contrast, the peninsulas between the Heathcote River meanders, both to the north and south of the river (in suburbs of St Martins, Beckenham and east Cashmere) have water table levels locally elevated by up to three metres above the river, with the median water table reaching > 4 m above sea level. It is possible the water table is influenced by flow from the Port Hills and/or head losses caused by discharge into the streambed. Other shallow groundwater features of importance along the lower slopes of the Port Hills are a series of springs that emerged between Heathcote Valley, St Martins and Cashmere following the Darfield Earthquake (Figure A.3, Appendix A; Rutter, 2010; Cox et al., 2012).

9.2 Comparison between Version 2 and Version 1

The updated median water table surface with data from September 2010-November 2013 can be compared with the older equivalent surface presented in Version 1 of the report (van Ballegooy et al., 2013 – ≥9 month records, September 2010-December 2012) using Figures 9.1 and 9.3. The differences between the surfaces are visually subtle, so calculated differences are highlighted by subtracting Version 1 from Version 2 (Figure 9.4).

Changes from the Version 1 to Version 2 surfaces are not consistent across large parts of the study area, such as might occur had there been different rainfall during the periods September 2010-December 2012 or September 2010-November 2013 modelled. Instead, the differences tend to be isolated small areas, typically a result of one of the following:

- An increase in number of piezometers used from Version 1 to Version 2, which has increased the spatial resolution of piezometers and provides a greater degree of control of the interpolated surface.

- Refinement of river level values has resulted lower groundwater levels along the rivers strings where used in both surfaces, and has resulted in higher groundwater elevations along the added tributary strings of the rivers (used in Version 2).

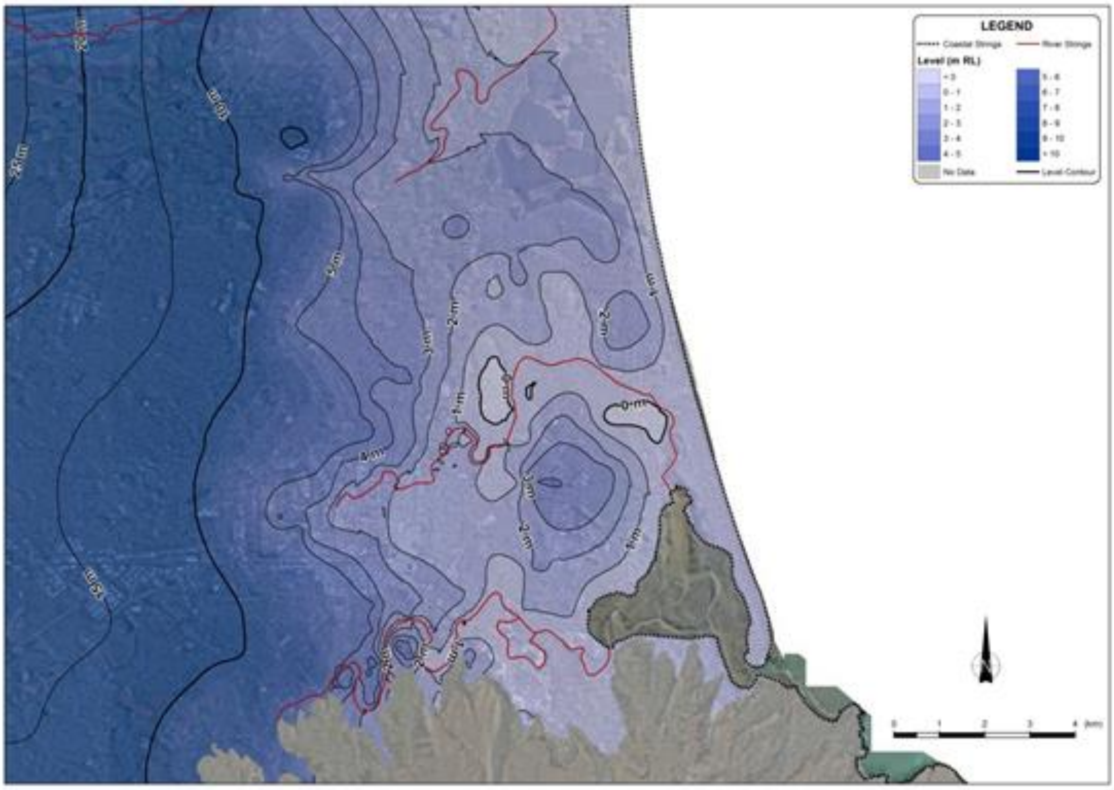


Figure 9.3 Elevation of the post-Darfield Earthquake median water table Version 1, 2013 (≥ 9 months data).

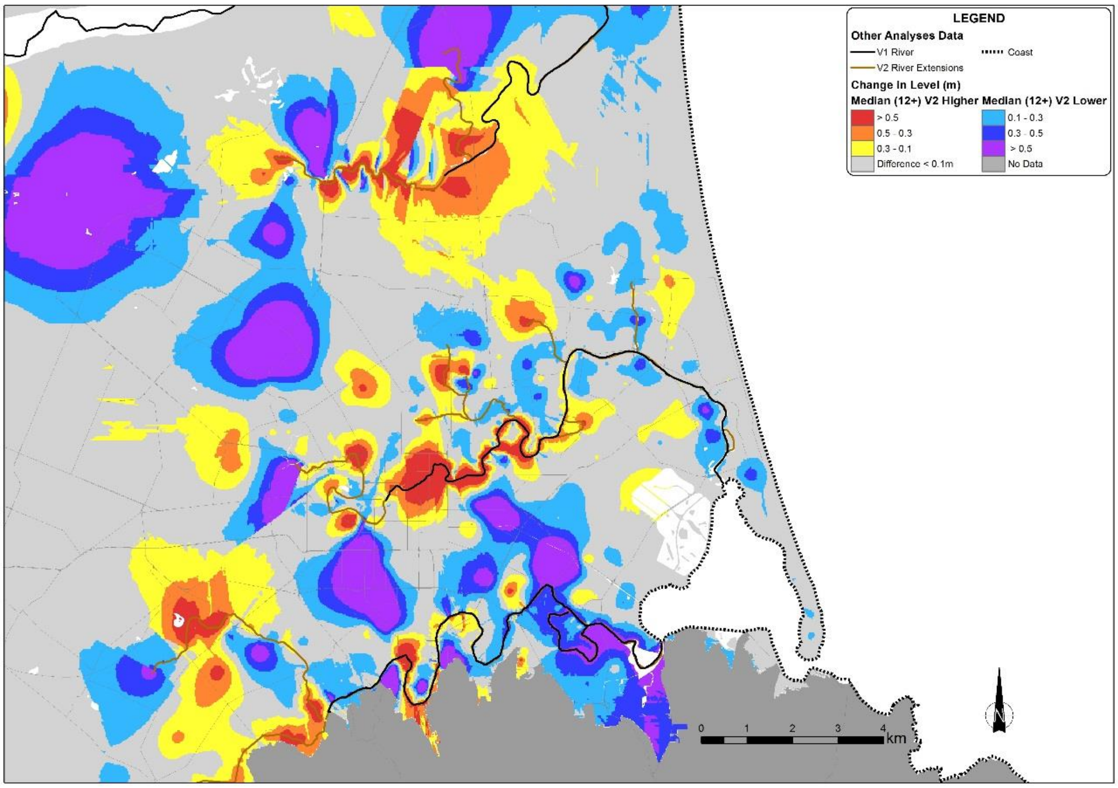


Figure 9.4 Difference between the new 2014 Version 2 and 2013 Version 1 median water table surfaces (using ≥ 12 and ≥ 9 months data, respectively).

9.3 Percentile surfaces

Post-Darfield Earthquake 15th and 85th percentile surfaces are newly developed for Version 2, to compliment the median water table surface. These enable the user to quantify variation in the observed groundwater records that have occurred during the period September 2010-November 2013 (see also Section 11 for pre-earthquake variation).

The 15th and 85th percentile water table surfaces have been developed by:

1. Calculating the differences between 85th percentile-median and 15th percentile-median at each monitoring location (with ≥ 12 readings);
2. Contouring the difference values, including the adjustment values adopted to represent the variation of groundwater at rivers/coastline (see Section 7.3 and 7.4);
3. Inspecting the difference surface contours to confirm all surface values are positive;
4. Adding /subtracting contoured difference to the median surface to produce the relevant percentile surface;
5. Manual checking and refinement to remove anomalous spikes or hollows (as per the median surface - Section 8.3);
6. Examining the depth to 85th percentile surface to look for wet areas. Add drawdown points where necessary (85th percentile difference surface only). Go back to step 2 and add these points with an assigned value of +0.1 m relative to the median.

The rationale for using a median ± contoured difference value, rather than contouring actual percentile values, is because it avoids compounding uncertainties in absolute elevations and minimises differences in mathematical artefacts from one surface to another (Section 3.2).

The magnitude of the difference between the 85th percentile - median and the median-15th percentile levels is not the same. Generally the 85th percentile is further above the median than the 15th percentile surface is below it. The produced surfaces confirm that groundwater measurements recorded in the piezometer network are not evenly distributed around the median – a phenomenon that has importance for liquefaction assessment, and validates the use of non-parametric statistics (cf. parametric statistics that assume a normal distribution).

9.3.1 15th percentile surface

Grids of the difference between the median and 15th percentile (in m), the absolute 15th percentile surface elevation (in m RL), and depth to 15th percentile groundwater (in m relative to ground) are presented as contour maps in Figures F.5, F.6 and F.7 (Appendix F). Some key observations of the 15th percentile surface maps, and how they differ from the median surface, are:

- The 15th percentile groundwater levels were between 0.05 and 0.4 m below the median water table surface in the Coastal Zone, increasing to between 0.5 m to 1.1 m below the median in the Inland Zone.
- There are some localised anomalies to this general trend. A 1 km by 1 km area in Spreydon and Sydenham has 15th percentile values 0.6 m below the median water table level. Similar differences are present is smaller areas of Hoon Hay, Avondale,

Bexley, Dallington and South New Brighton. For the most part these are anomalous areas are caused by measurements/fluctuations in a single monitoring well.
- Areas of South New Brighton, Bexley, Avondale and additionally an area of Dallington, directly south of Horse Shoe Lake, have a 15th percentile water table occurring below mean sea level.

9.3.2 85th percentile surface

Grids of the difference between the 85th percentile and the median (in m), the absolute 85th percentile surface elevation (in mRL), and depth to 85th percentile groundwater (in m relative to ground) are presented as contour maps in Figures F.8, F.9 and F.10 (Appendix F).
Key observations are:

- The 85th percentile levels of the water table were typically 0.1 m to 0.4 m above the median in the Coastal Zone and Transitional Zone, but increase in the west to reach as much as 1.8 m in the Inland Zone.
- There are some localised anomalous areas up to 0.5 km by 0.5 km in size, where the 85th percentile surface is > 0.5 m above the median groundwater surface. These areas are located in Hoon Hay, Somerfield, Beckenham, and Avonside/Wainoni. For the most part these are anomalous areas are caused by fluctuations in a single monitoring well.

10.0 USE OF SHORT-TERM MONITORING WELL DATA

10.1 Introduction

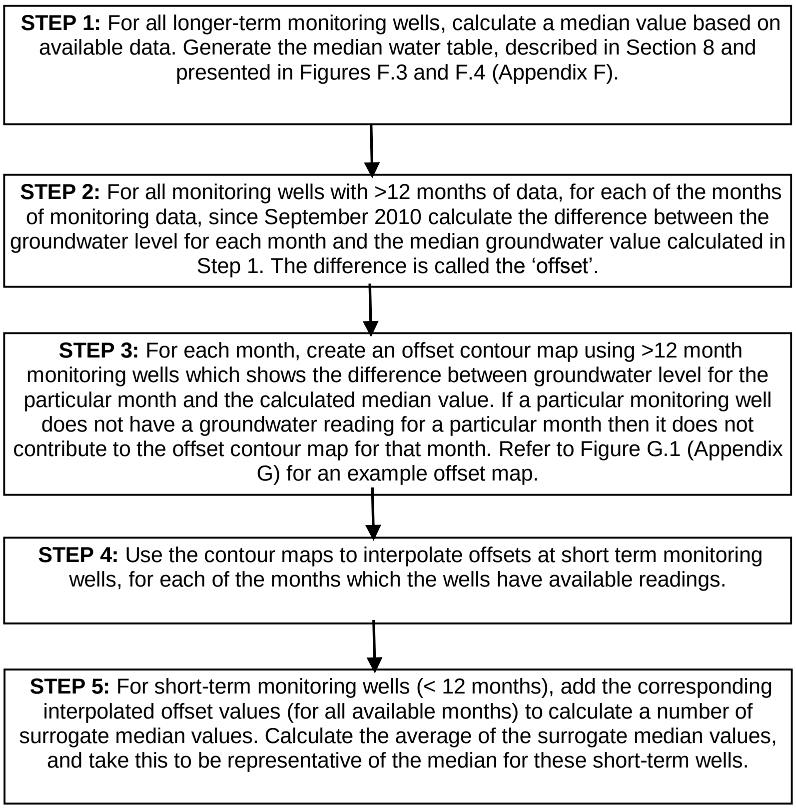
There are 124 (approximately 20%) of the EQC Initial Phase monitoring wells, and 186 (83% EQC TC3 Phase monitoring wells, for which data records are less than 12 months (Table 4.1). Monitoring wells with short-term (< 12 months) data were judged unlikely to have sufficient readings for their median to be representative of the full range of seasonal cycles (Section 6.2). For this reason, they were excluded from the median water table calculated in Section 9 (Figures F.2, F.3, and F.4, Appendix F). These wells may, however, provide measurements that are locally important and reduce the spatial uncertainty in the water table.

This section outlines a methodology in which short-term (< 12 months) groundwater monitoring data has been considered in the context of any available longer-term data in nearby wells, to provide a surrogate median value that takes into account seasonal fluctuations and enables all available data to be utilised. The methodology has been applied to provide surrogate median water table elevation values for the 124 EQC Initial Phase monitoring wells and 186 TC3 Phase monitoring wells. Surrogate medians were then included in a data set with the longer-term (≥ 12 months) data from other sources to calculate a second water table surface, which is then compared against the water table with only longer-term.

A situation may arise where a geotechnical engineer, or other end user of this study, may have their own instantaneous or short-term groundwater monitoring data on the water table elevation at a particular site, but may not be in a position to wait for a 12 month period in order to obtain a representative median for their geotechnical assessment. In such a case they may wish to consider their observations in the context of the median water table elevation presented in Section 8 and Appendix F, and could manually apply this methodology using data from nearby monitoring wells to obtain a surrogate median water table elevation for their particular site of interest.

10.2 Calculation of surrogate median water table elevations

For short-term monitoring wells which have less than 12 months of readings since September 2010, but at least one reading per month since installation, a surrogate median water table value has been estimated following the procedure in Figure 10.1.



STEP 1: For all longer-term monitoring wells, calculate a median value based on available data. Generate the median water table, described in Section 8 and presented in Figures F.3 and F.4 (Appendix F).

STEP 2: For all monitoring wells with >12 months of data, for each of the months of monitoring data, since September 2010 calculate the difference between the groundwater level for each month and the median groundwater value calculated in Step 1. The difference is called the 'offset'.

STEP 3: For each month, create an offset contour map using >12 month monitoring wells which shows the difference between groundwater level for the particular month and the calculated median value. If a particular monitoring well does not have a groundwater reading for a particular month then it does not contribute to the offset contour map for that month. Refer to Figure G.1 (Appendix G) for an example offset map.

STEP 4: Use the contour maps to interpolate offsets at short term monitoring wells, for each of the months which the wells have available readings.

STEP 5: For short-term monitoring wells (< 12 months), add the corresponding interpolated offset values (for all available months) to calculate a number of surrogate median values. Calculate the average of the surrogate median values, and take this to be representative of the median for these short-term wells.

Figure 10.1 Flowchart summarising the method for obtaining surrogate medians of water table elevation for wells with short-term monitoring records.

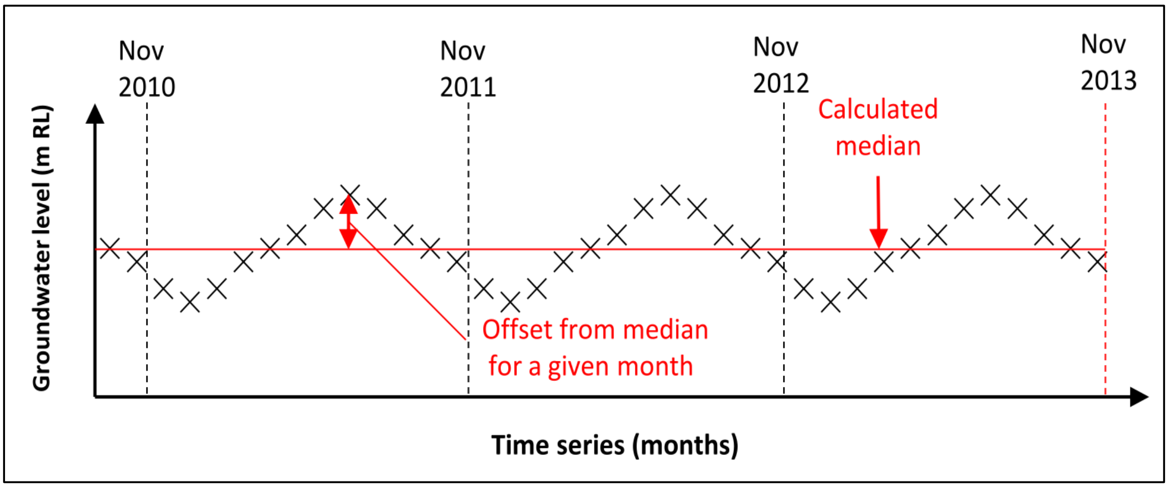


Figure 10.2 Median and offset calculation for >12 month monitoring well.

A manual worked example of the surrogate estimation method is provided below:

STEP 1:

The median water table elevation is calculated (as described in Section 6) for monitoring wells that have longer-term (>12 month) data records. An example for long duration well is shown in Figure 10.2.

STEP 2:

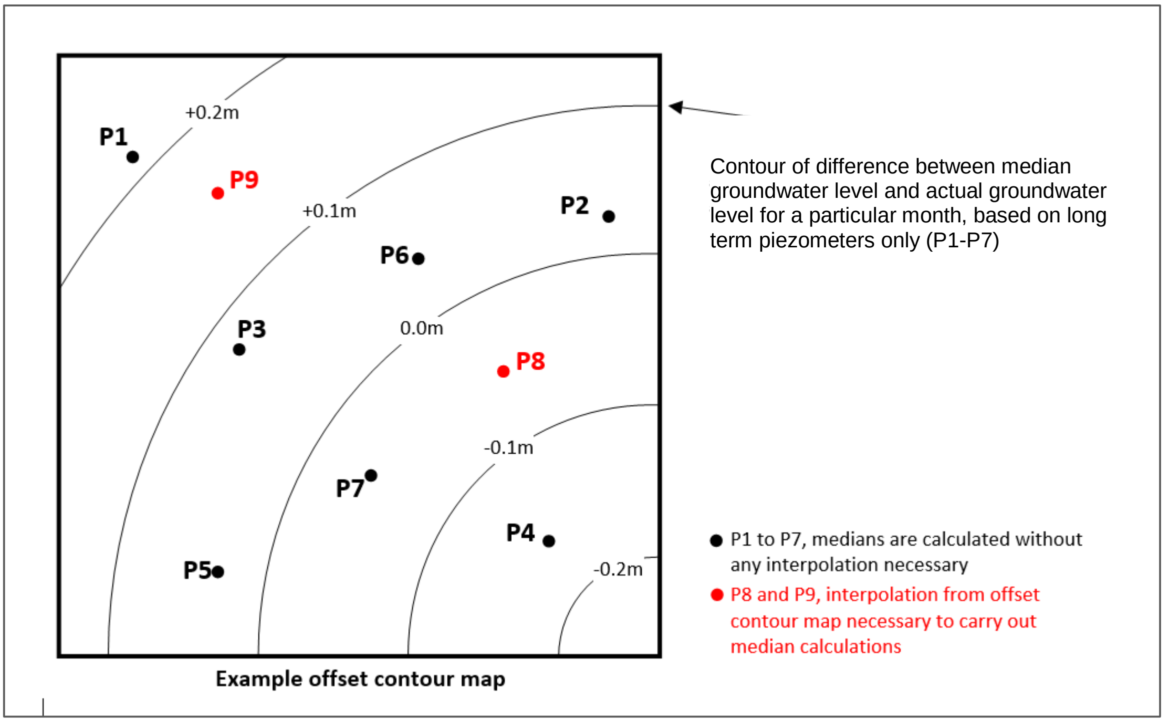
To be carried out on all longer-term monitoring wells. For each of the last 12 months (where data are available for this particular well) the 'offset' is calculated, being the difference between the water table elevation for the particular month and the median value calculated in Step 1. An example monitoring well is shown in Table 10.1.

Table 10.1 Example offset calculation for monitoring well.

Month	Offset (m)
Dec 2012	-0.3
Jan 2013	-0.4
Feb 2013	-0.3
Mar 2013	-0.1
Apr 2013	0
May 2013	+0.1
Jun 2013	+0.4
Jul 2013	+0.5
Aug 2013	+0.4
Sep 2013	+0.2
Oct 2013	0
Nov 2013	-0.1

STEP 3:

Based on the calculated medians for monitoring wells with longer-term records, create 12 offset contour maps representing each month. An indicative example is given for one month in Figure 10.3. An example of an actual offset grid for December 2012 is provided in Figure G.1 (Appendix G).



Contour of difference between median groundwater level and actual groundwater level for a particular month, based on long term piezometers only (P1-P7)

- ● P1 to P7, medians are calculated without any interpolation necessary
- ● P8 and P9, interpolation from offset contour map necessary to carry out median calculations

Figure 10.3 **Example offset contour map for a particular month.**

STEP 4:

Use the set of monthly offset contour maps to extrapolate offsets to the location of short-term monitoring wells. This is done only for those months where readings are available.

STEP 5:

For short duration monitoring wells, use the extrapolated offset values to adjust the actual monthly reading (for all available months), to estimated median values. Calculate the average of the monthly estimate values, and take this surrogate to represent the yearly median. An example well is shown in Table 10.2, for which only three monthly readings are available.

Table 10.2 **Example of a surrogate median calculation for a short-term monitoring well P9 where there are only three observations of groundwater level.**

Month	Measured water table elevation (m RL) in P9	Offset correction (m) from P1 to P7 wells	Estimated P9 median water table elevation (m RL)
Oct 2012	9.0	0.2	9.2
Nov 2012	8.6	0.1	8.7
Dec 2012	8.7	-0.2	8.5
Surrogate (average calculated from estimated medians)			**8.8 m RL**

10.3 Median water table including short-term data (< 12 months)

In order to generate contours of the median water table surface which include short-term data (< 12 months), the methodology outlined in Sections 8.1 to 8.2 was repeated. Co-ordinates and calculated median water table elevations (including surrogate median values for monitoring wells with short-term data) have been input into Surfer for:

- CCC, EQC and ECan monitoring wells (discrete locations);
- river breaklines and coastline points (continuous lines of surface water elevation).

Figure G.2 (Appendix G) is a contour plan of the median water table (m RL) using all monitoring well locations. The procedure discussed in Section 8.3 for manual checking and refinement of the water table was carried out once again on the surface which included short-term data. Drawdown points (denoted by black stars on Figure G.3) were used to refine wet areas, and any localised areas showing unreasonably anomalous spikes or dips in contours were smoothed manually.

The final contour plot of the median water table elevation (m RL), including short-term data, is presented in Figure G.3 (Appendix G). Figure G.4 is a depth to median groundwater surface (m bgl), generated by taking the water table surface plotted in Figure G.3 and subtracting these elevations from ground elevations defined by the LiDAR DEM (Post-Dec 2011 where available, or Post-June 2011 elsewhere). The location of drawdown points are shown in both Figures G.3 and G.4 (denoted by black stars), which are the same as those needed/adopted for Figures F.6 and F.10.

10.4 Comparison of water table with/without short-term data

In most places the post-Earthquake water table generated with short-term surrogate medians is much the same as the surface using only longer-term data (≥ 12 months). This can be seen by comparing Figures G.3 and F.3, which are very similar at the scale of the study area. The difference between the two surfaces is plotted in Figure 10.4 (see also Figure G.5, Appendix G). It provides confidence in the method of using nearby monitoring wells with longer-term data to take account of wells with short-term data and develop surrogate medians. Analysis of the difference between the two gridded surfaces indicates most of the data are within ± 0.5 m, which is less than the seasonal variability of the water table (see Section 11). There are a few places where they deviate by > 1 m, particularly along the western edge of the study area, which can also be seen by comparing the position of the contours in Figures G.3 and F.3.

Areas of approximately 2 km^2 or less within Christchurch City, where the water table using short-term data is more than 0.5 m **below** the surface calculated using longer-term data include: North New Brighton; Shirley; Strowan; Hoon Hay and Spreydon. For the most part these differences relate to the addition of one monitoring well.

Places of approximately 2 km^2 or less within Christchurch City, where the water table calculated using short-term data is more than 0.5 m **above** the surface calculated using longer-term data include: Woolston; the CBD (between Madras Street, Stanmore Road, Linwood Ave, Cashel Street); and the CBD (between Hills Road, Whitmore Street, Holly Road, Canon Street, Park Terrace and the Avon River). The differences for each of these areas are the result of including a number of short-term monitoring wells.

There are strengths and weaknesses in both approaches and resulting median water table surfaces. The authors preferred median water table (only using >12 month data) uses longer-term data, river breaklines, coastal data strings and drawdown points (Figure 9.1 for water table elevation, or Figure 9.2 for depth to water table – see also Figures F.3 and F.4, Appendix F). Alternatively the surrogate approach provides improved spatial resolution albeit with shorter duration data. End users should decide whether the median water table using short-term data (< 12 months) and surrogates is more appropriate, particularly in areas where there is a poor coverage of long-term data (> 12 months) but good coverage of short term data (< 12 months).

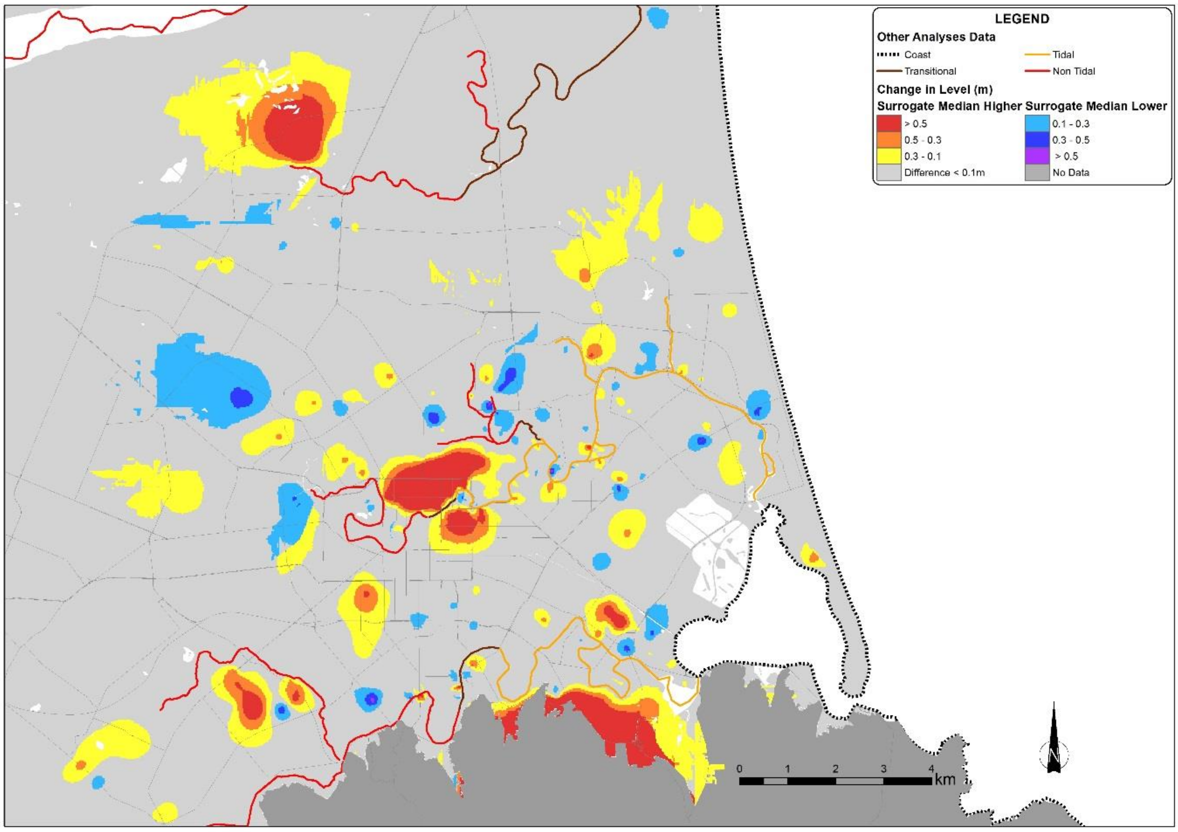


Figure 10.4 Difference between the median water table surface using >12 months of data and the surrogate median water table surface utilising all available groundwater data (irrespective of record length).

10.5 Confidence index for water table elevation

As described in Section 1.5 there are two main areas of uncertainty in the median water table elevation. Firstly there are temporal uncertainties in the median values due to a non-uniform observation period in observation wells. This uncertainty should not be confused with the temporal fluctuations in the water table elevation, as quantified by the post-Darfield Earthquake 15th and 85th percentiles (Section 9) or long-term variation (Section 11). Secondly, there are spatial uncertainties that result from interpolation of the water table elevation estimates (i.e., from monitoring wells, rivers and coastline data) into a continuous surface. Uncertainty quantification is never straightforward and rigorous numerical methods are often strongly theoretical, depend on the independence (or otherwise) of data variables, and are strongly debated (e.g. Clark et al., 2011; Beven et al., 2012 - and references therein). Nonetheless, it is important to review data currently available and provide at least some indication of the confidence in the derived median water table elevation.

A **qualitative** confidence map (Figure G.6, Appendix G) was developed for the median water table elevation in the study area through subjective consideration of the input data including: the spatial density of monitoring wells; the duration of monitoring records; and proximity to rivers and the coast. The map indicates the areas of lower, medium and higher confidence in the water table elevation. The purpose of the confidence map is to indicate areas where the water table surfaces are based on closely spaced monitoring wells with longer duration monitoring records. Additionally the confidence map aims to distinguish areas where the groundwater surfaces are based on interpolation of groundwater levels in areas of low density of monitoring wells. Here the end user will need to use engineering judgement as to whether they should obtain additional groundwater data to get better spatial resolution for their particular design purposes.

The confidence index is as follows:

- lower ≤ 2
- medium > 2 and < 7
- higher ≥ 7

The value of the confidence index is the sum of (possibly) overlapping discrete confidence values for the monitoring wells and river/coastal lines. An individual monitoring well is assigned a confidence value that depends on the monitoring duration (Table 10.3). The thresholds between higher - medium - lower confidence levels are subjective, based on the judgement and experience of the authors for the Christchurch setting. Higher confidence values do not necessarily mean that the values at those points are precise or accurate, just that there is a greater degree of confidence based on the length of the record or proximity to monitoring wells, rivers or the coast.

An example (Figure 10.5) shows confidence values and decay rates applicable to two monitoring wells that are in close proximity to each other, plotted on a grid with 25 m interval between grid points. One of the wells has 20 months of data and a confidence value of 8. The other well has 15 months of data and a confidence value of 6. Each well has a decay rate of 1 confidence value per 25 m of distance from the well location. Confidence ‘rings’ overlap in some locations. A confidence value is calculated for each grid point according to its proximity to confidence rings by interpolation between rings. If confidence rings from more than one well overlap on top of a grid point, as in Figure 10.5, then the confidence rings are summed to provide a confidence value for each grid point. The decay rate in confidence value away from rivers differs from monitoring wells and the coastline, to reflect there are assumptions about groundwater – surface water interaction (see Section 7).

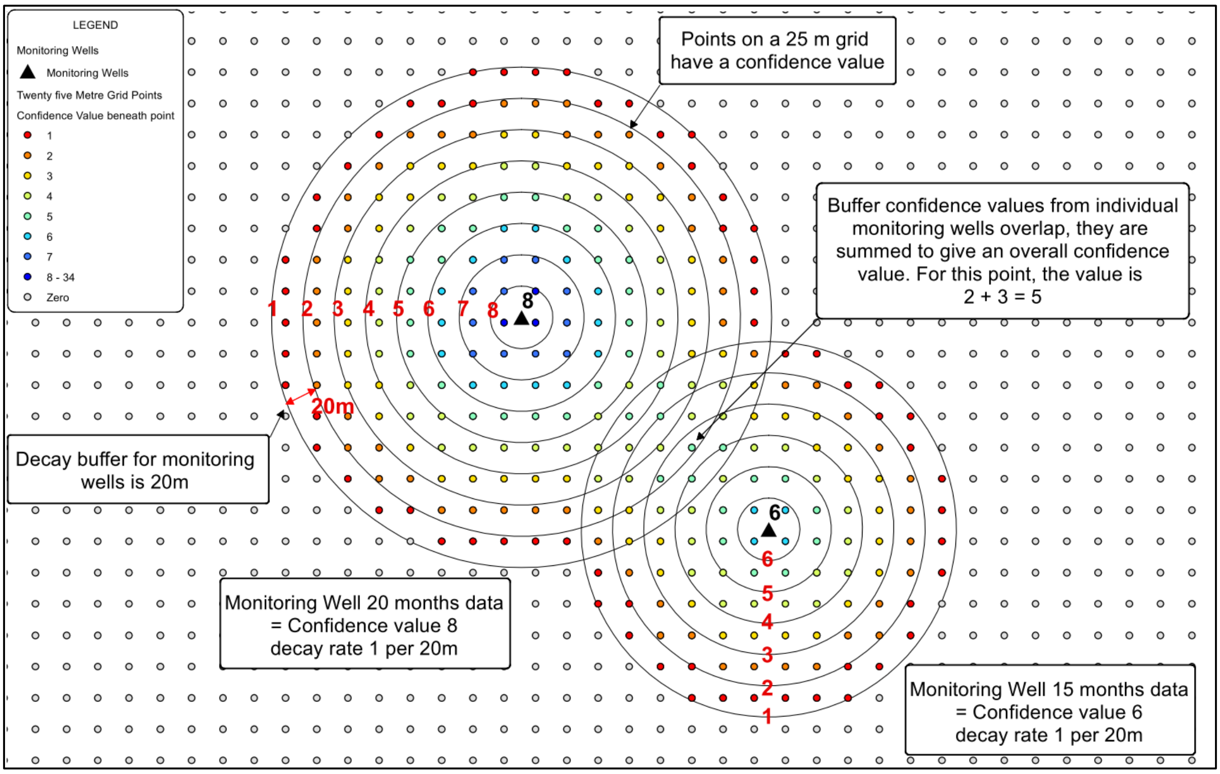
The confidence map in Figure G.6 (Appendix G) includes EQC wells with short-term (< 12 months) data (as at 30 November 2013), which are spaced at around 100 m or greater. The confidence index has been designed for the current spacing of monitoring wells and may not be directly suitable for future monitoring well distributions. For example, if three wells spaced 25 metres apart were added to the data set, in which only 3-5 months' worth of data had been collected, the calculation method would result in confidence values that are locally 'high', but where there is still temporal uncertainty. The decay rates would need to be readjusted for monitoring well distributions that are dense, so as not to produce misleading results.

Figure G.6 indicates that the confidence index is higher (overall confidence value ≥ 7) in areas where monitoring wells with > 12 months data are in close proximity to one another, and where they are close to rivers and sections of coastline. Areas of lower confidence index (overall confidence value ≤ 2) are predominantly inland, to the west of Christchurch City, and between rivers. As longer data records become available and more monitoring wells are installed, the indices may change and the confidence in the 15th percentile, median and 85th percentile water table elevation will increase.

Uncertainty in the water table elevation at a particular site partially reflects the underlying geology and whether or not the site is in the less-variable Coastal Zone (which shows less groundwater fluctuation), the Transitional, or more-variable Inland Zone. Based on development of a number of different models (van Ballegooy et al., 2013; Tonkin & Taylor, 2013), differences between Version 2 and Version 1 (Figure F.11), or between only >12 month data and including < 12 month data, it is clear that the largest differences between models tend to be in the western part of the study area. This is where the hydraulic gradients are steeper, the hydrogeology locally variable, and the fluctuations larger. Places where the water table is above 4 m have been distinguished within the lower confidence area of Figure G.6. On the basis of modelling experience, the precision of the post-Darfield Earthquake median water table is likely to be as follows: west of/above the 4 m median water table contour, lower confidence areas should have precision of between ± 0.5 to ± 1.0 m, whereas other areas of lower confidence index will have precision of about ± 0.4 m; medium confidence areas will have precision of ± 0.2 m; and higher confidence areas ± 0.1 m. Note that these values are indicative of precision of the interpolated median values for the September 2010-November 2013 data which are quite distinct from, and should not be confused with, the temporal variability (outlined in Section 11).

Table 10.3 Assigned values for developing a confidence index

Point or breakline	Confidence value assigned	Decay rate (single confidence value drop per distance away from point/breakline)
Monitoring well, 1 – 6 months available data	2	1 per 25m
Monitoring well, 6 – 12 months available data	4	1 per 25m
Monitoring well, 12 – 18 months available data	6	1 per 25m
Monitoring well, 18 – 24 months available data	8	1 per 25m
Monitoring well, 24 – 36 months available data	10	1 per 25m
Coastal line	10	1 per 20m
Avon/Otakaro River	8	1 per 20m
Styx River	8	1 per 20m
Heathcote River	8	1 per 20m
Waimakariri River	8	1 per 20m



Points on a 25 m grid have a confidence value

Buffer confidence values from individual monitoring wells overlap, they are summed to give an overall confidence value. For this point, the value is 2 + 3 = 5

Decay buffer for monitoring wells is 20m

Monitoring Well 20 months data = Confidence value 8 decay rate 1 per 20m

Monitoring Well 15 months data = Confidence value 6 decay rate 1 per 20m

Figure 10.5 Example diagram for calculation of overall confidence value.

11.0 WATER TABLE FLUCTUATION

In defining the post-Darfield Earthquake median water table for Christchurch City and surrounding areas, it is useful to understand the potential scale of fluctuations and variation in this surface in order to inform engineering and planning for the future. Unfortunately, the post-Darfield Earthquake data record (2010-2013) is short and may not encompass all of the potential influences, for example, seasonal and annual variations in rainfall due to the El Nino/ Southern Oscillation cycles (e.g. Figure 1.3; Kidson et al., 2009). There are, however, extensive records of natural fluctuations from pre-earthquake monitoring.

The purpose of this section is:

- to examine the variation of pre-Darfield Earthquake shallow groundwater elevation with a view that these provide the best possible indication of likely post-Darfield Earthquake variability, and to assess the relative magnitude of inter-annual variations in groundwater elevation compared to the annual seasonal signal.
- to examine the data sets for any changes that may have been caused by the earthquake sequence.

While marked changes in absolute ground surface and groundwater elevations occurred both during and after the earthquakes (Beavan et al., 2011, 2012; Cox et al., 2012; Section 5), the approach in this report has been to start by assuming that the scale of fluctuations in the future are likely to be similar to those in the past, although recognising they may occur about a different median elevation where/if the water table position has changed. Information for testing the validity of this assumption is presented in Section 11.2.

Groundwater levels beneath, and the flow rate of springs into, Christchurch City reflect the changing balance between recharge from rainfall and river infiltration, versus outflow by discharge and abstraction (Brown, 2001; White et al., 2012). The elevation of the water table in the west, for the most part, is more elevated above sea level but deeper below ground due to the westerly rise of the land surface across the Canterbury Plains towards the mountains. Groundwater flow is in an overall northwest to southeast direction, with rapid flow occurring through a myriad of braided interconnected permeable pathways (Talbot et al., 1986; Weeber, 2008). Groundwater flow modelling suggests the aquifer system beneath Christchurch City has relatively active shallow flow, with recharge dominated by Waimakariri River infiltration (Scott, 2000a, b; White et al., 2012).

A significant proportion of groundwater outflow occurs as springs at the transition between Inland and Eastern/Coastal zones (Figure A.3, Appendix A), where there is a change from unconfined or semi-confined aquifers, to confined aquifers beneath less permeable fine-grained marine/estuarine sediment (White, 2009). Pressure gradients are downwards in the west but upwards in the east, with the location of the transition zone between these regimes varying in position with time, depending on the balance between recharge and outflow (Weeber, 2008). The location of the transition zone helps define the hydrogeological boundary between the Inland and Eastern/Coastal zones (Weeber, 2008 – see also Section 2 above). The shallow water table in eastern Christchurch City occurs within an aquitard of fine marine/estuarine sediment (Christchurch Formation), with groundwater at artesian pressures in confined aquifers at greater depths below.

11.1 Groundwater elevation fluctuations

Data from as many monitoring wells as possible were obtained for an investigation of fluctuations in water table elevation during the period 4 September 1990 to 4 September 2010, representing the 20 year period immediately prior to the M_w7.1 Darfield Earthquake. Fluctuations were assessed in 55 wells, of which 29 covered the complete 20 year period (Figure H.1, Appendix H). Other wells with partial records but large (> 300) numbers of measurements were also used to infill data gaps and provide an even spatial spread across the study area. The CCC wells are referenced in Figure H.1 with three letter codes (e.g. SBE, AP2) whereas ECan wells are referenced with map sheet/number codes (e.g. M35/1603). These wells were all deemed to be monitoring the water table (see Section 4.3), except in the case of monitoring well M36/2452 which is one of the deepest wells (25.4 m), and possibly reflects semi-confined groundwater in aquifers at depth. Fluctuations in M36/2452 were, however, still analysed as it has groundwater at relatively shallow depth (~12 m below ground) comparable with that in other shallow wells nearby, and the style and scale of fluctuations in M36/2452 mimic those of nearby wells. Retaining M36/2452 in the analysis helped improve the spatial density of data points.

Figure H.2 (Appendix H) illustrates the range of water table elevation in each well, obtained by subtracting the minimum from the maximum elevation measured during the 1990-2010 period ('pre-Darfield Earthquake'). The largest ranges are in the west, where fluctuations greater than 4 m are common. Ranges in wells in the eastern suburbs of Christchurch City (Eastern/Coastal Zone) are markedly lower, for the most part less than 2 m. Monitoring wells in the Hoon Hay-Hornby area and at Belfast (well SBE) have intermediate ranges. While there is a general agreement between the range and the general westward increase in elevation/depth of the water table below surface, and the Inland versus Eastern/Coastal zones, the range is defined only by two measurements during the 20 year period (the maximum and minimum elevations) so, in some ways, is a very limited way of representing fluctuations.

Fluctuations in water table elevation are a result of both inter-annual variability and seasonal variability. In the Inland zone, annual cycles in shallow groundwater elevation (Aquifer 0) show close correspondence with that measured in deeper aquifers (Aquifer 1) (Weeber, 2008), suggesting the groundwater in the west has some degree of hydraulic connection between these aquifers. Ten CCC monitoring wells were selected for further assessment of these fluctuations on the basis of: (a) substantive length of records (> 18 years); (b) complete capture of records, with no periods when groundwater dropped below or rose above the top of casing (causing water to flow out of the well); (c) no unexplained data shifts that might be caused by, for example, development of nearby drainage; (d) spatial location, so as to provide two N-S transects across both the Inland and Coastal/Eastern groundwater zones. The selected wells are highlighted with tick symbols in Figure H.1 and listed in Table 11.1.

Table 11.1 Monitoring wells selected for detailed assessment of 1990-2010 variation of shallow groundwater levels, with a selection of statistics representing groundwater position and fluctuation.

ID	Well_No	E_NZMG	N_NZMG	Length	Start	Median (m RL)	Max (m RL)	Min (m RL)	n	Range (m)	85th %tile (m RL)	15th %tile (m RL)
AAY	M35/5413	2474888	5746274	20 year	17/09/1990	18.45	20.26	17.58	769	2.68	19.13	18.15
ARC	M35/5420	2476456	5741774	20 year	17/09/1990	12.54	13.34	11.40	762	1.94	12.87	12.08
HHM	M36/5719	2475139	5739342	18 year	13/04/1992	15.56	16.67	14.91	697	1.76	15.89	15.32
HHL	M36/3168	2475213	5736871	20 year	17/09/1990	12.77	13.93	11.35	1005	2.58	13.32	12.27
HSH	M36/5709	2476043	5736070	18 year	13/04/1992	10.46	11.35	9.66	927	1.69	10.75	10.09
SDA	M35/5425	2485451	5755547	20 year	3/09/1990	0.67	1.47	-0.08	764	1.55	0.98	0.43
ACR	M35/5422	2479901	5745517	18 year	3/02/1992	5.47	5.80	5.12	706	0.68	5.52	5.41
ABI	M35/5412	2484098	5744055	20 year	24/09/1990	0.67	1.49	0.45	770	1.04	0.83	0.58
AWO	M35/5407	2484382	5742416	20 year	24/09/1990	2.09	2.89	1.69	766	1.20	2.29	1.97
HGO	M36/3175	2484854	5739149	20 year	24/09/1990	0.51	0.90	0.14	766	0.76	0.63	0.38

11.1.1 Inter-annual variability

Figure H.3 (Appendix H) shows the water table elevation for selected monitoring wells plotted against the Julian Day – being the day of the year numbered 1-365 from January 1st each year. Wells from the Inland Zone (AAY, ARC, HHM, HHL, HSH – plotted from north to south in blue) are distinguished from those of the Eastern/Coastal Zone (SDA, ACR, ABI, AWO, HGO – also listed from north to south, green). The graphs have the same vertical scale range of 3 m, so that fluctuations in one graph can be visually compared against another, although note that the actual elevation of the water table varies between graphs/wells.

Monitoring wells in the Inland Zone had greater variation in water table elevation than those in the Eastern/Coastal Zone (Figure H.3). The inter-annual variation, being the range in water table elevation for any particular week or month during the 20 year period, was greatest in AAY, ARC and HHL where it was around 2 m. The inter-annual variation from 1990-2010 in the Eastern/Coastal Zone wells was less pronounced, being less than 1.2 m, and was less than 0.5 m in well ACR. There was very little variation in ACR which is located in an area of Papanui mapped as peat swamp (now drained) (Brown & Weeber, 1992).

The time-series records of these ten monitoring wells are shown in Figure H.4 (Appendix H). Wells in the Inland Zone are those at higher ground elevation and have correspondingly higher water table elevation, whereas those in the Eastern/Coastal Zone measure the water table at lower elevation. A close correspondence can be seen between the magnitude and style of fluctuations in some wells, for example HHM, HHL and HSH, or AWO and SDA, suggesting they are changed equally by the same external influences. ACR stands out as anomalous. In a number of wells the water table fluctuations appear subtly more subdued between Jan 2003-Dec 2005. For comparison an estimate of the rainfall and rainfall recharge (in mm), based on rainfall at Christchurch Airport (data from NIWA Climate database http://cliflo.niwa.co.nz/ station H32451) using modelling methodology presented in Scott (2004), is plotted at the base of the time-series graph. Recharge modelled from rainfall during the post-Darfield Earthquake period appears to be at around average amounts and does not appear to be anomalous (see also Figure 1.3), although heavy rainfall caused localised surface flooding in April and November 2011 and August 2012[9]. Recharge to the water table could also have been higher when precipitation occurred as snow (White 2007b). There were significant, heavy snowfalls (10-15 cm) during July 2011 and June 2012, and during the latter event the city experienced the lowest maximum daily temperatures (0.4°C) in its 149 year climate record (NIWA 2012).

11.1.2 Seasonal (Annual) variability

The water table also shows seasonal variability, fluctuating between low levels during late summer and high levels in late winter-early spring. The annual cycle was particularly pronounced in wells HHL and HSH in Figure H.3, but most showed at least some weak seasonal variation during 1990-2010. The seasonal variation was around 1 m in the monitoring wells of the Inland Zone, whereas only around 0.5 m or less in wells of the Eastern/Coastal Zone. Other studies have suggested seasonal fluctuations in groundwater levels are increasing over time due to groundwater use, which may affect spring flow and spring location in the headwaters of the Avon/Otakaro River (e.g. Brown, 2001; White et al., 2001).

11.2 Earthquake-related fluctuations and changes

11.2.1 Background

Hydrologic responses at the earth's surface to earthquakes, such as liquefaction and the appearance or disappearance of springs, or changes in river flow, have been observed for more than 1,000 years (Wang & Manga, 2010). Within the past century, the careful monitoring of wells has revealed subsurface responses, including both persistent groundwater level changes (Roeloffs, 1998) and short-term groundwater oscillations, the latter sometimes observed in wells located thousands of kilometres from the epicentre of earthquakes (e.g. Kitagawa et al., 2006; Sil & Freymueller, 2006; Taira et al., 2009; and West et al., 2005). Earthquake-induced groundwater level changes in Christchurch City wells had been noticed as long ago as 23 May 1989 (Brown & Weeber, 1992), when they fluctuated in response to a M8.2 earthquake on Macquarie Ridge approximately 1500 km south of the city.

Hydrologic responses in wells are controlled by such factors as the magnitude and depth of the earthquake, and distance from the earthquake’s epicentre (Chia et al., 2008). The depth of the well, whether in a confined or unconfined aquifer, consolidated rock or unconsolidated sediment, and well construction also influence the nature of fluctuations in groundwater levels. One of the most commonly observed well responses is an instantaneous groundwater level offset, or step change, to either a higher or lower new level. Recovery to the pre-earthquake levels can be so rapid that no change will be detected if the groundwater level is measured infrequently, or it may take as long as days or months. Short-term oscillations in groundwater level appear to be a regular phenomenon, but are less-commonly recorded by monitoring programs. In the few cases where groundwater levels are recorded at very high frequency (e.g. < 1 sec intervals), they can resemble long-period seismograms, sometimes referred to as hydroseismograms (Brodsky et al., 2003). The frequency of monitoring has an important

---

[9] And there was recent, and more-extensive flooding during March and April 2014.

influence in the style of responses observed and reported.

Subsurface responses to earthquakes also commonly produce, or are linked to, surficial or near-surficial hydrological responses, such as changes in river discharge or ponding of water. Changes to stream flow following earthquakes is a widely recognised phenomenon (e.g. Muir-Wood & King, 1993; Wang & Manga, 2010). Discharge increases appear to be coseismic, typically peaking within a few days to weeks of the earthquake. “Excess” stream flows (the difference between the actual discharge and an estimate of what discharge would have been in the absence of an earthquake) may persist for months to years, although earthquake-induced changes commonly become obscured by rainfall events. Excess stream flow volumes over a one year period can be significant, for example: 0.7 km^3 - 1999 M_w7.5 Chi-Chi earthquake in Taiwan (Wang et al., 2004); 0.5 km^3 following the 1959 M_w7.5 Hebgen Lake earthquake (Montana, USA) and 0.3 km^3 following the 1983 M_w7.3 Borah Peak earthquake (Idaho, USA) (Muir-Wood & King, 1993).

11.2.2 Canterbury aquifer responses

In the first systematic review of earthquake-induced hydrological responses in New Zealand, Cox et al. (2012) examined the effects of the 4 September 2010 M_w7.1 Darfield Earthquake. Hydrologic responses in confined aquifers beneath Christchurch City (Eastern/Coastal Zone) differed from those in semi-confined and unconfined aquifers of the Canterbury Plains (Inland Zone). A pronounced change was observed for the groundwater elevation in wells in shallow-intermediate depth aquifers (< 80 m) beneath Christchurch City. There were initial increases of up to 2 m (20 kPa), followed by a fall during the post-seismic interval to as much as 1 m below pre-earthquake levels. Cox et al. (2012) suggested that either groundwater pressures fell due to the confining layers having been breached, and/or groundwater was forced out of the aquifers up onto the surface. A contributing observation was that prior to the earthquake relatively few springs emerged through the Christchurch City confined aquifers in the south and east of the city (White, 2009), but immediately following the 4 September 2010 earthquake a series of new springs began to flow in this area (Figure A.3, Appendix A). Cox et al. (2012) postulated that release of groundwater pressure may have influenced the severity of the liquefaction and lateral spreading damage, a subject that now forms the basis for on-going investigations by the research team and international partners under the Natural Hazards Research Platform.

The M_w6.2 Christchurch 1 Earthquake on 22 February 2011 was a shallower event, centred closer to the city and directly beneath the confined coastal aquifer region. Substantially greater pressure increases occurred in confined aquifers beneath Christchurch City during this earthquake than during the M_w7.1 earthquake, with changes of up to 8 m (80 kPa) followed by falls to new decreased groundwater levels (Environment Canterbury 2011a; Gulley et al., 2013). Immediately following the main earthquakes of 2011 (Table 2.3), significant volumes of surface water ponded in low-lying areas and caused localised flooding in Christchurch City. While the style of responses during the February and other 2011 earthquakes appears to have been similar to the 2010 M_w7.1 event, the hydrologic response to these latter earthquakes have been less well-documented because of progressive damage that occurred to ECan's hydrological monitoring infrastructure (Environment Canterbury 2011b,c). Importantly, recent work has demonstrated that the Canterbury earthquake sequence caused both short to medium-term fluctuations (days to weeks), as well as more persistent changes (many months) which may reflect potential changes in aquifer properties and/or flow-paths. Such changes to the deeper aquifer system have potential to affect the position of the shallow water table.

11.2.3 Water table assessment

As part of this study on the shallow water table, the records of shallow ECan and CCC monitoring wells were assessed for any transient or persistent changes that may have been caused by the earthquakes. Records for the 'pre-Darfield Earthquake' period of 4 September 1990 to 4 September 2010 were compared with a 'post-Darfield Earthquake' period of 4 September 2010 to 30 November 2013 in 44 ECan and CCC wells which survived the earthquakes and for which long-term monitoring has continued. Examples of groundwater elevation fluctuations are provided in Figures H.5 and H.6 (Appendix H), with displays of both significant changes in elevation and no change in elevation. Groundwater levels are represented in Figures H.5 and H.6 by lines and dots, coloured with blue pre-Darfield Earthquake values for the Inland zone, green for the Eastern/Coastal confined zone, and red for all post-Darfield Earthquake data. Groundwater elevation values have been adjusted for changes in ground and well-head measuring point (MP) elevations during the earthquake sequence following the methodology adopted in Section 5.3. Time-series data for wells ABI, AWO, HGO and HLR is provided in greater detail in Figure H.7.

The data have been assessed in three ways:

(i) visual comparison of pre- and post-Darfield Earthquake elevation of the groundwater levels, plotted according to the Julian Day (numbered 0-365) (e.g. Figure H.5, H.6 – left side);

(ii) calculation of differences of the post-Darfield Earthquake median, range, 15th and 85th percentiles, compared with equivalent statistics for the pre-Darfield Earthquake period (1990-2010), to highlight wells where notable changes had occurred (Figure H8);

(iii) time series records and the presence/absence of a clear step in groundwater elevation coinciding with a known earthquake event (e.g. Figure H.5, H.6 – right side, or Figure H.7);

Table 11.2 summarises observed differences in pre- and post-Darfield Earthquake median groundwater levels, the degree of their significance, and identifies those which can be clearly interpreted to be earthquake-induced. Figure H.8 shows the difference in elevation of the median groundwater levels from pre- to post-Darfield Earthquake data sets. In 30 of the 44 wells, the differences lie within the natural variation of the well, so are 'not significant'. At these locations there is no evidence to suggest the water table is permanently affected by the earthquakes.

Short-term ‘transient’ fluctuations were, however, observed in 10 wells during earthquakes, and in 4 the groundwater levels returned to pre-earthquake levels within the period of one or two measurements. The sharp rises in groundwater elevation, shaped like a ‘spike’ in time-series plots, are mostly less than 1 m, with a maximum +1.5 m change in well ABI during the February 2011 M_w6.2 Christchurch Earthquake. It is possible that short and/or transient responses occurred in many wells but were not captured by the weekly-monthly measurement frequency.

There are six wells in the Eastern/Coastal Zone that had significant differences of -0.2 to -1.4 m in the position of their median groundwater levels. Lowering of the median between the pre-Darfield Earthquake (1990-2010) and post-Darfield Earthquake (2010-2013) data sets reflects a combination of both hydrological changes and land elevation changes (subsidence/uplift) which, importantly, coincide with the timing of an earthquake in these wells. Changes in ABI, AWO, HLR and ACR were ‘clearly significant’, in that their post-Darfield Earthquake 85th percentiles were below the elevation of their pre-Darfield Earthquake 15th percentiles, whereas HGO and SDA had a post-Darfield Earthquake medians falling below the pre-Darfield Earthquake 15th percentiles so record changes that were deemed to be ‘potentially significant’ (Table 10.2).

In wells ABI, AWO, HGO and HLR the post-Darfield Earthquake groundwater levels (red) are mostly below pre-Darfield Earthquake elevations (green) (Figures H.5 & H.6), although record maximum, or near-maximum, elevations were measured after the 22 February 2011 Christchurch 1 Earthquake and some near-record high elevations were reached during July and August 2012. 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 wells. Such an observation of changed position of the water table relative to land surface (i.e. extremes of shallow groundwater) could have relevance for flood hazard studies.

Figure H.7 is a more-detailed view of the ABI, AWO, HGO and HLR groundwater elevation data, which also shows the change in ground level as defined by LiDAR survey (Figure C.1) and surveyed/re-surveyed elevation of well measuring points (MP). Ground in the vicinity of ABI, AWO and HLR has subsided as a result of the earthquakes, changing in cumulative elevation by -0.6, -0.3 and -0.4 m respectively, whereas at HGO it has been uplifted +0.3 m. Importantly, decreases in water table elevation have occurred regardless of whether the land surface was uplifted or subsided. To many people, including the authors of this report, this has been a surprising and counter-intuitive result. The total decreases in median groundwater elevation (ABI -1.4 m; AWO -1.4 m; HGO -0.2 m; HLR -0.9 m) are more than twice the cumulative changes in ground elevation at each site.

The major change in ABI groundwater elevation occurred in September 2010 after the first Darfield Earthquake, whereas the changes 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 Darfield Earthquake caused liquefaction and lateral spreading damage. The EQC monitoring wells in this area all appear to have water table elevation below sea level, as shown by the zero contour on Figures F.2 and F.3 (Appendix F). CCC have indicated that drainage and pumping stations along the river probably account for the level of the water table here (G. Harrington, pers. comm.). Groundwater levels in AWO also fell below sea level between June 2011 and March 2012 during an extensive period of dewatering being performed for the nearby sewer repair work on Woodham Road (Figure H.7).

Groundwater levels in AWO, HGO and HLR appear to have fallen to new post-Darfield Earthquake elevations with median elevations that correspond approximately to the nearby level of the Avon/Otakaro and Heathcote rivers. These wells occur in areas where the ejection of liquefaction material was extensive. One possible explanation is 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 aquifer / monitoring well and the nearby river. It is also possible that cracking caused by ground surface oscillation and lateral spreading could produce a similar effect. While the exact mechanism is not yet known, it does appear that the water table elevation decreased significantly at these sites. What is yet to be demonstrated is whether or not this is a site specific or could be a more widespread phenomenon. If such processes are widespread in land subjected to liquefaction and lateral spreading damage, it could have implications for the characterisation of future liquefaction potential both in Christchurch City and elsewhere, so is worthy of further investigation.

SDA in Brooklands showed a transient increase in groundwater level following the Darfield Earthquake in September 2010, and then it fell to sea level (Figure H.6). The water table remained at sea level until the February 2011 Christchurch 1 Earthquake, when it experienced another transient increase elevation before rising and settling about a new median. The net median water table change of -0.4 m is mostly easily explained by the subsidence (c. -0.3 m) in ground elevation at this site indicated by LiDAR survey. The difference between pre- and post-Darfield Earthquake groundwater levels in ACR, a well that has little variation (Figures H.3 & H.4), also matches the amount of local ground subsidence.

There are a number of wells in which changes in groundwater levels are not clearly coincident with the arrival time of earthquakes, or where there are anomalous fluctuations which are less straightforward to interpret. None of the observed pre- to post-Darfield Earthquake differences in the Inland or Transitional zones can be unambiguously attributed to earthquake-induced change, but some may be indirectly related to earthquake events or associated human activity:

- Six wells in the Inland/Transitional zones showed -0.3 to -0.6 m differences in the position of their median groundwater levels between the pre-Darfield Earthquake (1990-2010) and post-Darfield Earthquake (2010-2013) data sets. For the most part these occurred without any changes in ground or wellhead (MP) elevation. Changes in M36/4741 were deemed 'clearly significant', in that the post-Darfield Earthquake 85th percentile was below the pre-Darfield Earthquake 15th percentile, whereas M35/0948, M35/3614, M36/5436, M36/5560 had post-Darfield Earthquake medians falling below the pre-Darfield Earthquake 15th percentiles, recording differences deemed to be 'potentially significant' (Figure H.8). Because there were no clear steps/changes in the time-series that can be directly attributed to any particular earthquake, differences need to be explained by other processes. It may reflect a subtle change in the position of downwards vs upwards pressure gradients during 2010-2013 vs 1990-2010 (see Figure H.1). Lowering of groundwater during 2010-2013 might be due to increased irrigation abstraction, although this period saw slightly higher than normal rainfall (Figure 1.3).

- HHM has experienced some abrupt groundwater elevation decreases since August 2012 to record low levels (Figure H.5), that may be transient pumping or engineering improvements to local drainage. There has been major waste water repair work in close proximity to the well that may have affected the local water table. But since these anomalous fluctuations are relatively short, the pre- and post- Darfield Earthquake median groundwater levels were not significantly different.

- M35/8968 near Waimakariri River is a 7.6 m deep well in which the groundwater level has become progressively lower with time, reaching record low levels during Mar-May 2012 (not shown). The post-Darfield Earthquake median water table is distinctly lower than the pre-Darfield Earthquake median, which may reflect Waimakariri River flow volumes (White et al., 2012), natural shifts in the position of Waimakariri river channels, gravel extraction activities in the river bed, and/or groundwater flow.

- Three wells in the Kaiapoi region (M35/0601, M35/0724, M35/6507) recorded anomalously high groundwater levels during August 2012. The post-Darfield Earthquake median level is clearly higher than the pre-Darfield Earthquake median groundwater level in M35/0724, (but not M35/0601 or M35/6507), potentially caused by earthquake-related subsidence and/or human influences on Kaiapoi River. These wells warrant further investigation with a detailed knowledge of activities in the area.

Table 11.2 Summary of differences observed pre-Darfield Earthquake (1990-2010) and post-Darfield Earthquake (2010-2013) groundwater levels in shallow CCC and ECan monitoring wells.

Well_Nos	Observed Differences	Significance
ABI, AWO, HLR	Persistent change to lower groundwater levels, with or without short-term (transient) fluctuation. Post-Earthquake 85th percentile below pre-Darfield Earthquake 15th percentile. Caused by a combination of both subsidence (decrease in ground/MP RL) and increased depth to water below MP.	CLEARLY SIGNIFICANT EQ-induced lowering
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 percentile. Increased depth to water below MP despite uplift (increase in ground/MP RL).	POTENTIALLY SIGNIFICANT EQ-induced lowering
ACR	Lowering of median groundwater due to subsidence (ground/MP elevation change). Post-Darfield Earthquake 85th percentile below pre-Darfield Earthquake 15th percentile. Depth to water appears constant.	CLEARLY SIGNFICANT EQ-induced lowering
SDA	Apparent lowering of median groundwater 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 percentile. Depth to water appears constant.	POTENTIALLY SIGNIFICANT EQ-induced lowering
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 SIGNFICANT rise
M36/4741	Lowering of median groundwater level despite little change in ground/MP RL. Post-Darfield Earthquake 85th percentile below pre-Darfield Earthquake 15th percentile. Caused by increased depth to groundwater.	CLEARLY SIGNFICANT fall
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 SIGNFICANT fall
M35/0948, M35/3614, M35/5436, M35/5560	Lowering of median groundwater despite little change in ground/MP RL. Post-Darfield Earthquake median below pre-Darfield Earthquake 15th percentile. Increased depth to groundwater might be explained by irrigation practices.	POTENTIALLY SIGNIFICANT lowering
NDW	Rise of median water table despite little change in ground level/MP. Post-Darfield Earthquake median above pre-Darfield Earthquake 85th percentile. Decreased depth to groundwater	POTENTIALLY SIGNIFICANT rise
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, nor changes in variability.	NONE

11.2.4 Summary of earthquake-related effects

Key observations from the review of earthquake-related fluctuations and changes in the water table are as follows:

- 44 ECan and CCC wells have extended (decadal) monitoring records that span the earthquake sequence, but the majority (30) do not show evidence of any significant persistent changes in median groundwater elevation. Persistent changes as a result of the earthquakes can be demonstrated in the Eastern/Coastal Zone, but none can be unambiguously attributed to earthquake-induced change in the Inland-Transitional zones.

- Minor, transient elevation increases of up to 1.5 m have been recorded in some monitoring wells coincident with the main earthquakes. These are considerably smaller than the equivalent phenomenon observed by other studies in wells screened within deeper aquifers, but the weekly to monthly monitoring could easily have missed short-term fluctuations.

- There are three monitoring wells (AWO, HGO and HLR) where definitive earthquake-related changes occurred that clearly involved hydrological-phenomenon as well as changes in ground elevation. In each case, the water table fell to a new median elevation after a short transient rise had occurred. This pattern of response mimics the ‘spike offset negative’ responses observed in deeper aquifers beneath the Christchurch area (Cox et al., 2012; Gulley et al., 2013). Similar response probably occurred in well ABI, but this well lies in an area permanently affected by pumping/dewatering.

- The lowering of the median water table in AWO, HGO, HLR and ABI is more than twice the amplitude of ground elevation changes at the same sites, but water table lowering has been observed both where the ground has been uplifted and where it has subsided. Where ground subsided there is no clear evidence that the water table elevation had locally increased relative to sea level. On the contrary, sites ACR and SDA subsided and the median water table appears to have lowered commensurate with the scale of ground subsidence.

- In AWO, HGO and HLR, where definitive earthquake-related changes occurred, the water table appears to have fallen to a new base level controlled by nearby drainage (within ~700 m). In these wells, however, water table elevations near the pre-Darfield Earthquake (1990-2010) maximum occurred during winter 2012. It is possible the range and variation of the water table has also changed at these sites. Where subsidence occurred, groundwater was unable to maintain the same elevation.

- Lowering of the water table relative to ground (increased depth to water, as opposed to ground subsidence with constant depth to water), was not a widespread phenomenon. It was observed in four wells located in the Eastern/Coastal zone where there was extensive land-damage. It may reflect changes to hydrologic properties of the subsurface caused by liquefaction and lateral spreading damage. As yet it is unknown if such changes are just localised, or widespread within areas of major ground damage.

11.3 Implications for median water table

Groundwater levels in Canterbury are not static but fluctuate due to variations in rainfall, river recharge, and abstraction. In the absence of detailed studies of the potentiometric surface, and until a more complete post-earthquake time series has been obtained, the scale and periodicity of fluctuations of the water table in the future is thought likely to be similar to those during the 20 years preceding the Darfield Earthquake, although:

- The extent to which the total water balance in the study area has changed as a result of the earthquakes is unknown. It seems unlikely that inflow from rainfall and river infiltration have changed substantially, but it is possible that changes have occurred to outflow, for example, due to the emergence of new springs, land subsidence, changes to local drainage, infrastructure, or even amounts of water abstracted. There may be subtle differences between pre- and post-Darfield median groundwater elevations near the transition from Inland-Eastern/Coastal Zone (wells M35/0948, M35/3614, M36/5436, M36/5560, M36/4741).

- There may also be earthquake-induced changes in the specific yield or permeability of the shallow deposits, (as proposed at wells AWO, HGO and HLR) with changes in porosity caused by liquefaction and lateral spreading (see also Cox et al., 2012). Settling and subsidence may potentially influence the range of fluctuation of the potentiometric surface in the future.

- A few monitoring wells have water table elevations that were found to be near or exceeding the pre-Darfield Earthquake maximum during the winter of 2012, even though the post-Darfield Earthquake median elevation had dropped (Figures H.6 and H.7). This observation could be relevant for flood hazard assessment.

- Sea level rise is likely to result in some future changes to water table elevation in the low-lying coastal areas of Christchurch City.

The analysis of the 1990-2010 'pre-Darfield Earthquake' monitoring well data (Figures H.2-H.4) showed water table ranges in elevation that are greater than 4 m in the west, but substantially less in the east. Of the monitoring wells selected for detailed analysis, those in the Inland zone showed a greater inter-annual variation (around 2 m) than seasonal variation (around 1 m). Wells in the Eastern/Coastal Zone fluctuated less, but inter-annual variation (around 1.2 m) was similarly greater than the seasonal variation (0.5 m). Relatively few persistent changes can be directly attributed to earthquakes, with wells in the Eastern/Coastal Zone showing water table lowering of 0.2-1.4 m. The median water table might therefore be expected to fluctuate with inter-annual variations that are approximately twice the seasonal variations, and ranges in elevation that are greater in the west than in the east.

For engineering and geotechnical assessment, it may not be relevant whether variations are inter-annual or seasonal. Instead, it may be more useful to have a measure of a level to which the water table may rise above the median elevation and an indication of the probability this elevation may be exceeded. Here, the difference (in metres) between the 85th percentile and the median value (in metres) was calculated at each well then gridded by kriging (Figure H.9). The 85th percentile was selected arbitrarily, but the 75th or 95th percentiles may also be useful depending on requirements. The difference between the 85th percentile and the median provides a measure of the past fluctuation of the water table that was exceeded only 15% of the time during 1990-2010. The 85th percentile values are less elevated above the median in eastern Christchurch (< 0.4 m) than in the west (where they are > 1 m). Figure H.9 has equivalence to Figure F.8 calculated for the shorter 2010-2013 post-Darfield Earthquake period that was developed with a greater density of wells. A similar diagram of the difference between the median and the 15th percentile for the longer-term 1990-2010 period is presented in Figure H.10, for comparison with the equivalent Figure F.5 showing the 2010-2013 post-Darfield Earthquake median-15th percentile difference. The differences between the 85th percentile-median and median-15th percentile are slightly higher for the post-Darfield Earthquake data sets than the long-term pre-Darfield Earthquake dataset, suggesting variation may have been greater during 2010-2013 than 1990-2010.

12.0 SUMMARY

12.1 Current study

The sequence of Canterbury earthquakes during 2010 and 2011 caused substantial changes to the land in Christchurch City and surrounding areas, including widespread uplift and subsidence. Liquefaction triggered by the major earthquakes resulted in extensive land damage, including ground surface deformation and lateral spreading. The depth to the water table surface is an important parameter when undertaking liquefaction assessments to determine the potential future damaging effects of liquefaction for building foundation design purposes.

The elevation of the water table has been derived as a median surface for Christchurch City and surrounding areas, based on monitoring data collected between the 4 September 2010 M_w7.1 Darfield Earthquake and 30 November 2013. The study includes data from an area between Prebbleton in the southwest, Swannanoa in the northwest, and the coastline in the east but is specifically intended as elevation maps for use in urban residential areas zoned TC2, TC3 and Red Zone areas. There has been widespread installation of monitoring wells following the earthquakes, providing a significant improvement in the spatial density of water table information. Variations within the groundwater records during the post-Darfield Earthquake period were quantified by development of 85th and 15th percentile water table surfaces.

Data from monitoring wells was obtained from CCC, ECan, and geotechnical investigations for EQC. The duration and frequency of the data varied between sources. CCC well records were generally at least 13 years, with some having 50-year records, typically measured at weekly or fortnightly intervals. ECan well records were generally decades long, however many of the ECan records ceased during or before 2010. Frequency of readings for ECan wells ranged between 15-minute to monthly intervals. A large number of EQC monitoring wells were installed after the 4 September 2010 Darfield Earthquake, and readings were typically measured at monthly intervals.

The monitoring wells selected for calculation of the water table were assessed to ensure they provide data only on the water table aquifer (as opposed to confined aquifers). To qualify monitoring wells were required to be either (a) a shallow depth (< 10 m) in the Eastern/Coastal or Transitional zones, with groundwater elevation that was not locally anomalous; or (b) an intermediate depth (from < 10 to 35 m) in the Inland Zone, west of Christchurch City but with a well record suggesting it was not screened beneath confining layers, and with groundwater elevation that was not locally anomalous.

Data from 967 shallow monitoring wells were obtained from CCC, ECan and geotechnical investigations carried out for EQC. 657 monitoring wells had records of 12 months or longer from which a representative median water table elevation was determined for each site. 310 wells had short-term records, from which surrogate medians were estimated by using nearby wells with longer-term records. Median values were determined for a 'post-Darfield Earthquake' period (4 September 2010 to 30 November 2013). LiDAR Digital Elevation Models (DEMs) have been used in conjunction with physical survey data to correct the monitoring well measuring points (i.e. the well head) for ground elevation changes as a result of the sequence of earthquakes.

Groundwater and surface water interact in the study area, with the rivers supplying, or being supplied, by groundwater. The median water levels in the Avon/Otakaro, Heathcote, Styx and Waimakariri rivers were assumed to be a close approximation of the water table elevation in the river banks, so that the rivers could be used as breaklines and provide bounding values in the water table surface contouring. River surface elevation data from computer flow modelling for the Avon/Otakaro, Heathcote and Styx Rivers was provided by CCC, and data for the Waimakariri River was provided by ECan. Sea level along sections of coastline on the study area's eastern extent was also used as a bounding value for the water table contouring. A mean sea level (0.064 mRL) was assumed along sections of coastline for the generation of the median water table surface.

The median water table has been depicted as a surface by contour maps, in which values for sites between monitoring wells, rivers and the coast have been interpolated by kriging using Surfer software. The use of river breaklines helped shape and position the water table contour maps at places of significant groundwater-surface water interaction. As there was spread in the relationship between the median water table elevation and ground surface elevation, the co-kriging method has not been used for interpolation of the water table, but is a worthy avenue for future refinement of the surface. After initial calculation of the water table, any apparent wet areas on the contour map that do not reflect actual known wet areas in Christchurch City were refined in Surfer by using drawdown points which act as 'drains', creating a boundary condition to keep the water table surface just below the ground surface. As well as this iteration, the water table surface was reviewed further by manually smoothing any irregular small-scale anomalies such as might be caused by a single measurement error.

The water table slopes downward from greater than 10 m elevation, relative to sea level, west of Christchurch City to less than 1 m elevation in the eastern suburbs, approximately coincident with the ground elevation. A depth to groundwater map is derived from the difference between the water table elevation and ground elevation determined by LiDAR surveys. The water table is generally at a depth more than 5 m below ground west of Christchurch City, decreasing to less than 2 m beneath much of the city. There are only subtle localised differences between the median water table calculated using short-term data with surrogate medians, and that calculated using only longer-term data. In most places the difference in elevation is less than ± 0.5 m, but areas of up to 1 km^2 have been identified where the difference exceeds this threshold. The post-Darfield Earthquake surface developed from longer-term data (≥ 12 months), river and coast breaklines, and drawdown points (Figures 9.1 and 9.2) is preferred by the authors, but there are strengths and weaknesses in each of the water table calculations. End users should decide whether the median water table using short-term data (< 12 months) and surrogates is more appropriate, depending on the specific engineering requirements and local site observations.

Post-Darfield earthquake 15th and 85th percentile surfaces were created by calculating the difference between the 15th and 85th percentile and the median water level at each site, interpolating these differences, then subtracting or adding the relative differences to the interpolated median surface. The expected variation of groundwater at rivers and along the coastline were included in the calculations, based on observed surface water observations, and at drawdown points the 85th percentile values were set at ground level. The resulting surfaces have included uncertainty of absolute elevations (surveying relative to sea level) only once in calculations, and are consistent relative to each other in all places. During the post-Darfield Earthquake period (2010-2013) differences between the 85th percentile-median and the median-15th percentile were typically between 0.1 m and 0.4 m in the Eastern/ Coastal Zone. Further west, differences are higher, being greater (up to 2.4 m) for the 85th-median than the median-15th percentile (up to 1.1 m). The 15th and 85th percentile surfaces provide a context to the median water table surface in terms of observed variation in the water table that has occurred, and how this varied in different parts of the city.

Groundwater levels in Canterbury fluctuate due to inter-annual and seasonal variations in rainfall and river recharge. The full range of natural fluctuations may not have been observed during the relatively short 'post-Darfield Earthquake' period used in this study, but the post-Darfield Earthquake fluctuations appear to have been slightly greater than the pre-Darfield Earthquake fluctuations. A comparison of pre- and post-Darfield Earthquake data in the 44 wells indicates median water table levels were unaffected by the earthquakes at many sites, with relatively few changes that can be directly attributed to earthquakes: 9 wells had transient increases in water table elevation of up to 1.5 m recorded for a short period after the earthquake; four showed persistent change, being a 0.2-1.4 m lowering of the water table to a new base level and median value; two other wells showed water table lowering associated with subsidence. Analysis of selected monitoring wells indicates that inter-annual variations (around 2 m in the west and 1.2 m in the east) were approximately two times those of seasonal variations (around 1 m in the west, 0.5 m in the east) between 1990 and 2010. Fluctuations can also be described statistically to indicate the probability the water table will exceed a particular elevation. For example, 85th percentile values of water table elevation indicate levels that were exceeded 15% of the time.

Engineers and scientists using the median water table presented in this report will need to understand the limitations and assumptions that have been made to develop the surface. They should consider BOTH the temporal and spatial reliability of the median water table elevation and depth maps, whether or not additional site-specific surveying and groundwater investigations are required, and whether these maps are appropriate for their design/analysis application. To aid these decisions, a qualitative confidence index was developed taking into account the density of monitoring wells and the duration of the monitoring period. A map of this index gives an indication where there is a lower, medium and higher confidence in the water table maps. Indicative precision of the interpolated median water table values are: ± 0.5 to ± 1.0 m (lower confidence areas, west); ± 0.4 m (lower confidence areas, east); ± 0.2 m (medium confidence areas); ± 0.1 (higher confidence areas) but these may not encompass the full range of possible fluctuations.

12.2 Recommendations for extension of work

The median water table surface might be improved by:

- Installing a set of purpose built multi-piezometers in the western part of the study area, in both gravel-dominated interbedded fine-sediment/gravel facies of Springston Formation, to establish vertical hydraulic gradients and improve definition of the position of the shallow water table in the Inland zone (Sections 1.4, 2.1, 4.1);

- Exploring the option of co-kriging, whereby the ground elevation helps inform the interpolation of the water table surface (Section 8.1.1). Confidence was not gained in the provisional co-kriging attempts carried out for this study, but the geostatistical method is used internationally and has yet to be explored to its full potential in Christchurch City;

- Exploring relationships between surface water and groundwater, in particular the extent to which there are local differences between median river levels and the nearby water table (Section 7). There are now many monitoring wells installed near the rivers and monitoring at a higher frequency would enable relationships between river levels, and/or tidal shifts, to be better understood.

- Understanding whether the earthquake-induced fall of the water table observed in monitoring wells ABI, AWO, HGO and HLR (Section 11.3) is very localised in the vicinity of these wells, or a more-widespread phenomenon in areas where there has been liquefaction and lateral spreading damage;

- Re-assessing whether the changes to the water table created by the earthquake sequence are significant compared with the fluctuations associated with seasonal and inter-annual variability (Section 11.1). The period of observations since the 4 September 2010 Darfield Earthquake is relatively limited compared with the length of some data sets available. While many monitoring wells have been installed since the earthquake, providing over four times the number of points available for contouring than available to previous investigations, this study found relatively few earthquake-induced changes in those wells which were monitored before and during the earthquakes. By incorporating inter-annual variations of pre-September 2010 data sets into calculations it may be possible to improve confidence in the future position of the median water table surface.

13.0 ACKNOWLEDGMENTS

This work was funded in part by the Earthquake Commission (EQC) and in part by a Natural Hazards Research Platform (www.naturalhazards.org.nz) project investigating the possible contribution of earthquake-induced groundwater pressure release to liquefaction (Contract 2012-GNS-05-NHRP). We would like to thank many people for supporting both this update and the first edition (Version 1), including: Raj Agnihotri, John Begg, Ian McCahon and David Scott – who were first edition authors; Kathleen Crisley, Bryan Todd, Kelly Palmer and Kerri Osten at Environment Canterbury; Mark Lockley at Christchurch City Council; Marty Flanagan and Jeremy Rutherford at NIWA; and Hugh Cowan at the Earthquake Commission. James Lyth, Chris Pedrezuela and John Carter from Tonkin & Taylor helped in the production of figures and diagrams. Grant O'Brien and Belinda Smith-Lyttle from GNS Science helped in the analysis of groundwater fluctuations, variability and earthquake-induced changes, and the production of related figures and diagrams. We also wish to thank colleagues Kelvin Berryman, Terry Webb, Phil Glassey and Peter Barker for discussions and comments. Critical comments and thoughtful reviews by Paul White, Stewart Cameron and Gil Zemansky (Version 1) from GNS Science, David Painter from David Painter Consulting [DPC] Ltd, and Nick Rogers from Tonkin & Taylor, considerably improved this report and its earlier version.

14.0 REFERENCES

Arcement GJ, Schneider VR 1989. '*Guide for selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*.' US Geological Survey Water-Supply Paper 2339. 38 pages.

Bannister SC, Fry B, Reyners ME, Ristau J, Zhang H 2011. '*Fine-scale relocation of aftershocks of the 22 February M_w 6.2 Christchurch Earthquake using double-difference tomography*' Seismological Research Letters 82(6): 839-845.

Beavan RJ, Samsonov S, Motagh M, Wallace LM, Ellis SM, Palmer NG 2010. '*The Darfield (Canterbury) earthquake: geodetic observations and preliminary source model.*' Bulletin of the New Zealand Society for Earthquake Engineering 43(4): 228-235.

Beavan RJ, Fielding EJ, Motagh M, Samsonov S, Donnelly N 2011. '*Fault location and slip distribution of the 22 February 2011 M_w 6.2 Christchurch, New Zealand, earthquake from geodetic data.*' Seismological Research Letters 82(6): 789-799.

Beavan RJ, Motagh M, Fielding EJ, Donnelly N, Collett D 2012. '*Fault slip models of the 2010-2011 Canterbury, New Zealand, earthquakes from geodetic data and observations of postseismic ground deformation.*' New Zealand Journal of Geology and Geophysics 55(3): 207-221.

Beca 2004. '*Christchurch Liquefaction Study – Stage IV*'. Environment Canterbury Report U04/25. 31 pages + 2 appendices.

Beca 2005. '*Christchurch Liquefaction Study – Stage IV (Addendum Report).*' Environment Canterbury Report U04/25/2. 13 pages + 4 maps.

Beven K, Smith P, Westerberg I, Freer J 2012. '*Comment on "Pursuing the method of multiple working hypotheses for hydrological modelling" by P. Clark et al.*', Water Resources Research 48, W11801, doi:10.1029/2012WR012282.

Brackley HL (compiler) 2012. '*Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts*'.

GNS Science Consultancy Report 2012/218.

Bradley BA, Cubrinovski M 2011. '*Near-source strong ground motions observed in the 22 February 2011 Christchurch Earthquake*'. Seismological Research Letters 82(6): 853-865.

Brodsky EE, Roeloffs E, Woodcock D, Gall I, Manga M 2003. *'A mechanism for sustained groundwater pressure changes induced by distant earthquakes.*' Journal of Geophysical Research Solid Earth 108: doi 10.1029/2002jb002321.

Brown LJ 2001. '*Chapter 23 Canterbury*'. In: Rosen MR, White PA eds. Groundwaters of New Zealand. Wellington, New Zealand Hydrological Society Inc., Pp 441-459.

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

Brown LJ, Weeber JH 1994. '*Hydrogeological implications of geology at the boundary of Banks Peninsula volcanic rock aquifers and Canterbury Plains fluvial gravel aquifers.*' New Zealand Journal of Geology and Geophysics 37(2): 181-193.

Cameron SG 1993 '*A hydrogeological study of the interaction between Avon River baseflow and shallow groundwater, Christchurch, New Zealand*'. MSc thesis, University of Canterbury.

CERA 2014 '*Verification of LiDAR acquired before and after the Canterbury Earthquake Sequence Technical Specification 03*, and may be accessed from this link https://ttgd.projectorbit.com/ReportList/ReportList.aspx.

Chung, J-W 2007. '*Development of a Geographic Information System-based Virtual Geotechnical Database and Assessment of Liquefaction Potential for the St Louis Metropolitan Area'*. PhD Dissertation, University of Missouri-Rolla.

Cox SC, Rutter HK, Sims A, Manga M, Wier JJ, White PA, Horton TW, Scott D 2012. *'Hydrological effects of the M_w 7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand.*' New Zealand Journal of Geology and Geophysics 55(3): 231-247.

Cowan H 1987. 'Hydrogeology and Groundwater Quality in the Harewood-Styx area'. Unpublished report to the North Canterbury Catchment Board. Copy held by Tonkin & taylor, Auckland. 66 pages.

Clark MP, Kavetski D, Fenicia F 2011. *'Pursuing the method of multiple working hypotheses for hydrological modeling*'. Water Resources Research 47 W09301, doi:10.1029/2010WR009827.

Cubrinovski M, Bray JD, Taylor M, Giorgini S, Bradley BA, Wotherspoon L, Zupan J 2011. '*Soil liquefaction effects in the central business district during the February 2011 Christchurch Earthquake*'. Seismological Research Letters 82(6): 893-904.

Department of Building and Housing 2011. '*Revised guidance on repairing and rebuilding houses affected by the Canterbury earthquake sequence'*. http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/guide-canterbury-earthquake-revised.pdf [accessed on 13/2/2013].

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.

Environment Canterbury 2011a. Earthquake impacts on groundwater. Update Report #1. http://Environment Canterbury.govt.nz/publications/General/earthquake-impacts-groundwater-update-1-130411.pdf [accessed on 23/1/2013].

Environment Canterbury 2011b. Earthquake impacts on groundwater. Update Report #2.

http://Environment Canterbury.govt.nz/publications/General/earthquake-impacts-groundwater-update-2-130511.pdf [accessed on 23/1/2013].

Environment Canterbury 2011c. Earthquake impacts on groundwater. Update Report #3. http://ecan.govt.nz/publications/General/earthquake-impacts-groundwater-update-3-010911.pdf [accessed on 23/1/2013].

Fry B, Gerstenberger MC 2011. '*Large apparent stresses from the Canterbury earthquakes of 2010 and 2011'*. Seismological Research Letters 82(6): 833-838.

Fry B, Benites RA, Kaiser AE 2011. *'The character of accelerations in the M_w 6.2 Christchurch Earthquake*.' Seismological Research Letters 82(6): 846-852.

Fordyce E 2013. *'Groundwater dynamics of a shallow, coastal aquifer'*. Unpublished M.Sc. thesis, Geography Department, University of Otago, Version submitted for examination Dec 2013. 155 pages.

Forsyth PJ, Barrell DJA, Jongens R (compilers) 2008. '*Geology of the Christchurch area Institute of Geological and Nuclear Sciences 1:250 000 geological map 16.*' GNS Science. 1 map plus 67 p. supplement.

Gledhill KR, Ristau J, Reyners ME., Fry B, Holden C 2011. '*The Darfield (Canterbury, New Zealand) M_w7.1 earthquake of September 2010: a preliminary seismological report.*' Seismological Research Letters 82(3): 378-386.

Gulley A, Dudley Ward NF, Cox SC, Kaipio JP 2013. '*Groundwater responses to the recent Canterbury Earthquakes: a comparison'*. Journal of Hydrology 504: 171-181.

Hoeksema RJ, Clapp RB, Thomas AL, Hunley AE, Farrow ND, Dearstone KC 1989. '*Cokriging model for estimation of water table elevation'.* Water Resources Research 25(3): 429-438.

Kaiser AE, Holden C, Beavan RJ, Beetham RD, Benites RA, Celentano A, Collet D, Cousins, WJ, Cubrinovski M, Dellow GD, Denys P, Fielding E, Fry B, Gerstenberger MC, Langridge R M, Massey CI, Motagh M, Pondard N, McVerry GH, Ristau J, Stirling MW, Thomas J, Uma S. R, Zhao JX 2012. *'The M_w6.2 Christchurch Earthquake of February 2011: preliminary report.*' New Zealand Journal of Geology and Geophysics 55(1): 67-90.

Kidson J, Renwick JA, McGregor J 2009. '*Hemisphere scale seasonality of the Southern annular mode and impacts on climate in New Zealand.*' Journal of Climate 22: 4759-4770.

Kitagawa Y, Koizumi N, Takahashi M, Matsumoto N, Sato T 2006. *'Changes in groundwater levels or pressures associated with the 2004 earthquake off the west coast of northern Sumatra (M9.0)*'. Earth Planets and Space, 58: 173-179.

Lashgary PF, Beavan J, Motagh M, Townend J 2012. '*Satellite interferometric measurements of interseismic and postseismic deformation in Canterbury, New Zealand.*' Abstract. Geoscience Society of New Zealand Conference, Hamilton 25-28 November 2012. Geoscience Society of New Zealand Miscellaneous Publication 134A. p 30.

Muir-Wood R, King GCP 1993. *'Hydrological signatures of earthquake strain*'. Journal of Geophysical Research-Solid Earth 98: 22035-22068.

NIWA 2012. '*NIWA Climate Centre National Climate Summary June 2012*'. https://www.niwa.co.nz/sites/default/files/climate_summary_june2012.pdf [accessed on 27/8/2012].

Orense RP, Kiyota T, Yamada S, Cubrinovski M, Hosono Y, Okamura M, Yasuda S 2011. *'Comparison of liquefaction features observed during the 2010 and 2011 Canterbury earthquakes'*. Seismological Research Letters 82(6): 905-918.

Quigley M, Van Dissen RJ, Litchfield NJ, Villamor P, Duffy B, Barrell DJA, Furlong K, Stahl T, Bilderback E, Noble D 2012. '*Surface rupture during the 2010 M_w7.1 Darfield (Canterbury) earthquake: implications for fault rupture dynamics and seismic-hazard analysis.*' Geology 40(1): 55-58.

Rekker J 2012. '*The South Dunedin Coastal Aquifer & Effect of Sea Level Fluctuations*'. Report published by the Otago Regional Council. ISBN 978-0-478-37648-7, 25 p.

Reyners ME 2011. '*Lessons from the destructive M_w6.3 Christchurch, New Zealand, earthquake.*' Seismological Research Letters 82(3):371-372.

Roeloffs EA 1998. *'Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes*' Journal of Geophysical Research-Solid Earth 103: 869-889.

Rutter H 2010. '*Earthquake Related Springs*'. Aqualinc Report No C11069. Prepared for the New Zealand Earthquake and War Damage Commission (EQC).

Rutter HK, Cox SC, Bell D, Stephen-Brownie C 2012. '*Earthquake-induced springs*'. New Zealand Hydrological Society Conference, Nelson 2012. New Zealand Hydrological Society. p. 170-171.

Scott DM 2000a. '*Christchurch – West Melton Groundwater Investigation: Simulation of alternative groundwater abstraction scenarios and their effects on base flows of the Avon and Heathcote Rivers.*' Environment Canterbury Report U00/33, 54 p.

Scott DM 2000b. '*Christchurch – West Melton Groundwater Investigation: Groundwater flow model documentation – Draft report.*' Environment Canterbury Report U00/39, 51 p.

Scott DM 2004. *'Groundwater allocation limits - land-based recharge limits*'. Environment Canterbury Unpublished Technical Report U04/97, 39 p.

Sil S, Freymueller JT 2006. *'Well water level changes in Fairbanks, Alaska, due to the great Sumatra-Andaman earthquake*'. Earth Planets and Space 58: 181-184.

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

Taira TA, Silver PG, Niu F, Nadeau RM 2009. '*Remote triggering of fault-strength changes on the San Andreas fault at Parkfield*'. Nature 461: 636-U77.

Talbot JD, Weeber JH, Freeman MC, Mason CR, Wilson DD 1986. '*The Christchurch Artesian Aquifers. North Canterbury Catchment Board and Regional Water Board.*' ISBN 0-908764-05-07, 159 p.

Tonkin & Taylor 2010. '*Darfield Earthquake 4 September 2010 Geotechnical Land Damage Assessment & Reinstatement Report – Stage 2 Report.*' Report for Earthquake Commission. http://www.eqc.govt.nz/canterbury-earthquakes/land-claims/land-reports/stage-2-land-reports [accessed on 13/2/2013].

Tonkin & Taylor 2011. '*Christchurch Central City Geological Interpretative Report.*' Report for Christchurch City Council. http://resources.ccc.govt.nz/files/CentralCityDecember2011/TonkinTaylorChristchurchCentralCityGeologicalInterpretativeReport/01TonkinTaylorGeologicalInterpretativeReport.pdf [accessed on 13/2/2013].

Tonkin & Taylor 2013. 'Liquefaction Vulnerability Study'. Report for the Earthquake Commission. T&T ref. 52020.0200/v1.0. Report prepared by S. van Ballegooy & P. Malan, Feb., available at: https://canterburygeotechnicaldatabase.projectorbit.com.

van Ballegooy S, Cox SC, Agnihotri R, Reynolds T, Thurlow C, Rutter HK, Scott DM, Begg JG, McCahon I 2013. '*Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake'*. GNS Science Science Report

2013/01, 66 pages plus 8 appendices.

Wang C-Y, Manga M 2010. Earthquakes and water: Lecture Notes in Earth Sciences, v. 114, 235 pages.

Wang C-Y, Wang CH, Manga M 2004. '*Coseismic release of water from mountains: Evidence from the 1999 (M_w=7.5) Chi-Chi, Taiwan, earthquake*'. Geology 32: 769-772.

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.

West M, Sanchez JJ, McNutt SR 2005. *'Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake*'. Science 308: 1144-1146.

White PA 2007a. *'Geological model of the Christchurch Formation and Springston Formation.*' GNS Client report 2007/87 to Environment Canterbury. Environment Canterbury report U07/24. 99p.

White PA 2007b. '*Snow storms in Canterbury and recharge to groundwater.*' GNS Client report 2007/117 to Environment Canterbury. 46p.

White PA 2008. '*Riccarton Formation, Burnham Formation and Windwhistle Formation lithologies in the vicinity of Christchurch City.*' GNS Science Consultancy report 2008/157 for Environment Canterbury.

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

White PA, Clausen B, Hunt B, Cameron S, Weir J 2001. '*Groundwater-surface water interaction*'. In: Rosen MR, White PA eds. Groundwaters of New Zealand. Wellington, New Zealand Hydrological Society Inc., Pp 133-160.

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.

White PA, Kovacova E, Zemansky G, Jebbour N, Moreau-Fournier M 2012. '*Groundwater-surface water interaction in the Waimakariri River, New Zealand, and groundwater outflow from the river bed*'. Journal of Hydrology (NZ) 51(1): 1-24.

Wilson DD 1976. '*Hydrogeology of Metropolitan Christchurch'*. New Zealand Journal of Hydrology 15: 101-120.

15.0 GLOSSARY

Artesian	An adjective referring to groundwater confined under hydrostatic pressure. Artesian pressure is the hydrostatic pressure of artesian water, often expressed in terms of height relative to the land surface that a column of water that would be supported by the pressure. A flowing artesian well yields water at the land surface without pumping as it taps an artesian aquifer in which the head is sufficient to raise the water in the well above the land surface. Although the term has been used widely in the past, its use has been abandoned by many hydrologists.
CCC	Christchurch City Council.
CERA	Canterbury Earthquake Recovery Authority.
CGD Canterbury Geotechnical Database	A public database of geotechnical data for the Canterbury region and used in this analysis. Located at: https://canterburygeotechnicaldatabase.projectorbit.com
Confined aquifer	An aquifer bounded above and below by lower permeability layers which confine the groundwater; the head of water in the aquifer is above the elevation of the base of the top confining unit.
CPT Cone Penetration Test	Geotechnical ground investigation test pushing an instrumented cone into the ground at a controlled rate and measuring the tip resistance, sleeve friction and often dynamic pore water pressure.
DBH	Department of Building and Housing. Refer to ‘MBIE’.
DEM	Digital Elevation Model.
ECan	Environment Canterbury. Environment Canterbury is the trading name of the Canterbury Regional Council.
EQC	The Earthquake Commission.
GNS	GNS Science, Te Pu Ao, a Crown Research Institute.
Groundwater surface	Representation of groundwater in terms of a reference datum, shown in two dimensions on maps as a grid or contours, or as a numerical surface (in three dimensional models). In this report the term ‘shallow groundwater surface’ is considered synonymous with the term water table.
Groundwater elevation	The elevation of the water table (or another potentiometric surface) at a particular place or in a particular area, as represented by the level of water in wells or other natural or artificial openings or depressions communicating with the saturated zone. Given in values relative to mean sea level or some other vertical datum.

Groundwater depth	Depth to the water table (or another potentiometric surface) at a particular place or in a particular area, measured relative to the level of ground at that place.
Hyporheic zone	A region beneath and alongside a river bed, where there is mixing of shallow groundwater and surface water. The flow dynamics and behaviour in this zone (termed hyporheic flow or underflow) is recognised to be important for surface water/groundwater interactions and river ecology.
LiDAR Light Detection and Ranging	A method and instrument that measure distance to a reflecting object by emitting timed pulses of light and measuring the time between emission and reception of reflected pulses. The measured time interval is converted to distance. As used in this report, refers to an aerial surveying methodology.
LINZ	Land Information New Zealand – Toitū te whenua. A New Zealand government department responsible for land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, managing Crown property and a variety of other functions
Liquefaction	A phenomenon whereby a saturated soil substantially loses strength and stiffness in response to an applied stress, usually earthquake shaking, causing it to behave like a liquid.
MBIE	Ministry of Business, Innovation and Employment (formerly the Department of Building and Housing).
Median	The numerical value separating the higher half of a data set, from the lower half. The *median* of a list of numbers can be found by arranging all the observations from lowest value to highest value and picking the middle one.
Monitoring well	A well that is used for the purpose of monitoring groundwater level or quality. Often a monitoring well comprises cased and screened sections fixed inside a borehole. In this report the term includes wells with pressure transducers recording at regular intervals, and wells measured manually using an electronic water sensor tape.
Natural Hazards Research Platform	A multi-party research platform funded by the New Zealand Government that is dedicated to increasing New Zealand's resilience to Natural Hazards through high quality collaborative research (see www.naturalhazards.org.nz)
NIWA	National Institute of Water and Atmospheric Research, Taihoro Nukurangi, a Crown Research Institute.
Percentile	Indicates the value below which a given percentage of observations in data set fall. i.e. 15% of the data set will be below the 15th percentile.
Pre-Darfield Earthquake	The 20 year period 1990-2010, prior to the 4 September 2010, for which groundwater fluctuations have been assessed for this report

Post-Darfield Earthquake	The period between 4 September 2010 and 31 November 2013, for which monitoring well data have been assessed for this report
Piezometer	A small diameter monitoring well or borehole constructed to measure hydraulic head at a specific location. The section of monitoring well (i.e. screened section) is very short. Refer also to 'Monitoring well'.
Residential Red Zone	An area defined by the Government as unsuitable for continues residential occupation at the present time. Generally this area encompasses the most severely damaged land in Canterbury.
Screen	The open gaps in the tube of a monitoring well or piezometer, that allow water to flow into the well.
Screen depth	Depth below a datum of the top and/or base of the screened section of a well. Generally reported as depth below ground level.
Surfer 11	Surfer is a full-function 3D visualization, contouring and surface modelling package that runs under Microsoft Windows. Surfer is used extensively for terrain modelling, bathymetric modelling, landscape visualization, surface analysis, contour mapping, watershed and 3D surface mapping and volumetrics.
TC1 Technical Category 1	A classification of land developed by the Department of Building and Housing (now MBIE) for foundation investigation purposes
TC2 Technical Category 2	A classification of land developed by the Department of Building and Housing (now MBIE) for foundation investigation purposes
TC3 Technical Category 3	A classification of land developed by the Department of Building and Housing (now MBIE) for foundation investigation purposes.
Unconfined aquifer	An unconfined aquifer in which the water table forms the upper boundary. Water is not confined under pressure beneath a confining bed/layer.
Water Table	The upper surface of a body of unconfined groundwater at which pressure is equal to atmospheric pressure, marking the change between the unsaturated and saturated zone. The earth below the water table, if the aquifer it is not perched, will be saturated while the earth above the water table will be generally unsaturated, but may contain saturated zones (e.g., portions of the capillary fringe) or be temporarily saturated during recharge events. In this report the term 'water table' is considered to be synonymous with the term shallow groundwater level. In places the term 'water table surface' is used to specifically refer to the calculated grid and contour dataset that represents the water table across the study area.

GNS SCIENCE
TE PŪ AO

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657