

**Median water table elevation in
Christchurch and surrounding area
after the 4 September 2010 Darfield Earthquake
Version 1**

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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. Liquefaction and liquefaction risk is now a major engineering concern for land remediation and assessment in the city. The depth to the water table is a fundamental parameter when undertaking liquefaction assessments which aim to determine the potential future damaging effects of liquefaction for the purposes of building foundation design.

Maps of the median water table elevation and depth below ground have been derived for Christchurch City and surrounding area, for the period since the 4 September 2010 M_w 7.1 Darfield Earthquake. The study covers an area between Prebbleton in the southwest, Swannanoa in the northwest, and the coastline in the east. Monitoring well contour and grid data sets will be provided via the Canterbury Earthquake Recovery Authority (CERA) Canterbury Geotechnical Database (CGD) website, then updated periodically as new data become available. Users will need to understand the assumptions and limitations of the calculated median water table. This report provides documentation of the methodology, data sets, assumptions used to derive the water table maps, confidence levels, as well as new observations, results and recommendations for updates in the future.

Data from 806 shallow monitoring wells were obtained from Christchurch City Council (CCC), Environment Canterbury (ECan) and geotechnical investigations carried out for the Earthquake Commission (EQC). 550 monitoring wells had records of nine months or longer from which a representative median water table elevation was determined for each site. 256 wells had short-term records, from which surrogate medians were estimated using data from nearby wells. 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 were used as breaklines to help shape and position the water table contour maps at places of significant groundwater-surface water interaction. Differences between the (preferred) median water table derived from post-Darfield Earthquake longer-term data (≥ 9 month records), and a surface derived using surrogate medians derived from short-term (< 9 month) data, are subtle and in most places ± 0.5 m. There are strengths and weaknesses in each surface, so end users should decide which is more appropriate depending on their specific engineering requirements and local site observations.

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. The water table surface is generally more than 5 m below ground west of Christchurch City, but less than 2 m deep beneath much of the city. A qualitative confidence index, taking into account the density of monitoring wells and varied duration of groundwater monitoring, indicates where there is a low, medium or high confidence in the median water table elevation map. A comparison of pre- and post-Darfield Earthquake data from 55 wells with extended (decadal) records indicates that the water table was in most places unaffected by the earthquakes, other than short-term fluctuations. In four wells the median water table elevation was lowered by 0.5–1.0 m to new base levels, independent of whether there was ground uplift or subsidence. 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. Until such a time as more data become available, these pre-Darfield Earthquake data provide a useful measure of likely scales of water table elevation in the future.

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

CONTENTS

EXECUTIVE SUMMARY	II
1.0 INTRODUCTION	1
1.1 Motivation and objectives	1
1.2 Outline	1
1.3 Study area	2
1.4 Datum	2
1.5 Applicability	4
1.6 Previous work	4
1.7 Water table and selection of well data	4
1.8 Limitations and assumptions	5
2.0 BACKGROUND	6
2.1 Christchurch City hydrogeology	6
2.2 Canterbury earthquake sequence	9
3.0 METHODOLOGY FOR MEDIAN WATER TABLE CALCULATION	11
3.1 Overview	11
4.0 MONITORING WELL DATA	13
4.1 General	13
4.2 Christchurch City Council monitoring wells	14
4.3 Environment Canterbury monitoring wells	14
4.4 EQC geotechnical investigation monitoring wells	15
5.0 GROUND ELEVATION FROM LIDAR SURVEYS	17
5.1 Precision and accuracy of the LiDAR surveys	18
5.2 Ground elevation at monitoring well locations	18
5.2.1 Example well head elevation correction for CCC and ECan monitoring wells	21
5.2.2 Example well head correction for EQC (Initial or TC3 Phase) monitoring wells	22
6.0 MEDIAN WATER TABLE ELEVATION FROM MONITORING WELL DATA.....	23
6.1 Selection of data	23
6.2 Median water table elevation from wells with longer-term data records (≥ 9 months).....	23
7.0 WATER TABLE ELEVATION FROM SURFACE WATER.....	26
7.1 Rivers Overview.....	26
7.1.1 General	26
7.1.2 Calculation of median values.....	28
7.2 Avon/Otakaro, Heathcote and Styx rivers.....	28
7.3 Waimakariri River	28
7.4 Coastline	29
8.0 CONTOURING AND REFINEMENT OF WATER TABLE SURFACE	30
8.1 ‘Surfer’ software	30
8.2 Adopted gridding method: kriging	30
8.2.1 Suitability of co-kriging	31
8.3 Variogram options.....	32
8.4 Surfer output contour plots	32
8.5 Manual checking and refinement.....	33
8.6 Results and observations	33

9.0	USE OF SHORT-TERM MONITORING WELL DATA.....	36
9.1	Introduction	36
9.2	Calculation of surrogate median water table elevations from wells with short-term data records (< 9 months)	36
9.2.1	Flowchart for estimation of surrogate medians	37
9.2.2	Worked Example	37
9.3	Contouring of median water table including short-term data (< 9 months)	40
9.4	Comparison of water table with/without short-term data	40
9.5	Confidence index for water table elevation	42
10.0	WATER TABLE FLUCTUATION	45
10.1	Groundwater elevation fluctuations	46
10.1.1	Inter-annual variability	47
10.1.2	Seasonal (Annual) variability	48
10.2	Earthquake-related fluctuations and changes	48
10.2.1	Background	48
10.2.2	Canterbury aquifer responses	49
10.2.3	Water table assessment	50
10.2.4	Summary of earthquake-related effects.....	54
10.3	Implications for median water table	54
11.0	SUMMARY	56
11.1	Current study	56
11.2	Recommendations for next version	59
	ACKNOWLEDGMENTS	60
	REFERENCES.....	60
	GLOSSARY	64
	APPENDICES.....	67

FIGURES

Figure 1.1	Map of the study area location.....	3
Figure 3.1	Flowchart of adopted methodology.....	12
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.....	19
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.....	21
Figure 5.3	Schematic changes in well head elevation, with data from LiDAR surveys.	22
Figure 6.1	Typical range of monitoring duration for various monitoring well sources, and the data duration required to calculate a representative median water table elevation.....	25
Figure 8.1	The 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 (≥ 9 months) and drawdown points, is provided in Figure F.3 (Appendix F).....	34
Figure 8.2	The 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 (≥ 9 months) and drawdown points, is provided in Figure F.4 (Appendix F).	34
Figure 9.1	Flowchart summarising the method for obtaining surrogate medians of water table elevation for P5 and P6 wells with short-term monitoring records.....	37
Figure 9.2	Median and offset calculation for a type P1 monitoring well.	38
Figure 9.3	Example offset contour map for a particular month.	39
Figure 9.4	Example diagram for calculation of overall confidence value.	43

TABLES

Table 2.1	Summary of the principal geological units near and beneath Christchurch City and surrounding area.....	7
Table 2.2	Christchurch City groundwater protection zones (adapted from Weeber, 2008).	8
Table 2.3	Summary of major Canterbury earthquakes in the 2010-2011 sequence.....	10
Table 4.1	Water table readings available since September 2010, by monitoring well source.	13
Table 5.1	Christchurch City LiDAR surveys, typically collected at least one month after each major earthquake.	17
Table 5.2	Procedures to correct for changes in well head elevation.	20
Table 6.1	Selection of data based on monitoring duration.	24
Table 7.1	Summary of river level monitoring stations.....	27
Table 8.1	Summary of gridding methods (Surfer version 11).....	31
Table 9.1	Example offset calculation for a type P1 monitoring well	38
Table 9.2	Example of a surrogate median calculation for a Type P6 monitoring well.....	40
Table 9.3	Assigned values for developing a confidence index	43
Table 10.1	Monitoring wells selected for detailed assessment of 1990-2010 variability of shallow groundwater levels. A selection of both parametric and non-parametric statistics are provided.	47
Table 10.2	Summary of earthquake-induced changes of water table elevation observed in shallow CCC and ECan monitoring wells.....	51

APPENDICES

APPENDIX A: BACKGROUND FIGURES

- Figure A.1** Extract from geological map of Christchurch area
- Figure A.2** Schematic geological cross-section of aquifers
- Figure A.3** Christchurch Groundwater Protection Zones
- Figure A.4** Earthquake epicentres, 4 September 2010 – 4 April 2012

APPENDIX B: MONITORING WELL DATA

- Figure B.1** Location plan for monitoring wells
- Figure B.2** Depth of monitoring wells
- Figure B.3** Example CCC monitoring well log
- Figure B.4** MP and GL sign convention for ECan wells
- Figure B.5** Example ECan monitoring well log
- Figure B.6** EQC Initial Phase standard monitoring well detail
- Figure B.7** EQC TC3 Phase standard monitoring well detail

APPENDIX C: LIDAR INFORMATION

LiDAR survey and benchmark comparisons

- Figure C.1** Cumulative ground elevation difference
- Figure C.2** Survey benchmark locations and land zonation

APPENDIX D: SENSITIVITY OF DATA SELECTION FOR MONITORING WELLS

- Figure D.1** Change in median water table level with reduction in available data for ECan monitoring wells
- Figure D.2** Change in median water table level with reduction in available data for CCC monitoring wells

APPENDIX E: RIVER LEVEL DATA

- Figure E.1** Location plan for river monitoring stations, cross-sections and breaklines
- Figure E.2** Location plan for Avon/Otakaro River monitoring stations
- Figure E.3** Location plan for Heathcote River monitoring stations
- Figure E.4** Location plan for Styx River monitoring stations
- Figure E.5** Location plan for Waimakariri River cross-sections

APPENDIX F: CALCULATION OF SURFACE SHOWING MEDIAN WATER TABLE ELEVATION

- Figure F.1** Relationship between ground surface level and median water table elevation
- Figure F.2** Median water table elevation (reduced level), using longer-term data, including river breaklines but excluding drawdown points
- Figure F.3** Median water table elevation (reduced level), using longer term data, including river breaklines and drawdown points
- Figure F.4** Depth to median water table

APPENDIX G: CALCULATION OF SURFACE SHOWING MEDIAN WATER TABLE ELEVATION, INCLUDING SURROGATE MEDIANS FROM SHORT-TERM DATA

- Figure G.1** Offset plot for December 2012
- Figure G.2** Median water table elevation (reduced level), including surrogate medians from <9 month data and river breaklines, excluding drawdown points
- Figure G.3** Median water table elevation (reduced level), including surrogate medians from <9 month data, including river breaklines and drawdown points
- Figure G.4** Depth to median water table, including surrogate medians from <9 month data
- Figure G.5** Confidence index for water table elevation and water table depth

APPENDIX H: WATER LEVEL FLUCTUATION

- Figure H.1** Location of monitoring wells used in the assessment of pre-earthquake fluctuations
- Figure H.2** Range of groundwater elevation in metres, for the period 1990-2010
- Figure H.3** Standard deviation of groundwater elevation in metres, for the period 1990-2010
- Figure H.4** Groundwater elevation in selected monitoring well water levels, 1990-2010, plotted by Julian Day of the year
- Figure H.5** Groundwater elevation in selected monitoring wells, rainfall and groundwater recharge, 1990-2010 time series
- Figure H.6** Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence
- Figure H.7** Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence
- Figure H.8** Ground and shallow groundwater elevation changes in selected monitoring wells during the Canterbury earthquake sequence
- Figure H.9** Difference between the 85th percentile and the median groundwater elevation, 1990-2010

1.0 INTRODUCTION

1.1 Motivation and objectives

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.

The objectives of this study were to develop contour maps of the water table elevation and water table depth across Christchurch City and the surrounding area for the period following the 4 September 2010 M_w 7.1 Darfield Earthquake. These 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. The maps will also be of use in the future assessment on the effects of earthquakes on shallow groundwater. A secondary objective has been to observe and document any effects of the earthquake on the water table.

1.2 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) website¹. Its purpose is to document the methodology, data sets, assumptions and confidence levels used to derive the water table maps, 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 2010 and 2011 earthquakes in the region. Section 3 summarises the methodology that was adopted in order to maximise the amount of data and number of sites used in the post-Darfield Earthquake water table calculation. The uncertainty is reduced by incorporating as many observations from new monitoring wells as possible.

Sections 4 to 8 describe the sources of data and details of median water table calculations and corrections at each site, and 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. Despite the large number of monitoring wells recently installed, there is a relatively limited period of observations since the Darfield Earthquake. Section 9 presents a method for estimating a surrogate median water table elevation for wells where there are only single observations or short-term data records of < 9 months duration, in order to account for seasonal variation. The method utilises records of nearby wells in which there are longer periods of monitoring and could be adapted by geotechnical engineers faced with limited data records undertaking site-specific investigations. Section 9 also outlines a subjective approach developed to incorporate spatial

¹ <https://canterburygeotechnicaldatabase.projectorbit.com>

and temporal uncertainty, and display the varied level of confidence in the water table maps across the study area.

Section 10 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 11 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 CERA CGD website.

1.3 Study area

The study focuses on the 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:

- minimum easting 1557000, maximum easting 1582000
- minimum northing 5174025, maximum northing 5198475

1.4 Datum

The vertical datum used in this report is the 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 recorded relative to LVD-37 (refer to Section 4);
- river level data for the Avon/Otakaro, Heathcote and Styx Rivers, collected by Christchurch City Council, were provided 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 be relative to LVD-37 (Section 7.2);
- river level data for Waimakariri River, collected by Environment Canterbury, were provided relative to LVD-37 (Section 7.3);
- 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.

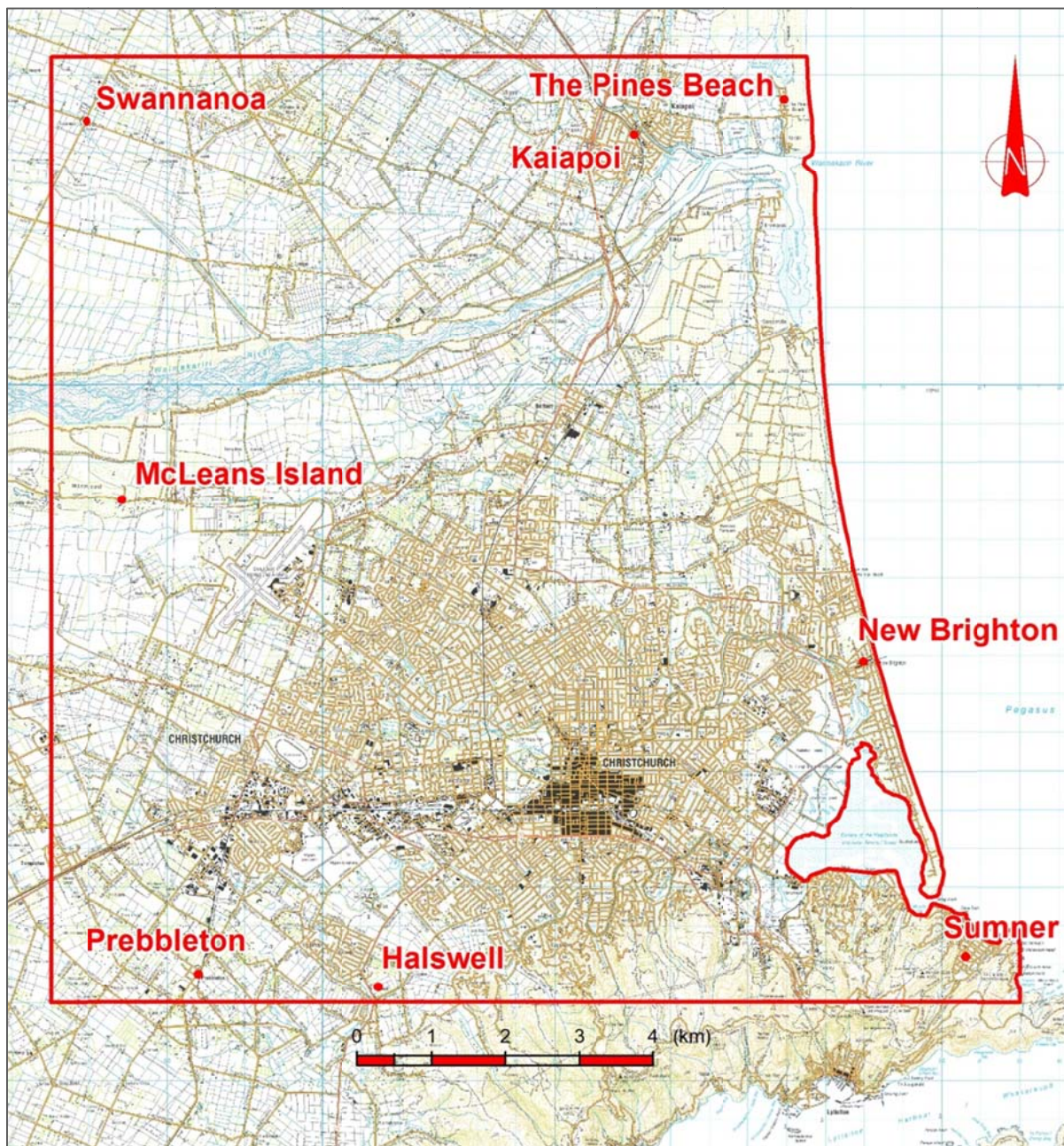


Figure 1.1 Map of the study area location.

1.5 Applicability

This report aims to improve liquefaction hazard assessments by understanding the water table elevation. In particular, the depth to the water table is a principal consideration when assessing the potential damage from liquefaction. The work has been 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).

The median water table developed in this report may also be useful for:

- managing Christchurch City underground water supply and wastewater collection pipe networks by better understanding infiltration and inflow;
- managing the Christchurch City drainage network including the efficacy of the open channel network;
- geotechnical assessments that wish to place individual or limited-period observations of groundwater elevation into a longer-term context;
- understanding the hydrological effects of the earthquakes and tracing their impact on the flow of groundwater between aquifers.

1.6 Previous work

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 published by Begg & Scott 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, using 192 measurements in wells and 572 LiDAR-derived points for surface water. By comparison, this study used data for 806 monitoring wells, many of which have been installed since the 4 September 2010 M_w 7.1 Darfield Earthquake, and has accounted for changes in ground elevation because of the earthquakes. While all of the studies have produced groundwater surfaces that are superficially similar in appearance, they are distinctly different in detail and generation method and should not be confused. For most purposes, this new study with over four times the number of wells will supersede the Begg & Scott and Beca models.

1.7 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 and screened at shallow levels. The analysis of the median water table in this study has, as far as possible, excluded any monitoring wells considered to be screened in confined aquifers. These wells are identified using available well logs to assess the groundwater levels and type of sediment (i.e. fine-grained sediment or gravel) intercepted by the bore hole. Monitoring wells are included in the assessment where the well log suggests that the screened zone is measuring unconfined groundwater and/or the elevation of recorded groundwater is similar to nearby

surface water elevation. The term 'water table surface' is used with respect to the calculated grid and contour dataset that represents the elevation of the water table across the study area.

1.8 Limitations and assumptions

While the water table surface presented in this report may be used for a variety of purposes, it is important that anyone using it understands the limitations and assumptions that have been made to develop it. Firstly, the water table has been developed as a median with a focus of providing a measure of the most likely median water table depth, derived from interpolation of median values of observed water table elevation. While this is useful for, and aimed directly at, geotechnical assessments it creates a 'statistical' surface 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 these values in attempting to contour a potentiometric surface that would be used to indicate the direction of groundwater flow.

Secondly, the level of confidence in the median water table is a function of the density of the monitoring wells in an area, as well as the duration of the monitoring period available for each well. The position of the water table fluctuates both inter-annually as well as seasonally. Engineers and scientists using the median water table surface presented in this report will need to consider not only the spatial reliability (and whether or not additional groundwater investigations are required) but also whether the use of a median water table is appropriate for their particular application. Sea level rise has not been considered in this report, and it is likely that sea level rise will result in changes to groundwater in the low-lying areas of Christchurch City in the future.

2.0 BACKGROUND

2.1 Christchurch City hydrogeology

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

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 is exposed 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). A schematic west-east geological cross-section along the upper part of the coastal Waimakariri River floodplain is presented in Figure A.2 (Appendix A). 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 is related to the geological complexity of the subsurface layers spatially (e.g. White, 2009) and temporal variations in recharge/discharge. While not precise, the subdivision of Christchurch City hydrogeology into three zones (Table 2.2) was found to be useful and is adopted in 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, that 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 in Appendix A). Springs in near-surface channels provide base flow of the Avon/Otakaro, Styx, Heathcote, and Halswell rivers (Cameron, 1993; Earl, 1998; White, 2009). Prior to the 4 September 2010 Darfield Earthquake, relatively few springs emerged through the Christchurch City confined aquifers in the south and east of the city (White et al.,

2007), but immediately following the earthquake a series of new springs began to flow in this area. Other springs developed at the margin of the Canterbury Plains along lower slopes of the Port Hills (Rutter, 2010; Cox et al., 2012; Rutter et al., 2012).

2.2 Canterbury earthquake sequence

On 4 September 2010, a series of faults hidden beneath the Canterbury Plains ruptured in a complex sequence to produce the Greendale Fault trace (approximately 30 km long), accompanied by the M_w 7.1 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_w 6.2 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_w 5.6 and M_w 6.0 on 13 June 2011; and the M_w 5.8 and M_w 5.9 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 the amounts of liquefaction, ground surface deformation and lateral spreading (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 MEDIAN WATER TABLE CALCULATION

3.1 Overview

The process of developing a median water table 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);
- calculation of a ground surface DEM using LiDAR measurements (Figure 3.1, Stage 1);
- calculation of a water table elevation at each well (i.e. ground surface minus water table depth) and a median of this elevation; calculation of the median water table elevation represented by median river levels (along the centre line of the rivers) and the coastal boundary (Figure 3.1, Stage 1);
- developing maps of median water table elevation and depth using the above data and river breaklines to locate changes in the slope direction of the water table (Figure 3.1, Stages 2 and 3);
- examining the effects of including longer-term versus short-term data and assessing uncertainty in the maps (Figure 3.1, Stage 3).

The flowchart in Figure 3.1 below provides a summary of the methodology. Further discussion and details are provided in sections 4 to 8.

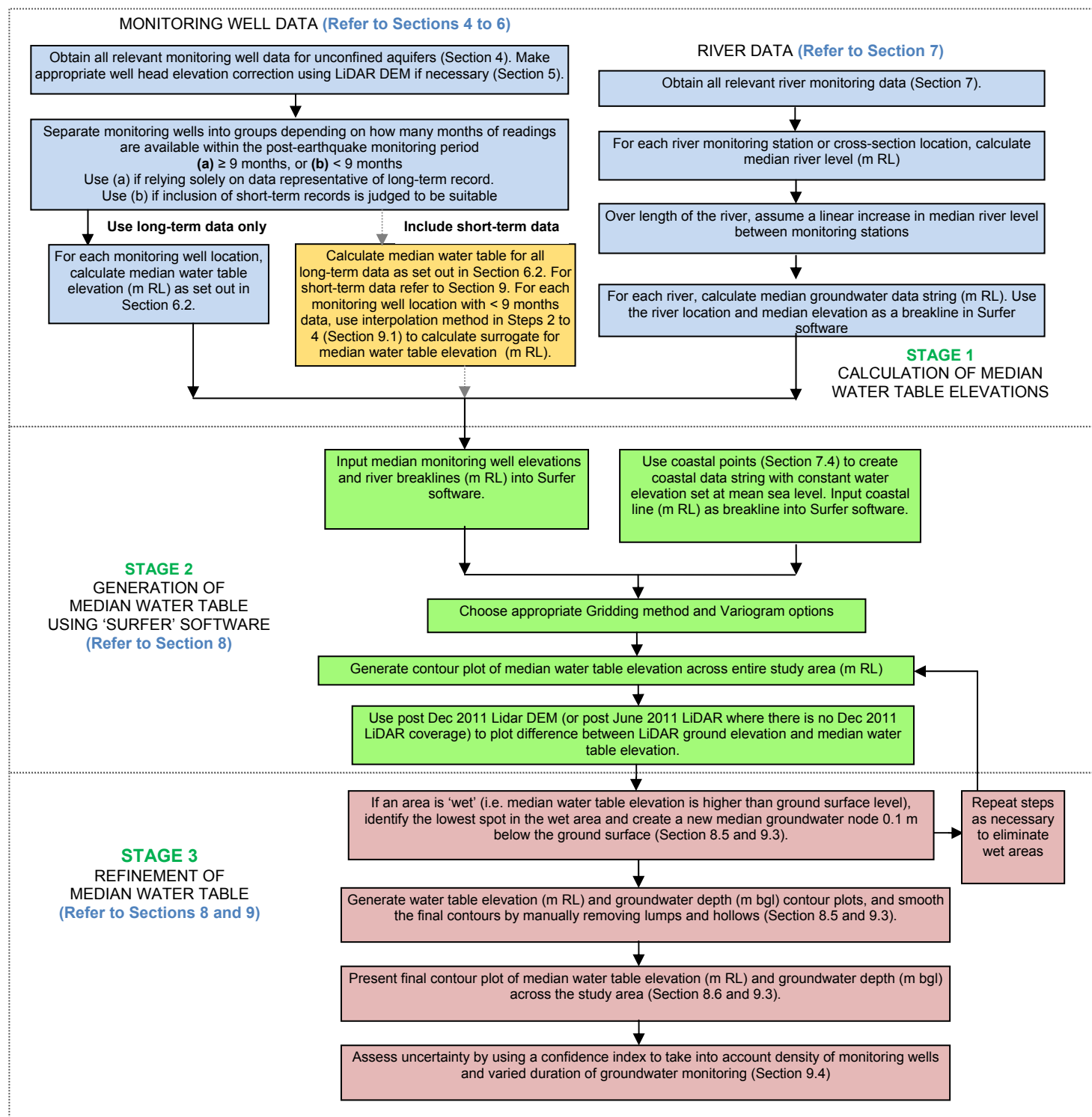


Figure 3.1 Flowchart of adopted methodology.

4.0 MONITORING WELL DATA

4.1 General

This section outlines the sources of monitoring well data and some of the ways these data have been used. Data obtained from CCC, ECan and EQC monitoring wells are discussed individually. Figure B.1 (Appendix B) presents an overview of all the monitoring wells used for this study. Table 4.1 below summarises the number of wells and duration of well monitoring data.

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

Number of months within 28-month post-Darfield Earthquake period (Sept 2010 until Dec 2012) 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	-	-	32	122	See section 9 for use of short-term data (< 9 months data)
4 - 6	-	-	49	-	
7 - 8	-	-	53	-	
9 - 12	-	-	258	-	See sections 5 to 8 for use of longer-term data (≥ 9 months data)
13 - 15	-	-	245	-	
16 - 18	-	1	3	-	
19 - 21	-	3	-	-	
22 - 24	-	4	-	-	
25 - 28	22	14	-	-	
Total	22	22	640	122	

The monitoring wells selected for calculation of the median water table (Section 6) are only those thought to measure the water table aquifer (as opposed to confined aquifers). To qualify as being representative of the water table aquifer, wells were 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 aquifers on the western side of Christchurch City, where Weeber (2008) demonstrated connectivity between Aquifer 0 and Aquifer 1 in the Inland zone.

Well logs have been 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. Figure B.2 (Appendix B) shows the distribution and depths of all monitoring wells used for water table calculations.

4.2 Christchurch City Council monitoring wells

Christchurch City Council has installed monitoring wells in Christchurch City for the purpose of observing depth below ground level to the water table. 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 was 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 m below the MP). An example CCC monitoring well record sheet (accessed via the Environment Canterbury website), is presented in Figure B.3 (Appendix B). The elevation of 22 measuring points (Figure B.1, Appendix B) were re-surveyed in December 2012 (Section 5.2) and these wells were included in the calculation of the median water table. Five CCC wells were excluded from the analysis in this report as these have yet to be re-surveyed at the time of writing. Data from all 27 monitoring wells were used in the assessment of pre-Darfield Earthquake fluctuations in water table elevation (see Section 10).

4.3 Environment Canterbury monitoring wells

Environment Canterbury monitors groundwater in wells throughout Canterbury, including both 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 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 identify the water table.

ECan has some data records that extend as far back as 1894, and many that are 30 - 50 years old. A number of ECan wells have only been monitored for short periods of time (i.e. weeks or months after completion of the well). The frequency of groundwater measurements in these monitoring wells ranged from once every 15 minutes to monthly. Quite a few of the ECan monitoring wells with pressure transducers no records since 2010, as parts of the monitoring network were damaged and became non-functional during the Canterbury earthquake sequence (Environment Canterbury, 2011c).

A total of 22 ECan monitoring wells (Figure B.1, Appendix B) were selected to contribute to the map of the post-Darfield Earthquake median water table. Data provided by ECan includes the well head measuring point (MP) elevation and the surrounding ground level (GL). 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). Data from 28 ECan monitoring wells were used in the assessment of pre-Darfield Earthquake fluctuations in water table elevation (Section 10).

4.4 EQC geotechnical investigation monitoring wells

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 the EQC. The wells were constructed in two separate phases of work, including the Initial Phase and the TC3 phase, as outlined below. Examples of well installation details these wells 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. The well head is likely to be at, or close to, the ground surface.

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 first 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 that was 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 laboratory testing;
- (c) geophysical testing primarily comprising multi-channel analysis of surface waves (MASW); and,
- (d) construction of monitoring wells to measure water table depths.

Wells have been installed in some of the drilled boreholes and CPTs 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 bgl. Water table depth data was collected at the time of installation and was generally measured by manual dipping at monthly intervals since well completion. Electronic water pressure transducers were installed in 22 monitoring wells recording at 15-minute intervals. In some cases, monitoring wells were damaged by subsequent earthquakes and records ceased.

Data from 640 initial investigation phase monitoring wells were examined for analysis of the post-Darfield Earthquake median water table. Monitoring of these wells commenced as early as June 2011. 506 of the wells had groundwater monitoring readings for at least 9 months since September 2010 (Section 6). Only monitoring wells with ≥ 9 months data were used for calculation of the median water table as set out in Sections 5 to 8 and Appendix F.

134 initial phase wells had short-term or discontinuous groundwater monitoring data records (< 9 months) for which a surrogate of the median water table elevation was estimated. These wells are discussed further in Section 9 and used in Appendix G.

TC3 Phase (2012 onwards)

A further geotechnical investigation at relatively closely spaced intervals is currently being carried out by EQC, private insurers and property owners, in areas of land identified by the MBIE as requiring further geotechnical investigation for dwelling foundation design purposes. These areas of land are referred to as Technical Category 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. This investigation is likely to include an additional 10,000 to 15,000 CPTs and 1,000 to 2,000 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).

At the time of writing, all of the 122 TC3 Phase monitoring well data are considered to be short-term, as monitoring of the water table in these wells commenced in October 2012, and therefore only 3 months of data falls within the study time period ending 31 December 2012. These short-term groundwater monitoring data records (< 9 months) were used in the calculation of a median water table (Section 9 and Appendix G), should an end-user decide that this is appropriate for their particular design application.

5.0 GROUND ELEVATION FROM LIDAR SURVEYS

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

5.1 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. The procedure compared survey levels for benchmarks with the adjacent LiDAR survey points. The following conclusions were made from the results of the analysis:

- 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' digital elevation model has 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 50 mm;
- the standard deviation of each LiDAR survey point is approximately 160 mm for the 'Pre-Earthquake' digital elevation models, and approximately 50 mm for the subsequent data sets.

5.2 Ground elevation at monitoring well locations

Ground elevation at many monitoring well locations has changed as a result 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.

The ground elevation changes suggest the measuring point elevation at the top of the well head may also have changed since the wells were first installed. The assumptions and corrections that have been made for the various monitoring wells are summarised in Figure 5.1 and Table 5.2. Corrections were applied to the time-series of monitoring data values used to calculate the water table elevations.

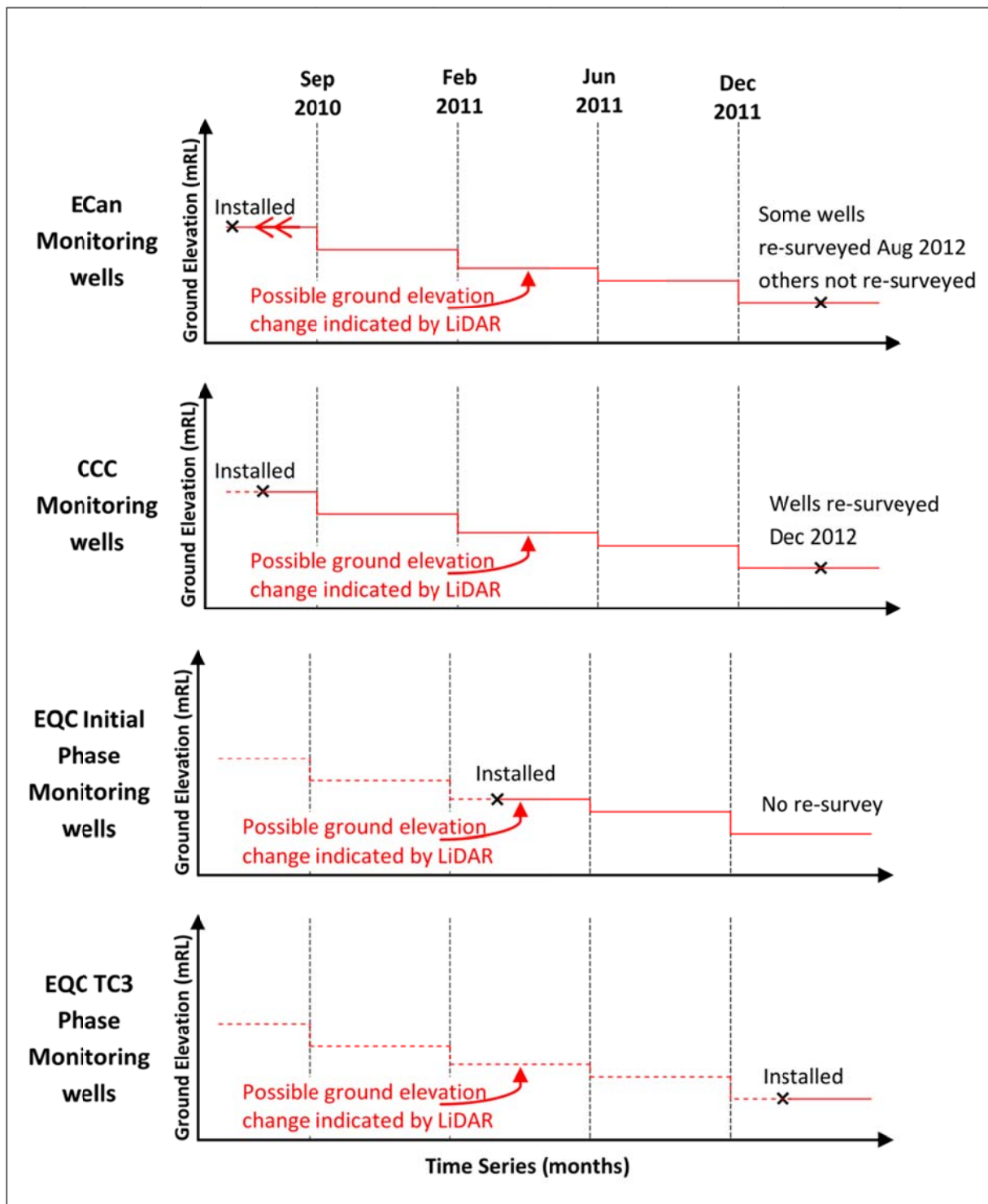


Figure 5.1 Examples of the different types of ground elevation data available for correcting the measuring point elevation of monitoring wells, depending on their source and time of installation.

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 Darfield Earthquake. Elevation of measuring points (well head) re-surveyed in December 2012 for 22 of the 27 CCC wells. <pre> graph TD Q1[Has measuring point (well head) been re-surveyed after Dec 2011?] -- YES --> Q2[Does the LiDAR indicate the same pattern of change as the re-survey? i.e. do both indicate an overall change of net subsidence or net uplift?] Q1 -- NO --> A3[As locations could not be confirmed, do not use in model] Q2 -- YES --> A1[Apply well head correction as discussed in Section 5.2.1] Q2 -- NO --> A2[Use Dec 2012 re-survey elevation as a constant measuring point throughout the post-earthquake period] </pre>
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. <pre> graph TD Q1[Has measuring point (well head) been re-surveyed after Dec 2011?] -- YES --> Q2[Does the LiDAR indicate the same pattern of change as the re-survey? i.e. do both indicate an overall change of net subsidence or net uplift?] Q1 -- NO --> A3[Apply well head correction as discussed in Section 5.2.2] Q2 -- YES --> A1[Apply well head correction as discussed in Section 5.2.1] Q2 -- NO --> A2[Use Aug 2012 re-survey elevation as a constant measuring point throughout the post-earthquake period] </pre>
EQC Initial Phase	Monitoring wells generally installed from May 2011 onwards, so they have sustained up to 2 significant earthquakes: Christchurch 2 (June 2011) and Christchurch 3 (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 5.2.2.
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.

5.2.1 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 well head elevation (L_1 to L_5) due to major earthquakes.

In the example (Figure 5.2):

- $S_1 - S_2 = 100$ mm
- $L_1 - L_3 = 40$ mm
- $L_1 - L_5 = 90$ mm
- the well head elevation at L_3 after the 22 February 2011 Christchurch Earthquake, is adjusted so that it is 44 mm (i.e. $40/90 \times 100$ 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.

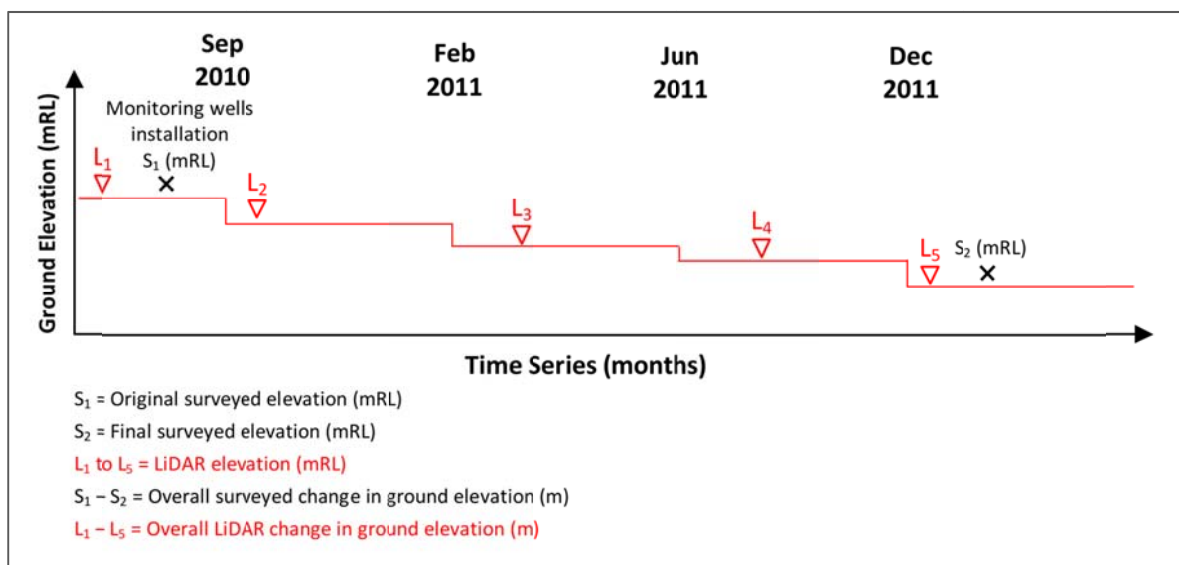


Figure 5.2 Schematic changes in well head elevation, with data from re-surveys of CCC and ECan well head measuring points and/or LiDAR surveys.

5.2.2 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 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_3 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 S_1 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 may vary from S_1 , however the important feature of this method is that the incremental changes to the well head elevation, S , match the changes in LiDAR elevation L_3 to L_5 .

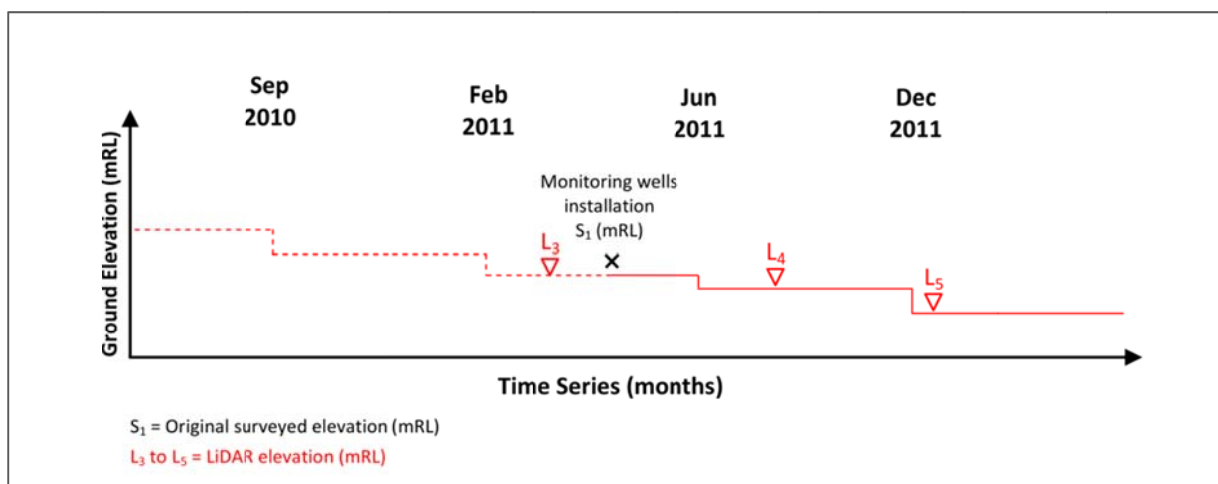


Figure 5.3 Schematic changes in well head elevation, with data from LiDAR surveys.

6.0 MEDIAN WATER TABLE ELEVATION FROM MONITORING WELL DATA

6.1 Selection of data

Stage 1 of the flowchart in Figure 3.1 (Section 3) 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 (in mRL) using a data set from the post-Darfield Earthquake period (i.e. 4 September 2010 – 31 December 2012).

A median was 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 median water elevation for the particular month was used to represent readings for that month. Table 4.1 (Section 4.1) indicates the proportion of wells (from the varying sources) that had at least one monthly reading over the 28 month post-Darfield Earthquake period.

The monitoring wells also have varying availability of monthly readings (Table 4.1). Therefore, the data used to calculate the median for each monitoring well has to be chosen so that it does not bias or skew the results. For example, if 18 monthly readings are available for a well near central Christchurch City, with 12 of the readings from autumn/winter months (wetter) and only 6 readings from spring/summer months (drier), then it is reasonable to assume that an 18-month median calculation could be biased by the fact that there are more wet months in the data set.

6.2 Median water table elevation from wells with longer-term data records (≥ 9 months)

A complete set of monthly readings within the post-Darfield Earthquake period is available for the CCC and ECan monitoring wells described in Sections 4.2 and 4.3. This data has been used to carry out a sensitivity check on the effect of data duration selection within the 28-month post-Darfield Earthquake period. The results of the sensitivity check are presented in Figures D.1 and D.2 (Appendix D).

Figures D.1 and D.2 show different median values for each well, calculated by increasing the number of months (prior to December 2012) used to calculate the median. In each graph the medians are variable for short periods of measurement, but converge towards a single value when a larger number of measurements are used. Where only 9 readings are available within a 12-month period, then the calculated median based on 9 readings is still reasonably representative of the median based on 12 readings, suggesting that a 9 month duration of monitoring is sufficient to account for the seasonal variation over an annual cycle. A similar logic could reasonably be assumed for a 2-year period, where a median based on 24 readings ± 3 months would result in a median value that is representative of a median based on 24 readings, accounting for seasonal variation.

Table 6.1 below summarises the methodology that has been followed regarding data selection for the purpose of calculating a median for each monitoring well. To accompany the summary in Table 6.1, Figure 6.1 is a schematic diagram summarising the typical data series available for the various monitoring well sources.

Monitoring wells with < 9 months data have insufficient readings to be representative of a 1-year period and a different approach is required if these data are to be used (see Section 9). The approach is to estimate a surrogate value that can be used in the calculation of the median water table. Example well types P5 and P6 in Figure 6.1 below indicate examples of wells that would be considered to have a short-term record.

Table 6.1 Selection of data based on monitoring duration.

No. of months since September 2010 for which at least 1 monthly reading is available	Comments
21 – 27 months	Effectively 24±3 months, taken to be representative of a 2-year period. Use 24±3 months to calculate median. Refer to example well type P1 in Figure 6.1 below.
16 – 20 months	Longer than a 1-year period but not enough readings to be representative of a 2-year period. Therefore use up to 12+3 months maximum to calculate median and ignore the earlier months. Refer to example well type P2 in Figure 6.1 below.
9 – 15 months	Effectively 12±3 months, taken to be representative of a 1-year period. Use 12±3 months to calculate median. Example well type P3 in Figure 6.1 below indicates a 9 month data series, but up to 15 months may be used if available.
< 9 months	Not enough readings to be representative of a 1-year period. If end user decides that short-term data record (< 9 months data) is to be used, then the interpolation method specified in Section 9 should be adopted. Refer to example well types P5 and P6 in Figure 6.1 below.

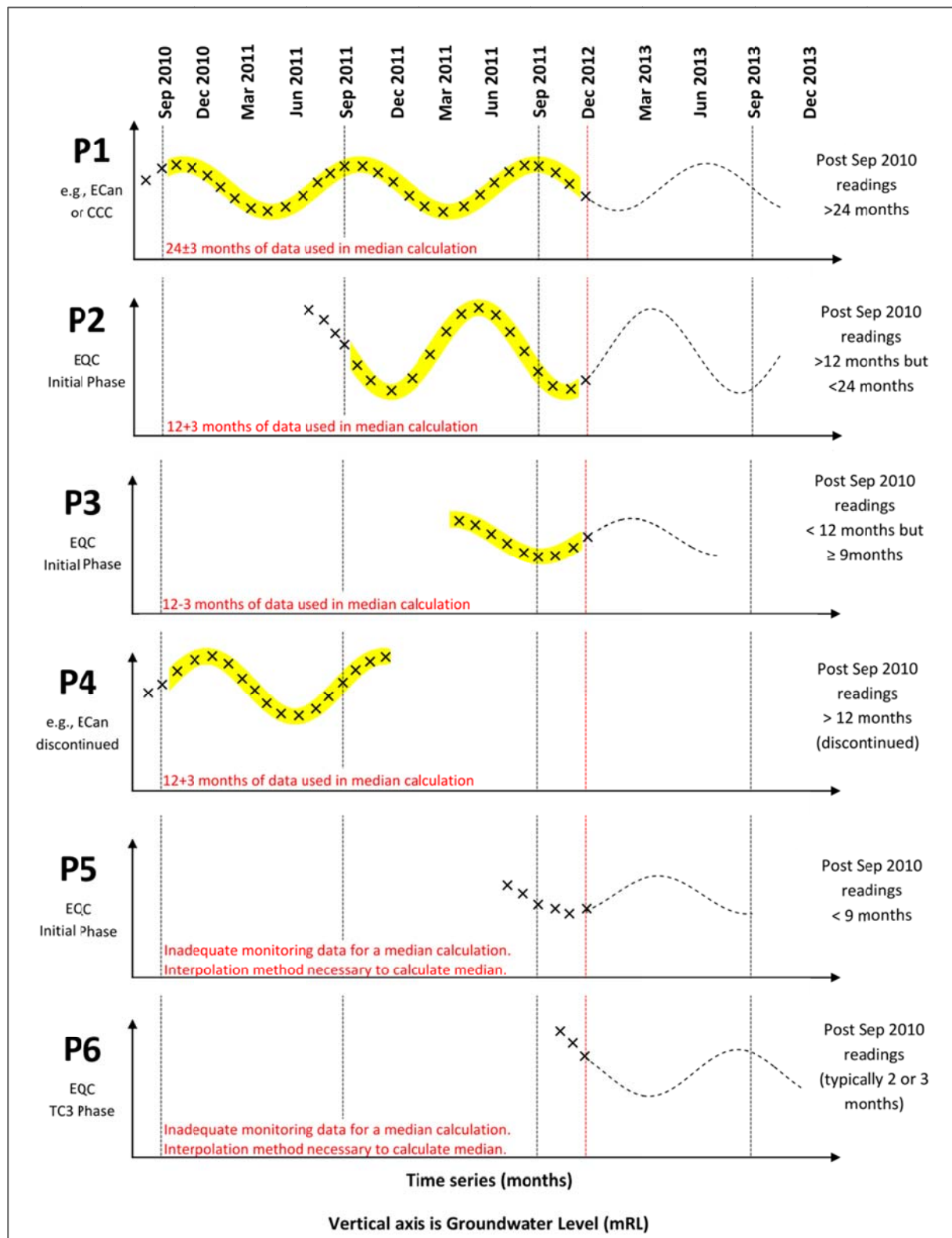


Figure 6.1 Typical range of monitoring duration for various monitoring well sources, and the data duration required to calculate a representative median water table elevation.

7.0 WATER TABLE ELEVATION FROM SURFACE WATER

7.1 Rivers Overview

7.1.1 General

Groundwater and surface water are nearly always linked (White et al., 2001). Within the study area, rivers are both losing to, and gaining from, groundwater. For example, outflow from the Waimakariri riverbed provides a major source of groundwater for Christchurch City (White et al., 2012). However, there are also numerous places within, and near, Christchurch City, where springs emerge to feed the Styx, Avon/Otakaro and Heathcote rivers. These springs were classified by Cameron (1993) as 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 it is possible to use their levels as a proxy for the water table elevation immediately adjacent to the riverbank. However, there are situations, or scales of observation, where such an approach may not be valid, 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. The Waimakariri River, for example, has an unconfined aquifer with groundwater between 1 and 3 m below riverbed (White et al., 2001, 2012), where the difference in levels may be a result of low permeability material in the river bed. 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. The surface water level in these reaches is likely to be slightly lower than the water table due to head loss through the hyporheic zone/streambed.

The scale of the elevation difference between the median river level and the nearby water table is dependent on factors such as the river bank topography or the hydraulic properties of the river bank and shallow aquifer. Differences in the Avon/Otakaro, Heathcote and Styx river elevation relative to the water table do not appear to have been studied in detail, however relevant observations can be found in Cameron’s (1993) MSc study of the Avon/Otakaro River. 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, we expect the difference to be typically less than 1 m. This is a topic worthy of future work, although it should also be noted that the levels of these rivers are complicated by a variety of factors including the Christchurch drainage network, pumping, dewatering activities and tidal flows.

In this study, we have assumed that the changes in shape of the water table are most likely to occur close to the rivers, with either ridges or troughs in the water table where there is recharge or loss of groundwater near rivers, respectively. The approach was to adopt river lines as breaklines in the water table contouring, first by interpolating a median water level between river monitoring stations, then adopting this to represent the median water table elevation along the river profile. River lines were not used to inform the Beca (2004, 2005) study, but were used by Begg & Scott in Brackley (Compiler) 2012.

Data from monitoring stations of the following rivers have been used to contribute to the monitoring well data used to calculate of the median water table elevation:

- Avon/Otakaro River;
- Heathcote River;
- Styx River; and,
- Waimakariri River.

Table 7.1 below summarises the available river level monitoring stations for the four rivers inside the study area. A plan showing the location of the available river level monitoring points is presented in Figure E.1 (Appendix E). River centrelines used in this assessment were obtained from LINZ 1:50,000 topographical maps.

Table 7.1 Summary of river level monitoring stations.

River	Data provider	Number of monitoring points	Monitoring stations that contribute to data set
Avon/Otakaro River	CCC	4	AEB ALA ALB AGL
Heathcote River	CCC	4*	HFM HOP HBX HFE
Styx River	CCC	4	SBL SBK SSP SRF
Waimakariri River	ECan	1 + 47 cross-sections**	Old Highway Bridge (OHB)

*Note: Two additional river monitoring points were available for Heathcote River (HWE and HHA) however these were not used as they were for stormwater/retention ponds

** Note: Since only one useful river monitoring point was available, 47 ECan river cross-sections were also used to add to the data set for the Waimakariri River

7.1.2 Calculation of median values

Data from the river monitoring stations were used to calculate a median water table elevation for each particular gauging station (in m RL) using a data set from the post-Darfield Earthquake period (4 September 2010 until 31 December 2012). Details specific to the various rivers are provided in sections 7.2 and 7.3.

The median water level between river monitoring stations was assumed to increase linearly along the length of river between stations. While this is clearly a simplification, as it does not account for irregular gradients across riffles and pools, the river gradients across the lower Canterbury Plains are very low, so any errors introduced by the simplification are minor (at least compared with the assumption of direct hydraulic connection between rivers and the water table). A 'data string' for the median water elevation along the river profile is then created, and used in the water table modelling as a 'breakline' in Surfer software (Section 8). As noted in Section 1.4, all river level data was converted to the LVD-37 datum.

7.2 Avon/Otakaro, Heathcote and Styx rivers

Monitored river level data for the Avon/Otakaro, Heathcote and Styx rivers were provided by CCC. Levels are recorded at 15-minute intervals at various gauging locations along the length of the rivers. The river levels provided were relative to the Christchurch Drainage Datum (CDD), which is 9.043 m higher than +0.0 mRL. Data from 10 September 2010 until 31 December 2012 were used in order to estimate median water elevation (m RL) along each of the river profiles. Data from 4 river monitoring stations have been used to create the median data strings for each river. The location of the Avon/Otakaro, Heathcote and Styx stations and river strings are illustrated in Figures E.2, E.3. and E.4, respectively, with tables of median water elevation at the monitoring sites (Appendix E).

7.3 Waimakariri River

On the Waimakariri River there is only one monitoring station within the study area - Old Highway Bridge (OHB). Monitored river level data for the Waimakariri River was provided by ECan, in m RL 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, the site has been used by ECan and other organisations for flow modelling.

A set of estimated 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 at the location of the monitoring station 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.

The table in Figure E.5 (Appendix E) summarises the median water elevation (mRL) at OHB and the other 47 locations, from which the median data string was created.

7.4 Coastline

In a manner similar to the rivers, the sea interacts with groundwater. Sea level along sections of coastline on the study area's eastern extent is assumed to be connected to, and directly influence, the water table elevation within the study area. These sections of coastline include:

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

Approximately 950 location points along the coastline have been used in the analysis of the median water table. The assumed mean sea level at each of the points is +0.064 mRL, that, as discussed in Section 1.4, applies a datum correction to mean sea level.

For the purpose of this water table assessment, mean sea level has been taken to represent the median water table level at the coastline location points for the time period that affects the analysis. Tidal shifts of around 1.2 m occur in the study area, but because they are regular and high-frequency and are accounted for by 'mean sea level', they are for the most part not relevant in this assessment. In a coastal dune sand tidal oscillations are completely damped within 400 m of the mid-tide line. Where the water table occurs in material of lower permeability the damping occurs much closer to the shoreline or river channel edge. Sea level rise has not been considered in this report, but it is likely that sea level rise will result in changes to water table elevation in the low-lying coastal areas of Christchurch City in the long-term future. The coastline used in the modelling was taken from LINZ 1:50,000 topographical maps.

8.0 CONTOURING AND REFINEMENT OF WATER TABLE SURFACE

Reference should be made to Stages 2 and 3 of the flowchart in Figure 3.1 (Section 3).

8.1 ‘Surfer’ software

A software program called ‘Surfer 11’ (Golden Software, Inc), henceforth referred to as just ‘Surfer’, has been used to create median water table contours based on the discrete median values of water table elevation (m RL) calculated for monitoring wells, rivers and coastlines, described in Sections 4 to 7.

8.2 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 a median water table 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 water table during the analysis. Studies of groundwater elevation contouring approaches have commonly shown that kriging is generally the best 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 a median water table surface, 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 25m grid has been adopted for this study.

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 we don'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

8.2.1 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 in Appendix F presents a plot of median water table elevation for the monitoring wells (as calculated in Section 6) against 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 not a strong relationship between median water table elevation and ground surface elevation for the majority of monitoring wells (particularly where ground surface elevation is less than 10m RL). Also, there appears to be a break in the trend line for data points with ground elevation above 20 m RL, although above this level there is much less data available.

Given that there is not a strong correlation 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 DEM's from LiDAR surveys, it is an avenue worthy of further research and should be considered for future updates of this report.

8.3 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 to 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 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 surface.

8.4 Surfer output contour plots

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 (continuous lines of water elevation).

After carrying out the kriging analysis in Surfer using this input data, a plot was created that shows the median water table (m RL) as a contour map across the study area. Figure F.2 (Appendix F) is a contour plan of the median water table (m RL) based only on monitoring well locations with 9 months or more of monitoring data and median river level breaklines.

8.5 Manual checking and refinement

Mathematical modelling of surfaces sometimes produces some unexpected and unrealistic results that reflect the distribution of data points rather than reality. In order to check and refine the surface generated to represent the median 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 median water table (m RL) is higher than the LiDAR DEM ground elevation (m RL), that would indicate that the area is 'wet', but where it is known that the water table is below ground. 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 great 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 (Section 3). This included identifying the lowest spot in the wet areas and creating a new median water table 'drawdown point' set at 100 mm below the ground surface. Once remodelled in Surfer, this drawdown 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 plot of the median water table (m RL) was 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 anomalous spikes or hollows in the water table at less than 200 m wavelength.

8.6 Results and observations

The final contour plot of the median water table as an elevation (m RL) is presented in Figure 8.1, based on monitoring well locations with 9 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 8.2, generated by taking the water table surface plotted in Figure 8.1 and subtracting these elevations from ground elevations defined by the Post-Dec 2011 LiDAR digital elevation model. 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). Generated using longer-term monitoring wells, Figures 8.1 and 8.2 are conservative representations of the post-Darfield Earthquake median water table elevation and depth. These are the preferred version of the elevation and depth surfaces (see Section 9.4) until such time as the water table calculation is updated.

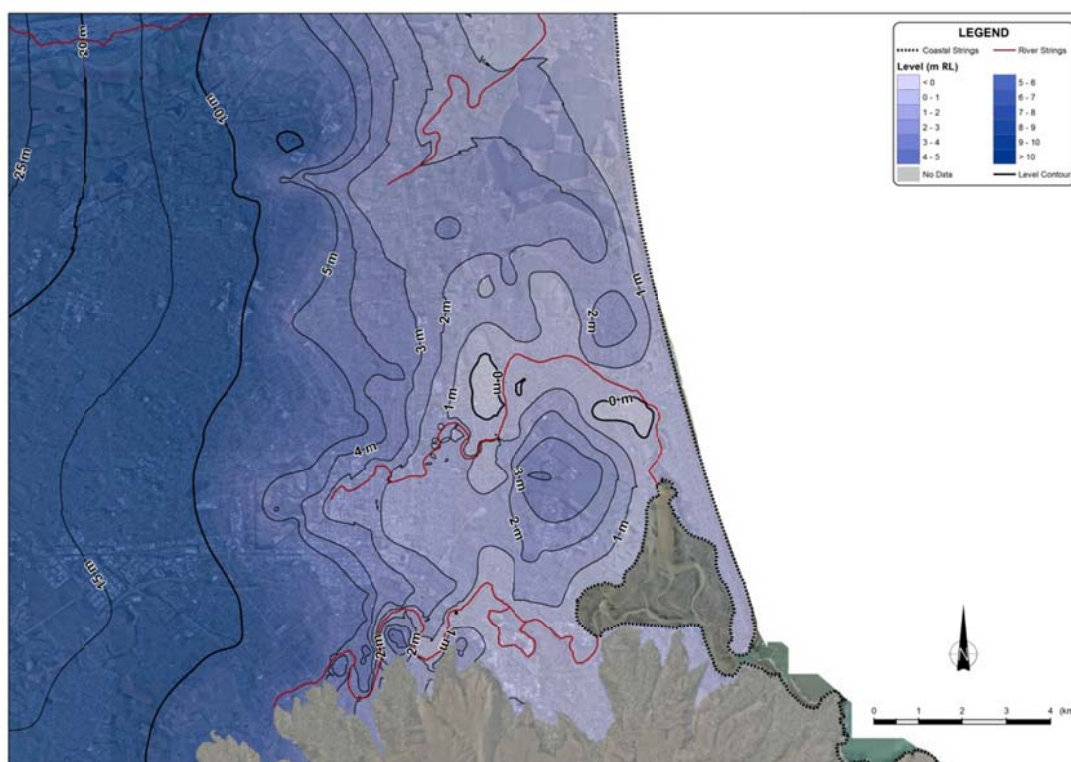


Figure 8.1 The elevation of the post-Darfield Earthquake median water table (preferred model). A more detailed version of the map, showing monitoring wells with longer-term data (≥ 9 months) and drawdown points, is provided in Figure F.3 (Appendix F).

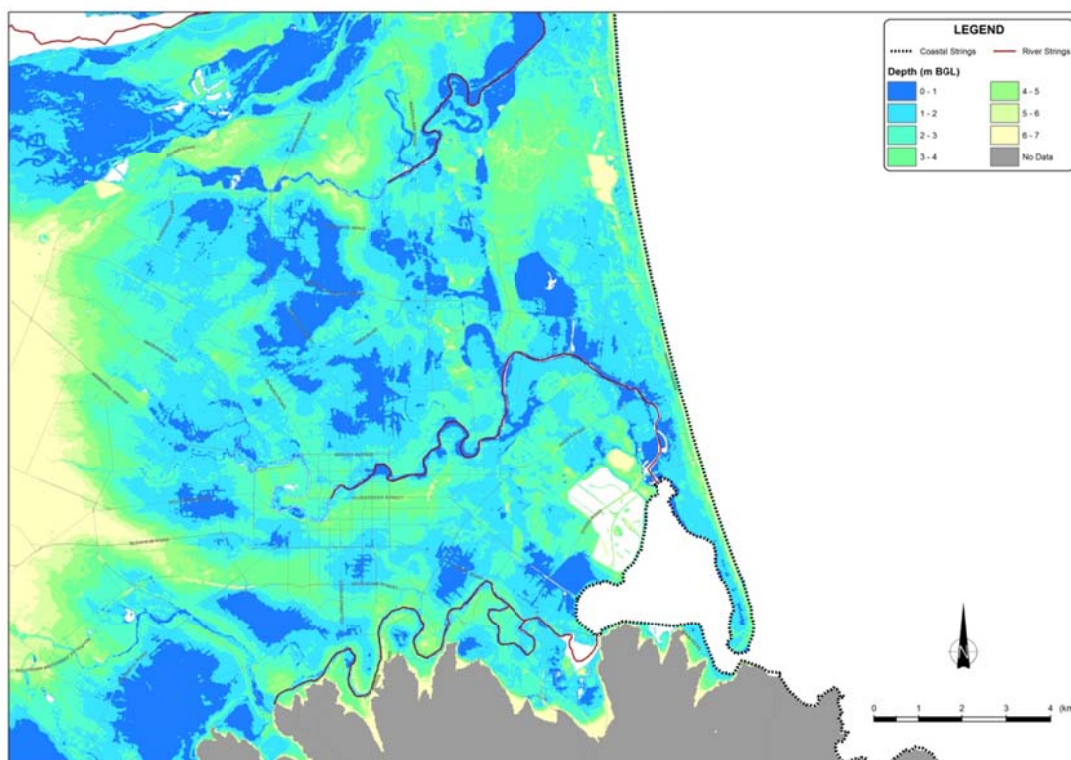


Figure 8.2 The depth of the post-Darfield Earthquake median water table (preferred model). A more detailed version of the map, showing monitoring wells with longer-term data (≥ 9 months) and drawdown points, is provided in Figure F.4 (Appendix F).

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), (< 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 Bexley, where the median water table is also below sea level. Smaller areas where the median water table is depressed below sea level also occur in Avondale, and there are four EQC monitoring wells with < 9 months data in South New Brighton that also show depression of the water table 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 that it reflects head loss through the hyporheic zone/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; Rutter, 2010; Cox et al., 2012).

9.0 USE OF SHORT-TERM MONITORING WELL DATA

9.1 Introduction

Monitoring wells with short-term (< 9 months) data were judged unlikely to have sufficient readings for their median to be representative of a 12-month period (Section 6.2). For this reason, 134 (approximately 20%) of the EQC Initial Phase monitoring wells, and all 122 of the EQC TC3 phase monitoring wells were excluded from the median water table calculated in Sections 6 to 8 (Figures F.2, F.3, and F.4). These wells, referred to as type P5 and P6 wells in Figure 6.1, may provide measurements that are locally important and reduce the spatial uncertainty in the water table. Consequently a surrogate estimation method has been adopted to enable all available data to be utilised, should an end user judge this to be appropriate for the particular design application.

This section outlines a methodology in which short-term groundwater monitoring data (< 9 months) can be 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. The methodology has been applied to provide surrogate median water table elevation values for 134 EQC Initial Phase monitoring wells and 122 TC3 Phase monitoring wells. Surrogate medians were then included in a data set with the longer-term (≥ 9 months) data from other sources to calculate a second water table. The water table calculated with the short-term surrogates is then compared against the water table with only longer-term data as a test of the method.

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 the same methodology using data from nearby monitoring wells to obtain a surrogate median water table elevation for their particular site of interest.

9.2 Calculation of surrogate median water table elevations from wells with short-term data records (< 9 months)

Examples P5 and P6 in Figure 6.1 represent monitoring wells that have less than 9 months of readings since September 2010, but at least one reading per month since installation. There is not enough data for these monitoring wells to enable a median to be calculated which can be reliably taken to be representative of a 12-month period (Section 6, Figures D.1 and D.2). The estimation method relates the P5 and P6 monitoring wells to the P1 to P4 wells (which have a more complete data set and for which a median has already been calculated, as presented in Sections 6 to 8).

9.2.1 Flowchart for estimation of surrogate medians

Figure 9.1 summarises the methodology used to estimate surrogate median water table values using short-term data (i.e. types P5 and P6 monitoring wells).

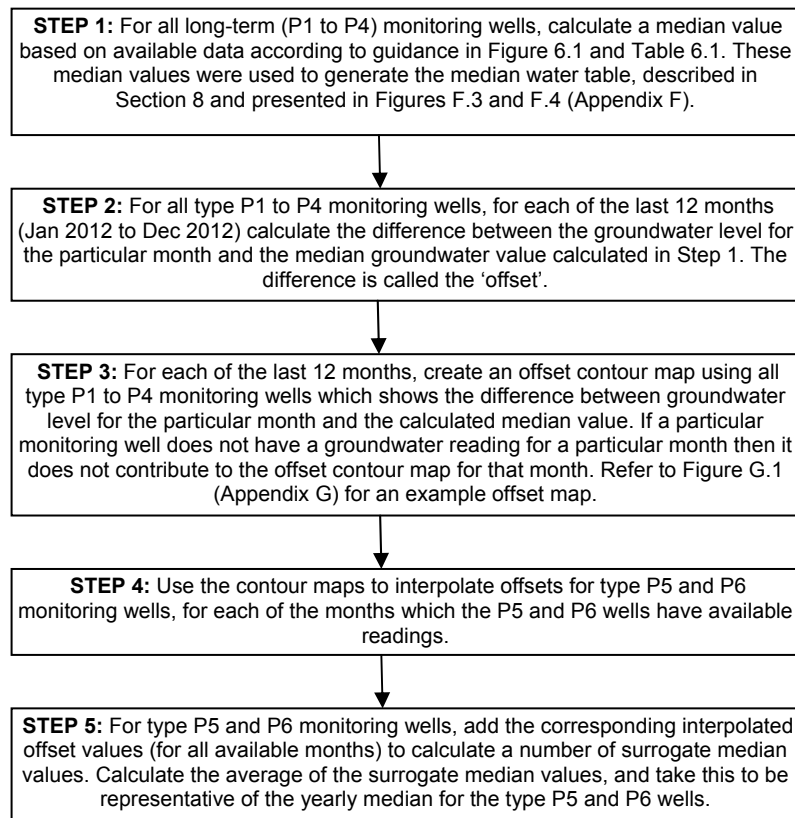


Figure 9.1 Flowchart summarising the method for obtaining surrogate medians of water table elevation for P5 and P6 wells with short-term monitoring records.

9.2.2 Worked Example

A manual worked example of the surrogate estimation method (summarised in Section 9.2.1) is provided below:

STEP 1:

To be carried out on all type P1 to P4 monitoring wells. An example for a P1 well is shown in Figure 9.2 below. The median water table elevation is calculated as described in Section 6 (Table 6.1 and Figure 6.1).

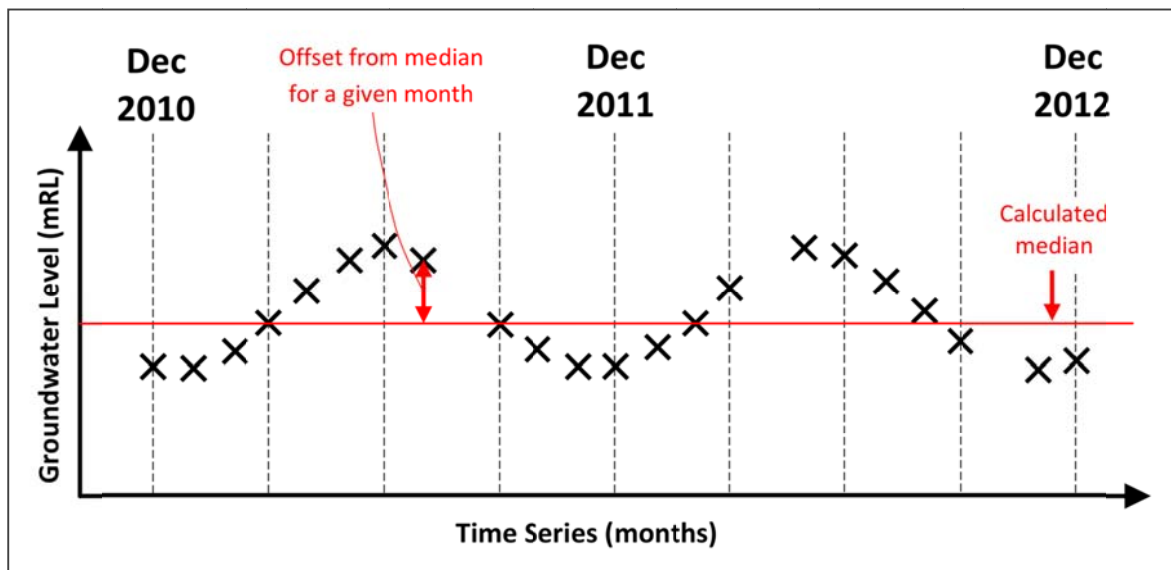


Figure 9.2 Median and offset calculation for a type P1 monitoring well.

STEP 2:

To be carried out on all type P1 to P4 monitoring wells. For each of the last 12 months (where data are available for this particular P1 well) the 'offset' is calculated i.e. the difference between the water table elevation for the particular month and the median value calculated in Step 1. An example for a P1 monitoring well is shown in Table 9.1 below.

Table 9.1 Example offset calculation for a type P1 monitoring well

Month	Offset (m)
Jan 2012	-0.3
Feb 2012	0
Mar 2012	+0.4
Apr 2012	N/A
May 2012	+0.6
Jun 2012	+0.5
Jul 2012	+0.4
Aug 2012	+0.1
Sep 2012	-0.2
Oct 2012	N/A
Nov 2012	-0.4
Dec 2012	-0.3

STEP 3:

Based on the calculated medians for type P1 to P4 monitoring wells, create 12 offset contour maps representing each month of the previous 12-month period. An indicative example is given for one month in Figure 9.3 below. An example of an actual offset grid for December 2012 is provided in Figure G.1.

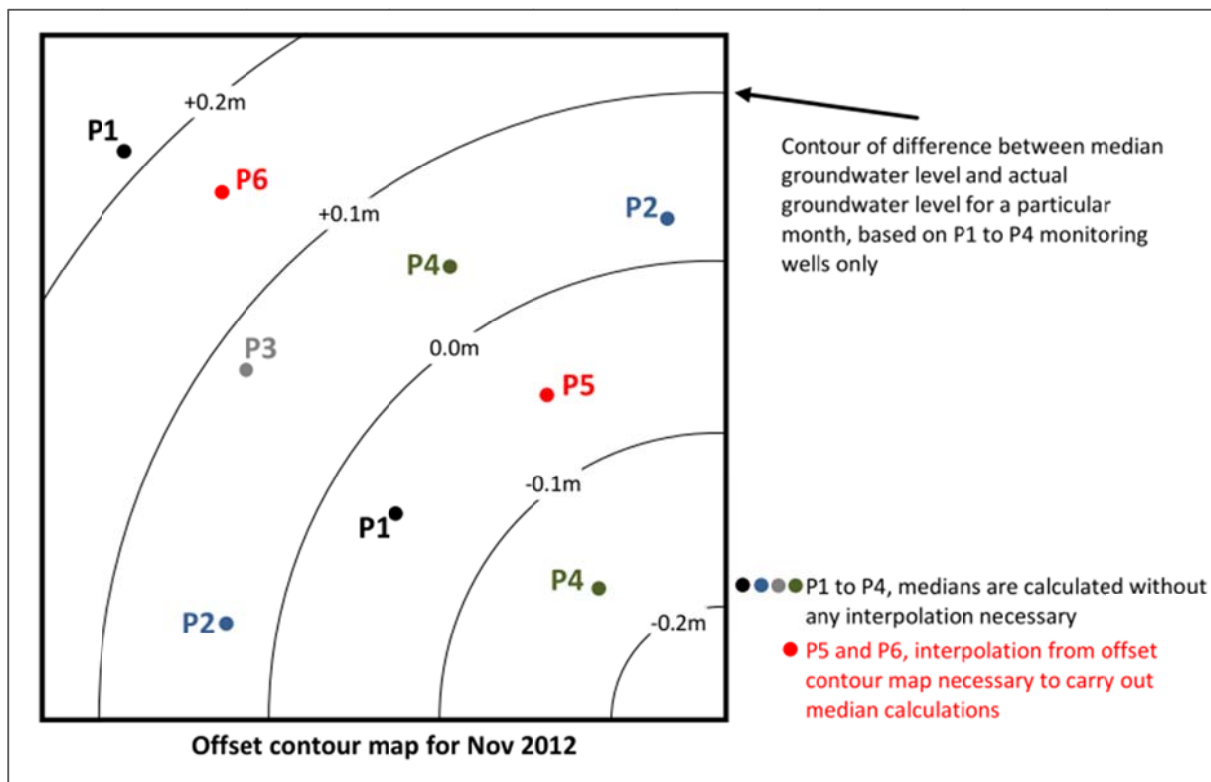


Figure 9.3 Example offset contour map for a particular month.

STEP 4:

Use the set of monthly offset contour maps to interpolate offsets for type P5 and P6 monitoring wells. This is done only for those months where readings are available for the type P5 and P6 wells.

STEP 5:

For type P5 and P6 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 for the particular P5 or P6 well. An example for a P6 monitoring well is shown in Table 9.2 below, for which only three monthly readings are available.

Table 9.2 Example of a surrogate median calculation for a Type P6 monitoring well

Month	Measured P6 water table elevation (m RL)	Offset correction (m) from P1 to P4 wells	Estimated P5 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

9.3 Contouring of median water table including short-term data (< 9 months)

In order to generate contours of the median water table surface which include short-term data (< 9 months), the methodology outlined in Sections 8.1 to 8.4 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 8.5 for manual checking and refinement of the water table was carried out once again on the surface which included short-term data. Drawdown points (black stars) 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 Post-Dec 2011 LiDAR digital elevation model. The location of drawdown points are shown in both Figures G.3 and G.4 (black stars).

9.4 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 (≥ 9 months). This can be seen by comparing Figures G.3 and F.3, which are very similar at the scale of the study area. 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 10). There are a few places where they deviate by > 1 m, which can be seen by comparing the position of the 1 m contours in Figures G.3 and F.3.

There are six places, all of approximately 1 km² or less, where the water table using short-term data are more than 0.5 m **below** the surface calculated using longer-term data. These are:

1. Avonside between Breezes Rd, Wainoni Rd and Avonside Drive;
2. North New Brighton between Keyes Rd, New Brighton Rd and Bower Ave;
3. Shirley near the intersection of Shirley Rd and Marshland Rd;
4. The CBD between Oxford Tce, Barbados St, Fitzgerald Ave and Kilmore St;
5. The CBD between Cambridge Tce, Montreal St and Gloucester St;
6. Halswell-Hoon Hay, between Halswell Rd and Sparks Rd.

There are also six places of approximately 1 km² or less, where the water table calculated using short-term data are more than 0.5 m **above** the surface calculated using longer-term data. These are:

1. The CBD between Kilmore St, Salisbury St, Barbados St and Colombo St;
2. Addington between Oxford Tce, Brougham St, Selwyn St and Colombo St;
3. Halswell-Hoon Hay, between Halswell Rd and Sparks Rd;
4. Linwood between Ferry Rd, Hargood St, Linwood Ave and Smith St;
5. Burwood near the intersection of Burwood Rd and Lake Terrace Rd;
6. Northwood near the intersection of Talbot Rd and Northwood Blvd.

Until more data have been collected from monitoring wells at these places, there is a lack of certainty whether the difference reflects short-term departures or the long-term position of the post-Darfield Earthquake median water table in these areas. Significantly, these are relatively small areas in which the short-term data are both positively and negatively anomalous, and is not a straightforward lowering (or raising) of the water table caused by a relatively wet (or dry) period.

There are strengths and weaknesses in both calculation methods. The authors preferred median water table is the more-conservative version developed with longer-term data, river breaklines, coastal data strings and drawdown points (Figure 8.1 for water table elevation, or Figure 8.2 for depth to water table – see also Figures F.3 and F.4, Appendix F). End users may decide the median water table using short-term data (< 9 months) and surrogates is more appropriate, depending on the specific engineering requirements and local site observations.

9.5 Confidence index for water table elevation

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 (Section 10). 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 hotly 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.5, 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 low, medium and high confidence in the water table elevation.

The confidence index is as follows:

- low ≤ 1
- medium > 1 and < 7
- high ≥ 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 or river/coastal breakline is assigned a confidence value that depends on the monitoring duration (Table 9.3). The thresholds between high - medium - low confidence levels should by no means be considered to be quantitative. Instead they are subjective, based on the judgement and experience of the authors for the Christchurch setting. High confidence values do not necessarily mean that the values at those points are precise or accurate, just that there is a higher level of confidence in the median water table elevation at those points based on the length of the record and proximity to monitoring wells, rivers or the coast.

An example (Figure 9.4) 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 9 months of data and a confidence value of 8. The other well has 8 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 9.4, 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 and there is a greater degree of uncertainty in the use of river elevation data (see Section 7).

Table 9.3 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 – 2 months available data	2	1 per 25m
Monitoring well, 3 – 5 months available data	4	1 per 25m
Monitoring well, 6 – 8 months available data	6	1 per 25m
Monitoring well, 9 – 20 months available data	8	1 per 25m
Monitoring well, 21 – 28 months available data	10	1 per 25m
Coastal line	10	1 per 25m
Avon/Otakaro River	8	1 per 10m
Styx River	8	1 per 10m
Heathcote River	8	1 per 10m
Waimakariri River	6	1 per 10m

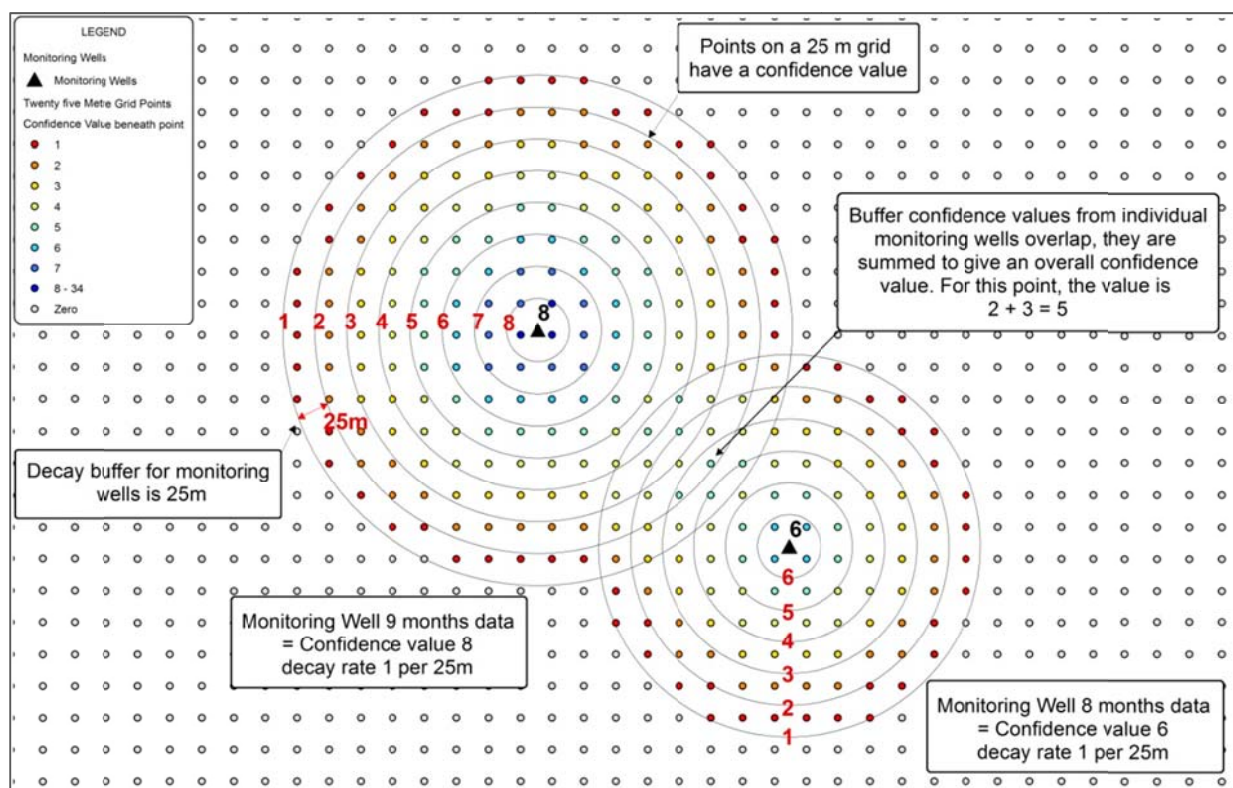


Figure 9.4 Example diagram for calculation of overall confidence value.

The confidence map in Figure G.5 (Appendix G) includes EQC wells with short-term (< 9 months) data (as at 31 Dec 2012), 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.5 indicates that the confidence index is high (overall confidence value ≥ 7) in areas where monitoring wells with > 9 months data are in close proximity to one another, and where they are close to rivers and sections of coastline. Areas of low confidence index (overall confidence value ≤ 1) 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 will change and the confidence in the median water table elevation will increase.

10.0 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 fluctuations and future variability in this water surface in order to inform engineering and planning for the future. Unfortunately, the post-Darfield Earthquake data record is short and may not encompass all of the potential influences, for example, seasonal and annual variations in rainfall such as might be caused by El Nino-La Nina conditions. There are, however, extensive records of natural fluctuations from pre-earthquake monitoring.

The purpose of this section is:

- to examine the variability 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 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 assume 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 the water table position has changed.

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 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 slightly in position with time, depending on the balance between recharge and outflow. The location of the transition zone helps define the hydrogeological boundary between the Inland and Eastern/Coastal zones (Weeber, 2008 – see also Section 3 above). The shallow water table in eastern Christchurch City occurs above an aquitard of fine marine/estuarine sediment (Christchurch Formation), with groundwater at artesian pressures in confined aquifers at greater depths below.

Continuous monitoring of groundwater levels has been carried out for extended periods by both CCC and ECan. Elevation of the water table has been recorded in relatively shallow wells (to depths of 10 m) at weekly-fortnightly intervals by NIWA for CCC. In contrast, ECan records both 15 minute and monthly data and although their monitoring is mostly aimed at the deeper Springston Formation (Aquifer 0) and Riccarton Gravels (Aquifer 1), it also includes some shallow wells and monitoring of the water table in the Christchurch Formation. Data records and information for individual monitoring wells can be viewed through ECan's online well-card facility².

10.1 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 its groundwater is 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. The standard deviation obtained at each site, shown in Figure H.3 (Appendix H), is a more-complete way to represent the data distribution. A simple kriging of the standard deviation is also shown in Figure H.3, with contours at 0.2 m intervals, in order to interpolate for areas between the wells.

² <http://ecan.govt.nz/services/online-services/tools-calculators/Pages/well-card.aspx>

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 10.1.

Table 10.1 Monitoring wells selected for detailed assessment of 1990-2010 variability of shallow groundwater levels. A selection of both parametric and non-parametric statistics are provided.

ID	Well No	E_NZMG	N_NZMG	Length	Start	Mean (m RL)	Median (m RL)	Max (m RL)	Min (m RL)	Std Dev (m)	n	Range (m)	85th%tile (m RL)	15th%tile (m RL)	Difference 85th%tile- Median (m)
AAY	M35/5413	2474888	5746274	20 year	17/09/1990	18.58	18.45	20.26	17.58	0.51	769	2.68	19.13	18.15	0.68
ARC	M35/5420	2476456	5741774	20 year	17/09/1990	12.49	12.54	13.34	11.40	0.37	762	1.94	12.87	12.08	0.33
HHM	M36/5719	2475139	5739342	18 year	13/04/1992	15.60	15.56	16.67	14.91	0.29	697	1.76	15.89	15.32	0.33
HHL	M36/3168	2475213	5736871	20 year	17/09/1990	12.75	12.77	13.93	11.35	0.48	1005	2.58	13.32	12.27	0.55
HSH	M36/5709	2476043	5736070	18 year	13/04/1992	10.44	10.46	11.35	9.66	0.30	927	1.69	10.75	10.09	0.29
SDA	M35/5425	2485451	5755547	20 year	3/09/1990	0.69	0.67	1.47	-0.08	0.27	764	1.55	0.98	0.43	0.31
ACR	M35/5422	2479901	5745517	18 year	3/02/1992	5.46	5.47	5.80	5.12	0.06	706	0.68	5.52	5.41	0.05
ABI	M35/5412	2484098	5744055	20 year	24/09/1990	0.70	0.67	1.49	0.45	0.14	770	1.04	0.83	0.58	0.16
AWO	M35/5407	2484382	5742416	20 year	24/09/1990	2.11	2.09	2.89	1.69	0.16	766	1.20	2.29	1.97	0.20
HGO	M36/3175	2484854	5739149	20 year	24/09/1990	0.51	0.51	0.90	0.14	0.13	766	0.76	0.63	0.38	0.12

10.1.1 Inter-annual variability

Figure H.4 (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 have greater variability in water table elevation than those in the Eastern/Coastal Zone (Figure H.4). The inter-annual variability, being the range in water table elevation for any particular week or month during the 20 year period, is greatest in AAY, ARC and HHL where it is around 2 m. The inter-annual variability in the Eastern/Coastal Zone wells is less pronounced, being less than 1.2 m and is less than 0.5 m in well ACR. There is very little variability 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.5 (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 have their 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 influenced equally to the same external influences. ACR stands out as anomalous. In a number of wells the water table fluctuations seem 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, although heavy rainfall caused localised surface flooding in April and November 2011 and August 2012. 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).

10.1.2 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 is particularly pronounced in wells HHL and HSH in Figure H.4, but most show at least some weak seasonal variation. The seasonal variability is around 1 m in the monitoring wells of the Inland Zone, whereas it is 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).

10.2 Earthquake-related fluctuations and changes

10.2.1 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 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 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 km³ - 1999 M7.5 Chi-Chi earthquake in Taiwan (Wang et al., 2004); 0.5 km³ following the 1959 M7.5 Hebgen Lake earthquake (Montana, USA) and 0.3 km³ following the 1983 M7.3 Borah Peak earthquake (Idaho, USA) (Muir-Wood & King, 1993).

10.2.2 Canterbury aquifer responses

In the first systematic review of earthquake-induced hydrological responses in New Zealand, Cox et al. (2010) 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. (2010) 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 (see Figure A.3, Appendix A). Cox et al. (2010) 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_w 6.2 Christchurch 1 Earthquake on 22 February 2011 was a shallower event, centred closer to the city and directly beneath the confined coastal aquifer region. Unpublished preliminary work suggests substantially greater pressure increases occurred in confined aquifers beneath Christchurch City during this earthquake than during the M_w 7.1 earthquake, with changes of up to 8 m (80 kPa) followed by falls to new decreased groundwater levels (ECan 2011a; Gulley et al. in prep). 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_w 7.1 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 (ECan 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 at depth have potential to affect the position of the shallow water table.

10.2.3 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 4 September 1990 to 4 September 2010 were compared with a 'post-Darfield Earthquake' period of 4 September 2010 to 31 December 2012 in 55 ECan and CCC monitoring wells (Figure H.1, Appendix H). Examples of water table elevation fluctuations are provided in Figures H.6 and H.7 (Appendix H), with examples of both significant changes in water table elevation and no change in elevation. Water table elevation in Figure H.6 is represented 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.

The data have been assessed in three ways: (a) a comparison of pre- and post-Darfield Earthquake elevation of the water table, plotted according to the Julian Day (numbered 0-365) (e.g. Figure H.6 – left side); (b) time series records (e.g. Figure H.6 – right side); (c) comparison of the post-earthquake median, range, 5th, 15th, 85th and 95th percentiles, or mean and standard deviation, with equivalent non-parametric and parametric statistics for the pre-Darfield Earthquake period (1990-2010), to highlight wells where statistically notable changes had occurred.

Table 10.2 presents a summary of potential earthquake-related responses, or lack of them. The majority of wells show no significant long-term change in weekly-monthly data, and short-term fluctuations were observed in 5 wells, but their values of water table elevation returned to pre-Darfield Earthquake levels within the period of one or two measurements. The sharp rises in water table 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_w 6.2 Christchurch 1 Earthquake. While it is possible shorter and/or transient water table elevation responses may have occurred in all wells, there is no evidence to suggest the median water table elevation has been demonstrably affected in 43 out of 55 well locations.

Table 10.2 Summary of earthquake-induced changes of water table elevation observed in shallow CCC and ECan monitoring wells.

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

The four wells that show significant and definitive earthquake-related changes are ABI, AWO, HGO and HLR, all located in the Eastern/Coastal Zone. Post-Darfield Earthquake water table elevation (red) in these wells are mostly below pre-Darfield Earthquake elevation (green) (Figures H.6 and H.7), although record maximum, or near-maximum elevations were recorded 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 increased in these four wells.

A more detailed view of the ABI, AWO, HGO and HLR water table elevation data (Figure H.8, Appendix H) 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, changing in cumulative elevation by -0.5, -0.3 and -0.4 m respectively, whereas at HGO it has been uplifted +0.2 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 decreases in median water table elevation (ABI -0.6 m; AWO -1.1 m; HGO -0.5 m; HLR -0.7 m) are almost twice the cumulative changes in ground elevation at each site.

The major change in ABI water table elevation occurred in September 2010 after the first Darfield Earthquake, whereas the decreases in AWO, HGO and HLR occurred after the February 2011 Christchurch 1 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.). The new 'post-Darfield Earthquake' median water table elevation in AWO is at sea level, which is also the mean elevation of the Avon/Otakaro River nearby. At times there are slightly negative values representing water table elevation below mean sea level, this could be explained by various factors, including: measurements made at low tide; effects of local pumping; the level of uncertainty in water table elevation measurement or measuring point surveys; and/or post-earthquake drainage/dewatering work. For a period of time, the water table elevation in AWO was (anomalously) below mean sea level, that was caused by dewatering being performed for the nearby sewer repair work on Woodham Road between June 2011 and March 2012 (T. Borkus, SCIRT, pers. comm.). As the period of dewatering is comparatively short compared with the total post-Darfield Earthquake period, this did not significantly lower the post-Darfield Earthquake median. Data collected during dewatering was not removed from the calculation. AWO is situated in Linwood, around 700 m from the Avon/Otakaro River whereas HGO in Woolston and HLR in Opawa are both situated around 100 m from the Heathcote River.

The four wells showing persistent earthquake-related changes in water table elevation appear to decrease to new post-Darfield Earthquake median water table elevations that correspond to nearby base levels, being either sea level or a nearby river level. ABI, AWO, and HGO occur in areas where the ejection of liquefaction material was extensive. One possible explanation 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 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 has decreased at these four sites. What is yet to be demonstrated is whether or not this is a site specific or more widespread phenomenon. If the phenomenon is 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 requires more detailed investigation.

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

- HHM in Wigram has experienced some abrupt water table elevation decreases since August 2012 to record low levels ~14 m (Figure H.6), that may be transient pumping or engineering improvements to local drainage. Again there has been major waste water repair work in close proximity to this observation well, that may have affected the local water table elevation. Since the period of dewatering was very short compared with the total post-Darfield Earthquake period, inclusion of these data have only a very minor lowering of the post-Darfield Earthquake median elevation for this site.
- SDA in Brooklands showed a short-term increase in water table elevation following the Darfield Earthquake in September 2010, then it fell to sea level (Figure H.7). The water table remained at sea level until the February 2011 Christchurch 1 Earthquake, when experienced another transient increase elevation before rising and settling about a new median at 0.52 m. The change in median water table elevation, being a 0.15 m drop from 0.67 m to 0.52 m, is nearly equivalent to the 0.21 m subsidence in ground elevation indicated by LiDAR survey during the earthquake sequence at this site.
- XRU has shown significant post-Darfield Earthquake variability, with larger seasonal fluctuations than those experienced in the past decade (Figure H.7). It now has a median water table elevation slightly lower than in the past decade, but similar to the elevation and variability from 1990-2000. Detailed knowledge of site conditions would be required to understand whether the earthquake has influenced the water table in this monitoring well. The monitoring point is very close to the oxidation ponds, that are known to have been severely damaged by the earthquakes, and this may possibly account for some of the observed changes.
- M35/7896 (not shown) had much sediment in the well that was flushed in 3 May 2011. The water table has since dropped significantly to a new record low elevation. The water table elevation could have been affected by well damage and repair.
- M35/8968 at McLeans Island near Waimakariri River is a 7.6 m deep well in which the water table has become progressively lower with time, reaching record low levels during Mar-May 2012 (not shown). The post-Darfield Earthquake median water table elevation is distinctly lower than the pre-Darfield Earthquake median, but this may reflect Waimakariri River flow (White et al., 2012), natural shifts in the position of Waimakariri river channels and/or groundwater flow. The hydrogeology in the vicinity of McLeans Island is known to be complicated (Weeber, 2008; White et al., 2012).
- Three wells in the Kaiapoi region (M35/0601, M35/0724, M35/6507) recorded anomalously high water table elevation during August 2012 that are potentially influenced by human- and/or earthquake-related change to Kaiapoi River. They warrant further investigation with a detailed knowledge of activities in the area.

10.2.4 Summary of earthquake-related effects

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

- Extended (decadal) monitoring records available for most ECan and CCC wells do not show evidence of any significant persistent change in median elevation of the water table as a result of the earthquake.
- 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 fortnightly monitoring could easily have missed short-term fluctuations.
- There are only four monitoring wells (ABI, AWO, HGO and HLR) where definitive earthquake-related changes occurred. 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., 2010; Gulley et al., in prep).
- The lowering of the median water table in these four wells is almost 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 or stayed the same relative to sea level, but such changes could be obscured by inter-annual variability.
- In these four wells 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). However, in all cases water table elevations near the pre-Darfield Earthquake maximum occurred during winter 2012 in the post-Darfield Earthquake period. It is possible the range and variability of water table surface at these sites has also changed.
- Lowering of the water table was not a widespread phenomenon, observed in only four wells. 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 localised or widespread within areas of major ground damage.

10.3 Implications for median water table

Groundwater levels in Canterbury are not static but fluctuate due to variations in rainfall and river recharge. 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 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, or even amounts of water abstracted.
- there may also be earthquake-induced changes in the specific yield or permeability of the shallow deposits, (as proposed at wells ABI, 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).
- 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 (Figure H.2) 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 variability (around 2 m) than seasonal variability (around 1 m). Wells in the Eastern/Coastal Zone fluctuated less, but inter-annual variability (around 1.2 m) was similarly greater than the seasonal variability (0.5 m). Relatively few persistent changes can be directly attributed to earthquakes, with four wells in the Eastern/Coastal Zone showing water table lowering of 0.5-1.0 m. The water table derived in this study is therefore 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), not surprisingly showing similarity with the map pattern of standard deviation (Figure H.3). If it is accepted that fluctuations in the pre-Darfield Earthquake data are representative of future variability, Figure H.9 can be used with the post-Darfield Earthquake median water table elevation (Figure F.3) to approximate the future probability of a certain groundwater level being exceeded (until longer post-earthquake records become available).

11.0 SUMMARY

11.1 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 since the 4 September 2010 M_w 7.1 Darfield Earthquake. The study covers an area between Prebbleton in the southwest, Swannanoa in the northwest, and the coastline in the east. There has been widespread installation of monitoring wells following the earthquakes, providing a significant improvement in the spatial density of water table information.

Data from monitoring wells was obtained from Christchurch City Council (CCC), Environment Canterbury (ECan), and geotechnical investigations for the Earthquake Commission (EQC). The duration 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 806 shallow monitoring wells were obtained from Christchurch City Council (CCC), Environment Canterbury (ECan) and geotechnical investigations carried out for the Earthquake Commission (EQC). 550 monitoring wells had records of nine months or longer from which a representative median water table elevation was determined for each site. 256 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 31 December 2012). 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 was 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. Monitored river level data for the Avon/Otakaro, Heathcote and Styx Rivers was provided by CCC, and river level data for the Waimakariri River was provided by ECan. Duration of monitoring data for the rivers varied from 15-minute to 6-hour intervals. 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 not a strong correlation 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. Since the 'default' and 'custom' variogram options within Surfer predicted the known water table elevation at well locations accurately, and visually the contours generated were hydrologically reasonable, the default variogram option was used for the purpose of kriging the contoured median water table 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 km² have been identified where the difference exceeds this threshold. The post-Darfield Earthquake surface developed from longer-term data (≥ 9 months), river breaklines, coasts and drawdown points (Figures 8.1 and 8.2) is conservative and preferred by the authors, but there are strengths and weaknesses in each of the water table calculations. End users may decide the median water table using short-term data (< 9 months) and surrogates is more appropriate, depending on the specific engineering requirements and local site observations.

Groundwater levels in Canterbury fluctuate due to inter-annual and seasonal variations in rainfall and river recharge. Data obtained since the Darfield Earthquake demonstrates that such events can also impact on the water table elevation. The full range of natural fluctuations may not have been observed during the relatively short 'post-Darfield Earthquake' period used in this study. It has been assumed that variability of the water table elevation during the 20 years prior to the earthquakes will be a useful indicator of future behaviour. A comparison of pre- and post-Darfield Earthquake data in the 55 wells indicates the water table was unaffected by the earthquakes in most places, 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; but only four showed persistent change, which was a 0.5-1.0 m lowering of the water table to a new base level and median value. Until such a time as more data become available and the post-Darfield Earthquake calculations updated, the pre-Darfield Earthquake data are a useful proxy of variability, providing a measure of expected fluctuations from the water table median surface. 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 to 2010. Variability 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 for the 1990-2010 period, indicating levels exceeded 15% of the time, are typically greater than 1 m above the median to the west of Christchurch City but less than 0.4 m above the median in the east of the city.

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 also consider the temporal and spatial reliability of the median water table elevation and depth maps (and whether or not additional site-specific groundwater investigations are required) and whether the use of these maps is 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 low, medium and high confidence in the water table maps. Variations in the elevation of the water table, including both seasonal and inter-annual fluctuations, may also need to be considered.

11.2 Recommendations for next version

It is intended that this report and accompanying data sets will be re-issued periodically to reflect ongoing groundwater monitoring of existing wells as well as monitoring of additional wells that will be installed during the rebuilding of Christchurch City.

The median water table surface might be improved by:

- incorporating data from as many monitoring wells as possible, in particular those monitoring wells that had < 9 months worth of data as at December 2013 (Section 9), but whose records will presumably be sufficiently long to incorporate seasonal variation for future versions of the report;
- exploring the option of co-kriging, whereby the ground elevation helps inform the interpolation of the water table surface (Section 8.2.1). 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 7.1). 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. Once the relationships have been established, a correction might need to be applied to river level elevations used as breaklines in the contouring. It may then be worthwhile adjusting the river profiles between gauging stations using LiDAR elevations along the river banks, rather than using a simplified linear interpolation between river level monitoring sections;
- understanding whether the earthquake-induced fall of the water table observed in monitoring wells ABI, AWO, HGO and HLR (Section 10.3) 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 10.1). 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-Darfield Earthquake data sets into calculations it may be possible to improve confidence in the future position of the median water table surface.

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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.
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.

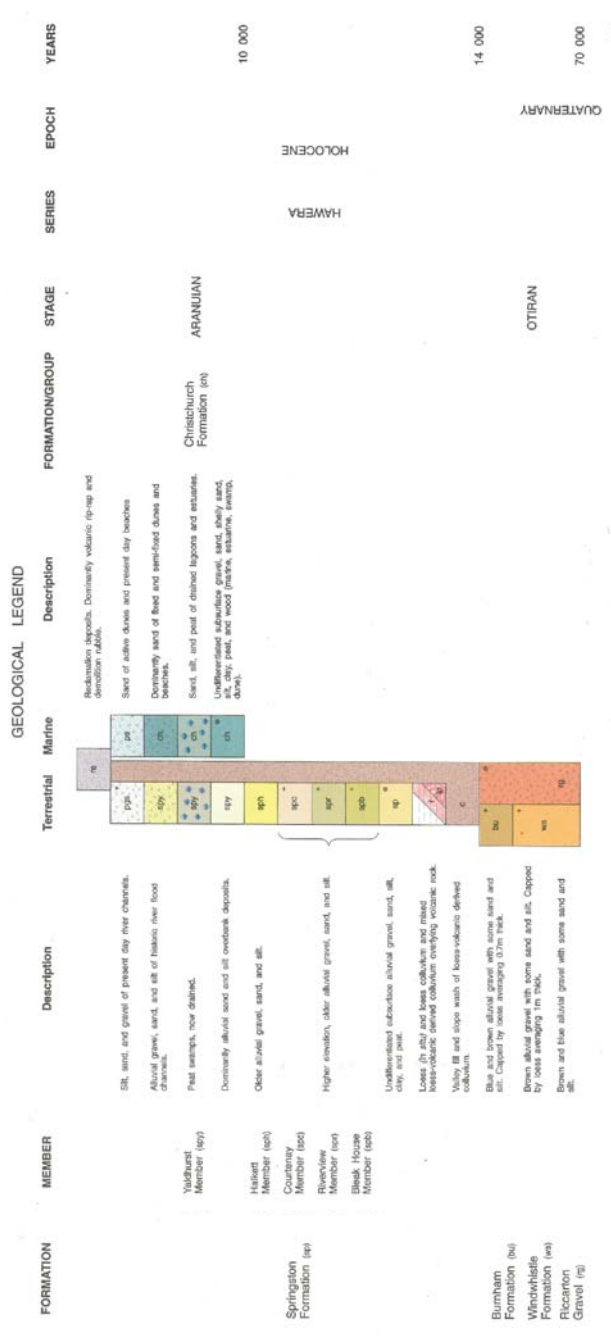
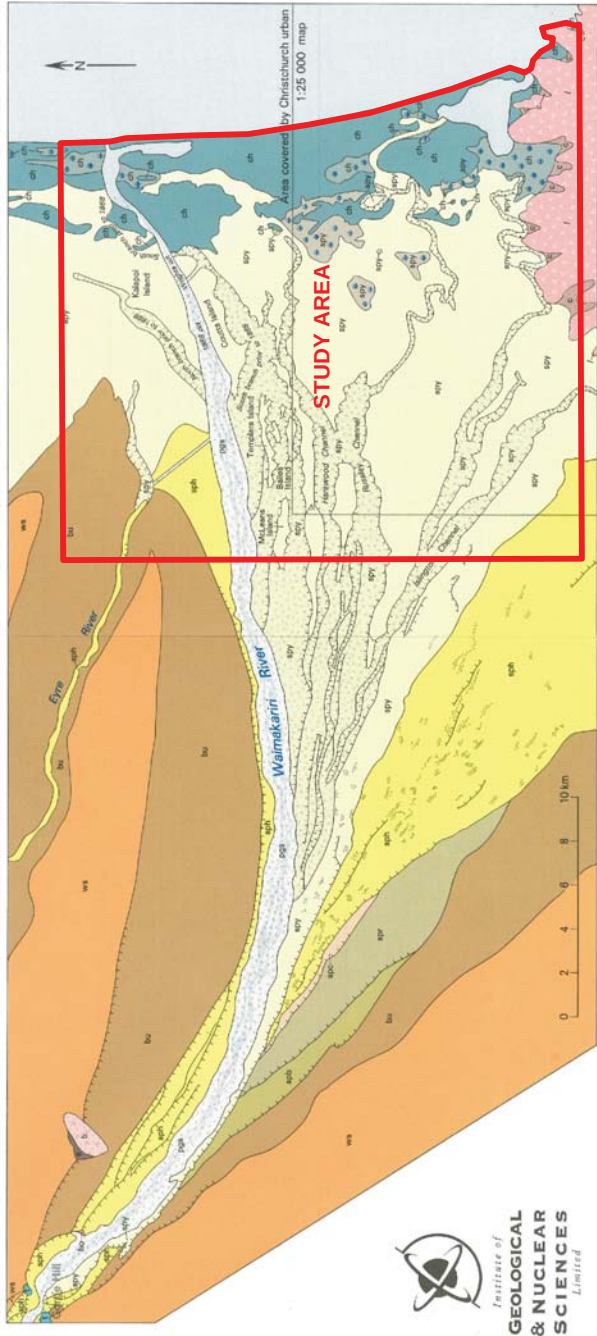
Groundwater depth	Depth to the water table (or another potentiometric surface) at a particular place or in a particular area, measured relative to the level of ground at that place.
LiDAR Light Detection and Ranging	A method and instrument that measure distance to a reflecting object by emitting timed 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.
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).
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.
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 December 2012, 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'.
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.
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 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.

APPENDICES

APPENDIX A: BACKGROUND FIGURES

- **Figure A.1** Extract from geological map of Christchurch area
- **Figure A.2** Schematic geological cross-section of aquifers
- **Figure A.3** Christchurch Groundwater Protection Zones
- **Figure A.4** Earthquake epicentres, 4 September 2010 – 4 April 2012



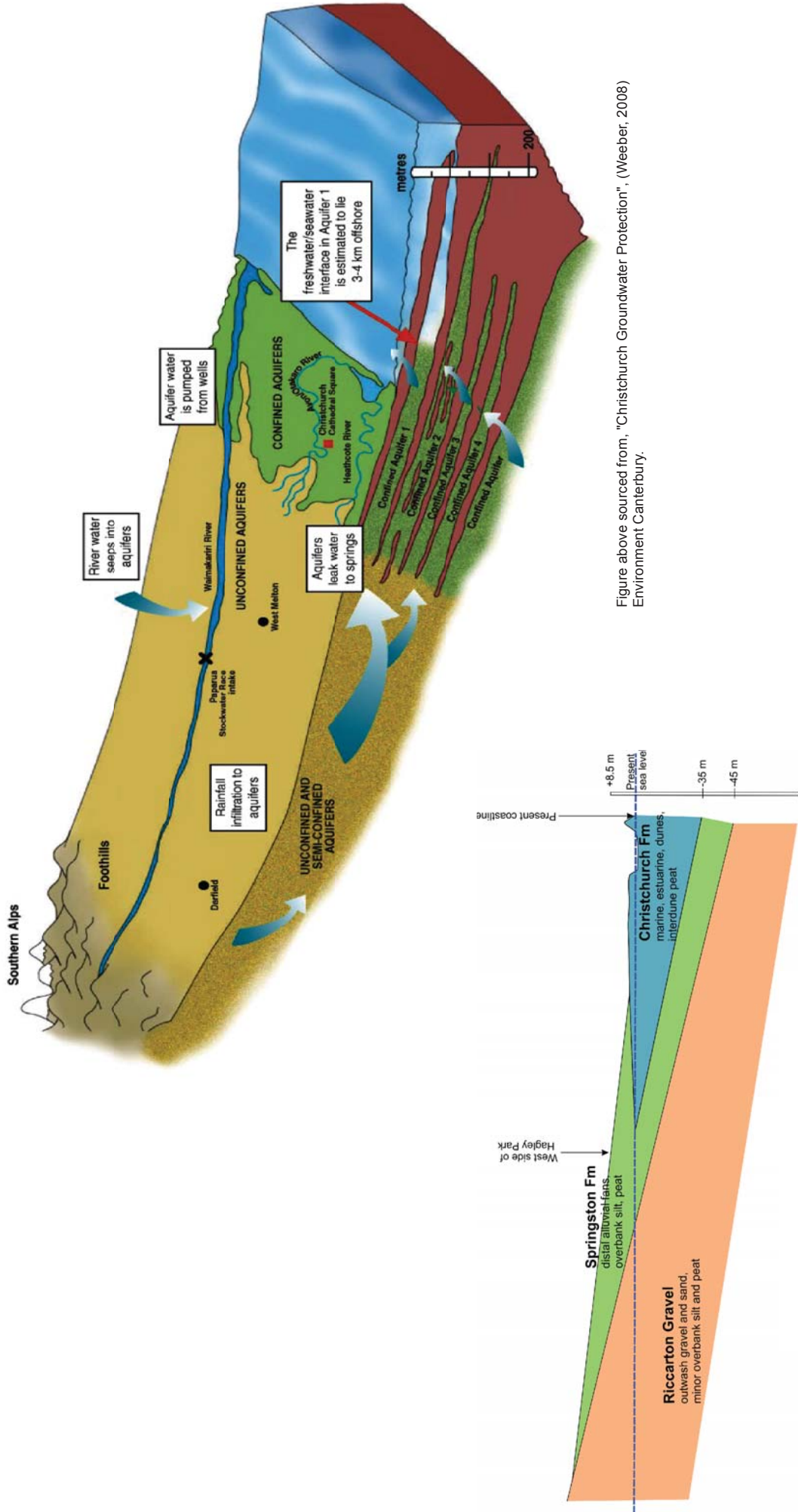


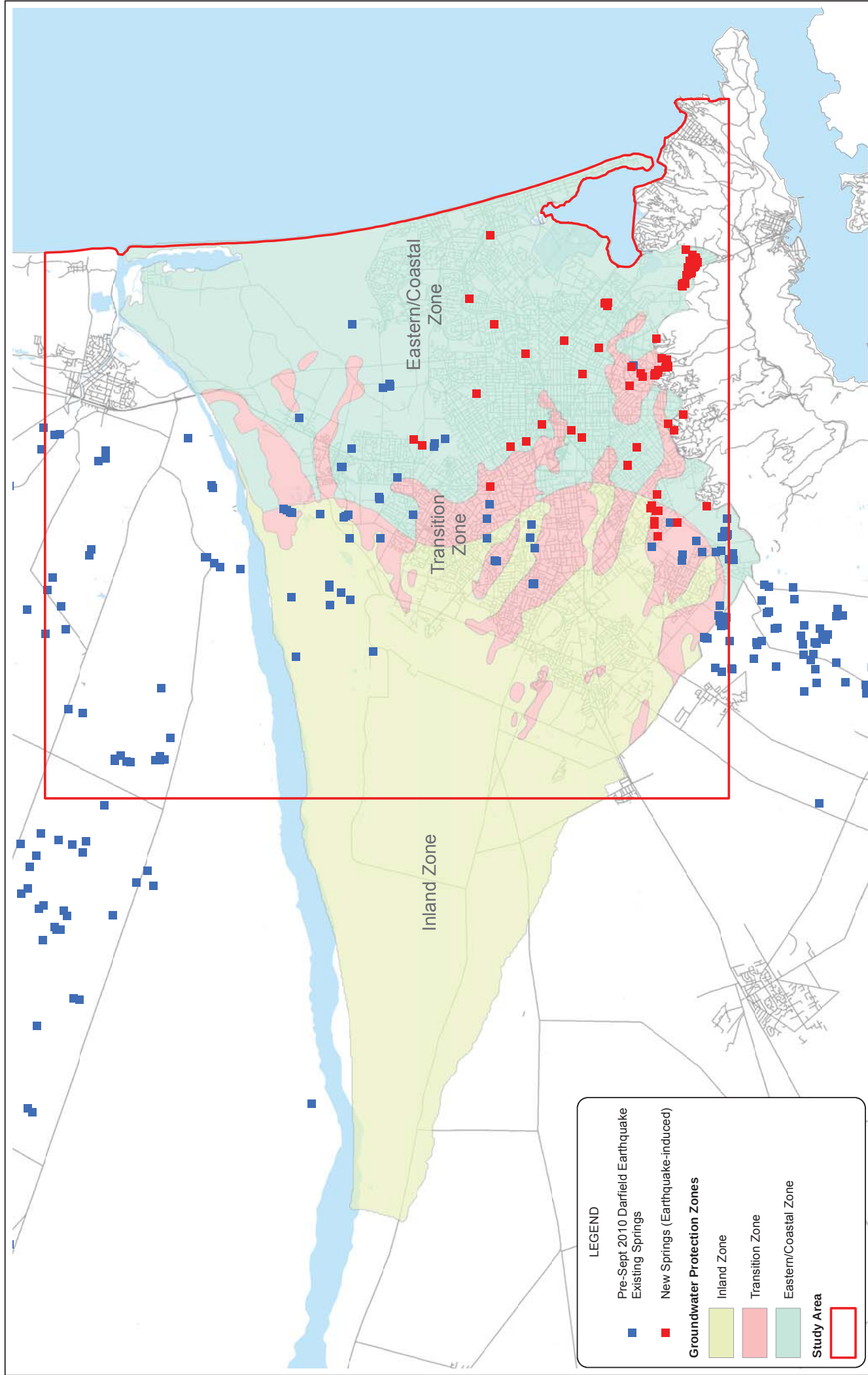
Figure above sourced from, "Christchurch Groundwater Protection", (Weeber, 2008)

Notes:



DRAWN	CXP	Feb.13
CHECKED		
APPROVED		
ARCFILE	52020-0200-CPT021	
SCALE	(A3 SIZE)	

CHRISTCHURCH MEDIAN WATER		
TABLE ELEVATION REPORT		
Schematic Geological Cross-Section of Aquifers		
FIGURE No.	Figure A.2	Rev. 0
Prepared By	Tonkin & Taylor Ltd.	
Ref.	52020.0200	



LEGEND

- Pre-Sept 2010 Darfield Earthquake Existing Springs
- New Springs (Earthquake-induced)

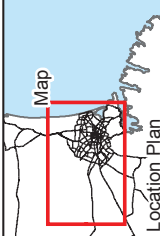
Groundwater Protection Zones

- Inland Zone
- Transition Zone
- Eastern/Coastal Zone

Study Area

Notes: Figure above sourced from, "Christchurch Groundwater Protection", (Weeber, 2008) Environment Canterbury

A3 SCALE 1:125,000

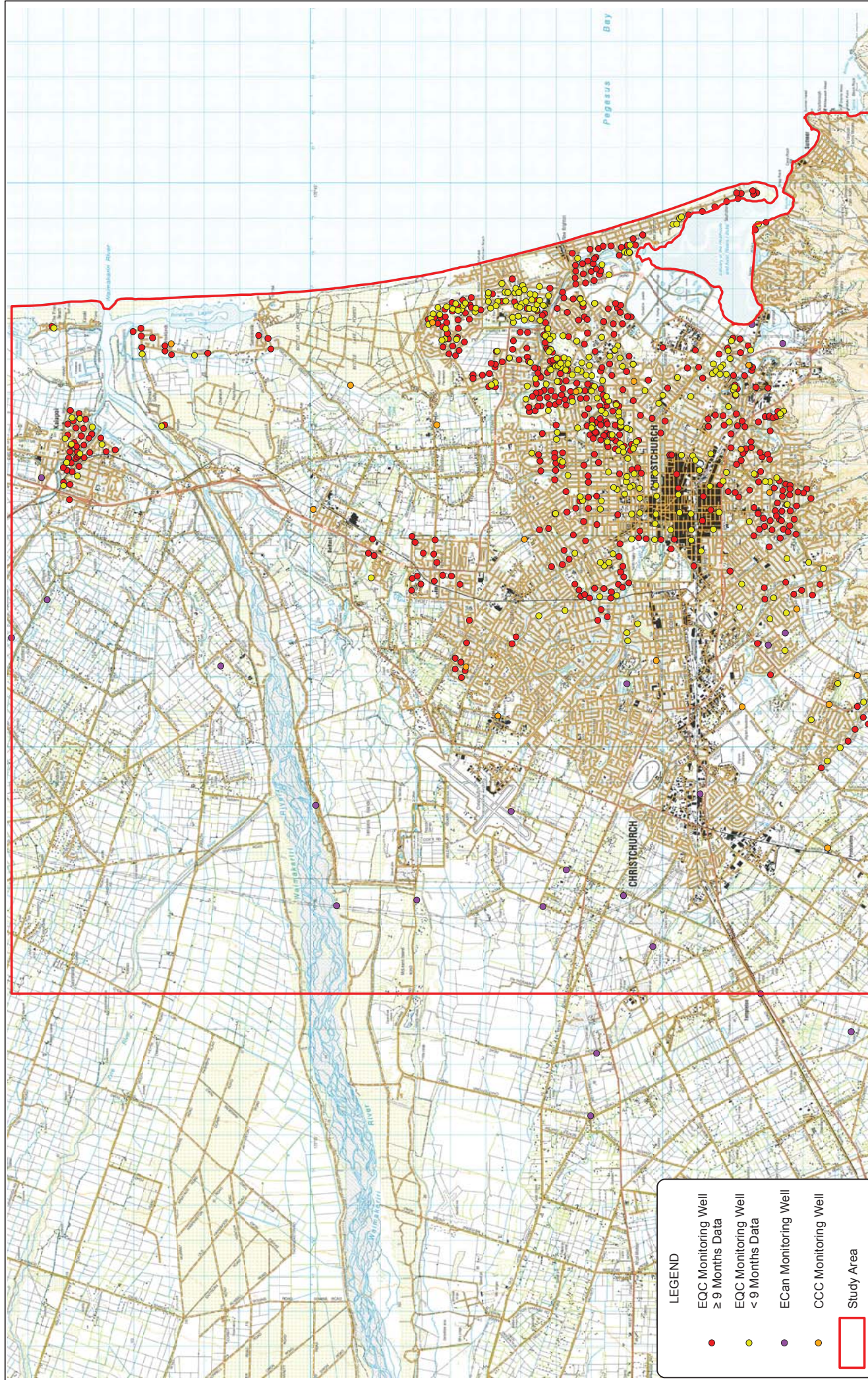


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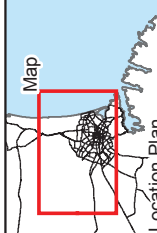
FIGURE No. Figure A.3

APPENDIX B: MONITORING WELL DATA

- **Figure B.1** Location plan for monitoring wells
- **Figure B.2** Depth of monitoring wells
- **Figure B.3** Example CCC monitoring well log
- **Figure B.4** MP and GL sign convention for ECan wells
- **Figure B.5** Example ECan monitoring well log
- **Figure B.6** EQC Initial Phase standard monitoring well detail
- **Figure B.7** EQC TC3 Phase standard monitoring well detail



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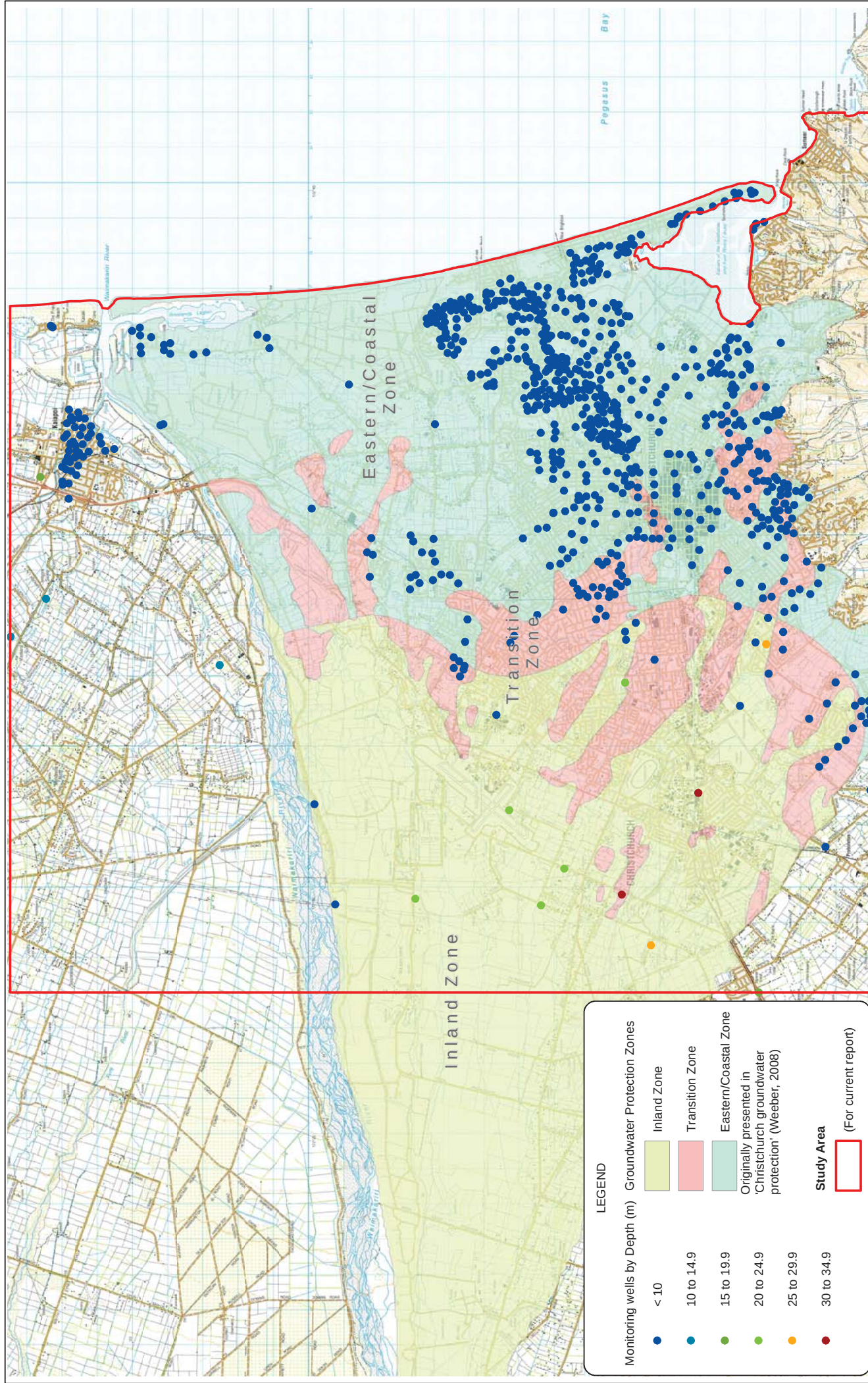
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SCALE (A3 AS IS)	1:100,000	
Prepared by	Tonkin & Taylor Ltd.	
Ref.	52020.0200	

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT

Location Plan for Monitoring Wells

FIGURE No. Figure B.1

Rev. 0



LEGEND

Monitoring wells by Depth (m)

- < 10
- 10 to 14.9
- 15 to 19.9
- 20 to 24.9
- 25 to 29.9
- 30 to 34.9

Groundwater Protection Zones

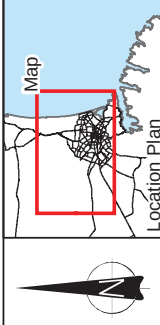
- Inland Zone
- Transition Zone
- Eastern/Coastal Zone

Originally presented in 'Christchurch groundwater protection' (Weeber, 2008)

Study Area

(For current report)

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DRAWN	JJC Feb 13
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APPROVED	
ARTICLE	52020-0200-GWM64
SCALE (A3 AS SHOWN)	1:100,000

Bore or Well No: M36/3167**Well Name:** HHN**Owner:** CHRISTCHURCH CITY COUNCIL**Street of Well:** 140 SPARKS ROAD**File No:****Locality:** HOON HAY**Allocation Zone:** Christchurch/West Melton**NZGM Grid Reference:** M36:77915-37799 QAR 2**NZGM X-Y:** 2477915 - 5737799**Location Description:** TOBY BOX, END OF
DRIVEWAY UNDER
KOHUHU**Uses:** Water Level Observation**ECan Monitoring:** Christchurch City Council**Well Status:** Active (exist, present)**Drill Date:****Water Level Count:** 1755**Well Depth:** 2.97m -GL**Strata Layers:** 0**Initial Water Depth:** -2.51m -MP**Aquifer Tests:** 0**Diameter:** 51mm**Isotope Data:** 0**Yield/Drawdown Tests:** 0**Measuring Point Ait:** 10.28m MSD QAR 4**Highest GW Level:** 0.22m below MP**GL Around Well:** 0.00m -MP**Lowest GW Level:** 2.99m below MP**MP Description:****First Reading:** 07 Jul 1969**Last Reading:** 05 Jun 2012**Driller:** not known**Calc. Min. GWL:** -2.74m -MP**Drilling Method:** Unknown**Last Updated:** 17 Oct 2006**Casing Material:****Last Field Check:** 05 Jun 2012**Pump Type:** Unknown**Yield:****Screens:****Drawdown:****Screen Type:****Specific Capacity:****Top GL:****Bottom GL:****Aquifer Type:** Unknown**Aquifer Name:****Date****Comments**

23 Oct 1998

In the grounds of Sparks Road pumping station. Grid reference verified by field visit.

26 Jan 2004

Data supplied by the Christchurch City Council, measured by and original data held by NIWA

10 May 2011

First WL reading set as ISWL

Notes:

Well log sourced from Environment Canterbury website.



DRAWN	CXP	Feb.13
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APPROVED		
ARCFILE		
52020-0200-CPT024		
SCALE (AT A3 SIZE)		
Prepared by Tonkin & Taylor Ltd		
Ref. 52020.0200		

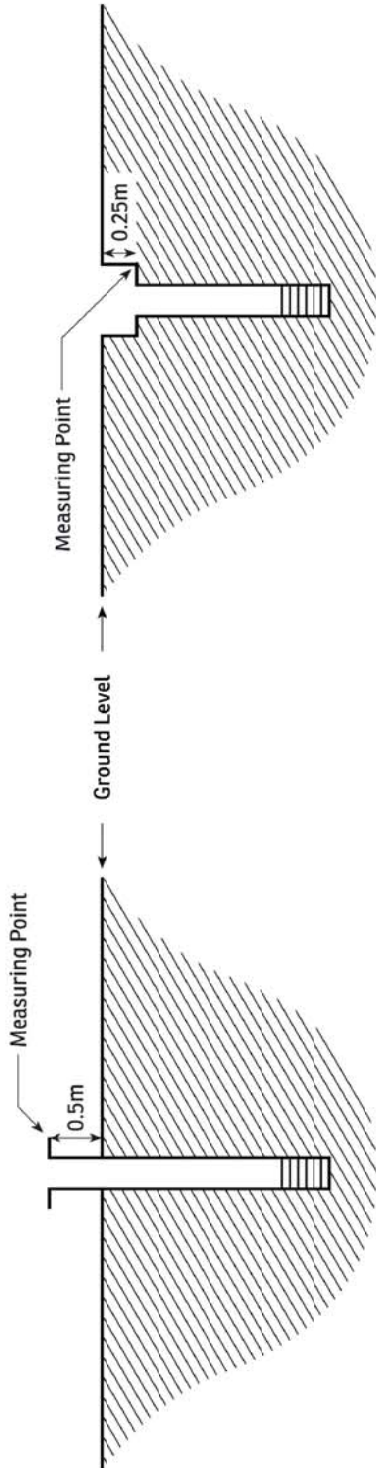
**CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT**

Example Christchurch City Council Monitoring Well Log

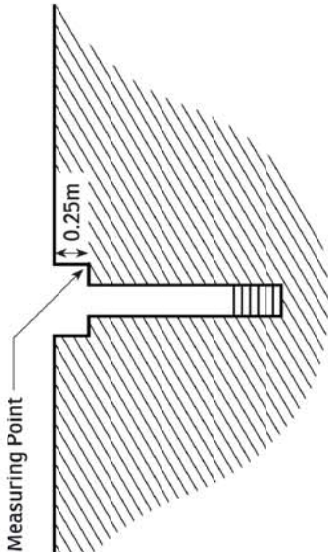
FIGURE No. Figure B.3

Rev. 0

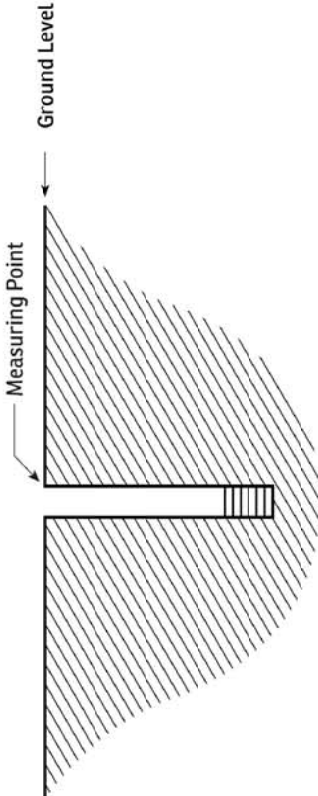
Ground Level Distance from Measuring Point



"-0.5m - MP" on well card



"0.25m - MP" on well card



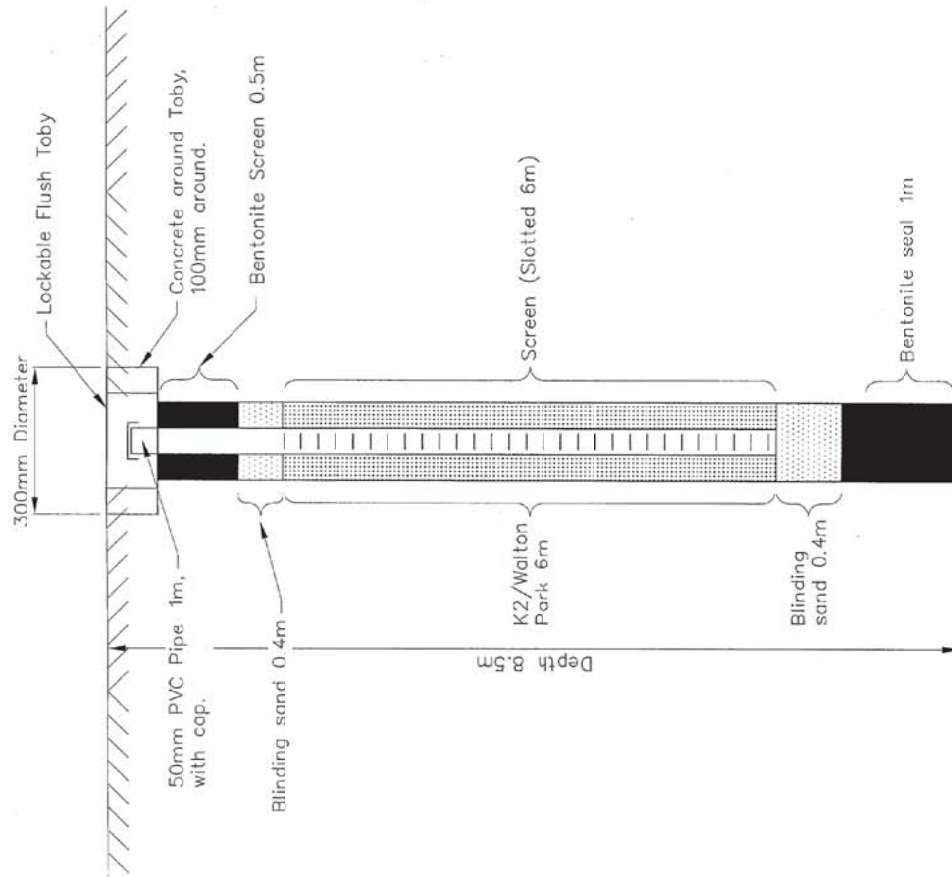
"0m - MP" on well card

Notes: Sourced from Environment Canterbury.

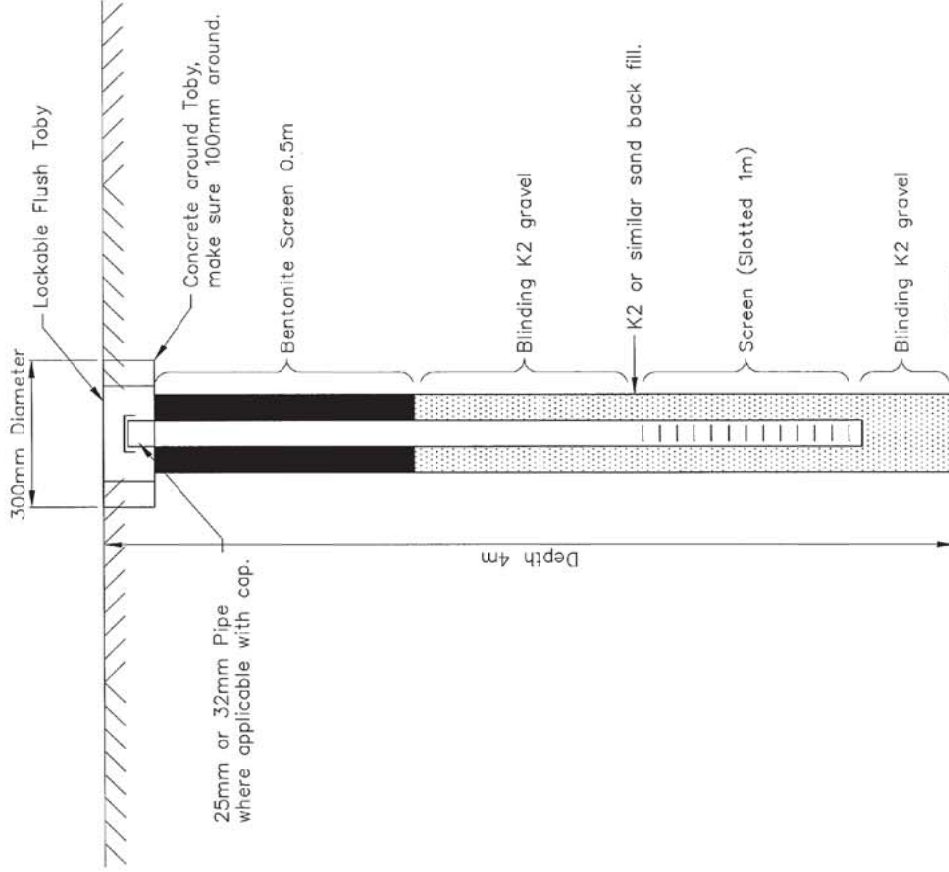


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ARCHFILE		
52020-0200-CPT020		
SCALE (AT A3 SIZE)		

Prepared By Tonkin & Taylor Ltd.
Ref: 52020.0200



EQC
GEOTECHNICAL INVESTIGATIONS
CHRISTCHURCH EARTHQUAKE RECOVERY
Stand Pipe Detail for Bore Holes



EQC
GEOTECHNICAL INVESTIGATIONS
CHRISTCHURCH
Stand Pipe Detail for CPT Holes

Notes:



DRAWN	CXP	Feb13
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APPROVED		
ARCHFILE		
52020-0200-CPT022		
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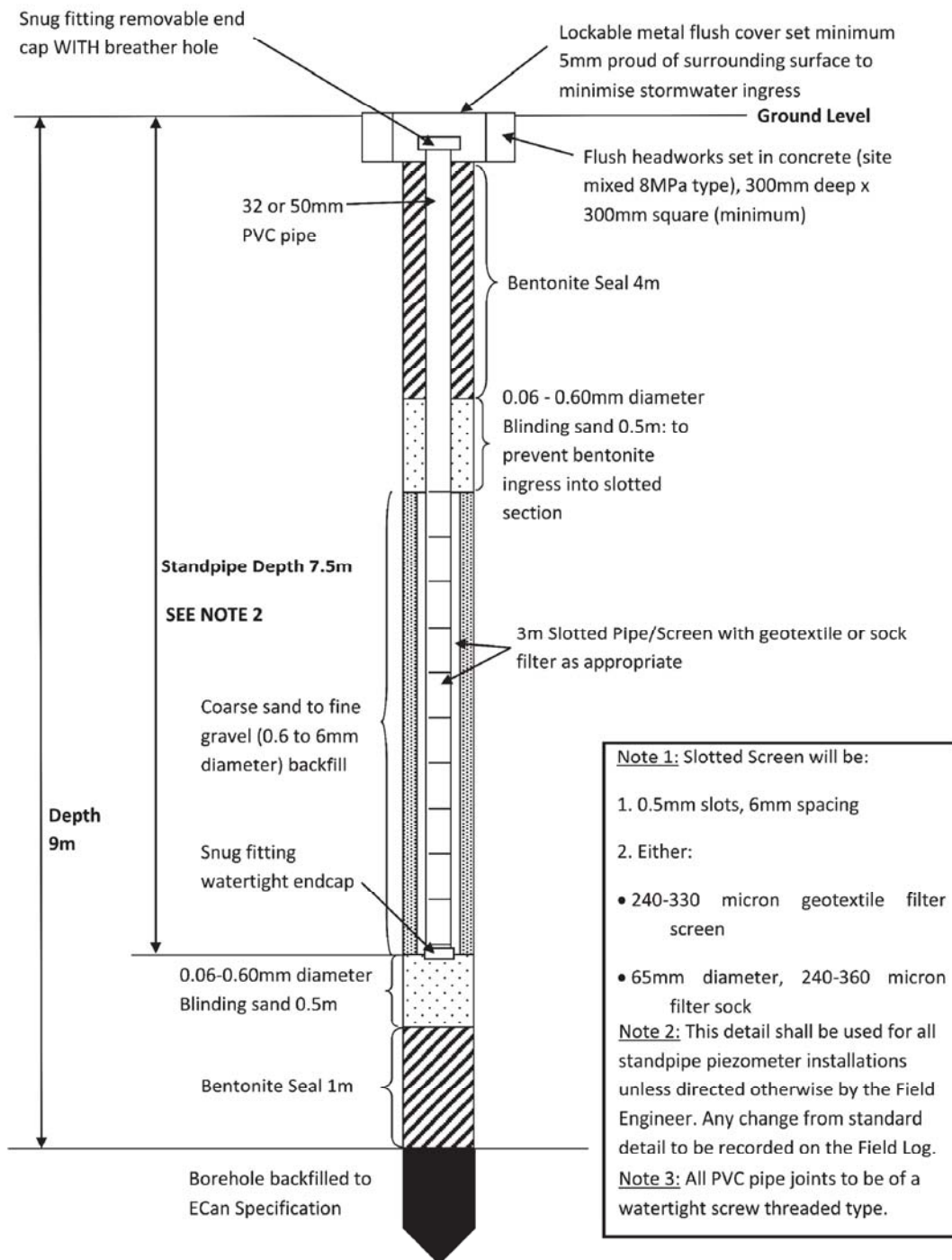
Prepared By Tonkin & Taylor Ltd.
Ref: 52020.0200

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
Standard Monitoring Well detail for
2010/2011 ground investigations (EQC)

FIGURE No: Figure B.6

REV: 0

Standpipe Piezometer Installations (Revision B, 30th July 2012): Standard Detail for Boreholes – Technical
Category 3 Area Wide Investigations



Notes:



Tonkin & Taylor

DRAWN	CXP	Feb.13
CHECKED		
APPROVED		
ARCFILE	52020-0200-CPT019	
SCALE	(AT A3 SIZE)	
Prepared by	Tonkin & Taylor Ltd	
Ref.	52020.0200	

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
 Standard Monitoring Well detail for TC3
 ground investigations (EQC)

FIGURE No. Figure B.7

Rev. 0

APPENDIX C: LIDAR INFORMATION

- **LiDAR survey and benchmark comparisons**
- **Figure C.1 Cumulative ground elevation difference**
- **Figure C.2 Survey benchmark locations and land zonation**

LiDAR and survey benchmark comparisons

1 LiDAR survey data

The elevation of the ground surface around Canterbury was measured remotely using airborne LiDAR surveys. A baseline survey of Christchurch was flown in 2003 and additional surveys were flown after each of the main aftershocks.

Airborne LiDAR provides measurements in GPS-space, with absolute elevations at X, Y northing and easting coordinates measured relative to the ellipsoidal datum of the satellite network. The measurement data, commonly termed a 'point cloud', was processed using the simultaneously recorded aerial photographs to identify and remove points reflected from water and from above-ground features such as structures and vegetation that were judged to be higher than 0.5 m above the surrounding ground surface.

The LiDAR was typically acquired at least one month after each major earthquake (with the exception of the post-September 2010 LiDAR that was flown the day after the 4 September 2010 earthquake). This delay provided time for ejected sand and silt to be removed from most locations in order to measure changes to the ground surface level. The extent of each LiDAR survey was different for each event, with the extent chosen to cover areas believed to have been affected by ground surface subsidence caused by the preceding earthquake.

The LiDAR surveys were acquired by AAM Brisbane (AAM) and New Zealand Aerial Mapping (NZAM). The suppliers also classified the acquired points as ground or non-ground. The LiDAR sources and commissioning agencies are listed in Table C1 below.

Table C1- LiDAR source and commissioning agencies

DEM	Source LiDAR	Commissioning Agencies
Pre-earthquake	AAM, 6-9 Jul 2003	Christchurch City Council
	AAM, 21-24 Jul 2005	Environment Canterbury & Waimakariri District Council
	AAM, 6-11 Feb 2008	Environment Canterbury & Selwyn District Council
Post-Sept 2010	NZAM, 5 Sep 2010	Ministry of Civil Defence and Emergency Management
Post-Feb 2011	NZAM, 8-10 Mar 2011	Ministry of Civil Defence and Emergency Management
	AAM, 20-30 May 2011	Christchurch City Council
Post-June 2011	NZAM, 18 & 20 Jul, 11 Aug, 25-27 Aug, and 2-3 Sep 2011	Earthquake Commission
Post-Dec 2011	NZAM 17-18 Feb, 2012	Earthquake Commission

2 LiDAR elevation accuracy and precision

The equipment and flying heights for the post-earthquake LiDAR surveys produced point clouds with a fundamental vertical specification accuracy of ± 0.10 m. This one standard deviation accuracy target provided by NZAM is for points reflected from hard surfaces in areas of open ground, and applies to all points in the point cloud. The equipment produces less accurate horizontal positions (± 0.4 to ± 0.55 m), so elevations will be more accurate

than 0.10 m for points directly beneath the aircraft and less accurate than this at the edges of the scan swath (± 20 degrees from vertical). The pre-earthquake LiDAR point cloud had less accuracy and a larger spacing between the points.

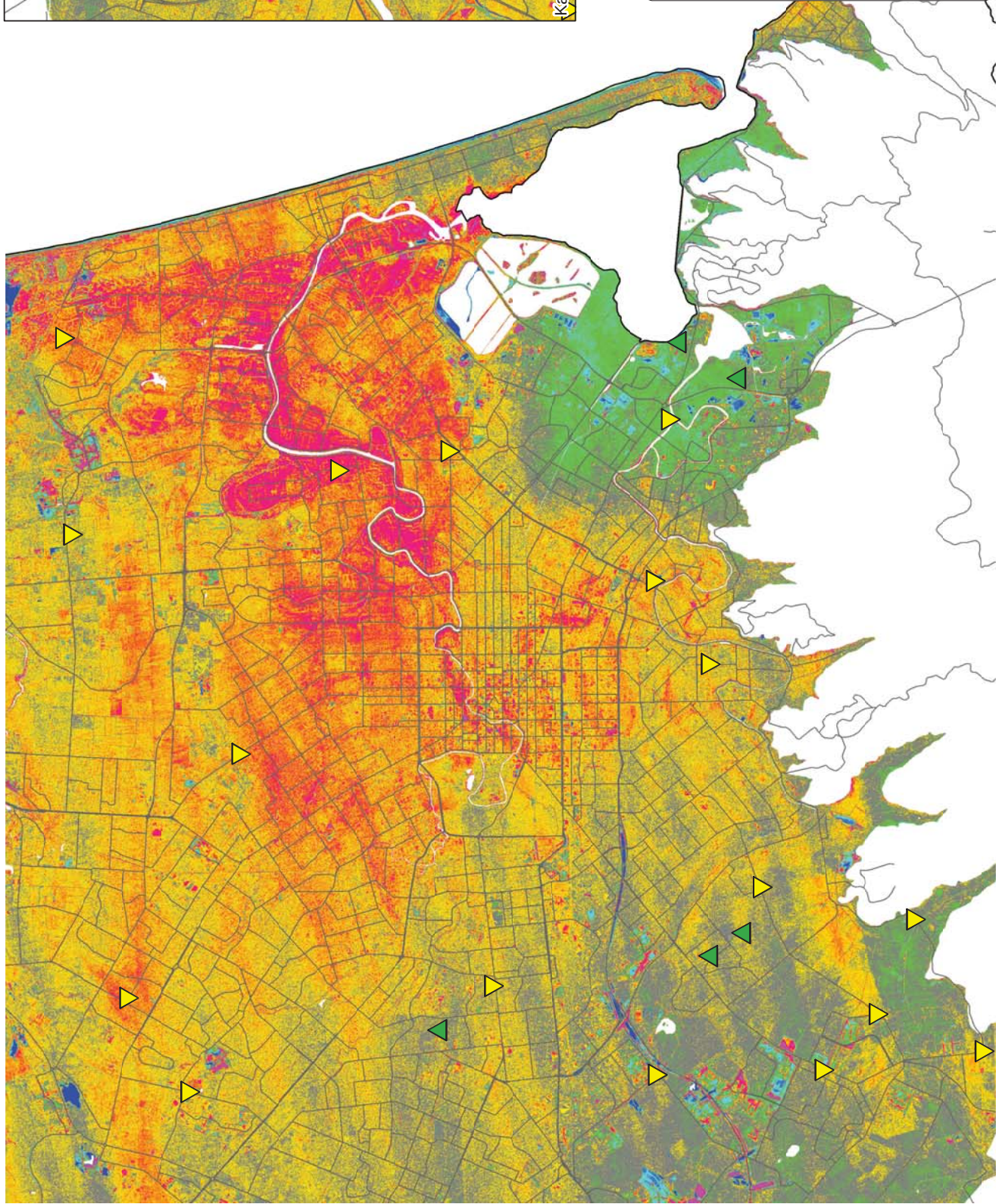
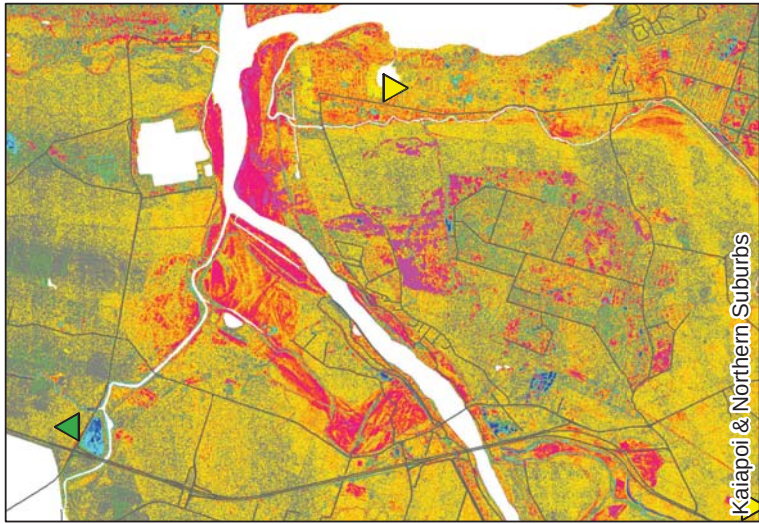
The LiDAR survey suppliers offset the vertical elevation of the entire point cloud to accommodate atmospheric effects that affected the light path and hence the distance measurement, by comparing elevations with reference elevations from GPS field surveys of flat hard surfaces. The vertical precision is therefore the precision of the field survey, which for GPS surveys is typically quoted as 0.03 m (one standard deviation).

After each major aftershock, Land Information New Zealand (LINZ) re-surveyed the elevations and locations of a network of survey benchmarks around Canterbury. The LINZ surveys re-established the benchmark locations relative to the rest of the physical survey network around New Zealand. This survey information provides a convenient method of verifying the accuracy of the elevations provided by the GPS based LiDAR points against the ground based survey points. These also provide a larger, well distributed set of known elevations than those used by the LiDAR supplier, so they can be used as more-precise point cloud offsets.

The complete set of benchmark locations are shown in Figure C.2. Only subsets of these benchmarks were surveyed before the 4 September 2010 earthquake and surveyed again after each particular earthquake (note that some benchmarks were not surveyed after some events and some were destroyed by localised movements).

All of the LiDAR elevation measurements within a 1 m radius of each benchmark were extracted from the point cloud, and the elevation was compared to the re-surveyed elevation. The elevation difference between each measurement point and the benchmark were plotted over an aerial photograph, and points that were clearly not ground surface measurements (e.g. fence tops, vegetation, cars etc.) were removed from the data set. The resulting elevation differences have unquantified errors associated with the elevation difference between the benchmark and its surrounding ground. This includes differences associated with local features such as sloping ground (due to the lower horizontal position accuracy) and with kerbs and other depressed or raised surfaces.

A cumulative-frequency plot of the elevation differences is shown for each of the point-cloud sets in Figure C.3. This clearly illustrates the larger standard deviation for the older equipment used for the 2003 pre-earthquake LiDAR. It also shows that the elevations for the post-June 2011 LiDAR point cloud are about 50 mm too high relative to the other LiDAR point clouds, which are within the 30 mm tolerance for the GPS reference field surveys. On this basis, the post-June 2011 DEM has been adjusted downward by 50 mm.



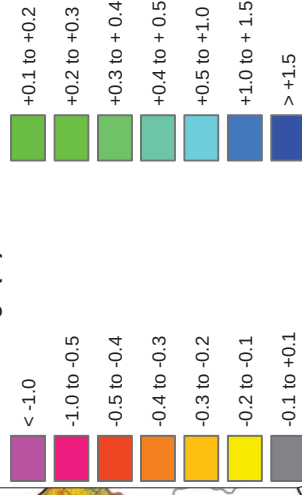
Legend

Monitoring Well Locations

CCC

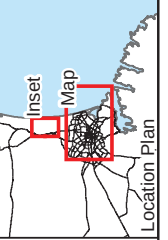
ECAN

Elevation Change (m)



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A3 SCALE 1:60,000



Location Plan



DRAWN	CXP	Feb13
CHECKED		
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PROJECT	52020-0200-GWM55	
SCALE (A3 AS SHOWN)	1:60,000	
Prepared by	Tonkin & Taylor Ltd.	
Ref:	52020-0200	

CHRISTCHURCH MEDIAN WATER

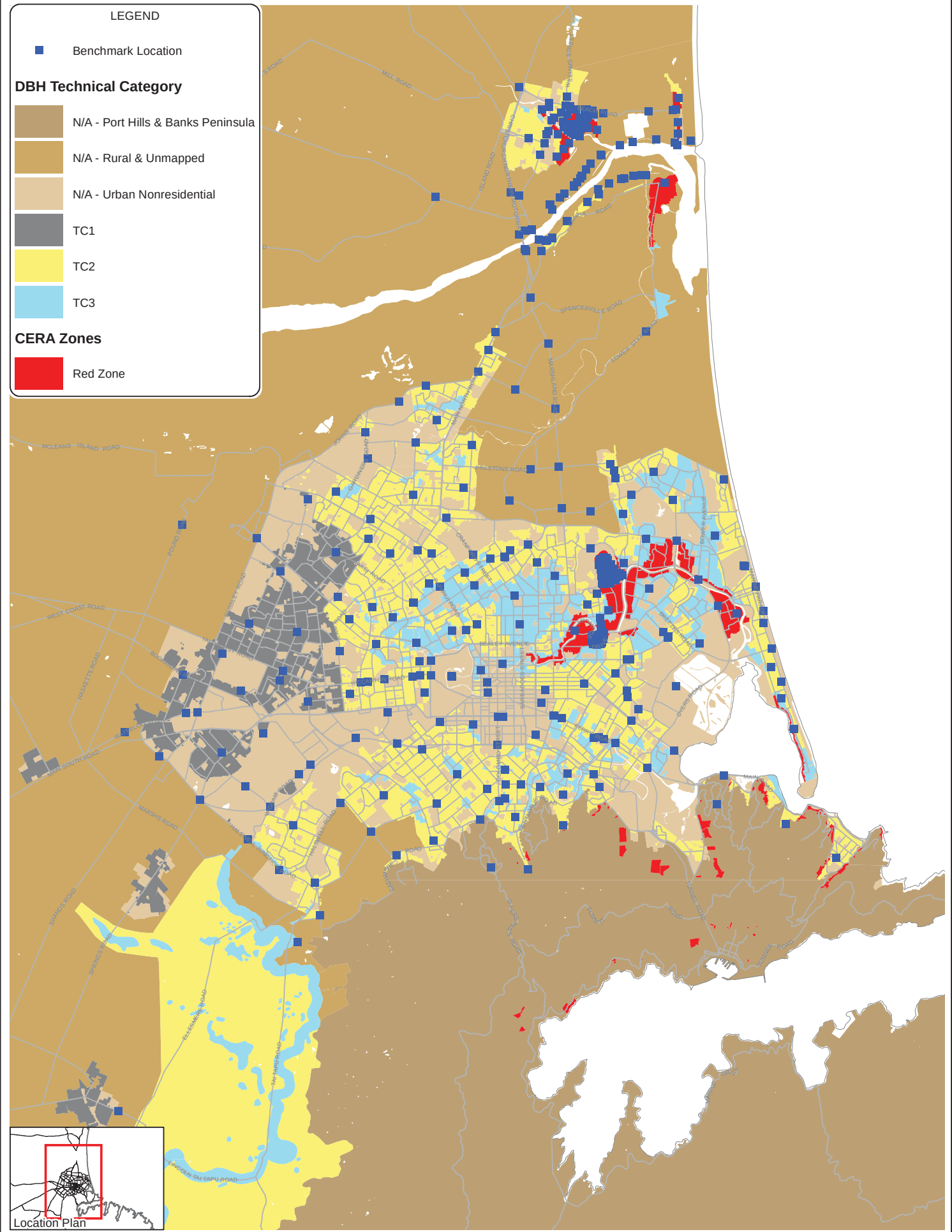
TABLE ELEVATION REPORT

Cumulative LIDAR Elevation Difference

(Pre September 2010 to Post June/Dec 2011)

FIGURE No. Figure C-1

Rev. 0



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A3 SCALE 1:100,000

0 1 2 3 4 5 (km)



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APPROVED		
ARCFILE	52020-0200-SBM019	
SCALE	(AT A3 SIZE)	
Prepared by	Tonkin & Taylor Ltd	
Ref.	52020-0200	

**CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT**
Survey Benchmark Locations of those
used in the Benchmarks and LiDAR comparison

FIGURE No. **Figure C.2**

Rev. **0**

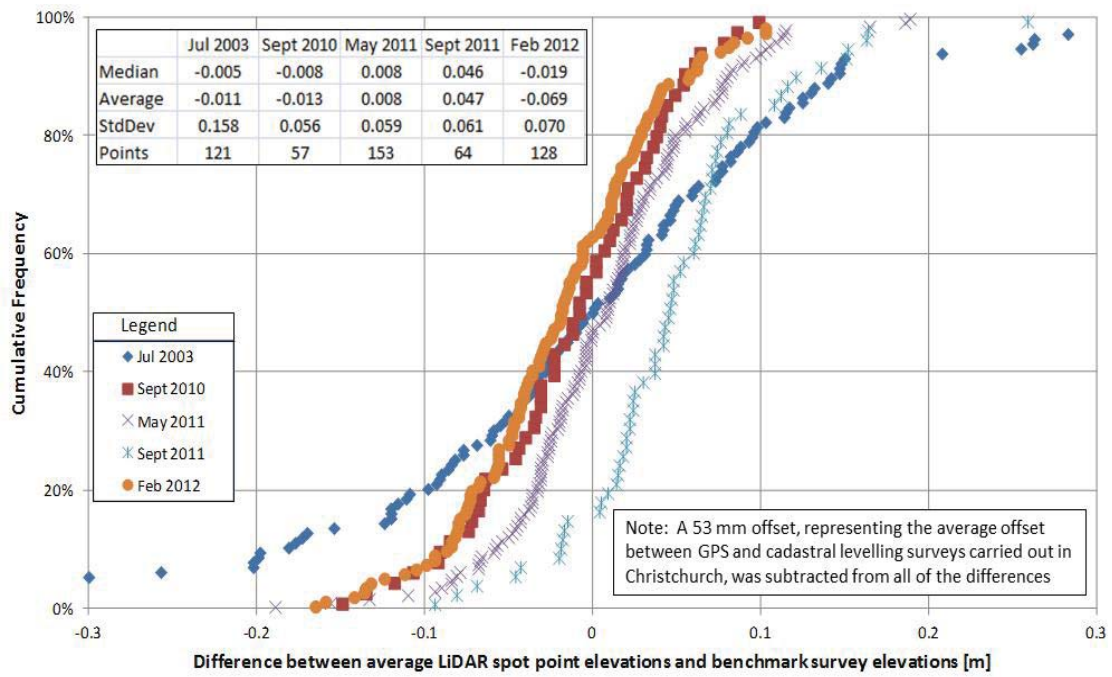
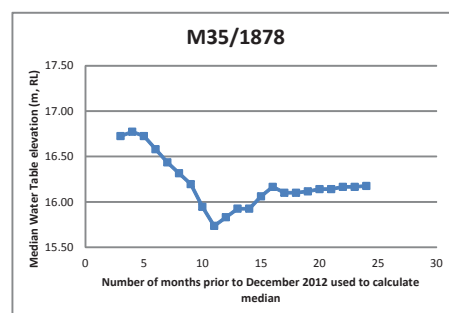
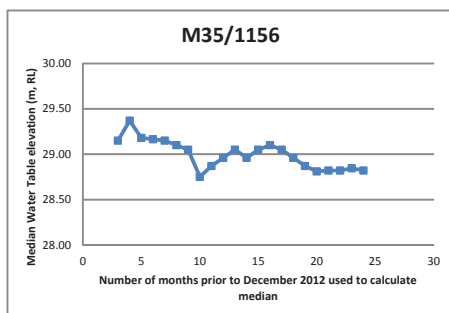
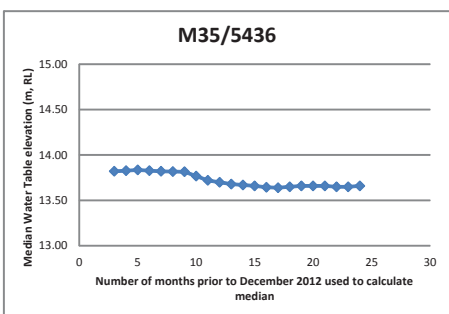
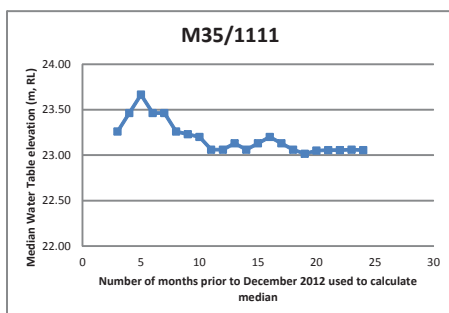
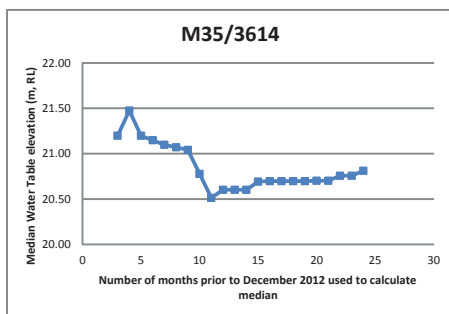


Figure C.3 - Cumulative frequency plots of the difference between the measured LiDAR elevations and the benchmark elevations from field surveys

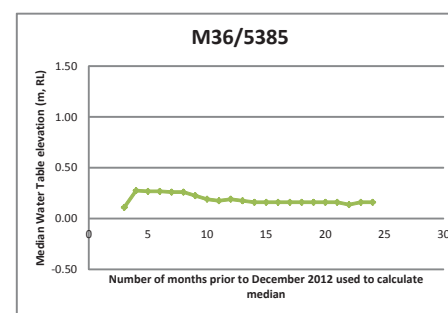
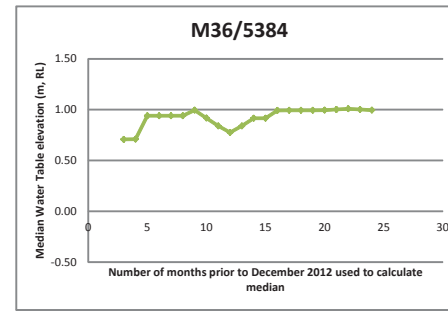
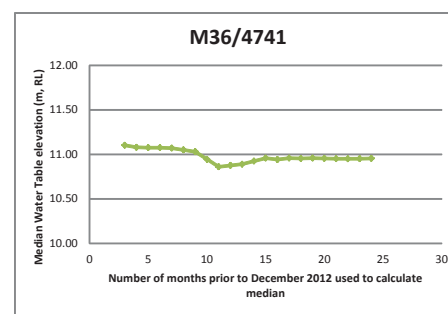
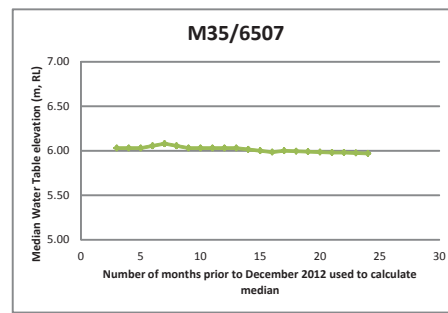
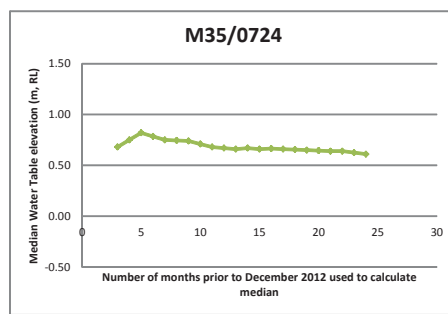
APPENDIX D: SENSITIVITY OF DATA SELECTION FOR MONITORING WELLS

- **Figure D.1 Change in median water table level with reduction in available data for ECan monitoring wells**
- **Figure D.2 Change in median water table level with reduction in available data for CCC monitoring wells**

Inland Zone



Eastern Coastal Zone



The ECan and CCC monitoring wells were typically measured at least once a month, and have been monitored in this way since their installation (prior to the September 2010 Darfield earthquake). The plots presented in this figure show the effect of data selection in relation to calculation of the median water table level for discrete monitoring well locations. The x-axis refers to the number of months prior to December 2012 which have been used to calculate a median value. It can be seen that a median based on 12 months is less influenced by the seasonal effects caused by choosing a shorter duration to calculate the median (e.g. for a 6 month period). Generally the median calculated for a period of 12 ± 3 months is representative of a yearly median value that is not biased by seasonal effects.

Notes:



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ARCFILE 52020-0200-CPT053		
SCALE (AT A3 SIZE)		
Prepared by Tonkin & Taylor Ltd		
Ref. 52020.0200		

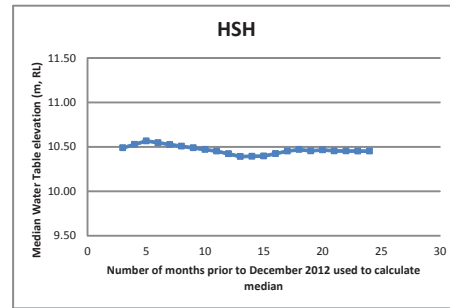
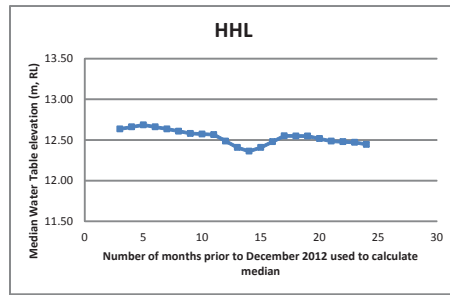
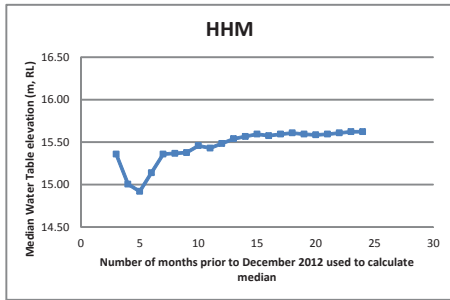
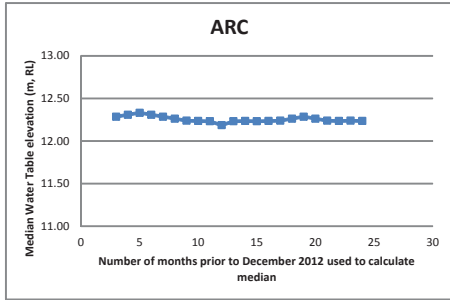
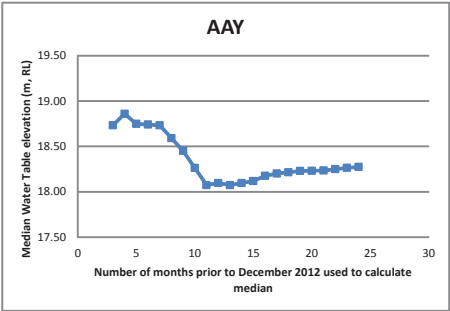
CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT

Change in median water table level with reduction in available data In ECan Monitoring wells

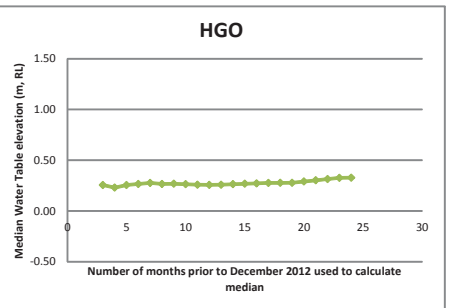
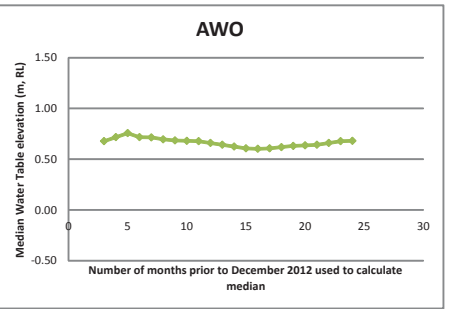
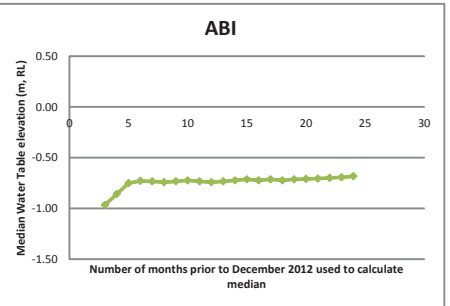
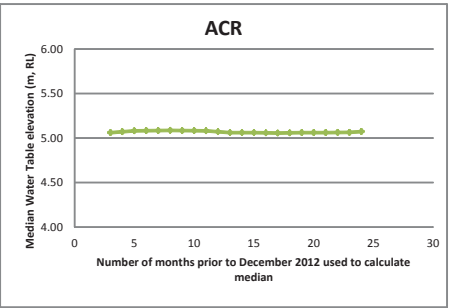
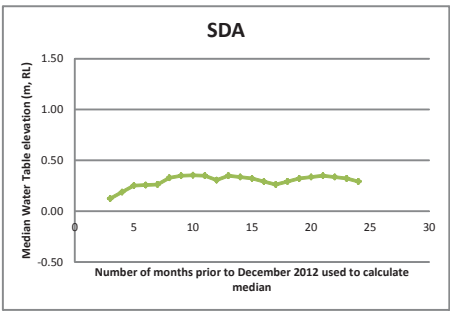
FIGURE No. Figure D.1

Rev. 0

Inland Zone



Eastern Coastal Zone



The ECan and CCC monitoring wells were typically measured at least once a month, and have been monitored in this way since their installation (prior to the September 2010 Darfield earthquake). The plots presented in this figure show the effect of data selection in relation to calculation of the median water table level for discrete monitoring well locations. The x-axis refers to the number of months prior to December 2012 which have been used to calculate a median value. It can be seen that a median based on 12 months is less influenced by the seasonal effects caused by choosing a shorter duration to calculate the median (e.g. for a 6 month period). Generally the median calculated for a period of 12 ± 3 months is representative of a yearly median value that is not biased by seasonal effects.

Notes:



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ARCFILE	52020-0200-CPT057	
SCALE	(AT A3 SIZE)	
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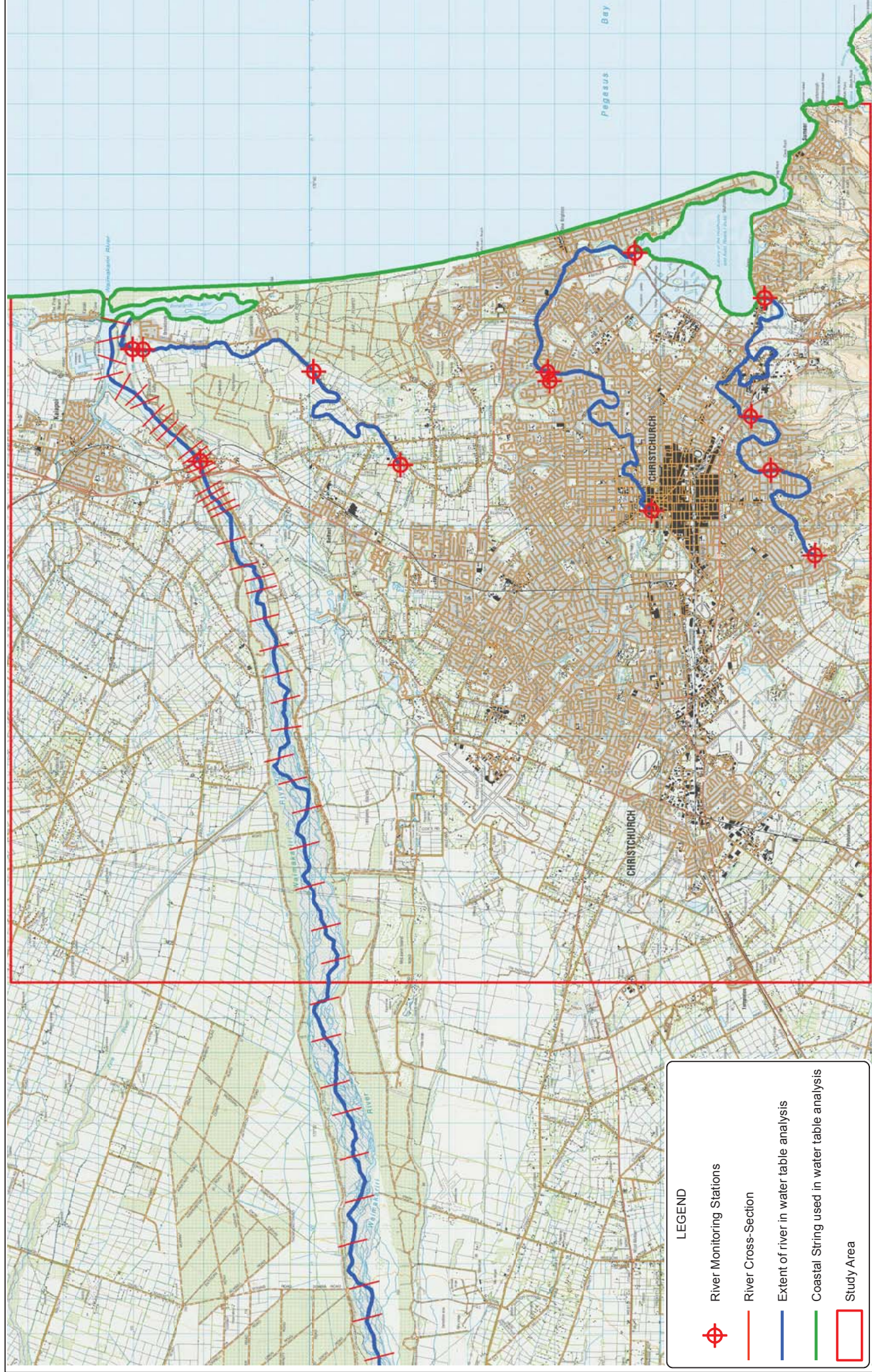
CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
Change in median water table level with
reduction in available data In CCC Monitoring wells

FIGURE No. Figure D.2

Rev. 0

APPENDIX E: RIVER LEVEL DATA

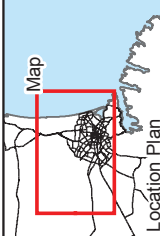
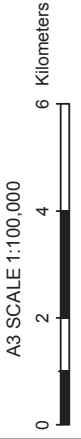
- **Figure E.1** Location plan for river monitoring stations, cross-sections and breaklines
- **Figure E.2** Location plan for Avon/Otakaro River monitoring stations
- **Figure E.3** Location plan for Heathcote River monitoring stations
- **Figure E.4** Location plan for Styx River monitoring stations
- **Figure E.5** Location plan for Waimakariri River cross-sections



LEGEND

- River Monitoring Stations
- River Cross-Section
- Extent of river in water table analysis
- Coastal String used in water table analysis
- Study Area

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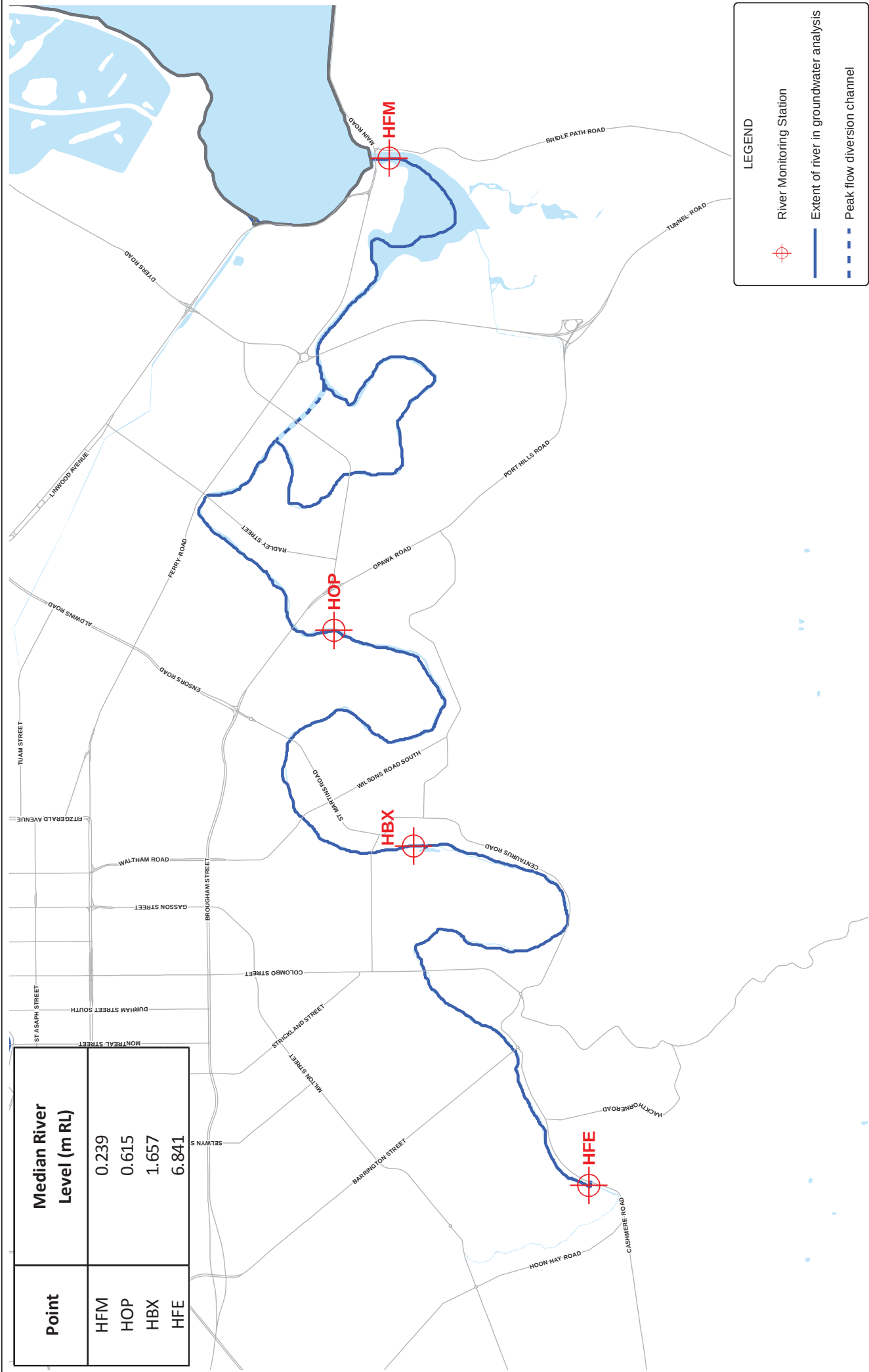


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52020-0200-CPT028		
SCALE (A3 SIZE)		

1:100,000
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Ref: 52020.0200

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT Location Plan for River Monitoring Stations and Cross-Sections

FIGURE No. Figure E.1



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A3 SCALE 1:25,000

0 500 1,000 1,500 Meters

Map

Location Plan

DRAWN	CXP	Feb13
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APPROVED		
ARCFILE 52020-0200-CPT016		
SCALE (AT A3 SIZE) 1:25,000		
Prepared By Tonkin & Taylor Ltd. Ref: 52020.0200		

CHRISTCHURCH MEDIAN WATER

TABLE ELEVATION REPORT

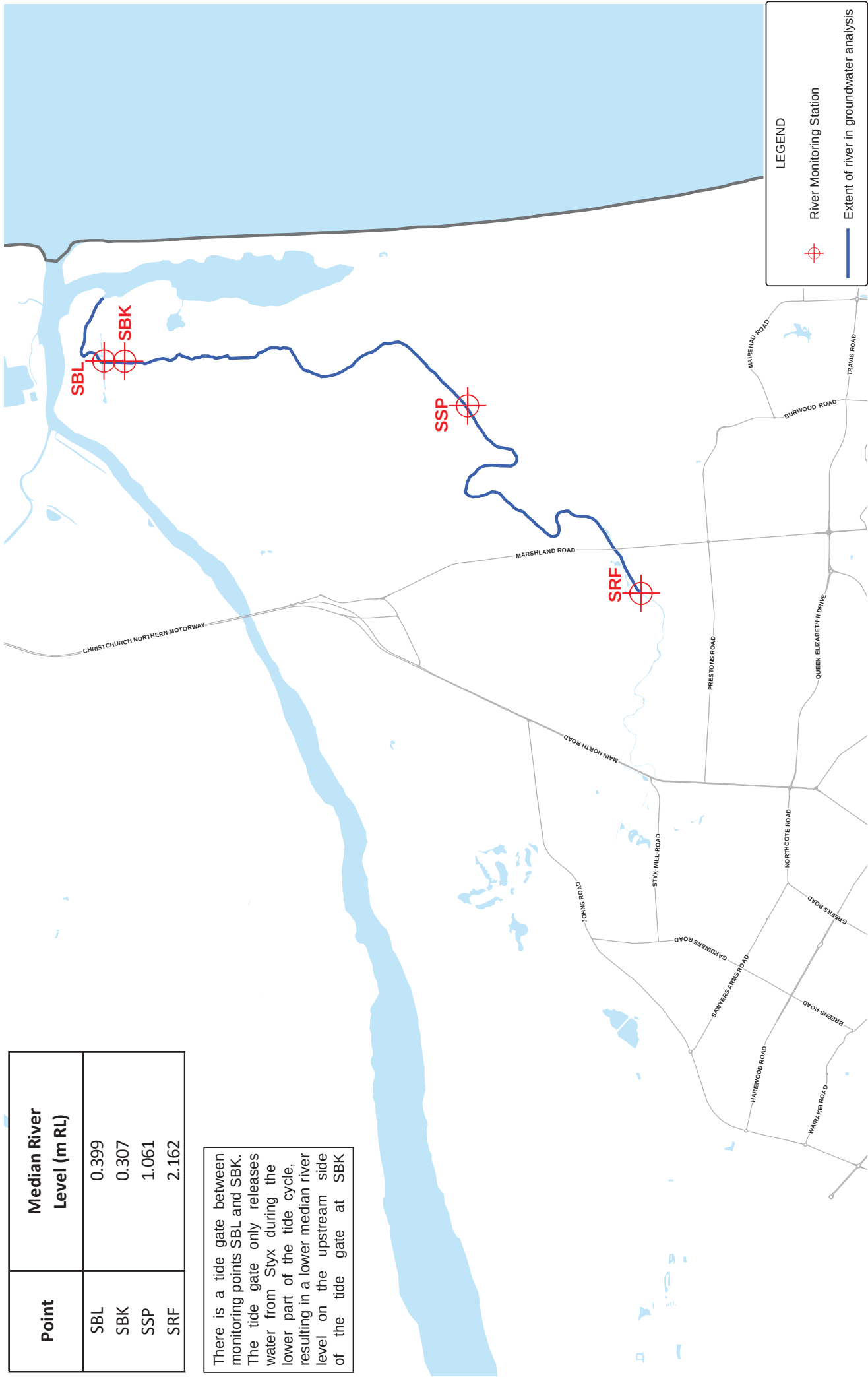
Location Plan for Heathcote River Monitoring Stations

FIGURE No. Figure E.3

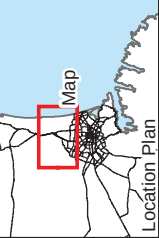
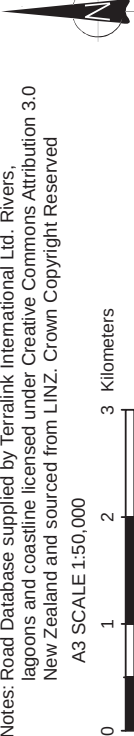
Rev. 0

Point	Median River Level (m RL)
SBL	0.399
SBK	0.307
SSP	1.061
SRF	2.162

There is a tide gate between monitoring points SBL and SBK. The tide gate only releases water from Styx during the lower part of the tide cycle, resulting in a lower median river level on the upstream side of the tide gate at SBK

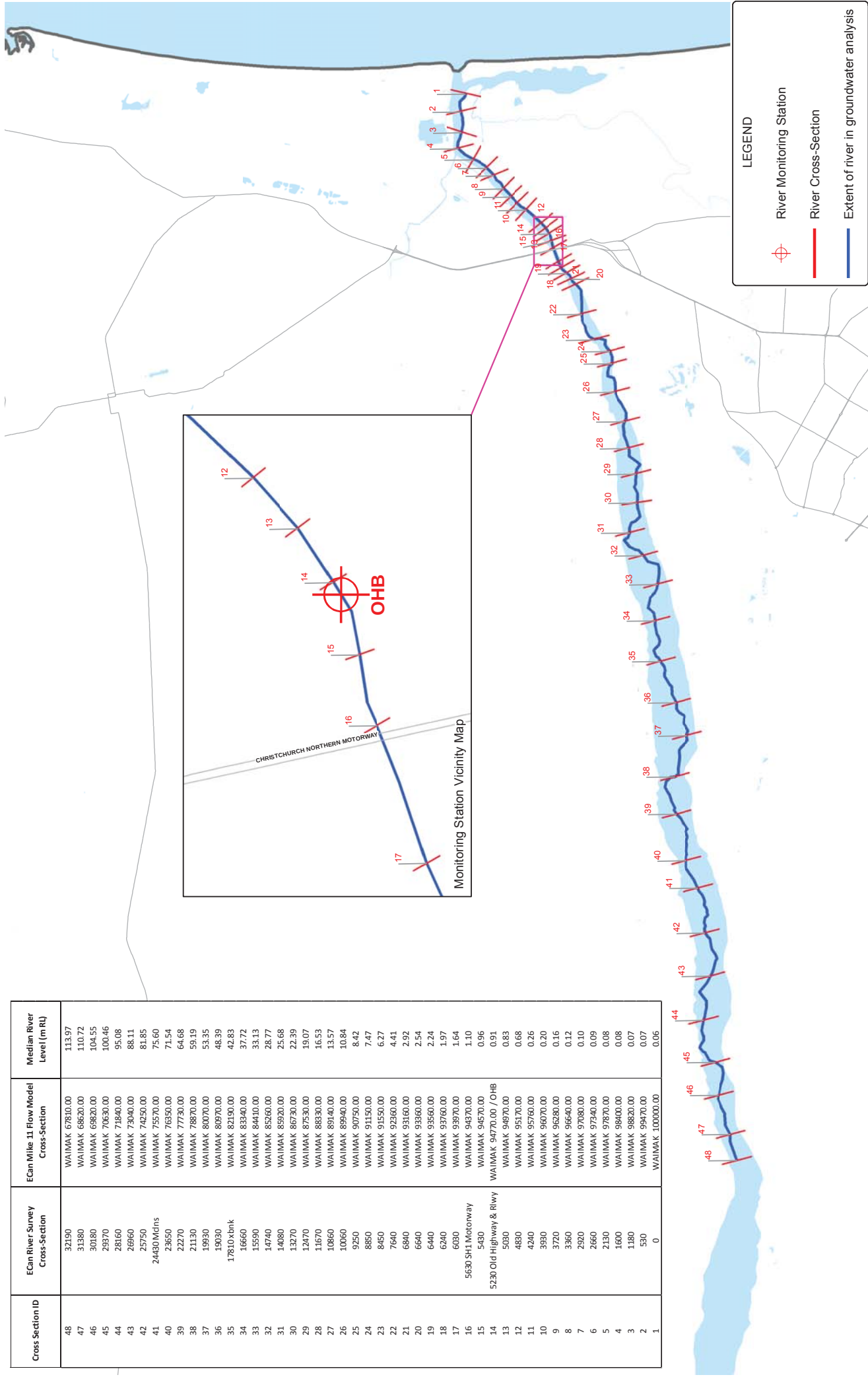
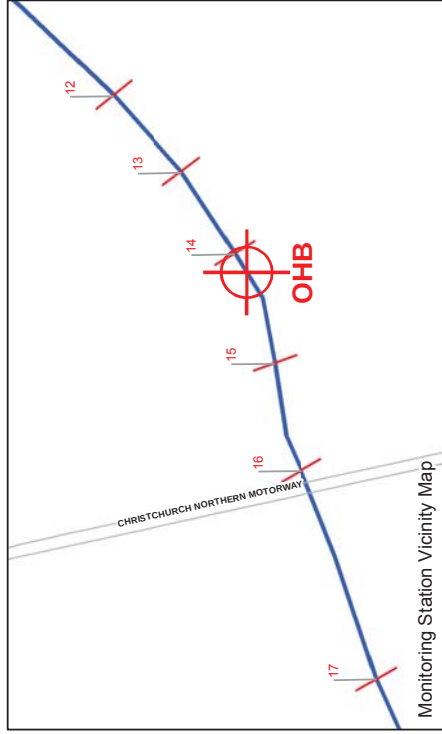


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52020-0200-CPT017		
SCALE (AT A3 SIZE)		
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Ref: 52020.0200		

Cross Section ID	ECan River Survey Cross-Section	ECan Mile 11 Flow Model Cross-Section	Median River Level (m RL)
48	32190	WAIMAK 67810.00	113.97
47	31380	WAIMAK 68620.00	110.72
46	30180	WAIMAK 69820.00	104.55
45	29370	WAIMAK 70630.00	100.46
44	28160	WAIMAK 71840.00	95.08
43	26960	WAIMAK 73040.00	88.11
42	25750	WAIMAK 74250.00	81.85
41	24430 Midns	WAIMAK 75570.00	75.60
40	23650	WAIMAK 76950.00	71.54
39	22270	WAIMAK 77730.00	64.68
38	21130	WAIMAK 78870.00	59.19
37	19930	WAIMAK 80070.00	53.35
36	19030	WAIMAK 80970.00	48.39
35	17810 xbrnk	WAIMAK 82190.00	42.83
34	16660	WAIMAK 83340.00	37.72
33	15590	WAIMAK 84410.00	33.13
32	14740	WAIMAK 85260.00	28.77
31	14080	WAIMAK 85920.00	25.68
30	13270	WAIMAK 86730.00	22.39
29	12470	WAIMAK 87530.00	19.07
28	11670	WAIMAK 88330.00	16.53
27	10860	WAIMAK 89140.00	13.57
26	10060	WAIMAK 89940.00	10.84
25	9250	WAIMAK 90750.00	8.42
24	8850	WAIMAK 91150.00	7.47
23	8450	WAIMAK 91550.00	6.27
22	7640	WAIMAK 92360.00	4.41
21	6840	WAIMAK 93160.00	2.92
20	6640	WAIMAK 93360.00	2.54
19	6440	WAIMAK 93560.00	2.24
18	6240	WAIMAK 93760.00	1.97
17	6030	WAIMAK 93970.00	1.64
16	5630 SH1 Motorway	WAIMAK 94370.00	1.10
15	5430	WAIMAK 94570.00	0.96
14	5230 Old Highway & Rlwy	WAIMAK 94770.00 / OHB	0.91
13	5030	WAIMAK 94970.00	0.83
12	4830	WAIMAK 95170.00	0.68
11	4240	WAIMAK 95760.00	0.26
10	3930	WAIMAK 96070.00	0.20
9	3720	WAIMAK 96280.00	0.16
8	3360	WAIMAK 96640.00	0.12
7	2920	WAIMAK 97080.00	0.10
6	2660	WAIMAK 97340.00	0.09
5	2130	WAIMAK 97870.00	0.08
4	1600	WAIMAK 98400.00	0.08
3	1180	WAIMAK 98820.00	0.07
2	530	WAIMAK 99470.00	0.07
1	0	WAIMAK 100000.00	0.06



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A3 SCALE 1:100,000

0 2 4 6 Kilometers

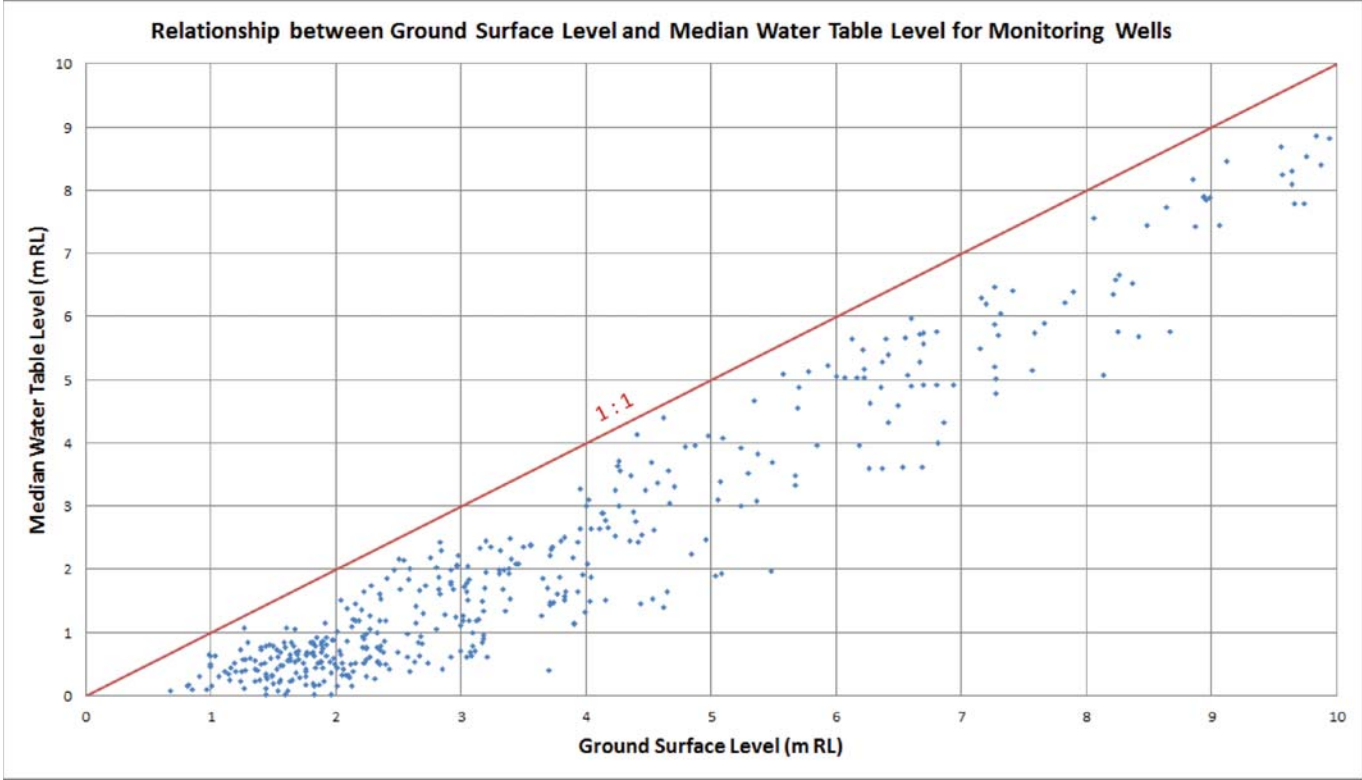
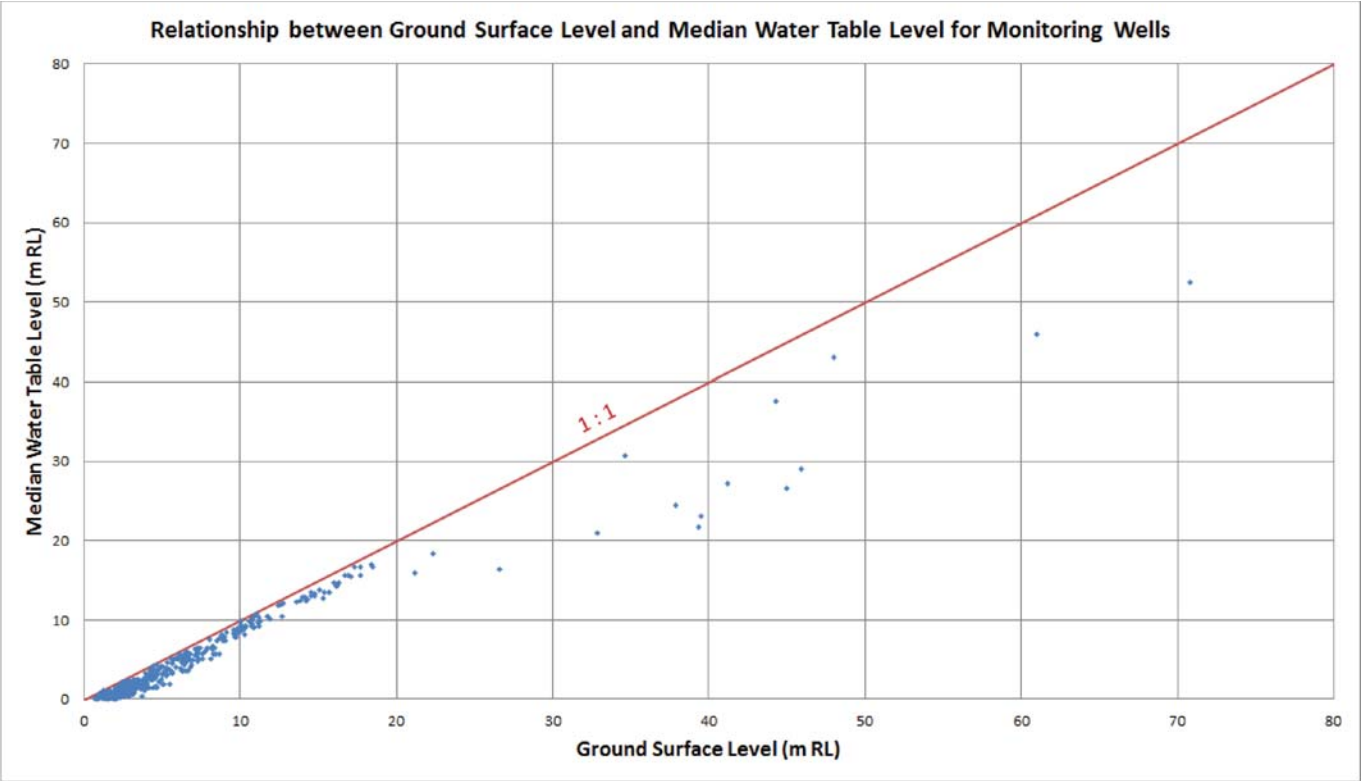


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ARGFILE		
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1:100,000		
Prepared By	Donna C. Taylor Ltd.	
FIGURE No.	Figure E.5	
Rev.	0	

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT Location Plan for Waimakariri River Cross-Sections

APPENDIX F: CALCULATION OF SURFACE SHOWING MEDIAN WATER TABLE ELEVATION

- **Figure F.1 Relationship between ground surface level and median water table elevation**
- **Figure F.2 Median water table elevation (reduced level), using longer-term data, including river breaklines but excluding drawdown points**
- **Figure F.3 Median water table elevation (reduced level), using longer term data, including river breaklines and drawdown points**
- **Figure F.4 Depth to median water table**



Notes:

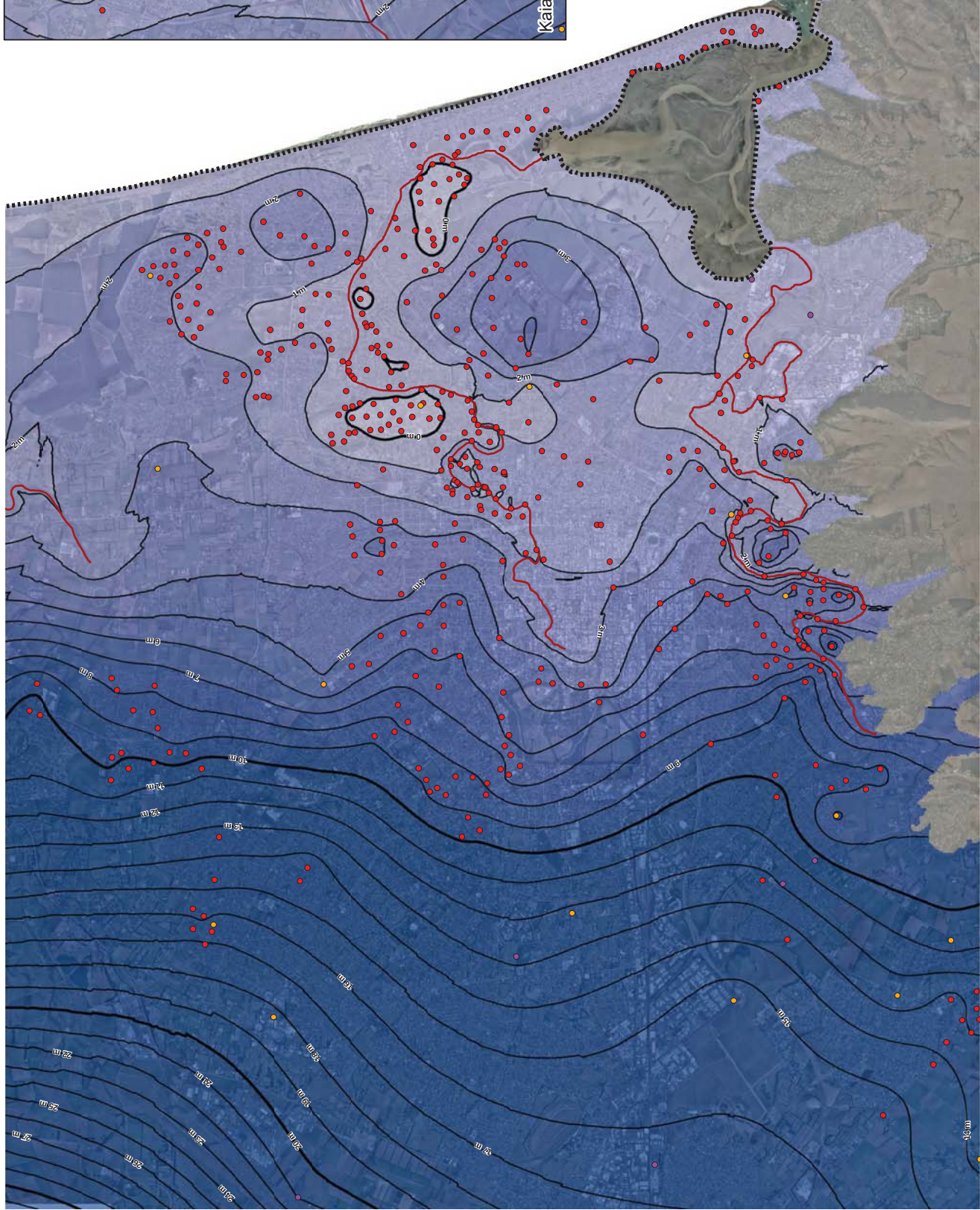
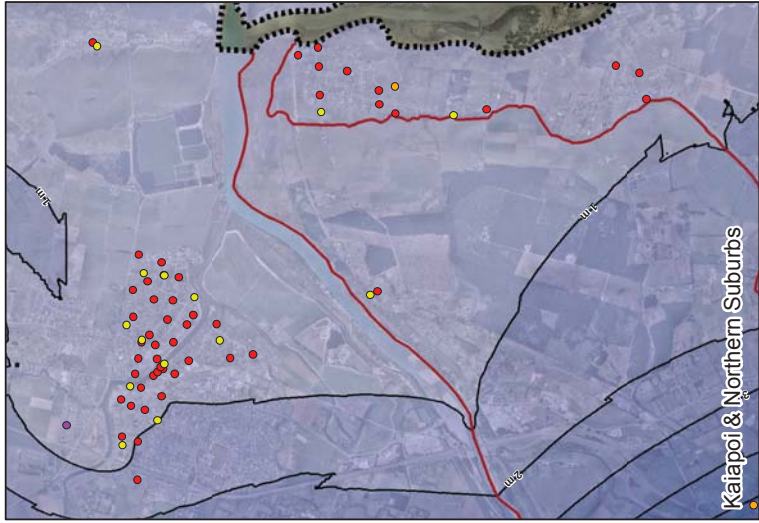


DRAWN	JSD	Feb.13
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APPROVED		
ARCFILE		
52020-0200-GWM56		
SCALE (AT A3 SIZE)		
Prepared by Tonkin & Taylor Ltd		
Ref. 52020.0200		

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
Relationship between ground surface level and
median water table level

FIGURE No. Figure F.1

Rev. 0



LEGEND

Monitoring Wells

- EQC Monitoring Well
- CCC Monitoring Well
- ≥ 9 Months Data
- ECan Monitoring Well

Other Analyses Data

- Coastal Strings
- River Strings

Level (m RL)

< 0	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	> 10
-----	-------	-------	-------	-------	-------	-------	-------	-------	-------	--------	------

Level Contour

No Data

Notes: Aerial Imagery supplied by New Zealand Aerial Mapping Ltd.

A3 SCALE 1:60,000

0 1 2 3 4 (km)

Location Plan

Inset Map

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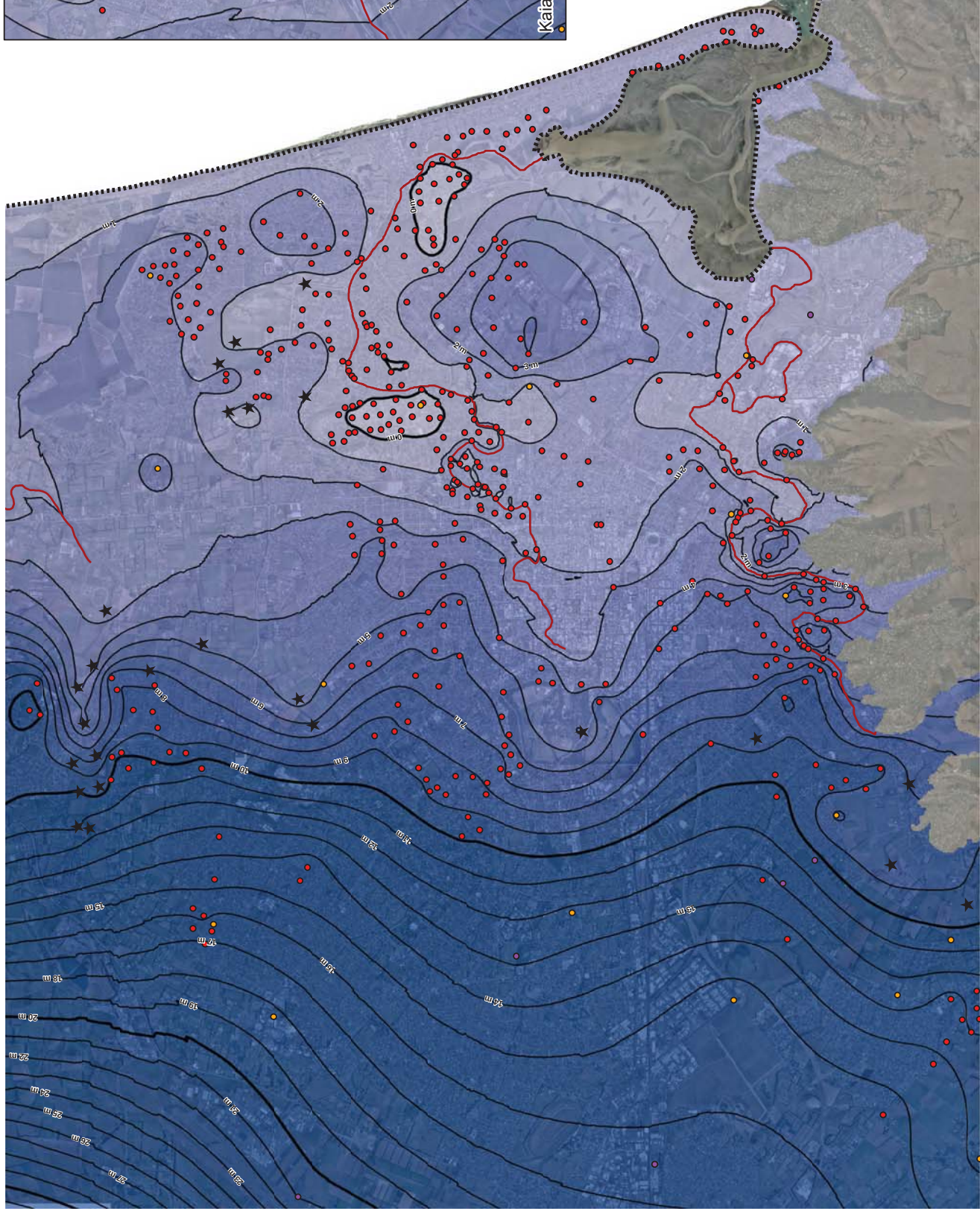
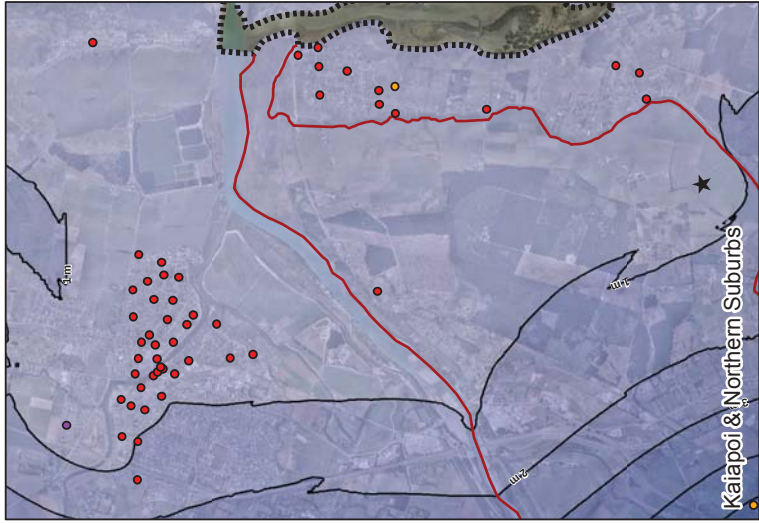
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DRAWN	JEL	Feb.13
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APPROVED		
ARCFILE	52020-0200-GWMM59	
SCALE (AT A3 SIZE)	1:60,000	
Prepared by	Tonkin & Taylor Ltd	
Ref	52020-0200	

FIGURE No. Figure F.2

Rev.

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
Median Water Table Reduced Level
(Excluding Drawdown Points)



LEGEND

Monitoring Wells

- EQC Monitoring Well
- ≥ 9 Months Data
- ECan Monitoring Well

Other Analyses Data

- Coastal Strings
- River Strings
- Drawdown Points

Level (m RL)

- < 0
- 0 - 1
- 1 - 2
- 2 - 3
- 3 - 4
- 4 - 5
- 5 - 6
- 6 - 7
- 7 - 8
- 8 - 9
- 9 - 10
- > 10
- No Data
- Level Contour

Notes: Aerial Imagery supplied by New Zealand Aerial Mapping Ltd.

A3 SCALE 1:60,000

0 1 2 3 4 (km)

North Arrow

Inset Map

Location Plan

TONKIN & TAYLOR

GNS SCIENCE

Drawn: JEL, Feb.13

Checked: []

Approved: []

Project: 52020-0200-GWM70

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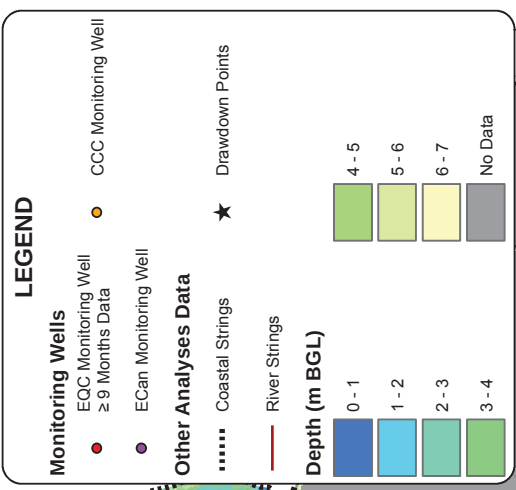
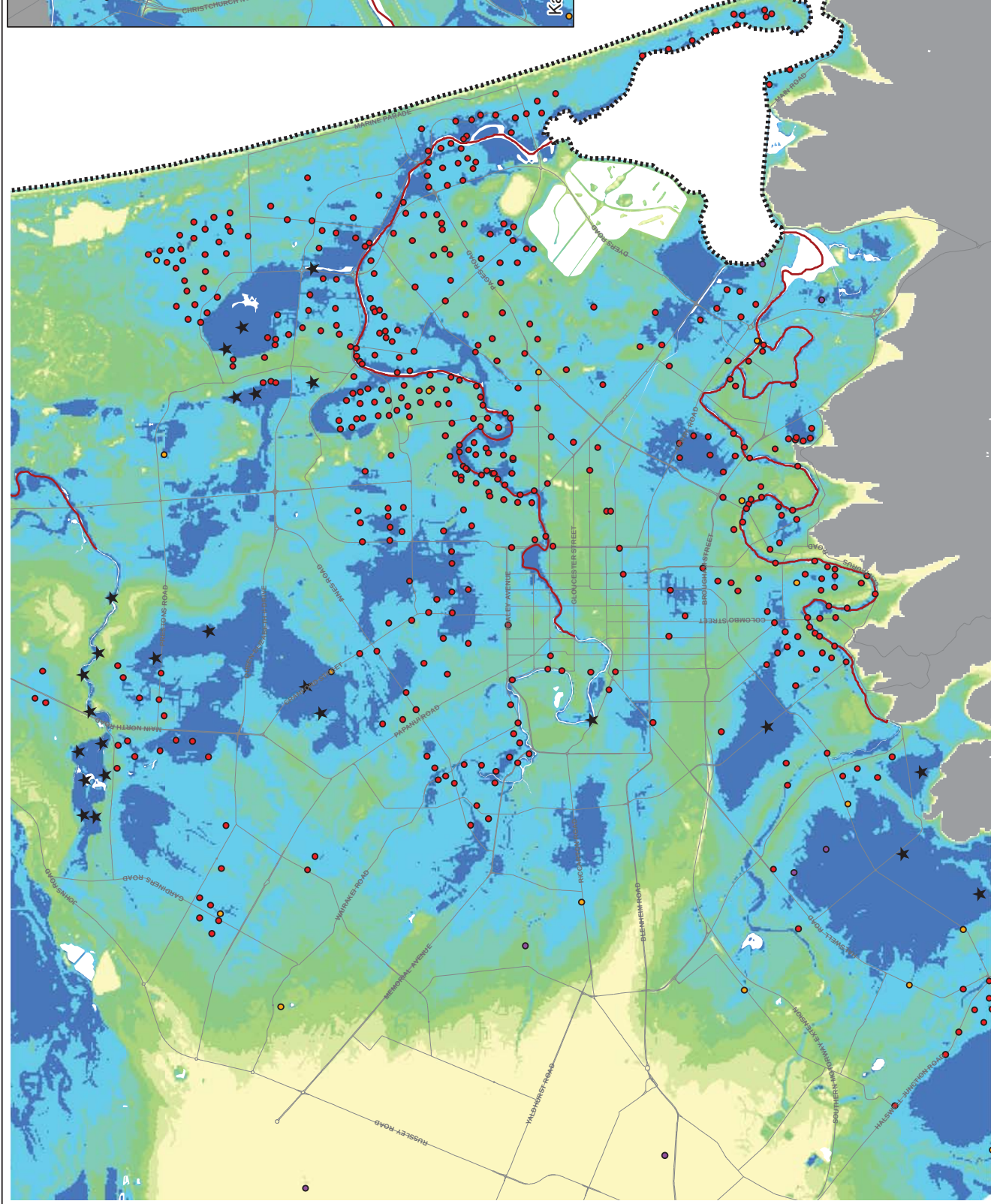
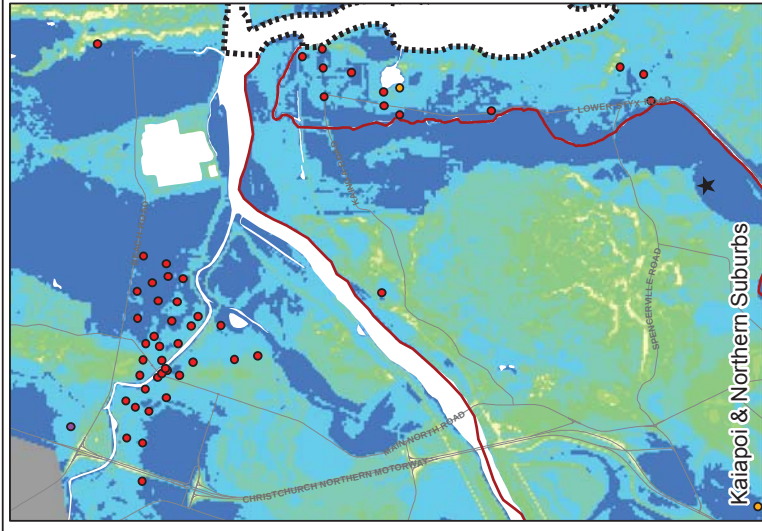
Prepared by: Tonkin & Taylor Ltd

Rev: 52020-0200

Figure F.3

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT

Median Water Table Reduced Level



CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT
Median Depth to Water Table

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A3 SCALE 1:60,000

0 1 2 3 4 (km)

Inset Map

Location Plan

Scale: 1:60,000

PROJECT No: 52020-0200

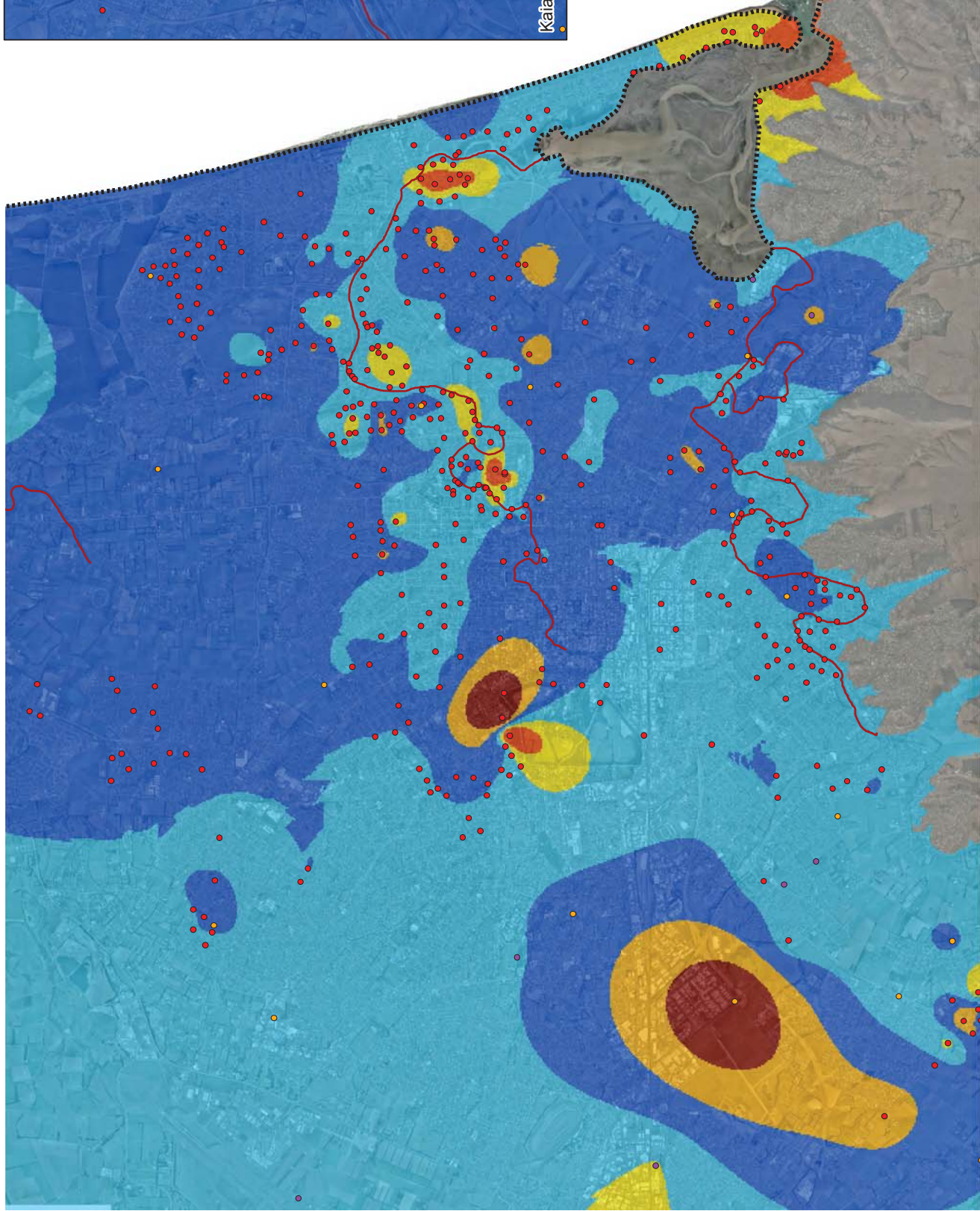
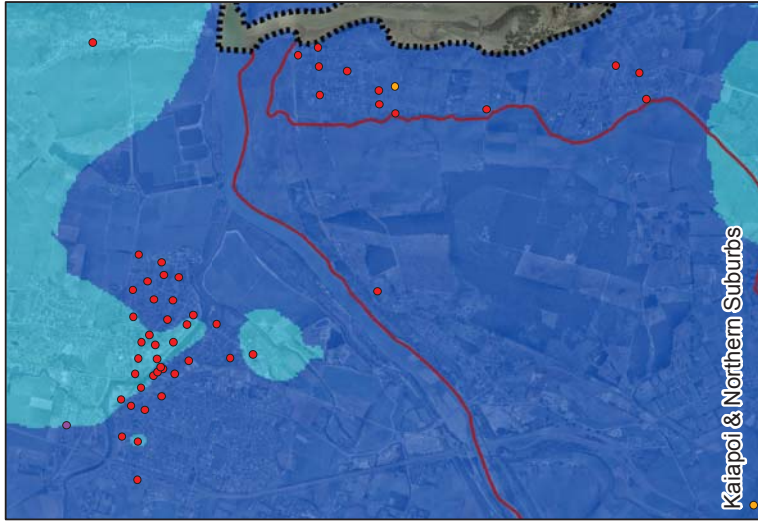
FIGURE No: Figure F.4

Rev.

DATE: 26/02/2013 Time: 4:13:51 p.m.

**APPENDIX G: CALCULATION OF SURFACE SHOWING MEDIAN
WATER TABLE ELEVATION, INCLUDING
SURROGATE MEDIANS FROM SHORT-TERM DATA**

- **Figure G.1** Offset plot for December 2012
- **Figure G.2** Median water table elevation (reduced level), including surrogate medians from <9 month data and river breaklines, excluding drawdown points
- **Figure G.3** Median water table elevation (reduced level), including surrogate medians from <9 month data, including river breaklines and drawdown points
- **Figure G.4** Depth to median water table, including surrogate medians from <9 month data
- **Figure G.5** Confidence index for water table elevation and water table depth



LEGEND

Monitoring Wells

- EQC Monitoring Well ≥ 9 Months Data
- EQC Monitoring Well
- ECan Monitoring Well

Other Analyses Data

- Coastal Strings
- River Strings

Offset (m)

- < -0.5
- $-0.5 - -0.25$
- $-0.25 - 0$
- $0.0 - 0.25$
- $0.25 - 0.5$
- > 0.5
- No Data

Notes: Aerial Imagery supplied by New Zealand Aerial Mapping Ltd.



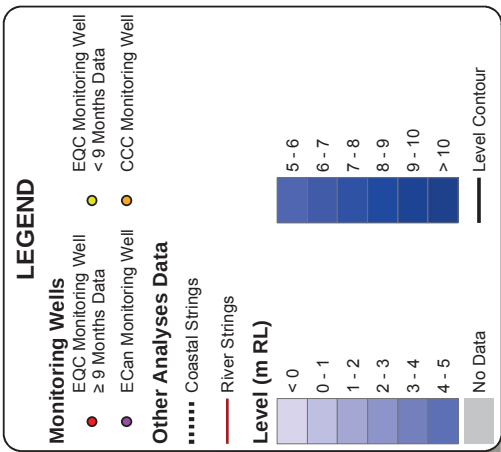
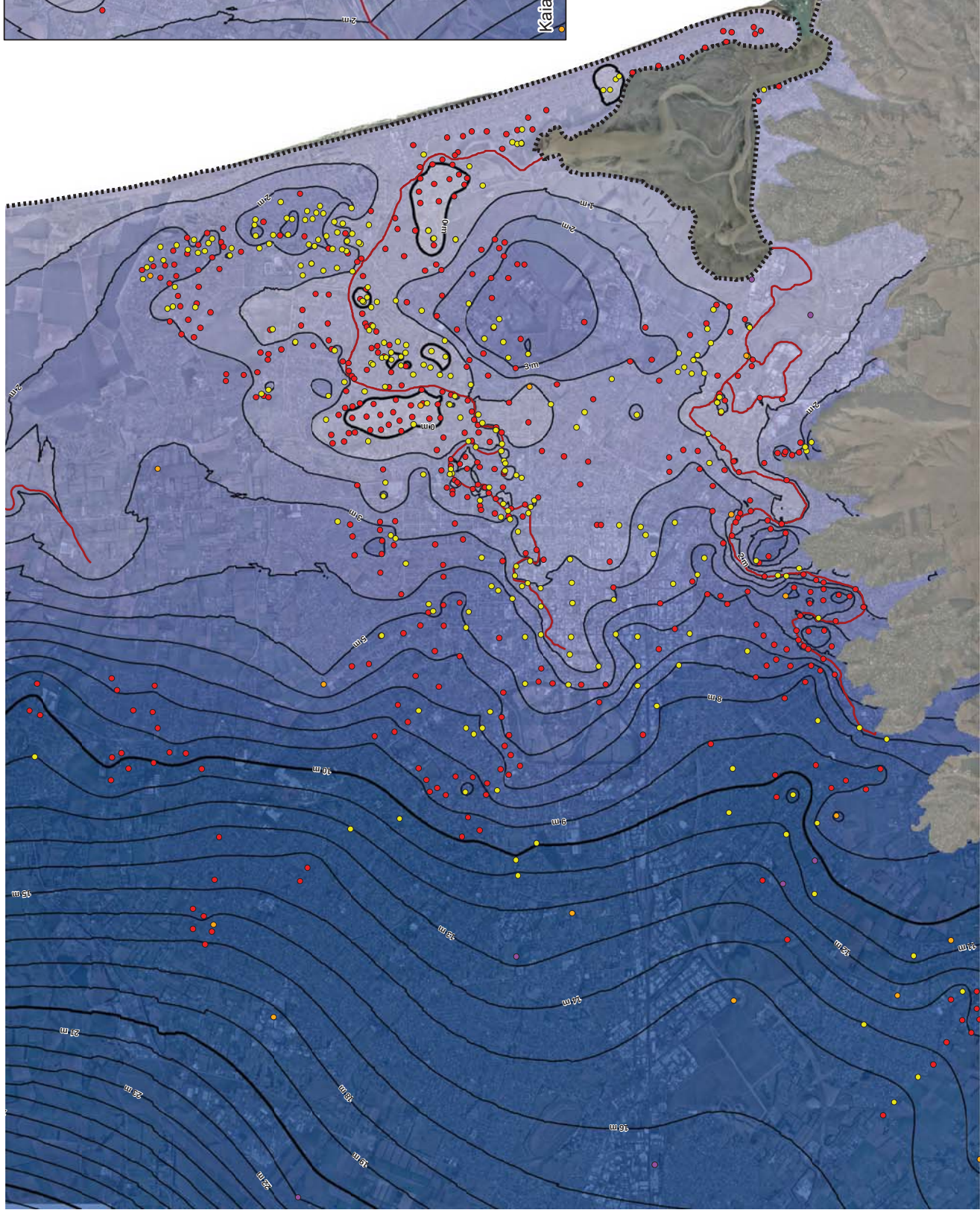
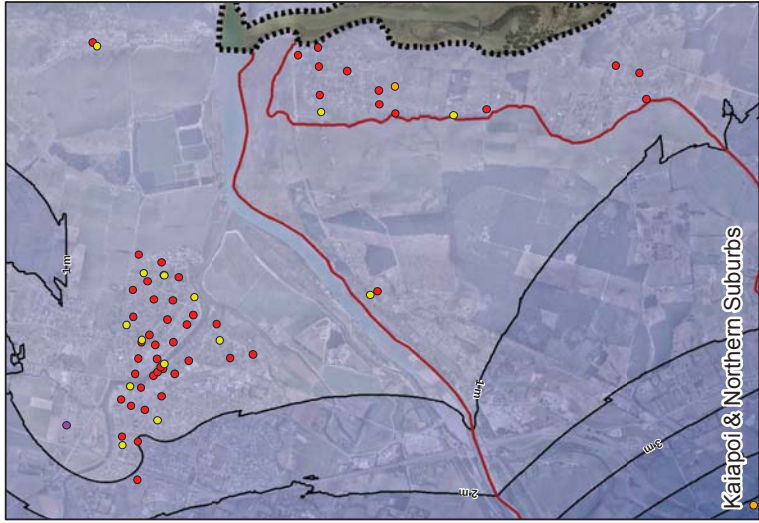
DRAWN	JEL	Feb.13
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APPROVED		
PROJECT	52020-0200-GWM60	
SCALE (A3 SIZE)	1:60,000	
Prepared by	Tonkin & Taylor Ltd	
Ref	52020-0200	

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT
December 2012 Offset Plot

FIGURE No. 52020-0200

Figure G.1

Rev.



Notes: Aerial Imagery supplied by New Zealand Aerial Mapping Ltd.

A3 SCALE 1:60,000

0 1 2 3 4 (km)

Location Plan

Inset Map

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APPROVED		
PROJECT	52020-0200-GWMM61	
SCALE (A3 SIZE)	1:60,000	
Prepared by	Tonkin & Taylor Ltd	
Ref	52020-0200	

FIGURE No. 52020-0200

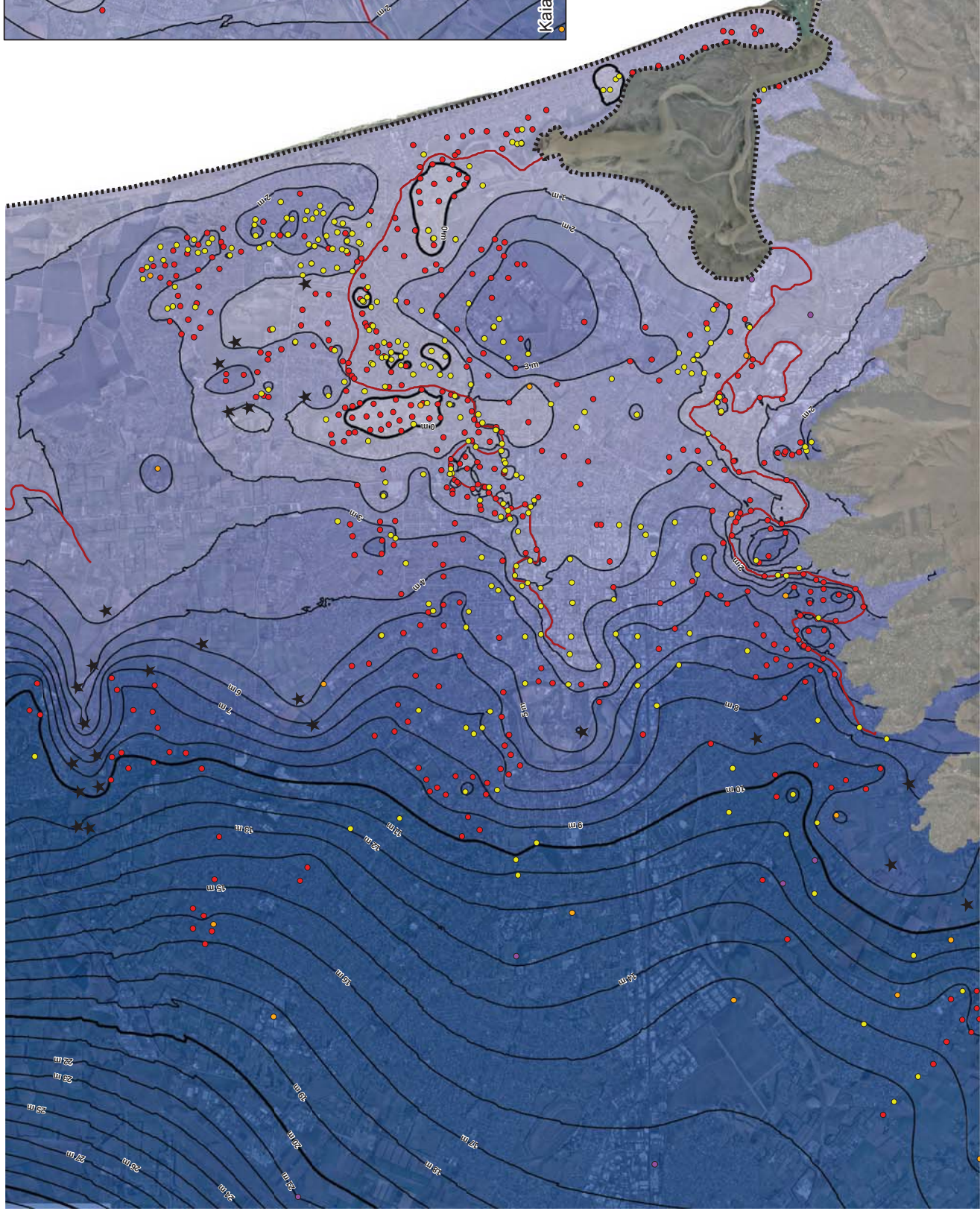
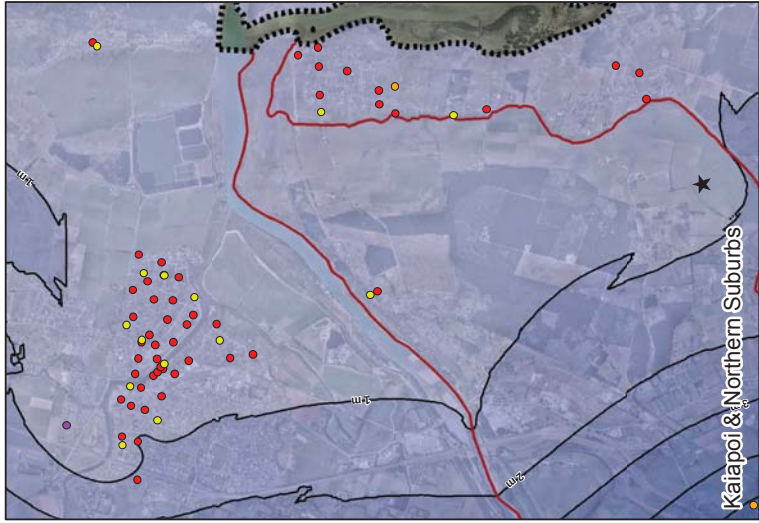
Rev.

CHRISTCHURCH MEDIAN WATER
TABLE ELEVATION REPORT

Median Water Table Reduced Level, Including
Data < 9 Months. (Excluding Drawdown Points)

FIGURE No. 52020-0200

Rev.



LEGEND

Monitoring Wells

- EQC Monitoring Well ≥ 9 Months Data (Yellow dot)
- EQC Monitoring Well < 9 Months Data (Red dot)

Other Analyses Data

- Coastal Strings (Dashed line)
- River Strings (Solid line)
- Drawdown Points (Star symbol)

Level (m RL)

< 0	0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	> 10
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	--------	--------

Level Contour (Solid line)

Notes: Aerial Imagery supplied by New Zealand Aerial Mapping Ltd.

A3 SCALE 1:60,000

0 1 2 3 4 (km)

Location Plan

Inset Map

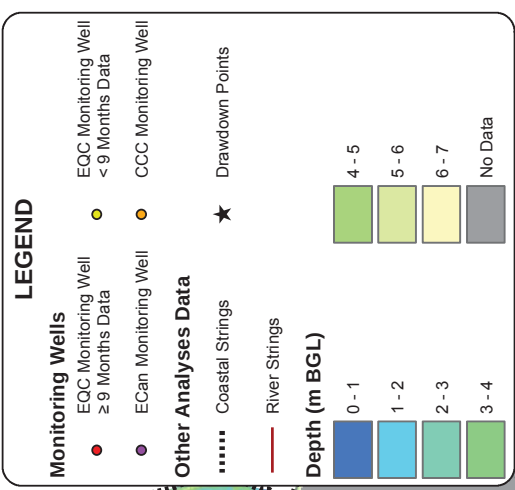
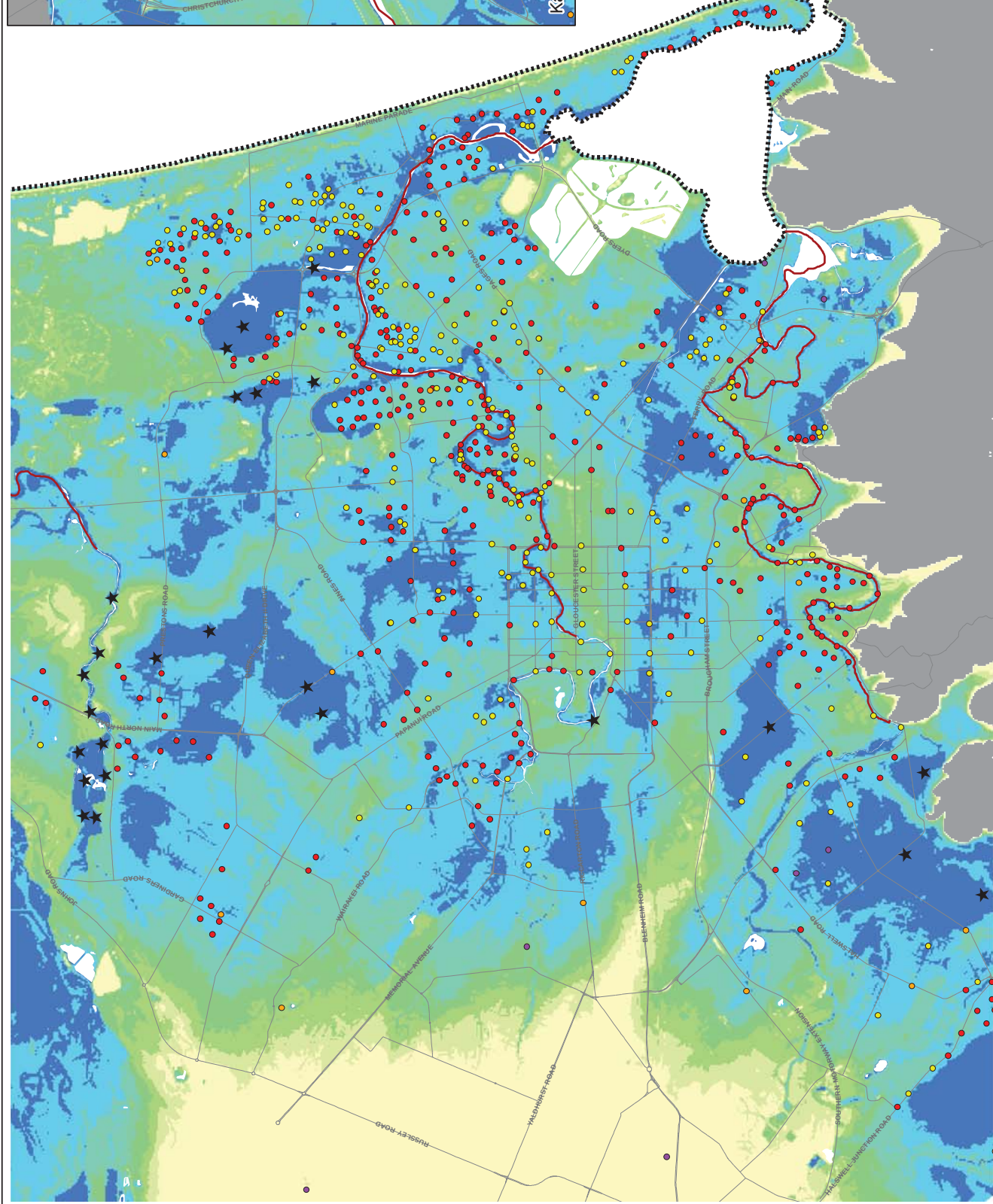
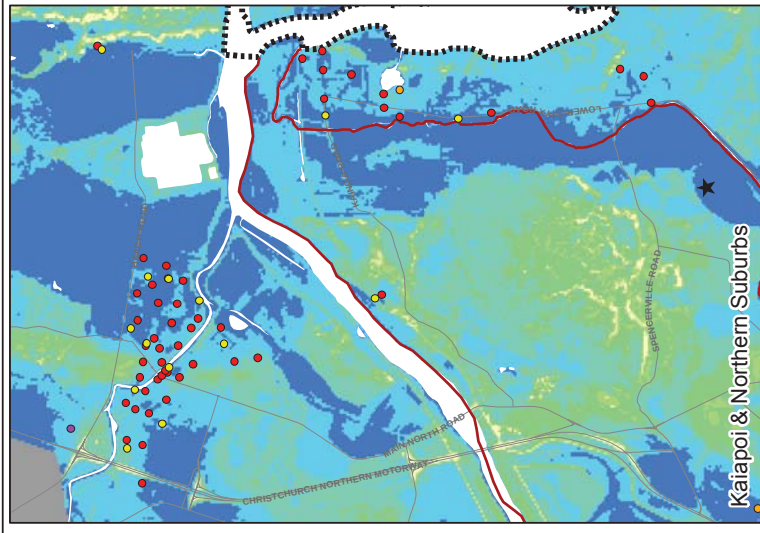
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APPROVED			
PROJECT 52020-0200-GWMM41			
SCALE (AT A3 SIZE) 1:60,000			
Prepared by Tonkin & Taylor Ltd			
Ref: 52020-0200			

FIGURE No: Figure G.3

Rev.



CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT
Median Depth to Water Table, Including Data < 9 Months

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A3 SCALE 1:60,000

0 1 2 3 4 (km)

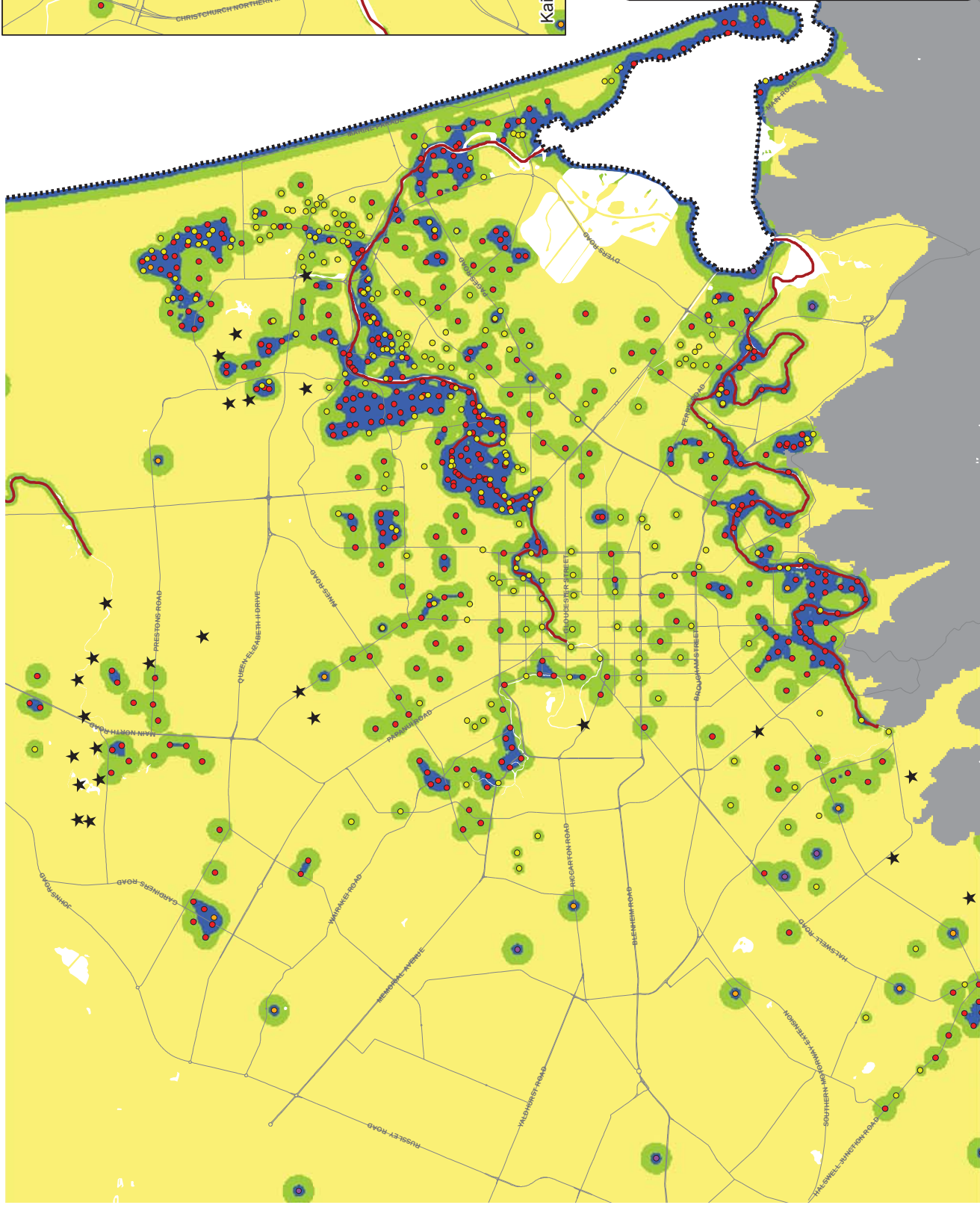
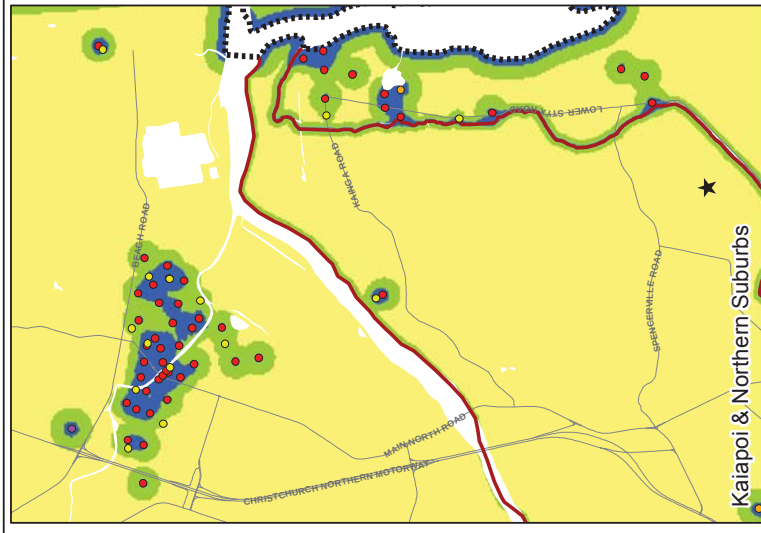
Location Plan

Inset Map

GNS SCIENCE

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DRAWN	JEL	Feb.13
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APPROVED		
PROJECT No. 52020-0200		
SCALE (A3 SIZE) 1:60,000		
FIGURE No. Figure G.4		
Rev.		



LEGEND

Monitoring Wells

- EQC Monitoring Well ≥ 9 Months Data
- EQC Monitoring Well < 9 Months Data
- CCC Monitoring Well

Other Analyses Data

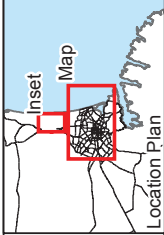
- Coastal Strings
- River Strings
- Drawdown points

Confidence Index

- Low
- Medium
- High
- No Data

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A3 SCALE 1:60,000



DRAWN	JJC/Mar/13
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APPROVED	
PROJECT	52020-0200
SCALE	1:60,000
SCALE (A3 SIZE)	1:60,000
PROJECT No.	52020-0200

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT

Confidence index for water table elevation and water table depth

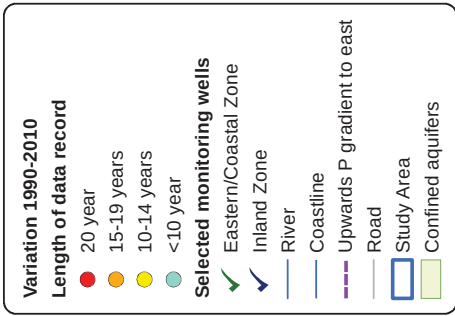
FIGURE No. Figure G.5

Rev.

APPENDIX H: WATER LEVEL FLUCTUATION

- **Figure H.1** Location of monitoring wells used in the assessment of pre-earthquake fluctuations
- **Figure H.2** Range of groundwater elevation in metres, for the period 1990-2010
- **Figure H.3** Standard deviation of groundwater elevation in metres, for the period 1990-2010
- **Figure H.4** Groundwater elevation in selected monitoring well water levels, 1990-2010, plotted by Julian Day of the year
- **Figure H.5** Groundwater elevation in selected monitoring wells, rainfall and groundwater recharge, 1990-2010 time series
- **Figure H.6** Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence
- **Figure H.7** Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence
- **Figure H.8** Ground and shallow groundwater elevation changes in selected monitoring wells during the Canterbury earthquake sequence
- **Figure H.9** Difference between the 85th percentile and the median groundwater elevation, 1990-2010

Map showing the location of monitoring wells used in the assessment of shallow groundwater fluctuations, coloured according to the length of available continuous record. Monitoring wells selected for extended analysis are annotated with ticks. The area of confined aquifers (green polygons) and the approximate transition (thick dashed purple line) between downwards water pressure gradients (west of line) and upwards water pressure gradients (east of line) follows Weeber (2008), supplied by Environment Canterbury.

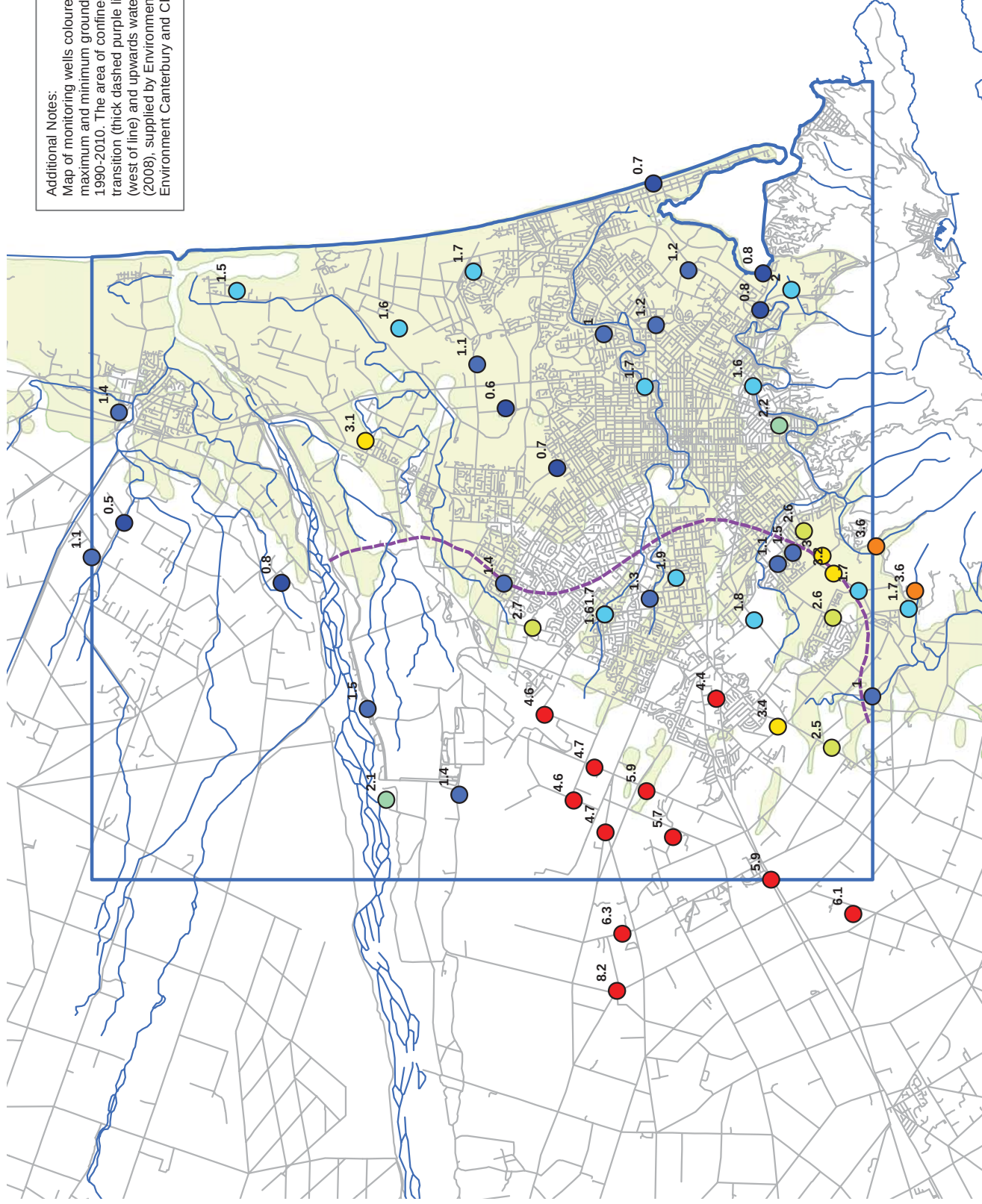


DRAWN	CXP	Feb13
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APPROVED		
ARCFILE 52020-0200-CPT035 SCALE (AT A3 SIZE) 1:125,000		
Prepared By Tonkin & Taylor Ltd. Ref. 52020 0200		

FIGURE No. **Figure H.1**

Additional Notes:

Map of monitoring wells coloured according to the range (in metres) between maximum and minimum groundwater elevations recorded during the period 1990-2010. The area of confined aquifers (green polygons) and the approximate transition (thick dashed purple line) between downwards water pressure gradients (west of line) and upwards water pressure gradients (east of line) follows Weeber (2008), supplied by Environment Canterbury. Monitoring data supplied by Environment Canterbury and Christchurch City Council.

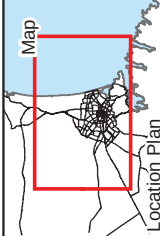


Variation 1990-2010
Range = Max-Min (m)

- >4
- 3.5 - 4.0
- 3.0 - 3.5
- 2.5 - 3.0
- 2.0 - 2.5
- 1.5 - 2.0
- 1.0 - 1.5
- <1.0

- River
- Coastline
- Upwards P gradient to east
- Road
- Study Area
- Confined aquifers

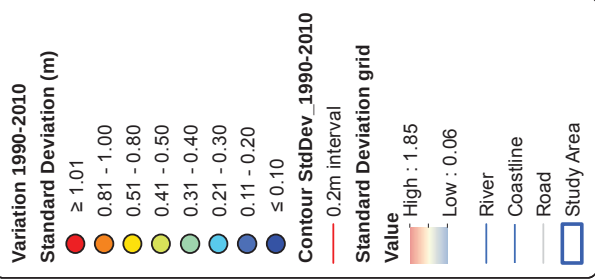
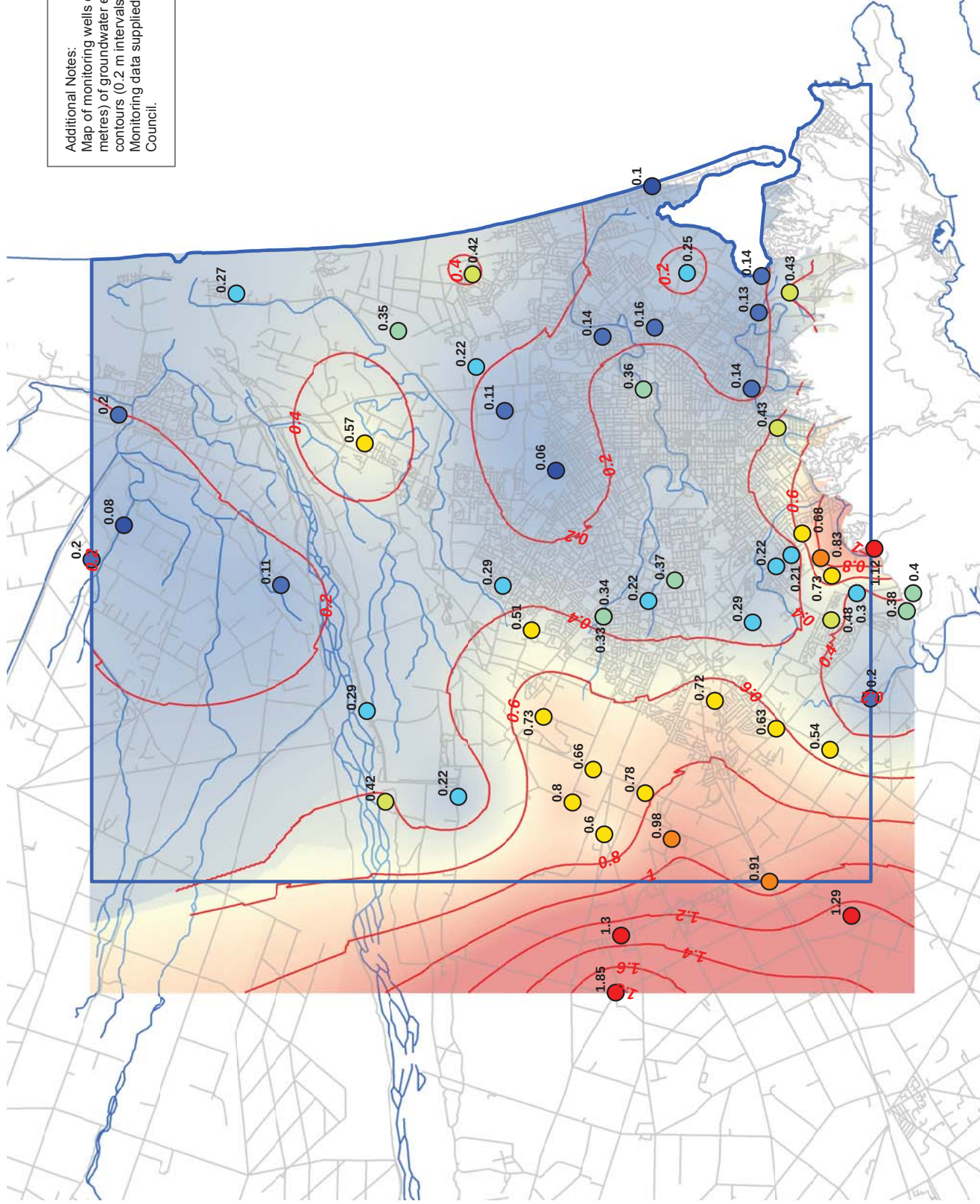
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A3 SCALE 1:125,000



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ARCHFILE		
52020-0200-CPT036		
SCALE (AT A3 SIZE)		
1:125,000		
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Ref: 52020.0200		

Additional Notes:

Map of monitoring wells coloured according to the standard deviation (in metres) of groundwater elevations during the period 1990-2010. A grid and contours (0.2 m intervals) have been interpolated from these data by kriging. Monitoring data supplied by Environment Canterbury and Christchurch City Council.

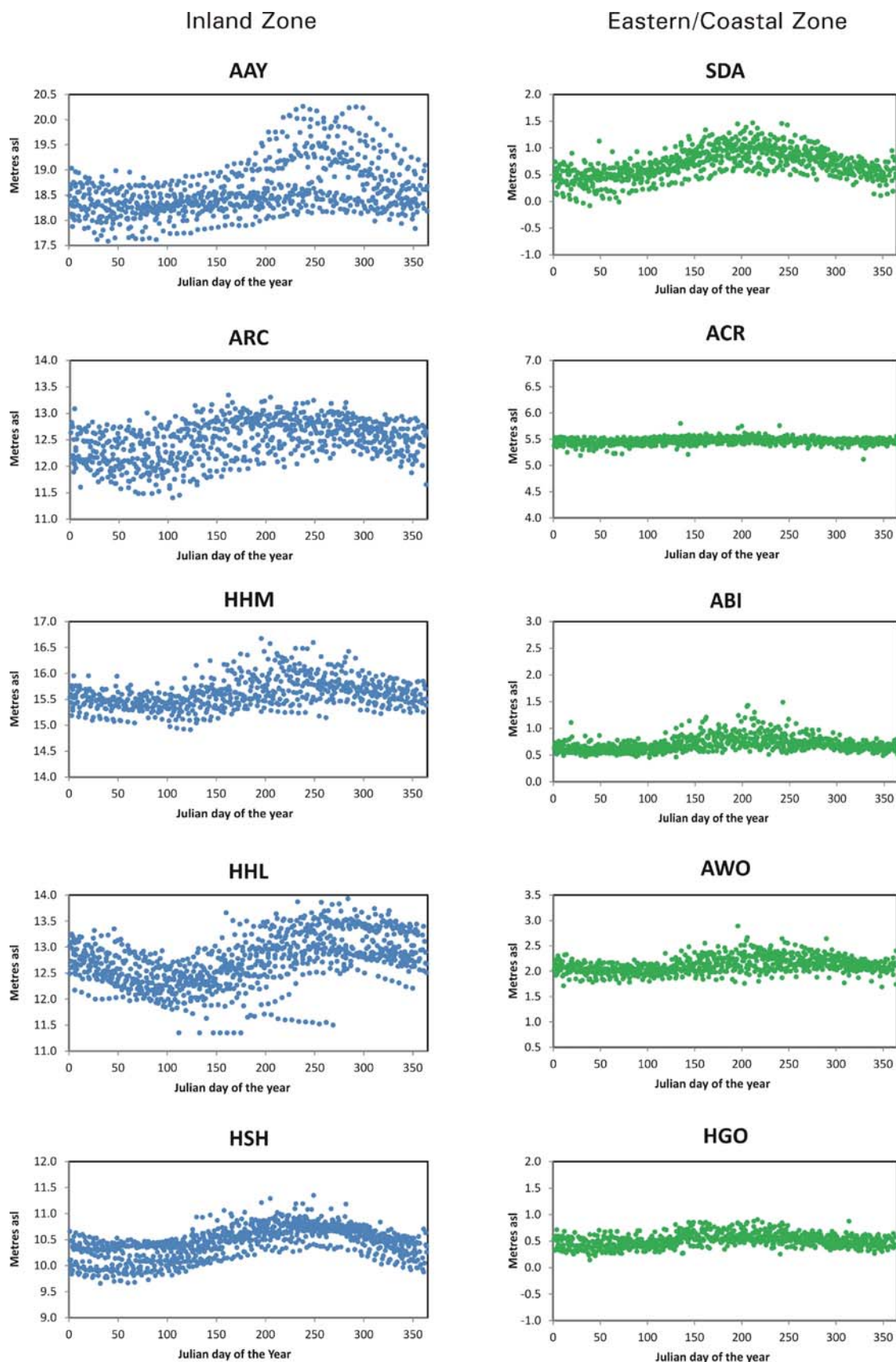


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A3 SCALE 1:125,000



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52020-0200-CPT037		
SCALE (A3 AS SIZED)		
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Notes:
Groundwater elevations (in mRL above sea level) in selected monitoring wells for the period 1990-2010, plotted according to the numerical (Julian) day of the year (0-365). Monitoring wells from the inland zone (blue) are distinguished from the eastern coastal zone (green). The scale ranges of the water elevations (vertical axes) are all the same (3 m), although absolute values differ between graphs, for ease of comparison between graphs. Monitoring data collected by NIWA and supplied by Christchurch City Council.



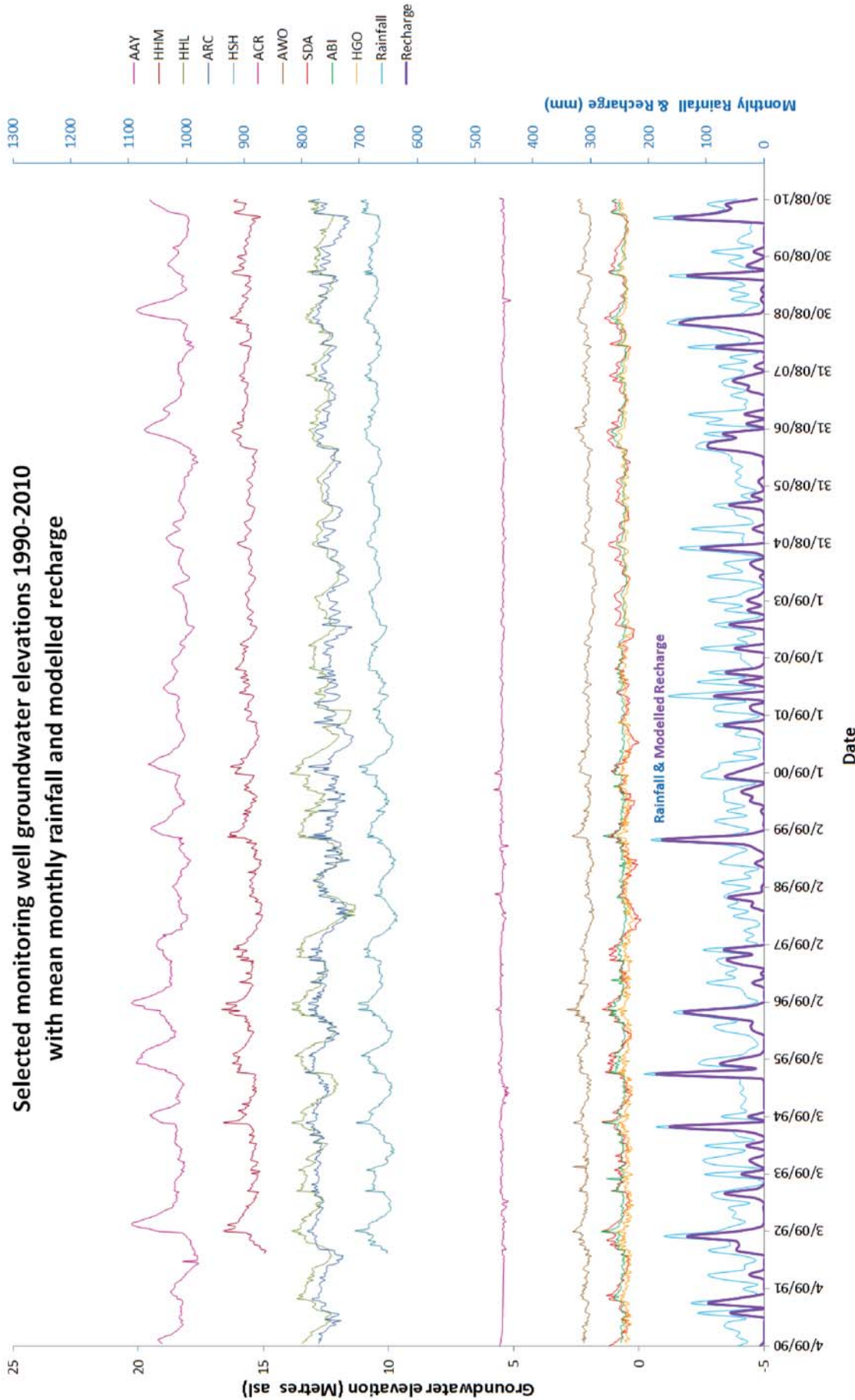
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ARCFILE	52020-0200-CPT040	
SCALE (AT A3 SIZE)		
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Ref.	52020.0200	

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT

Groundwater elevation in selected monitoring well water levels,
1990-2010, plotted by numerical (Julian) day of the year

FIGURE No. Figure H.4

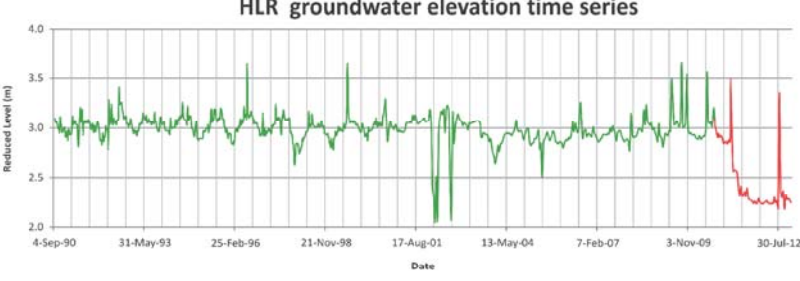
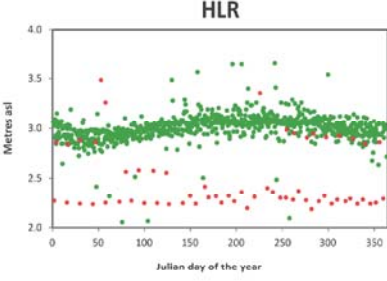
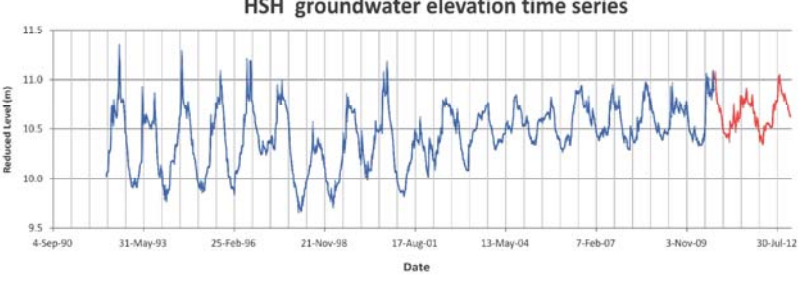
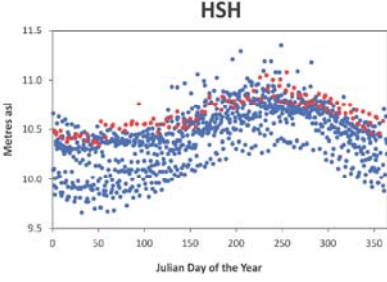
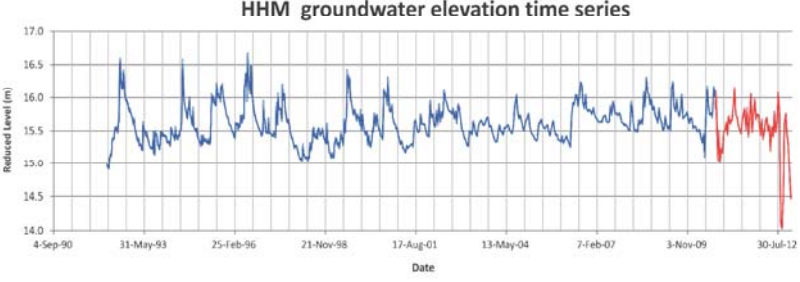
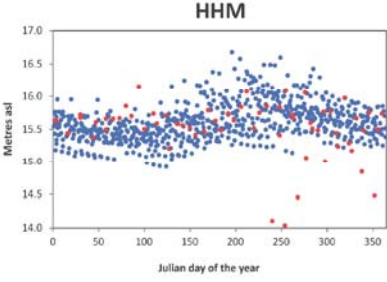
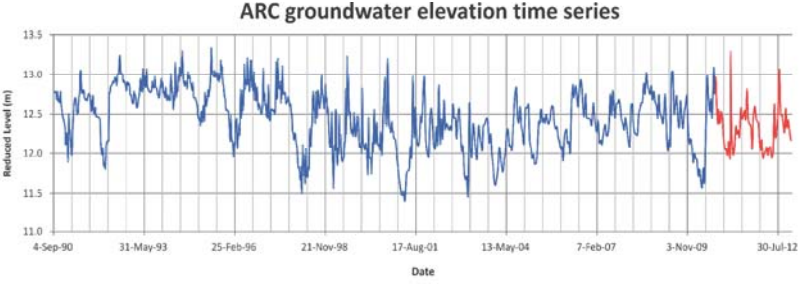
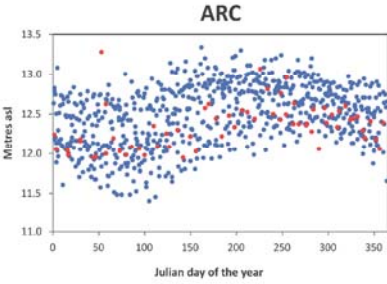
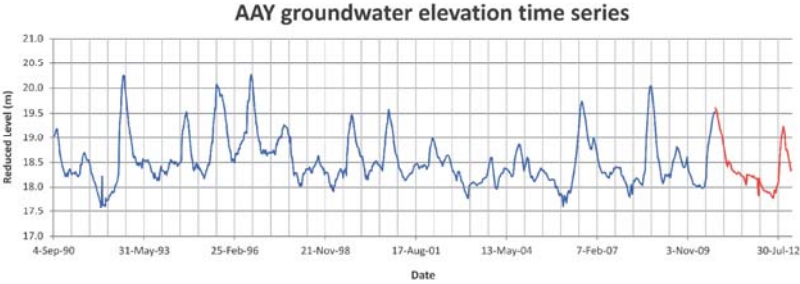
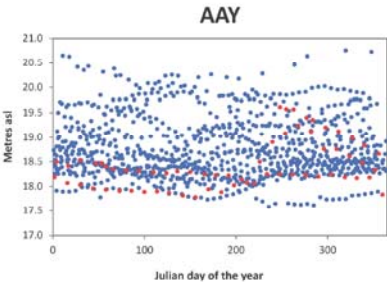
Rev. 0



Notes: Time series plot of water level fluctuations in selected monitoring wells during the period 1990-2010.
Data collected by NIWA and supplied by Christchurch City Council. The mean monthly rainfall and modelled groundwater recharge (in mm – right axis) at Christchurch airport is shown at the base of the graph for reference. Monitoring data collected by NIWA and supplied by Christchurch City Council. Rainfall data sourced from NIWA through the Cliflo database.



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SCALE (AT A3 SIZE)		



Inland Zone
• pre Darfield Earthquake
• post Darfield Earthquake

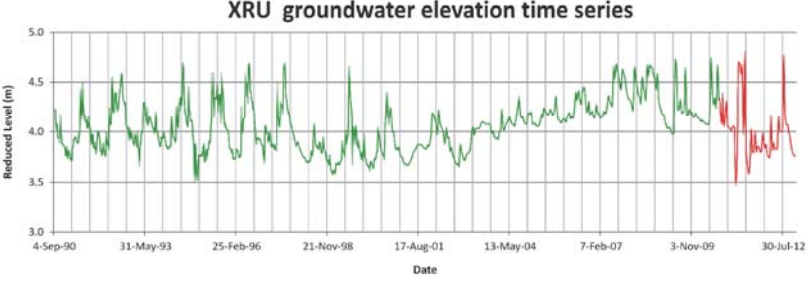
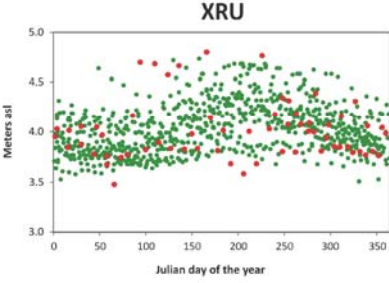
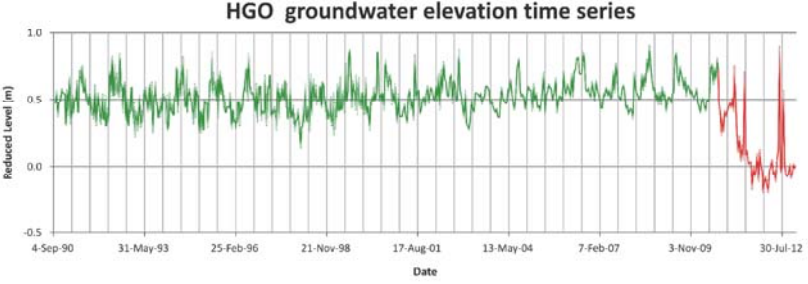
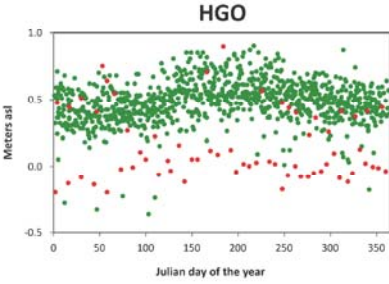
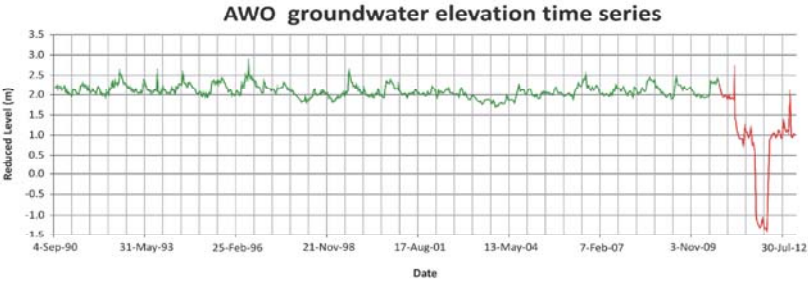
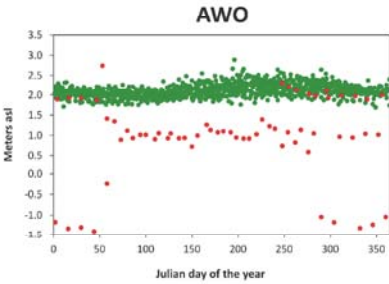
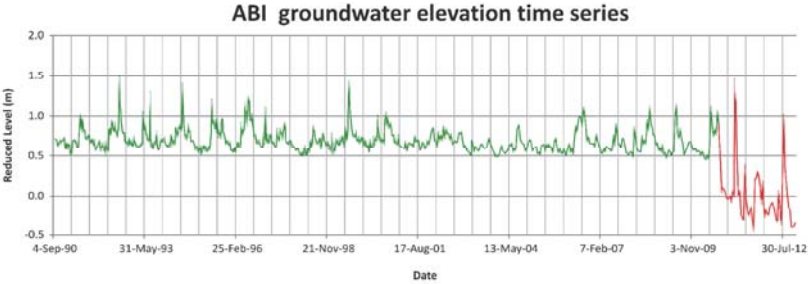
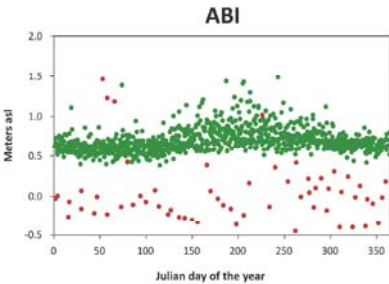
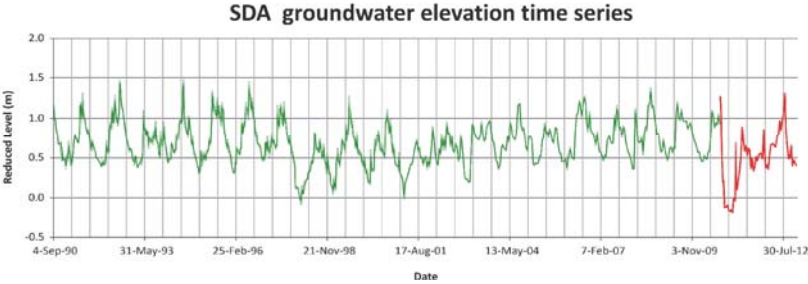
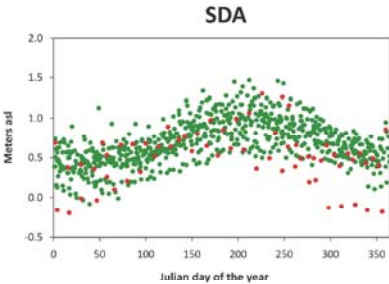
Eastern/Coastal Zone
• pre Darfield Earthquake
• post Darfield Earthquake

Notes:



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APPROVED		
ARCFILE		
52020-0200-CPT054		
SCALE (AT A3 SIZE)		
Prepared by Tonkin & Taylor Ltd		
Ref. 52020.0200		

CHRISTCHURCH MEDIAN WATER TABLE ELEVATION REPORT	
Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence	
FIGURE No. Figure H.6	Rev. 0



Eastern/Coastal Zone

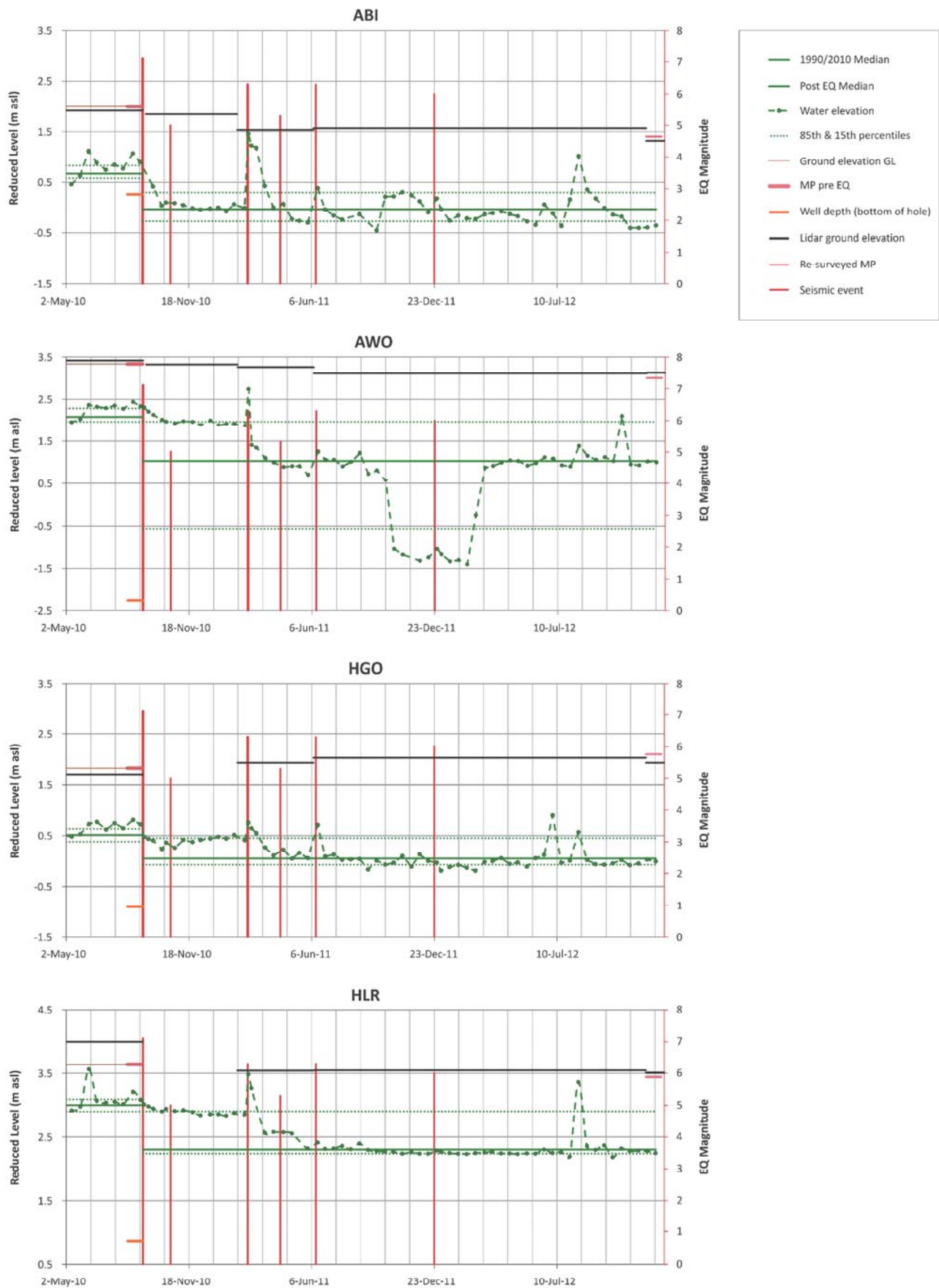
- pre Darfield Earthquake
- post Darfield Earthquake

Notes:



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ARCFILE		
52020-0200-CPT055		
SCALE (AT A3 SIZE)		
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CHRISTCHURCH MEDIAN WATER		
TABLE ELEVATION REPORT		
Comparison of shallow groundwater elevation in monitoring wells before and during the Canterbury earthquake sequence		
FIGURE No.	Figure H.7	Rev. 0



Notes:



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APPROVED		
ARCFILE	52020-0200-CPT056	
SCALE	(AT A3 SIZE)	
Prepared by	Tonkin & Taylor Ltd	
Ref.	52020.0200	

CHRISTCHURCH MEDIAN WATER		
TABLE ELEVATION REPORT		
Ground & shallow groundwater elevation changes in selected		
monitoring wells during Canterbury earthquake sequence		
FIGURE No.	Figure H.8	Rev.
		0

Additional Notes:

Map of monitoring wells coloured according to the difference (in metres) between the 85th percentile and the median groundwater elevation recorded from 1990-2010. A grid and contours (0.2 m intervals) have been interpolated from these data by kriging. Monitoring data supplied by Environment Canterbury and Christchurch City Council.

Variation 1990-2010
Difference 85percentile-Median (m)

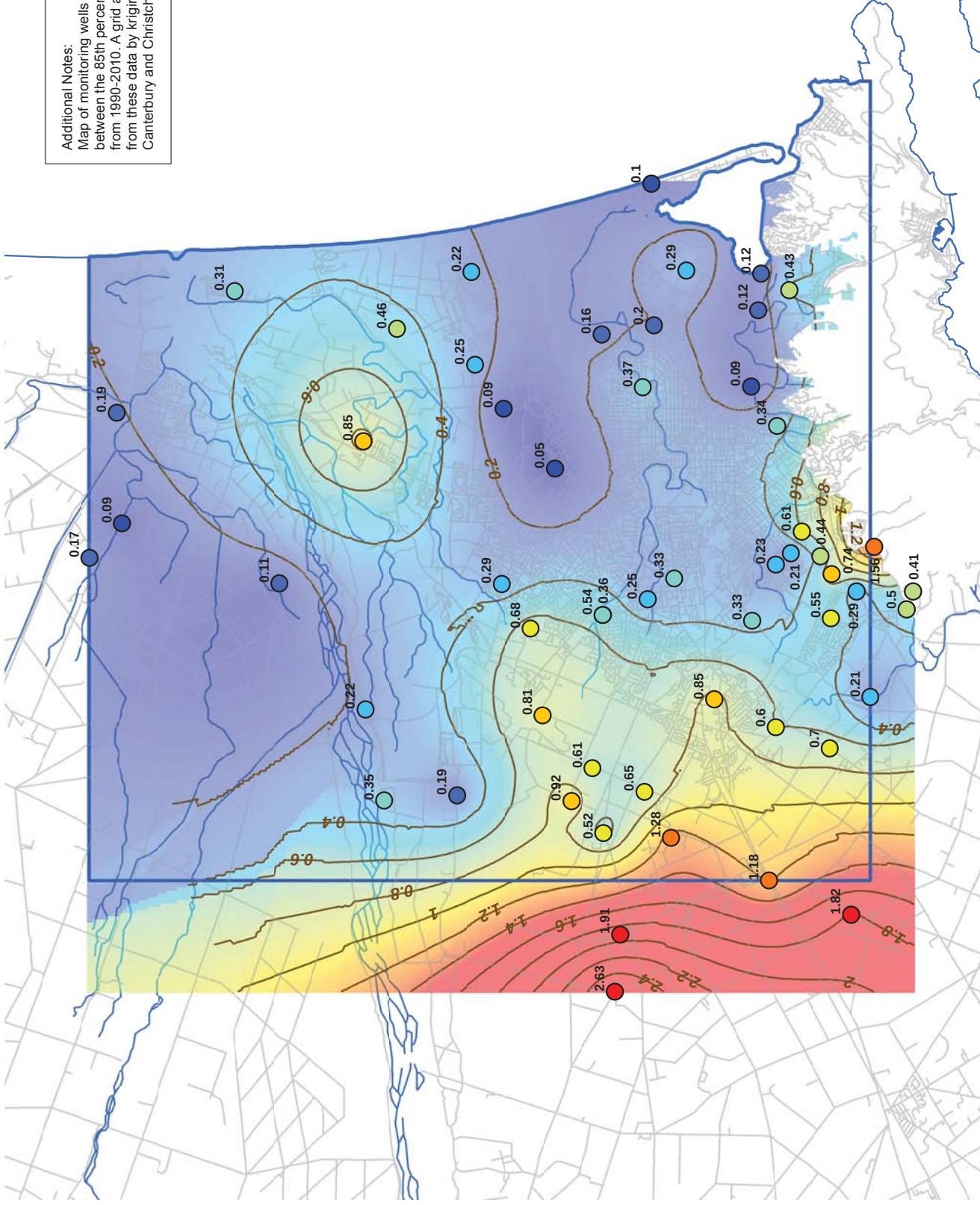
- ≥ 1.61
- 1.01 - 1.60
- 0.71 - 1.00
- 0.51 - 0.70
- 0.41 - 0.50
- 0.31 - 0.40
- 0.21 - 0.30
- 0.11 - 0.20
- ≤ 0.10

Contour Diff. 85%tile_median_1990-2010
0.2m interval

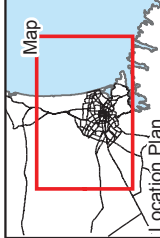
Difference 85percentile-Median grid

Value
High : 2.63
Low : 0.05

- River
- Coastline
- Road
- Study Area



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A3 SCALE 1:125,000



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Ref.	52020.0200	



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