ARTESIAN HEATING AND COOLING IN CHRISTCHURCH

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ABSTRACT

Christchurch's aquifers are ideally suited to ground-sourced energy extraction because of the highly permeable strata, consistent temperature of the source, and high thermal attenuation upon reinjection. As such, there is increasing utilisation of aquifers beneath the Christchurch Central Business District (CBD) during the earthquake rebuild to source energy.

Groundwater is pumped from deeper aquifers at approximately 12 to 15 °C and run through heat exchange plant to extract or dispose of heat energy, which can be used to heat or cool a building. The groundwater is then reinjected back into shallower aquifers or discharged into waterways at up to an 8 °C temperature change, resulting in a non-consumptive or hydrogeologically neutral "take".

Reinjection wells are commonly drilled into Aquifer 1 (Riccarton Gravel Formation), found at about a depth of 25 to 45 m below ground level. Groundwater extraction generally occurs from the deeper aquifers (Aquifers 2 to 4), at about 65 to 140 m depth. The vertical distribution of the aquifers limits hydraulic connectivity and recirculation of the discharged water from the abstraction wells, and allows pairs of reinjection and abstraction wells to be positioned in close proximity to each other. The positioning of wells is a critical factor in space-constrained urban sites, and ensuring access for drilling rigs to maintain the wells becomes a key planning consideration in developing these systems and sites.

Reinjection wells are designed in a similar manner to normal pumping wells with the addition of a grout sealed annulus to prevent short-circuiting around the well casing under pressure. Flow and pressure testing are completed at the same time as the testing of the abstraction wells, and projects to date indicate that Aquifer 1 has a remarkably high capacity for reinjection.

Key issues include excessive pressures in the aquifer where reinjection occurs, reinjection pressures within the reinjection wells and interference from surrounding reinjection wells that are hydraulically connected within Aquifer 1. Wider pressure increases in Aquifer 1 have the potential to develop due to reinjection, and approaches to avoid the unintended emergence of groundwater seepage at surface or around build environment assets is required.

The paper discusses technical highlights of ground-source well development in the Christchurch CBD and makes suggestions for the design of resilient and sustainable ground-source supply and reinjection infrastructure.

KEYWORDS

Hydrogeology, groundwater, aquifer, ground source, cooling, heating, reinjection, water wells, earthquake rebuild, sustainable water management

PRESENTER PROFILE

Mike Thorley is an Associate Hydrogeologist based at Beca Ltd in Christchurch specializing in ground-source heating and cooling projects, including the design and testing of abstraction and reinjection wells and numerical groundwater modelling to support design and effects assessment.

1 INTRODUCTION

The rebuild of Christchurch has presented a unique opportunity to develop alternative energy sources for larger commercial and civic projects. Ground-source energy from the underlying Christchurch Artesian Aquifer system is being utilized to both source and discharge heat energy through mechanical heat exchange. The underlying artesian aquifer system is ideally suited to high flow and low temperature heating and cooling plant due to the high yielding nature and relatively steady temperature of about 12 to 15 °C. About a dozen large building projects in the Christchurch CBD have been or are being constructed utilizing this technology. Figure 1 shows the locations of the major ground-source heating and cooling projects in the CBD.

Figure 1: Sites in the Christchurch CBD utilizing ground source heating and/or cooling

Ground-sourced heating is widely recognized as one of the most energy efficient and sustainable methods for heating and cooling buildings. The process involves pumping water through a heat exchanger and extracting or discharging heat, depending on whether the system is operating in cooling or heating mode. In the Christchurch CBD, the volume of water required ranges from about 15 to 150 L/s depending on the design of the heat exchange system and the heating and cooling requirements of the building.

Ground-sourced heating and cooling system provides the following benefits:

- Lower operating costs;
- Lower energy usage;
- More reliable system than cooling towers;
- No local emissions compared to a boiler system; and
- Lower maintenance costs than compared to a boiler and cooling tower system due to the legionella risk.

2 HYDROGEOLOGY

The geology of the Christchurch area comprises a sequence of aquifers (zones of high groundwater-yielding gravels) and aquitards (zones of lower permeability silts) that extend to approximately 500 m deep (Brown and Weeber, 1992). A schematic diagram of the aquifer structure beneath Christchurch is shown in Figure 2 below.

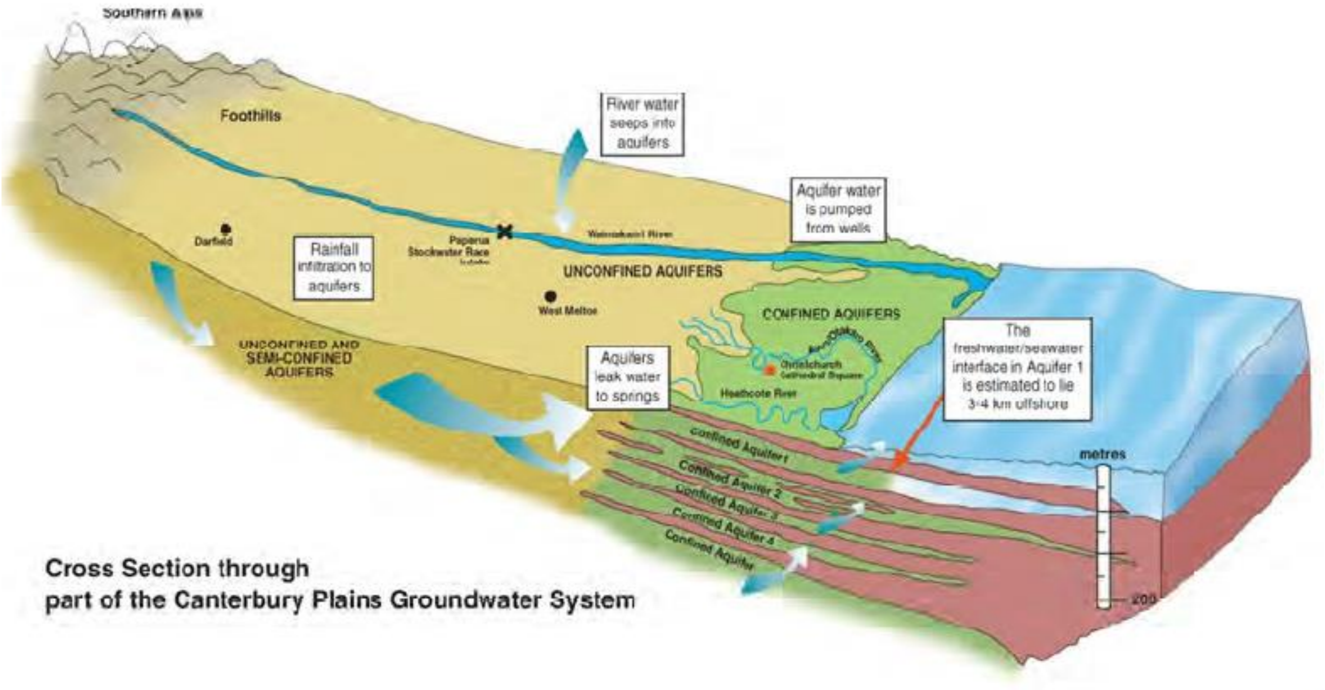


Figure 2: Schematic cross-section of the Christchurch Aquifer System (from Weeber, 2008)

The geology underlying Christchurch can be inferred from surrounding bore logs and is characterised by unconsolidated alluvial gravel, sand, and silt over-bank deposits and marine or lagoon derived deposits comprising sand, silt, clay, and peat. Figure 3 shows the sequence of geological formations and aquifers beneath Christchurch and the aquifers from which water can be abstracted or reinjected.

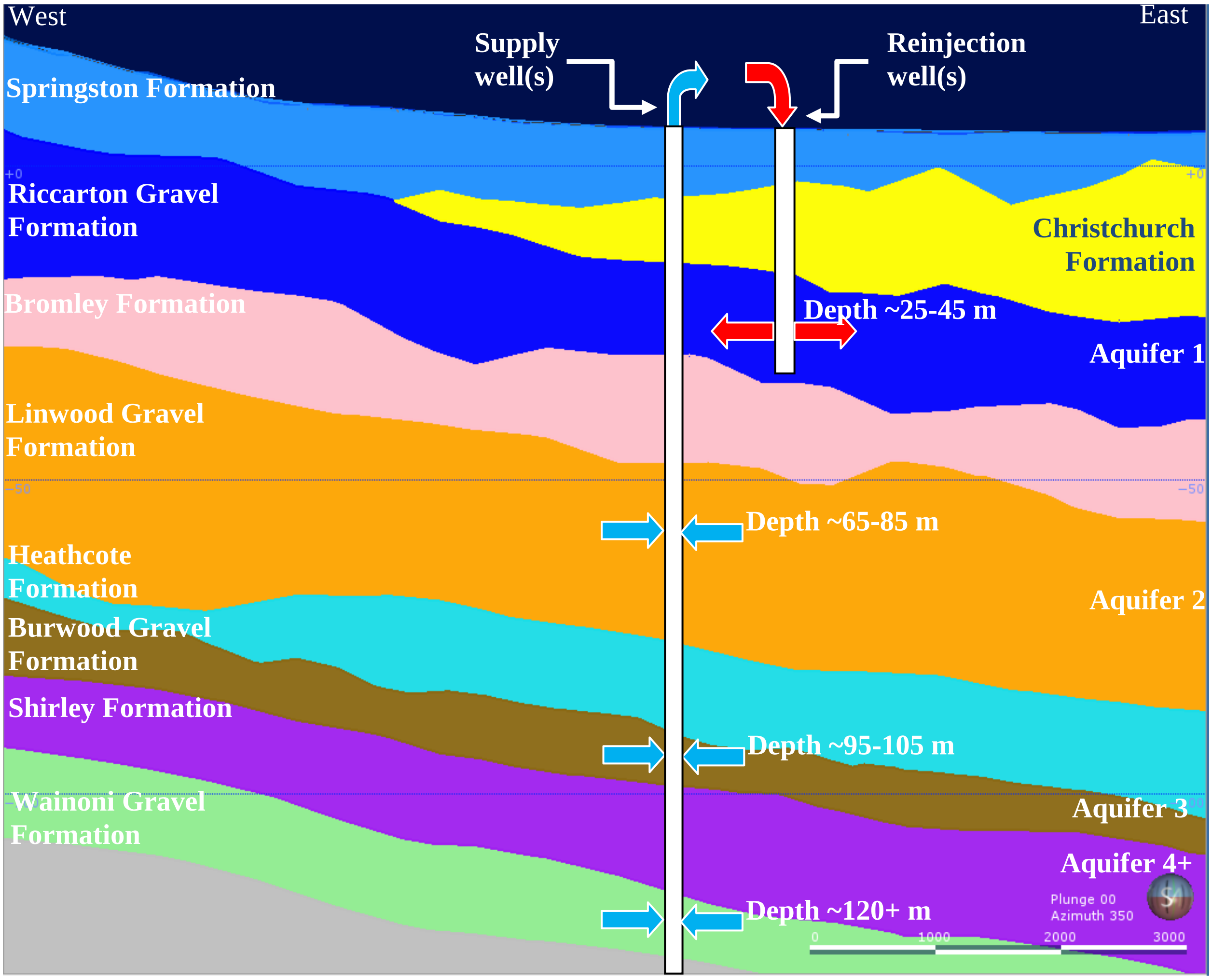


Figure 3: Cross-section of the hydrogeology beneath Christchurch showing the depths of the aquifers from which ground-source heating and cooling is taken and reinjected (adapted from the geological model described in Thorley and Scott, 2010)

2.1 BORE DRILLING AND WELL INSTALLATION

Abstraction wells are screened within a range of aquifers depending on the flow rates required, water quality requirements, and pump design requirements (i.e. submersible or surface). The upper-most abstraction aquifer is generally Aquifer 2 (Linwood Gravel Formation) which can contain highly variable gravel deposits suitable for well development, and is known to be "sandy" and "gap-graded" which can limit the yields which can be taken before sand migration is too high. Aquifer 3 (Burwood Gravel Formation) can be very high yielding, but is sporadic in its occurrence and can have "sand issues" similar to the Aquifer 2. Aquifer 4+ (Wainoni Gravel Formation) has traditionally been used for deep, secure drinking water supplies and provides very high yields and low sand content.

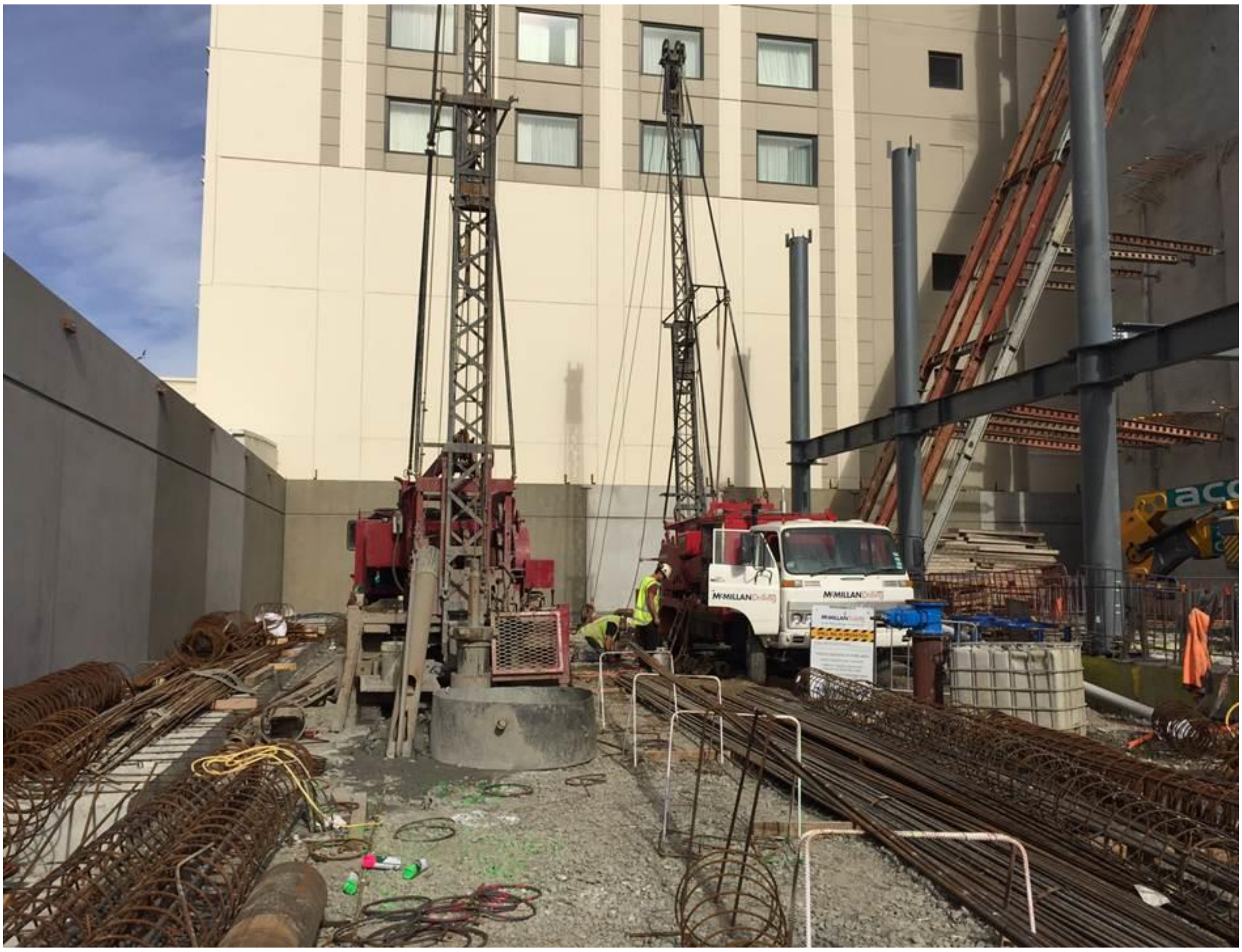
Wells screened in Aquifers 3 to 4+ have a higher artesian head of circa 5 m above ground level and are better suited to surface pumps. Aquifer 2 has artesian heads of circa 2.5 m above ground level but normally requires submersible pumps due to lower transmissivity, finer screen slot sizes due to sand which results in higher head losses under pumping. Reinjection wells screened in the upper part of Aquifer 1 (Riccarton Gravel Formation) demonstrate high injection capacity and lower artesian head under natural conditions of circa 0.5 m above ground level.

The vertical offset of abstraction and reinjection wells allows for pairs to be spaced about 5 m apart. Photograph 1 shows a pair of abstraction and reinjection wells during a pumping test whereby the effects of pumping and reinjection are tested simultaneously with a flow meter and downhole pressure sensors. Although the drilling process and ongoing maintenance requires sufficient space for access by large drilling rigs and support vehicles and plant (e.g. drilling rig, generators, water baffle tanks, sediment sorter, etc.). Access and space requirements for drilling rigs etc. have been a major issue when including ground-source systems into what are normally constrained sites.

Photograph 1: Pumping test of an abstraction well (left) and reinjection well (right) to determine well hydraulic performance (photo courtesy of McMillan Drilling)

Two main types of drilling methods are used to drill and install ground source wells in Christchurch. The first is the percussion cable tool method and has been used in

Canterbury for over 100 years, as shown in Photograph 2. The casing is hammered into the ground usually in 6 m lengths with the sediment cleared using a clam-shell bucket. This method is relatively slow but minimizes "disturbance" to the surrounding strata and provides good control of sample collection. Wells which require a tight annulus seal, such as reinjection wells and the tops of abstraction wells, are installed using this method. Reinjection wells are usually over drilled to start with so that a grouted annulus seal can be tremmied alongside the permanent casing to prevent upwards leakage once additional hydraulic head is introduced at the reinjection well screen.



Photograph 2: Cable tool drilling rigs working on abstraction and reinjection wells simultaneously in central Christchurch (photo courtesy of McMillan Drilling)

The second common method of drilling is dual rotary (air/mud). This is a relatively quick method as it advances a drill bit just ahead of the casing, and pushes the drill cutting back to surface using high pressure air or mud (Photograph 3). The turn table independently turns and advances the casing alongside the drill string. This is the preferred method for going to the deeper aquifers (Aquifer 4+).

Photograph 3: Dual rotary drilling rig working on an abstraction well in central Christchurch (photo courtesy of McMillan Drilling)

The screens are typically washed developed which is a process of mechanical agitation to mobilize the fine grained sediment siting within the matrix of coarser grained clasts outside of the well screen. Removing the finer grained material creates a filter pack across which groundwater can flow cleanly to the well screen. This process usually takes 5 to 10 days per well (although in some cases can been observed to take up to 18 days). There can be challenges in disposing of the development water in the CBD due to the lack of green space or open areas to hold and treat the sediment laden water, and in some cases, the sewer is the only disposal option.

Well head design is also crucial to finishing wells and minimizing the risk from seismic activity. Significant damage of well chambers were observed across Christchurch following the 2010/2011 Canterbury Earthquake sequence. Incorporating flexible connections in pipe work and joints between the chamber floor and well casing have become standard approaches to minimizing earthquake damage. Above ground well head installations are preferred for safety in design and resilience considerations, and can be made to fit within landscape plans if considered early enough in the design process. The ability to relieve pressure and isolate the artesian head within an artesian well is also important for ongoing maintenance (e.g. pump change outs and redevelopment) and restoring services following seismic events.

2.2 WELL PERFORMANCE – CASE STUDY

Two stepped rate pumping tests were undertaken across two sets of abstraction and reinjection wells spaced approximately 30 m apart. The two sets of wells will form the abstraction and discharge points for a ground-sourced heating and cooling system and a secondary fire supply for a new commercial building development. The target peak rate is 25 L/s from each well.

The abstraction wells BX24/0735 and BX24/0738 were constructed to depths of 83.25 m and 73.6 m below land surface, respectively in Aquifer 2 (Linwood Gravel Formation). Although the ground level is less than 1 m between the wells, the aquifer structure encountered within Aquifer 2 was different across a lateral distance of 30 m (hence the difference in total depth). The bore logs are included as Appendix A. The abstraction wells have a 250 mm diameter casing from ground level and a telescoped 200 mm diameter stainless steel screen. The static water level in BX24/0735 was about 3.1 m above ground level because it was screened in the lower section of Aquifer 2. The static water level in BX24/0738 was 1.52 m above ground level because it is screened in the upper section of Aquifer 2.

Two reinjection wells BX24/0736 and BX24/0737 were constructed to depths of 34.75 m and 34.15 m below land surface, respectively. The wells are the same diameter and have the same diameter well screen as the abstraction wells, albeit with a slightly larger slot size and longer length at 9 m. The static water level in BX24/0736 was 0.12 m above ground level prior to the commencement of the step drawdown pumping test. The static water level in BX24/0737 was 0.76 m above ground level due to lower ground elevation.

2.2.1 STEPPED PUMPING TEST BX24/0735 & BX24/0736

The first stepped rate pumping test was undertaken by pumping groundwater from abstraction well BX24/0735 and reinjecting into well BX24/0736. The levels were monitored in pumping well BX24/0735 and reinjection well BX24/0736 and the other two wells (BX24/0737 and BX24/0738) as observation wells. The recorded water level responses (blue and red) recorded during the stepped rate pumping test and the flow rate (dashed) is displayed in Figure 4.

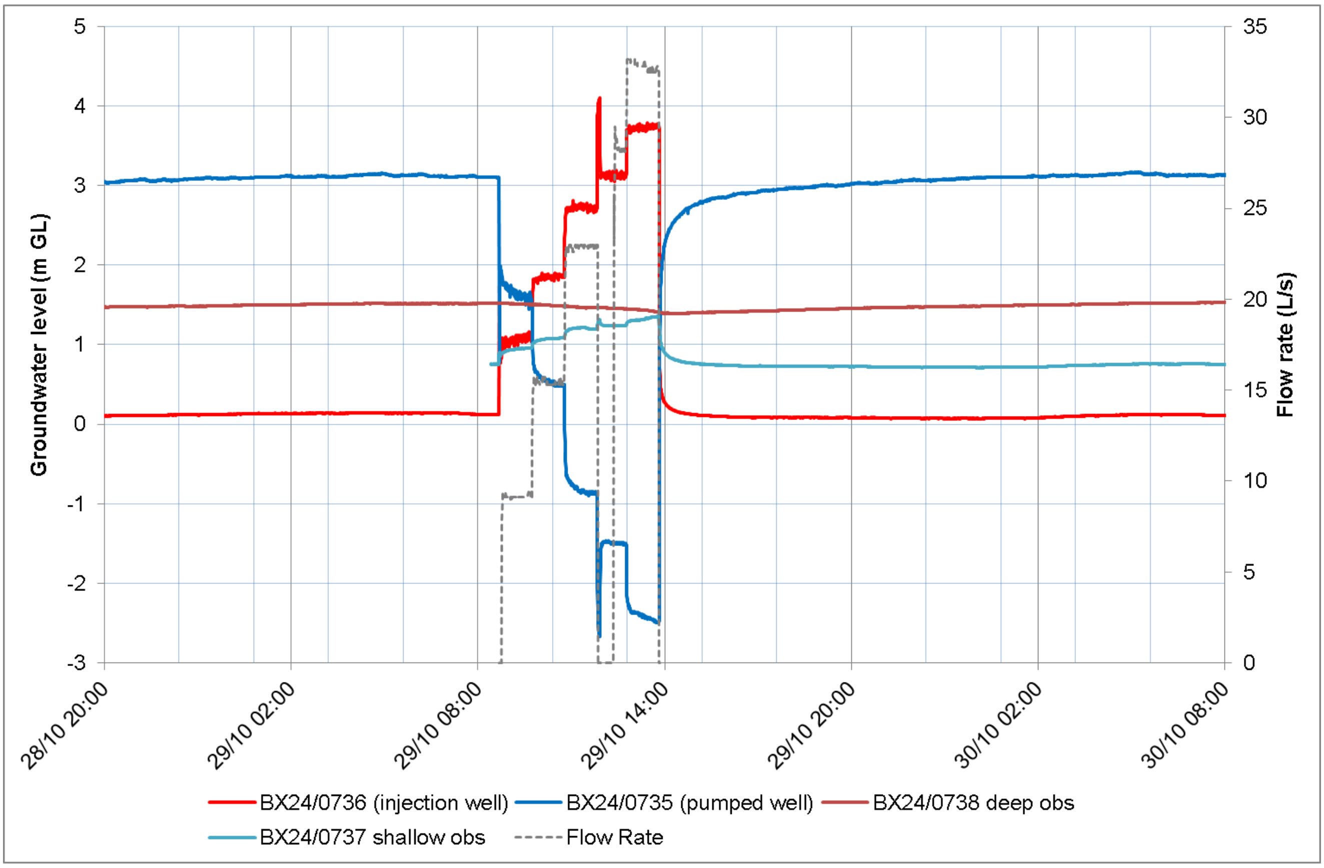


Figure 4: Head change and flow recording during the pumping test in wells BX24/0735 and BX24/0736

Pumping well BX24/0735 showed a total drawdown of 5.57 m at the end of the step test with a corresponding drawdown response of 0.16 m in the neighboring deep observation well (BX24/0738). This indicates there is a low hydraulic connection even though these two wells are screened in different strata separated by an aquitard. The reinjection well BX24/0736 showed a rise in level of up to 3.75 m by the end of the step test with a corresponding rise of about 0.58 m in the shallow observation well (BX24/0737). There was no apparent recirculation of water, and it is unlikely that the discharge water would have influenced the drawdowns recorded in the pumping well during testing.

2.2.2 STEPPED PUMPING TEST BX24/0738 & BX24/0737

The second stepped rate pumping test was undertaken by pumping groundwater from abstraction well BX24/0738 and reinjecting into well BX24/0737. The levels were monitored in pumping well BX24/0738 and reinjection well BX24/0737 and the other two wells (BX24/0735 and BX24/0736) as observation wells. The recorded water level responses (blue and red) recorded during the stepped rate pumping test and the flow rate (dashed) is displayed in Figure 5.

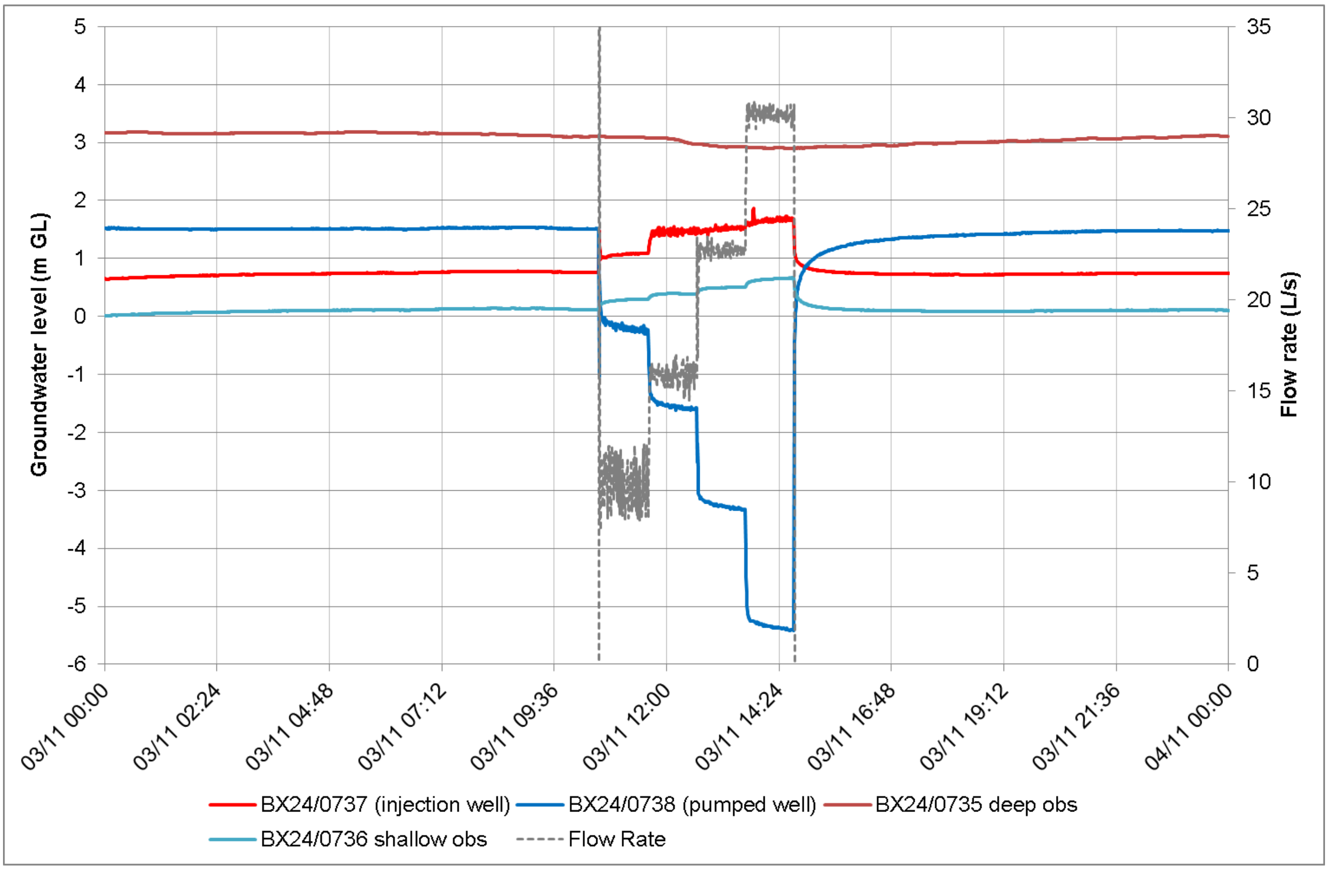


Figure 5: Head change and flow recording during the pumping test in wells BX24/0738 and BX24/0737

The pumping well BX24/0738 showed a total drawdown of 6.93 m at the end of the step test with a corresponding drawdown response of about 0.2 m in the neighboring deep abstraction well (BX24/0735). This indicates there is a muted connection even though these two wells are screened in different strata and are not directly connected. The reinjection well BX24/0737 showed a rise in level of up to 0.92 m by the end of the step test with a corresponding rise in the shallow observation well BX24/0736 of about0.55 m.

The drilling and pumping test results were used to confirm the yield for the heat and cooling system and the secondary fire supply. The results show fine scale heterogeneity in the strata and variable hydraulic performance in abstraction and reinjection wells across a single site. Generally in Aquifer 2 (Linwood Gravel Formation), if the lower basal gravel unit at about 85 m depth can be intercepted, the wells will yield more water with less drawdown and less potential for sand migration. The hydraulic performance of the reinjection wells is also variable, and the ability of the drillers to "wash" the surrounding gravel pack is crucial to achieving lower operating heads in reinjection bores.

2.3 GROUNDWATER QUALITY

There are three main options available for the discharge of ground-source water: stormwater, soakage, and reinjection. The stormwater system in central Christchurch is considered to be at or near capacity, and the asset owner has been reluctant to allow use of the stormwater network for disposal of ground-source water. There have been a couple of instances where ground-source projects located adjacent to the Avon River have been authorised to discharge to the river. Given space limitations in the CBD and unfavorable ground soakage characteristics, discharging cooling water to soakage is generally not viable. Therefore, reinjection provides a reliable and convenient option for disposal of ground-source water within spaced constrained sites.

The existing groundwater quality in the Christchurch CBD is reported by Hayward (2002), which shows a general improvement in quality with depth, although only small variations occur between Aquifer 1 and Aquifer 2. The groundwater quality of Aquifer 1 is influenced by land use activities, however deeper aquifers are generally not subject to such influences because of the confined and artesian nature of the deeper aquifers.

The temperature of groundwater in Aquifer 1 is stable at approximately 12 to 13 °C, increasing to 14.5 °C in Aquifer 4+, as shown in Figure 6 below.

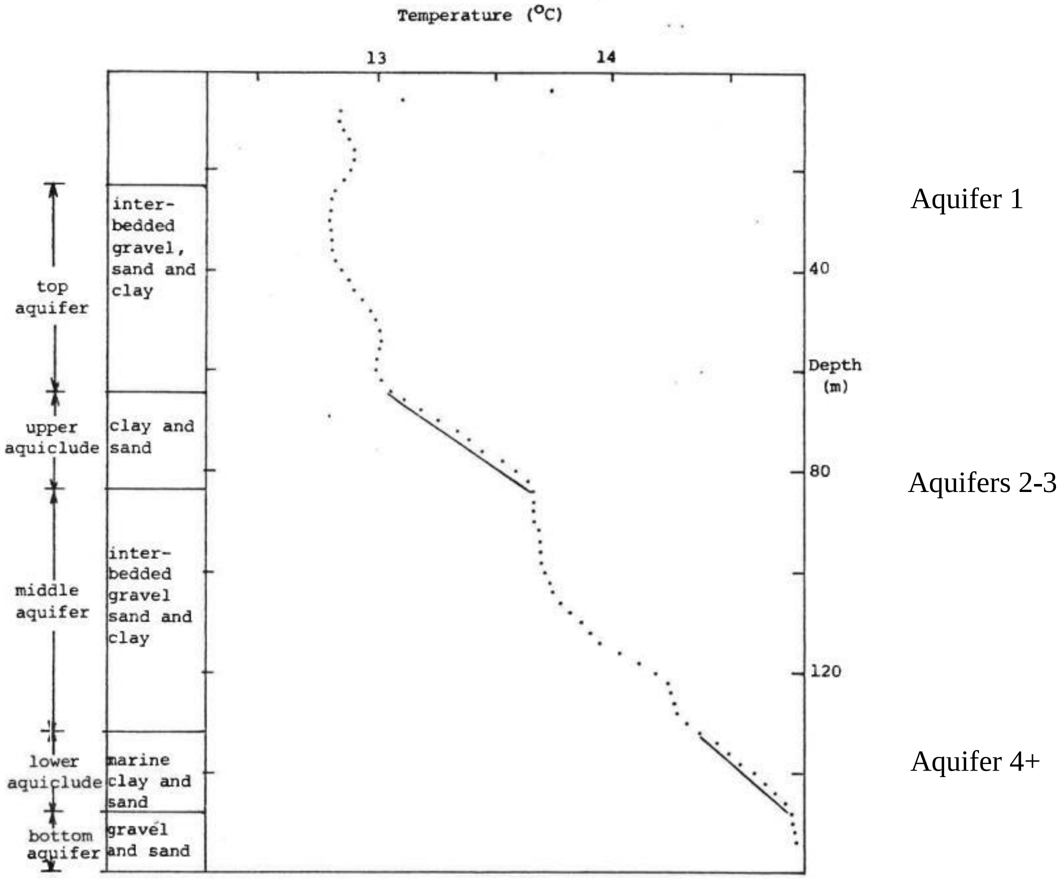


Figure 6: Temperature profile and geological log for well CC1 located in Central Christchurch City (from Burden (1982)

The temperature of the water discharged back to the aquifer is expected to be no more than ±8 °C from the ambient groundwater temperature, and is expected to attenuate back to normal temperature very quickly.

2.4 GROUNDWATER MODELLING TO ASSESS EFFECTS OF REINJECTION

To examine how the reinjection affects the aquifer temperature Beca developed a simplified 3-D numerical flow model. The model is based on the MODFLOW SEAWAT (Langevin et al., 2007) code developed by USGS and simulates variable-density groundwater flow and multi-species solute and heat transport. The model inputs include a continuous reinjection rate as point source with a change from ambient background temperature of 8 °C at the reinjections wells. The model parameters that were used in the model are shown in Table 1.

In this case, a continuous flow rate of 46 L/s was input into the model and the calculated thermal plume after 35 years of discharge is shown in Figure 7. The equipotential lines correspond to estimated aquifer temperature increase in 1 °C. The zone where the aquifer temperature is expected to increase by more than 0.1 °C extends less than 90 m from the injection bores. The high matrix density of the greywacke strata and through-flow of the aquifer system are the main factors in the rapid attenuation of heat into the aquifer following discharge.

Table 1. SEAWAT model parameters

Parameter	Value	Units	Comment
Hydraulic Conductivity	75	m/d	Based on a Transmissivity of 2000 m^2/day and a thickness of Aquifer 1 of 27 m (23 m BGL to 50 m BGL).
Storage/Storativity	0.15 / 10^{-5}	-	
Porosity	0.3	-	
Matrix density	2640	kg/m^3	
Water density	1000	kg/m^3	
Matrix thermal conductivity	3	W/mC	USGS 1988, "Thermal properties of rocks", open file report, 88-441.
Water thermal conductivity	0.58	W/mC	
Matrix specific heat capacity	710	J/kg/C	USGS 1988, "Thermal properties of rocks", open file report, 88-441.
Water specific heat capacity	4183	J/kg/C	
Temperature distribution coefficient	0.00017	m^3/kg	USGS 2008, "SEAWAT Version 4: A computer program for simulation of multi-species solute and heat transport", equation 24, pp.39
Dispersivity	10	m	
Flow rate	4000	m^3/day	Split evening across the two reinjection wells

Furthermore, the discharge of ground-source water should not contain any additional contaminants other than water of a different temperature. The heating and cooling systems are typically a closed system, meaning that contaminants will not be able to enter the cycle. Most projects in Christchurch have adopted the following measures to prevent contamination of the artesian water from the heat exchange plant:

- "Aquifer-side" water is maintained at higher pressures than the "building-side" water in the plate heat exchange units. Therefore, in the unlikely event of a leak in the plate heat exchange unit "well-side" water will leak into the "building-side" water and not the other way around;

- An air gap is maintained within the plate heat-exchangers;

- The "well-side" water supply to and from the heat exchangers are able to be isolated by valves for maintenance and cleaning purposes;

- The above ground pipework are pressure tested and cleaned prior to connection to the aquifer.

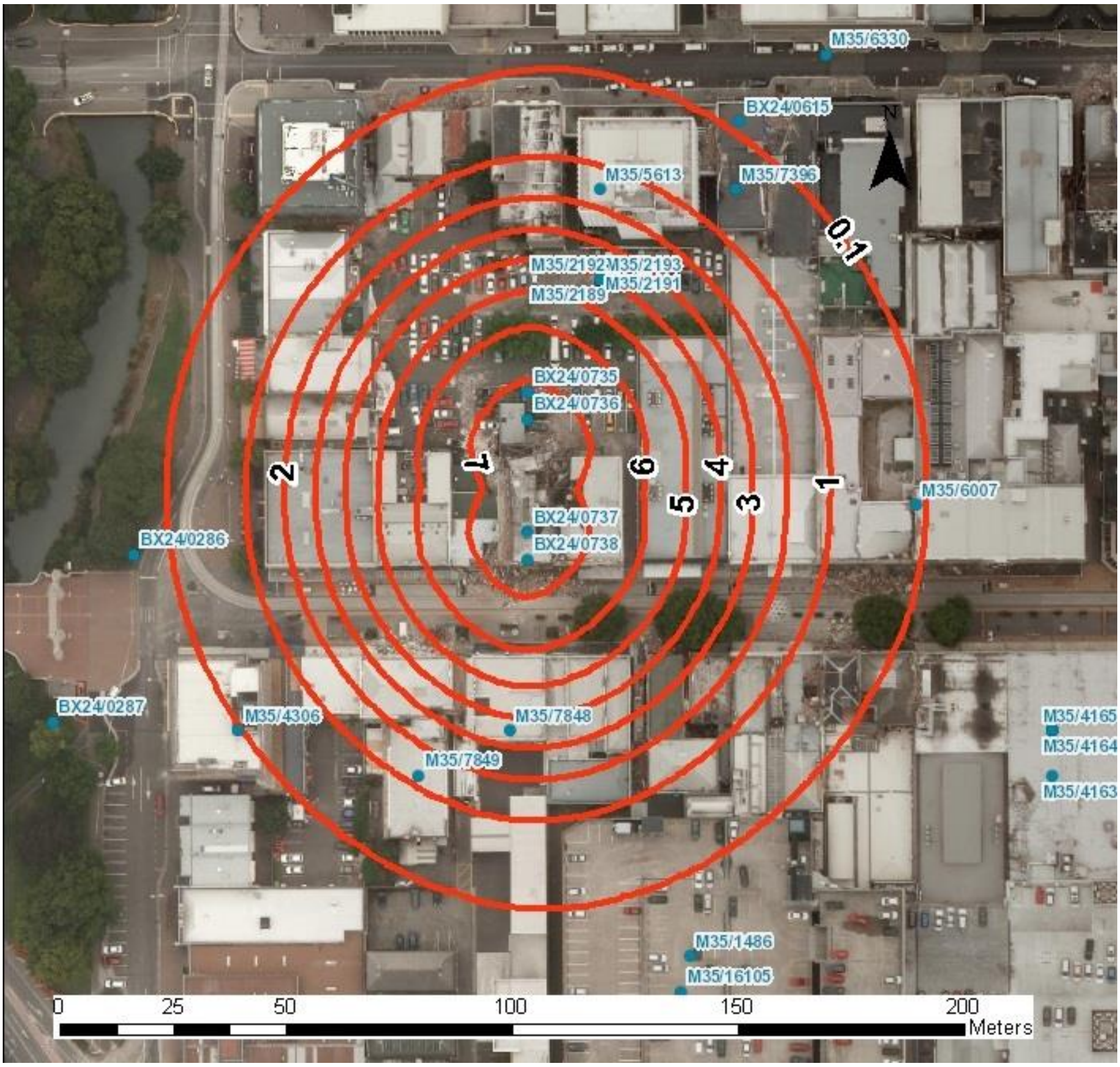


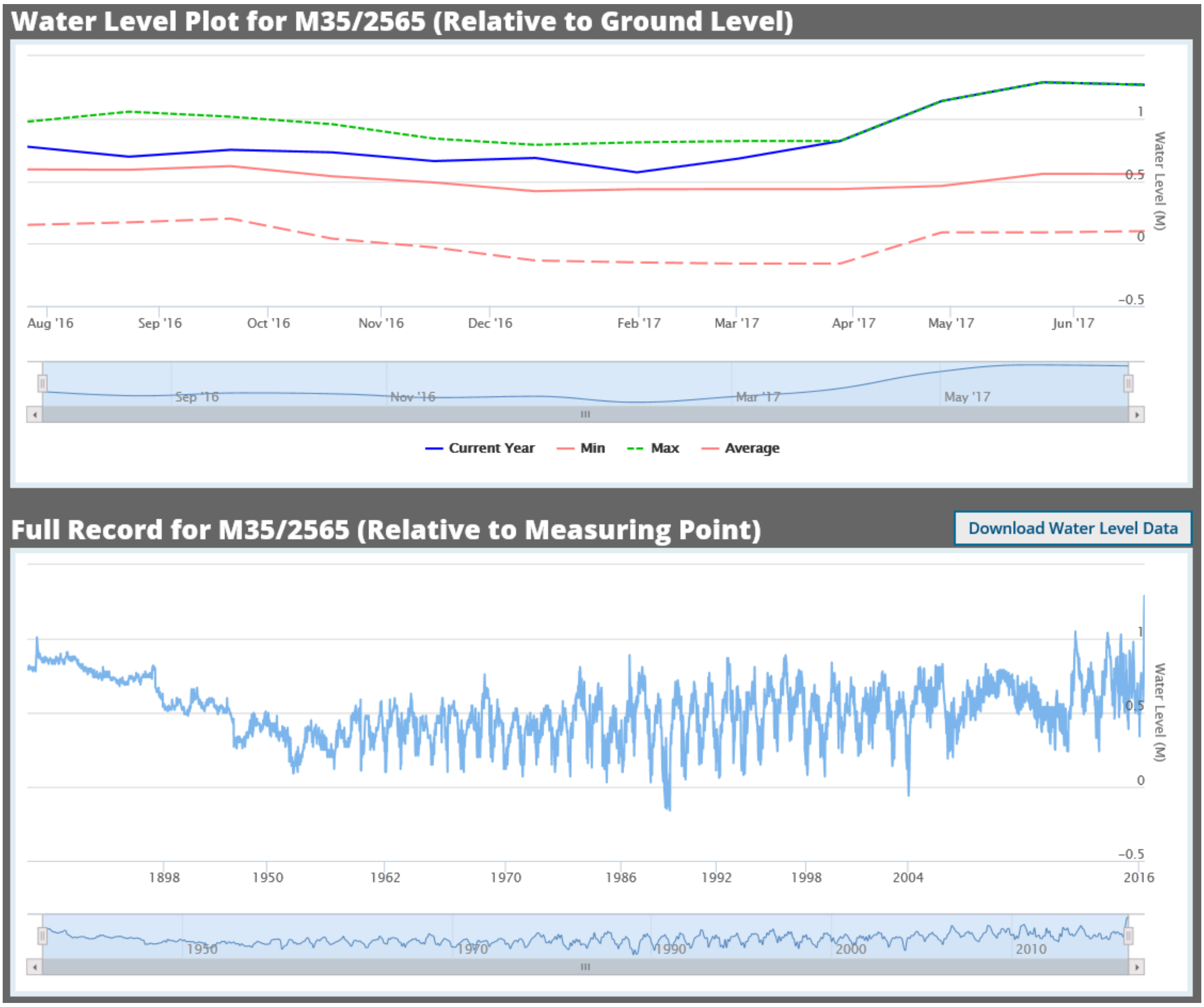
Figure 7: Calculated thermal plume contours / extent (change in °C) at 35 years of continuous discharge at 4000 m^3/day (combined) as determined using the numerical MODFLOW SEAWAT model.

3 AQUIFER RESPONSE AND SUSTAINABILITY

Groundwater abstraction in the CBD was relatively low prior to the earthquakes because the reticulation sourced most of its water from reservoirs located on the Port Hills and a small pumping station to the north of the CBD. However, now the total pumping capacity across a dozen or so sites in the Christchurch CBD utilizing ground-source heating and cooling is estimated to be greater than 500 L/s. Even though the allocation limit has been capped off by Environment Canterbury in Christchurch, the taking of water from the deeper aquifers is considered "non-consumptive" because the water is placed back into the hydrological system, and a neutral change to the overall water balance is maintained.

Each of these projects is required to conduct well interference assessments according to Environment Canterbury's rules, although the cumulative effect of the reinjection is starting to appear in long term monitoring sites. The ground-source projects abstract groundwater from a range of deep aquifers (Aquifers 2 to 4+), but nearly all reinjection goes back into the same aquifer (Aquifer 1).

There are now reports of geotechnical drilling rigs experiencing higher than normal flowing artesian groundwater levels of a couple of meters above ground level when drilling in the Riccarton Gravel Formation (Aquifer 1). The long term groundwater monitoring site at the Canterbury Museum is showing record high flowing artesian groundwater levels at 1.3 m above ground level, which is nearly 1 m higher than normal for June. The 30 m deep groundwater level monitoring station at the museum is Canterbury's longest monitored well with over 100 years of groundwater records from Aquifer 1. Figure 8 shows the long term groundwater level record and reveals a marked step in groundwater levels (compared to long term average conditions) at the end of March 2017. The increase in groundwater level coincides with the opening and commissioning of a couple of nearby ground-source projects although there is limited information regarding the utilization of the systems that have been installed.



Water Level Plot for M35/2565 (Relative to Ground Level)

Full Record for M35/2565 (Relative to Measuring Point)

Figure 8: Groundwater level plots for the Canterbury Museum monitoring station in central Christchurch – well M35/2565 (from Environment Canterbury website)

The cumulative effect of all of the discharges into Aquifer 1 (Riccarton Gravel Formation) is expected to permanently increase the flowing artesian pressures over a large area beneath Christchurch because of the “confined” nature of Aquifer 1. A confined aquifer has low specific storage capacity due to it being under fully saturated and flowing artesian pressure. Therefore, when water is directly injected, there is an immediate and wide pressure response in the aquifer.

Environment Canterbury introduced permitted activity rules following the earthquakes making it easier to gain access to the groundwater resource for the purposes of ground-source heating and cooling. Currently there are no limits or guidelines on the acceptability of such pressure increases.

A review is underway on the sustainability and management approach of the aquifers due to concerns about potential increased seepage into or around the built environment via piles, opening old or new spring vents, or flooding deep excavations such as basements and carparks. Alternatively, increased seepage could benefit base flow conditions in the Avon and Heathcote Rivers. Improved monitoring and understanding of the flows and potential for migration of increased flowing artesian pressure through the aquitard overlying the Riccarton Gravel Formation is required.

More rigorous assessments of mounding interference effects between reinjection wells would assist in establishing the degree of hydraulic connection and overall capacity of the aquifer for these discharges.

Christchurch Artesian Aquifer system is ideally suited to this alternative and “free” source of energy, particularly for larger open-loop projects. Careful management of this resource will ensure such innovative uses for our natural resources can continue to benefit the community.

There may also be opportunities to link up water supplies and reinjection wells in the future such that ground-source water can be shared across the CBD as an alternative to shared heating and cooling plant, which are typically very site/user specific. A shared water supply and discharge system would make best use of the resource and could assist in “smoothing” out the reinjection pressures across localized areas.

4 CONCLUSIONS

The Christchurch Artesian Aquifer system is ideally suited for open loop ground-source heating and cooling. About a dozen projects have been developed since the earthquakes and extract or disperse heat via mechanical heat exchange processes and is a more sustainable form of heating and cooling.

Groundwater temperatures are steady year-round at approximately 12 to 15 °C and following heat exchange, the groundwater is changed by up to ±8 °C. The attenuation of heat in the aquifer has been estimated using numerical groundwater models which shows rapid return to background water temperatures following reinjection into the aquifer system.

The vertical offsets of abstraction and reinjection wells has enabled the close spacing of pairs of these wells which is beneficial in space constrained urban sites. Drilling and pumping tests have reflected the fine-scale heterogeneity of the aquifer structure and hydraulic performance of wells.

In commercial building projects, completing the drilling and testing results early in the process or as an early works package can reduce uncertainty for designers, enable consents to be sought within suitable timeframes, and avoid delays during construction.

Whilst the groundwater is abstracted from a range of deep aquifers, most of the water is being reinjected into Aquifer 1 apart from a small discharge to the Avon River at the Botanic Gardens. Long-term monitoring of groundwater levels is showing record high groundwater levels in recent months coinciding with the commissioning of two recent ground-source projects going online in the CBD. There are approximately six of the twelve projects now in operation.

Careful management of reinjection flows is required to protect the built environment from the effects of increased flowing artesian groundwater pressures and seepage. Increased monitoring and understanding of the response of the groundwater to reinjection of large volumes of water will be required to ensure ongoing access to this resource.

ACKNOWLEDGEMENTS

We would like to acknowledge all of our clients and McMillan Drilling for their assistance and support in developing the ground-source systems in the Christchurch CBD and in preparing this paper.

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APPENDIX A – BORE LOGS

McMILLAN Drilling GROUP

Bore Report

Client: Hereford Holdings Limited

Bore No.: BX24/0735

Job No.: 13363

Project: Drilling of 10" (250mm) Abstraction Bore
Site Location: The Terrace Stage 1, Hereford Street, CHRISTCHURCH
Driller(s): T. Cook
Method: Cable Tool

Date Completed: 29/10/2015
Grid Reference:
Consent No.: CRC144554
Lot Number:

Material Description | **Graphic Log** | **Depth (m)** | **R.L. (MDC)** | **Casing & Screen Installation**

Casing Details (from first page)

Yellow hard CLAY
Small-Medium round-subrounded brown stained light Sandy GRAVELS
Golden brown SAND with traces of Organics
Blue SILT
PEAT
Blue Gray SILT
Brown/blue GRAVELS, fine Sand and traces of Clay
Yellow CLAY
Small-medium brown stained GRAVELS, some fine Sand
Sticky SILT with traces of Peat
Brown sticky SILT
Small-medium brown GRAVELS, with fine-medium Sand
Medium brown very Sandy GRAVELS
Poorly sorted brown Sandy GRAVELS
Small-medium brown Sandy GRAVELS with traces of yellow Clay
Poorly sorted brown GRAVELS with less Sand
Small-medium very Sandy brown GRAVELS
Small-medium brown GRAVELS with less Sand
Small-medium brown GRAVELS with moderate Sand
Orange CLAY
Small-medium brown stained GRAVELS with light-moderate Sand
Small-medium brown GRAVEL with moderate-heavy Sand
Yellow CLAY
Sandy GRAVELS
Yellow CLAY with hard, dry brown Silt
Silty SAND
Blue SILT with Peat and Organics
PEAT
SILT
Peat and yellow Clay SILT
Medium GRAVELS, brown stain, moderate Sand with traces of Silt
Small-medium with some large, moderately sorted stained GRAVELS with traces of Sand
Small-medium brown stained GRAVELS with some Sand
Small-medium stained GRAVELS with less Sand
Hard yellow CLAY with some Gravels

46.10
46.65
49.58
53.28
53.43
56.20
57.60
57.62
58.13
59.00
60.13
60.80
62.30
62.82
63.10
64.20
64.54
65.25
66.53
67.20
69.40
70.23
70.50
70.88
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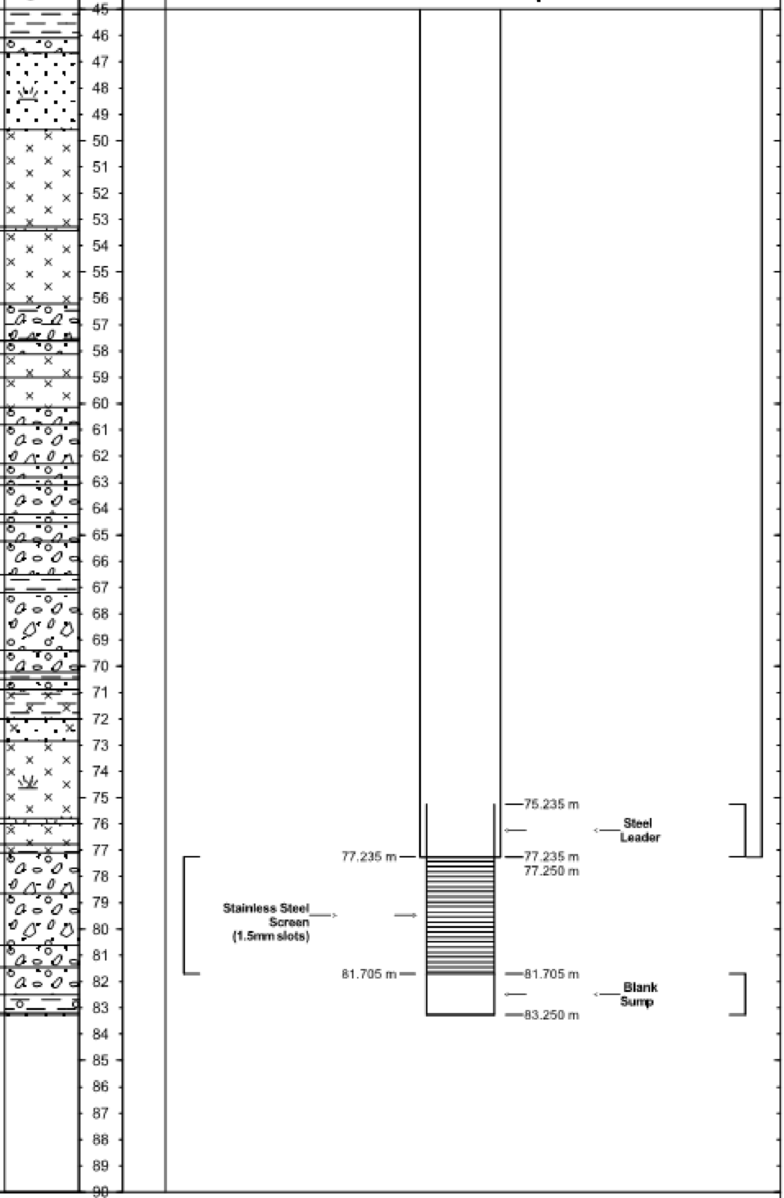
82.50
83.20
83.25



Remarks:
Well completed with sluice valve and blank flange
Sand migration observed at flows above 30L/s (recommended maximum yield 30L/s)

Bore Diameter (mm): 250
Static Water Level (SWL) (m): -3.1
Total Bore Depth (m): 83.25
Total Depth Drilled (m): 83.25

Development Duration (hr): 88

Pumping Duration (hr): 5

Flow Rate (gpm)	Flow Rate (l/sec)	Draw Down (m)	Duration (hr)
120	9.1	1.480	1.00
205	15.5	2.610	1.00
304	22.9	3.960	1.00
371	28.1	4.920	1.00
428	32.4	5.750	1.00

Report Created: 18/11/2015 2:00:47 p.m.

McMILLAN Drilling GROUP

Client: Hereford Holdings Limited

Bore Report

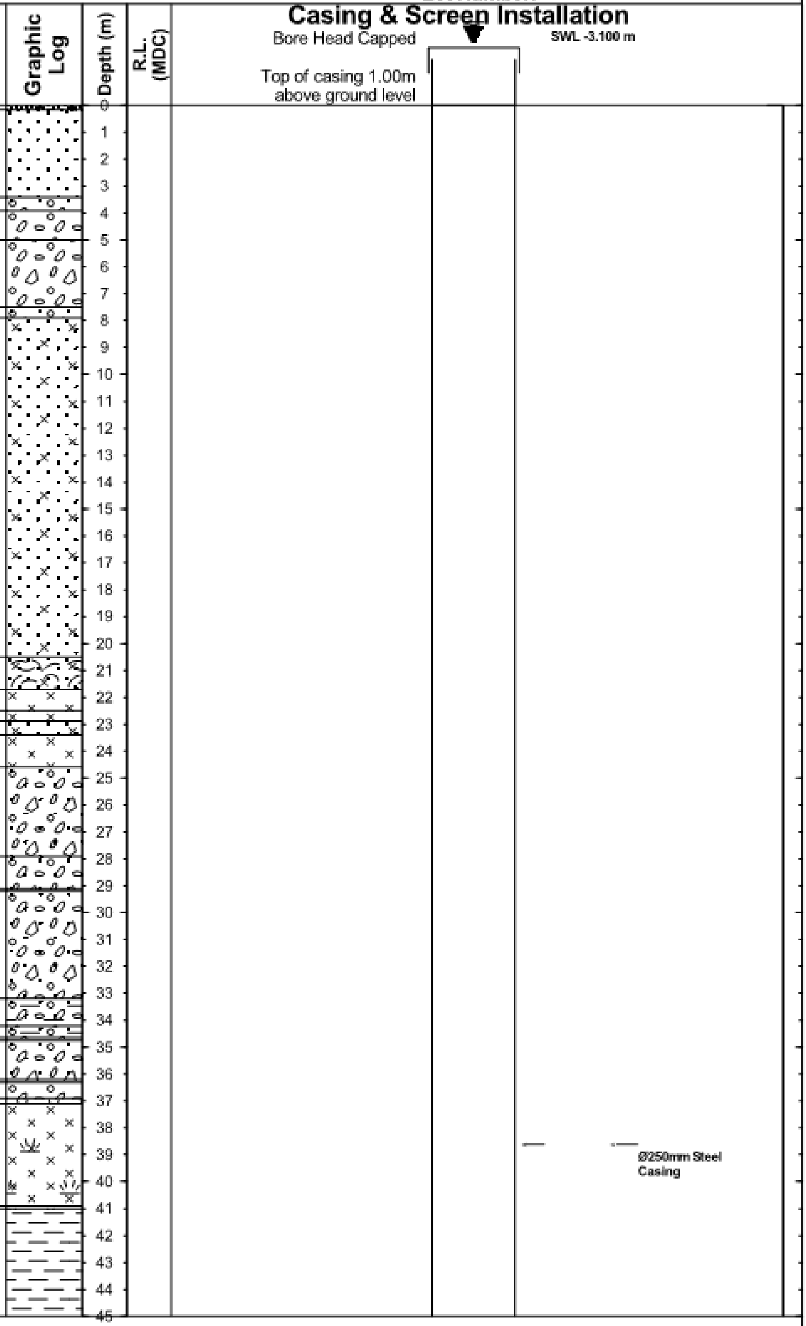
Bore No.: BX24/0735

Job No.: 13363

Project: Drilling of 10" (250mm) Abstraction Bore
Site Location: The Terrace Stage 1, Hereford Street, CHRISTCHURCH
Driller(s): T. Cook
Method: Cable Tool

Date Completed: 29/10/2015
Grid Reference:
Consent No.: CRC144554
Lot Number:

Material Description	
CONCRETE	0.15
Brown SAND	
Very Sandy GRAVELS	3.40 3.90
Small to medium brown GRAVELS	
Blue/Brown GRAVELS	5.00
Small-medium Sandy GRAVELS	7.50 7.90
SAND and Silt	
SAND and Silt with Shells	20.50
Sticky SILT with Peat	21.70
Brown SILT with Peat	22.50
Brown Silty SAND	22.90 23.40
Brown sticky SILT	
Small-medium brown GRAVEL with moderate Sand	24.60
Small free well stained moderately Sandy free GRAVELS	27.90
Yellow CLAY	28.70 29.10
Small-medium well stained moderately Sandy free GRAVELS	
Claybound Sandy GRAVELS	33.20
Small-medium-large Sandy GRAVELS with some traces of Clay	34.20 34.65 34.75
Light Brown CLAY	
Medium stained GRAVELS with Sand	36.20 36.30 36.90 37.10
Light Tan CLAY	
Blue well rounded small-medium GRAVELS	
PEAT	
Gray SILT with traces of Peat	
Blue SILT	40.90 41.00
Yellow hard CLAY	



Remarks:
Well completed with sluice valve and blank flange
Sand migration observed at flows above 30L/s (recommended maximum yield 30L/s)

Bore Diameter (mm): 250
Static Water Level (SWL) (m): -3.1
Total Bore Depth (m): 83.25
Total Depth Drilled (m): 83.25

Development Duration (hr): 88

Pumping Duration (hr): 5

Flow Rate (gpm)	Flow Rate (l/sec)	Draw Down (m)	Duration (hr)
120	9.1	1.480	1.00
205	15.5	2.610	1.00
304	22.9	3.960	1.00
371	28.1	4.920	1.00
428	32.4	5.750	1.00

Report Created: 18/11/2015 2:00:47 p.m.

McMILLAN Drilling GROUP

Client: Hereford Holdings Limited

Bore Report

Bore No.: BX24/0738

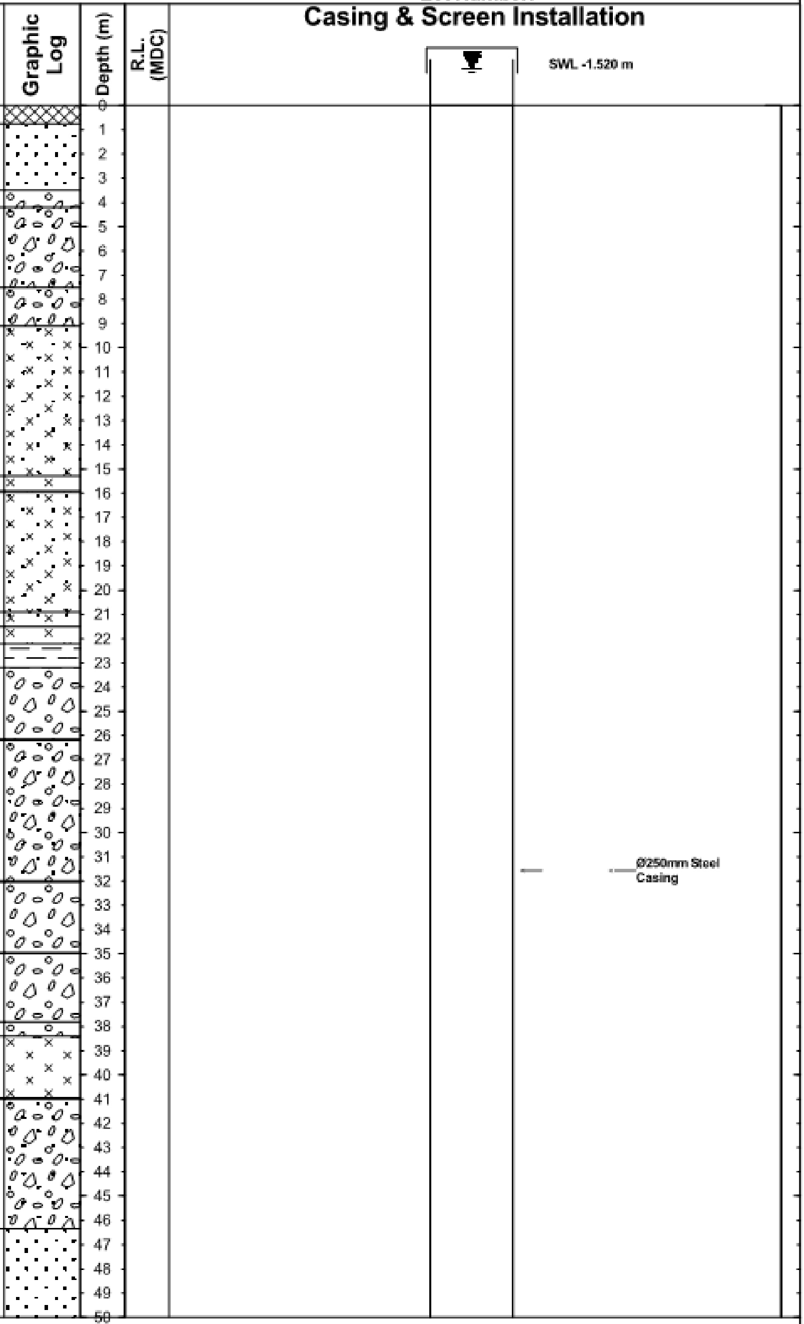
Job No.: 13363

Project: Drilling of 10" (250mm) Abstraction Bore
Site Location: The Terrace Stage 1, Hereford Street, CHRISTCHURCH
Driller(s): N. Langridge
Method: Cable Tool

Date Completed: 19/09/2015
Grid Reference:
Consent No.: CRC144554
Lot Number:

Material Description	
Brick, concrete and metal FILL. Brick, red.	0.75
SAND; brown.	3.50
Fine to medium GRAVEL; brown stained. Subrounded to rounded.	4.20
Sandy fine to coarse GRAVEL with some wood; Light bluish brown, stained. Subrounded to rounded. Sand, coarse, light brown. Wood, red, hard.	7.50
Sandy fine to medium GRAVEL and some wood; bluish grey. Subrounded to rounded. Sand, coarse, bluish grey.	9.10
Sand and silt with trace organics and wood	15.30
SILT with wood; bluish grey.	15.90
CLAY; bluish grey. Soft.	15.95
Sand and silt; blue. Sand, fine to coarse.	20.90
Sand and silt with some shells; bluish grey.	21.50
SILT with trace peat; blue. Cohesive behaviour.	22.21
CLAY with trace peat; light grey. Hard, consolidated patches.	23.20
Fine to medium GRAVEL with minor sand; greyish brown, stained. Subrounded to rounded. Sand, coarse, grey.	26.16
CLAY; light brown. Very soft.	26.20
Sandy fine to medium GRAVEL; light brown. Gravel, subrounded to rounded	32.00
CLAY; light brown.	32.05
Fine GRAVEL with some very light sand and trace clay; heavy brown staining. Gravel, rounded.	34.95
Claybound GRAVEL; yellowish tan.	35.00
Fine to medium GRAVEL with some light sand; brown stained. Gravel, subrounded to rounded.	37.80
Fine to medium GRAVEL; blue with brown stains. Subrounded to rounded.	38.40
SILT with peat layers; grey. Hard, cohesive behavour.	40.95
CLAY; yellowish tan. Hard.	41.00
Sandy fine to medium GRAVEL; brown. Subrounded to rounded.	46.35
SAND with some organics; yellowish.	

Casing & Screen Installation



Remarks:
Well completed with sluice valve and blank flange
Sand migration observed at flows above 25L/s (recommended maximum yield 25L/s)
Telescopic section placed within screen section to partially blank off worst sand migration zone

Bore Diameter (mm): 250
Static Water Level (SWL) (m): -1.52
Total Bore Depth (m): 73.6
Total Depth Drilled (m): 83.84

Development Duration (hr): 158.5

Pumping Duration (hr): 4

Flow Rate (gpm)	Flow Rate (l/sec)	Draw Down (m)	Duration (hr)
127	9.6	1.820	1.00
206	15.6	3.120	1.00
300	22.7	4.860	1.00
396	30	6.930	1.00

Report Created: 18/11/2015 2:25:49 p.m.

Bore Report

McMILLAN Drilling GROUP

Client: Hereford Holdings Limited

Bore No.: BX24/0738

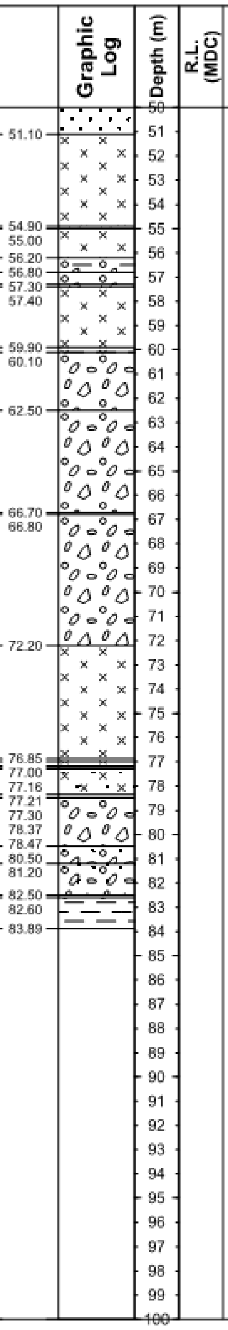
Job No.: 13363

Project: Drilling of 10" (250mm) Abstraction Bore
Site Location: The Terrace Stage 1, Hereford Street, CHRISTCHURCH
Driller(s): N. Langridge
Method: Cable Tool

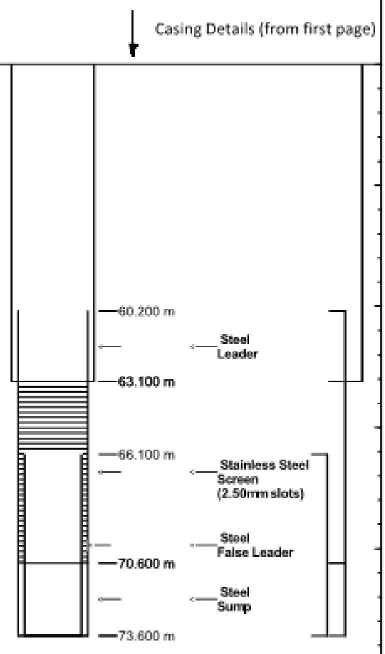
Date Completed: 19/09/2015
Grid Reference:
Consent No.: CRC144554
Lot Number:

Material Description

SAND with some organics; yellowish.
SILT; blue. Consolidated.
PEAT.
SILT; greyish blue. Consolidated.
Clayey fine to medium GRAVEL; bluish brown. Gravel, subrounded to rounded. Clay; brown, consolidated.
Fine to medium GRAVEL with some clay layers and light sand; grey. Gravel, subrounded to rounded. Clay, brown.
PEAT. Consolidated.
SILT with trace peat and wood; dark grey. Silt, consolidated.
Silty CLAY with trace gravel; grey with some light brown seams. Very hard
Fine to medium GRAVEL with some light sand; brownish grey, stained. Tightly packed; Subrounded to rounded.
Fine to medium free GRAVEL with some light sand; brown stained
CLAY; yellowish. Dry, stiff.
Fine to medium free GRAVEL with some sand; brown stained. Sand, medium.
SILT; greyish blue brown. Dry, consolidated.
SILT with some peat; greyish blue.
SILT with some organics; blue. Consolidated.
SILT; yellow. Consolidated.
PEAT.
Sandy SILT with some peat; light grey. Plastic behaviour.
CLAY; yellowish with oxidised layers. Hard, consolidated.
Fine to medium GRAVEL with some sand; brown stained. Gravel, rounded. Sand, light brown.
Sandy fine to medium GRAVEL; brown stained. Gravel, subrounded to rounded. Sand; brown, medium.
Sandy fine to medium GRAVEL; brown. Gravel, subangular to subrounded.
Sandy fine to medium GRAVEL with trace clay seams; brownish. Gravel, subrounded to rounded.
CLAY with trace gravel; brownish. Soft. Gravel, fine.
Beyond depth drilled.



Casing & Screen Installation



Remarks:
Well completed with sluice valve and blank flange
Sand migration observed at flows above 25L/s (recommended maximum yield 25L/s)
Telescopic section placed within screen section to partially blank off worst sand migration zone

Bore Diameter (mm): 250
Static Water Level (SWL) (m): -1.52
Total Bore Depth (m): 73.6
Total Depth Drilled (m): 83.84

Development Duration (hr):	Flow Rate (gpm)	Flow Rate (l/sec)	Draw Down (m)	Duration (hr)
158.5	127	9.6	1.820	1.00
	206	15.6	3.120	1.00
Pumping Duration (hr):	300	22.7	4.860	1.00
4	396	30	6.930	1.00

Report Created: 18/11/2015 2:25:49 p.m.