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Causes and consequences of rising groundwater levels in the shallow Christchurch aquifer system

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Abstract

Urban infrastructure is designed and built for the prevailing hydrogeological conditions at the time of development. Groundwater levels can change over time, however, due to both direct anthropogenic influences such as post-industrial declines in groundwater abstraction and indirect influences such as climate change and sea level rise, with significant effects on urban infrastructure. Rising groundwater levels can result in water inflows to basements, tunnels and buried pipework and reduce the strength of soils upon which buildings are founded.

The water table depth beneath central Ōtautahi/Christchurch, New Zealand, was the subject of recent media attention following complaints from building owners experiencing basement flooding and increased pumping requirements. The development of Ground Source Heat Pump systems, which transfer a significant volume of water from a deep aquifer (typically Wainoni Gravel) to the first confined aquifer (Riccarton Gravel), leading to upward seepage to the water table aquifer in the central city, was identified as a possible cause. This study analysed groundwater level monitoring data under the Before/After and Control/Impact framework in conjunction with parallel lines of evidence and found that the significant rise in groundwater levels in the central city is likely to be connected to the Ground Source Heat Pump development. In addition to the basement water ingress issues discussed in the press articles, the higher groundwater levels also increase liquefaction potential in the event of a future earthquake.

Keywords

shallow groundwater; rising water table; ground source heat pumps; urban groundwater issues

Introduction

Although rising groundwater has been a known problem for cities founded on artesian aquifers for many years (e.g., Johnson, 1994), the issue has recently risen into prominence in some parts of the world, notably in Germany, the United Kingdom (UK) and Canada (Becker *et al.*, 2022). Drivers of shallow groundwater issues can be grouped into hydrological process-driven (e.g., pluvial, fluvial, and sea level rise) and anthropogenic process-driven (e.g., reduced groundwater abstracion, anthropogenic groundwater recharge), with anthropogenically-forced climate change becoming an increasing significant driver of the former set of processes.

Groundwater level recovery associated with significant post-industrial groundwater pumping declines in several UK cities (London, Birmingham, Liverpool and Nottingham) was identified as a potential source of harm because many buildings and groundwater level-sensitive structures were constructed at a time when water levels were lower (Johnson, 1994). By way of example, Greswell *et al.* (1994) showed that groundwater abstraction in Birmingham peaked in the 1940s and 1950s with a subsequent rapid decrease from 1960 to 1980. Groundwater levels recovered by 20 m, prompting fears over the structural integrity of some deep foundations. Dewatering wells were installed inside certain buildings in one area to protect their structural integrity. The authors noted that such schemes are expensive and mean that an operator pays for remediation resulting partly, if not entirely, from the activities of others. Additional anthropogenic process drivers include the effects of estuary and river barrages in raising groundwater levels and increased aquifer recharge from leaky water and sewerage infrastructure (Johnson, 1994). Becker *et al.* (2022) explained that sealing of the leaky sewer system in the Ruhr region of Germany meant that the sewer would no longer act as an unintended drainage system, with the water table recovering back to its natural level in the absence of compensating groundwater management measures.

Johnson (1994) discusses the geotechnical response to rising groundwater and explains that the principal responses of a soil to an increase in water pressure or saturation are a change in ground stresses, a reduction in strength, and a change in volume. Shear strength reduces under increasing pore water pressure, with implications for all types of foundation and their bearing capacity. The types of infrastructure considered to be at risk include basements, foundations, tunnels and other subsurface structures. Monk *et al.* (2016) studied groundwater table response to rising sea levels and the associated influence on the thickness of the non-liquefying layer and liquefaction vulnerability in the coastal suburb of New Brighton, Ōtautahi/Christchurch, New Zealand. The analysis showed that a 0.5 m water table increase would have a dramatic impact on liquefaction vulnerability at that location and correspondingly the amount of liquefaction-related land damage that would result.

Groundwater issues in several commercial buildings in Christchurch's central business district (CBD) received media coverage in 2021, with groundwater ingress causing basement flooding, an ongoing pumping requirement in two buildings and an increase in the pumping requirements in another (Van Beynen, 2021). The media article noted that the observed flooding could be due to a host of factors including weather events, building infrastructure (e.g., redevelopment following the Canterbury earthquake sequence of 2010–11), and river flows. Ground Source Heat Pump (GSHP) systems, which transfer water from a deep confined artesian aquifer (typically Wainoni Gravel) to the shallow Riccarton Gravel artesian aquifer (see Figure 1) and had, at that stage, been installed in eight buildings around central Christchurch, were identified as another possible cause (Van Beynen, 2021). While the media article does not provide rigorous analysis of the issue, the coverage highlights the interest in the matter and the need for further investigation.

The Christchurch aquifer system consists of a highly transmissive sequence of outwash gravels (inland) interfingered by low conductivity marine sediments which increase in thickness to the coast (Browne and Naish, 2003). This geological structure yields a series of confined/leaky aquifers interbedded with thick sequences of lower permeability material beneath Christchurch, as shown in Figure 2. There is a strong upward gradient in the aquifer system, with the water level typically found at 2–3 m depth in the Springston Formation unconfined (water

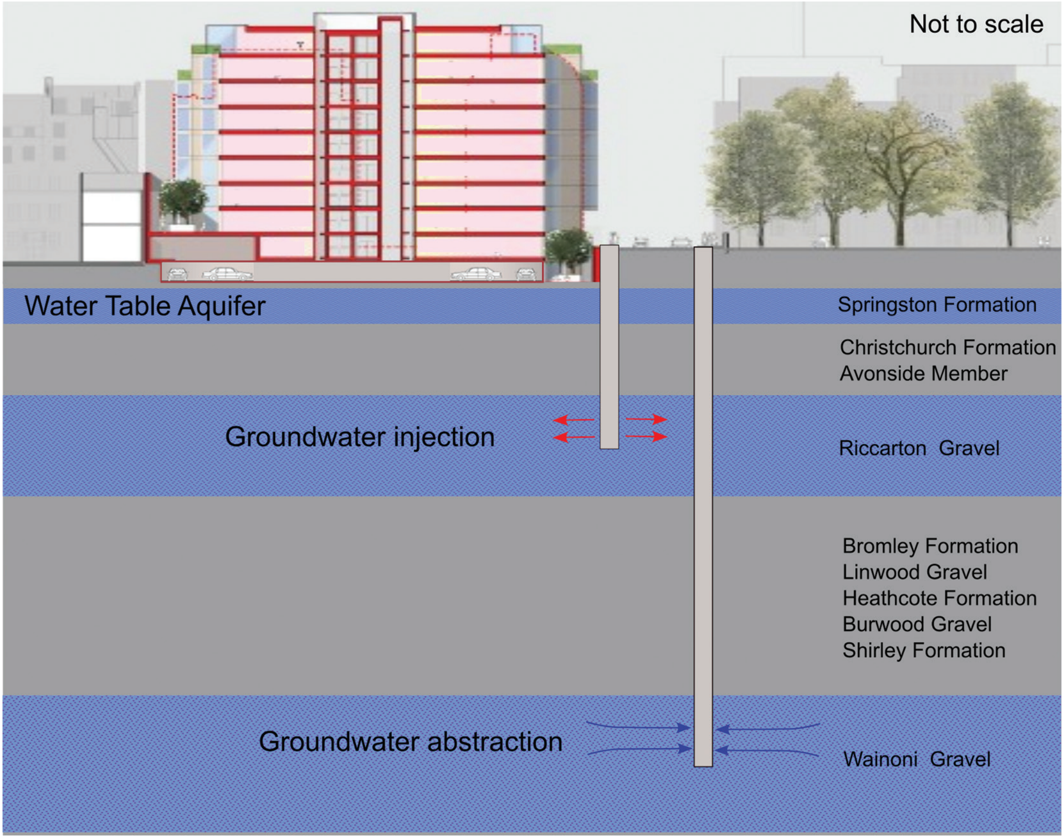

Figure 1 – Schematic cross section of GSHP configuration in Christchurch.

table) aquifer beneath the CBD, which overlies the Christchurch Formation (see Begg *et al.*, 2015). Artesian aquifer pressures increase from 0.5–1 m above ground level (agl) in the Riccarton Gravel aquifer (which is sometimes referred to as the first confined aquifer, or Aquifer 1) to around 10 m agl in the deeper Wainoni Gravel aquifer beneath the CBD (see Talbot *et al.*, 1986). Setiawan *et al.* (2022) notes that although the Christchurch Formation is commonly termed an aquitard, groundwater flow between the Christchurch Formation and the underlying aquifers can be significant.

The development of GSHP systems in Christchurch was supported by policy amendments to the Canterbury Land and Water Regional Plan in 2015 (Seward *et al.*, 2017). Plan rules allow groundwater to be used for heating and cooling schemes in the central city as a permitted activity (i.e., a consent is not required) if certain conditions are able to be met, including that groundwater is abstracted from between 30 and 100 m depth and discharged to the Riccarton Gravel aquifer, with discretionary applications required where these criteria are not met. The intent of the policy was to remove a potential barrier to implementation of this energy-efficient technology during rebuild of the city following the 2010–11 earthquake sequence (Seward *et al.*, 2017). Whilst an outcome of the policy was to incentivise GSHPs that transfer water from the deeper aquifer to the shallow confined system, alternative well configurations are possible. By way of

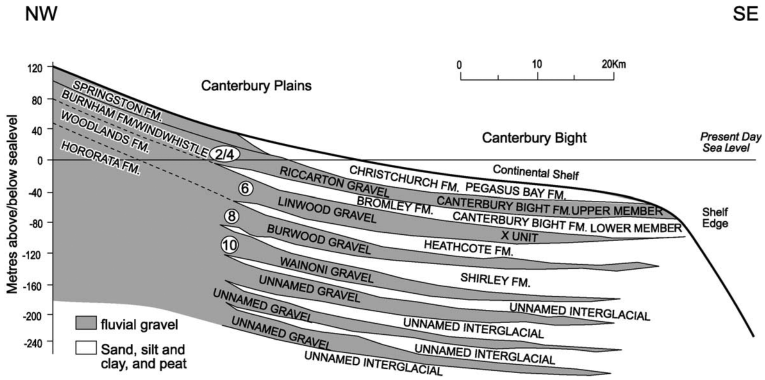

Figure 2 – Christchurch aquifer system (after Browne and Naish, 2003).

example, the vast majority of GSHP systems in the UK abstract from and discharge to the same stratigraphic unit (largely because they are not in complicated multi-level aquifer sequences like in Christchurch).

The potential effects of GSHPs on the depth to groundwater beneath Christchurch city were subsequently modelled by Rekker (2017) on behalf of the Canterbury Regional Council (Environment Canterbury). The study concluded that when GSHPs discharge to the Riccarton Gravel it has the knock-on effect of raising the water table in the overlying shallow water table system, with an associated potential for inundation of the upper ground profile in parts of the CBD. Under steady-state conditions the model predicted worst-case mounding in the Riccarton Gravel of up to 2.4 m above current levels, which would have a further effect of inducing diffuse rises in the overlying water table aquifer of up to 0.4 m. The study necessarily relied on modelling with significant uncertainties and recommended further work using more robust investigation tools.

A limited field investigation was conducted by Environment Canterbury later in 2017 in response to a complaint about groundwater flooding in a basement in the Christchurch CBD. The investigation monitored the effects of shutting down and restarting one GSHP system on groundwater levels in the Riccarton Gravel and overlying water table aquifers. The GSHP, which was pumping approximately 10 L/s into the Riccarton Gravel aquifer at approximately 40 m depth prior to the investigation, was shut down for two days and subsequently restarted at 32 L/s to induce a stress change in the groundwater system. Monitoring showed that while the water level in the Riccarton Gravel aquifer injection well dropped by 0.7 m during shut down and increased by ~5.9 m when the system was restarted, there was no discernible water level change in the water table aquifer monitoring wells. The study concluded that there was no evidence to suggest that groundwater discharge into the basement was related to operation of the GSHP system. A review of the Environment Canterbury investigation by an expert engaged by the flooded basement building owner postulated that the duration of the test may have been too short to induce a water level change in the water table aquifer (I. McCahon, personal communication, December 2017). The information above highlights the interest in the effects of GSHP systems on the Christchurch aquifer system, some of the uncertainties surrounding previous assessments and the need for further investigation.

In this paper we review groundwater level records from the Riccarton Gravel aquifer and overlying water table aquifer within the Springston Formation, in conjunction with pumping records from GSHPs in central Christchurch and estimates of the shallow aquifer throughflow and recharge, to determine the most likely cause of the rising water table issue reported in the CBD. We discuss the potential consequences of a higher water table on the vulnerability of central Christchurch buildings to increased liquefaction damage in the event of future earthquakes.

Methods

The main components of our methodology comprised (a) collation of information on the timing of GSHP system development within the city, their consented pumping/recharge rates and their water pumping records; (b) evaluation of the pre- and post-GSHP groundwater flux through the Riccarton Gravel aquifer to provide context for the volume of water discharged to this aquifer by GSHPs; and (c) analysis of groundwater level data for wells in the Riccarton Gravel aquifer and the shallow unconfined Christchurch aquifer (referred to as the water table aquifer) following the Before/After and Control/Impact (BACI) method (Underwood, 1992). Trend analysis was undertaken using Sen's slope estimator (Virtanen *et al.*, 2020) for those wells where a Mann-Kendall test met a significance threshold of 0.05.

Information on GSHP development was obtained from Environment Canterbury's consents database and through an information request for water meter records.

The pre- and post-GSHP development Riccarton Gravel aquifer groundwater flux was evaluated to determine the significance of increased aquifer throughflow rates associated with water transfer from the deep confined aquifer system associated with the GSHP systems. Piezometric contours from Talbot *et al.* (1986), Riccarton Gravel lateral hydraulic conductivity and Christchurch Formation vertical hydraulic conductivity values used by Rekker (2017), and average measured groundwater levels in these two aquifers were used to estimate (via Darcy's Law calculations) the rate of pre-GSHP Riccarton Gravel aquifer groundwater flow beneath central Christchurch. All available water meter records for the GSHPs were analysed to determine the percentage increase in groundwater throughflow associated with GSHP discharges to the Riccarton Gravel aquifer.

The underlying principle of the widely used BACI method is that an anthropogenic disturbance in the impact location will cause a different pattern of change from before to after it starts compared with natural change in the control location. This can be detected as a statistical interaction in analysis of variance of the data. A real environmental impact requires there to be greater difference between the impacted and control locations than there is generally among the controls (Underwood, 1992).

Three sources of groundwater level monitoring data are available for the greater Christchurch area from networks installed by Environment Canterbury, Christchurch City Council (CCC) and the Earthquake Commission (EQC). The artesian aquifer system is monitored by Environment Canterbury and includes four Riccarton Gravel aquifer monitoring wells within the Christchurch urban area. The CCC water table aquifer monitoring network originally comprised 32 shallow monitoring wells across the urban area. Of these, five sites were destroyed during the earthquakes, but the remaining 27 sites are still being monitored manually on a weekly or fortnightly basis, with up to 61 years of records. A dense network of piezometers was installed across the city by the EQC to monitor the water-table depth following the 2010–11 earthquake sequence. The latter network, referred to as the Automatic Piezometer Project (APP), consists of 247 shallow groundwater sites equipped with loggers automatically recording the water-table elevation every 10 minutes (downgraded to 15 minutes around 2020) (Bosserelle *et al.*, 2023).

Control sites (i.e., outside of the area of likely groundwater level changes from GSHPs) and impact groundwater level monitoring sites (within the area of potential water level change) were selected based on the study of Rekker (2017). The effects of GSHPs on the shallow Christchurch aquifers were evaluated using an Analytical Element Model. Model parameters were adjusted manually and via PEST to match groundwater levels in the Linwood, Riccarton and Springston Formation aquifers such that the measured upward hydraulic gradient was replicated within reasonable bounds. Twenty GSHP systems were implemented in the model comprising the eight schemes consented at the time of the 2017 study, two schemes with pending applications and a further ten hypothetical future schemes. The modelled pumping/recharge rate for all 20 schemes was 510 L/s, comprising the consented rates for GSHPs at that time plus assumed rates for the hypothetical future schemes. The model was run in transient mode and steady-state mode; results showed a maximum mounding of 0.4 m in the Springston Formation (i.e., the water table aquifer) and up to 2.4 m in the Riccarton Gravel. The model outputs included a modelled 0.1 m mounding

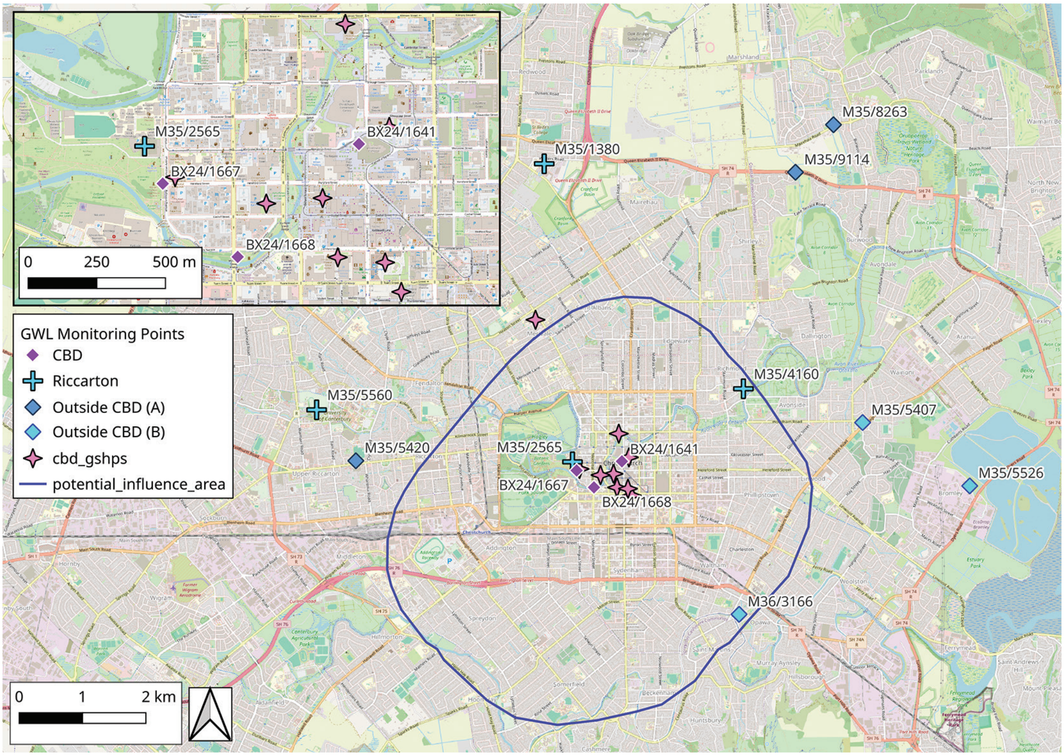

Figure 3 – Central Christchurch GSHP locations, modelled 0.1 m mounding contour, and control and impact monitoring sites.

contour for the Riccarton Gravel, which was used to delineate the maximum likely extent of mounding impact in both the Riccarton Gravel and overlying water table aquifer for the purposes of this current study. The true area of mounding influence is likely to be much smaller than this because the groundwater pumping rate for all central Christchurch GSHPs is likely to be in the order of 140 L/s (i.e., 30% of the rate assumed by Rekker, 2017) as per the pumping rate data summarised Table 1.

The location of the four Riccarton Gravel aquifer monitoring wells (one control and three impact) and water table aquifer control and impact sites selected for analysis are shown in Figure 3.

Results

GSHP system development and water usage

The approximate commencement dates, consented daily pumping rates, and measured or estimated water usage rates for the eight GSHPs in the central Christchurch area at the time the model was developed are summarised in Table 1. Flow meter records for those schemes with consistent records show that approximately 60% of the consented water take and discharge rate is used on average. The combined average rate of water transfer from the deep artesian system (generally the Wainoni Gravel, found at around 120+ m depth) to the Riccarton Gravel aquifer is approximately 12,300 m^3/d (140 L/s).

Table 1 – GSHP systems in central Christchurch.

Scheme name	Consent number	Approximate commencement date	Consented daily pumping rate (m^3/d)	Actual usage (m^3/d)
Bus Interchange	CRC210241	May 2015	690	302[2]
Environment Canterbury offices	CRC146483	April 2016	2,500	860
The Arts Centre	CRC154729/30	June 2016[1]	6,084	1,211
King Edwards Barracks	CRC201497	March 2017	5,184	1,548
Justice Precinct	CRC190795	September 2017	6,635	3,054
The Terrace	CRC175832	March 2018	3,429	1,233
Tūranga Central Library)	CRC191541	October 2018	2,916	1,698[2]
Town Hall	CRC183997	December 2018	4,752	2,365[2]

1. Public information ("Christchurch Arts Centre", 2025) indicates that the Great Hall opened in 2016, but the earliest flow meter reading is from April 2017; it is unclear whether the GSHP was operational when the hall opened, but regardless it is likely that usage of the system has increased over time with the progressive reoccupation of buildings.
2. Estimated based on average % usage of annual volume limit for GSHPs with flow metering records available to us, i.e., 58%.

Riccarton Gravel aquifer flux

Rekker (2017) provides a representative Riccarton Gravel aquifer top and bottom elevation of -17 and -33 m aMSL (approximately 23–39 m depth), respectively, beneath the CBD. The author's summary of aquifer test interpretation results for wells within the Christchurch aquifer system includes a mean transmissivity of 3,845 m^2/d derived from pumping tests on 10 wells and a modelled transmissivity of 5,700 m^2/d. Groundwater contours for the Riccarton Gravel aquifer presented in Talbot *et al.* (1986) show a gradient of 0.0003 beneath central Christchurch. The aquifer width parallel to the groundwater contours through the model area of central Christchurch is approximately 1 km, giving a throughflow of 13 and 20 L/s for the mean pumping test-derived and modelled transmissivity values, respectively. Given the significant vertical gradient between the Riccarton Gravel aquifer and overlying Springston Formation water table aquifer, the total aquifer flux also includes upwards seepage. Rekker (2017) provides a modelled vertical hydraulic conductivity of 0.065 m/d for the Springston Formation, although we note that this value is subject to significant uncertainty. Taking the 3 m water level difference between the pre-GSHPs groundwater level in Riccarton Gravel monitoring well M35/2565 (see Figure 4) and the central Christchurch water table monitoring wells (see Figure 6), the upward hydraulic gradient over the typical 12 m vertical interval between the top of the Riccarton Gravel and the top of the Christchurch Formation/base of Springston Formation is estimated to be 0.25. The pre-GSHPs vertical specific discharge from the Riccarton Gravel aquifer to the Springston Formation is therefore estimated to be in the order of 0.016 m/d, equating to a flux of 188 L/s over the circa 1000 × 1000 m area within which the central Christchurch GSHPs are installed. The total pre-GSHPs aquifer flux in this area is therefore estimated to be in the order of 200 L/s. The average GSHP systems' combined water discharge to the Riccarton Gravel aquifer of 140 L/s therefore equates to a 70% increase in the Riccarton Gravel aquifer discharge. We discuss this further below.

Riccarton Gravel aquifer water levels

Groundwater levels relative to ground level in the Riccarton Gravel aquifer impact well (M35/2565) and control wells (M35/1380, M35/4160 and M35/5560) are shown in Figure 4 together with cumulative maximum consented GSHP pumping rates.

Well M35/4160 shows a downward step change in water levels between 2010 and 2011, coinciding with the Canterbury earthquake sequence, before recovering from 2014 onwards. The well water level subsequently increased to a higher elevation than previously observed, in line with a statistically significant increasing long-term groundwater level trend. Well M35/2565 has a visually apparent step increase in groundwater levels of almost 1 m between 2015 and 2017, coincident with the development of several GSHP systems in the city. Water level variations in wells M35/5560 and M35/1380 are less pronounced. Post-earthquake groundwater levels are generally higher than pre-earthquake in well M35/5560, but this may be natural variation given the absence of a trend. Well M35/1380 shows an increasing trend overall. Post-earthquake groundwater elevations are lower than pre-earthquake relative to the Sen-slope regression, with the deviation occurring immediately after the earthquake. The groundwater level data analysis therefore shows a statistically significant groundwater level increase over the observation period in the impact site and in two of the three control sites. The impact site shows a step increase in groundwater levels coincident with the development of several GSHP systems in the

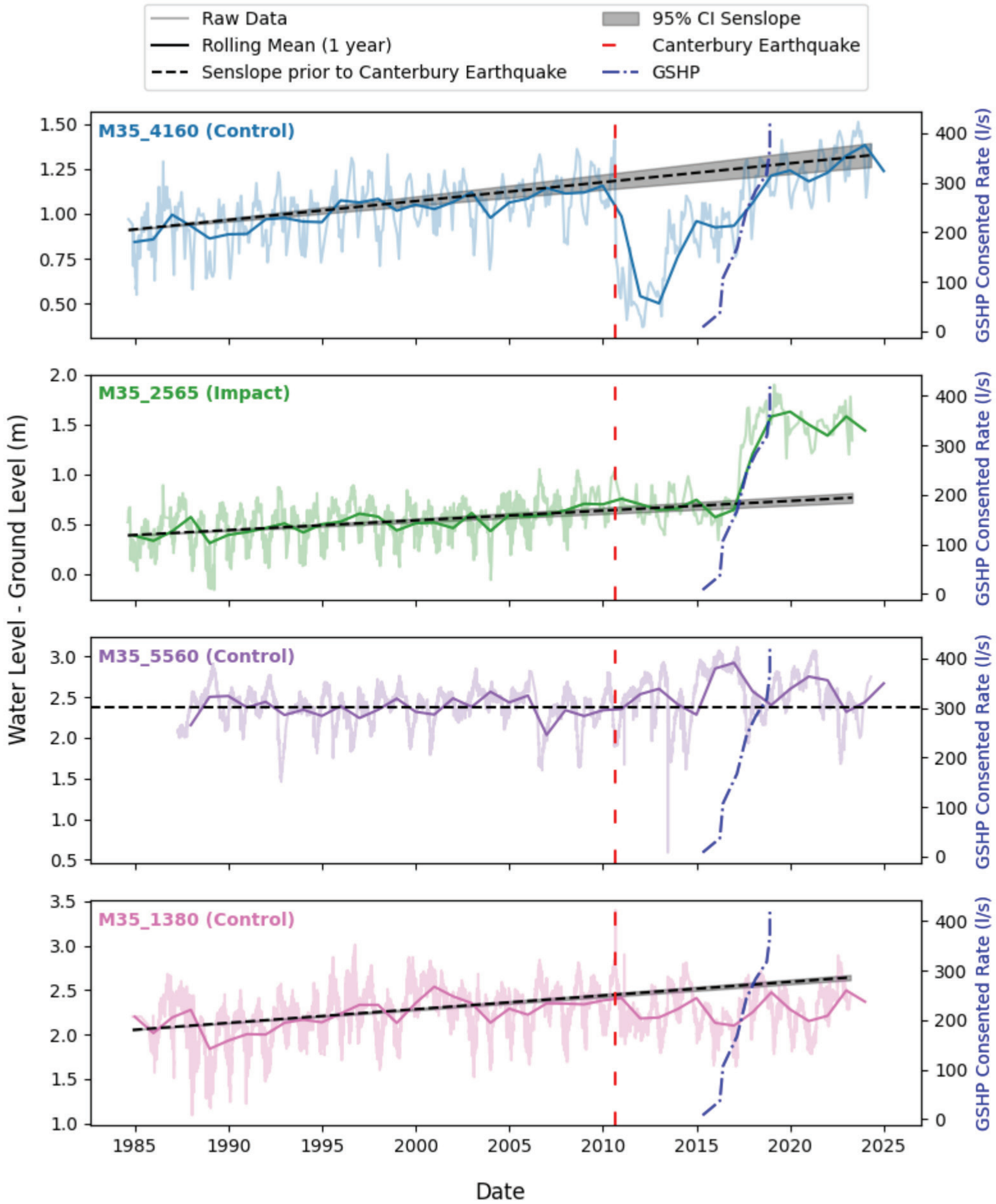

Figure 4 – Riccarton Gravel aquifer groundwater level records, mid-1980s to 2023/24, at one control and three impact monitoring sites in central Christchurch. The GSHP consented rate (right axis) is the cumulative consented discharge rate for all GSHP systems that discharge to the Riccarton Gravel.

city. No such step increase is observed at the control sites.

Shallow aquifer groundwater level analysis outside the CBD: control sites

We investigated groundwater levels in the shallow water table aquifer (i.e., the Springston Formation) at six control sites, which are divided into two groups in Figure 5: (A) Those with a significant decreasing trend (M35/8263) or no significant trend; and (B) those with a significant increasing trend. All trends were assessed using a Mann-Kendall test with a significance threshold of 0.05 for the dataset after the Christchurch earthquake on 22 February 2011. See Figure 7 for the groundwater monitoring site locations. The control sites were selected from the Environment Canterbury groundwater level monitoring database by firstly filtering to provide wells with at least 20 years of regular monitoring data and a depth of less than 10 m and then selecting the six sites to provide spatial coverage around the CBD.

Shallow aquifer groundwater level analysis within the CBD: impact sites

Six shallow monitoring wells are present within the potential GSHP impact area (i.e., the Christchurch CBD) comprising three wells that were present pre-2016 and three replacement wells that were monitored from late 2017 onwards, presumably due to loss of/damage to the original wells. We treat the respective original and replacement wells as a single well for the purpose of this analysis given that their depths and locations are effectively the same. Groundwater levels

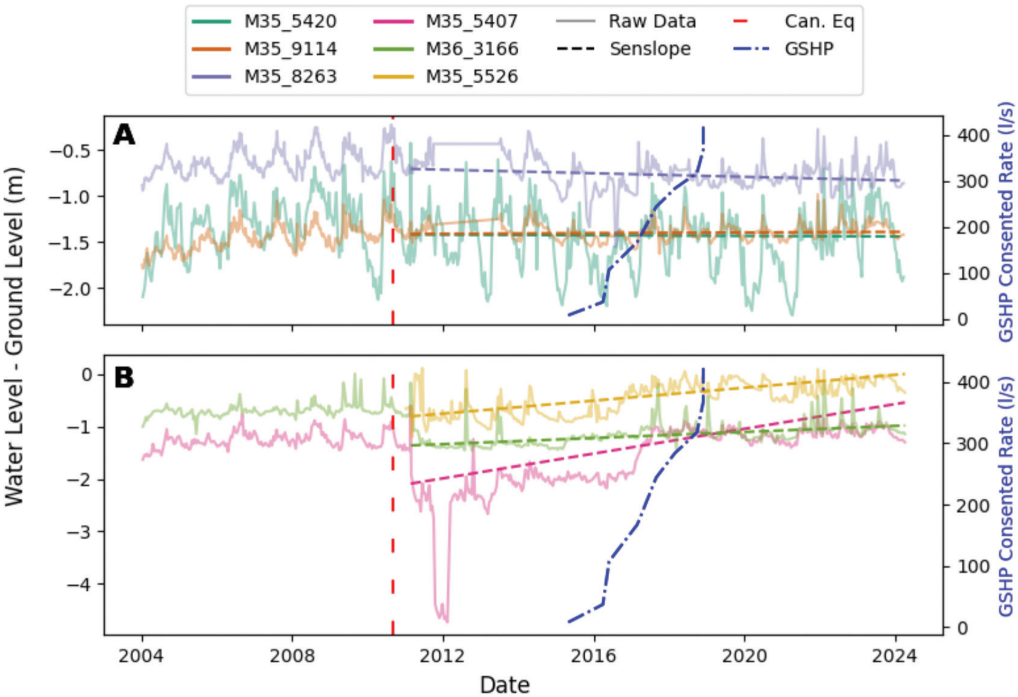

Figure 5 – Water table aquifer water levels at control sites outside the Christchurch CBD with (A) decreasing water levels or no significant trend and (B) increasing water levels. Can. Eq = date of February 2011 earthquake. GSHP = cumulative consented pumping rate for GSHP systems in central Christchurch, increasing as each GSHP consent is activated (right axis).

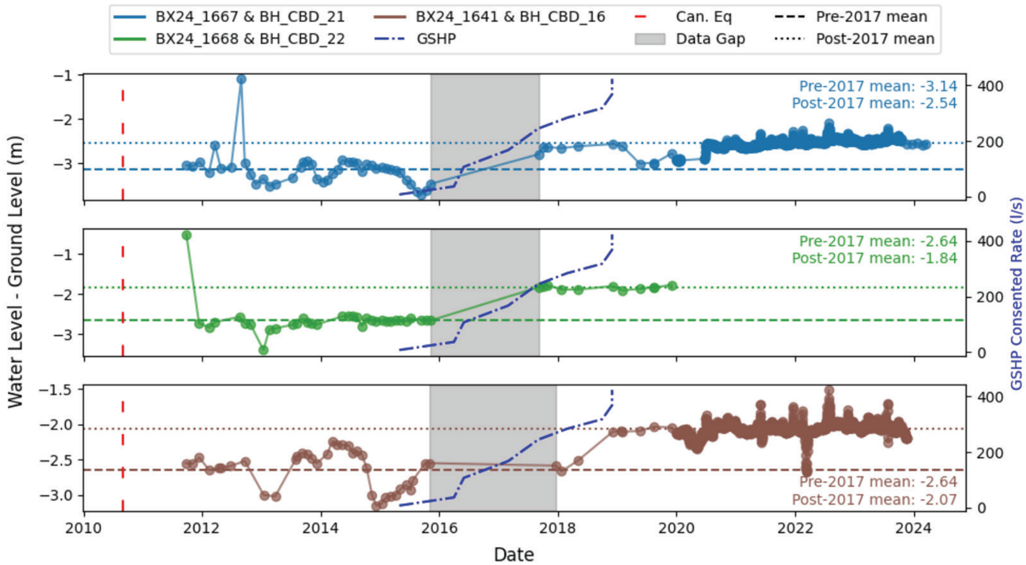

Figure 6 – Water table aquifer groundwater level records from three monitoring wells in the Christchurch CBD. Can. Eq = date of February 2011 earthquake. GSHP = cumulative consented pumping rate for GSHP systems in central Christchurch, increasing as each GSHP consent is activated (right axis).

from 2012 to 2024 are presented in Figure 6. All three well water level records have a data gap between 2016 and late 2017, and all show significant water level increases (0.60, 0.80, and 0.57 m for wells BX24/1667, BX24/1668, BX24/1641, respectively) over the monitoring period.

Discussion

The causes of rising groundwater

Eight GSHP systems were activated in central Christchurch between 2015 and 2018. The resource consents for these schemes allow for transfer of up to 373 L/s of water from the deep Wainoni Gravel aquifer to the shallower Riccarton Gravel aquifer. The typical (total) operational transfer rate appears to be in the order of 140 L/s, which equates to a 70% increase in the flux through this aquifer according to our estimates. This suggests that GSHPs represent a significant stress change in the local aquifer system, noting that the estimate of the natural groundwater flux through the Riccarton Gravel aquifer is unsophisticated and subject to significant uncertainty margins.

Groundwater levels recorded in the central Christchurch Riccarton Gravel aquifer monitoring well (our designated impact site under the BACI framework) are approximately 1 m higher after activation of the GSHPs consents than before. This represents a significant increase in the artesian water level, from approximately 0.5 m to 1.5 m above ground level at the monitoring site location. The pressure increase in the Riccarton Gravel aquifer is likely to be greater towards the centroid of the combined GSHP injection wells.

Of the three Riccarton Gravel aquifer control sites (outside of the central city), water levels in two wells (M35/1380 and M35/5560) do not show any significant change before and after the activation of the GSHP systems, with the water levels in M35/1380 falling slightly compared to the pre-earthquake trend. Well M35/4160 shows an increase in groundwater levels in the period after installation of the GSHP systems, but this is consistent with a longer-term pattern of water level recovery following significant drawdown immediately after the 22 February 2011 earthquake. M35/4160 is located in an area of both high liquefaction damage potential and of significant buried wastewater pipework repairs (see Figure 7 and the associated discussion below). The post-earthquake groundwater level decline and recovery pattern in this well is similar to that seen in the Group B wells in Figure 5. Groundwater inflows to the reticulated stormwater and wastewater network were significant in the post-earthquake period due to elevated groundwater and/or reduced land levels combined with widespread pipe damage, with a resultant 60% increase in the wastewater network flow on average (Christchurch City Council, 2014). The groundwater level decline and subsequent recovery in well M35/4160 therefore appears to relate to post-earthquake groundwater drainage via damaged infrastructure, with a subsequent reduction in drainage and an associated groundwater level recovery following pipework repairs. This suggests relatively close connectivity between the Riccarton Gravel aquifer and the water table aquifer, within which buried services are installed, with important implications for the effects of GSHP system discharges to the Riccarton Gravel.

We therefore conclude that groundwater levels in the Riccarton Gravel aquifer beneath central Christchurch have increased significantly because of the GSHP system installations. The similarity of water level patterns in the Riccarton Gravel and some of the water table aquifer monitoring control sites suggests relatively close connectivity between these two aquifers.

It is noteworthy that three of the four Riccarton Gravel aquifer monitoring wells (comprising the impact site and two of the three control sites) show a long-term increasing groundwater level trend over the 1985 to 2024 period. The cause of this is unknown but might relate to the reduction in groundwater abstraction from this aquifer for the city's water supply in favour of the deeper aquifer system, which is more secure in terms of microbial contamination risk.

Groundwater levels recorded in the Springston Formation (water table aquifer) impact monitoring sites are on average 0.7 m higher after activation of the GSHP systems than before. Of the six water table aquifer control sites, four show no discernible water level change immediately pre- and post-GSHP activation. Two sites show a groundwater level increase that coincides with the broader pattern of post-earthquake groundwater level recovery elsewhere in the city. The absence of pre-earthquake water table monitoring in the central Christchurch control sites means that it is not possible to differentiate between recovery of a temporary post-earthquake water table depression and a GSHP-driven water table rise. This gives rise to an alternative hypothesis: that rather than being due to GSHP system effects, the 0.7 m average groundwater level increase instead relates to post-earthquake pipework repairs and an associated recovery in groundwater levels to their pre-earthquake levels. The lack of consistent patterns across the control and impact sites in relation to one another and to rainfall data indicates that groundwater level increases are not related to rainfall/recharge and hence natural variability is not supported by the data as the cause.

Groundwater level monitoring data provided within a pumping test report for the Christchurch Town Hall GSHP system consent application (Lough and Steffans, 2018) shows a 0.1 m increase in water table elevation in two shallow monitoring wells. This occurred after three days of Wainoni Gravel aquifer pumping and associated Riccarton Gravel aquifer recharge at approximately 50 L/s in 2017 and demonstrates that at least one of the city's GSHP systems causes water table mounding. Our review of readily accessible consent application documents for other schemes found that water table mounding was typically not assessed for the application, with no water table monitoring during test pumping. The consent application for the St Georges Hospital GSHP, which is located outside of the Christchurch CBD and is not included in Table 1, included a conservative analytical model-based assessment of potential water table mounding and concluded that shallow water levels could theoretically increase to above ground level in close proximity to the injection bore. These two pieces of information lend weight to the hypothesis that the observed increase in water table height is at least partially attributable to the GSHP systems.

The likelihood of post-earthquake water table depression and recovery at a monitoring location, due to drainage by the damaged stormwater and wastewater network, is a function of the extent of pipework damage and water table depth relative to pipework depth. Liquefaction Resistance Index Zone and wastewater repair mapping (Cubrinovski *et al.*, 2014) provides information on pipework damage in the vicinity of monitoring sites included in this study as per Figure 7. The water table monitoring control sites with a significant post-earthquake increasing trend (Group B in Figure 5) are closer to areas with more extensive wastewater repairs and in more liquefaction-prone zones than the control wells with decreasing or no significant trends (Group A in Figure 5). There are no recorded pipework repairs within the vicinity of the Group A wells. The most significant post-earthquake groundwater level decline and recovery is observed in M35/5407, which is in the most liquefaction-prone area. The Liquefaction Resistance Index Zone classification and the intensity of wastewater pipework repairs within the vicinity of a monitoring well therefore appear to be predictors of post-earthquake water table drainage and recovery, noting that data availability is insufficient to evaluate the strength of these predictors. The GSHP water table impact monitoring sites, BX24/1667 and BX24/1641 in particular, are in areas classified as having high liquefaction resistance, with no local wastewater pipe repairs. These sites are much less likely to have been affected by a significant post-earthquake increase in water table drainage and recovery due to inflows to damaged pipework. Furthermore, groundwater levels in the Group B water table monitoring control sites are approximately 1 m below ground level on average, whereas groundwater levels in the impact monitoring sites in central Christchurch are 2–2.5 m below ground level. Buried pipework is much more likely to intersect the water table at 1 m depth than at 2–2.5 m depth.

This analysis therefore suggests that the Group B control sites could have been impacted by a phenomenon that is unlikely to have affected either the impact sites or the Group A control sites, hence the Group B sites can therefore be excluded from the BACI analysis. The analysis then shows that anthropogenic disturbance in the impact location (in this case the GSHP-driven transfer of significant volumes of water from the deep Wainoni Gravel aquifer to the shallow Riccarton Gravel aquifer beneath the CBD) is the most likely cause of a notably different pattern of pre-and post-disturbance change relative to natural change in control site locations.

The timing of groundwater level increases in the water table monitoring impact sites

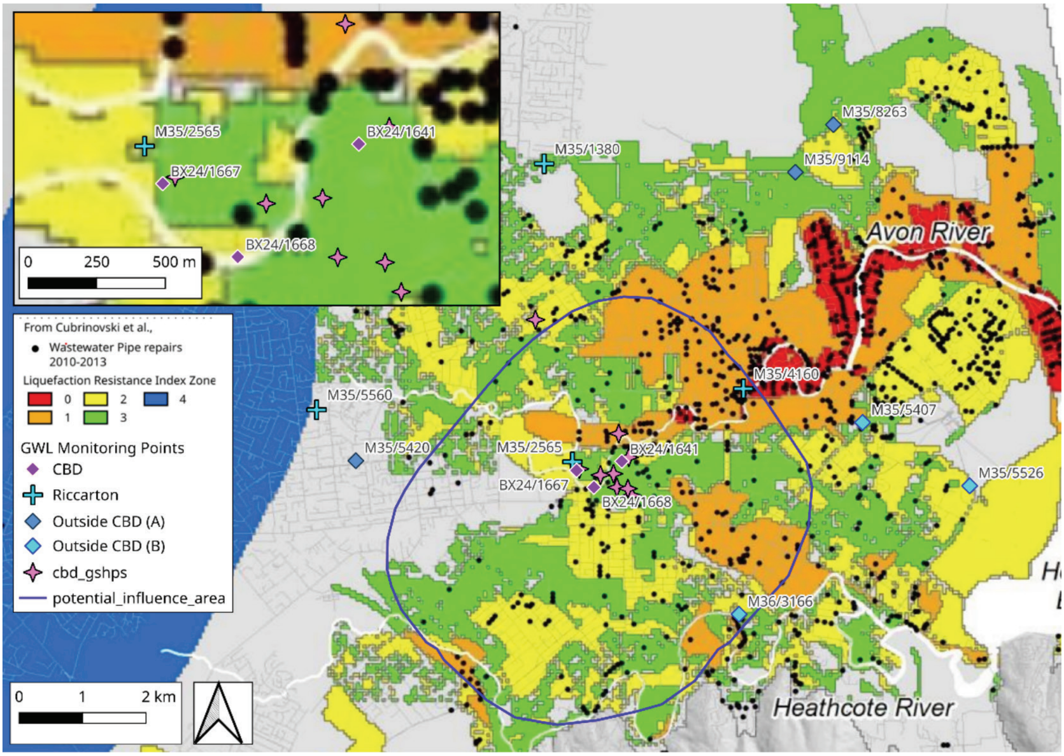

Figure 7 – Monitoring locations overlayed on the Liquefaction Resistance Index (0 = poor resistance, 5 = high resistance) from Cubrinovski *et al.* (2014).

lends further weight to the findings of the BACI analysis. The water level increase in wells BX24/1667 and BX24/1668 had occurred by September 2017. BX24/1667 is located very close to the Arts Centre GSHP and close to the King Edward Barracks GSHP. BX24/1668 is close to the King Edward Barracks and Justice Precinct GSHPs. These schemes became operational in the 2016–17 period. The increase occurred between May and December 2018 in BX24/1641. BX24/1641 is located close to the Central Library GSHP, which became operational in 2018.

The consequences of rising groundwater levels

The potential consequences of rising groundwater levels were discussed in the introductory section of this paper and include (1) basement flooding and ongoing pumping requirements; and (2) reduction in soil strength with implications for all types of foundation and their bearing capacity, and a significant increase in liquefaction vulnerability. It is noteworthy that the 0.7 m water table rise identified in this study is greater than the 0.5 m increase modelled in the Monk *et al.* (2016) study, which was found to have a dramatic impact on liquefaction vulnerability and correspondingly the amount of liquefaction-related land damage that would result at that location. Christchurch City Council (n.d.) provides information on liquefaction damage potential in the city under a range of earthquake intensities and water table depths via an interactive map. For the polygon within which Cathedral Square is located (middle of the CBD) and a ground acceleration of 0.4 g from a magnitude 6 earthquake (5% probability over 50 years), a 0.5 m water table rise causes the proportion of land expected to experience minor to moderate damage and moderate to severe damage to increase from 17% and 7% to 28% and 12%, respectively, according to the tool. A 1 m water table increase changes the latter two values to 19% and 35%. A linear interpolation of these figures for the 0.7 m water table rise measured in the central Christchurch water table monitoring wells gives an increase in minor to moderate damage and moderate to severe damage from 17% and 7% to 24% and 21%, respectively. The area of land expected to experience minor to moderate damage is therefore likely to have increased by approximately 40% and the area expected to experience moderate to severe damage has increased by 300%.

Conclusions

Christchurch is vulnerable to rising groundwater levels due to the underlying shallow water table and liquefiable soils. Eight GSHP systems were installed in the central city between 2015 and 2018, with resource consents that in combination allow for transfer of up to 373 L/s of water from the deeper aquifer system (generally the Wainoni Gravel) to the shallower Riccarton Gravel aquifer. Groundwater level monitoring data show a sustained increase in the water table elevation beneath central Christchurch of approximately 0.7 m between 2016 and 2018. BACI analysis and other supporting information presented in this paper show that the water table elevation increase is likely to be due to the transfer of groundwater to the shallow aquifer by the GSHP systems. This water table rise is consequential: for example, some building owners in the city have experienced basement groundwater ingress issues following the installation of these systems, and analysis using a Christchurch City Council tool suggests the area of land expected to experience moderate to severe building damage under a 0.6 g earthquake is projected to substantially increase due to the increased liquefaction risk. Further investigation, particularly given the range of uncertainties, of this matter by the relevant authorities is recommended.

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