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History and use of Ōtautahi/Christchurch's shallow groundwater monitoring network

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Abstract

The purpose of this paper is to highlight the unique shallow groundwater monitoring network in Ōtautahi/Christchurch, describe investigations that have been carried out using its data, and outline the future needs for shallow groundwater monitoring and modelling. As a legacy of the Canterbury Earthquake Sequence in 2010/2011, Christchurch has a unique and world-class shallow groundwater monitoring network, the data from which supports research that will help Aotearoa New Zealand better understand the spatial and temporal characteristics of shallow groundwater systems. The collection and use of the data will help prepare Christchurch for changing climate and rising sea levels. Current and future research will provide an exemplar of what can and needs to be done to understand shallow groundwater as a hazard in itself and as a contributing factor to other hazards.

Whilst the Canterbury earthquakes were the catalyst for the installation of Christchurch's groundwater monitoring network, socio-economic values, political will, and individual motivation and persistence have very much influenced the shape and development of the network.

The paper provides an outline of the network, its history and development, and key studies that have utilised the network's data. The reader is directed to the references provided to explore the results of the research in further detail.

Swamp to city – or city to swamp?

The evolution of Ōtautahi/Christchurch City (Christchurch) is the result of a transformation of a swampy, wetland-dominated landscape to a modern urban area. This transformation involved significant environmental management efforts, particularly related to water and groundwater systems (Hercus, 1942; Watts, 2011; Wilson, 1989). Pre-19th century and before European settlement, Christchurch was characterised by extensive wetlands, particularly in the low-lying areas. The wetlands were important to indigenous Ngāi Tahu people for their food resources (mahinga kai) and ecological values. Europeans who settled in the area in the mid-19th century saw the potential for productive land in the region, but recognised that drainage of the wetlands was essential to lower the water table, enabling the expansion of farming areas and urban development (Hobbs *et al.*, 2022). From the 1850s onward drainage efforts began, with the construction of ditches and subsurface wastewater systems. This process of land drainage continues to this day and requires ongoing management using extensive water infrastructure.

Several interrelated factors, both natural and anthropogenic, impact the vulnerability of urban Christchurch and the city is particularly susceptible to natural hazards (Bosserelle *et al.*, 2022; Hughes *et al.*, 2015). First, the geological and hydrological settings (low-lying terrain and shallow groundwater) make the city vulnerable to hydrological hazards, with the shallow groundwater system increasing the risk of groundwater flooding, especially after heavy rainfall (Quigley and Duffy, 2020). Second, the conversion of wetlands to urban areas has left the city with a legacy of drainage challenges (Foster *et al.*, 2011). The reliance on artificial drainage systems means that any failure or overwhelming of these systems (e.g., during extreme weather events) can lead to flooding and other water-related issues. Third, the region's seismically active setting, liquefaction-prone soils and shallow groundwater make parts of Christchurch particularly susceptible to land damage by liquefaction and lateral spread during earthquakes. The Canterbury Earthquake Sequence (CES) in 2010/2011 (particularly the earthquakes on 4 September 2010 and 22 February 2011) caused widespread liquefaction, where saturated soils temporarily lost strength and stiffness, leading to ground subsidence and damage to infrastructure (Quigley *et al.*, 2016). Fourth, generally and in the context of Christchurch, subsurface infrastructure, including wastewater and drainage systems, interacts with the shallow groundwater, making the infrastructure vulnerable to changes in groundwater levels (Sangsefidi *et al.*, 2023; Sartirana *et al.*, 2022). Damage to these systems during earthquakes or floods can lead to significant urban disruption.

As sea levels rise due to climate change, Christchurch faces increased risks of coastal flooding and saltwater intrusion into freshwater systems (Bosserelle *et al.*, 2023; Morgan, 2024; Setiawan *et al.*, 2023a). Shallow groundwater levels are expected to rise in coastal areas and close to tidal reaches of rivers (Rutter, 2020; Bosserelle *et al.*, 2022). Climate change is also likely to bring more intense and frequent rainfall events, which could overwhelm the city's drainage systems and exacerbate flooding risks.

Continued urban expansion has further stressed the city's drainage and groundwater management systems. As the city expands, the need for robust infrastructure to manage water and protect against flooding becomes even more critical. Past environmental management and historical land use created a city susceptible to natural hazards. The transformation from wetlands to urban areas has created a long-term vulnerability that requires constant management, and the legacy of this transformation is that Christchurch must continuously invest in and adapt its infrastructure to manage environmental risks.

From a resource perspective, investigations of shallow groundwater have traditionally been a lower priority than those of deeper groundwater (Bosserelle and Hughes, 2024a; Setiawan *et al.*, 2022b). This is because groundwater research has tended to focus on water as a resource, and shallow groundwater is often considered unsuitable as a resource because it is less reliable and more vulnerable to contamination than deep groundwater. From a hazards perspective, shallow groundwater has (until recently) mostly been unrecognised because it is mostly unknown and invisible, or its contribution is masked by more visible pluvial flooding.

However, in recent years, shallow groundwater has been increasingly recognised as a natural hazard and an exacerbator of other hazards (Rutter, 2020; Cox *et al.*, In Press) and increased monitoring is being put in place. Recognition of groundwater's role in flooding and liquefaction susceptibility and effects on horizontal infrastructure, structures and health has led to acknowledgement of the need to understand shallow groundwater, spatially and temporally. In Christchurch's case, the CES caused substantial land damage, prompting the development of a groundwater monitoring network that could be used to inform liquefaction susceptibility assessments and thus land damage payouts. The network has provided critical data that have been used not only for assessing liquefaction risk assessment, but also for assessing risks from groundwater flooding and long-term sea level rise impacts.

In modelling and assessing Christchurch's shallow groundwater system, it is helpful to acknowledge the system as having three interconnected components: the physical formations and response of groundwater to drivers (such as surface water and climate), passive anthropogenic influences (such as infiltration into wastewater and stormwater systems or exfiltration from systems) and active anthropogenic influences (such as dewatering and artificial recharge). Crucially, these factors are not related in a linear way: as groundwater levels change, the influence of natural and anthropogenic controls can change. As a result, interpretation of and understanding impacts is hugely challenging (Attard *et al.*, 2016; Bosserelle *et al.*, 2023).

The monitoring network

Between 4 September 2010 and 23 December 2011, Christchurch was struck by earthquakes and aftershocks up to Mm 7.1, referred to as the CES. The CES killed 185 people and caused extensive damage throughout Christchurch with severe liquefaction, lateral spreading, and damage to infrastructure resulting in abandonment of many parts of the city. To understand ground conditions and depth to groundwater, for the assessment of liquefaction susceptibility and land damage, thousands of cone penetration tests (CPTs) were carried out to inform geotechnical studies about soil conditions across Christchurch.

The Earthquake Commission (EQC: now Toka Tū Ake Natural Hazards Commission/NHC), is Aotearoa New Zealand's national insurer of residential properties against natural disasters. The EQC subsequently constructed around 1,000 piezometers across Christchurch that were used to monitor shallow groundwater (Figure 1) (Rutter *et al.*, 2018; Cox *et al*, 2021). This network recorded data that was later used to inform modelling of the water table, providing information across the urban area with unprecedented spatial resolution (Rutter, 2020; van Ballegooy *et al.*, 2014; Weir *et al.*, 2024). A small subset (44) of piezometers had long-term (>20 year) records that included the earthquake sequence, but generally with only fortnightly or monthly depth-to-water readings. Data from these piezometers generated questions as to the influence of earthquakes on the water table and highlighted the inter-annual variability in the water table (van Ballegooy *et al.*, 2014).

EQC/NHC has two major workstreams: insurance and investment in natural hazards research. The piezometer network was constructed to inform the insurance workstream, to identify ground conditions in order to price repair options and to identify where vulnerability to liquefaction and flooding had worsened due to the earthquakes. Even early on, as the insurance claim work was still

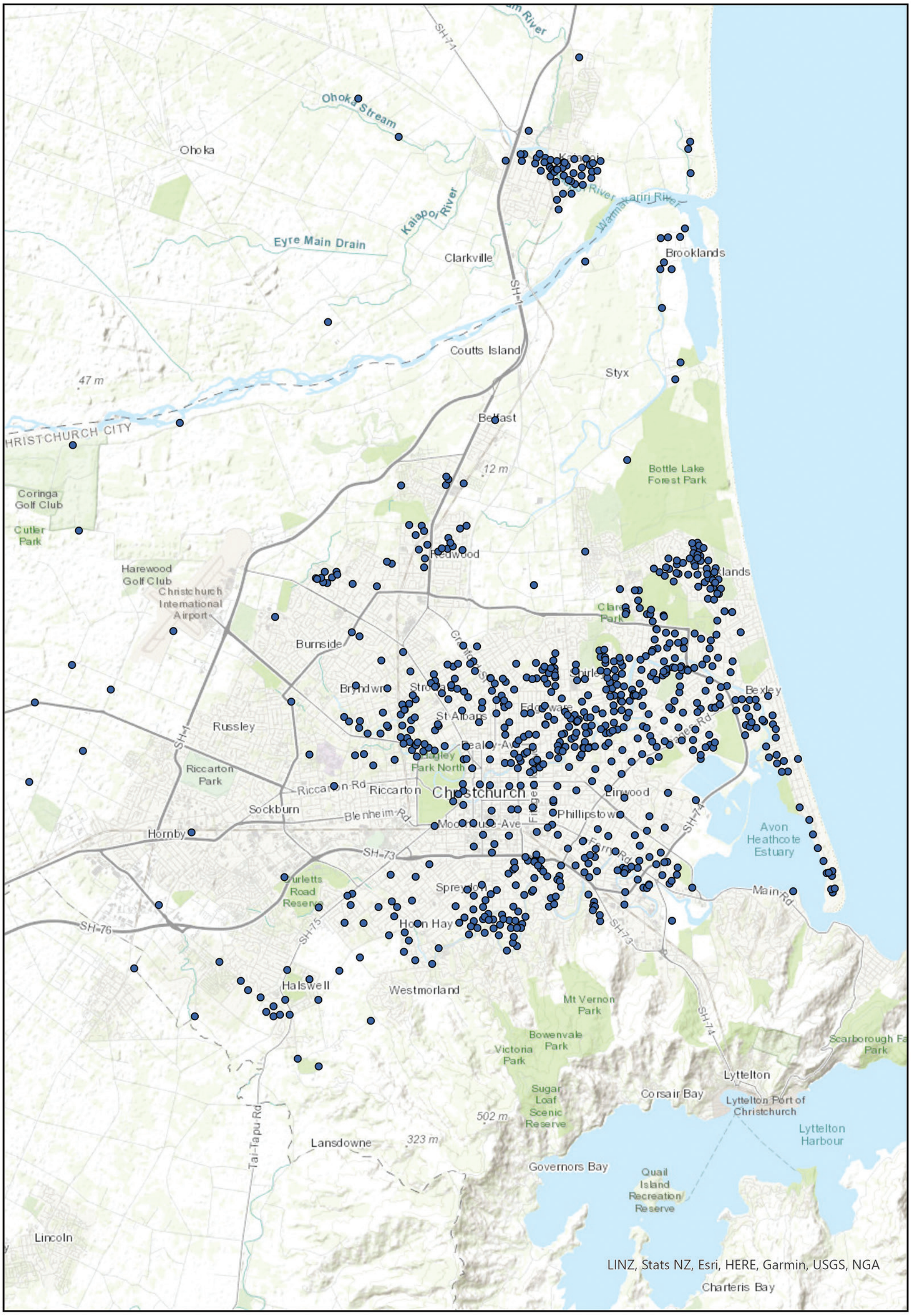

Figure 1 – Original EQC shallow groundwater monitoring network, consisting of ~1,000 piezometers.

very much front and centre, members of the EQC natural hazards research workstream were very aware of the value that could be gained by maintaining the piezometer network for the purposes of long-term research into natural hazards. Long-term ownership, monitoring and maintenance of such a piezometer network was, however, outside the scope of EQC's remit. In August 2013, Dr Richard Smith of EQC/NHC began to seek a new 'home' for the piezometer network once EQC's insurance responsibilities were discharged, approaching, amongst others, the Canterbury Regional Council (Environment Canterbury) and Christchurch City Council (CCC).

In 2016, EQC opted to reduce the spatial extent of the monitoring network and signalled their intention to fit approximately 250 piezometers with transducers, logging groundwater pressure and temperature at 10- to 15-minute intervals. This network was to become known as the Automated Piezometer Project (APP) network.

Dr Smith's vision for the ongoing usefulness of the network led him to collaborate with numerous stakeholders to investigate how the proposed network could be most usefully configured to meet their needs. Key members of the team included Simon Cox of GNS and Helen Rutter of Aqualinc, along with members of Environment Canterbury's Natural Hazards (Marion Schoenfeld), Groundwater, and Contaminated Sites teams; University of Canterbury/Lincoln University Waterways Group; University of Canterbury Geography and Engineering schools; NIWA Monitoring and Groundwater Modelling teams; CCC and Waimakariri District Council Three Waters teams; Land Information New Zealand (LINZ); Tonkin and Taylor; and the Canterbury Earthquake Recovery Authority (CERA).

There was universal interest in the proposed network, with value recognised for many workstreams. The initial meeting showed organisations expressed many and varied interests in the data. For example:

- **CCC** expressed interest in inflow and infiltration (I&I) into pipe networks; management of assets, including where to replace systems; identifying the impacts of stormwater networks on baseflow; interest in the interaction between surface water/flooding and shallow groundwater; and integration of information on pipe networks and flooding. Better knowledge/information could aid in the redesign of pipe networks potentially saving millions of dollars and could help inform the best type of system to install. They had particular interest in areas which, due to subsidence, were now at greater risk of flooding (including Mairehau, Richmond, and St Albans). CCC were also interested in using the data to inform their Urban Development Strategy/Land Use Recovery Plan, although they recognised that most piezometers were in areas that are already developed.
- **Environment Canterbury's Contaminated Land team** were interested in groundwater quality monitoring and potential transport of contaminants.
- **Environment Canterbury's Hazards team** expressed interest in groundwater information to inform liquefaction vulnerability analysis (including sea level rise and associated rising groundwater levels). Their Land Use Recovery Plan and Natural Environment Recovery Plan both identified the groundwater monitoring as important to continue.
- **Aqualinc** were committed to working with CCC to understand earthquake and climate change impacts on shallow groundwater as a hazard and were interested in the data to support refinement of shallow groundwater level surfaces.

- **Environment Canterbury's Groundwater team**, as is the case with most regional councils, considered groundwater as a resource and traditionally had little interest in shallow groundwater. However, they identified capability in terms of managing and storing groundwater information and considered they could offer support in this area. They also expressed interest in monitoring shallow groundwater quality and informing state of the environment reporting and long-term trends.
- **GNS** recognised that the data included uncharacteristically wet post-earthquake conditions. They were interested in the fact that there was so much variability between sites and that each presented a unique insight to understand processes. They considered that the data could be used to understand short-, medium- and long-term variations, and could be used to investigate the relationships between shallow geology and groundwater or effects of tidal and barometric variations.
- **CERA** recognised the cost savings from the data, estimating that they could save $5M in investigation costs. They recognised the use of data to aid in identifying the best systems to install (e.g., where vacuum wastewater systems were advantageous).
- **EQC** had an ongoing interest, less from an insurance point of view and more from a science point of view. They wanted to see the investment EQC had made in this asset producing a lasting legacy for Canterbury, Aotearoa New Zealand and internationally. They noted there was a great deal of international interest in Canterbury following the CES.

Planning the APP monitoring network was a prolonged process. The monitoring locations were extensively discussed, and Cox (pers. comm.) developed an initial monitoring network plan. The plan prioritised sites based on: even spacing; likelihood of groundwater being affected by sea level rise; areas where groundwater was < 2 m above mean sea level and/or < 2 m depth below surface; location either side of mapped boundaries on the geological/soil maps so that water table and/or permeability differences could be investigated; and locations that would create transects perpendicular to rivers so that tidal efficiency and/or sea level rise could be investigated.

The aim of this plan was to ensure a distributed monitoring network across the city, but the assessment specifically did not take into account engineering aspects, land damage zones, etc. Ultimately, the final ranking was more weighted for the purpose of land damage assessments for EQC, which resulted in a network that was optimum for its purpose at the time but is not necessarily optimum for other users now (Figure 2). For example, there are few piezometers in Christchurch's CBD or the residential red zone[1] and none in the Port Hills area.

Many of the newly instrumented piezometers were existing EQC/NHC sites, but others were newly installed piezometers, some installed in areas that previously had no monitoring. The high temporal resolution records were to provide a significant dataset that is valuable for understanding the dynamics and rapid responses of shallow groundwater levels to rainfall and other drivers. The automated logging also addressed an issue with the earlier network regarding the long length of time required to collect measurements during each monitoring round.

Automated monitoring began in mid-2016. Over the ensuing years there was discussion on future ownership of the network. Whilst all concerned saw the value of the network and the data, no single organisation

1 Land in and around Christchurch that experienced severe earthquake damage and was deemed infeasible to rebuild on.

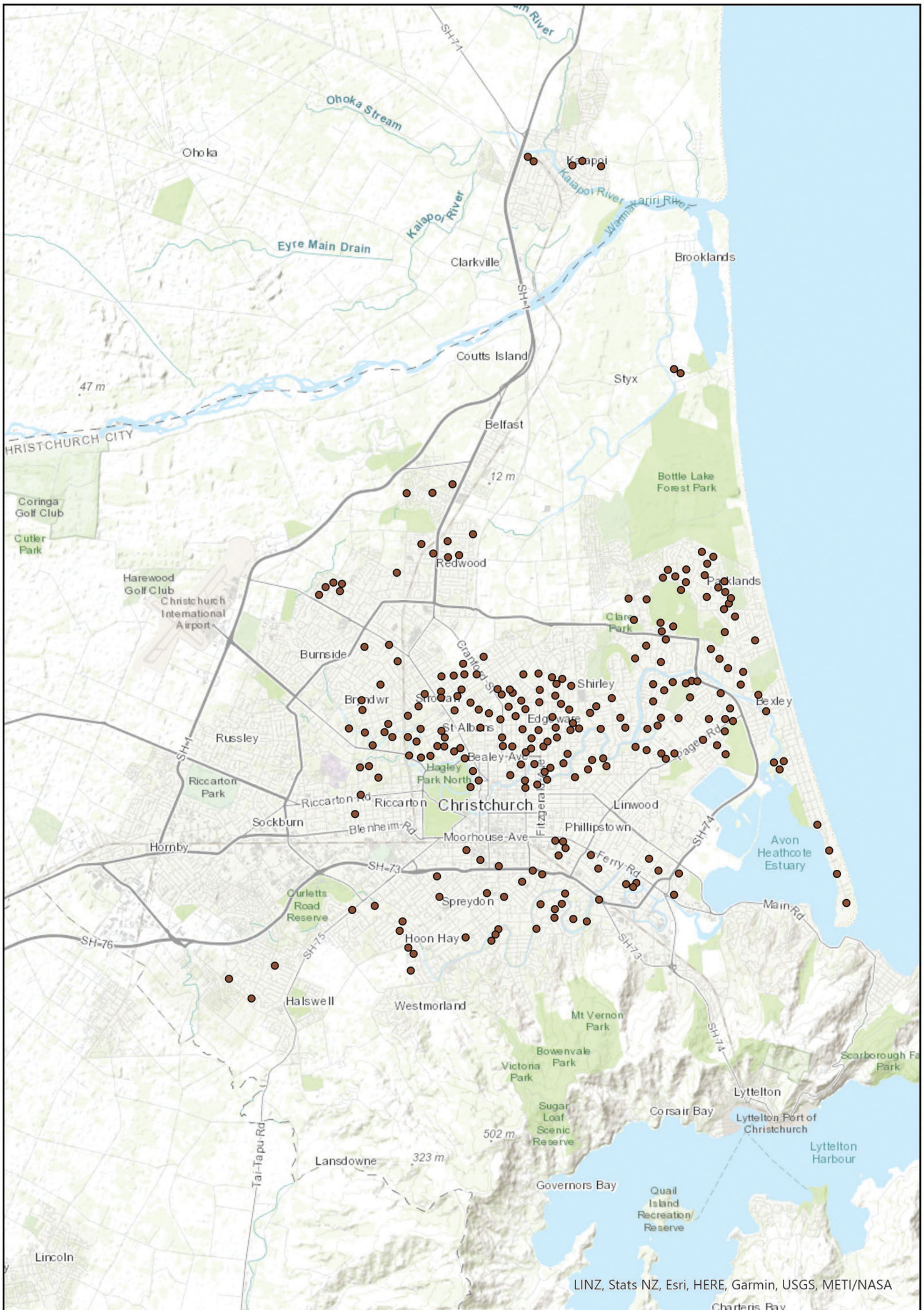

Figure 2 – Current Automated Piezometer Project monitoring network.

wanted to fund its ongoing monitoring and maintenance, and management and hosting of data. It was not until late July 2019 that an agreement was brokered in principle, and the end of December 2019 for legal issues to be covered off, such that that the network finally found a new home (EQC, 2019). The agreement reached was that EQC would gift the piezometer network to CCC, and they would be responsible for organising data downloads and network maintenance. Environment Canterbury would own the data and be responsible for data quality assurance and hosting/making the data available.

This successful outcome was down to the vision and persistence of a core group of individuals in various organisations[2]. It is worth noting from this example that it can be profoundly difficult to achieve this level of ongoing monitoring even when it is widely acknowledged that there is huge value in the data, initial costs of network establishment have been covered, and the network is to be donated cost-free to local government. Christchurch is fortunate to have been able to achieve this and to benefit from such an ongoing wealth of data.

In the years since, the data have continued to be collected by CCC and stored within Environment Canterbury's database. The data are available on request from Environment Canterbury, or via their web-based portal (Well search | Environment Canterbury (ecan.govt.nz)). The data monitoring interval was recently extended from 10 minutes to 15 minutes, in order to prolong battery life of transducers and to increase the time between downloads, thus reducing ongoing operational costs. Telemetering the network – or some piezometers within the network – to make real-time data available has been considered, as has reconfiguration of the network and possible installation of new piezometers in key locations to optimise data for council and other needs.

Unfortunately, some of the piezometers have been lost to attrition by contractors during roadworks or have been buried by overgrowth of grass on verges between data downloads, but around 220 of the 250 APP network piezometers remain. In 2019 and 2020, information labels were installed under the cap for the situation where contractors find piezometers before works. This simple approach has been found to be successful, reducing the attrition rate.

Bosserelle and Hughes (2024b) investigated the integrity of the Christchurch shallow groundwater monitoring network, focusing on its development, the data it provides, and the challenges associated with managing and interpreting the data in the context of the unique urban and coastal conditions. The study underscored the importance of maintaining and expanding the monitoring network but recognised that this would require ongoing investment and technical expertise, which can be challenging to sustain over the long term. Bosserelle and Hughes (2024b) considered that the network was robust, fit for purpose, and highly transferable, but also found that some groundwater monitoring assets required maintenance. Some issues were found, including non-existent screens, general construction issues, and exposure to the public and traffic. The review acknowledged that some monitoring sites should not be included in data analyses due to poor data quality.

This groundwater monitoring network and the data from it is likely globally unique and provides information for better decision support and more sustainable urban water management, including of urban shallow groundwater. However, the network and datasets need to be more accessible and more

2 Including Marion Schoenfeld (ECan/CCC), Helen Rutter (Aqualinc), Simon Cox (GNS), Richard Smith and John Scott (EQC) and Graham Harrington (CCC).

collaborative work needs to occur to optimise the use of the network.

Initial use of the data

Shallow groundwater information from the original EQC and later APP network has been used for various applications, including predicting groundwater flooding, assessing the impacts of sea level rise, and understanding the effects of seismic activity on groundwater levels. The low temporal resolution data from the ~1,000 EQC piezometers were initially used to model the shallow water table to inform land damage payouts post-earthquakes (van Ballegooy *et al.*, 2014). The water table models had subtle differences depending on whether only piezometers with longer-term (>9 month) records were used or a larger dataset was used that included <9 month records with proxy values inferred for annual variability (van Ballegooy *et al.*, 2013). A statistically more-robust model version (van Ballegooy *et al.*, 2014) used median values from 967 monitoring piezometers over a longer period accompanied by statistical surfaces (e.g., 15th and 85th percentiles) to account for the range of seasonal fluctuations. Depth-to-water models were determined by subtracting water table elevations from LiDAR surveys of land elevation.

From 2016, Aqualinc Research Ltd (Aqualinc) undertook analysis of the piezometer data as part of CCC's LDRP45[3] programme (Rutter, 2020). This study derived updated site-specific statistics for each piezometer and regenerated the depth-to-water and developed elevation surfaces using more advanced geostatistical techniques than had initially been used. The data records used are listed in Table 1.

A baseline groundwater elevation surface was developed to inform the current state and was subtracted from a digital elevation model (derived from LiDAR data) to determine areas that were likely to experience shallow groundwater. One of the aims of the project had been to define the depth at which shallow groundwater was a hazard, but this was found to be impossible to define because each stakeholder had a different view on when groundwater was an 'issue'.

Table 1: Sources of data used to generate shallow groundwater level elevation surfaces Rutter, 2020).

Dataset	Comments
EQC shallow water table piezometers	Data from 723 piezometers used from an initial dataset of 971. Water levels recorded monthly over variable time periods between 2011 and 2017.
CCC/Environment Canterbury long-term monitoring bores	55 shallow bores, monitored weekly to monthly. CCC shallow piezometer data was collected by NIWA and some of the data provided to Environment Canterbury for inclusion in their database.
Short-term monitoring data	Other short-term data from monitoring associated with construction work.
APP bores	Total of 249 bores, 49 of which were in new locations and did not coincide with the location of the original EQC piezometers.

3 LDRP: Land Drainage Recover Programme - LDRP-Summary-Report-November-2015.pdf (ccc.govt.nz). LDRP45 refers to this study being project number 45 of the programme.

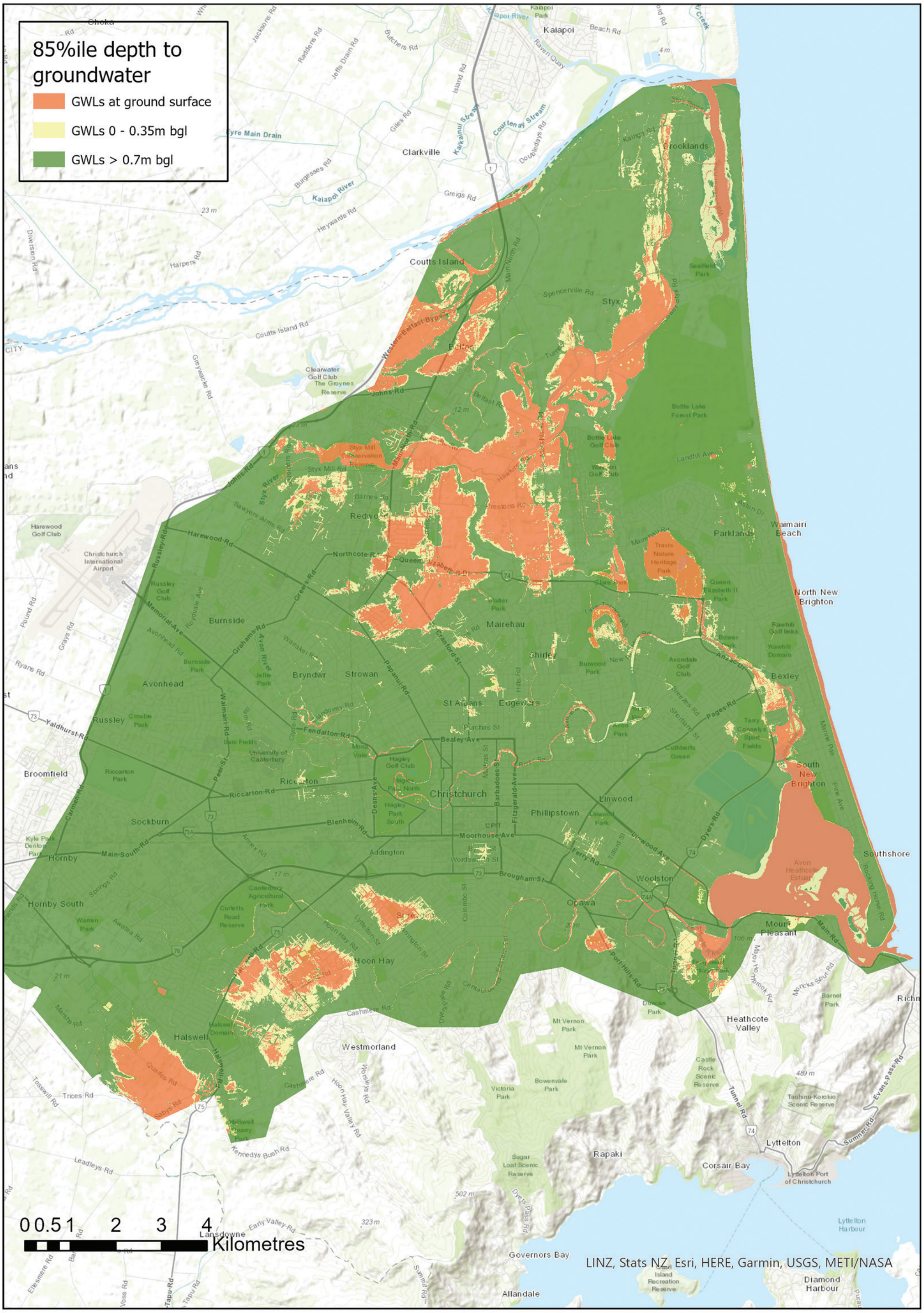

Figure 3 – Baseline depth to groundwater categorised into < 0 m, 0–0.35 m and > 0.35 m below ground level (bgl) (Rutter, 2020).

Ultimately the threshold was defined as the 85th percentile depth to water surface showing groundwater at less than 0.35 m below ground level (Rutter, 2020). Figure 3 shows the interpolated depth to groundwater, colour-coded using the 0.35 m threshold. Conditional simulation was carried out, which involved generating multiple possible surfaces that approximated the known data. This suggested a high level of variability in the data and a high degree of uncertainty in the resulting interpolation at distances of more than 300 m from a measurement point (Rutter, 2020).

The project was concerned with how shallow groundwater hazards might change with sea level rise. An existing numerical groundwater model (Weir *et al.*, 2024) was modified and used to model potential changes in groundwater level due to sea level change, based on predicted sea level rise scenarios. The modelled differences were added to the baseline surface to generate the potential groundwater surfaces under different sea level rise scenarios and the results used in multi-hazard assessment work by CCC.

By 2024 the shallow groundwater level datasets had captured some extreme rainfall events (for example, July 2017, February 2018, May 2021 and July 2022) as well as some very dry periods (for example, the summers of 2015/16 and 2016/17). These events, together with the new high-frequency monitoring from the APP network, had the potential to change the statistics that were derived from the earlier manually read data as well as the interpolated surface of depth to shallow groundwater. Therefore, data from the network was reassessed in 2024 to determine whether or not the new data had changed the statistics, and whether or not the new APP monitoring points adequately filled gaps in areas with no previous monitoring (Weir *et al.*, 2024). The updated analysis provided the additional benefit of identifying opportunities to rationalise the monitoring network.

The new depth to shallow groundwater surface was compared against the equivalent generated for the LDRP45 project by Rutter (2020). The difference between the original and new surfaces (in terms of areas with shallow groundwater less than 0.35 m below ground level) was minor in some areas but more significant in others (Figure 4) (Weir *et al.*, 2024).

Although the value of the additional spatial data was limited (as many of the new piezometers were located close to existing bores), confidence in the predictions improved in some areas where there was previously little information. As expected, greatest confidence was achieved in areas that are close to measurement sites and in areas where the original and new surfaces were consistent.

It was recognised that the surfaces generated were steady state conditions and that the highly dynamic response of groundwater to climate, river, coastal, and other drivers would have an additional impact. The LDRP45 project investigated but was not able to clearly identify the role of different drivers on groundwater responses. One piece of work within the project investigated the relationship between shallow groundwater levels and climate. The methodology followed that of a peer-reviewed investigation of the water table response to rainfall events in central Florida (Van Gaalen *et al.*, 2016). Two approaches were taken. The first was using the long-term data (collected by CCC and Environment Canterbury) to assess the groundwater level response to long-term (interannual and decadal-scale) climate cycles. The second approach was to use the high-resolution data from the APP piezometer network to assess the dynamic response to event-scale rainfall, tides and other drivers. There was limited success in relating groundwater level variability to different

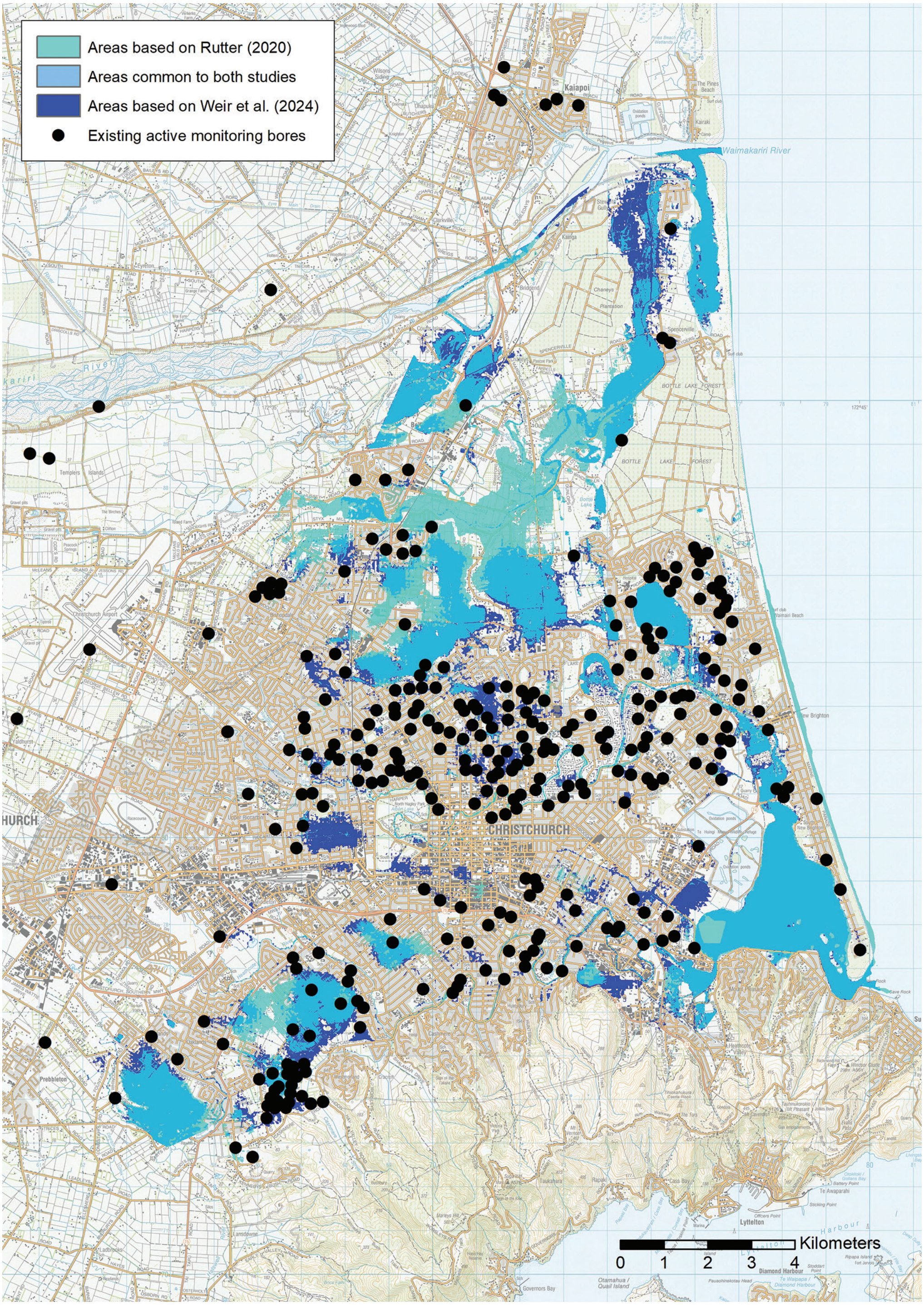

Figure 4 – Areas where the 85th percentile depth to groundwater is predicted to be less than 0.35 m below ground level: original (Rutter, 2020) versus new post-2016 surfaces (Weir *et al*., 2024).

drivers. For example, assessing groundwater level responses to event-scale rainfall did not identify any consistent spatial pattern, with the ratio of response to rainfall ranging from almost non-existent to over 8:1 (mm/mm).

Identifying the key controls on groundwater responses remains a complex challenge. Despite (now) having around eight years of APP data, and many investigations into controls on groundwater level responses to different drivers, the very high degree of variability of responses between piezometers suggests the controls on responses are highly complicated. Rutter (2020) identified that confidence in data interpolation significantly decreased beyond approximately 300 m of a measurement point, highlighting the high spatial variability in the measured groundwater levels. Bonneau et al. (2017) highlighted the potential role of 'urban karst' in groundwater flow, the karst-like effect resulting from networks of human-made subsurface pathways (e.g., stormwater and wastewater pipes and associated high-permeability trenches). It is quite likely that this urban karst plays a role in controlling shallow groundwater levels and flow directions, possibly to the extent of reversing the regional flow direction in some cases. The complex interaction between natural (rainfall, river stage, tides, lithological variability, topography, etc) and anthropogenic (urban karst, stormwater disposal, etc.) has yet to be resolved and is an area that requires investigation.

Use of the data in research

There have been multiple research projects investigating groundwater level responses using the original EQC and the higher resolution APP data, including assessment of surface water–groundwater interaction (Steinhage *et al.*, 2014) and the implications of sea level rise on liquefaction vulnerability (Risken *et al.*, 2015). Two doctoral research projects made extensive use of data from the shallow monitoring network in urban Christchurch (Bosserelle, 2024; Setiawan, 2023). Setiawan (2023) aimed to improve the understanding of riparian saltwater intrusion dynamics, and vulnerability under sea level rise in an urban setting with a focus on Christchurch. Bosserelle (2024) focused on groundwater dynamics in response to sea level rise in built environments with the presence of subsurface and surface infrastructure systems using Christchurch as an example.

Steinhage *et al.* (2014) suggested that the tidal signal propagated through the shallow groundwater to less than a kilometre from tidal sections of the Ōtākaro/Avon River. They carried out a survey across four transects and plotted the tidal range (maximum to minimum level during a tidal cycle). Their findings suggested that even at short distances (around 50 m) from the channel, the tidal signal had reduced by 60%. It was difficult to identify a tidal signal at distances greater than 200 m from the channel. These results align with the study by Bosserelle *et al.* (2023), which found the closer the groundwater monitoring site to the tidal rivers, the higher the correlation to the ocean levels.

Setiawan *et al.* (2022b) used data collected from the APP network during a survey in September and October 2020 to map shallow groundwater salinity using spatial interpolation. The survey dataset included specific conductance (as a proxy for salinity) and other groundwater quality parameters recorded across 99 piezometers in urban Christchurch (Setiawan *et al.*, 2022a). Two areas of high salinity were identified, in Southshore and in Bexley, near to the Avon River. The investigation also assessed the exposure of municipal assets to brackish shallow groundwater, observing that this is rarely considered compared to impacts of salinisation on water resources. In addition, this study quantified the vertical hydraulic gradient between the surficial water table aquifer and the underlying semi-confined gravel aquifer near areas of measured brackish groundwater. They found that the underlying gravel aquifer used by the local authority for water supply was not vulnerable to downward contamination by saltwater during the analysed time period.

Setiawan *et al.* (2023b) used data from the APP network and installed additional monitoring wells to establish two transects straddling the Avon River in Bexley, where high groundwater salinity was detected previously (Setiawan *et al.*, 2022b). Transducers measuring temperature, pressure and specific conductance at ten-minute intervals were installed in the monitoring wells and in the Avon River, midway between the two transects. Signal processing methods were used on five months of data to quantify sea, river and groundwater relationships to confirm the tidal influence on both groundwater levels and salinity nearby to the river. Hydraulic gradients (between the river and groundwater) and the river specific conductance varied with tides, resulting in the alternation of saltwater intrusion and retreat (in the groundwater), with varying time delays. They also found that the groundwater hydraulic gradient was (on average) steeper on the outside of the river meander than on the inside of the river meander, resulting in less saline intrusion and explaining salinity patterns found earlier by Setiawan *et al.* (2022b). Land subsidence and sea level rise, increased drought, and decreased river flows could increase the occurrence of negative hydraulic gradients, which may result in increased groundwater salinisation from estuarine rivers.

Later work by Setiawan *et al.* (2023a) developed tools to highlight areas most vulnerable to riparian saltwater intrusion under current and future conditions to identify areas for further monitoring and management. These tools were applied to the Christchurch area, including the Avon and Ōpāwaho/Heathcote rivers under current sea level and sea level rise scenarios using GIS. All this work served to highlight the effects of saline intrusion in shallow groundwater, particularly riparian saline intrusion along tidally influenced rivers, an issue that is seldom addressed yet has been experienced in various locations around New Zealand.

The importance of city-wide groundwater monitoring networks, such as those in Christchurch and other cities in Aotearoa New Zealand, were emphasised by Bosserelle *et al.* (2022). The important role of high-frequency data collection networks, such as the APP, in establishing baseline conditions and predicting future hazards was highlighted. The research noted the significance of managing urban groundwater levels in the face of sea level rise, especially in coastal urban areas where shallow groundwater directly impacts resilience. To plan urban resilience against future hazards (including earthquakes and sea level rise-induced flooding) and to help develop adaptation to these risks, a crucial ongoing need for monitoring and use of the data was identified.

In a later article, Bosserelle *et al.* (2023) aimed to characterise shallow groundwater in Christchurch and investigate the spatial fluctuations in depth to groundwater. The purpose of this study was to determine characteristics of shallow groundwater, including spatial and temporal trends in depths to groundwater and their relationships to natural and anthropogenic stressors using data-driven analyses (including spatial interpolation, autocorrelation, clustering, cross-correlation and trend analysis). The approach revealed some discernible clusters and trends within the dataset, one of the key features in classification being proximity to tidal rivers. The time series analysis indicated that in areas of shallow groundwater low variation in levels occurred, and this was confirmed using clustering. It was hypothesised that increasing water level trends could be attributed to one or more of various factors, including land subsidence, anthropogenic drivers (i.e., interaction with infrastructure water-related networks) or sea level rise. Those locations could potentially guide future research and investigations of the possible cause of the groundwater rise. Overall, attributing clusters to specific stressors was found to be difficult.

Operational use of the data

Public awareness of shallow groundwater and the issues that it brings in Christchurch has been very low due to the invisibility of groundwater. Even geotechnical professionals using shallow groundwater levels in design calculations are often unaware of the profoundly dynamic nature of groundwater levels. The use of limited (and possibly anomalously low) measurements of groundwater has sometimes led to serious issues with structures, including structural buoyancy and basement flooding when groundwater levels returned to higher levels. To date, socio-economic values, political will and individual motivation have very much shaped and influenced the development of Christchurch's groundwater monitoring network. CCC has used data from the APP network to develop a coastal hazards viewer (https://gis.ccc.govt.nz/hazard-viewer/) that includes depth to groundwater maps with increments of sea level rise to begin communicating with the public as part of their coastal adaptation programme, but much more work needs to be done to raise awareness of issues and initiatives.

Within CCC, data have been used to inform studies into localised sudden changes in shallow groundwater in relation to groundwater infiltration into pipe networks, potential contamination of groundwater by leaking pipes at a petrol station and locations where potholing frequently occurs in roads. The data were used to identify areas subject to shallow groundwater, along with other natural hazard information, when considering urban densification planning, district planning and spatial planning. Work has commenced on including information on shallow groundwater on Land Information Memoranda (LIMs). If the network was telemetered, and data available in real-time, it could be used to inform operational management of groundwater during routine maintenance of roads and pipes (i.e., the likelihood of needing to pump to keep works dry) and potentially for civil defence purposes in identifying antecedent conditions for flooding in advance of forecast rainfall to enable sandbagging or other mitigations to be deployed.

Future directions

Christchurch is home to a globally unique shallow groundwater dataset that includes the broader EQC's low temporal resolution data, the more spatially confined APP's high frequency data, and various other datasets from long-term CCC and Environment Canterbury bores, as well as data collected from site-specific investigations. Previous research has provided valuable insights into shallow groundwater behaviour while also sparking numerous questions. To enhance groundwater modelling and assessment, it is important to consider both the physical and technical aspects (environmental conditions, technology, and infrastructure) and the social and economic factors (community behaviour, economic conditions, and cultural practices) to gain a comprehensive understanding of how they influence each other (Bach *et al.*, 2014). This holistic approach could lead to more effective and sustainable solutions for complex problems. Furthermore, extensive research is required to unveil the intricate interdependencies between natural and anthropogenic controls (assets) on shallow groundwater hazards, as well as how shallow groundwater impacts the service life of these assets (Eggimann *et al.*, 2017). The looming impacts of climate change, including sea level rise and extreme events, are likely to dominate research efforts to further explore adaptive planning and resilience strategies. This paper proposes these approaches necessitate the application of a transdisciplinary data management framework that acknowledges crucial inputs and knowledge from multiple stakeholders and experts thereby constructing a new, more nuanced understanding of cause and effect, and impacts of changing climate.

To initiate a transdisciplinary approach to managing shallow groundwater data in Christchurch, we need to recognise that the way the city's groundwater data are collected is inevitably underpinned by central government directives and the priorities and concerns of different organisations within the city. How these organisations value and interact with the data influences what, where, and how it is stored, and can result in critical decisions around accessibility and management.

Organisational activities and the roles of disciplinary experts and collaborators, alongside information from place-based, local community knowledge and cultural values are intrinsic to the amount and quality of monitoring, investigating, and data management undertaken (Sutriadi, 2023). The data components, connections, relationships, and interactions with different groundwater experts and organisations shape their daily practices and broader organisational processes. These organisational activities, networks and interactions create informal structures that have been referred to as 'soft infrastructures' (Sutriadi, 2023; Wiechman and Vicario, 2022). Such soft infrastructures are integral to the management of the groundwater monitoring network and influence whether Christchurch's groundwater network information is readily accessible to stakeholders.

Transdisciplinary groundwater data management could better prepare Christchurch for a changing climate and rising sea levels and provide an exciting opportunity for groundwater experts to create a data management exemplar. Creating an open-source platform for groundwater management organisations (such as water supply, stormwater and wastewater departments within local and regional councils, catchment organisations, environmental agencies, groundwater engineers, and hydrogeologists) would significantly increase engagement with and knowledge of local groundwater data (Pointet, 2022). At a global scale, The Groundwater Project (https://gw-project.org/) facilitates public outreach for high-quality information from experts to make groundwater knowledge accessible to everyone. A smaller-scale platform could be created for Christchurch to expedite transdisciplinary work involving multiple stakeholders and generate new knowledge from this comprehensive and collaborative approach.

A platform that facilitates high-quality information from experts to make groundwater knowledge accessible to everyone could be created for Christchurch. This could include data integration, stakeholder involvement, use of innovative technologies and analytical techniques, data sharing through collaborative platforms, education and policy development

Summary

Ōtautahi/Christchurch has a unique shallow groundwater monitoring network that has driven investigations into shallow groundwater responses and triggered national and global interest. The studies completed to date have provided important insights into shallow groundwater but have also highlighted future needs for shallow monitoring and modelling, for example, to investigate groundwater level response to sea level rise or the impacts of shallow groundwater on river flood management. It is critical to continue monitoring and using the data to start to answer some of these questions. The data will help to prepare Christchurch for changing climate and rising sea levels and provides Aotearoa New Zealand with an exemplar of what can and needs to be done to understand shallow groundwater as a hazard and as a contributing factor to other hazards.

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