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Mapping shallow groundwater salinity in a coastal urban setting to assess exposure of municipal assets

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ABSTRACT

Study region: Christchurch, New Zealand.
Study focus: Low-lying coastal cities worldwide are vulnerable to shallow groundwater salinization caused by saltwater intrusion and anthropogenic activities. Shallow groundwater salinization can have cascading negative impacts on municipal assets, but this is rarely considered compared to impacts of salinization on water supply. Here, shallow groundwater salinity was sampled at high spatial resolution (1.3 piezometer/km^2), then mapped and spatially interpolated. This was possible due to a uniquely extensive set of shallow piezometers installed in response to the 2010–11 Canterbury Earthquake Sequence to assess liquefaction risk. The municipal assets located within the brackish groundwater areas were highlighted.
New hydrological insights for the region: Brackish groundwater areas were centred on a spit of coastal sand dunes and inside the meander of a tidal river with poorly drained soils. The municipal assets located within these areas include: (i) wastewater and stormwater pipes constructed from steel-reinforced concrete, which, if damaged, are vulnerable to premature failure when exposed to chloride underwater, and (ii) 41 parks and reserves totalling 236 ha, within which salt-intolerant groundwater-dependent species are at risk. This research highlights the importance of determining areas of saline shallow groundwater in low-lying coastal urban settings and the co-located municipal assets to allow the prioritisation of sites for future monitoring and management.

1. Introduction

Monitoring shallow groundwater salinity in coastal areas is crucial for water resources management. Saline water can have cascading implications for roads (Dasgupta et al., 2014; Tenison, 2014), groundwater quality in deeper aquifers (Navoy and Carleton, 1995; Onodera et al., 2008), groundwater dependent ecosystems (Eamus et al., 2016), ecosystem services, human health and

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well-being (Tully et al., 2019), wastewater treatment plant operations (Miranda et al., 2019; Osman et al., 2017), and subsurface infrastructure (Luo et al., 2015). Saline groundwater corrodes subsurface infrastructure such as concrete, steel, bricks and masonry, that is periodically or constantly exposed to saline groundwater, causing it to fail prematurely (Fig. 1) (Luo et al., 2015), costing local government significantly more in upkeep and maintenance. In areas where shallow water table aquifers are not used for water supply purposes (where deep groundwater infrastructure exists, e.g., Shamsudduha et al., 2019), shallow groundwater may often not be the focus of regular groundwater quality monitoring efforts, as shown by a lack of water quality data in many shallow aquifers around the world (e.g., Navoy and Carleton, 1995). However, salinity in shallow aquifers is of increasing interest due to the potential for infrastructure damage, particularly under the increased risks of salinization under climate change induced sea-level rise (e.g., Befus et al., 2020).

Shallow groundwater salinity demonstrates the occurrence or degree of aquifer salinization due to saltwater intrusion, geological weathering conditions, and anthropogenic activities such as groundwater abstraction, sewage disposal, and agriculture (Hammami Abidi et al., 2017). Saltwater intrusion is driven by the lowering of hydraulic head, which can be induced by groundwater pumping, land drainage (e.g., due to land use changes), reduced recharge, increased evapotranspiration (Jiao and Post, 2019; Werner et al., 2013), or sea level rise (Passeri et al., 2015; Werner and Simmons, 2009). While saltwater intrusion occurs primarily at the coast, with seawater being the source of salinity (e.g., Ketabchi et al., 2016; Werner et al., 2013), it also occurs in shallow aquifers adjacent to tidal surface water bodies (rivers, estuaries and lagoons), a process that has received considerably less attention than saltwater intrusion from the coast (Mikhailova, 2013; Shalem et al., 2015, 2019). Tidal surface water bodies can act as conduits that facilitate saltwater travelling upstream, which can contaminate adjacent fresh aquifers (Fig. 1) (Tully et al., 2019). Climate change impacts such as sea level rise, drought, extreme events, and reduced river flows, coupled with land subsidence due to, for example, mining or excessive groundwater pumping, would likely increase the distance that saltwater can travel up rivers, resulting in greater risk for saltwater intrusion from tidal rivers (Mikhailova, 2013; Wang et al., 2020).

Low-lying coastal cities and countries worldwide are vulnerable to shallow groundwater salinization due to anthropogenic activities and climate change (Ferguson and Gleeson, 2012), having been observed in Bangladesh (Shamsudduha et al., 2019), the Dutch Delta cities (Amsterdam, Rotterdam, The Hague, and Utrecht) (Oude Essink et al., 2010), California (Befus et al., 2020), south east Florida (Renken et al., 2005), and Australia (Morgan and Werner, 2015). As a low-lying coastal city with several tidal rivers, Christchurch, New Zealand, is comparable to many areas globally. The city has extensive subsurface infrastructure that could be vulnerable to premature deterioration from shallow aquifer salinization, particularly due to sea level rise, including the water supply, stormwater, and wastewater pipe networks, as well as the downstream wastewater treatment plants (Hummel et al., 2018). Known as the "garden city of New Zealand" (NZ On Screen, 2020), Christchurch has numerous parks and reserves, many of which include tidal river reaches, which can impact the surrounding salt-intolerant vegetation within this ecosystem and the services they provide (e.g., Mexia et al., 2018). Importantly, Christchurch has a uniquely extensive set of recently installed shallow groundwater monitoring wells (detailed further in Section 1.1) that to date have not been used for salinity monitoring. Although some studies have mapped shallow groundwater salinity or chloride concentration as a measure of saltwater intrusion in urban settings using groundwater sampling and geophysical methods (Oude Essink et al., 2010; Shamsudduha et al., 2019), the impacts of shallow groundwater salinization on municipal assets were not the focus of these studies.

Mapping shallow groundwater salinity is valuable to highlight brackish and saline groundwater areas and the municipal assets that can be impacted, which can then be prioritised for further monitoring and management. In this study, shallow groundwater salinity

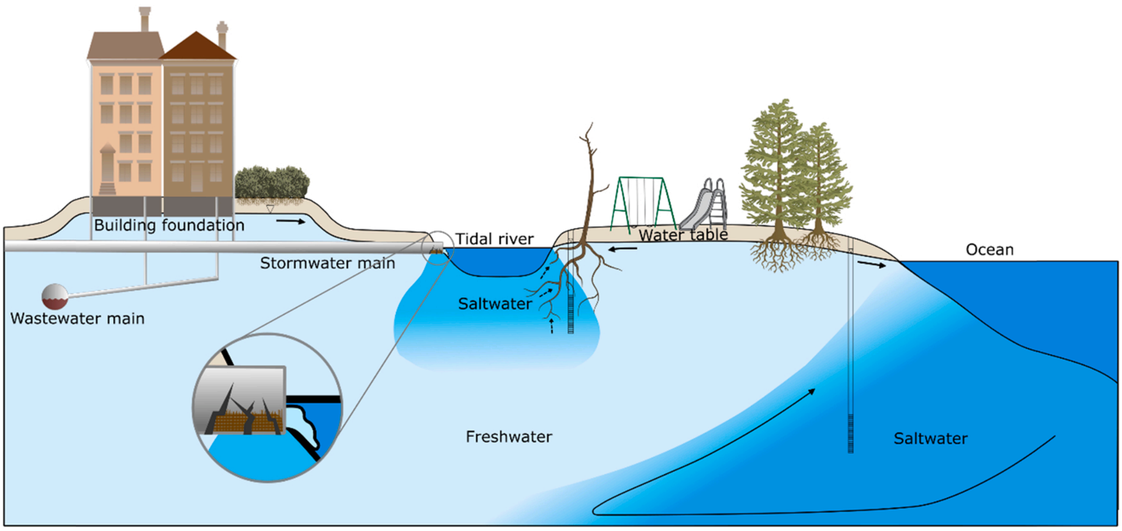

Fig. 1. Conceptual diagram of saltwater intrusion at the coast and from a tidal river, within an urban subsurface environment. The impacts of saltwater intrusion illustrated here are the corrosion of subsurface pipes and the death of salt-intolerant riparian vegetation. Symbols courtesy of the Integration and Application Network, University of Maryland, Center for Environmental Science (ian.umces.edu/media-library/symbols/).

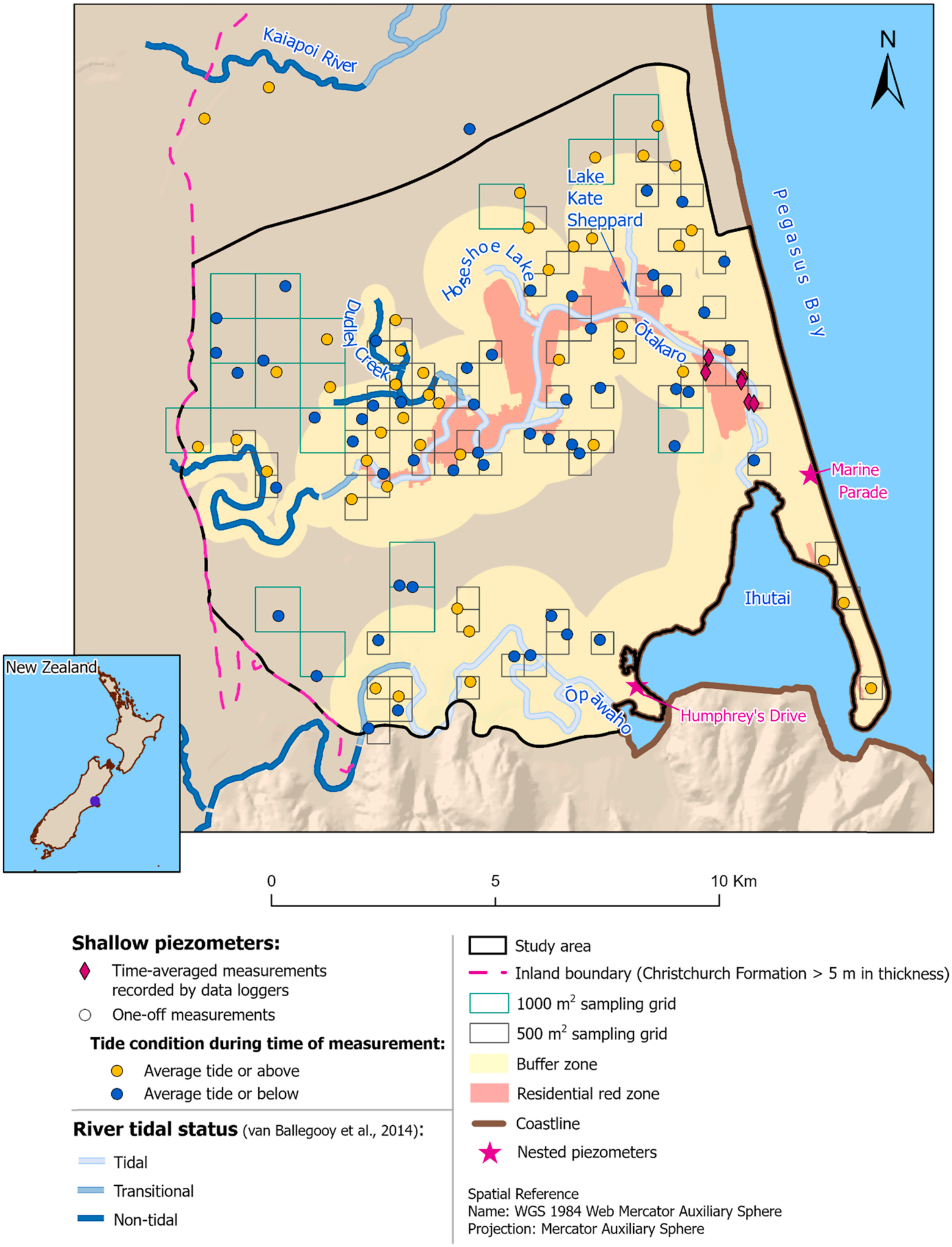

Fig. 2. The study area within Christchurch, selected shallow piezometers (where measurements are time-averaged or one-off taken in certain tide conditions) based on the 500 m^2 sampling grid within the buffer zone and 1000 m^2 sampling grid outside the buffer zone, river tidal status (van Ballegooy et al., 2014), inland boundary (processed from Begg et al., 2015), the Residential Red Zone (Canterbury Earthquake Recovery Authority, 2013), the coastline (National Topographic Office, 2012), and nested piezometer sites (Environment Canterbury, 2021b).

was sampled, at high resolution, and mapped in the low-lying coastal city of Christchurch, New Zealand, and the municipal assets located within brackish groundwater areas were highlighted. The study adds to the current literature by discussing the potential impacts of shallow groundwater salinization to existing municipal assets in an urban setting.

1.1. Study area

Christchurch, built on drained swampland (Wilson, 1989), is the second-most populated city in New Zealand with a population of 394,700 (Stats NZ, 2020) and has a temperate oceanic climate with a median annual precipitation of 618 mm (Macara, 2016). Residents are solely dependent on groundwater for their water supply (Christchurch City Council, 2021b). The local regional council in Christchurch is Environment Canterbury, which is a common source of information cited in this paper. The study area of 81 km^2 is within the tidally-influenced Ōtākaro/Avon River and Ōpāwaho/Heathcote River catchments, which flow into the Ihutai/Avon-Heathcote Estuary (Fig. 2).

Between 4 September 2010 and 23 December 2011, Christchurch was struck by earthquakes and aftershocks up to moment magnitude 7.1, referred to as the Canterbury Earthquake Sequence (CES). The CES killed 185 people and caused extensive damage throughout Christchurch estimated at ~NZ$40 B (~US$31 B) (Quigley et al., 2016). The severe liquefaction, lateral spreading, and damage to infrastructure caused by the CES resulted in a voluntary central government buyout of ~7400 properties on flat land that was deemed infeasible to rebuild on, termed the Flat Land Residential Red Zone (forthwith Residential Red Zone), including in the suburbs of Bexley (along the Ōtākaro/Avon River corridor) and Southshore (see Fig. 2) (Canterbury Earthquake Recovery Authority, 2016; Quigley et al., 2016).

In 2011, a shallow groundwater monitoring network (the Automated Piezometer Network, APN) was installed by the Earthquake Commission to assess liquefaction risk in Christchurch. The APN is comprised of 1000 shallow piezometers, with 249 of these containing sensors measuring water level and temperature (but not electrical conductivity) every 10 min (Rutter, unpublished results). A large number of the piezometers used in the present study were selected from this monitored shallow piezometer network.

The Christchurch coastal aquifer system is a multi-layered aquifer system alternating between productive gravel-dominated alluvial deposits and low-permeability marine sediments as a result of glacial and interglacial periods during the Quaternary period (Brown and Weeber, 2001). The deepest bore drilled in Christchurch to a depth of 240 m below ground revealed seven layers of gravel-dominated deposits alternating with low-permeability sediments (Brown, 1998 as cited in Begg et al., 2015). Christchurch is a groundwater discharge zone, while groundwater recharge is sourced from Waimakariri River seepage (a gravel-bed braided river located north of Christchurch) and rainfall on the plains further inland (west of Christchurch) and the area between the Waimakariri River and Christchurch (Stewart, 2012).

The unconfined water table aquifer, named the Christchurch Formation, is made up of Holocene-age beach, estuarine, lagoon, dune, and coastal swamp deposits of gravel, sand, silt, clay, shell, and peat (Brown and Weeber, 1992; White, 2007). The Christchurch Formation is approximately 40 m thick at the coast and gradually pinches out inland (White, 2007). The aquifer material is spatially variable; along the New Brighton beach, it is predominantly made up of sand, while sections around the Ōtākaro/Avon and Ōpāwaho/Heathcote River mouths and the Ihutai/Avon-Heathcote estuary are composed of less porous sand, silt, and peat of drained lagoons and estuaries (Brown and Weeber, 1992). The hydraulic conductivity of the Christchurch Formation was measured to be about 5 m/day along the margins of Lake Kate Sheppard (Fig. 2) (Scaife, unpublished results), which is considered a semi-pervious, poor aquifer by Bear (1972).

The Christchurch Formation is underlain by the semi-confined Riccarton Gravel aquifer, which is made up of well-graded gravels up to cobble size (100 mm) transported from the Southern Alps and deposited during the last glacial period (Brown and Weeber, 1992). This aquifer provides about 15% of the water supply for Christchurch (Morgan and Rosado, 2018), is artesian in places and is a source of flow for the spring-fed Christchurch streams, such as the Ōtākaro/Avon and Ōpāwaho/Heathcote Rivers (Stewart et al., 2018).

Although the Christchurch Formation is commonly termed an aquitard (Environment Canterbury, 2001), groundwater flow between the Christchurch Formation and the underlying aquifers can be significant, so much so that Lough and Williams (2009) recommend that the strata should not be managed as separate entities.

2. Material and methods

2.1. Piezometer selection

For the present study, 106 piezometers were selected for sampling. These comprised 98 piezometers from the APN, one piezometer from the Christchurch City Council groundwater monitoring network, four piezometers installed for the current project, and three piezometers installed by an environmental consultancy for Christchurch City Council. The APN piezometers were drilled using the sonic method (Environment Canterbury, 2021a). The PVC standpipes are capped at the bottom with depths of up to 7.5 m below ground level and screen lengths of one to three metres long from the bottom of the well (van Ballegooy et al., 2014). Further details on individual piezometers are provided in the supplementary spreadsheet.

Several parameters were considered during the selection of piezometers used for water quality analysis in this study. First, the inland boundary of the sampling area was determined using the five-metre thickness contour line of the Christchurch Formation from Begg et al. (2015) (Fig. 2). Second, the sampling density was chosen depending on the proximity of the piezometers to tidal water features. This is because tidal water features (including the ocean, lagoons, estuaries and tidal reaches of rivers) pose greater saltwater intrusion risk than fresh or non-tidal surface water bodies. Buffer zones were created around surface water bodies and the width of these buffer zones was dependent on whether the surface water body was tidal (1000 m buffer zone), transitional (500 m buffer zone) or non-tidal (250 m buffer zone). A 500 m^2 sampling grid was used to select wells within the buffer zones, while a 1000 m^2 sampling grid was used outside the buffer zones, aiming for a minimum of one well in each grid at both resolutions (Fig. 2). The tidal status of major Christchurch rivers (Fig. 2) was statistically derived by van Ballegooy et al. (2014) solely using river level data (i.e., how far the tidal oscillation can travel up the river). As such, the actual position of the saltwater wedge within Christchurch rivers is not captured by these tidal status lines. However, they are considered conservative estimates of river salinity since the tidal oscillation would travel further upstream compared to the saltwater wedge within the river.

2.2. Shallow groundwater measurements

In this study, specific conductivity (SC) was used as a proxy for salinity, which is a standard practice (Jiao and Post, 2019). SC measures the ability of water to conduct electrical current at a reference temperature, usually 25 °C, and depends on the amount of dissolved ions present.

The shallow groundwater SC measurements were conducted from 8 September to 21 October 2020. A survey during springtime likely represents a conservative measure of shallow groundwater salinity from a hazard perspective, as winter recharge often increases groundwater level and reduces salinity e.g., Abliz et al. (2016).

To sample each well, an Isco PTP-150 portable pump (Isco Inc, 1992) was used and approximately three times the standing water volume was pumped from each well before sampling to remove standing water and ensure a representative sample, while monitoring water quality parameters (temperature, SC at 25 °C, pH, and dissolved oxygen) to ensure stabilisation (Daughney et al., 2006). The wells that did not meet these criteria (e.g. dried following some pumping) were removed from the analysis. The pump outflow was connected to a YSI 6850 flow cell (YSI Inc, 2021). The water quality parameters were recorded during and after pumping using the YSI Professional Plus multiparameter instrument (YSI Inc, 2009).

To identify if the elevated SC is caused by seawater intrusion, rather than another source of dissolved ions such as sewage leakage from damaged waterwater pipes (Wolf et al., 2004), the shallow groundwater was also sampled for chloride and bicarbonate concentrations. Chloride is the dominant ion in seawater, with a typical concentration of ~19,000 mg/L, whereas fresh groundwater contains significantly less chloride with a concentration of $\leq$ 300 mg/L (Oude Essink, 2001). Therefore, the relationship between groundwater SC and chloride concentration can identify if increases in SC are caused by seawater intrusion (Chang et al., 2019). In addition, bicarbonate is a major constituent of fresh groundwater and found in negligible amounts in seawater; thus, the chloride to bicarbonate ratio is also a useful indicator of seawater intrusion (Revelle, 1941).

Out of the 106 measured sites, spot check samples from 27 randomly selected piezometers were measured for alkalinity as calcium carbonate in the field using a Hach digital titrator model 16900 (Hach Company, 2013). Calcium carbonate was converted into bicarbonate concentration based on Rice et al. (2017). The filtered samples from these 27 piezometers were also analysed for chloride concentration in the laboratory using a Thermo Fisher Scientific Dionex Ion Chromatograph (Thermo Fisher Scientific, 2012).

The previously mentioned four piezometers installed for the current project and the three piezometers installed by an environmental consultancy for Christchurch City Council were equipped with water level, temperature and electrical conductivity data loggers, of which details are presented in the supplementary spreadsheet. Seven SC data points were obtained from these instrumented shallow piezometers (Fig. 2) and were added to the SC map. These time-averaged data points therefore capture some temporal variation, such as variation over tidal cycles. In addition, 18 surface water SC measurements at selected sites in close proximity to the shallow piezometers were taken using a Solinst 107 TLC meter (Solinst Canada Ltd, 2017).

Tidal stage can influence coastal groundwater salinity with various time lags (e.g., Kim et al., 2008). Therefore the tide condition during the time of measurement is shown in Fig. 2 and the supplementary spreadsheet, as average tide or above and average tide or below. The time lags between high tide and maximum salinity in individual piezometers were unknown, however the tidal influence was approximated to have little influence on the salinity patterns at the relatively large scale of the analysis.

2.3. Spatial interpolation method

The shallow groundwater SC was spatially interpolated in ArcGIS Pro 2.7 (ESRI, 2021) using universal kriging with log transformation (due to the right skewness of the data) and a constant order of trend removal was imposed, since this resulted in the lowest root-mean-square compared to other orders of trend removal. A standard error of prediction layer was produced using this interpolation method and is provided in the supplementary document (Fig. S1). The interpolated SC surface was categorised into salinity groupings of fresh (<500 μS/cm), marginal (500–1500 μS/cm), brackish at 3–9% seawater (1500–5000 μS/cm), brackish at 9–28% seawater (5,000–15000 μS/cm) and brackish at > 28% seawater (>15000 μS/cm). The reference for seawater SC used was 53,000 μS/cm (Jiao and Post, 2019).

Although a recirculating plume of seawater may be present at the coastline within the shallow aquifer caused by tides and waves (Werner et al., 2013), no boundary conditions were imposed in the interpolation process (e.g., seawater salinity at the coastline). However, an interpolated map of shallow groundwater SC with an ocean boundary (SC of 53,000 μS/cm) imposed along the coast using universal kriging with log transformation and first order of trend removal (chosen due to the lowest root-mean-square compared to other orders of trend removal) is provided in Fig. S2 of the supplementary document. This surface was not used owing to a lack of sufficient data to fully characterise the near-coastal zone and the non-ocean boundary scenario statistically provided a better overall fit.

2.4. Analyses of municipal assets within the interpolated brackish groundwater areas

Municipal assets not designed to operate in saline environments, but that are inadvertently exposed to saline groundwater, can be at risk of premature deterioration. The assets that are co-located with the interpolated brackish areas (Section 2.3) were analysed in ArcGIS Pro 2.7 (ESRI, 2021).

The location of parks and subsurface pipes in Christchurch, including the wastewater, water supply, and storm water pipes and their construction material were sourced from a spatial data set supplied by the Christchurch City Council (2021a). The number and area of parks, and the total length of pipes and their construction material within the interpolated brackish shallow groundwater areas were derived using the Clip tool.

To evaluate the potential for downward contamination of the underlying deeper aquifer (Riccarton Gravel) by saltwater, the vertical hydraulic gradients within or near the interpolated brackish groundwater areas were analysed. The vertical hydraulic gradients in nested piezometer sites were derived by dividing the difference in hydraulic heads (sourced from Environment Canterbury, unpublished) between the two piezometers at the nested sites by the vertical distance between the mid-point of well screens. The piezometer details are presented in Table 2.

3. Results

3.1. SC measurements and interpolation

The groundwater SC measurements follow a right-skewed distribution (histogram provided in Fig. S3 of the supplementary document) and ranged from 107 to 22,851 μS/cm, with a mean of 608 μS/cm, median of 297 μS/cm, and mode of 310 μS/cm. Out of the 106 wells that were sampled, 82 wells were classified as fresh, 14 as marginal, 6 as brackish at 3–9% seawater, none as brackish at 9–28% seawater, and 4 as brackish at > 28% seawater (Fig. 3). Thirty-eight out of 53 piezometers (72%) located greater than four kilometres from the coast were fresh.

The shallow groundwater SC surface interpolated brackish groundwater at > 28% seawater in Southshore, Bexley, and New Brighton (Fig. 4). The root-mean-square of the interpolation was 3025 μS/cm and the standard error ranged from 1 to 11,550 μS/cm (Fig. S1 of the supplementary document). Marginal groundwater was interpolated in the area between the two major rivers (Ōtākaro/ Avon and Ōpāwaho/Heathcote Rivers), which also had the largest uncertainty due to the lack of piezometers. Mostly fresh groundwater was measured in the north and northeast of the Christchurch CBD. On the other hand, areas of marginal groundwater were measured in several locations more than four kilometres from the coast (e.g., the south and west of the Christchurch CBD), which is an otherwise fresh groundwater area. Long-term median shallow groundwater level contours in metres below ground for the period of 4 September 2010–30 November 2013, developed by van Ballegooy et al. (2014), are also provided in Fig. S4 of the supplementary document.

The most saline groundwater was measured in the suburb of Southshore which is built on sand dunes of a spit between the Ihutai/ Avon-Heathcote Estuary and the ocean (Fig. 3 and Fig. 4). However, the three piezometers at the Southshore spit had a large variation in SC from north to south at 509 μS/cm (marginal), 22,851 μS/cm (brackish at >28% seawater), and 1885 μS/cm (brackish at 3–9%

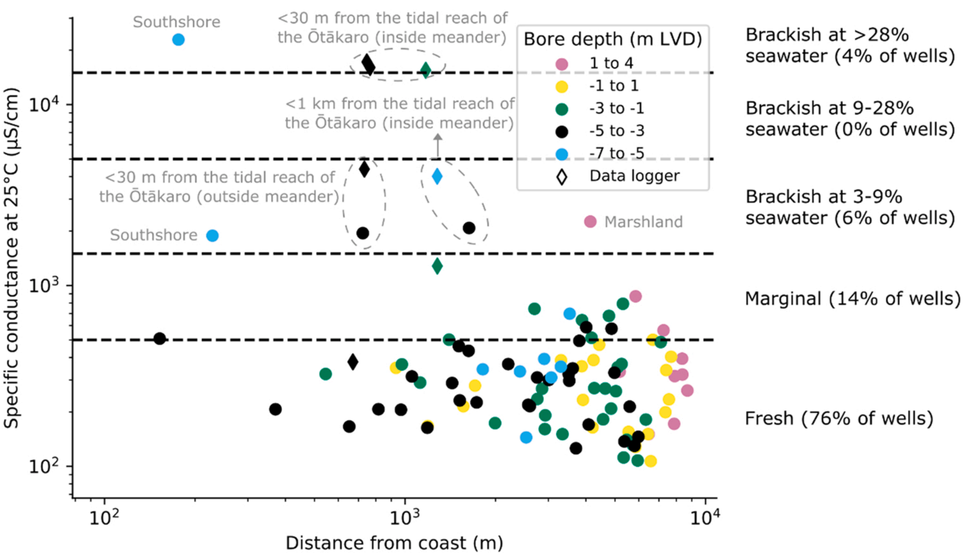

Fig. 3. The shallow groundwater specific conductance and the distance from the coastline (brown line in Fig. 4) in logarithmic scales with colour-coded bore depths in reference to the local vertical datum (LVD). Data points derived from time-averaged data loggers are shown using diamond markers.

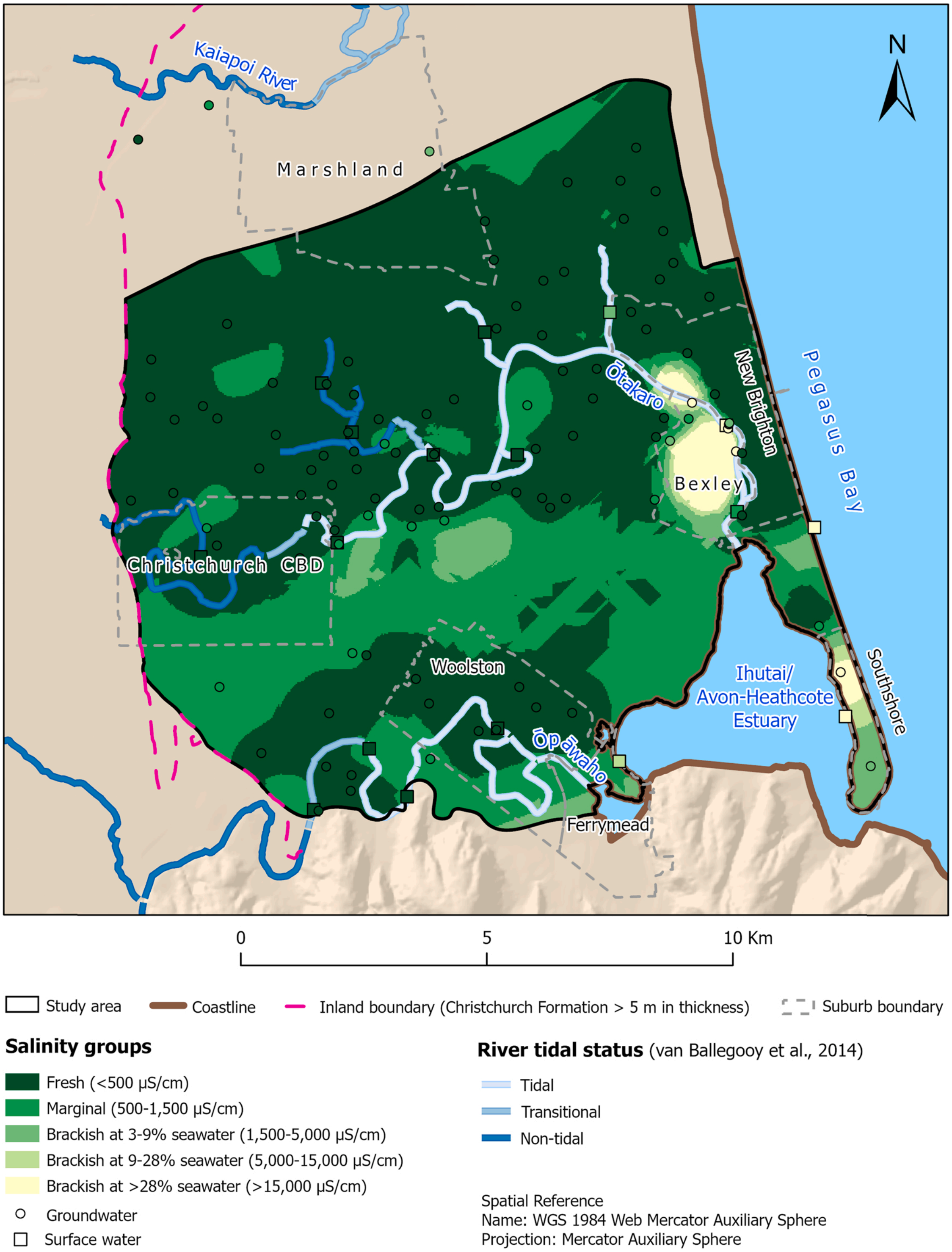

Fig. 4. Surface water SC measurements, shallow groundwater SC measurements and interpolation, river tidal status (van Ballegooy et al., 2014), inland boundary (processed from Begg et al., 2015), suburb boundaries (Fire and Emergency NZ, 2020), and coastline (National Topographic Office, 2012).

seawater), respectively, taken during average tide or above conditions (Fig. 2).

Inside the tidal Ōtākaro/Avon River meander in Bexley groundwater SC was brackish at > 28% seawater and ranged between 15,471 and 17,200 μS/cm. However, on the outside of the meander groundwater was brackish at 3–9% seawater with an SC of 4395 μS/cm 5 m from the river, and SC of 1946 μS/cm 23 m from the river. There were seven wells located along the tidal Ōtākaro/Avon River meander that were equipped with data loggers (Fig. 2 and Fig. 3) where time-averaged SC was recorded.

The SC of surface water bodies measured in close proximity to the piezometers ranged from 157 to 29,000 μS/cm (Fig. 4). The details of individual measurements and their relation to ocean tide levels are shown in the supplementary spreadsheet. As expected, the salinity of surface water measurements trended higher downstream towards the coast, except for one measurement taken at the Ōtākaro/Avon River mouth during low tide (Fig. 4). Higher SC values were measured further upstream in the Ōtākaro/Avon River than the Ōpāwaho/Heathcote River, despite that both waterways are tidal and connected to the estuary. Groundwater adjacent to the Ōtākaro/Avon River was consistently more saline than that adjacent to the Ōpāwaho/Heathcote River.

A strong positive correlation (R^2 =0.92) was found between groundwater SC and chloride concentration, as well as between groundwater SC and chloride to bicarbonate ratio (R^2 =0.87) in 27 randomly selected shallow bores.

3.2. Exposure of municipal assets to brackish shallow groundwater

3.2.1. Subsurface infrastructure

The total length of the stormwater, wastewater, and water supply pipes within the interpolated brackish groundwater area was 118 kilometres. The majority of stormwater pipes (69%) and 17% of wastewater pipes are constructed from steel-reinforced concrete and 24% of water supply pipes are constructed from asbestos cement within the interpolated brackish areas. The “other” category not elaborated in Table 1 includes: (i) metal systems such as steel (with and without concrete lining), galvanised steel, cast iron, ductile iron (with and without cement lining), (ii) ceramic systems such as vitrified clay, and (iii) plastic systems such as glass-reinforced plastic.

3.2.2. Parks

There were 41 parks and reserves within the interpolated brackish areas, totalling 236 ha (including the Residential Red Zone) (Christchurch City Council, 2021a). The three largest parks within the interpolated brackish areas are the Ōtākaro corridor (Residential Red Zone), Bexley Park, and Southshore Beach Park.

3.2.3. Wastewater treatment plant

In the Bromley wastewater treatment plant, the salinity and chloride concentration of wastewater have not been regularly monitored and generally have not been of concern, although spot checks have been conducted (L. Liaw, personal communication, 28 April 2021). Furthermore, no particular issues with regards to salinity have been observed, and no salinity thresholds have been established with regards to specific wastewater treatment processes at the plant.

3.2.4. Deeper aquifer and drinking supply wells

The vertical hydraulic gradient between the Christchurch Formation and Riccarton Gravel units from January 2020 to January 2021 was positive (indicating upward groundwater flow) at Marine Parade and Humphrey’s Drive (Table 2 and see Fig. 2 for nested piezometer locations). Based on water quality data from the Environment Canterbury database (https://www.ecan.govt.nz/data/water-quality-data/) and measurements from the current study, we assume that the groundwater in the nested piezometers was fresh and therefore does not require density correction. Additionally, a sensitivity analysis was conducted to assess whether downward flow can be induced under salinized shallow groundwater conditions of 50% seawater and 100% seawater density-corrected using the freshwater head equation in Post et al. (2018) (supplementary spreadsheet). Positive hydraulic gradient was maintained under the two salinized shallow groundwater scenarios, and downward flow was not induced.

4. Discussion

4.1. SC measurements and interpolation

The piezometers to the north and northeast of the Christchurch CBD had mostly fresh shallow groundwater (Fig. 4), possibly due to their location being closer to the Waimakariri River, the dominant source for groundwater recharge. On the other hand, marginal groundwater was measured in inland areas greater than four kilometres from the coast. A potential reason for the marginal

Table 1
The top three construction materials for stormwater, wastewater, and water supply pipes, which are in service as of 3 February 2021 (Christchurch City Council, 2021a), within the interpolated brackish shallow groundwater areas.

Stormwater pipes		Wastewater pipes		Water supply pipes	
Length (km)	31	Length (km)	32	Length (km)	55
Material	%	Material	%	Material	%
Reinforced Concrete Rubber Ringed	69	Unplasticised Polyvinyl Chloride	36	High Density Polyethylene	32
Unplasticised Polyvinyl Chloride	9	Polyethylene 100	23	Asbestos Cement	24
Earthenware	6	Reinforced Concrete Rubber Ringed	17	Medium Density Polyethylene 80	17
Other	16	Other	24	Other	27

Table 2
The vertical hydraulic gradient between the Riccarton Gravel and Christchurch Formation, derived from hydraulic head data provided by Environment Canterbury.

Nested piezometer site	Wells		Vertical hydraulic gradient			
	Name	Depth (m)	Range	Average	Measurement period	Number of measurements
Marine Parade	M35/7896	6.5	0.03–0.07	0.05	1/01/2020 00:00–25/01/2021 11:45	37,461
	M35/7753	55				
Humphrey's Drive	M36/5385	6	0.03–0.04	0.04	8/01/2020 18:15–26/01/2021 07:15	36,455
	M36/5325	33				

groundwater areas could be leakage from earthquake-damaged wastewater laterals (i.e., pipes that carry wastewater from private properties to the state-owned wastewater main) that have not been repaired (Christchurch City Council, n.d.).

The well at the Southshore spit with the highest specific conductance overall was also the deepest well, suggesting that the freshwater lens system at the sand dunes was transitioning into seawater at a depth of about seven metres below ground level at the time of the investigation. Following the CES and damage to subsurface pipes, a wastewater pumping station in Southshore pumped saline water, which damaged the system (D. Pinkney, personal communication, 26 February 2021) indicating that the saltwater-freshwater interface in the lens system may be proximal to the depths of the wastewater pipes.

The shallow groundwater inside of the tidal Ōtākaro/Avon River meander in Bexley was brackish at > 28% seawater, while the outside of the meander was brackish at 3–9% seawater. The factors that influence the difference in salinity between the inside and the outside of the meander may be the variation in aquifer hydraulic conductivity (identified by the different soil drainage, historical landscape, and vulnerability to liquefaction) and hydraulic gradient. Aquifer hydraulic conductivity influences the extent and severity of saltwater intrusion from saline rivers into shallow aquifers. For example, Shalem et al. (2019) found that saltwater intrusion into a low hydraulic conductivity unit such as silty clay resulted in the entrapment of saltwater, due to the difficulty in flushing out or displacing saltwater with freshwater in the system. The inside of river meanders are depositional zones, where the river flow is slowest and sediment build-up occurs slowly through individual lateral accretions during floods when the deposits are submerged (Jackson et al., 2005; Reineck and Singh, 2012). Inside the Ōtākaro/Avon River meander in Bexley, the soil down to one metre from ground level is dominantly silt and poorly drained (Landcare Research, 2019). In contrast, the soil outside the river meander is dominantly sand and well drained. Moreover, prior to land drainage by European settlers, the inside of the meander was a wetland, whereas the outside of the meander was sand hills (Environment Canterbury et al., 2019). Furthermore, the inside of the meander suffered severe liquefaction following the CES (resulting in government acquisition of the land) whereas the outside of the meander was not as severely impacted (Earthquake Commission, 2012), implying that the inside and the outside of the meander have different soils. The distinction in soil drainage, historical landscape, and vulnerability to liquefaction between the inside and the outside of the Ōtākaro/Avon River meander in Bexley suggests that the different salinity levels reflect differences in near-surface geology and aquifer hydraulic conductivity. In addition, the river-aquifer hydraulic gradient may also be a factor influencing groundwater salinity (Smith and Turner, 2001), though it was not measured in this study.

The groundwater SC measured in areas that experienced land subsidence following the CES was more saline than in the areas that experienced uplift. Following the CES, the Bexley area inside the meander of the Ōtākaro/Avon River experienced land subsidence of 0.52 m on average, whereas Ferrymead around the Ōpāwaho/Heathcote River mouth area experienced uplift of 0.14 m (where data exists; Hughes, 2015; Quigley et al., 2016). The median post-CES land elevation in Bexley is 1.1 m lower than in Woolston (processed from [dataset] Land Information New Zealand, 2015). The land subsidence in the lower reach of the Ōtākaro/Avon River (uniquely mimicking a local sea-level rise effect; see Orchard et al., 2020) would result in the ability for seawater to travel further upstream than before, increasing the risk for saltwater intrusion from the tidal river into the adjacent shallow aquifer. Uplift in the lower reach of the Ōpāwaho/Heathcote area would have the opposite effect.

The strong positive correlation between groundwater SC and chloride concentration (R^2 =0.91), as well as between groundwater SC and chloride to bicarbonate ratio (R^2 =0.79) in 27 randomly selected shallow bores indicate that the majority of brackish wells are exposed to seawater. However, outliers exist, such as at a former market garden site in Marshland where groundwater pollution may have occurred (Environment Canterbury, 2015), and brackish groundwater was found despite its distance from the coastline and any tidal reaches.

4.2. Exposure of municipal assets to brackish shallow groundwater

4.2.1. Subsurface infrastructure

The majority of stormwater pipes (69%) and 17% of wastewater pipes are constructed from steel-reinforced concrete and 24% of water supply pipes are constructed from asbestos cement within the interpolated brackish areas. In addition to the global issue of ageing infrastructure (e.g., Houlihan, 1994), a proportion of the earthquake-damaged wastewater lateral pipes that lie on private land may have not been repaired (Christchurch City Council, 2021). When damaged or degraded, the steel reinforcement within the concrete pipe can become exposed to the water it carries and the surrounding groundwater environment. The steel reinforcement in concrete is vulnerable to premature failure when exposed to chloride underwater, and is even more significantly sensitive in wetting-drying conditions (Luo et al., 2015). Groundwater levels in coastal aquifer systems can fluctuate in response to tides (Jiao and Post, 2019), further exacerbating the groundwater conditions for vulnerable materials when they are exposed to groundwater such as the steel reinforcement in concrete.

Other ferrous metal structures present in the brackish groundwater areas such as steel and cast iron pipes are also vulnerable to corrosion triggered by high salinity groundwater and the presence of aggressive salts such as chloride and sulphate (Cole and Marney, 2012; Luo et al., 2015). Concrete structures are also vulnerable to attacks from these aggressive salts resulting in premature deterioration, however they are significantly more resistant to corrosion than steel structures (Luo et al., 2015). On the other hand, plastic pipes (including polyvinyl chloride, polyethylene, and glass-reinforced plastic) and ceramic pipes (including earthenware and vitrified clay) present within the interpolated brackish groundwater areas are chemically resistant (Seymour, 1953; Walsh, 2011) and may not be vulnerable to premature failure from brackish groundwater exposure. Despite this, there are other aspects to be considered that are not covered in this paper when deciding which pipe material to install at a given site.

In addition to subsurface pipes, building foundations can be exposed to brackish or saline water tables, which may induce premature deterioration depending on various factors (Department of Environment and Climate Change New South Wales, 2008). The data for building foundation depths and materials are not recorded in Christchurch and they are only available on individual building plans, preventing a wide-spread analysis for this paper. Other subsurface infrastructure not considered in this analysis include highway and road foundations, utility pipelines, and underground structures such as building basements and tunnels.

4.2.2. Parks

Groundwater salinity is an aspect of groundwater quality that determines which species might survive in an environment, in addition to groundwater level and flux (Eamus et al., 2016). Shallow groundwater salinization can have several effects, including coastal forest loss due to the failure of seedlings to germinate, yield reductions in agricultural land, eutrophication in surface water bodies, invasion of salt-tolerant species, marsh migration upland (Tully et al., 2019), and reduction of biodiversity (Zeng et al., 2020).

There were 41 parks and reserves within the interpolated brackish areas, totalling 236 ha (including the Residential Red Zone) (Christchurch City Council, 2021a). The salinity tolerance thresholds of different plant species need to be considered when deciding what species to plant in areas with brackish or saline water table. The salinization of shallow groundwater can threaten the survival of groundwater-dependent salt-intolerant species (Greene et al., 2016). For example, impacts of increased salinity intrusion up the Ōpāwaho/Heathcote River and salinization of the adjacent shallow groundwater include the death of trees, as well as the slumping of river banks (Watts, 2011). In addition, evapotranspiration increases soil salinity, especially when the depth to water table is less than four metres below ground (Greene et al., 2016), which is the case in this part of Christchurch (van Ballegooy et al., 2014). Saltmarsh vegetation has also been observed in areas that overlap with the brackish regions (Bexley, Southshore, and Ferrymead) (Orchard et al., 2020). Alternatively, the natural landward migration of saltmarsh, which provides abundant ecosystem services, can be achieved depending on the availability and the hydrologic connectivity of intertidal space (as has been observed in Southshore), with careful planning, infrastructure design, and protection of saltmarsh land (Orchard et al., 2020).

4.2.3. Wastewater treatment plant

Saline groundwater can travel into wastewater pipes through pipe cracks and faults and increase wastewater salinity and hydraulic load coming into treatment plants (Miranda et al., 2019). High salinity wastewater can corrode wastewater assets, increase sulphide generation (Miranda et al., 2019), impact the operation of wastewater treatment plants, and limit the reusability of the treated water (Osman et al., 2017). For example, saline wastewater decreases sedimentation due to its greater buoyancy force compared to wastewater (Jang et al., 2013). Saline wastewater has also been shown to reduce microbial activity and diversity in activated sludge processes (Wu et al., 2008). The biological treatment of wastewater has been shown to be acceptable up to a total dissolved solids (TDS) of 4000 mg/L (equivalent to an SC of 7243 μS/cm) and inhibited above a TDS of 8000 mg/L (Alipour et al., 2017).

The salinity and chloride concentration of wastewater have not been regularly monitored and generally have not been of concern at the Bromley wastewater treatment plant. Although wastewater salinity is not currently a pressing issue, the monitoring of wastewater salinity can be useful to detect changes early on and future-proof the optimality of wastewater assets, especially under climate change impacts (Hughes et al., 2021; Singh and Tiwari, 2019).

4.2.4. Deeper aquifer and drinking supply wells

The vertical hydraulic gradient between the Christchurch Formation and Riccarton Gravel units from January 2020 to January 2021 was positive (indicating upward groundwater flow) at Marine Parade and Humphrey's Drive under fresh groundwater conditions (Table 2 and see Fig. 2 for nested piezometer locations). Furthermore, a vertical hydraulic gradient sensitivity analysis (supplementary spreadsheet) showed that positive hydraulic gradient would be maintained under hypothetical salinized shallow groundwater conditions of 50% seawater and 100% seawater calculated using freshwater head (Post et al., 2018). Therefore, the Riccarton Gravel aquifer may not have been vulnerable to downward contamination by saltwater within this measurement period at these sites. Interestingly, the vertical hydraulic gradient has increased compared to the values described in Lough and Williams (2009) and Hertel (1998), who recorded a downward hydraulic gradient at the Humphrey's Drive site. There are three community drinking supply wells that extract from the Riccarton Gravel aquifer located less than 2.8 kilometres from the Ihutai Estuary (Environment Canterbury, 2017); these wells may be vulnerable to saltwater intrusion if the vertical hydraulic gradient shifts downward.

A downward hydraulic gradient due to excessive pumping can result in the flow of contaminants from shallow to deeper confined aquifers, as has been observed in cities such as Jakarta and Bangkok (Onodera et al., 2008). This has also been observed in Christchurch previously, in the suburb of Woolston, where saline water moved from the Ihutai/Avon-Heathcote Estuary into the underlying semi-confined Riccarton Gravel aquifer (Hertel, 1998). In response to this, pumping restrictions were put in place to ensure an upward vertical hydraulic gradient (Callander et al., 2011). Low-lying coastal areas with leaky confining layers may be more vulnerable to seawater intrusion under downward hydraulic gradient and would warrant close monitoring.

4.3. Limitations and recommendations for future research

The tidal variations were approximated to have minor influence on the groundwater salinity patterns at the overall scale of the analysis, and the groundwater salinity was approximated to be at dynamic equilibrium over the majority of the study area. Some temporal variations in the groundwater salinity would be expected during the sampling period within tidally-influenced areas, but those areas would be limited and generally only indicate oscillations rather than event-based or long-term changes.

This study did not consider the piezometer depths in the interpolated map output, although the piezometer depths were shown in Fig. 3. Parts of the interpolated area are sparser in data points compared to other parts, such as the area between the Ōtākaro/Avon and Ōpāwaho/Heathcote Rivers. The interpolated SC values need to be interpreted with caution and should be considered as indicative values or trends only.

For future research, we recommend a wider analysis of chemical markers to confirm the source of shallow groundwater salinity, such as boron concentrations to investigate the presence of wastewater. In addition to shallow groundwater chloride concentrations, other useful parameters to measure and map include pH and sulphate concentrations to assess groundwater conditions and the potential vulnerability of exposed subsurface infrastructure (Luo et al., 2015). Extensive hydraulic head data from the APN could be used to inform which piezometers are tidally-influenced and it would be worthwhile installing data loggers to monitor SC over time. The elevation of subsurface infrastructure could be analysed in relation to hydraulic head data, which can be used to assess the vulnerability of underground assets, especially in combination with groundwater SC data.

5. Conclusion

In this study, shallow groundwater salinity was measured and mapped in a low-lying coastal city in New Zealand, Christchurch, and the municipal assets located within the brackish groundwater areas were highlighted. Brackish shallow groundwater at greater than 9% seawater (SC $>$ 5000 μS/cm) was found in the suburb of Southshore (located on a sand dune spit between the Ihutai/Avon-Heathcote Estuary and the ocean) and Bexley (located inside of the meander of the Ōtākaro/Avon River tidal reach). Pockets of marginal (SC 500–1500 μS/cm) shallow groundwater were found inland, potentially attributed to wastewater leakage. Shallow groundwater north and northeast of the Christchurch CBD was mostly fresh (SC $<$ 500 μS/cm), potentially due to the close proximity to the recharge source, the Waimakariri River.

The municipal assets located within the brackish groundwater areas were highlighted. The majority of stormwater pipes (69%) and 17% of wastewater pipes in these areas are made of steel-reinforced concrete, which, if damaged, is vulnerable to premature deterioration when exposed to chloride underwater, especially under wetting-drying conditions (Luo et al., 2015). There were 41 parks, totalling 236 ha that lie within the brackish groundwater areas, where groundwater-dependent salt-intolerant species can be at risk. The salinity and chloride concentration of wastewater coming into the wastewater treatment plant have not been regularly monitored and generally have not been of concern; the lack of information could present a vulnerability in itself. In addition, the vertical hydraulic gradient between the surficial Christchurch Formation aquifer and the underlying semi-confined Riccarton Gravel aquifer was upward at the two nested piezometer sites within or near brackish groundwater areas in January 2020 to January 2021. Therefore, the Riccarton Gravel was not vulnerable to downward contamination by saltwater during the analysed time period.

Key attributes that can inform other low-lying coastal cities include:

- Monitoring shallow groundwater salinity is crucial for water resources management in low-lying coastal cities, with implications for park management, subsurface pipes, wastewater assets, and deeper aquifers.
- Groundwater salinity could be taken into account when deciding what subsurface infrastructure material to install if it will interact with groundwater, whether constantly or periodically. Additionally, brackish groundwater conditions could be factored in to the expected service life of existing subsurface infrastructure that are exposed to it, and inform decisions on maintenance or infrastructure monitoring efforts.
- The salinity of shallow groundwater at a planting site could be taken into account when deciding what species to plant and their salinity thresholds to support plant survival.
- Saline groundwater can infiltrate into wastewater pipes through cracks and faults and increase wastewater salinity and hydraulic load coming into treatment plants. It is therefore important to monitor the salinity of wastewater to inform management decisions and future-proof the optimality of wastewater assets.
- Useful areas to install piezometers include: (i) areas near tidal surface water bodies, (ii) transects of piezometers perpendicular to a tidal surface water body in particular can show how groundwater salinity changes with distance, (iii) low elevation areas with the water table close to the ground surface (higher likelihood of interaction between shallow groundwater and subsurface infrastructure as well as vegetation root systems), (iv) areas where downward saltwater contamination is of concern (e.g., installation of nested piezometers near water supply wells to monitor vertical hydraulic gradient and groundwater salinity).

This study expands on the current literature by linking areas of saline groundwater to the existing municipal assets that reside within those areas, which will continue to become more vulnerable under climate change conditions. In addition, the compilation of the cascading impacts of shallow groundwater salinization, while drawing on examples in Christchurch, New Zealand can be useful to groundwater managers and decision-makers in similar urban settings. Lastly, the identified potentially vulnerable municipal assets from saline shallow groundwater exposure can then be prioritised for further monitoring and management.

CRediT authorship contribution statement

Irene Setiawan: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Project administration, Writing - original draft. **Leanne K. Morgan:** Conceptualization, Supervision, Writing - Review & Editing. **Crile Doscher:** Supervision, Writing - Review & Editing. **Amandine Bosserelle:** Methodology. **Kelvin Ng:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.100999.

References

Abliz, A., Tiyip, T., Ghulam, A., Halik, Ü., Ding, J.-l, Sawut, M., Abliz, A., 2016. Effects of shallow groundwater table and salinity on soil salt dynamics in the Keriya Oasis, Northwestern China. Environ. Earth Sci. 75 (3), 260. https://doi.org/10.1007/s12665-015-4794-8.

Alipour, V., Moein, F., Rezaei, L., 2017. Determining the salt tolerance threshold for biological treatment of salty wastewater. Health Scope 6 (1), e36425. https://doi.org/10.17795/jhealthscope-36425.

Bear, J., 1972. Dynamics of Fluids in Porous Media. American Elsevier Publishing Company.

Befus, K.M., Barnard, P.L., Hoover, D.J., Finzi Hart, J.A., Voss, C.I., 2020. Increasing threat of coastal groundwater hazards from sea-level rise in California. Nat. Clim. Change 10 (10), 946–952. https://doi.org/10.1038/s41558-020-0874-1.

Begg, J.G., Jones, K.E., Barrell, D.J.A., 2015. Geology and Geomorphology of Urban Christchurch and Eastern Canterbury. Institute of Geological and Nuclear Sciences Limited, Lower Hutt, New Zealand.

Brown, L.J., Weeber, J.H., 1992. Geology of the Christchurch urban area, 1:25 000 geological map, IGNS Map 1 and booklet. Institute of Geological and Nuclear Sciences.

Brown, L.J., Weeber, J.H. (2001). Groundwaters of the Canterbury Region: Environment Canterbury Technical Report R00/10. Retrieved from ⟨https://api.ecan.govt.nz/TrimPublicAPI/documents/download/301800⟩.

Callander, P., Lough, H., Steffens, C., 2011. New Zealand Guidelines for the Monitoring and Management of Sea Water Intrusion Risk on Groundwater: Report Prepared for Envirolink (Project 420-NRLC50). Pattle Delamore Partners Limited, Christchurch, New Zealand. Retrieved from. ⟨http://envirolink.govt.nz/assets/Envirolink/420-NLRC50-Guidelines-for-the-monitoring-and-management-of-sea-waterintrusion-risks-on-groundwater.pdf⟩.

[dataset] Canterbury Earthquake Recovery Authority, 2013 [dataset] Canterbury Earthquake Recovery Authority. (2013). MBIE Technical Categories. Retrieved from ⟨https://opendata.canterburymaps.govt.nz/datasets/mbie-technical-categories⟩.

Canterbury Earthquake Recovery Authority. (2016). Land Zoning Policy and the Residential Red Zone: Responding to land damage and risk to life. Retrieved from ⟨https://quakestudies.canterbury.ac.nz/store/object/524765?search=Land%2520Zoning%2520Policy%2520and%2520the%2520Residential%2520Red%2520Zone%253A%2520Responding%2520to%2520land%2520damage%2520and%2520risk%2520to%2520life⟩.

Chang, S.W., Chung, I.-M., Kim, M.-G., Tolera, M., Koh, G.-W., 2019. Application of GALDIT in Assessing the Seawater Intrusion Vulnerability of Jeju Island, South Korea. Water 11 (9), 1824. https://doi.org/10.3390/w11091824.

[dataset] Christchurch City Council, 2021a [dataset] Christchurch City Council. (2021a). Corporate Data. Retrieved from ⟨https://gis.ccc.govt.nz/arcgis/rest/services/CorporateData⟩.

Christchurch City Council. (2021b). Where our water comes from. Retrieved 10 March, 2021, from ⟨https://ccc.govt.nz/services/water-and-drainage/water-supply/where-our-water-comes-from⟩.

Christchurch City Council. (n.d.). Wastewater lateral repairs. Retrieved 29 April, 2021, from ⟨https://ccc.govt.nz/services/water-and-drainage/wastewater/maintenance-and-repairs/wastewater-lateral⟩.

Cole, I.S., Marney, D., 2012. The science of pipe corrosion: a review of the literature on the corrosion of ferrous metals in soils. Corros. Sci. 56, 5–16. https://doi.org/10.1016/j.corsci.2011.12.001.

Daughney, C., Jones, A., Baker, T., Hanson, C., Davidson, P., Zemansky, G., Thompson, M., 2006. A National Protocol for State of the Environment Groundwater Sampling in New Zealand. Ministry for the Environment, Wellington, New Zealand. ⟨https://environment.govt.nz/publications/a-national-protocol-for-state-of-the-environment-groundwater-sampling-in-new-zealand/⟩.

Dasgupta, S., Hossain, M.M., Huq, M., Wheeler, D., 2014. Climate Change, Groundwater Salinization and Road Maintenance Costs in Coastal Bangladesh (English). World Bank Group, Washington, DC. ⟨http://documents.worldbank.org/curated/en/828391468004833607/Climate-change-groundwater-salinization-and-road-maintenance-costs-in-coastal-Bangladesh⟩.

Department of Environment and Climate Change New South Wales. (2008). Building in a saline environment. Sydney, Australia. Retrieved from ⟨https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Land-and-soil/building-in-saline-environment-080145.pdf⟩.

Eamus, D., Fu, B., Springer, A.E., Stevens, L.E., 2016. Groundwater dependent ecosystems: classification, identification techniques and threats. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.-D., Ross, A. (Eds.), Integrated Groundwater Management: Concepts, Approaches and Challenges. Springer International Publishing, Cham, pp. 313–346. ⟨https://doi.org/10.1007/978-3-319-23576-9_13⟩.

Earthquake Commission, 2012. Canterbury Earthquakes 2010 and 2011: Land Report as at 29 February 2012. Tonkin & Taylor. ⟨https://www.eqc.govt.nz/canterbury-earthquakes/land-claims/land-reports/stage-3-land-report⟩.

Environment Canterbury. (2001). Our water in the balance: Christchurch West Melton rivers and groundwater: Issues and options: A discussion document contributing to the preparation of the Natural Resources Regional Plan. Canterbury, New Zealand. Retrieved from ⟨https://api.ecan.govt.nz/TrimPublicAPI/documents/download/330161⟩.

Environment Canterbury. (2015). Listed Land Use Register for 16 Prestons Park Drive and 436 Prestons Road. Retrieved 8 March, 2021, from ⟨https://llur.ecan.govt.nz/⟩.

[dataset] Environment Canterbury, 2017 [dataset] Environment Canterbury. (2017). Community Drinking Water Supply Points. Retrieved from ⟨https://opendata.canterburymaps.govt.nz/datasets/community-drinking-water-supply-points⟩.

Environment Canterbury. (2021a). Well database. Retrieved from ⟨https://www.ecan.govt.nz/data/well-search/⟩.

[dataset] Environment Canterbury, 2021b [dataset] Environment Canterbury. (2021b). Wells and Bores - All. Retrieved from ⟨https://opendata.canterburymaps.govt.nz/datasets/wells-and-bores-all⟩.

[dataset] Environment Canterbury, 2019 [dataset] Environment Canterbury, Te Rūnanga o Ngāi Tahu, Archives New Zealand, & Micrographics. (2019). Black Maps - Digitized. Retrieved from ⟨https://opendata.canterburymaps.govt.nz/datasets/c5f7d946b8fb43ce80fd3441cde5b78e⟩.

ESRI, 2021. ArcGIS Pro: Release 2.7. Redlands. Environmental Systems Research Institute, CA.

Ferguson, G., Gleeson, T., 2012. Vulnerability of coastal aquifers to groundwater use and climate change. Nat. Clim. Change 2 (5), 342–345. https://doi.org/10.1038/nclimate1413.

[dataset] Fire and Emergency NZ, 2020 [dataset] Fire and Emergency NZ. (2020). Fire and Emergency NZ Localities. Retrieved from ⟨https://data.linz.govt.nz/layer/104830-fire-and-emergency-nz-localities/⟩.

Greene, R., Timms, W., Rengasamy, P., Arshad, M., Cresswell, R., 2016. Soil and aquifer salinization: toward an integrated approach for salinity management of groundwater. In: Jakeman, A.J., Barreteau, O., Hunt, R.J., Rinaudo, J.-D., Ross, A. (Eds.), Integrated Groundwater Management: Concepts, Approaches and Challenges. Springer International Publishing, Cham, pp. 377–412. ⟨https://doi.org/10.1007/978-3-319-23576-9_15⟩.

Hach Company. (2013). Digital Titrator Model 16900. USA. Retrieved from ⟨https://www.hach.com/asset-get.download-en.jsa?id=7639982643⟩.

Hammami Abidi, J., Farhat, B., Ben Mammou, A., Oueslati, N., 2017. Characterization of recharge mechanisms and sources of groundwater salinization in Ras Jbel Coastal Aquifer (Northeast Tunisia) using hydrogeochemical tools, environmental isotopes, GIS, and statistics. J. Chem. 2017 https://doi.org/10.1155/2017/8610894.

Hertel, I. (1998). Groundwater contamination in the Heathcote/Woolston area, Christchurch, New Zealand [Master's Thesis, University of Canterbury]. ⟨https://ir.canterbury.ac.nz/handle/10092/13050⟩.

Houlihan, B., 1994. Europe's ageing infrastructure: politics, finance and the environment. Uti. Policy 4 (4), 243–252. https://doi.org/10.1016/0957-1787(94)90015-9.

Hughes, J., Cowper-Heays, K., Olesson, E., Bell, R., Stroombergen, A., 2021. Impacts and implications of climate change on wastewater systems: a New Zealand perspective. Clim. Risk Manag. 31, 100262 https://doi.org/10.1016/j.crm.2020.100262.

Hughes, M., Quigley, M., van Ballegooy, S., Deam, B., Bradley, B., Hart, D., Measures, R., 2015. The sinking city: earthquakes increase flood hazard in Christchurch, New Zealand. GSA Today 25 (3), 4–10. https://doi.org/10.1130/GSATG221A.1.

Hummel, M.A., Berry, M.S., Stacey, M.T., 2018. Sea level rise impacts on wastewater treatment systems along the U.S. Coasts. Earth's Fut. 6 (4), 622–633. https://doi.org/10.1002/2017EF000805.

Isco Inc. (1992). PTP-150 Portable Pump Instruction Manual. USA. Retrieved from ⟨https://www.fieldenvironmental.com/assets/files/Manuals/ISCO%20150%20Portable%20Sampling%20Pump%20Manual.pdf⟩.

Jackson, J.A., Mehl, J.P., Neuendorf, K.K.E., Institute, A.G., 2005. Glossary of Geology. American Geological Institute.

Jang, D., Hwang, Y., Shin, H., Lee, W., 2013. Effects of salinity on the characteristics of biomass and membrane fouling in membrane bioreactors. Bioresour. Technol. 141, 50–56. https://doi.org/10.1016/j.biortech.2013.02.062.

Jiao, J., Post, V., 2019. Coastal Hydrogeology. Cambridge University Press. https://doi.org/10.1017/9781139344142.

Ketabchi, Hamed, Mahmoodzadeh, Davood, Ataie-Ashtiani, Behzad, Simmons, Craig T., 2016. Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. Journal of Hydrology 535, 235–255. https://doi.org/10.1016/j.jhydrol.2016.01.083.

Kim, K.-Y., Chon, C.-M., Park, K.-H., Park, Y.-S., Woo, N.-C., 2008. Multi-depth monitoring of electrical conductivity and temperature of groundwater at a multilayered coastal aquifer: Jeju Island, Korea. Hydrol. Process. 22 (18), 3724–3733. https://doi.org/10.1002/hyp.6976.

[dataset] Land Information New Zealand, 2015 [dataset] Land Information New Zealand. (2015). Canterbury - Christchurch and Selwyn LiDAR 1m DEM (2015). Retrieved from ⟨https://data.linz.govt.nz/layer/53587-canterbury-christchurch-and-selwyn-lidar-1m-dem-2015/⟩.

[dataset] Landcare Research, 2019 [dataset] Landcare Research. (2019). Smap Soil Texture Aug 2019. Retrieved from ⟨https://lris.scinfo.org.nz/layer/103668-smap-soil-texture-aug-2019/⟩.

Lough, H., & Williams, H. (2009). Vertical flow in Canterbury groundwater systems and its significance for groundwater management: Environment Canterbury Report R09/45. Retrieved from ⟨https://api.ecan.govt.nz/TrimPublicAPI/documents/download/1198256⟩.

Luo, C.-Y., Shen, S.-L., Han, J., Ye, G.-L., Horpibulsuk, S., 2015. Hydrogeochemical environment of aquifer groundwater in Shanghai and potential hazards to underground infrastructures. Nat. Hazards 78 (1), 753–774. https://doi.org/10.1007/s11069-015-1727-5.

Macara, G.R. (2016). The Climate and Weather of Canterbury: National Institute of Water & Atmospheric Research (NIWA). Retrieved from ⟨https://niwa.co.nz/static/web/canterbury_climatology_second_ed_niwa.pdf⟩.

Mexia, T., Vieira, J., Príncipe, A., Anjos, A., Silva, P., Lopes, N., Pinho, P., 2018. Ecosystem services: urban parks under a magnifying glass. Environ. Res. 160, 469–478. https://doi.org/10.1016/j.envres.2017.10.023.

Mikhailova, M.V., 2013. Processes of seawater intrusion into river mouths. Water Resour. 40 (5), 483–498. https://doi.org/10.1134/S0097807813050059.

Miranda, T., Hill, T., Lockett, R., Schnelle, M., Bustamante, H., 2019. Salt Water Ingress in Coastal Wastewater Catchments: a novel methodology for assessing salt water ingress. Water e-J. 4 (1), 16. https://doi.org/10.21139/wej.2019.014.

Morgan, L.K., & Rosado, C. (2018). Untreated groundwater supply and the Christchurch coastal aquifer system. Gdansk, Poland. Retrieved from ⟨https://swim2018.syskonf.pl/conf-data/SWIM2018/files/25_SWIM_2018_proceedings_www.pdf⟩.

Morgan, L.K., Werner, A.D., 2015. A national inventory of seawater intrusion vulnerability for Australia. J. Hydrol. Reg. Stud. 4 (Part B), 686–698. https://doi.org/10.1016/j.ejrh.2015.10.005.

[dataset] National Topographic Office, 2012 [dataset] National Topographic Office. (2012). NZ Coastlines and Islands Polygons (Topo 1:50k). Retrieved 25 March, 2021, from ⟨https://data.linz.govt.nz/layer/51153-nz-coastlines-and-islands-polygons-topo-150k/⟩.

Navoy, A.S., Carleton, G.B., 1995. Ground-water Flow and Future Conditions in Potomac-Raritan-Magothy Aquifer System, Camden area, New Jersey (GSR 38). U. S. Geological Survey, West Trenton, New Jersey. ⟨https://www.state.nj.us/dep/njgs/pricelst/gsreport/gsr38.pdf⟩.

NZ On Screen. (2020). Christchurch - Garden City of New Zealand: Short Film (Full Length) – 1952. Retrieved from ⟨https://www.nzonscreen.com/title/christchurch-garden-city-of-new-zealand-1952⟩.

Onodera, S.-I, Saito, M., Sawano, M., Hosono, T., Taniguchi, M., Shimada, J., Delinom, R., 2008. Effects of intensive urbanization on the intrusion of shallow groundwater into deep groundwater: examples from Bangkok and Jakarta. Sci. Total Environ. 404 (2), 401–410. https://doi.org/10.1016/j.scitotenv.2008.08.003.

Orchard, S., Hughey, K.F.D., Schiel, D.R., 2020. Risk factors for the conservation of saltmarsh vegetation and blue carbon revealed by earthquake-induced sea-level rise. Sci. Total Environ. 746, 141241 https://doi.org/10.1016/j.scitotenv.2020.141241.

Osman, O., Aina, O.D., Ahmad, F., 2017. Chemical fingerprinting of saline water intrusion into sewage lines. Water Sci. Technol. 76 (8), 2044–2050. https://doi.org/10.2166/wst.2017.374.

Oude Essink, G.H.P., 2001. Improving fresh groundwater supply—problems and solutions. Ocean Coast. Manag. 44 (5), 429–449. https://doi.org/10.1016/S0964-5691(01)00057-6.

Oude Essink, G.H.P., van Baaren, E.S., de Louw, P.G.B., 2010. Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. Water Resour. Res. 46. https://doi.org/10.1029/2009wr008719.

Passeri, D.L., Hagen, S.C., Medeiros, S.C., Bilskie, M.V., Alizad, K., Wang, D., 2015. The dynamic effects of sea level rise on low-gradient coastal landscapes: a review. Earth's Fut. 3 (6), 159–181. https://doi.org/10.1002/2015EF000298.

Post, V.E.A., Banks, E., Brunke, M., 2018. Groundwater flow in the transition zone between freshwater and saltwater: a field-based study and analysis of measurement errors. Hydrogeol. J. 26 (6), 1821–1838. https://doi.org/10.1007/s10040-018-1725-2.

Quigley, M.C., Hughes, M.W., Bradley, B.A., van Ballegooy, S., Reid, C., Morgenroth, J., Pettinga, J.R., 2016. The 2010–2011 Canterbury Earthquake Sequence: environmental effects, seismic triggering thresholds and geologic legacy. Tectonophysics 672–673, 228–274. https://doi.org/10.1016/j.tecto.2016.01.044.

Reineck, H.E., Singh, I.B., 2012. Depositional Sedimentary Environments: With Reference to Terrigenous Clastics. Springer Berlin Heidelberg.

Renken, R.A., Dixon, J., Koehmstedt, J.A., Ishman, S., Lietz, A.C., Marella, R.L.,. Memberg, S. (2005). Impact of anthropogenic development on coastal ground-water hydrology in southeastern Florida, 1900–2000 (1275). Retrieved from ⟨http://pubs.er.usgs.gov/publication/cir1275⟩.

Revelle, R., 1941. Criteria for recognition of the sea water in ground-waters. Eos, Trans. Am. Geophys. Union 22 (3), 593–597. https://doi.org/10.1029/TR022i003p00593.

Rice, E.W., Baird, R.B., Eaton, A.D., 2017. Standard Methods for the Examination of Water and Wastewater. American Public Health Association, American Water Works Association, Water Environment Federation,.

Seymour, R.B., 1953. Modern materials and methods for joining sewer pipe. Sew. Ind. Wastes 25 (11), 1289–1296.

Shalem, Y., Weinstein, Y., Levi, E., Herut, B., Goldman, M., Yechieli, Y., 2015. The extent of aquifer salinization next to an estuarine river: an example from the eastern Mediterranean. Hydrogeol. J. 23 (1), 69–79. https://doi.org/10.1007/s10040-014-1192-3.

Shalem, Y., Yechieli, Y., Herut, B., Weinstein, Y., 2019. Aquifer response to estuarine stream dynamics. Water 11 (8). https://doi.org/10.3390/w11081678, 1678-200.

Shamsudduha, M., Joseph, G., Haque, S.S., Khan, M.R., Zahid, A., Ahmed, K.M.U., 2019. Multi-hazard groundwater risks to water supply from shallow depths: challenges to achieving the sustainable development goals in Bangladesh. Expo. Health 1–14. https://doi.org/10.1007/s12403-019-00325-9.

Singh, S., Tiwari, S., 2019. Climate change, water and wastewater treatment: interrelationship and consequences. In: Singh, R.P., Kolok, A.S., Bartelt-Hunt, S.L. (Eds.), Water Conservation, Recycling and Reuse: Issues and Challenges. Springer Singapore, Singapore, pp. 203–214. https://doi.org/10.1007/978-981-13-3179-4_11.

Smith, A.J., Turner, J.V., 2001. Density-dependent surface water–groundwater interaction and nutrient discharge in the Swan–Canning Estuary. Hydrol. Process. 15 (13), 2595–2616. https://doi.org/10.1002/hyp.303.

Solinst Canada Ltd (2017). TLC Meter Operating Instructions. Georgetown, Ontario, Canada. Retrieved from ⟨https://www.solinst.com/products/level-measurement-devices/107-tlc-meter/operating-instructions/107ins.pdf⟩.

Stats NZ. (2020). Subnational population estimates (TA, community board), by age and sex, at 30 June 2018–20 (2020 boundaries). Retrieved from ⟨http://nzdotstat.stats.govt.nz/wbos/Index.aspx?DataSetCode=TABLECODE7979#⟩.

Stewart, M.K., 2012. A 40-year record of carbon-14 and tritium in the Christchurch groundwater system, New Zealand: dating of young samples with carbon-14. J. Hydrol. 430–431, 50–68. https://doi.org/10.1016/j.jhydrol.2012.01.046.

Stewart, M.K., Morgenstern, U., Tsujimura, M., Gusyev, M.A., Sakakibara, K., Imaizumi, Y., Cox, S.C., 2018. Mean residence times and sources of Christchurch springs. J. Hydrol. 57 (2), 81–94.

Wang, H., Li, W., Zuo, C., Dong, J., Li, C., Xu, H., Pan, S., 2020. Saltwater intrusion in the Pearl River Estuary (China) variation characteristics and cause analysis. J. Coast. Res. 36 (6), 1145–1153.

Tenison, K. (2014). Salinity training manual: New South Wales Department of Primary Industries. Retrieved from ⟨http://www.dpi.nsw.gov.au/_data/assets/pdf_file/0008/519632/Salinity-training-manual.pdf⟩.

Thermo Fisher Scientific. (2012). Dionex ICS-2100 Ion Chromatography System Operator's Manual. Retrieved from ⟨https://tools.thermofisher.com/content/sfs/manuals/73382-Man-IC-ICS2100-Operators-Oct2012-DOC065291–03.pdf⟩.

Tully, K., Gedan, K., Epanchin-Niell, R., Strong, A., Bernhardt, E.S., BenDor, T., Weston, N.B., 2019. The invisible flood: the chemistry, ecology, and social implications of coastal saltwater intrusion. BioScience 69 (5), 368–378. https://doi.org/10.1093/biosci/biz027.

van Ballegooy, S., Cox, S.C., Thurlow, C., Rutter, H.K., Reynolds, T., Harrington, G., Smith, T., 2014. Median Water Table Elevation in Christchurch and Surrounding Area After the 4 September 2010 Darfield Earthquake. Version 2. GNS Science, Lower Hutt, New Zealand http://shop.gns.cri.nz/sr_2014-018-pdf/.

Walsh, T., 2011. 34 - The plastic piping industry in North America. In: Kutz, M. (Ed.), Applied Plastics Engineering Handbook. William Andrew Publishing, Oxford, pp. 585–602. https://doi.org/10.1016/B978-1-4377-3514-7.10034-0.

Watts, R.H., 2011. The Christchurch Waterways Story. Manaaki Whenua, Lincoln, New Zealand. ⟨https://www.landcareresearch.co.nz/uploads/public/researchpubs/LRSS-38.pdf⟩.

Werner, A., Bakker, M., Post, E.A., Vandenbohede, V., Lu, A., Ataie-Ashtiani B, C., Andrew Barry, D., 2013. Seawater intrusion processes, investigation and management: recent advances and future challenges. Adv. Water Resour. 51, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004.

Werner, A.D., Simmons, C.T., 2009. Impact of sea-level rise on sea water intrusion in coastal aquifers. Groundwater 47 (2), 197–204. https://doi.org/10.1111/j.1745-6584.2008.00535.x.

White, P.A., 2007. Geological model of the Christchurch formation and Springston formation. Institute of Geological and Nuclear Sciences Limited, Wairakei, Taupo, New Zealand. ⟨http://docs.niwa.co.nz/library/public/ECtrU07-24.pdf⟩.

Wilson, J., 1989. Christchurch - Swamp to City - A Short History of the Christchurch Drainage Board 1875-1989. Te Waihora Press, Lincoln, New Zealand. ⟨https://canterbury.royalcommission.govt.nz/documents-by-key/20110929.37⟩.

Wolf, L., Held, I., Eiswirth, M., Hotzl, H., 2004. Impact of leaky sewers on groundwater quality. Acta Hydrochim. Hydrobiol. 32 (4–5), 361–373. https://doi.org/10.1002/aheh.200400538.

Wu, G., Guan, Y., Zhan, X., 2008. Effect of salinity on the activity, settling and microbial community of activated sludge in sequencing batch reactors treating synthetic saline wastewater. Water Sci. Technol. 58 (2), 351–358. https://doi.org/10.2166/wst.2008.675.

YSI Inc (2009). YSI Professional Plus User Manual. Retrieved from ⟨https://www.ysi.com/File%20Library/Documents/Manuals/605596-YSI-ProPlus-User-Manual-RevD.pdf⟩.

YSI Inc (2021). Flow Cell Quatro. Retrieved 26 January, 2021, from ⟨https://www.ysi.com/accessory/id-606850/flow-cell-quatro⟩.

Zeng, Y., Zhao, C., Shi, F., Schneider, M., Lv, G., Li, Y., 2020. Impact of groundwater depth and soil salinity on riparian plant diversity and distribution in an arid area of China. Sci. Rep. 10 (1), 7272. https://doi.org/10.1038/s41598-020-64045-w.