Likelihood of offshore freshened groundwater in New Zealand

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Abstract
Offshore aquifer research is an emerging field that is becoming increasingly important as population growth and climate change put pressure on coastal water resources. One of the largest reserves, globally, of offshore freshened groundwater (OFG) was recently identified off the South Island of New Zealand. This has highlighted the potential for OFG elsewhere in New Zealand. This study aims to: (1) screen for New Zealand coastal aquifers most likely to contain OFG and, (2) document evidence for OFG in New Zealand. An OFG-likelihood rating scheme was developed as part of the study. An application of the rating scheme used survey responses from regional councils responsible for groundwater management, in combination with national and regional-scale technical documents. The rating scheme was found to be a simple and transparent first-pass approach for highlighting areas where OFG is more or less likely at the national scale. Results are presented in a map showing the likelihood of OFG around the New Zealand coastline. Regions with aquifers where OFG likelihood is high include Greater Wellington, Canterbury, Tasman, Hawkes Bay and Marlborough. Aquifers in these regions are associated with major fluvial depositional systems, including glacial outwash gravels. Despite high dependence on groundwater in these regions and extensive groundwater extraction near the coast, there are no major reported incidences of seawater intrusion, suggesting offshore groundwater may be augmenting onshore extraction.

Keywords Sustainability · Coastal aquifers · Salt-water/fresh-water relations · Participatory methods · New Zealand

Introduction
Coastal aquifers are an important source of freshwater at many locations globally (Ferguson and Gleeson 2012), including New Zealand (Ingham 2006; Moreau et al. 2019). However, increasingly dense human occupation of coastal zones is causing what has been termed a ‘coastal groundwater squeeze’ whereby groundwater is threatened with onshore contamination as well as seawater intrusion (Michael et al. 2017).

Coastal groundwater investigations traditionally focus on freshwater availability in onshore aquifers, i.e., in aquifers on the landward side of the shoreline. However, Post et al. (2013) recognised that vast reserves of offshore freshened groundwater (OFG) occur in submerged fringes of continents globally, including New Zealand. OFG can derive from present-day onshore recharge to coastal aquifers that extend offshore (Kooi and Groen 2001). OFG can also be paleo-groundwater that was derived from recharge during past glacial periods, when sea levels were lower. It is thought that the lower sea level caused steeper water tables, which increased topography-driven groundwater flow (Post et al. 2013). Additionally, in some cases, the exposure of continental shelves (due to lower sea levels) caused freshwater recharge from rainfall, paleo-rivers and ice sheets to become trapped under the sea-floor as sea level rose to present day levels (Person et al. 2003; Post et al. 2013). For OFG to persist despite transgressions of the sea, there needs to be an aquitard between the ocean and the underlying subsea aquifer, to impede the mixing of seawater and freshwater.

In addition to the emplacement mechanisms detailed in the preceding, Michael et al. (2016) has shown that large-scale heterogeneity resulted in farther offshore extension
of low salinity groundwater, and that a sea level lowstand may not be a necessary condition for large bodies of OFG. However, as the salinity distributions under this emplacement mechanism take a long time to reach a conceptual steady state (on the order of $10^4–10^5$ years), it is plausible to assume that heterogeneity and transient effects (i.e., recharge and sea level changes) act in tandem (Jiao and Post 2019).

A number of analytic models are available to estimate the offshore steady-state extent of OFG that originates from modern-day terrestrial recharge (Bakker 2006; Bakker et al. 2017; Werner and Robinson 2018). Specifically, these analytic models predict the position of the freshwater–saltwater interface assuming homogeneous and isotropic aquifer/aquitard properties. These solutions indicate that the extent of offshore groundwater is a function of the hydraulic gradient between onshore heads and heads at the coast (i.e., offshore groundwater flow), vertical conductance of the semiconfining layer (i.e., its ability to transmit water, which is a function of the hydraulic conductivity and thickness) and the offshore extent of the overlying semiconfining layer. The larger the offshore groundwater flow, the lower the conductance of the semiconfining layer, and the further offshore this layer extends, the further offshore the fresh groundwater will extend.

In this study, OFG is defined as an offshore groundwater body with a salinity less than seawater occurring within semiconfining aquifers that extend from onshore to offshore, and discharge through the continental shelf at the scale of a few km to 10s of km, i.e., at the embayment and shelf scale (Bratton 2010).

Offshore freshened groundwater is recognised as a potential water resource for many coastal communities through offshore pumping (Bakken et al. 2012; Post et al. 2013; UN-Water 2020). However, it is yet to be proved that OFG can be a viable source of freshwater for coastal communities. In New Zealand, the water utility Wellington Water carried out exploratory drilling in Wellington harbour to determine the viability of pumping fresh groundwater from beneath the harbour (Radio New Zealand 2017). This was for emergency water supply, as existing pipelines intersect geological faults and may rupture in the event of an earthquake. The groundwater was found to have elevated iron and manganese, and concept plans to pipe the groundwater direct to Wellington City via a seabed pipeline were abandoned due to the high costs of treatment. Also, there was concern about the risk of pumping-induced drawdown of saline harbour water into the aquifer. In addition to potential contamination from the overlying saline water, Yu and Michael (2019) have shown that offshore pumping can impact onshore aquifers through reduced flows and subsidence.

To date, there are no documented cases where offshore pumping is supplying water at a large scale. However, at many locations globally, OFG is augmenting onshore pumping and hence used for water supply, albeit unknowingly in many cases (Knight et al. 2018). That is, there are many places where onshore pumping wells would likely be salinised through seawater intrusion if OFG were not present (Morgan and Werner 2015; Knight et al. 2019). Perth in Western Australia is a good example of this, where onshore pumping in the confined Yarragadee aquifer has resulted in a 40-m head decline since the early 1980s, with heads now around 5 m below mean sea level. Despite this, large groundwater pumping schemes within 10 km of the coast have not become salinised and this is most likely due to a large OFG reserve (Knight et al. 2018; Morgan et al. 2018). As such, coastal aquifers with OFG may have a degree of resilience to seawater intrusion arising from the offshore location of the interface. However, it is important to understand the extent of OFG, and the location of the freshwater–saltwater interface in particular, so that onshore pumping can be managed sustainably. Once the migrating fresh-to-saline-water transition reaches coastal boreholes, it will be too late to put effective management controls in place. This is particularly important as groundwater exploitation and scarcity increases.

While New Zealand is well endowed with freshwater (Ministry for the Environment and Stats NZ 2019), high per capita water use (OECD 2018) and an uneven distribution of rainfall results in periodic water shortages and dependence on groundwater in some regions. The New Zealand economy is heavily reliant on agricultural exports. In recent decades, there has been a shift away from dryland sheep and beef farming to intensive dairy farming and horticulture (Ministry for the Environment and Stats NZ 2019). Much of the expansion has occurred in areas of low rainfall and irrigation requirements have increased. Between 1999 and 2010 the demand for groundwater approximately doubled (Rajanayaka et al. 2010), and it is recognised that groundwater is over-allocated in many regions of New Zealand (Boone and Fragaszy 2018).

There are numerous aquifers in New Zealand with diverse geologic, hydraulic and chemical properties (White 2001). A digital dataset showing the location and area of New Zealand’s aquifers has been developed by the Ministry for the Environment (2015) and is shown in Fig. 1. This dataset used aquifer extents first described by White (2001), with some of the boundaries updated by Moreau and Bekele (2015) from information supplied by regional councils and information from Lovett and Cameron (2015). The aquifer boundaries in this dataset are in some cases actual aquifer boundaries, and in other cases they are groundwater management zones. The dataset consists of 153 distinct aquifer location boundaries (polygons) and some of these contain more than one aquifer, particularly at locations where aquifers are stacked (i.e., where there are multiple aquifers vertically at a single location).
More broadly, Moreau et al. (2019) divided the New Zealand land mass into eight hydrogeological systems. The hydrogeological systems were defined as geographical areas with broadly consistent hydrogeological properties, resource pressures and management issues. The hydrogeological systems (and their proportion by land area) are coastal basin (30%), inland basin (11%), coastal volcanic (4%), inland volcanic (4%), inland river valley (2%), coastal independent (1%), basement infill (3%) and basement hard rock (44%). The coastal basin category represents systems with a coastal boundary and sedimentary surface geology. The location of coastal basin hydrogeological systems is shown in Fig. 1. At these locations, groundwater is a key water supply for municipal, industrial and agricultural uses (Moreau et al. 2019), and includes the Canterbury Plains aquifers which are estimated as containing around 70% of all of New Zealand’s...
groundwater by volume (Moreau and Bekele 2015). The Canterbury Plains aquifers can be seen in Fig. 1 as the contiguous aquifers to the north and south of Christchurch.

In 2011 a scientific offshore drilling expedition—the International Offshore Drilling Program, which is focused on understanding physical processes controlling continental margin sedimentation—reported low salinity pore water sediments in the Canterbury Bight at location U1353 (Fig. 1), suggesting OFG might be present (Expedition 317 Scientists 2011). Subsequently, a large-scale geophysical investigation has provided evidence from geophysics and borehole data of extensive and relatively shallow OFG at this location (Micallef et al. 2018). Numeric modelling indicates that a high degree of heterogeneity in the sedimentary framework of the Canterbury Bight, in combination with long-term sea-level variation, has likely emplaced groundwater up to 60 km offshore over the past 300 ka (Micallef et al. 2020).

Paleo-groundwater has been found elsewhere in New Zealand including in the northern South Island (Moutere Gravel aquifer; over 27 ka) and in the southern North Island (Whenuakura Formation, 31 ka; Shannon, 40 ka; Stewart et al. 2004). These findings, in combination with New Zealand’s extensive shallow bathymetry (Fig. 1) led Stewart et al. (2004) to conclude that: “The influence of changing sea levels in the recent past (geologically speaking) on the disposition of groundwater in coastal aquifers of New Zealand may have been far greater than we had previously realised, and New Zealand may be surrounded by a ‘skirt’ of pristine paleo-groundwater at deep levels.”

The studies of Stewart et al. (2004) and Micallef et al. (2020) highlight the potential for OFG in New Zealand and provide motivation for further research in this area. The aim of this study is to carry out a first-pass assessment of the scale of OFG in New Zealand. To achieve this, the study will: (1) systematically screen for coastal aquifers in New Zealand that are most likely to contain OFG and, (2) document direct and indirect evidence for OFG in selected New Zealand aquifers.

Methods

The study involves both the development and application of an OFG likelihood-rating scheme. The scheme is applied to all coastal aquifers (i.e., aquifers intersecting the coastline) in New Zealand with an area larger than 10 km². Datasets include: (1) responses to a survey of local government authorities responsible for managing groundwater; (2) information obtained from national and regional-scale technical documents and journal articles; and (3) aquifer locations from the Ministry of the Environment (2015). All of this information is combined to map the likelihood of OFG in New Zealand aquifer locations. Additionally, for aquifer locations assessed as having high OFG likelihood, the evidence for OFG is documented.

Offshore freshened groundwater likelihood-rating scheme

An OFG likelihood-rating scheme (Table 1) was developed using a set of OFG indicators. The indicators relate to physical properties and processes described in various publications, and detailed in section ‘Introduction’, as being favourable conditions for the emplacement of OFG or as being evidence for OFG. For simplicity, the indicators have been framed as questions and are designed to be answered with ‘Yes’, ‘Unknown’ or ‘No’ responses. The rating value is assigned depending on the answer, with a value of 0 for ‘No’, 1 for ‘Unknown’ and 2 for ‘Yes’. Question 8 is an exception to this, and has a rating system with a value of 0 for ‘Yes’, 1 for ‘Unknown’ and 2 for ‘No’. The rating values for all indicators are summed to arrive at a final rating score out of 22.

It is usual for large-scale screening tools to weight indicators according to the perceived importance of the indicator to the process being screened for (e.g., Lobo-Ferreira et al. 2007; Parizi et al. 2019). The product of the rating and weighting of each indicator are then summed to arrive at a final rating score. However, the value of weightings is generally determined subjectively, which is a drawback of these methods (Parizi et al. 2019). Weightings are not used in this study, to avoid extra and unnecessary subjectivity.

The first question in Table 1 screens for aquifers occurring within coastal basin hydrogeological systems, as defined and delineated for New Zealand by Moreau et al. (2019). The sedimentary geology and high groundwater use documented for these coastal basins suggest aquifers with large groundwater storage and flow, indicating potential for OFG. Also, sedimentary formations (particularly those that are unconsolidated) are often very heterogeneous, with inter-layering of high and low permeability materials. As pointed out by Zamrsky et al. (2020), “this heterogeneity is a major control on the fresh groundwater volume and groundwater salinity distribution within such systems”. Questions 2, 3 and 4 relate to aquifer type and geology and reward locations where confined/seconfined conditions exist with an overlying aquitard and offshore extension (Post et al. 2013; Kooi and Groen 2001; Knight et al. 2018). Questions 5 and 6 identify locations where low salinity water occurs offshore either as low salinity pore water or as springs and seeps. Questions 7 and 8 screen for locations where pumping takes place near to the coast without seawater intrusion occurring, a situation more likely when OFG is present (Knight et al. 2018). For question 8, evidence of seawater intrusion needs to be direct (measured). Question 9 and 10 relate to the two most common OFG emplacement mechanisms i.e., coastal discharge derived from modern-day terrestrial
recharge, and paleo-groundwater derived from eustatic change over glacial/interglacial cycles and recharged around 10,000–130,000 years ago (Post et al. 2013; Stewart et al. 2004). In question 9, the water budget refers to the aquifer inflows (e.g., recharge), outflows (e.g., pumping, coastal discharge) and change in storage over a given time period. Question 11 highlights locations where groundwater modelling has indicated that the interface between fresh and seawater in the aquifer is offshore.

**Survey of councils**

A survey using questions 2–10 in Table 1 was sent to 17 local government bodies (regional councils or unitary authorities) responsible for the allocation and management of groundwater in New Zealand under the Resource Management Act (1991). These local government bodies are simply referred to as ‘councils’ in this paper. It was requested that each coastal aquifer location in the council’s jurisdiction be included in the survey, using aquifer location delineations from Ministry for the Environment (2015), shown in Fig. 1. Also, information sources (e.g., technical documents) were requested to support the responses.

**Results**

Out of the 153 New Zealand aquifer locations (Ministry for the Environment 2015), 55 are coastal aquifer locations with an area greater than 10 km². An OFG likelihood-rating assessment was carried out for each of these aquifer locations. The remaining 98 aquifer locations were given an OFG likelihood-rating score of 0.

The OFG likelihood-rating scheme (Table 1) was completed for each aquifer location using a separate worksheet within a spreadsheet. An example application, for the Moutere Valley, is shown in Table 2. The survey response from the Tasman council was incorporated into the assessment and this is noted in the worksheet along with other sources of information used in the assessment.

Nine councils responded to the survey. These were Canterbury, Greater Wellington, Hawkes Bay, Horizons (Manawatu-Wanganui), Marlborough, Otago, Taranaki, Tasman and Waikato. The councils that responded include the four with the largest annual average groundwater use (as a percentage of the national total) i.e., Canterbury (62%), Hawkes Bay (9%), Wellington (7%), Otago (4%) (KC 2019).

The rating score determined for each aquifer location is shown in Table 3. Rating scores ranged between 20 (Hutt Valley in Greater Wellington) and 2 (Coromandel volcanic, Coromandel sand in Waikato). The answer to questions for each aquifer location is shown in Table S1 of the electronic supplementary material (ESM).

A rating score system is used to assign an OFG likelihood between low and high, to all aquifer locations. A rating score of equal to or greater than 16 was classed as high OFG likelihood, 11–15 was classed as moderate OFG likelihood, 5–10 was classed as low OFG likelihood. As noted previously, aquifer locations that were not assessed were given a rating of 0. Evidence for OFG at locations classed as high OFG likelihood is detailed in the following, with locations listed in order of highest to lowest rating score (see Table 3).

**Hutt Valley (Greater Wellington)**

The Hutt Valley is located on the south of the North Island (Fig. 2). It is a 655 km² flat alluvial plain formed from
fluvial deposition by the Hutt River. The main groundwater system is the Waikato aquifer, comprised of gravels and semiconfined by overlying fine-grained sediments. Aquifer recharge is primarily via infiltration from the Hutt River. Onshore groundwater extraction from the Waikato aquifer delivers up to 70% of the water supply to the Wellington metropolitan region (R. Morris, Senior Groundwater Scientist Greater Wellington Regional Council, personal communication, 2020). The Waikato aquifer is known to extend offshore beneath Wellington Harbour, where there is a monitored offshore freshwater borehole near Matiu Somes Island, and potentially extending out to the harbour mouth (Gyopari et al. 2018). Exploratory drilling in Wellington Harbour found fresh groundwater within the offshore extension of the Waikato aquifer at a distance of 3.4 km from the coast (Gyopari et al. 2018). Groundwater heads are artesian throughout the aquifer, including offshore. Artesian heads indicate that pressure in the aquifer is large enough that groundwater would flow over the land surface (or seabed) if the groundwater was not confined. Fresh groundwater from the Waikato aquifer discharges through the overlying semiconfining layer via springs in the harbour (Gyopari 2014). Harding (2000) investigated several submarine springs in Wellington Harbour and conducted flow measurements in areas of active OFG expulsion. It was shown that discharge from the springs is related to both tides and onshore extraction. Despite extensive onshore groundwater extraction from the Waikato aquifer, Greater Wellington Regional Council indicated that no reports of seawater intrusion have been recorded for these extraction wells. Groundwater modelling suggests that coastal discharge is a high proportion of the overall water budget (Gyopari 2014) and that the freshwater–saltwater interface occurs offshore (Gyopari et al. 2018).

Central Plains (Canterbury)

The Central Plains aquifer (Fig. 2) are part of the Canterbury Basin. The Canterbury Basin is about 50,000 km² in size and extends around 200 km down the east coast of the South Island of New Zealand. Onshore, the basin is made up of the Canterbury Plains and offshore it comprises the Canterbury Bight around to Pegasus Bay.

The Central Plains are the largest alluvial plain in New Zealand. The sedimentary sequence is more than 600 m thick and comprises a combination of glacial outwash and interglacial fluvial gravel, sand and silt deposits (Browne and Naish 2003). The main gravel aquifers occur within the upper 150 m depth and are grouped on a geographic basis into sectors bounded by the major rivers draining the Southern Alps. Aquifer recharge is primarily through infiltration from rivers and land surface infiltration from rainfall (Browne 2001). The regional flow of groundwater is eastward from the Southern Alps toward the coast.

The Central Plains aquifer lies within the Canterbury Plains and is geographically delineated as occurring south of the Waimakariri River and north of the Rakaia River. It includes the city of Christchurch, which is the largest by population in the South Island of New Zealand. The Central Plains are comprised of glacial fluvial gravel outwash deposits. At the coast, alternating fluvial gravels (mainly glacial) and interglacial marine and swamp deposits create a vertical sequence of aquitards and semiconfined to confined aquifers (hereafter referred to as confined aquifers;
The Table 3 shows the aquifer locations ranked according to likelihood of OFG using the rating score.

| Aquifer location                                      | Council                  | Rating score |
|-------------------------------------------------------|--------------------------|--------------|
| Hutt Valley                                           | Greater Wellington       | 20           |
| Central Plains                                        | Canterbury               | 19           |
| Ashburton-Rangitata Plains                            | Canterbury               | 17           |
| Waimakariri-Ashley Plains                             | Canterbury               | 17           |
| Moutere Valley, Marahau River                         | Tasman                   | 17           |
| Appleby Gravel, Hope Minor, Upper and Lower Conf.     | Tasman                   | 16           |
| Heretaunga Plains aquifer system                      | Hawkes Bay               | 16           |
| Wairau, Southern Valleys                              | Marlborough              | 16           |
| Marine Terrace, Whenakura Formation                   | Taranaki                 | 15           |
| South Canterbury                                      | Canterbury               | 15           |
| Rangitata-Levels Plains                               | Canterbury               | 15           |
| Rakaia-Ashburton Plains                               | Canterbury               | 15           |
| Kaikoura Plain                                        | Canterbury               | 15           |
| Wanganui                                              | Manawatu-Wanganui        | 15           |
| Manawatu                                              | Manawatu-Wanganui        | 15           |
| Wangaehui-Turakina, Rangitikei                        | Manawatu-Wanganui        | 15           |
| Horowhenua, Tararua, Coastal                          | Manawatu-Wanganui        | 15           |
| Matemateaonga Formation                               | Taranaki                 | 13           |
| Ashley Downs                                          | Canterbury               | 13           |
| Takaka Valley                                         | Tasman                   | 13           |
| Lower Awatere Valley                                  | Marlborough              | 12           |
| Rangitaiki Plains (assumes shallow system)            | Bay of Plenty             | 11           |
| Kapiti Coast                                          | Greater Wellington       | 11           |
| Banks Peninsula                                       | Canterbury               | 11           |
| Southland colluvial, alluvial, coastal, etc.          | Southland                | 11           |
| Nuhaka aquifer system                                 | Hawkes Bay               | 11           |
| Wairoa aquifer system                                 | Hawkes Bay               | 11           |
| Taranaki Volcanic                                     | Taranaki                 | 10           |
| Kaawa                                                 | Auckland                 | 10           |
| Marsden-Ruakaka                                       | Northland                | 10           |
| Inch Clutha Gravel aquifer                            | Otago                    | 10           |
| Wairarapa Valley                                      | Greater Wellington       | 10           |
| Mangawhai                                             | Northland                | 10           |
| Aupouri                                               | Northland                | 10           |
| Kapiti Coast - Otaki                                  | Greater Wellington       | 10           |
| North Otago Volcanics aquifer                         | Otago                    | 9            |
| Esk aquifer system                                    | Hawkes Bay               | 9            |
| Greywacke                                             | Auckland                 | 9            |
| Opotiki                                               | Bay of Plenty             | 9            |
| Coopers/Cable                                         | Northland                | 9            |
| Aorere Gravel                                         | Tasman                   | 9            |
| Waiemanu                                              | Auckland                 | 8            |
| Auckland coastal aquifers                             | Auckland                 | 8            |
| Mahia aquifer system                                  | Hawkes Bay               | 8            |
| Coastal aquifers                                      | Bay of Plenty             | 8            |
| Lower Waitaki Plains aquifer                          | Otago                    | 7            |
| Tauranga Group sediments, Hinuera Formation           | Waikato                  | 7            |
| Auckland Volcanics                                    | Auckland                 | 6            |
| Waipaoa Valley                                        | Gisborne                 | 6            |
| Waiapu and Tolaga Bay flats                           | Gisborne                 | 6            |
| Otorohanga and Orahiri limestone                      | Waikato                  | 6            |
Groundwater heads in the confined aquifers nearby to the coast are artesian. A widely reproduced conceptual diagram by Talbot et al. (1986) indicates a coastal aquifer system with four confined aquifers at the coast, all of which extend offshore. The upper confined aquifer is conceptualised as outcropping at the seafloor about 40 km offshore and the freshwater–seawater interface in this aquifer was predicted to occur ‘considerably offshore’. All of the deeper aquifers were conceptualised as pinching out and not outcropping at the seafloor. More recently, seismic data suggests that the first and second confined aquifers continue offshore for at least 33 km, outcrop at the seabed further than 30 km from the shoreline, and are about 20–25 m thick (Barnes 2015). Extensive pumping occurs in the aquifers nearby to the coast and seawater intrusion has not been recorded in recent years. Previously, there was one instance of downward leakage from an overlying estuary caused by over pumping (PDP 2011).

Mandel (1974) was the first to assert that the freshwater–saltwater interface was everywhere offshore, below the confining layers that extend out to sea. He also suggested that the lack of head decline in the aquifers underlying Christchurch over the long term may be due to inland movement of the interface that ‘props up’ the groundwater. A variable density numerical model developed by Hertel (1998) estimated the steady-state position of the freshwater–saltwater interface to be 3–4 km offshore in the upper confined aquifer. Knight et al. (2018) subsequently estimated that the interface could be up to 9 km offshore.

Age dating by Stewart (2012) shows that wells located near the coast of Christchurch draw older water than the rest of the city. Stewart (2012) attributed this to a large body of much older (perhaps glacial age) water stored beneath Christchurch and offshore. Stewart (2012) proposes that this old freshwater body will continue to provide Christchurch with water but will eventually be depleted and replaced by younger water derived from the Waimakariri River, which is the main source of recharge to this aquifer.

### Ashburton-Rangitata Plains (Canterbury)

The Ashburton-Rangitata Plains (Fig. 2) are located in Canterbury between the Ashburton and Rangitata rivers, which are to the north and south respectively. The Ashburton-Rangitata Plains have a similar depositional/stratigraphic framework to the Central Plains described previously. Groundwater is predominantly used for irrigation but also forms an important drinking water source (Hanson and Abraham 2013).

The International Offshore Drilling Program (IODP) identified pore water salinity less than seawater at depths between 40 and 65 m below the sea floor (Expedition 317 Scientists 2011) in the mid to outer Canterbury Bight in the vicinity of the Ashburton-Rangitata Plains region. The location of IODP drill site U1353 is shown in Figs. 1 and 2. Subsequently, Micallef et al. (2020) characterised OFG at this location by combining geophysical and borehole data with groundwater modelling. They found an OFG system comprising low salinity groundwater extending up to 60 km offshore with a seawater depth of 110 m. Two smaller bodies of low salinity groundwater were also found. The modelling results indicate that most of the OFG was emplaced by topography-driven flow during glacial periods over the past 300,000 years. Although paleo-groundwater has not been detected onshore, the modelling of Micallef et al. (2020) suggests that it may be present offshore.

### Waimakariri-Ashley Plains (Canterbury)

The Waimakariri-Ashley Plains (Fig. 2) occur in Canterbury, between the Ashley River to the north and the Waimakariri River to the south. The geological setting described previously for the Central Plains also applies in this region. However, the permeability contrast between interglacial and glacial period deposits is expected to reduce northwards (Etheridge 2019). Paleo-groundwater has been detected close to the coast at depths of over 100 m (Van der Raaij 2011; Etheridge 2019). Extensive pumping occurs in the aquifers nearby to the coast and seawater intrusion has not been recorded (Etheridge 2019; PDP 2011). It is not known whether coastal discharge is a large proportion of the overall water budget; however, Etheridge (2019) has estimated it within a range of 1.5–5.4 m³/s. This discharge rate is expected to be variable along the coastline, with values increasing northward of the Waimakariri River (Etheridge 2019).
Moutere Valley (Tasman)

The Moutere Valley (Fig. 2) covers an area of about 205 km² and is underlain by glacial outwash gravel from the Moutere Gravel Formation. The hydrogeology of the Moutere Valley has been detailed by Thomas (2001). The Moutere Valley has three gravel aquifers in vertical layers, the Shallow Moutere, Middle Moutere, and Deep Moutere. Intervening aquitards are comprised of clays with carbonaceous materials. Groundwater heads increase with depth and many bores deeper than 50 m are artesian (Stewart et al. 2004). Groundwater of the Moutere aquifers is recharged by direct rainfall infiltration through unconfined sections of the aquifer in the southwest of the catchment (Thomas 2001). Radiocarbon, oxygen-18, and chemical concentrations were used by Stewart et al. (2004) to identify paleo-groundwater in the Deep Moutere aquifer, recharged during the last ice age. Stewart et al. (2004) noted that the presence of this deep paleo-groundwater “suggests that there may be a large body of such water onshore and offshore at deep levels.”

Appleby Gravel, Hope Minor, Upper and Lower Confined (Tasman)

These aquifers occur under the Waimea Plains in the north of the South Island (Fig. 2). The Waimea Plains are comprised of gravels deposited by the Waimea River and its major tributaries during the late Quaternary (Thomas 2001). The Upper and Lower Confined aquifers are of most relevance to OFG and consist of river-deposited gravels, have high transmissivity and are confined by extensive low permeability overlying aquitards. The Lower Confined aquifer is known to extend offshore into Tasman Bay. However, “the nature of the seaward contact of the aquifer is unclear” (Thomas 2001). Despite extensive extraction close to the coast and declines in head (that have been linked to extraction), seawater intrusion has not occurred (Song and Zemansky 2013).

Heretaunga Plains (Hawkes Bay)

The Heretaunga Plains are on the east coast of the North Island (Fig. 2). The Heretaunga Plains consist of a broad floodplain of alluvial gravel sand and silt deposits interfingered with shallow marine sediments nearer the coast. Aquifer units span three glacial/interglacial climate cycles and form a multi-layered interconnected aquifer system to a depth of 250 m with high transmissivities of up to 20,000 m²/day (Brown et al. 1999). The aquifers are confined and artesian nearby to the coast, and extend offshore as an 11–18 km wide basin that extends across Hawke Bay to the west of Mahia Peninsula (see Fig. 2) (Mountjoy 2019). Note that the onshore region is called Hawkes Bay and the offshore region is known as Hawke Bay.

Extensive groundwater extraction is occurring at the coast for industrial and public water supply. Despite this, seawater intrusion has not been recorded. Groundwater modelling by Rakowski and Knowling (2018) indicated that coastal discharge is around 30% of the water budget. However, lower coastal discharge values have been estimated through other modelling activities indicating a high degree of uncertainty for these values (A. Elwan, Senior Scientist Hawkes Bay Regional Council, personal communication, 2020).

The navigation chart for Hawke Bay shows a number of submarine freshwater springs around 30 km from the coast (LINZ 2017). However, it is not certain how they were identified originally and Ridgeway and Stanton (1969) found no evidence of their presence; only high salinities were found at the bottom. More recently, Meyniel (2015) did find some evidence of reduced salinities in the vicinity of the springs but further work is needed to confirm that springs occur at this location. Mountjoy (2019) found that these spring locations do not coincide with the likely offshore extent of the Heretaunga aquifer.

Wairau (Marlborough)

The Wairau Plain is in the northeast of the South Island (Fig. 2). It is an alluvial aquifer system consisting of fluvial reworked gravels (Brown 1981). The Wairau aquifer is the largest of the aquifers in the Wairau Plain. It is recharged from the Wairau River and has high groundwater flow rates. It is confined nearby to the coast, with artesian pressures (Davidson 2001; Morgenstern et al. 2019).

The Wairau aquifer supplies all of the drinking water for the city of Blenheim and other townships in the area as well as water for agricultural irrigation. Extensive groundwater extraction is occurring close to the coast, but seawater intrusion has not been recorded. Coastal discharge is not thought to be a large proportion of the overall water budget, based on a regional-scale water balance (P. Davidson, Groundwater Scientist Marlborough District Council, personal communication, 2020).

Seismic reflection data indicates that the Wairau Plain aquifers could extend offshore beneath Cloudy Bay (BECA 2020). It is not known if springs occur in Cloudy Bay but it is feasible, based on seismic reflection profiles that show erosion and exposure of the Rapaura Formation over 20 km offshore (BECA 2020). There has not been any drilling to ascertain whether fresh groundwater occurs in subsea pore-water. Groundwater ages up to 40,000 years have been found at depth in the Wairau aquifer nearby to the coast (Stewart 2008; Morgenstern et al. 2019).
Fig. 2 Map showing OFG-likelihood for New Zealand coastal aquifer locations. Aquifer locations with high OFG likelihood are named. Other locations (in italics) show important offshore areas detailed in the text. The –120-m line indicates the approximate offshore extent (coastline) of the New Zealand land mass during the last glacial maximum.

Discussion

The rating scheme applies broadly to various coastal aquifer situations globally, but can be easily modified to suit specific locations if needed. Question 1 reads as quite specific to New Zealand but can be easily altered to instead reflect the general intent of the question, which is to identify coastal hydrogeological systems where there is large potential for groundwater storage and flow. Use of the rating scheme for other large-scale assessments will enable a direct comparison with results from this assessment, and provides the opportunity for ranking and benchmarking against this and future assessments that use the rating scheme presented here. The conversion of rating scores to descriptive OFG likelihood classifications (i.e., high, moderate and low) was determined in this study after application of the rating scheme to 53 aquifer locations. This process can benefit from refinement when more comprehensive methods of analysis have been applied.
While the rating scheme has been used in this study to determine areas most likely to contain OFG at the national level for New Zealand, it could also be used as a feasibility assessment tool to compare the likelihood of OFG in a list of prospective systems and assist in decisions relating to the allocation of resources for further exploration.

To assess whether the described ranking scheme makes sense, the results were considered with reference to the known framework for groundwater systems now and during past glacial periods. The aquifer locations assessed in this study as having high OFG likelihood are all associated with major fluvial depositional systems, including glacial outwash gravels. These systems are known to have continued offshore during sea level lowstands when the shoreline was significantly further offshore than its current position (Gibb 1986). The groundwater-bearing gravel deposits on the east coast of the South Island are an excellent example. These deposits were emplaced by the large braided rivers draining the Southern Alps, and are known to extend well out onto the continental shelf (Browne and Naish 2003). Other groundwater-bearing sedimentary systems associated with large rivers in more confined geographic settings, e.g., the Hutt Valley, Heretaunga Plains and Wairau, are also interpreted to extend offshore during sea-level-lowstand periods (Begg et al. 2004; Paquet et al. 2009; Barnes and Pondard 2010). Even without additional supporting information, the potential for OFG in these regions could reasonably be inferred, and with the additional evidence provided here, a compelling case is made for the presence of low salinity groundwater in offshore extensions of aquifers at these locations. Conversely, in other locations where the depositional environment is not dominated by large fluvial systems, e.g., the Auckland and Northland regions (in the northern half of the North Island). In these regions, steep hill country occurs adjacent to the coast and there are few large fluvial systems and depositional plains and it is therefore unlikely that any shelf scale OFG was able to form during sea level lowstand. This interpretation is borne out by the low likelihood of OFG in these regions.

It is important to note that the analysis uses the Ministry for the Environment (2015) aquifer locations model, which groups aquifers regionally. This means that, in some cases, multiple discrete aquifers are attributed with the same ranking. As an example, all aquifers in the Southland region (located at the most southern end of the South Island) have been given a ranking score of 11, including aquifers that are not coastal (Fig. 2). This is because all of the Southland aquifers are classified by Ministry of the Environment (2015) as a single aquifer location (called Southland coluvial, alluvial, coastal, etc., see Table 3).

The analysis in this study is intended to provide a framework for understanding the full extent of New Zealand’s coastal hydrogeological systems. The reviewed material provides some valuable insight into the potential for OFG; however, there is very little direct evidence (i.e., from physical samples) for freshwater beyond the coastline (notably this exists only in Hutt Valley and the Canterbury Bight). Increasing interest in OFG within New Zealand is likely to create more opportunities for the detection of OFG.

All of the aquifer locations determined as having high OFG likelihood had no reports of seawater intrusion in recent years, despite extensive groundwater extraction close to the coast. This suggests that extraction from onshore pumping wells is being augmented by OFG, and that the freshwater–seawater interface is offshore at these locations. There appears to be evidence for this in Christchurch where decadal monitoring (since 1976) of groundwater age at the coast is showing an increase, which is thought to be evidence that groundwater extraction is pulling in older water from depth and from offshore (Stewart 2012; Stewart and van der Raaij 2019). Recently, Knight et al. (2021) showed that alongshore freshwater circulation, driven by hydraulic gradients in the alongshore direction, are an additional mechanism for protection of coastal wells from salinisation.

The extension of this study is to develop specific stratigraphic framework models for aquifer locations determined in this study as having high OFG likelihood. These models can then be used, in combination with information relating to onshore system hydrology, to develop variable density numerical groundwater models. These models can be used to estimate the position of the freshwater–seawater interface, and the dynamics of the interface under various emplacement hypotheses, degrees of onshore-offshore connectivity and extraction and climate change scenarios.

Conclusions

This study is a first step in determining where significant offshore freshened groundwater occurs around New Zealand. All available information was reviewed, and groundwater managers in regional councils were communicated with directly, to enable a rating scheme developed as part of the project. The methodology used in this study can easily be modified for application to other countries or regions where wide continental shelves favour the development of offshore aquifers, and where groundwater resources are managed by local authorities.

In this study, eight aquifer locations (within five regions) were found to have a high likelihood of OFG: Hutt Valley (Greater Wellington), Central Plains (Canterbury), Ashburton-Rangitata Plains (Canterbury), Waimakariri-Ashley Plains (Canterbury), Moutere Valley, Marahau River (Tasman), Appleby Gravel, Hope Minor, Upper and Lower Conf. (Tasman), Heretaunga Plains aquifer system (Hawkes Bay),
Wairau, Southern Valleys (Marlborough). There is also potential for OFG in other areas. Coastal aquifers form a critical resource in New Zealand and this study has implications for how this resource is managed. Direct information about the location and dynamics of the freshwater–saline-water interface offshore will be critical to managing coastal groundwater abstraction with changing climates and increasing industrial pressure.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10400-022-02525-1.

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Declarations

Conflicts of interest There are no conflicts of interest.

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