Bridging Science to Practice

Report

Gisborne MAR Project
2017 - 2020 Injection Trials

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1.0   INTRODUCTION

1.1   The Gisborne MAR Project

The Gisborne District Council are undertaking research on the Poverty Bay Flat / Tūranganui-ā-Kiwa in Gisborne (Poverty Bay Flat) in order to address concerns related to over abstraction. This is known as the Gisborne Managed Aquifer Recharge (MAR) project.

The Poverty Bay Flat / Tūranganui-ā-Kiwa in Gisborne (Poverty Bay Flat) is home to a thriving horticulture industry which relies heavily on water for irrigation sourced from aquifers and surface water. Concerns about over-abstraction and long-term decline in aquifer water levels reported by various researchers (Barber 1993; White *et al* 2012) motivated Gisborne District Council (GDC) to initiate the Gisborne Managed Aquifer Recharge (MAR) project in 2014 as a possible solution to reverse the decline in groundwater levels. More recently, changes to groundwater quality and in particular increased salinity trends have been identified in various water supply wells across the Poverty Bay Flat (GNS 2016; Golder 2017a), which further underpins the need for better ways to manage the groundwater resources in the region. In May 2017, GDC commissioned the first injection trial as part of the Gisborne MAR project to investigate the feasibility of MAR to provide for a water management solution that would benefit the wider community.

During the Gisborne MAR project, water was injected into the Makauri Aquifer via an injection well, headworks and filtering system. The MAR site was selected approximately 13 km north west of Gisborne, on the Kaiaponi farmland, south of Waerengaahika (Figure 1). The source water was taken from the Waipaoa River via an existing infiltration gallery and irrigation network operated by Kaiaponi Farms. The injection well (GPE066) is approximately 500 m from the Waipaoa River and injects into the Makauri Aquifer at some 70 m depth below ground level.

Three injection periods of water injection were completed via two trial stages. The Stage 1 injection trial was conducted during June to September of 2017 - the irrigation offseason. Following a break over one year, the Stage 2 injection trial commenced in May 2019 and continued through to November in 2020.

Stage 1 trial results are reported by Golder (2017a) and key conclusions were as follows:

- 73,180 m^3 of water was injected during the 2017 injection period over 55 days.

- Augmentation of the Makauri Aquifer is technically viable, with a clear rise in Makauri Aquifer water levels was achieved, suggesting that reversal of the long-term downward trend could be accomplished if MAR would be deployed long-term.

- No material adverse effects on aquifer water quality where identified. Deployment of chlorine dosing of injection water was deemed unnecessary and potentially even harmful. Chlorine dosing is no longer applied.

- However, some hydrogeochemical processes could not be adequately monitored during the 2017 injection trial due to the limited amount of monitoring wells. Concerns about potential water quality and well clogging effects remained. Targeted groundwater monitoring and another injection trial could confirm whether potential adverse effect could occur.

The Stage 2 trial included ongoing groundwater monitoring of the 2017 injection plume within areas near the injection well, via four designated monitoring wells. This was followed by another two injection periods in 2019 and in 2020, and ongoing groundwater monitoring between August 2019 and December 2020. Monitoring results up to late 2019 for Stage 2 were reported by Golder (2020).

Total injected water volumes for Stage 2 of the trial were as follows:

- 39,881 m^3 of water was injected during the 2019 injection period over 69 days.

- 104,557 m^3 of water was injected during the 2020 injection period over 80 days.

1.2   Objectives

The feasibility of a MAR scheme depends on the ability to understand and manage potential risks (e.g., well clogging, water quality effects, etc.) and the ability to practically augment the aquifers, including the availability of a reliable source for injection water. A good understanding of the geology, hydrogeology and hydrogeochemistry of the aquifers is important in developing a successful MAR project.

Therefore, the primary objectives of the Stage 2 injection trial were to:

1)   understand the Makauri Aquifer's hydraulic and water quality response to the injection of river water;

2)   determine any adverse environmental effects from the 2017, 2019 and 2020 injection periods; and

3)   optimise injection infrastructure to give operational efficiencies and reduced running costs.

In addition, Golder has further assessed the water management challenges of the Poverty Bay Flat aquifer system and explored how MAR solutions could achieve a catchment-wide improvement of aquifer water quality and yield. This analysis has not been included in this report.

1.3   Approach

Golder collaborated with KWR Water Research Institute from the Netherlands to deliver the Gisborne MAR Stage 2 injection trial. The following steps were taken:

1)   Development of a targeted monitoring programme aimed at following both the 2017 injection plume still present in the area around the injection well prior to the Stage 2 injection trial, and the hydraulic and water quality response to the 2019 and 2020 injection periods.

2)   Technical review of the MAR infrastructure, including river abstraction, well head, filtering system, injection well and various controls, and providing recommendations for system upgrade and operational procedures. These upgrades were commissioned by GDC and completed between April and June 2019.

3)   Routinely assess if the monitoring data and information collected prior to, during and after the injection periods indicate any adverse environmental effects, and whether changes to the monitoring programme were required. This includes a review of both the hydraulic response from the injection trials and the hydrogeochemical processes that govern the water quality response. The compliance of the 2019 and 2020 injection trials with the conditions on the resource consent was also assessed.

4)   Review the Poverty Bay Flat groundwater system, including groundwater level and groundwater quality trends. Based on this and on results from the targeted injection plume monitoring, Golder improved the Gisborne groundwater model to make it more suitable for long-term prediction of groundwater level and water quality improvement from implementation of MAR solutions.

5)   Identify the key considerations for the development of a full-scale MAR system in Gisborne. This includes the assessment of the aquifer response characteristics to injection of river water and expected trends for the overall groundwater quality and levels to be considered for the development of a full-scale MAR system.

Golder has prepared this report for GDC to present the results of Stage 1 and 2 injection trials of the Gisborne MAR pilot project, which encompasses three periods of River water injection during in 2017, 2019 and 2020, and present options and considerations for future MAR developments in Gisborne.

LEGEND
- Wells used for analysis and interpretation
- Groundwater Abstraction from Makauri Aquifer
- Waipaoa Augmentation Plant
- Injection well GPE066
- Roads
- Rivers, streams and drains
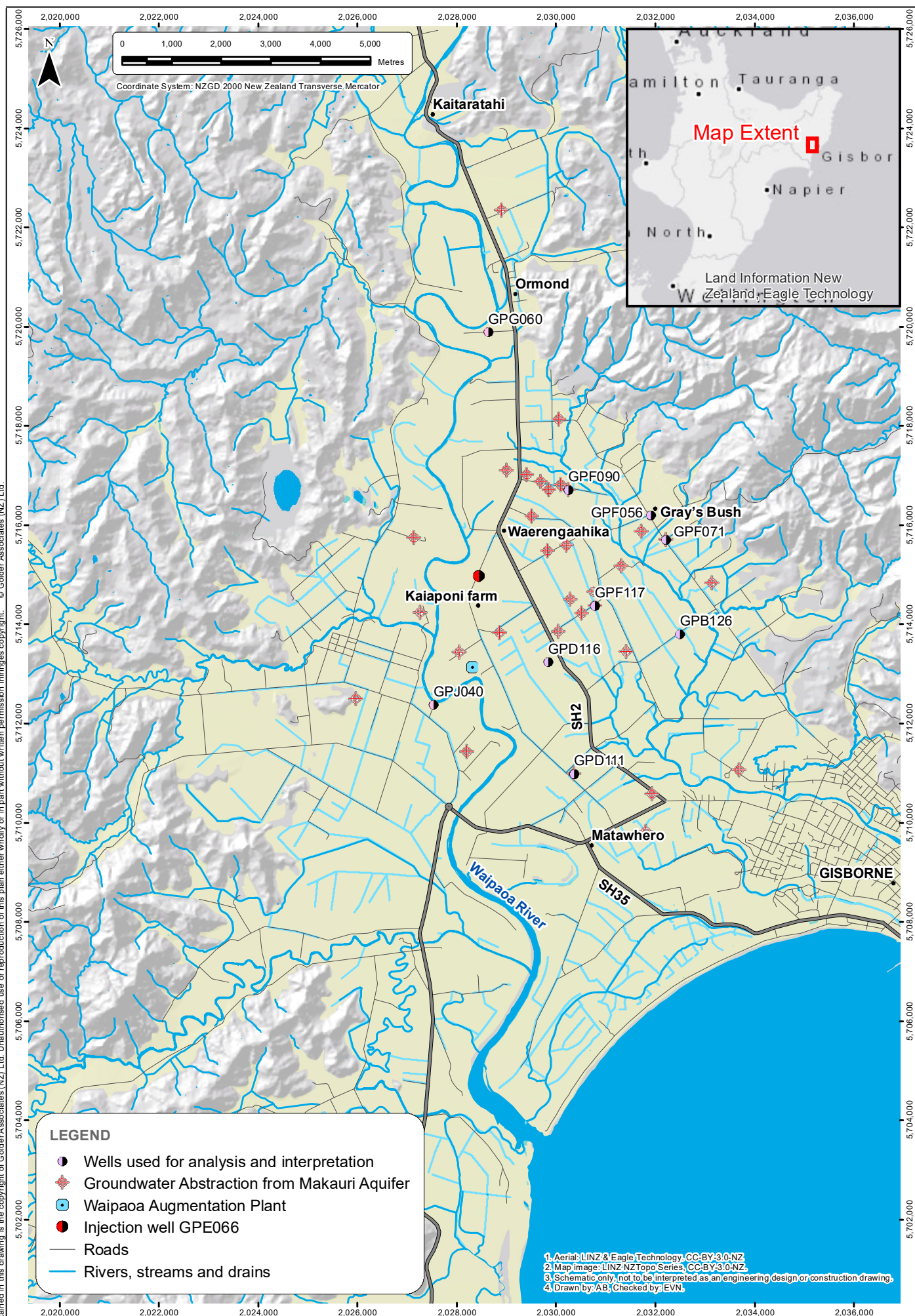
TITLE
Overview map

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1.4   Report Limitations

Your attention is drawn to the document, "Report Limitations", attached in Appendix A. The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

2.0   POVERTY BAY FLAT GROUNDWATER SYSTEM AND TRENDS

2.1   Conceptual Groundwater Model

This section provides a general description of the Poverty Bay Flat groundwater system (i.e., the conceptual model), including how the aquifers that comprise the groundwater system are replenished and how groundwater and surface water interact. Information about the regional geology is key to understanding the groundwater system and therefore relevant geological aspects are described as well. An analysis and interpretation of long-term trends in groundwater levels and groundwater quality, and how these may be relevant for future groundwater resource management decisions are included in the Sections 2.2 to 2.4.

2.1.1   Geology and hydrogeology

Various researchers (e.g., Barber 1993; Taylor 1994; White et al 2012; Golder 2014; Golder 2017a; Golder&KWR 2019) have provided detailed descriptions of the Poverty Bay Flats aquifer system. This section includes a brief overview of the Poverty Bay Flat hydrogeology and also provides an improved conceptual hydrogeological model. Specific attention has been given to processes that are now better understood following an area-wide review of bore logs and groundwater quality data. This enabled the development of a 3-dimensional geological model and numerical groundwater model which has been used to better understand groundwater flow processes.

The groundwater system of the Poverty Bay flats is characterised by an approximately 100 m thick sequence of layers of various composition. This includes relatively thin but highly permeable alluvial outwash gravels deposited during coastal regression (i.e., sea moving outwards), which form the deeper aquifers. These are mutually separated by thick confining layers of shallow marine and estuarine organic matter rich silts, clays, finer sands and pumice (which are volcanic) generally deposited during periods of coastal transgression (i.e., sea moving inward). More recent shallow fluvial gravels and dune sand deposits form the upper-most aquifer. An overview of the characteristics of the Poverty Bay Flat aquifers and confining layers are listed in Table 1 below, which is based on geological modelling from bore logs of water supply wells by Golder[1]. The lateral extent derived from geological modelling is shown in Figure 2.

Note that this Figure 2 includes a corrected figure for the lateral extend of the Te Hapara and Shallow fluvial deposits from Figure 2 as presented by Golder (2020).

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[1] The Poverty Bay geological model was developed by Golder based on bore log data received from GDC and geological information from GNS and other sources. This is Golder's first interpretation of the lateral extend of the aquifers. There are areas where there is little data available, and different interpretation of the geology could be made there. Golder refers to the model as 'indicative' to acknowledge there are data and information gaps, and that updating of the geological model is recommended as more data becomes available.
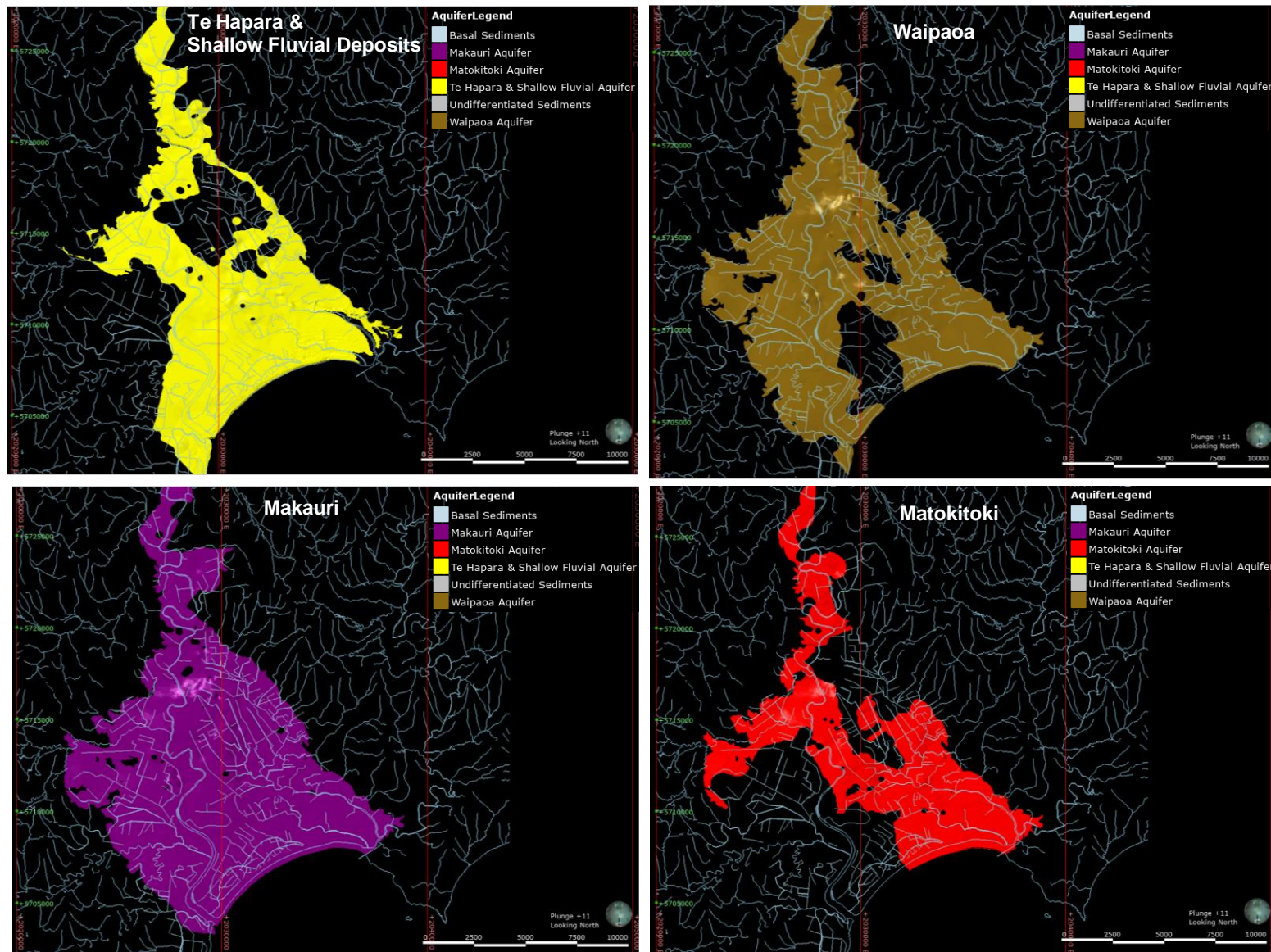
Figure 2: Modelled lateral extent of Poverty Bay Flat aquifers (indicative).

Table 1: Overview of Poverty Bay Flat aquifers and estimated thickness included in the Gisborne Groundwater Model (indicative).

Hydrogeological Unit	Lithology (generalised)	Average Thickness (m)	Maximum Thickness (m)
Shallow Fluvial Gravels / Te Hapara Sands Aquifer	Gravels and sands	6	24
First Confining Layer	fine sands, pumice, silts, clays and organic matter	16	45
Waipaoa Gravel Aquifer	Gravels and sands	3	23
Second Confining Layer	fine sands, silts, clays and organic matter	23	39
Makauri Gravel Aquifer	Gravels and sands	3	15
Third Confining Layer	fine sands, silts, clays and organic matter	19	38
Matokitoki Gravel Aquifer	Gravels and sands	2	14

The Waipaoa River catchment comprise basement rock of mainly Tertiary calcareous sandstone and siltstone and Cretaceous rock. Tectonic tilting and deformation have strongly influenced the basement rock by faulting and folding (Taylor 1994). The layers forming the Poverty Bay Flat groundwater system have been deposited in a basin extending from Kaitaratahi to the coast. There is also evidence of some uplift of the hills surrounding the Poverty Bay Flat which deformed the aquifers post-deposition.

Several researchers have suggested that the Waipaoa, Makauri and Matokitoki aquifers are 'blind', although Taylor (1994) suggests the Makauri aquifer must be discharging at its coastward end. Golder considers these aquifers are likely to extend beneath the bay area where they to 'pinch out' a few hundred metres to a few kilometres offshore. This is supported by bore logs of several near-coastal wells, such as GPC068, GPC039 and GPN015 (Figure 1), which show the Waipaoa and Makauri Aquifers of notable thickness near the coast. This suggests these two aquifers would laterally extend beneath the sea. In addition, groundwater salinity patterns recorded in nested piezometers near the Paokahu Landfill in the Awapuni area are clearly influenced by Waipaoa Aquifer through-flows extending southwards beyond the coastline. In any case, the Waipaoa and Makauri Aquifers are likely to predominantly discharge into the sea.

2.1.2 Groundwater abstraction and use

Groundwater is abstracted from the Poverty Bay Flat aquifers for various uses, but predominantly irrigation for horticulture. Golder understands Gisborne's water supply is from the Mangapoike Dams up-catchment of the Te Arai River, which is treated in the Waingake Treatment Plant, and then reticulated. The Waipaoa augmentation plant at Bushmere Rd, provides for extra capacity when needed, but is mostly not in use. GDC does not use groundwater for the town water supply.

GDC has recently reduced the total amount that is permitted to be abstracted from the Poverty Bay Flat aquifers (i.e., the groundwater allocation) citing long-term decline in groundwater levels caused by over-abstraction (further details in Section 2.2). Groundwater abstraction and use, as well as the permitted total abstraction as recently set by GDC are included in Table 2. The total abstraction for the October 2016 to October 2017 period has been estimated per aquifer based on data provided by GDC. The actual 2016-2017 total abstraction appears to be notably less than allocated.

Table 2: Current groundwater allocation and estimated annual groundwater abstraction and current allocation.

Aquifer	Current allocation (m³)	Estimated abstraction and use in Oct 2016 to Oct 2017 (m³)**
Shallow fluvial / Waipaoa*	27,589,755*	151,409
Te Hapara	705,556	
Makauri	1,684,647	732,985
Matokitoki	343,900	38,044
GDC considers the Shallow Fluvial and Waipaoa Aquifers to be fully hydraulically connected to the Waipaoa River such that any take from these aquifers is counted as a take from the river. ***Whilst records from GDC indicate an abstraction of only 0.9 Mm³ over this period, Golder notes that groundwater drawdown and evapotranspiration records suggest more groundwater abstraction may have occurred in this period.*		

However, the actual water demand and thus groundwater abstraction will vary from year to year, depending on seasonal weather conditions (affecting the level of evapotranspiration during summer). Higher total abstraction volumes have occurred in the past (e.g., 2013) and may occur again in the future.

It is noted that the abstraction records received from GDC for the 2016 to 2018 period appeared inconsistent with recorded evapotranspiration and in particular groundwater level drawdown in summer, which were notably higher than average over that period. Records from groundwater levels, daily potential evapotranspiration rate and monthly abstraction is shown in Figure 3.
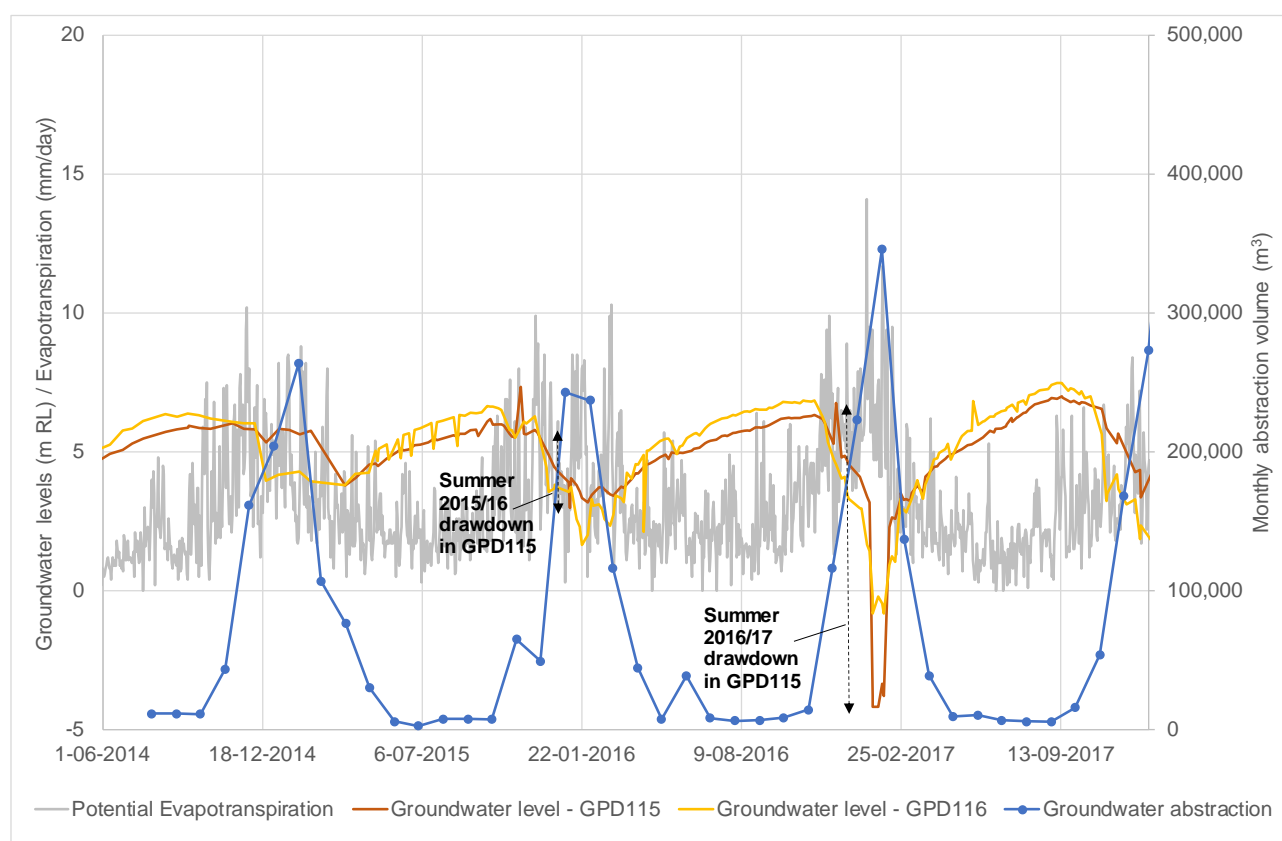
Figure 3: Recorded groundwater levels, potential evapotranspiration and abstraction for 2014-2018 period.

For groundwater modelling Golder has assumed a higher abstraction of about 1.3 Mm^3/year over this period and modelled groundwater level drawdown (Appendix B) appear to better match recorded data compared to the volume listed in Table 2.

2.1.3   Recharge, flows and levels

Aquifer water level contours show a gradual fall from the upper catchment towards the coast in all four aquifers, although the Shallow Fluvial / Te Hapara and Waipaoa aquifers are heavily influenced locally by rivers, streams and the network of manmade drains across the Poverty Bay flat. Makauri aquifer water level contours in winter are shown in the top pane of Figure 4. Abstraction predominantly for irrigation has a significant influence on groundwater levels in the summer as shown in the bottom pane of Figure 4, effectively forming a large 'sump' in the central area during summer. Groundwater is gradually drawn towards the area in the summer, although cessation of pumping over winter and natural groundwater recharge restore the groundwater levels to its unmodified flow pattern. This seasonal difference in Makauri Aquifer water level drawdown is also depicted in cross sections on the left of Figure 5.

Figure 5 below provides a schematic representation of the Poverty Bay Flat Conceptual Groundwater Model including the various forms of natural recharge and discharge of the aquifers:

- The shallow fluvial deposit and Te Hapara sands form one aquifer (i.e., they are not laterally separated by a low permeability layer, although there are some differences in hydraulic conductivity), which is recharged mainly from rainfall and some inflow from infiltrating streams which run off from the western and eastern hills. Average annual rainfall in the area is approximately 1,000 mm and 20 % to 50 % of this will infiltrate and replenish the shallow groundwater table, with the remainder lost by evapotranspiration and runoff. The rainfall recharge is mainly dependent on the type of land use with urban areas having generally the lowest recharge and horticulture the highest (further details are included in Appendix B). A dense network of land drains removes much of the shallow groundwater before it can infiltrate to deeper layers, although notable seepage to deeper layers is likely to occur near the hills where the confining layers are thinner.

- The Waipaoa, Makauri and Matokitoki aquifers are recharged predominantly from the Waipaoa River in the upper catchment around the Kaitaratahi township, and some inflow from rainfall recharge through the uppermost aquifer along the hills sides where the confining layers are much thinner, and the aquifers come closer to the surface.

- All three aquifers discharge into the sea beneath the Poverty Bay, but some Waipaoa and Makauri aquifer water could seep into coastal streams and rivers, such as the Waikanae Creek and Taruheru River.

- There is evidence of deep inflow into the Poverty Bay Flat aquifer system along its north-eastern boundary near the hills. Well GPF056 (111 m deep) located at Gray's Bush near the junction between Ormond Road and Harper Road (Figure 1) is flowing artesian (i.e., aquifer water level rises up to 3 m above ground level). The well is screened 14 to 17 m deep in a permeable pumice layer. Higher aquifer water levels occur in both the Makauri and Matokitoki Aquifers at various locations along the south-eastern boundary, creating groundwater level mounding. In addition, the water quality signature of GPF056 is that of freshwater with low degree of mineralisation and is oxic, where other Matokitoki Aquifer wells such as GPF117 and GPB126 (at a distance of 2.1 km southwest and 2.5 km southeast respectively) show a higher degree of mineralisation and anoxic conditions (see next section). Golder considers that local transmissive fault zones in the structural geology that comprise the eastern hills allow water that infiltrates in the upper hills catchments to flow into the Poverty Bay Flat aquifer system. Taylor (1994) also suggested possible inflow into the Makauri and Matokitoki Aquifers from the eastern hills.

Winter and Summer Groundwater Levels

Top map (Winter):

Coordinate System: NZGD 2000 New Zealand Transverse Mercator

LEGEND

Groundwater Levels in Winter
— Contours 0.5 m interval (mRL)
⊕ Groundwater Abstraction from Makauri Aquifer
● Injection well GPE066

Lake Repongaere

Flow Lines

SH2

SH35

Waipaoa River

Mangapapa
Te Hapara
Whataupoko
Elgin
Gisborne
Awapuni
Kaiti
Outer Kaiti
Okitu
Tamarau
Wainui

Land Information New Zealand, Eagle Technology

Map Extent

Gisborne

Bottom map (Summer):

LEGEND

Groundwater Levels in Summer
— Contours 0.5 m interval (mRL)
⊕ Groundwater Abstraction from Makauri Aquifer
● Injection well GPE066

Lake Repongaere

Flow Lines

SH2

SH35

Waipaoa River

Mangapapa
Te Hapara
Whataupoko
Elgin
Gisborne
Awapuni
Kaiti
Outer Kaiti
Okitu
Tamarau
Wainui

Land Information New Zealand, Eagle Technology

1. Aerial: LINZ & Eagle Technology. CC-BY-3.0-NZ.
2. Map image: LINZ NZTopo Series, CC-BY-3.0-NZ.
3. Schematic only, not to be interpreted as an engineering design or construction drawing.
4. Drawn by: AB, Checked by: EVN.

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Figure 5: Conceptual model of Poverty Bay Flat groundwater system (confining layers separating the aquifers are not shown).

Taylor (1994) suggests a Makauri Aquifer throughflow of 1.25 Mm^3 per year, based on age dating and average thickness of the aquifer of 10 m, but no abstraction. Groundwater modelling (Appendix B) indicate some 2.6 Mm^3/year of throughflow if abstraction of approximately 0.9 Mm^3/year is incorporated. Abstraction would increase inflow to the Makauri Aquifer, thus these estimates appear to be reasonably consistent with each other. Modelling without abstraction result in an estimated throughflow of 1.8 Mm^3/year.

Age dating of aquifer waters by Taylor (1994) indicate the Makauri Aquifer water in the central area is about 100 to 200 years old. Taylor (1994) indicates the that the Makauri Aquifer is recharged from the Waipaoa River near to, or upstream from Kaitaratahi. Indicative flow line calculations with the Gisborne groundwater model (Appendix B) also suggested the majority of the water abstracted by wells in the central area infiltrated from the Waipaoa River in the upper catchment near Kaitaratahi about 100 years ago. Flow line modelling indicate Matokitoki Aquifer water in the central area and Makauri Aquifer water west of the Waipaoa River (i.e., near the 'Western Saline Aquifer') to be older than 1,000 years.

Of interest is that Taylor (1994) derived a water age for the Matokitoki aquifer in the eastern area near Gray's Bush of more than 4,000 years on average. This may be associated with deep inflows of older water from the eastern hills through fault lines.

2.1.4   Interaction with surface water

The Waipaoa River is the main surface water body on the Poverty Bay flat. Several streams and smaller rivers flow into the area from the eastern and western hills. An abundance of manmade land drains across the area drain much of the shallow groundwater before it can infiltrate to deeper layers. Historically, the area harboured many natural wetlands (University of Auckland, 2000) which indicates the naturally poor drainage conditions.

There is a strong interaction between surface water and both the Shallow Fluvial / Te Hapara and Waipaoa Gravel Aquifers. The deeper Makauri and Matokitoki aquifers are separated from surface water by thick confining layers and their hydraulic connection to surface water (such as rivers, streams and springs) is likely to be low in general. Nonetheless, the Waipaoa River is the dominant source of recharge to the Makauri Aquifer, but recharge occurs up-catchment where the confining layers are thin, and the Makauri Aquifer comes close to the surface.

2.1.5   Groundwater quality

Groundwater quality signature varies considerably across the different aquifers and even laterally within each aquifer. The Shallow Fluvial / Te Hapara Sand aquifer is largely fresh reflecting the influence of rainfall recharge and inflow from hills streams. Near the coast beneath the Awapuni area, high salinity in the uppermost aquifer suggests ongoing saline intrusion within this aquifer near the coast (Golder, 2019b). Increases in salinity has also been observed in multiple shallow wells along the coast beyond the Awapuni area (Golder 2019b and Appendix D).

The deeper aquifers have various degrees of salinity, with higher salinity mostly present west and southwest of the Waipaoa River. Barber (1993) describes a 'Western Saline Aquifer' being present to the west of the Waipao River. This is likely to be connate or remnant seawater that is slowly seeping out of the confining layers of marine origin over time. The slow Makauri Aquifer throughflow west of the river results in this high saline water remaining present for centuries. Fresher groundwater is present in the Makauri and Matokitoki aquifer along the eastern hills, likely to be associated with deep inflow of fresh groundwater. In the central area east of the Waipaoa River, the Makauri and Matokitoki aquifer waters appear to be a mix between fresher and more saline waters. In addition, higher salinity water in the Makauri and Matokitoki aquifers appear to be in a reduced (i.e., anoxic) state, meaning that the water is near depleted from oxygen and also nitrate and sulphate levels are low. Ammoniacal-nitrogen is relatively high and methanic conditions may occur

under which methane gas can be formed. This is associated with the presence of organic material in overlying confining layers through which the recharge water passes before replenishing the aquifers (Appendix C). Fresher groundwater generally contains oxygen and sulphate and can be classed as 'oxic'.

Representative concentrations over the 2009 – 2019 period of several key water quality parameters is listed in Table 3 for four different water supply wells across the Poverty Bay Flat and the Waipaoa River (locations shown in Figure 1). These represent the typical water quality types that can be encountered in the Makauri and Matokitoki aquifers.

2.2   Long-term Groundwater Level Trends

Various researchers have investigated the long-term trends in aquifer water levels. Barber (1993) and White *et al* (2012) conclude there is a long-term decline in aquifer levels in the Poverty Bay Flat. Williams (2019) also acknowledges a decline for some periods in the past but concludes the groundwater levels are generally stable in the last few years.

Barber (1993) suggest that the trends in shallow wells indicate that extraction is not greater than recharge. However, for the Makauri gravel aquifer, Barber (1993) identified trends that show the recharge rate is not keeping up with the rate of groundwater abstraction in the period 1983 to 1993, with a continues drop of approximately 1.5 m in those 10 years. Based on groundwater level data from 1994 – 2010, White et al (2012) concluded that water levels in the shallow aquifers (Te Hapara Sands and Waipaoa Gravel) showed either no, or an increasing trend. White el al (2012) also concluded that wells in the Makauri Gravel Aquifer showed statistically significant decreasing trend of groundwater levels, which was confirmed in five of the eight selected wells. Aquifer water levels in the Matokitoki Aquifer also showed a statistically significant decreasing trend according to White et al (2012). Williams (2019) somewhat contradicts the earlier assertions. In general, the groundwater level trends for the Makauri and Matokitoki aquifers were declining from the 1980s until the late 1990's according to Williams (2019). From the 2000's onwards, groundwater levels are stable, although demonstrate shorter cycles of decline and recover. Williams (2019) notes that in the last 6 years (from 2012 onwards) there appears to be a recovery cycle, which is seen in all wells in the deeper aquifers.

Golder considers that a long-term decline has occurred in the past few decades and that this is mainly driven by a gradual increase in the amount of groundwater abstraction in the Poverty Bay Flat. With predicted increase in evapotranspiration caused by climate change (MfE 2018) and the possible further expansion of irrigated land in the area, it would be more useful to consider groundwater level trends over a longer term than a few years.

2.3   Groundwater Quality Trends

Groundwater quality appears to be gradually changing in the Poverty Bay aquifer system, in particular the salinity. The electrical conductivity (EC) forms a measure of salinity and for all red-coloured wells shown in Figure 6, a long-term increase in EC is confirmed as statistically significant. The results of the trend analysis are included in Appendix D. Groundwater salinity is gradually increasing in most Makauri aquifers wells to the south and west of the main irrigation area (i.e., saline intrusion), where some freshening seems to occur to the southeast (although salinity levels are still quite high there).

Table 3: Various groundwater quality types across the Poverty Bay Flat (chemical composition are median values for 2009 - 2019).

Well ID	GPJ040[1]	GPD115[2]	GPD189[2]	GPD116[1]	GPF056[1]	GPF090[2]	Waipaoa River[3]
Ground Elevation (m RL)	10.7	10.75	9.23	7.4	9.8	11.0	-
End Depth (m)	80	75.30	85.3	76.2	111	51.8	-
Aquifer	Makauri	Makauri	Matokitoki	Makauri	Matokitoki	Makauri	-
Water type	Anoxic mineralised water	Anoxic mineralised water	Mixed water	Mixed water	Oxic fresh water	Oxic fresh water	Oxic fresh water
General							
Total dissolved solids (mg/L)	1,050	-	-	912	503	504	261
Electrical Conductivity (µS/cm)	1,340	1,314	986	1,420	792	795	407
Major Ions							
Calcium (mg/L)	180	160	120	190	120	105	63
Magnesium (mg/L)	22	18.8	13	25	12	12	7
Sodium (mg/L)	158	88.5	62	97	30	63	23
Potassium (mg/L)	7.1	9.425	5.7	6.3	5.3	5.2	2.7
Bicarbonate (mg/L)	670	656	590	840	410	497	208
Chloride (mg/L)	220	145	45	65	26	35	11
Sulfate (mg/L)	0.5	0.04	0.04	0.5	30.0	1.0	68.1
Nutrients							
Ammoniacal-Nitrogen (mg/L)	1.30	3.85	0.69	1.35	0.31	0.57	0.05
Nitrate-Nitrogen (mg/L)	0.005	0.005	<0.004	<0.002	0.005	0.03	0.16
Metals							
Iron (total) (mg/L)	5.6	4.4	4.6	9.5	5.0	0.4	0.9
Manganese (total) (mg/L)	0.7	0.68	0.52	0.7	1.5	0.8	0.2

1) Median values of 2009 - 2019 period.

2) Average values of 2019 – 2020 period.

3) Average values of September 2018 to October 2019 period.

A comparison of the 1993 and 2015 EC contours shown Figure 6 suggest salinity typical of the 'Western Saline Aquifer' has encroached notably into the central area of the Makauri Aquifer, that is near heavy abstraction for irrigation. This is clearly visible in the change of the 1,500 µS/cm contour between 1993 and 2015. The three graphs in Figure 7 provide a visual representation of the salinity trends of wells across the area and show that salinity has increased by more than 50 % in the last 30 years in some wells, mainly to the southwest of the central area.

If these trends continue, Golder anticipates a much larger part of the Makauri aquifer beneath the Poverty Bay Flat may become more saline. It is likely the heavy abstraction for irrigation in the central area has caused or at least exacerbated the ongoing increasing salinity trends by drawing connate seawater from the overlying and underlying confining layers and drawing the saline water from the 'Western Saline Aquifer' towards the central area.

2.4   Key Points and Relevance to Managed Aquifer Recharge (MAR)

In addition to the likely long-term decline in groundwater levels, the overall groundwater observations indicate that continued over-abstraction of groundwater in the Poverty Bay Flat is likely to result in worsening of abstracted groundwater quality by induced seawater intrusion by mobilisation remnant saline groundwater from the 'Western Saline Aquifer' towards the central area.

By infiltrating river water into the Makauri aquifer, a full-scale Managed Aquifer Recharge (MAR) application can compensate for the over-abstraction and mitigate the deterioration of abstracted groundwater quality. However, a full-scale MAR system layout needs to be optimally designed to achieve the desired outcome and ensure the best cost-benefit is achieved. This is particularly crucial if abstracted water quality improvement is an objective in addition to mitigating drawdown.

Using the developed Gisborne groundwater flow model developed for the wider catchment area, the transport of the infiltrated river water and its impact on the spreading of the saline water within the groundwater system can be evaluated for different MAR scheme designs. This would include both the dependence on volumetric infiltration and its spatial distribution. This analysis has not been included in this report.

LEGEND

Salinity Trend
- ⊕ Decreasing
- ⊕ No significant trend
- ⊕ Increasing

EC Contours (µS/cm) in 1993 (Left) and 2015 (Right)
750-1,000-1,250-1,500

Coordinate System: NZGD 2000 New Zealand Transverse Mercator

1. Aerial: LINZ & Eagle Technology.
2. Schematic only, not to be interpreted as an engineering design or construction drawing.
3. Drawn by: EVN. Reviewed by: PG.

GOLDER

TITLE | Change in groundwater salinity from late-1980's to present in the Poverty Bay Flat.

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Figure 7: Examples of increased groundwater salinity (EC levels) in water supply wells across the Poverty Bay Flat in the past 30 years.

3.0   MAR INJECTION TRIAL SETUP AND RESULTS

3.1   MAR Injection Trial Setup

The type of MAR technology used in the Poverty Bay MAR pilot project is referred to as Aquifer Storage Transfer and Recovery (ASTR). ASTR entails the injection of water into an aquifer through an injection well and the recovery of this water some distance downgradient, after the injection water has passed that distance through the aquifer (Golder 2017a).

3.1.1   Injection well

The injection well (GPE066) was completed on 10 May 2017 by Honnor Drilling Ltd. Development of this well was carried out through a process of pumping and surging on 27 April 2017. Relevant technical specifications of the injection well and MAR monitoring well are listed in Table 4. Photos of the well screen, sump and screen leader are shown in Figure 8.

Table 4: Technical specifications Gisborne MAR injection well GPE066.

Parameter	Injection well
GDC identification number	GPE066
Easting (NZTMX)	2938328
Northing (NZTMY)	6276389
Distance from injection well (m)	-
Bore depth (m bgl)	73.5
Screened interval (m bgl)	69.5 – 72 (total length 2.5 m)
Casing internal diameter and material	300 mm steel with 250 mm PVC liner
Screen internal diameter and material	250 mm Stainless Steel
Screen slot size (mm)	2.5
Height of casing above ground level (m)	1.3
Static water level depth (m bgl)	7.45

Figure 8: MAR injection well (GPE066) screen shown in left photo; sump and screen leader shown in right photo.

3.1.2   Source water and MAR infrastruture

The water for injection was sourced from the Waipaoa River via abstraction from the existing Kaiaponi infiltration gallery. The gallery is screened between 2 m and 5 m below the base of the river in the underlying gravels (Figure 9). The infiltration gallery is also used for the Kaiaponi water supply system, which supplies irrigation water to the Kaiaponi farm via 150 mm diameter pipeline that crosses Bushmere Road (Golder 2017a). The Kaiaponi irrigation line branches off to the headworks and Arkal filter bank of the MAR injection well GPE066. The rate of flow (L/s) supplied to the MAR injection well is mainly controlled by the speed of the river infiltration gallery submersible pump (37 kW). Photos of the Waipaoa River intake are included in Figure 9. The current injection well and headworks are shown on the photos in Figure 10. An overview map of the MAR infrastructure layout and injection trial monitoring wells is included in Figure 11.

The Waipaoa Augmentation Plant is alternative source for supplying MAR water. The plant is located 1.8 km south of the MAR injection well (GPE066). The augmentation plant was commissioned in 1991 as an alternative supply to augment the Waingake water supply. The potential use of this site to source MAR injection water was previously considered by Golder (2016) but was not utilised for the Stage 1 and 2 trials because of the anticipation of high operational costs. The plant has the ability to produce water volumes up to 720 m³/hr or 17,000 m³/day (GDC 2008). GDC holds resource consent to take up to 13,392 m³/day from the Waipaoa River at the plant. GDC established a minimum Waipaoa River flow of 600 L/s at the Matawhero Bridge and 1,300 L/s at the Kanakanaia Bridge, below which restrictions may be applied.

The experience of the Stage 1 and 2 trials has found that river water turbidity has significantly restricted the volumes of water that could be injected, which has been exacerbated by the poor performance of the inline filter system. Given this experience, the potential to use the Waipaoa Augmentation Plant as a more effective source of MAR water should be re-examined.

Figure 9: Photos of the Waipaoa River infiltration gallery installation (top photo) and current river intake for Kaiaponi irrigation scheme (bottom photo).

Figure 10: Photo of the Gisborne MAR injection well GPE066 and headworks post-upgrading in 2019 (left photo) and downhole injection pipe (right photo).

Golder (2019a) provides detailed specifications of the MAR infrastructure including engineering design and operational procedures to the river water infiltration, pre-treatment and injection well system. The MAR infrastructure underwent several upgrades prior to the 2019 injection trial, which are summarised below:

- Installation and repositioning of various valves to provide better control of start-up and testing procedures.

- Installation of a by-pass line upstream of the Arkal filter bank to enable inlet flows to be diverted around the Arkal filter bank to the MAR waste line (i.e., for well and filter bank backwashing water).

- Installation of new flow meters and turbidity meters.

- Removal of the chlorine dosing equipment.

- Installation of a redesigned downhole injection pipe below the well water level to avoid cascading during injection start up (see photo in Figure 10).

A trigger for backwashing of the injection well was set based on injection well pressure at 2.5 m below top of casing. This was later revised to 1.5 m below top of casing (approximately ground level) to avoid frequent triggering of backflush cycles and allow for longer injection time. Another trigger to cease injection was set if turbidity levels downstream of the Arkal filter bank would rise above 10 NTU, to avoid injection water with high turbidity to be injected into the well.

Gisborne MAR infrastructure and targeted monitoring wells to track water quality and hydraulic response of injection trials

Legend

Modelled Plume Extent (Oct2019)

🔴 Injection well GPE066

◑ Injection monitoring wells

◄► MAR monitoring distances (m)

— MAR infrastructure (pipe line and river take)

— Roads

River intake - infiltration gallery

GPE066
GPE065
GPE069
GPE067
GPE068
GPD189
GPD115

Kaiaponi irrigation line

Map Extent

Gisborne

21
194
133
330

Coordinate System: NZGD 2000 New Zealand Transverse Mercator

GOLDER

TITLE | Gisborne MAR infrastructure and targeted monitoring wells to track water quality and hydraulic response of injection trials

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3.2   Injection and Monitoring Program

Injection trails were undertaken in 2017, 2019 and 2020 to investigate if injection of Waipaoa River water into the Makauri aquifer is possible at a practical rate and to assess potential risks of well clogging, water quality effects and operational issues.

3.2.1   Approach

The groundwater monitoring network was improved since the first injection trial in 2017 by the installation of three new monitoring wells, and a revised monitoring programme was developed to collect appropriate data and information required to assess effects on groundwater levels, flows and water quality of the 2019 and 2020 injection trial.

The injection water is sourced from the Waipaoa River, which has a significantly different composition to the ambient Makauri Aquifer groundwater. The most notable difference is that the river water is oxic and Makauri Aquifer water at the MAR site is anoxic. Furthermore, the overall mineral content of the river water is less than that of the Makauri Aquifer groundwater (Section 2.1.5). Groundwater quality sampling and laboratory testing was undertaken to collect information on possible chemical and biological reactions that can affect the groundwater quality. This can be used to identify possible short-term and long-term effects of MAR and to support decisions for future scheme management and operation.

An injection plume of filtered river water develops in the Makauri Aquifer around the injection well area and locally displaces the ambient groundwater. This is the 'injected water zone' as indicated in Figure 12. Some degree of dispersive mixing will occur at the edges of the injection plume and it is mainly in this area (i.e., the 'mixing zone') where biological and chemical reactions can cause changes in water quality. Both the injected water zone and mixing zone will gradually increase in size and laterally migrate in the dominant groundwater flow direction. The injection of river water into the Makauri Aquifer will also result in a rapid, almost instantaneous rise, in aquifer levels in an area of 1 to 2 km surrounding the injection well (i.e., 'hydraulically impacted zone'). This rise will remain more or less stable if the injection continues at the same rate.
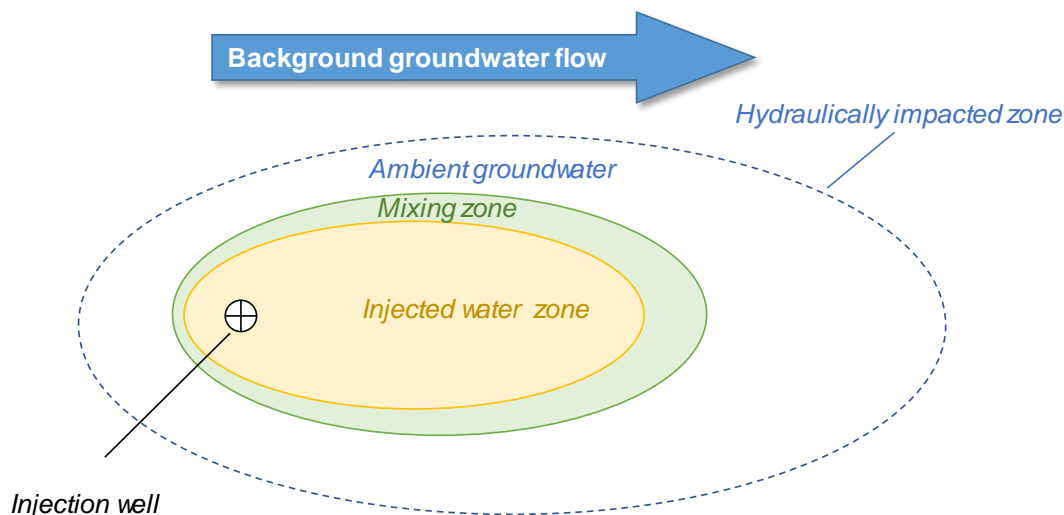
Figure 12: Schematic representation of injection plume development.

Four designated monitoring wells (Table 5) were used to monitor the aquifer responses and track the injected plume migration. In addition, the injection well and four existing water supply wells were included in the monitoring programme to assess water quality effects. The locations of the monitoring wells are included in the regional overview map in Figure 1 and MAR site overview map in Figure 11. The monitoring wells have

been installed at various locations so that both the hydraulic response, plume breakthrough and water quality response in the injection water zone (GPE065), the mixing zone (GPE067 and GPE068), and ambient upgradient groundwater (GPE069, GPD115, GPD089 and GPG060) can be monitored prior to, during and after the 2019 river water injection.

Table 5: Injection trial monitoring well details – Makauri Gravels Aquifer.

Well ID	Type	NZTMX	NZTMY	Ground Level Elevation (m RL)	Distance from Injection (m)	Depth (m)
GPE069	Monitoring well (50 mm PVC)	2028274	5714860	13.35	194	74.0
GPE065	Monitoring well (50 mm PVC)	2028454	5714952	12.89	21	72.6
GPE067	Monitoring well (50 mm PVC)	2028553	5714898	12.23	133	74.0
GPE068	Monitoring well (50 mm PVC)	2028629	5714696	11.33	330	74.0
GPE066	Injection well (300 mm steel with 250 mm PVC liner)	2028438	5714964	12.89	0	72.0
GPD089* (replaced by GPD189)	Irrigation well used for monitoring (details unknown)	2028866	5713819	9.23	1,223	85.3
GPD116	Irrigation well used for monitoring (details unknown)	2029842	5713237	7.42	2,226	76.2
GPD115	Irrigation well used for monitoring (details unknown)	2028056	5713435	10.75	1,595	75.3
GPG060*	Irrigation well used for monitoring (details unknown)	2028635	5719888	21.58	4,900	75.0
*These wells are likely screened in the Matokitoki Aquifer underlying the Makauri Aquifer.						

An overview of all groundwater level, flow and water quality monitoring that was undertaken prior to, during and after the injection trials in 2019 and 2020 is included in Table 6. The following suites of chemical parameters were tested, each with different purpose as follows:

- Suite 1: this comprises a limited number of test parameters that help track the injection plume. Parameters include general parameters (sum of cations an anions, alkalinity), field testing parameters (EC, dissolved oxygen (DO), pH and temperature), major cations and anions (Potassium, Calcium, Magnesium, Sodium, Arsenic, Iron, Manganese, Chloride, Sulphate and Bicarbonate), some nutrients (Nitrate-nitrogen) and bromide.

- Suite 2: this suite of parameters for lab testing, aimed to track the injection plume and also to assess hydrogeochemical processes that may have occurred. Parameters include the same parameters as Suite 1 but include a more comprehensive testing of metals (Aluminium, Barium, Boron, Nickel, Zinc), nutrients (Dissolved Reactive Phosphorous, Ammoniacal-nitrogen and Nitrite-nitrogen in addition to Nitrate-nitrogen) and some other parameters (Silicon, Sulphur and Total Organic Carbon).

- Suite 3: to assess the potential for 'emerging contaminants' being injected into the Makauri Aquifer, several groups of emerging contaminants including dioxins, personal care products & pharmaceuticals (PCP&P's), pesticides and some other chemicals have been tested.

- Suite 4: to assess the risk of injecting pathogens, such as bacteria and viruses, into the aquifer which can compromise the aquifer water quality, bacterial pathogen testing included indicators E.*coli*, Faecal Coliforms, Enterococcus. Adeno virus and somatic coliphages were also tested as these indicate the risk of virus breakthrough.

Automatic water level loggers were installed in all monitoring wells to record water levels and temperature every 15 minutes, and apart from GPE065, conductivity was also recorded in all wells. Flow meters and turbidity meters installed in the injection well headworks respectively recorded injection flows and turbidity every 15 minutes. The automatic data recordings from all wells apart from GPE067 were sent to a remote server via telemetry and displayed on a Scottech Envirodata website. Monitoring well GPE067 was equipped with a conductivity, temperature and water level logger from which the data could be manually downloaded.

The injection well performance has also been continuously monitored prior to, during and after the 2019 and 2020 injection trials. This is also planned to continue following the cessation of the water injection programme in 2020. This is described in Section 3.5.

Table 6: 2019 Injection trial monitoring programme – September 2018 to December 2020.

Monitoring site	Telemetry data collection	Water quality sampling and testing
Waipaoa infiltration chamber and headworks (source water)	(none)	■ Suite 1: 2x and Suite 2: 1x ■ Suite 3 and 4: 4x
GPE066 (injection well)	Automatic recording every 15 minutes of: ■ Injection flows ■ Injection turbidity ■ Well water levels ■ EC ■ Temperature (Flow and water level data was also recorded at 1 minute frequency)	■ Suite 1: 1x and Suite 2: 1x ■ Suite 3 and 4: 2x
GPE069	Automatic recording every 15 minutes of: ■ Well water levels ■ EC ■ Temperature	■ Suite 1: 4x and Suite 2: 4x ■ Suite 3 and 4: 4x
GPE065	Automatic recording every 15 minutes of: ■ Well water levels ■ Temperature	■ Suite 1: 5x and Suite 2: 5x ■ Suite 3 and 4: 4x
GPE067	Automatic recording every 15 minutes of: ■ Well water levels ■ EC ■ Temperature	■ Suite 1: 5x and Suite 2: 5x ■ Suite 3 and 4: 4x
GPE068	Automatic recording every 15 minutes of: ■ Well water levels ■ EC ■ Temperature	■ Suite 1: 5x and Suite 2: 5x ■ Suite 3 and 4: 3x
GPD189 and GPD116	Manual water level recording during sampling	■ Suite 1 and 2 at 1 occasion

GOLDER

3.2.2   Injection programme

Injection rates, volumes and timing of both the 2017, 2019 and 2020 injection periods are given in Table 7. No water injection was undertaken between 13 September 2017 (the cessation of the Stage 1 injection) and 7 August 2019 (recommencement of Stage 2 water injection).

Table 7: 2017-2019 injection trials details.

Injection Details	Winter 2017 Injection Period	Winter 2019 Injection Period	Autumn to Spring 2020 Injection Period
Trial period	20 July 2017 to 13 September 2017	5 August 2019 to 13 October 2019	12 May 2020 to 12 October 2020
Total injection period (days)	52	69	153
Number of days of injection		33	80
Total volume injected (m^3)	73,180	39,881	104,557*
Average injection rate (L/s)	14	14	15.3
Maximum injection rate (L/s)	19	20	19.9

* Water is occasionally abstracted from the well for backwashing and performance testing. The net volume injected is the difference between the total volume injected and the injection well backwashing and performance testing volume. This could only be confirmed for the 2020 injection period following installation of an additional flow meter. Backwash volume is small at approximately 1.5 % of the total injected flows.

Temporary cessation of injection for well backwashing was required for all three injection periods. However, during 2019 both injection pressure and turbidity downstream of the Arkal filter bank triggered several backwashing cycles and cessation of water injection. A stricter maximum turbidity trigger level of 50 NTU was required under the current resource consent for the two injection periods under Stage 2 (undertaken in 2019 and 2020), where this limit was 100 NTU for the Stage 1 trial (2017). This limited the time available for injection and thus the total amount of water that could be injected in Stage 2. Nonetheless, lower turbidity levels (less than 10 NTU) were injected during the 2019 and 2020 injection periods, which would have reduced the risk of well clogging from sediment. The stop and start times for water injection during the 2019/2020 Stage 2 trial are listed in Table 8.

Table 8: Injection periods in 2019-2020 (Stage 2 injection trial).

# Injection	Start Date	Stop Date	Duration (days)	Average Rate (L/s)
1	07/08/2019	12/08/2019	5	14.1
2	17/08/2019	23/08/2019	6	11.3
3	30/08/2019	05/09/2019	6	16.0
4	18/09/2019	25/09/2019	7	11.3
5	03/10/2019	13/10/2019	10	14.5
6	12/05/2020	15/05/2020	3	18.1
7	22/05/2020	01/06/2020	10	11.2
8	08/06/2020	18/06/2020	10	6.5
9	13/07/2020	16/07/2020	3	15.7
10	27/07/2020	04/09/2020	48*	12.9
11	07/09/2020	12/10/2020	35*	12.6
*Not continuous on all days				

3.3   Hydraulic Responses

Groundwater levels in Makauri Aquifer fluctuate under the influence of seasonal changes, with summer abstraction for irrigation resulting in a decline in groundwater levels, where winter cessation of pumping and increased recharge cause levels to rise again. These patterns are clearly visible in the groundwater level records of the designated monitoring wells in Figure 13. In addition, the MAR injection causes groundwater levels to clearly rise in all four monitoring wells and in the injection well itself. Golder (2017a) estimated that the distance from the injection well in which a noticeable rise would occur, to be about 1.5 km (i.e., hydraulically impacted zone). The modelled hydraulic response (i.e., mounding) of groundwater levels in the Makauri Aquifer in response to MAR injection is shown in Figure 18, and would appear to confirm that estimation. A description of the groundwater model used for this assessment is included in Appendix B.

In Figure 14, the groundwater level response during the 2020 injection period is shown, together with the injection flow rates. The graphs for the 2017 and 2019 injection periods are respectively presented in Golder (2017a) and Golder (2020). The graph indicates a rapid response from each injection cycle and recovery after cessation. Water level responses in the injection well (GPE066) are notably higher than in the four monitoring wells. Well losses will cause higher levels to be recorded in the injection well. Contrary to the levels recorded in the monitoring wells, the injection well water level does not represent the aquifer water level during injection (or abstraction). This is schematically depicted in Figure 15.

The well loss component in the recorded water level rise in the injection well can increase if the well's performance deteriorates from clogging. This if further discussed in Section 3.5.
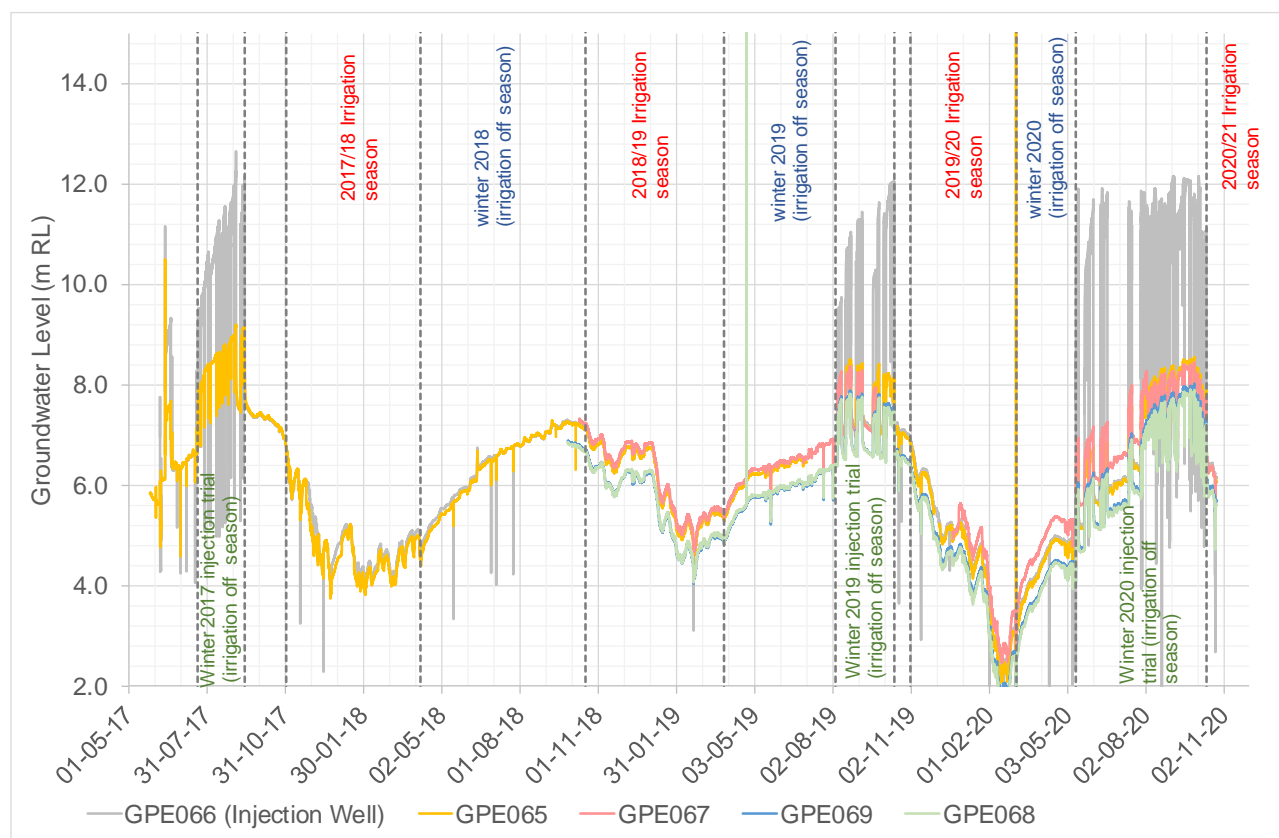
Figure 13: Groundwater levels 2017-2020.
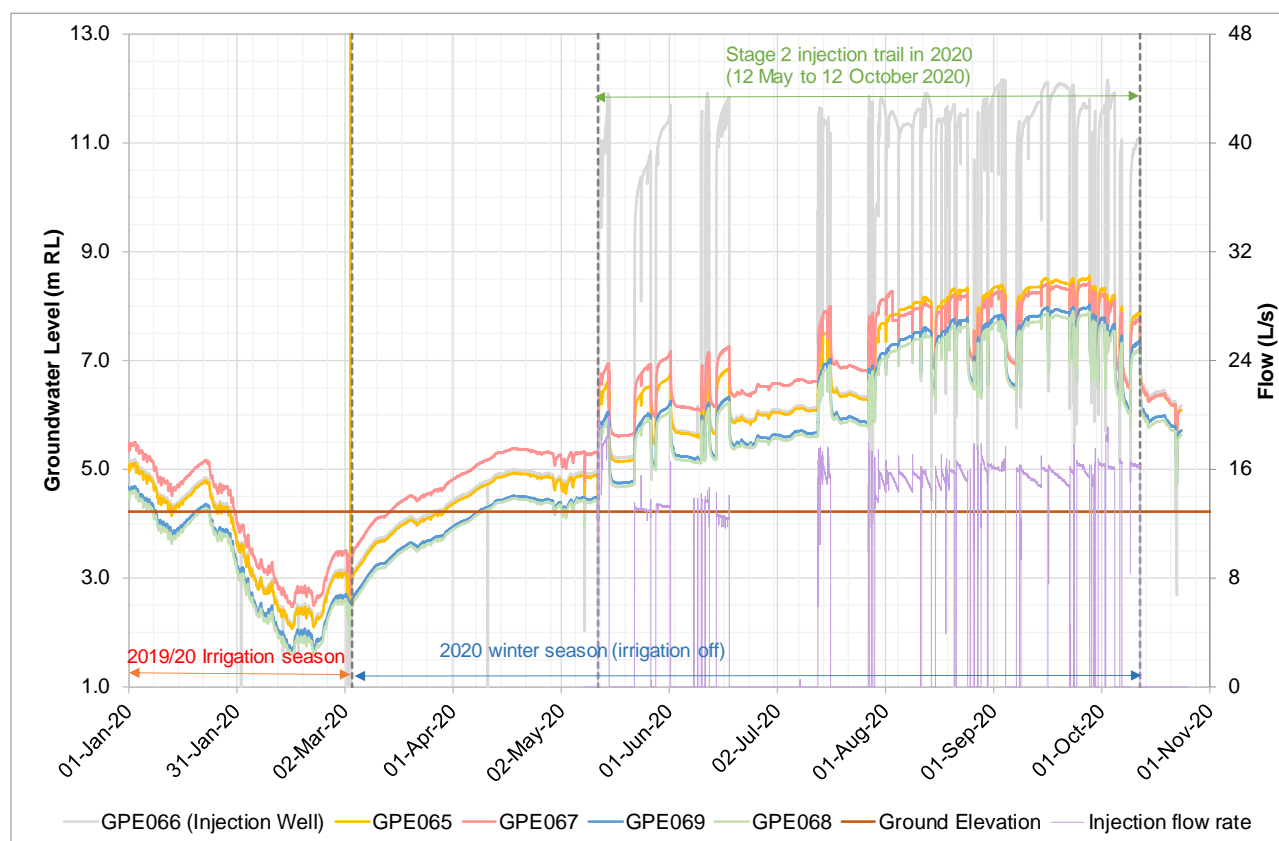
Figure 14: Groundwater levels and flow monitoring during 2020 injection period.
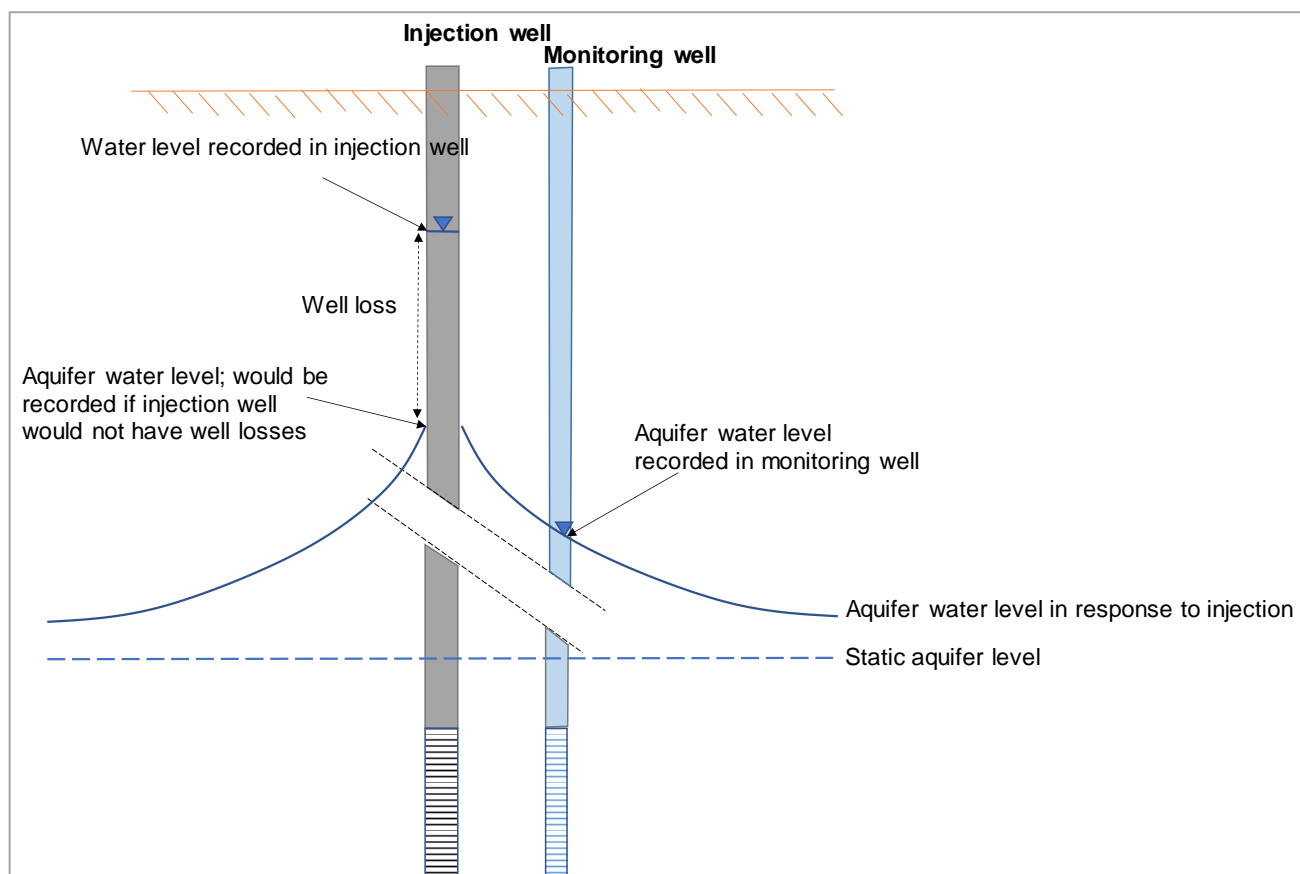
Figure 15: Schematic diagram of aquifer response and well losses caused by injection.

3.4   Injection Plume Tracking and Water Quality Responses

The injection of river water into the Makauri Aquifer during the MAR trials resulted in a localised change in groundwater quality as the river water has a different composition as the ambient groundwater in the Makauri Aquifer. The change in groundwater quality is the result of various processes, which can be grouped as follows:

■   Displacement: the injection water displaces the ambient groundwater and forms a plume around the injection well. This plume remains present to some degree after injection stops and then gradually moves downgradient under the influence of groundwater throughflow in the aquifer. Every time the groundwater flow direction changes, the injection plume will also change. At the Gisborne MAR site, this occurs for each change of season, where flow in the winter is generally south-eastwards, and the summer flow is eastwards due to abstraction for irrigation.

■   Dispersive mixing: the injection plume will disperse at the edges and mainly at the downgradient front of the plume, where it mixes with ambient groundwater. This is referred to as dispersive mixing.

■   Hydrogeochemical processes: various biological and chemical processes can cause a change in water quality when waters of different composition mix, or when water comes into contact with aquifer material as it flows through the aquifer.

These various processes described above were traced by the targeted monitoring (which includes frequent water quality sampling and testing) in the four screened monitoring wells in the Makauri Aquifer, surrounding the MAR injection well (locations shown in Figure 11). Furthermore, the chemical composition of the materials

that comprise the Makauri Aquifer and overlying confining layer were tested to assess their potential reactivity (Appendix C).

Injection plume tracking

During injection, the groundwater flow will be generally south to southeast away from the injection well and the plume will continue to expand as long as injection continues.

Water quality testing results obtained during the monitoring programme, show a clear difference in water quality in all four monitoring wells, with GPE065 most akin to the injected Waipaoa River water and GPE069 representing ambient groundwater in the Makauri Aquifer at this site before August 2020 (injection plume breakthrough was recorded in August 2020). Irrigation wells GPD115 and GPD189 both located south of the MAR site, are most akin to GPE069 (ambient groundwater), but show that the ambient water quality composition in the Makauri Aquifer is variable (Section 2.1.5 and Table 3).

The salinity expressed as either Electrical Conductivity (EC) or chloride provides good indicators to track the injection plume. The salinity (and thus EC and chloride) does not change notably by biological or chemical reactions and the Waipaoa River water is much fresher (i.e., has lower EC and chloride levels) than ambient Makauri Aquifer water at the site. EC levels have been recorded continuously with automatic loggers in GPE067, GPE068 and GPE069, and chloride has been obtained by sampling and lab testing (Figure 16). The EC and chloride recordings are not fully aligned in this graph. However, the general trend is consistent for both parameters.

EC and chloride levels, prior to the winter 2017 MAR injection trial, in GPE065 and GPE066 (injection well), are similar to those recorded in GPE069 before commencing the 2019 injection trial. This indicated that the 2017 injection plume had not reached GPE069. The other two wells (GPE067 and GPE068) showed various degrees of dispersive mixing between injected river water and ambient groundwater, suggesting the plume was not present near these wells.

The gradual change in salinity is shown in Figure 16. This clearly shows the injection plume is still present near GPE066 (injection well) and nearest monitoring well GPE065 but may have never reached GPE069 until August 2020 when the injection plume breaks through in that monitoring well. GPE067 and GPE068 have gradually become fresher after the 2017 injection and this process seems to be ongoing. At the start of both the 2019 and 2020 injection periods, the salinity in both these wells initially increased, as ambient groundwater was initially pushed towards these wells. However, as the injection trial continued, fresh injection water reached these wells, as indicated by a decline in salinity.
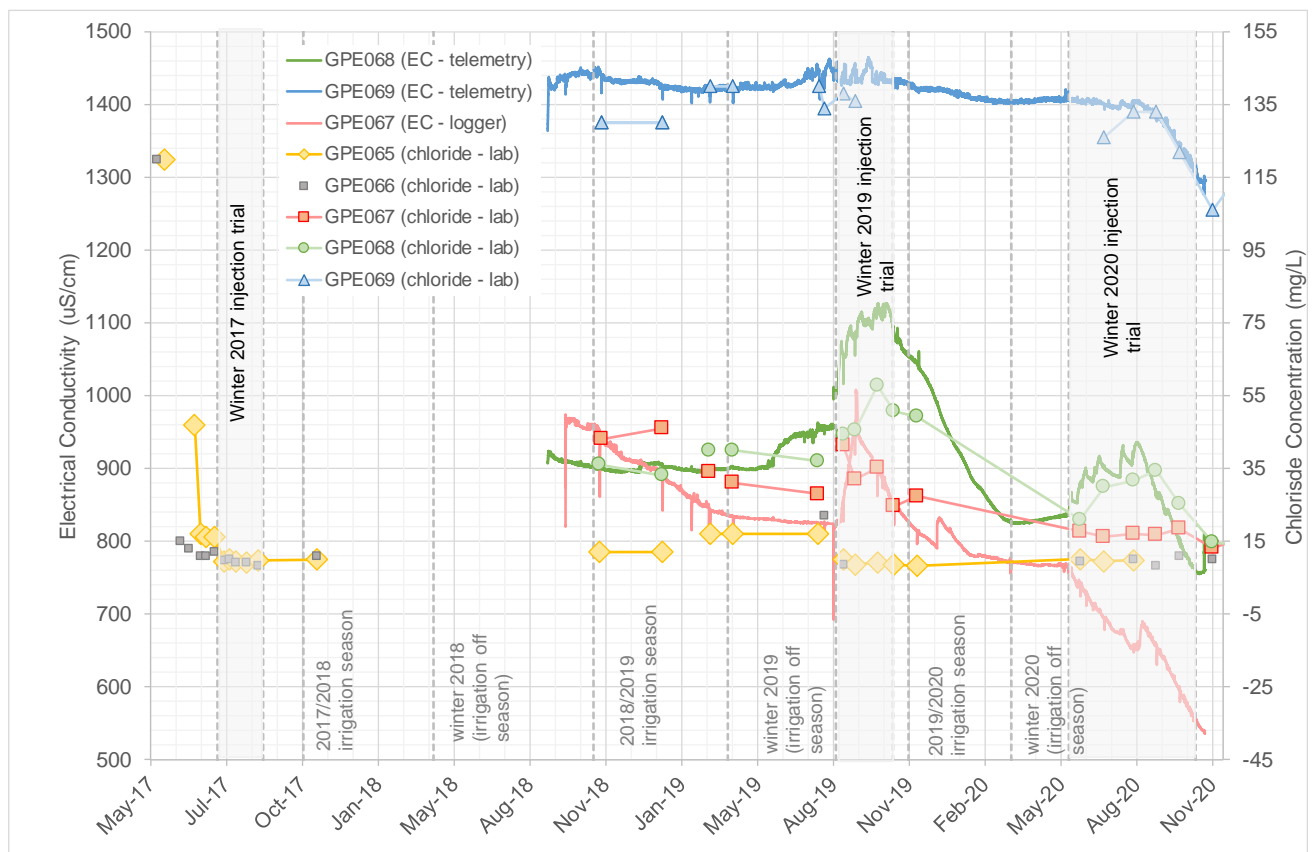
Figure 16: Gradual change in salinity expressed as EC and chloride - plume tracking.

A shift in water quality signature is observed in GPE067 in comparison to GPE068. A higher degree of dispersive mixing was observed in GPE067 than in GPE068 prior to March 2019, although GPE068 is at greater distance from injection well then GPE067. This has changed since November 2018, with GPE067 gradually becoming more akin to the injection water and GPE068 shifting to the water quality signature of ambient groundwater. This shift in water quality signature of GPE067 is caused by a change in direction of the 2017 injection plume due to summer abstraction for irrigation to the east of the MAR site. GPE067 was at the fringe of the injection plume in winter and spring 2018, but this shifted as the injection plume was drawn eastwards. During the 2019 and 2020 injection periods water quality in GPE067 becomes increasingly fresher and more so than GPE068. The salinity decreases observed during the Stage 2 trial were greater than the decreases seen in Stage 1 trial due to the larger volume of water injection. Concentration contours are conceptually depicted in Figure 17 below.
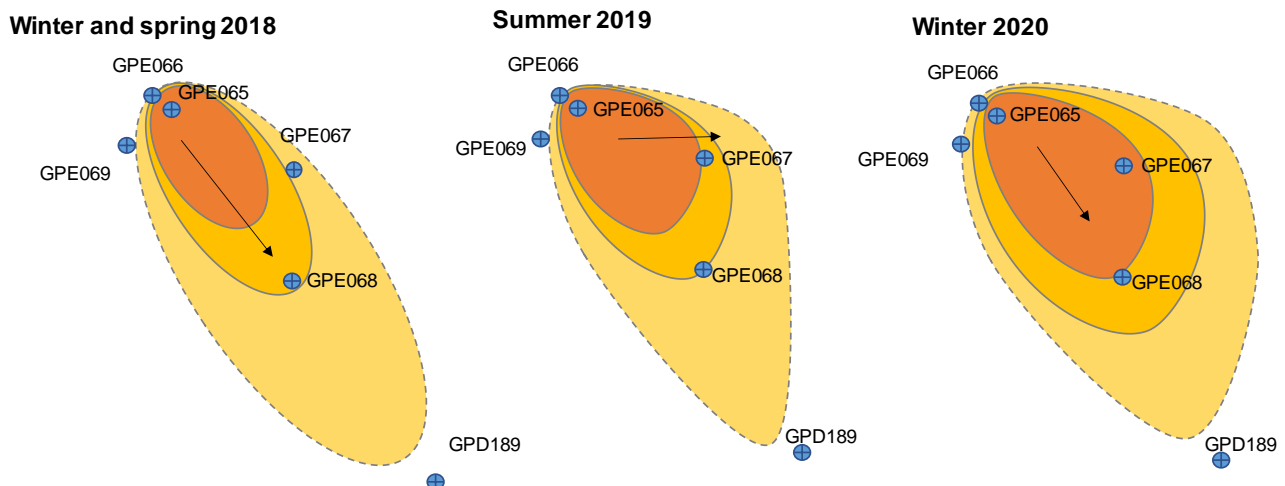
Figure 17: Schematic representation of injection plume development following the 2017 to 2020 injection trials (colour-shading indicatively represents concentration contours influenced by dispersive mixing).

The modelled extent of the injection plume as per December 2020 is shown as EC levels (in µS/cm) in Figure 18. The injection plume is approaching the general area of irrigation well GPD189 since the 2020 injection period, however, this well is likely screened in the underlying Matokitoki Aquifer and will not receive injection plume water.

Changes in hydrogeochemistry

Overall, due to the lower salinity of the river water compared to the ambient groundwater, the infiltration of river water has a freshening effect on the aquifer. This is illustrated by the more than ten times lower chloride concentrations in the river water as compared to the ambient groundwater. A detailed description of the relevant hydrogeochemical processes is included in Appendix C. A summary of key processes is provided below.

A confirmation of the active freshening of the aquifer sediments is the increase in sodium concentrations as the fresh river water displaces the more saline groundwater. This is the result of the sediment-sorbed sodium from the more brackish ambient groundwater being replaced by calcium which is higher in the river water.

With respect to carbonate and carbon dioxide (CO_2) gas clogging risks for groundwater abstraction wells, the infiltration of the river water will lower this risk as the infiltrated river water has a lower CO_2 pressure (atmospheric CO_2: ~0.04 %) compared to the elevated CO_2 pressure of about 10 % (based on PHREEQC calculations) in the ambient groundwater. The higher CO_2 levels in ambient groundwater are likely associated with methanogenesis, in which both methane and CO_2 are formed. In addition, since well clogging risks due to CO_2 degassing and carbonate scaling also depend on total gas pressure, the fact that atmospheric total gas pressure in the infiltrated river water is lower than in ambient groundwater (in which CO_2 and CH_4 are accumulated by methanogenesis) reduces the degassing risk to a very low level.

Gisborne MAR infrastructure and targeted Monitoring wells to track water quality and hydraulic response of injection trials

Legend

◌ Modelled Makauri groundwater level rise from MAR trial

● Injection well GPE066

◑ MAR monitoring wells

↔ MAR nearby monitoring well distances (m)

— MAR infrastructure (pipe line and river take)

— Roads

Modelled groundwater EC levels (uS/cm) for December 2020

■ <390
■ 390 to 600
■ 600 to 800
■ 800 to 1,000
■ 1,000 to 1,300
□ > 1,300 (background EC level)

GOLDER

TITLE

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\\Chc1-s-file02\chc_files\Projects-Dynamics\2014\7410\1415771_GDC_Stage II MAR Pilot\Data\Golder Data (Current)\GIS\MXD\Gisborne MAR - Fgi 16 MAR Overview Update - Dec2020.mxd
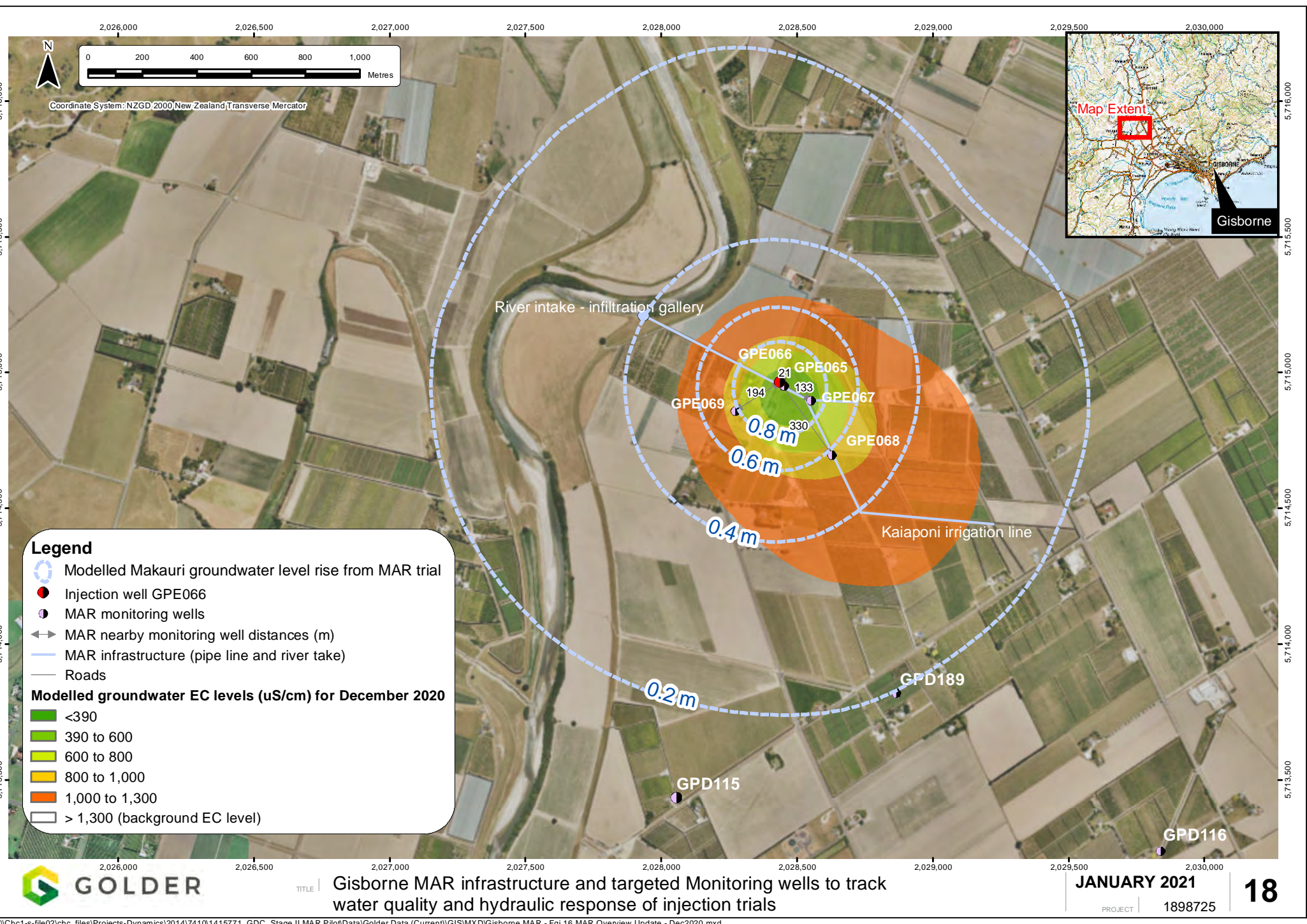
Results show that the main oxidants in the river water, since it is well oxygenated and contains some nitrate, are rapidly removed upon infiltration in the anoxic aquifer environment. There are no indications that this removal is caused by the oxidation of iron sulphides (pyrite) in the sediment, since there is no increase of sulphate observed, but instead a decrease that corresponds with the mixing of the river water with the sulphate-depleted ambient groundwater. Similarly, the concentrations of arsenic, a constituent that could be mobilised upon pyrite oxidation, do not increase during river water injection. Instead, the concentrations remain well below the concentrations in the ambient groundwater (~10 μg/L) and appear to be mainly controlled by the dilution of ambient groundwater by mixing with the infiltrated river water which is low in arsenic (<2 μg/L). No arsenic increase was recorded in groundwater during the previous injection trial in 2017. The only monitoring well in which a water quality change, caused by the injection trial could be recorded, was nearby well GPE065 (i.e., all other monitoring wells were too far away). A decrease in arsenic was observed in this well in all three injection trials in 2017, 2019 and 2020. This is because ambient groundwater has higher arsenic than the infiltration water.

For the continued injection of river water during full-scale MAR scheme operation, it is expected that for increasingly large parts of the aquifer, sodium concentrations due to freshening will go down to the level in the infiltrated river water, depending on the sorption capacity of the aquifer sediment. Cation exchange occurs on adsorption complexes within the aquifer. Calcium in the river water displaces sodium. The result is that downgradient from the injection well, the sodium concentrations initially go up, and then fall again once all sodium has been displaced from the adsorption complexes and the fresher injection water breaks through. The released sodium will migrate with the groundwater further downgradient and eventually discharge into the sea.

The oxidants in the infiltrated river water (i.e., oxygen and nitrate) are being removed by reacting organic matter in the aquifer' as these species will spread further into the aquifer, depending on the sediment reactivity. Nitrates broke down rapidly during the injection trials due to the presence of organic matter in the ambient groundwater (i.e., denitrification). This may however no longer occur within the injection plume once a full-scale MAR scheme has operated for a few years, as the injection plume will have the same water quality as the Waipaoa River. In comparison with many other rivers in New Zealand, the Waipaoa River nitrate-nitrogen levels (~0.3 mg/L) are relatively low.

Therefore, determining the sediment reactivity could be considered to better predict the rates of hydrogeochemical changes in the aquifer. Although pyrite oxidation does not seem to be responsible for the removal of the oxidants, assessing which processes are (e.g., organic matter or ferrous iron oxidation) will also be useful to better anticipate groundwater quality changes during full-scale MAR development.

In summary, well clogging from degassing of CO_2 (carbon dioxide) or CH_4 (methane) either of the injection well or downgradient water supply wells does not appear to be a risk at this site. There is no evidence of the mobilisation of arsenic, and this also does not appear to be a risk. Overall, the river water injection improves the Makauri aquifer water quality be making it fresher and less corrosive than ambient groundwater.

Pathogens

Several indicator pathogen parameters have been tested as part of Suite 4 of the Gisborne MAR monitoring programme, prior to and during the 2019 and 2020 injection periods. The results are included in Table 9.

Table 9: Pathogens test results 2019.

Component	Date	Adenovirus (presumptive) MPN/100 L	Enterococci cfu/100 mL	Escherichia coli cfu/100 mL	Faecal coliforms cfu/100 mL	Somatic coliphage PFU per 100 mL
Prior to 2019 MAR injection						
Waipaoa River Intake	22-07-19	<5.0	34	84	170	17
GPE066	22-07-19	<5.0	<1.6	<1.6	<1.6	11
GPE065	16-07-19	<5.0	8.2	<1.6	<1.6	7
GPE067	15-07-19	<5.0	<1.6	<1.6	<1.6	12
GPE068	15-07-19	<5.0	<1.6	<1.6	<1.6	-
GPE069	16-07-19	<5.0	<1.6	<1.6	<1.6	-
During 2019 MAR injection						
Waipaoa River Intake	16-08-19	<5.0	-	-	-	79
GPE066 (headworks)	16-08-19	<5.0	60	86	150	73
GPE065	16-08-19	<5.0	<1.6	<1.6	<1.6	<1
GPE067	16-08-19	<5.0	<1.6	<1.6	<1.6	<1
GPE068	16-08-19	-	-	-	-	-
GPE069	16-08-19	-	-	-	-	-
Waipaoa River Intake	28-08-19	-	-	-	-	3
GPE066 (headworks)	28-08-19	<5.0	4.9	23	64	3
GPE065	28-08-19	<5.0	1.6	<1.6	1.6	<1
GPE067	28-08-19	<5.0	<1.6	<1.6	<1.6	<1
GPE068	28-08-19	<5.0	-	-	-	-
GPE069	28-08-19	<5.0	<1.6	<1.6	<1.6	-
Waipaoa River Intake	25-09-19	-	-	-	-	3
GPE066 (headworks)	25-09-19	<5.0	1.6	<1.6	1.6	<1
GPE065	24-09-19	<5.0	<1.6	<1.6	<1.6	<1
GPE067	24-09-19	<5.0	<1.6	<1.6	<1.6	<1
GPE068	24-09-19	<5.0	<1.6	<1.6	<1.6	-
GPE069	24-09-19	<5.0	<1.6	<1.6	<1.6	-

Legend

Source water
Groundwater
Above detection limit
Not tested indicated as '-'

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Table 10: Pathogen test results 2020.

Component	Date	Adenovirus (presumptive) MPN/100 L	Enterococci cfu/100 mL	Escherichia coli cfu/100 mL	Faecal coliforms cfu/100 mL	Somatic coliphage PFU per 100 mL
Prior to 2020 MAR injection						
Waipaoa River Intake	14-10-19	-	-	-	-	890
GPE066 (headworks)	14-10-19	-	-	-	-	-
GPE065	14-10-19	<5.0	<1.6	<1.6	<1.6	<1
GPE067	14-10-19	<5.0	<1.6	<1.6	<1.6	<1
GPE068	14-10-19	<5.0	<1.6	<1.6	<1.6	-
GPE069	14-10-19	<5.0	<1.6	<1.6	<1.6	-
Waipaoa River Intake	06-05-20	-	2000	1400	1400	-
GPE065	06-05-20	-	<1.6	<1.6	<1.6	-
GPE067	06-05-20	-	<1.6	<1.6	<1.6	-
GPE068	06-05-20	-	<1.6	<1.6	<1.6	-
GPE069	06-05-20	-	<1.6	<1.6	<1.6	-
Waipaoa River Intake	12-05-20	-	-	-	-	66
GPE066 (headworks)	12-05-20	-	-	-	-	9
GPE065	12-05-20	-	-	-	-	<1
GPE067	12-05-20	-	-	-	-	<1
GPE068	12-05-20	-	-	-	-	<1
GPE069	12-05-20	-	-	-	-	<1
During 2020 MAR injection						
Waipaoa River Intake	26-05-20	-	-	-	-	-
GPE066 (headworks)	26-05-20	-	20	33	34	-
GPE065	26-05-20	-	<1.6	<1.6	<1.6	-
GPE067	26-05-20	-	*	<1.6	<1.6	-
GPE068	26-05-20	-	<1.6	<1.6	<1.6	-
GPE069	26-05-20	-	<1.6	<1.6	<1.6	-
Waipaoa River Intake	02-06-20	-	-	-	-	-
GPE066 (headworks)	02-06-20	-	-	-	-	-
GPE065	02-06-20	-	-	-	-	<1
GPE067	02-06-20	-	-	-	-	<1
GPE068	02-06-20	-	-	-	-	<1
GPE069	02-06-20	-	-	-	-	<1
Waipaoa River Intake	24-06-20	-	-	-	-	95
GPE066 (headworks)	24-06-20	-	-	-	-	-
GPE065	24-06-20	-	<1.6	<1.6	<1.6	<1
GPE067	24-06-20	-	<1.6	<1.6	<1.6	<1
GPE068	24-06-20	-	<1.6	<1.6	<1.6	<1
GPE069	24-06-20	-	<1.6	<1.6	<1.6	<1

Suspect result of 210 cfu/100mL of Enterococci reported by lab; not adopted as it appears to be an anomaly inconsistent with any other pathogen test results for groundwater in the 2018 – 2020 period.

Component	Date	Adenovirus (presumptive) MPN/100 L	Enterococci cfu/100 mL	Escherichia coli cfu/100 mL	Faecal coliforms cfu/100 mL	Somatic coliphage PFU per 100 mL
Waipaoa River Intake	29-07-20	-	-	-	-	11
GPE066 (headworks)	29-07-20	-	6.6	13	20	7
GPE065	29-07-20	-	<1.6	<1.6	<1.6	<1
GPE067	29-07-20	-	<1.6	<1.6	<1.6	<1
GPE068	29-07-20	-	<1.6	<1.6	<1.6	<1
GPE069	29-07-20	-	<1.6	<1.6	<1.6	<1
Waipaoa River Intake	26-08-20	-	220	600	650	96
GPE066 (headworks)	26-08-20	-	<1.6	56*	56*	44*
GPE065	26-08-20	-	<1.6	<1.6	1.6	<1
GPE067	26-08-20	-	<1.6	<1.6	6.6	<1
GPE068	26-08-20	-	<9.0*	<1.6	<1.6	<1
GPE069	26-08-20	-	<1.6	<1.6	<1.6	<1
GPD115	26-08-20	-	<1.6	<1.6	<1.6	-
Waipaoa River Intake	23-09-20	-	6.6	23	66	11
GPE066 (headworks)	23-09-20	-	<1.6	16	<1.6	<1
GPE065	23-09-20	-	<1.6	<1.6	<1.6	<1
GPE067	23-09-20	-	<1.6	<1.6	<1.6	<1
GPE068	23-09-20	-	<1.6	<1.6	<1.6	<1
GPE069	23-09-20	-	<1.6	<1.6	<1.6	<1
GPD115	23-09-20	-	<1.6	<1.6	<1.6	-
Waipaoa River Intake	02-11-20	-	21	33	70	-
GPE065	02-11-20	-	<1.6	<1.6	<1.6	-
GPE067	02-11-20	-	<1.6	26	25	-
GPE068	02-11-20	-	<1.6	<1.6	<1.6	-
GPE069	02-11-20	-	<1.6	<1.6	<1.6	-
GPD115	02-11-20	-	4.9	<1.6	<1.6	-
GPG060	02-11-20	-	<1.6	<1.6	<1.6	-
Waipaoa River Intake	01-12-20	-	410	250	310	-
GPE065	01-12-20	-	<1.6	<1.6	<1.6	-
GPE067	01-12-20	-	<1.6	<1.6	1.6	-
GPE068	01-12-20	-	<1.6	<1.6	<1.6	-
GPE069	01-12-20	-	<1.6	<1.6	<1.6	-
GPD115	01-12-20	-	<1.6	<1.6	<1.6	-

*headworks sample was taken during startup procedure when initial flows mostly go to waste – source water with listed concentration was injected for only 7 minutes.
**suspect test results as detection limit differ significantly from other test results.

The results indicate the pathogens can be present at significant levels in Waipaoa River water (i.e., the source water) abstracted by the Kaiaponi irrigation infrastructure. Elevated pathogen levels for Enterococci, E.*coli*, Faecal Coliforms and Somatic Coliphages (indicators of viruses) were recorded for some or all of these parameters in the MAR headworks in each sampling round of both the 2019 and 2020 injection periods, although at much lower levels than recorded in the Waipaoa River. This would have subsequently been injected into injection well GPE066. However, E.*coli* levels were below 100 cfu/100ml and as such the injection did not exceed compliance limits included in the resource consent.

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Pathogen contamination has been recorded in GPE065 and GPE067 in the 16 July 2019, 28 August 2019, 26 August 2020, 2 November 2020 and 1 December 2020 sampling rounds. No bacterial contamination has been recorded in GPE068 or GPE069 in any sampling round in 2019 and 2020.

Where pathogens are clearly present at high levels in Waipaoa River water on occasion, this is generally not the case in the groundwater monitoring wells located within the 2017, 2019 and 2020 injection plume, although some pathogens test positive in groundwater at low levels as previously reported. It appears the pathogens die off rapidly once injected.

Emerging contaminants

GDC has tested Waipaoa River and groundwater for several groups of 'emerging contaminants', including dioxins, personal care products & pharmaceuticals (PCP&P's), pesticides and other selected chemicals. Results for the July to September 2020 period are listed in Table 11.

Parameters tested positive (i.e., above detection limit) in the July to September 2020 period were caffeine, cotinine, paracetamol, triclosan, carbamazepine, lamotrigine, metaprolol, norcotinine, sulfamethoxazole, trimethoprim, diltiazem, glyphosate, AMPA, fluoxetine, and venlafaxine. Glyphosate is a pesticide, cotinine and norcotinine are found in tobacco products, caffeine is present in various beverages (such as coffee), and all other parameters listed are pharmaceuticals.

The emerging contaminants are encountered in the source water, in the injection plume (GPE065, GPE067 and GPE068), and in the upgradient monitoring well GPE069, which is likely to have represented ambient groundwater until plume breakthrough in August 2020 (although a small fraction of source water could have reached this well through dispersive mixing even before breakthrough was confirmed). The test results may suggest a rise in total emerging contaminant levels in the injection plume, although these are very low in both the Waipaoa River water and within the injection plume (i.e., in order of nanograms per litre [ng/L]).

Due to the erratic presence and human consumptive use of these compounds, these concentrations may have resulted from contamination during sampling and/or analysis or introduced during well installation. Norcotinine concentrations show very sharp rises and falls in the source water and all monitoring wells in the August to December 2020 sampling rounds, which cannot be explained by dispersive mixing processes. Natural decay would explain the results, but lab testing errors could not be ruled out either. However, the positive test results could also indicate the emerging contaminants have come from river injection water, from up-catchment sources. We do note that the Makauri Aquifer at the MAR site is confined by a silt and clay layer of approximately 40 m. As such, it is unlikely that the detected 'emerging contaminants' have entered the aquifer from the surface.

If emerging contaminants are present in the MAR source water (Waipaoa River) they will enter groundwater. If no natural decay occurs, these emerging contaminants will remain present within the injection plume which will grow ever large as the MAR progresses. With the Waipaoa River being a major natural source of recharge for the Makauri Aquifer it is inevitable that emerging contaminants will eventually enter the groundwater system via natural processes as well, and are likely to already be present in ambient groundwater. There is evidence of this, as emerging contaminants were consistently detected water samples from well GPD115, a Makauri Aquifer well located some 2 km south of the MAR site and well beyond the injection plume. In addition, upgradient well GPG060 has also tested above detection limit in the single sample taken from this well on 2 November 2020 (Table 11). No firm conclusions can be drawn from these initial test results other than that emerging contaminants, if present in source water, will enter the receiving aquifer, which is likely to have existing trace levels. Golder recommends a further review when more data is available across the wider catchment, including that of the Waipaoa River water.

Table 11: Emerging contaminants test results.

	Sample Date/Time	Caffeine (ng/L)	Cotinine (ng/L)	Paracetamol (ng/L)	Triclosan (ng/L)	Carbamazepine (ng/L)	Lamotrigine (ng/L)	Metaprolol (ng/L)	Norcotinine (ng/L)	Sulfamethoxazole (ng/L)	Trimethoprim (ng/L)	Diltiazem (ng/L)	Glyphosate (ug/L)	AMPA (ug/L)	Fluoxetine (ng/L)	Venlafaxine (ng/L)	Gemfibrozil (ng/L)	Triclocarban (ng/L)
Prior to 2019 MAR injection trial																		
GPE066 (headworks)	15-07-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	15-07-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	15-07-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	15-07-19	<0.5	27	9	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	16-07-19	<0.5	24	6	5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
During 2019 MAR injection trial																		
GPE066 (headworks)	14-08-19	7.4	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	14-08-19	2.3	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	14-08-19	9	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	14-08-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	15-08-19	3.4	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE066 (headworks)	28-08-19	1.9	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	28-08-19	3.9	2.8	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	28-08-19	4.3	2.3	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	28-08-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	28-08-19	2.8	4.9	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE066 (headworks)	24-09-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	24-09-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	24-09-19	24	<0.5	27	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	24-09-19	<0.5	<0.5	23	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	24-09-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20

Legend

Source water
Groundwater
Above detection limit

	Sample Date/Time	Caffeine (ng/L)	Cotinine (ng/L)	Paracetamol (ng/L)	Triclosan (ng/L)	Carbamazepine (ng/L)	Lamotrigine (ng/L)	Metaprolol (ng/L)	Norcotinine (ng/L)	Sulfamethoxazole (ng/L)	Trimethoprim (ng/L)	Diltiazem (ng/L)	Glyphosate (ug/L)	AMPA (ug/L)	Fluoxetine (ng/L)	Venlafaxine (ng/L)	Gemfibrozil (ng/L)	Triclocarban (ng/L)
Prior to 2020 MAR injection trial																		
Waipaoa River at infiltration chamber	14-10-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	14-10-19	149	6.8	58	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	14-10-19	19	9.4	1.7	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	14-10-19	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	14-10-19	25	8.3	3.4	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
Waipaoa River at infiltration chamber	06-05-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	06-05-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	06-05-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	06-05-20	10	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	06-05-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
During 2020 MAR injection trial																		
MAR headworks	26-05-20	3	10	<2	<0.5	<0.5	<0.5	<0.5	8	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	26-05-20	30	20	20	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	26-05-20	5	20	3	<0.5	<0.5	<0.5	<0.5	<1	<0.5	0.7	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	26-05-20	60	20	40	<0.5	<0.5	<0.5	<0.5	<1	0.9	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	26-05-20	20	20	10	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
MAR headworks	24-06-20	-	-	-	-	-	-	-	-	-	-	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	24-06-20	5	3	10	<0.5	1	40	0.9	5	2	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	24-06-20	3	5	6	<0.5	<0.5	3	<0.5	2	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	24-06-20	9	9	<2	<0.5	<0.5	0.9	<0.5	6	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	24-06-20	2	2	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
MAR headworks	29-07-20	3	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	29-07-20	2	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	29-07-20	4	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	29-07-20	3	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	29-07-20	3	<0.5	<2	<0.5	1	5	1	<1	0.8	0.9	1	<0.04	<0.04	<0.5	<0.5	<0.5	<20

GOLDER

	Sample Date/Time	Caffeine (ng/L)	Cotinine (ng/L)	Paracetamol (ng/L)	Triclosan (ng/L)	Carbamazepine (ng/L)	Lamotrigine (ng/L)	Metaprolol (ng/L)	Norcotinine (ng/L)	Sulfamethoxazole (ng/L)	Trimethoprim (ng/L)	Diltiazem (ng/L)	Glyphosate (ug/L)	AMPA (ug/L)	Fluoxetine (ng/L)	Venlafaxine (ng/L)	Gemfibrozil (ng/L)	Triclocarban (ng/L)
Waipaoa River at infiltration chamber	26-08-20	6	4	<2	<0.5	<0.5	<0.5	<0.5	<1	1	<0.5	<0.5	0.17	0.83	<0.5	<0.5	<0.5	<20
MAR headworks	26-08-20	5	6	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE065	26-08-20	3	3	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE067	26-08-20	30	3	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE068	26-08-20	4	2	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	26-08-20	5	2	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPD115	26-08-20	6	4	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
Waipaoa River at infiltration chamber	23-09-20	5	<0.5	<2	<0.5	<0.5	1	<0.5	100	<0.5	<0.5	<0.5	<0.04	<0.04	7	<0.5	<0.5	<20
MAR headworks	23-09-20	20	<0.5	<2	<0.5	<0.5	<0.5	<0.5	70	5	<0.5	<0.5	<0.04	<0.04	7	<0.5	<0.5	<20
GPE065	23-09-20	3	<0.5	<2	<0.5	<0.5	0.8	<0.5	60	<0.5	<0.5	<0.5	<0.04	<0.04	2	1	<0.5	<20
GPE067	23-09-20	20	<0.5	<2	<0.5	<0.5	<0.5	<0.5	80	<0.5	<0.5	<0.5	<0.04	0.36	5	<0.5	<0.5	<20
GPE068	23-09-20	5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	100	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	23-09-20	3	<0.5	20	<0.5	<0.5	<0.5	<0.5	80	4	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPD115	23-09-20	20	<0.5	10	3	1	1	<0.5	30	<0.5	<0.5	<0.5	<0.04	<0.04	1	<0.5	<0.5	<20
Waipaoa River at infiltration chamber	02-11-20	<0.5	0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	1	<0.5	<0.04	<0.04	1	<0.5	<0.5	<20
GPE065	02-11-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	1	<0.5	<0.5	<20
GPE067	02-11-20	20	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	0.6	<0.5	<0.5	<20
GPE068	02-11-20	20	<0.5	4	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	02-11-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPD115	02-11-20	9	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPG060	02-11-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	<1	<0.5	0.6	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
Waipaoa River at infiltration chamber	01-12-20	3	<0.5	<2	<0.5	<0.5	<0.5	<0.5	100	<0.5	3	<0.5	<0.04	<0.04	2	<0.5	0.9	<20
GPE065	01-12-20	2	<0.5	<2	<0.5	<0.5	<0.5	<0.5	100	<0.5	0.7	7	<0.04	<0.04	1	<0.5	<0.5	<20
GPE067	01-12-20	6	<0.5	<2	<0.5	<0.5	<0.5	<0.5	50	<0.5	5	<0.5	<0.04	<0.04	2	<0.5	<0.5	100
GPE068	01-12-20	6	0.5	<2	<0.5	<0.5	<0.5	<0.5	200	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPE069	01-12-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	100	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20
GPD115	01-12-20	<0.5	<0.5	<2	<0.5	<0.5	<0.5	<0.5	100	<0.5	<0.5	<0.5	<0.04	<0.04	<0.5	<0.5	<0.5	<20

3.5 Injection Well Performance

3.5.1 General

The injection and abstraction performance of the MAR injection well GPE066 can change over time, mostly indicated by an increase in drawdown (or mounding during injection) of the well water level in response to flow. Clogging can cause the performance to gradually deteriorate and periodic well inspection and remediation will be required (Section 3.5.2 below). Potential clogging occurs from the injection of sediment-laden water but could also be caused by the deposition of minerals such as iron sulphides on the well screen, as was confirmed to have occurred during the idle phase (i.e., October 2017 and August 2019), and was remediated by air-lifting in May 2019 (Section 3.5.2 below).

Well performance can be tested by the following tests:

■ Specific capacity testing

■ Stepped rate pumping testing (also referred to as 'stepped drawdown testing' or 'step test')

A more comprehensive well performance test is a stepped rate pumping test, which can also be undertaken by either injection or abstraction to test the well's performance. The flow rate (either for abstraction or injection) is increased in steps and kept stable for a certain period of time (e.g., 2 hours) during each step. The drawdown in the well is recorded. The data obtained from the stepped rate pumping test can be analysed and the well loss and aquifer loss components of the recorded drawdown. Ongoing clogging increases the well loss component.

Well performance testing is described in detail in Section 3.5.3 and 3.5.4.

Specific capacity testing

Reductions in well performance from clogging can be analysed by reviewing the specific capacity (SC in L/s/m) of the well, which equals the flow rate (Q in L/s) divided by the associated drawdown (dH in m):

$$SC = \frac{Q}{dH}$$

This is a relatively simple test to undertake and give a quick indication of changes in performance. The specific capacity can be tested by pumping from or injecting into the well for a period of time and recording flow rates and drawdowns. The specific capacity is often not constant during the test and different flow rates will result in different specific capacities. Therefore, ideally the results of tests of the same duration and same flow rate are compared.

The specific capacity for abstraction (i.e., the flow rate per metre drawdown) differs from the specific capacity for injection (i.e., the flow rate per metre rise) for most wells. Both can be tracked over time to review changes in well performance. To compare results, the specific capacity test has to be undertaken at similar flow rates and length of time.

A gradual decrease in specific capacity of the well can indicate the progression of well clogging. Most wells have different specific capacities for abstraction and injection. In general, abstraction specific capacities are higher.

3.5.2   Injection well inspection and maintenance

Prior to the 2019 injection period the well was inspected and tested, and subsequently the proposed upgrades described in Section 3.1 were implemented.

Camera inspection of the injection well on 26 April 2019, following lifting of the well head, riser pipe and pump on 17 April 2019, showed potential clogging of the injection well screen, which could lead to reduced performance.

Images from camera inspection footage and a photo of the pump after it was lifted are shown in the photos below. Both the well screen and the well pump show deposition or scaling of grey to black fine-grained material (Figure 19). Although the clogging material is clearly present on the well screen, it does not appear to have fully clogged the individual slots of the well screen. The grey/black material was sampled, and lab tested. Test results show the composition is predominantly iron. The clogging material is most likely formed by iron sulphide deposition, known to form black precipitates during sulphate reduction. The sulphur source is likely the injected river water as it has naturally high sulphate concentrations compared to no sulphate in the ambient groundwater. Since the injected surface water has very low iron, the iron source is likely the steel screen and pump materials themselves, indicative of a certain degree of corrosion occurring. Martin (2013) also points out that scale formation with iron sulphide is usually associated with corrosion problems.

The electro-chemical processes under which the iron sulphide is formed are different from those causing the precipitation of iron oxides, which typically leaves red staining on well casings and pumps. Iron oxide formation can occur if atmospheric air is drawn into the well casing from above during abstraction from the well. Dissolved iron concentrations in ambient Makauri Aquifer water that is within the general area around the MAR site are relatively high (~5 mg/L) and iron oxide precipitation is likely to occur 'naturally' in irrigation abstraction wells in the general area.

Figure 19: Well clogging photos of GPE066 in April 2019 (left: injection well screen; right: pump).

In May 2019 the injection well was re-developed with airlifting to remove the fine-grained sediment in the well by Honnor Well Drilling Ltd. Well performance testing was undertaken by GDC following completion of the re-development to assess current well performance and compare this with previous well performance data.

3.5.3 Abstraction performance of the well

Stepped rate pumping testing

Stepped rate pumping testing was undertaking on the injection well in May 2017, shortly after construction of the injection well (results shown in Table 12). This benchmarks the well performance to which future testing can be compared against. It was reported in Golder 2017 that towards the end of the test, dissolved gas within the aquifer water degassed when depressurised causing excessive drawdown and variation in flow rates of the test and subsequently this step was not assessed.

No stepped rate pumping testing was undertaken in 2019 following the well-redevelopment in May 2019. Well performance was assessed with specific capacity testing (described above). Specific capacities recorded in 2019 at flow rates around 15 L/s (i.e., 4.46 to 5.41 L/s/m) are higher than recorded in the stepped rate pumping test of 2017 at a flow rate of 13 L/s (i.e., 3.39 L/s/m). Comparing these results to Golder's 2017 stepped rate pumping test results, it appears well performance of the injection well had improved was due to redevelopment by airlifting to remove the clogging material has been largely successful at improving performance of the well.

A stepped rate pumping test (eight hours long with four steps of 120 minutes each) was undertaken in March 2020 (pre injection period) at well GPE066 by GDC (top graph in Figure 20 and Table 12). An additional stepped rate pumping test was undertaken on 22 October 2020 on well GPE066 by GDC after the 2020 trial period was completed. The bottom graph in Figure 20 shows the observed drawdown and flow rates of the October 2020 stepped rate pumping test (see also Table 14). At 15 L/s the specific capacity in the October 2020 step test is inferred to be 3.94 L/s/m, which is slightly less than recorded from the March 2020 specific capacity test (i.e., 4.10 L/s/m).

Comparing these results to Golder's 2017 stepped rate pumping test results, it appears well performance of the injection well has improved.
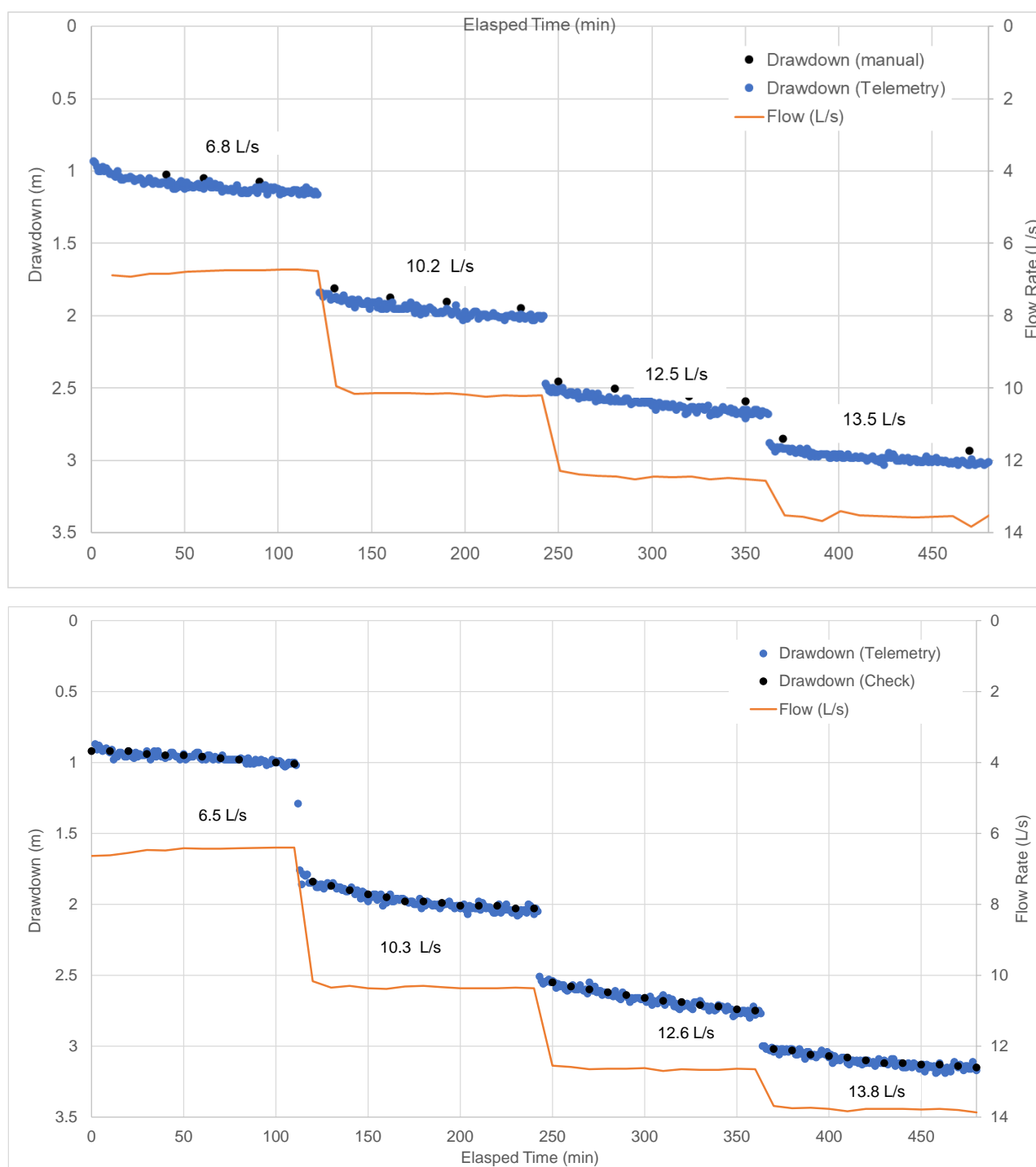
Figure 20: March 2020 (top pane) and October 2020 (bottom pane) stepped rate pumping test of injection well GPE066.

Table 12: Golder 2017 Stepped rate pumping test results of GPE066.

Step	Flow Rate (L/s)	Drawdown (m)	Specific capacity (L/s/m)
1	7	1.3	5.34
2	10	2.1	4.67
3	13	3.8	3.39
4	16	Not assessed	

Table 13: March 2020 Stepped rate pumping test results GPE066.

Step	Flow Rate (L/s)	Flow Rate (m³/day)	Drawdown (m)	Specific capacity (L/s/m)	Specific Drawdown (m/m³/day)	Apparent Efficiency %
1	7	588	1.14	5.96	0.0019	69
2	10	881	2.01	5.10	0.0023	60
3	12.5	1,080	2.67	4.68	0.0025	55
4	13.5	1,166	3.01	4.49	0.0026	53

Table 14: October 2020 Stepped rate pumping test results GPE066.

Step	Flow Rate (L/s)	Flow Rate (m³/day)	Drawdown (m)	Specific capacity (L/s/m)	Specific Drawdown (m/m³/day)	Apparent Efficiency %
1	6.5	560	1.01	6.41	0.0018	66
2	10.3	893	2.03	5.09	0.0023	55
3	12.6	1,092	2.75	4.59	0.0025	50
4	13.8	1,190	3.15	4.37	0.0026	48

The well efficiency at each step (which represents the portion of drawdown caused by laminar flow) was calculated at 48 % to 66 % for the October 2020 stepped rate pumping test, which is slightly less than the March 2020 stepped rate pumping test range of 53 % to 69 % (Table 13).

The injection of sediment-in river water is the main driver for clogging and slight reduction in well performance during that trial period. This underpins the importance of maintaining low turbidity of injected river water and frequent injection well backwashing for higher performance.

3.5.4   Injection performance of the well

No injection stepped rate pumping testing was undertaken on the well, and injection well performance was tested by deriving injection specific capacity testing from telemetered recordings of the 15-minute flow data.

Specific capacity over the entire 2019 and 2020 trial periods are plotted in Figure 21, together with the well turbidity data (1-minute data) as this represents the most dominant type of well clogging. The results suggest the following:

2019 injection trial period

- There is a general decline in specific capacity from 6 L/s/m at the beginning of the injection trial to approximately 3 L/s/m at the end. Injection flow rates varied from 15.5 L/s in the first half of the trial to 14.5 L/s in the second half of the trial.

- Over the five periods of injection during the 2019 trial, well backwashing between these periods of injection appear to have temporarily increased the specific capacity, but then decline rapidly.

- The injection specific capacity appears to decrease faster in each injection period.

Note that the temporary sudden spikes in specific capacity shown in Figure 21 (i.e., grey dots) are the results of temporary pressure responses from changes in flow rate and do not represent the actual specific capacity.

The results underpin the importance of controlling turbidity levels in the injection water to maintain well performance during injection. To minimise the risks of well clogging, periodic backflushing is recommended during the irrigation season when the well would be idle. During this idle there is also an opportunity to undertake trials to monitor the well performance.

2020 injection trial period

- During the 2020 injection trial, the specific capacity declined from ~4 L/s/m at the start in May 2020 to less than 2 L/s/m in June 2020.

- Since the well backwashing cycles, undertaken from July 2020 onwards, the injection specific capacity remained at above an average of ~2.4 L/s/m, with injection rates of ~15 L/s.

- Injection specific capacity was generally lower (~2 L/s/m) during the 2020 injection trial than in the 2019 injection trial (~3 L/s/m), however, flow rates were higher during the 2020 injection trial. The specific capacity is generally lower at higher injection rates, so a decline in the specific capacity at reduced injection rates would suggest ongoing well performance loss due to clogging.

Whilst some deterioration of injection well performance has occurred over the 2019 to 2020 period, it is considered that this deterioration is relatively minor (i.e., did not affect the volume that could be injected) and that the frequent backwashing during the second half of the 2020 injection trial has kept well performance stable.
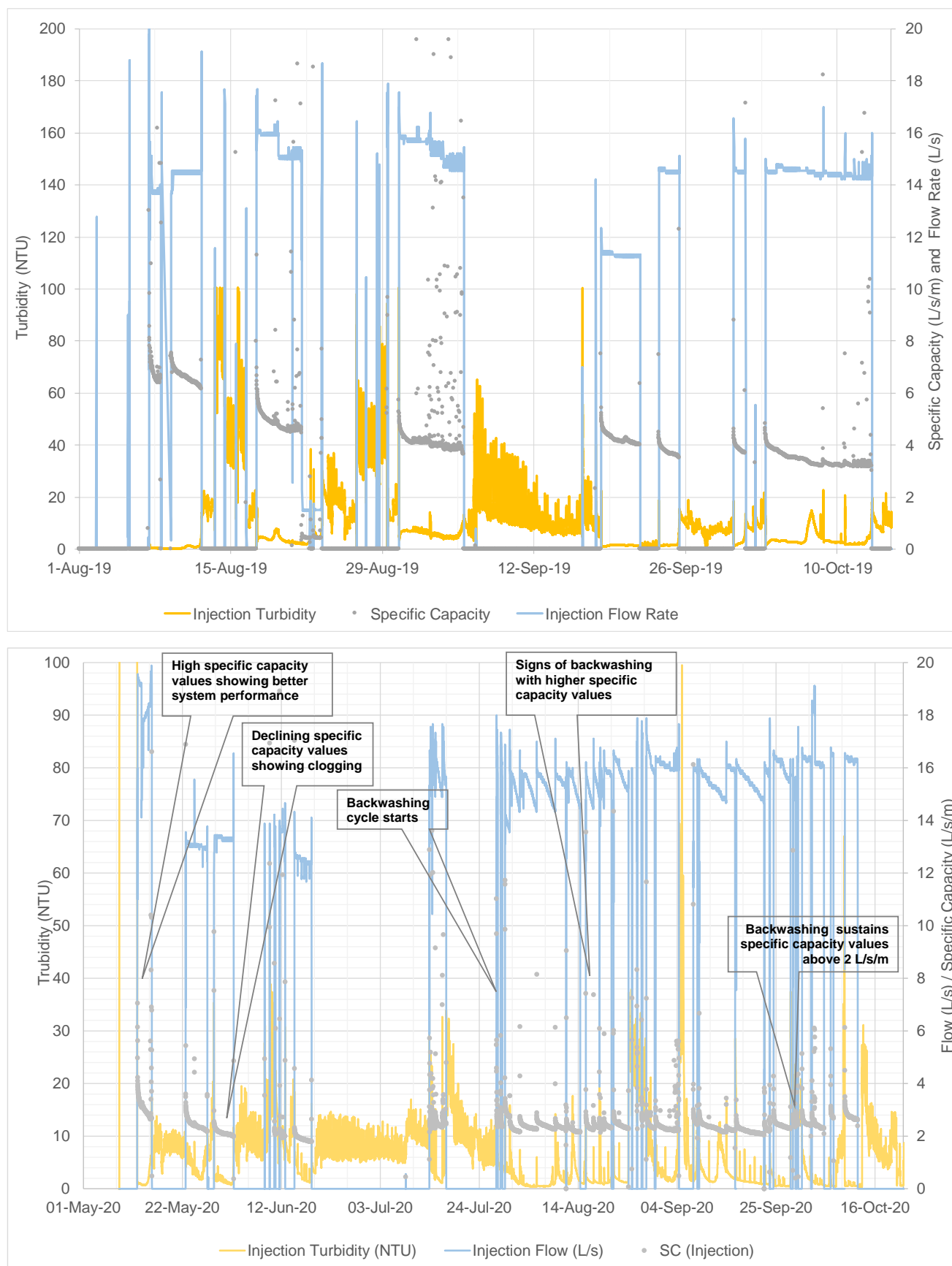
Figure 21: Injection specific capacity testing results for the 2019 injection trial (top pane) and 2020 injection trial (bottom pane).

3.5.5   Well and aquifer clogging

We have found no evidence of the aquifer being clogged or a decline in aquifer permeability during the Gisborne MAR injection trials, either by deposition with iron sulphides (which, in our view, are associated with well and pump material corrosion and may not occur in the formation), or entrainment of sediments in aquifer pore spaces. Airlifting prior to the 2020 injection trial seemed to have notably improved well performance. Furthermore, results from the stepped rate pumping tests prior to and after the 2020 injection, suggest only a small decrease in well performance. This suggests that clogging occurred mainly on the well screen and not within the aquifer. Aquifer clogging cannot be readily remediated with backflushing or airlifting of the well.

Literature on clogging with MAR systems confirms that aquifer clogging has been associated with recycled wastewater injection projects. This can result when microbes create a biofilm that reduces aquifer permeability (Pavelic et al 2008; Vanderzalm et al 2020). Pavelic (2008) also suggests that clay release due to the injection of low salinity water can result in rapid declines in permeability in brackish aquifers that contain reactive clays minerals. Neither of these seem applicable as the Gisborne MAR project, which involves injection of relatively clean river water into the highly permeable Makauri aquifer formed by largely free gravels.

Nonetheless, Semiromi & Ghasemian (2018) report that clay-sized suspended solids were found to be the most important determining factor in physical clogging occurrence of MAR systems when these migrate into the receiving aquifer material. As such, it is important to have low levels of the finest fractions of the suspended sediments (i.e. clay sized fraction) within injection source water. For a full-scale MAR scheme, the existing Arkal filter system's performance would need improving, or else alternative methods be employed (including the use of sedimentation ponds) for pre-treatment of River water prior to injection.

In regard to injection well performance, a key outcome of the three years of injection trials, is that well clogging could be managed through backflushing and if required scheduled well maintenance (before the next injection season). Techniques such as air lifting, surging with a surge block or over-pumping of the injection well to remove any clogging have all been shown to restore well performance and injectivity.

3.6   Assessment of Compliance with Resource Consent

An overview of conditions for resource consent, DW-2016-107113-01 and WS-2016-107114-01, being water take and discharge of water from the Waipaoa River to the Makauri Aquifer through an injection bore for a Managed Aquifer Recharge Trial is provided below (revised from WS-2016-107114-00 and DW-2016-107113-00).

3.6.1   Compliance of the 2017 Injection Trial

Compliance has been reported in Golder (2017a). No injection trial was undertaken in 2018.

3.6.2   Compliance of the 2019 Injection Trial

Compliance with conditions (written in italics below) in relation to the main injection trial are commented on (in brackets) and include the following matters:

■   Surface Water Take and Use – the conditions (16. to 23.) stated in the resource consents have been met (fully complies):

▪   *"With the daily quantity of water taken from Waipaoa River for the purposes of the pilot trial did not exceed 1,901 cubic metres"* (Daily maximum volumes range from 1,262 to 1,378 cubic metres are within the consented limit).

- *"The instantaneous rate of take from the Waipaoa River did not exceed 22 litres per second at any time"* (The rate of take varies from 11.3 to 16 litres per second during Phase 2 of the injection trial, within the consented limit. Records at the flow meter on 1 and 2 September 2019 shows anomalies with bursts from 50 to 350 litres per second, but the system is physically not capable of accepting those rates and these are considered as instrumentation malfunction in records.)

- *"With the abstraction from the Waipaoa River only occurred during periods when the flow at Kanakanaia is greater than 4,000 litres per second, and when it has been at or below 4,100 litres per second for a consecutive period of 5 or more days."* (The flow recorded at GDC's Waipaoa River flowmeter at Kanakanaia between 1 August and 15 October 2019 was between 8,675 L/s and 92,322 L/s, hence always above the minimum flow requirement for abstraction. Median flow was 16,031 L/s in that period).

- *"With water only used for the purpose of completing at the Phase 2 pilot trial of injecting water into the Makauri Aquifer."* (Water was taken only during the trial period from 7 August to 13 October 2019 for injection purpose. The injection and taking of water have been undertaken as authorised by GDC.)

- *"With the total volume of water abstracted from the Waipaoa River under this consent not exceeding 378,000 cubic metres per year."* (The total injection volume for 2019 of 39,852 cubic metres, below the annual consented limit.)

- *"With surface water abstraction shall only occur from the infiltration gallery as detailed in the application for this consent."* (Conditions met with the injection and taking of water undertaken as authorised by GDC.)

- *"Should adverse effects in the Waipaoa River or Makauri Aquifer be identified, then the injection or taking of water by this permit shall only occur as specifically authorised by the GDC Manager."* (No adverse effect was recorded.)

■ *"Water Use Monitoring – conditions (24. to 26.) GDC monitors the river take and injection with water meters on each pump which provide telemetric instantaneous readings at 1 minute interval (www.envirodata.co.nz)."* (It fully complies as daily flow records have been kept and provided to GDC which allows for compliance and calibration of instrumentations.)

■ *"Discharge of Water to Makauri Aquifer Conditions – conditions (27. to 32.)"* (partially complies):

- *"The rate of water injected into the Makauri Aquifer did not exceed 22 litres per second and the total volume of water injected under this consent shall not exceed 365,000 cubic metres per year for two years."* (The rate of take matches the rate of water injected during Phase 2 of the injection trial and also varies from 11.3 to 16 litres per second. Recorded bursts from 50 to 350 litres per second are considered faulty readings and do not represent actual injection flows.)

- *"The injection of water into the Makauri Aquifer and associated controls and monitoring shall be undertaken in general accordance with the Australian Guidelines for Water Recycling (AGWR) – Managed Aquifer Recharge document number 24 (July 2009)."*

  (MAR infrastructure, injection trial programme and associated monitoring is in general accordance with AGWR guidelines, thus fully complies.)

  "Water was only injected into the Makauri Aquifer via the injection bore GPE066 authorised under this consent. The consent holder GDC installed a suitable filter/s inline before injection water enters the Makauri aquifer to treat water prior to injection." (Fully complies)

- ▪ *"Discharge limits have complied during Phase 2 of the injection trial (2019):*

  (a) A concentration of E. coli of 100 cfu/100ml; and

  (b) Turbidity of 50 NTU; or"

  (Partially complies: field testing results indicate pathogens (E. *coli*) are present at significant levels in Waipaoa River water abstracted at the river intake pre- and post-2019 trial. Monitoring at GPE066 (injection headworks) shows exceedance during the trial (16 and 28 August 2019) during two sampling runs out of four in the course on the injection trial. No bacterial contamination has been recorded in GPE065, GPE067, GPE068 and GPE069 (see Section 3.4 for details) during trial sampling run. Turbidity automated field testing of the injection water pre- and post-2019 trial (see Section 3.5) recorded values generally below 50 NTU. No persistent exceedance of the consent limit has been recorded.)

- ▪ No amended limits were sought for the 2019 Stage 2 injection trial.

- ■ Pilot Trial Monitoring and Reporting – This report fulfils the requirements under conditions for resource consent DW-2016-107113-01 and WS-2016-107114-01 and the list of the 2018-2019 monitoring reports fully complies (*fully complies*):

  - ▪ Golder 2018. Gisborne MAR Stage 2 Injection Trial – Monthly Monitoring Report – December 2018. Letter-report 1898725-7403-005-LR-Rev1. December 2018.

  - ▪ Golder 2019. Review of Managed Aquifer Recharge Infrastructure. Gisborne District Council Poverty Bay MAR Pilot Trial. Report 1898725-7403-004-R-Rev0. February 2019.

  - ▪ Golder 2019. Gisborne MAR Stage 2 Injection Trial – Monthly Monitoring Report – August 2019. Letter-report 1898725-7403-007-LR-Rev0. September 2019.

  - ▪ Golder 2019. Gisborne MAR Stage 2 Injection Trial – Injection Well Specific Capacity Testing During Idle Phase. Letter-report 1898725-7403-008-LR-Rev0. October 2019.

3.6.3   Compliance of the 2020 Injection Trial

Compliance with conditions (written in italics below) in relation to the main injection trial are commented on and include the following matters:

- ■ Surface Water Take and Use – the conditions (16. to 23.) stated in the resource consents have been met (fully complies):

  - ▪ *"With the daily quantity of water taken from Waipaoa River for the purposes of the pilot trial did not exceed 1,901 cubic metres"*

    River abstraction rates have been below 1,901 m^3/day at all times during this monitoring period.

  - ▪ *"The instantaneous rate of take from the Waipaoa River did not exceed 22 litres per second at any time"*

    River abstraction rates from the 1-minute readings have exceeded the rate of 22 L/s at 123 occurrences between 13 July 2020 and 2 October 2020. However, river abstraction rates from the 15-minute readings have exceeded the rate of 22 L/s four times between 25 and 27 August 2020, and on 7 September 2020 for less than 15 minutes. River flows during those periods were well above 4,000 L/s (between 26,000 and 53,000 L/s) during the 2020 injection trial.

- ▪ *"With the abstraction from the Waipaoa River only occurred during periods when the flow at Kanakanaia is greater than 4,000 litres per second, and when it has been at or below 4,100 litres per second for a consecutive period of 5 or more days."*

  During the 2020 injection trial the river abstraction has taken place when river flows was above 4,000 L/s most of the time. However, at the start of the monitoring period, between 12 and 14 May 2020 river flows were below 4,000 L/s in the Waipaoa River at both the Kanakanaia and Matawhero flow monitoring sites. Approximately 4,000 m^3 was abstracted from the river during those 2 days.

- ▪ *"With water only used for the purpose of completing at the Phase 2 pilot trial of injecting water into the Makauri Aquifer."*

  Water was taken only during the trial period from 12 May to 12 October 2020 for injection purpose. The injection and taking of water have been undertaken as authorised by GDC.

- ▪ *"With the total volume of water abstracted from the Waipaoa River under this consent not exceeding 378,000 cubic metres per year."*

  The total injection volume for 2020 of 104,557 cubic metres, below the annual consented limit.

- ▪ *"With surface water abstraction shall only occur from the infiltration gallery as detailed in the application for this consent."*

  Conditions met with the injection and taking of water undertaken as authorised by GDC.

- ▪ *"Should adverse effects in the Waipaoa River or Makauri Aquifer be identified, then the injection or taking of water by this permit shall only occur as specifically authorised by the GDC Manager."*

  No adverse effect was recorded.

As such, this injection trial did not fully comply with conditions 16 to 19 of the resource consent.

- ■ *Condition 20 - Water shall only be used for the purpose of completing Phase 2 pilot trial of injecting water into the Makauri Aquifer, or in the case of discharging water to land in accordance with the resource consent application document.*

  All water abstracted from the river for the Gisborne MAR injection trial has been used for that purpose at all times during this monitoring period.

- ■ *"Water Use Monitoring – conditions (24. to 26.) GDC monitors the river take and injection with water meters on each pump which provide telemetric instantaneous readings at 1 minute interval (www.envirodata.co.nz)."*

  It fully complies as daily flow records have been kept and provided to GDC which allows for compliance and calibration of instrumentations.

- ■ *"Discharge of Water to Makauri Aquifer Conditions – conditions (27. to 32.)"* (partially complies):

  - ▪ *"The rate of water injected into the Makauri Aquifer did not exceed 22 litres per second and the total volume of water injected under this consent shall not exceed 365,000 cubic metres per year for two years."*

    As stated above, river abstraction rates from the 1-minute readings have exceeded the rate of 22 L/s at 123 occurrences between 13 July 2020 and 2 October 2020. However, river abstraction rates from the 15-minute readings have exceeded the rate of 22 L/s four times between 25 and 27 August

2020, and on 7 September 2020 for less than 15 minutes. These rates were recorded during injection start-ups. The maximum injection rate was 19.9 L/s.

▪ *"The injection of water into the Makauri Aquifer and associated controls and monitoring shall be undertaken in general accordance with the Australian Guidelines for Water Recycling (AGWR) – Managed Aquifer Recharge document number 24 (July 2009)."*

MAR infrastructure, injection trial programme and associated monitoring is in general accordance with AGWR guidelines, thus fully complies.

▪ "Water was only injected into the Makauri Aquifer via the injection bore GPE066 authorised under this consent. The consent holder GDC installed a suitable filter/s inline before injection water enters the Makauri aquifer to treat water prior to injection."

Fully complies, as GDC has installed an Arkal filter bank which treats the water before injection. However, it is noted that the filter bank may not work properly.

▪ *"Discharge limits have complied during Phase 2 of the injection trial (2019):*

(a) A concentration of E. coli of 100 cfu/100ml; and

(b) Turbidity of 50 NTU; or

(c) Any amended limit(s) adjusted with the approval of an independent and suitably qualified and experienced professional and certified by the GDC Manager. "

There have been no instances in which water with E.coli levels of above 100 cfu/100 ml (as recorded in the MAR headworks) or turbidity above 50 NTU have been injected into the Makauri Aquifer during this monitoring period.

No amended limits were sought for the 2019 Stage 2 injection trial.

As such, this injection trial did not fully comply with conditions 27 to 32 of the resource consent.

■ Pilot Trial Monitoring and Reporting – This report fulfils the requirements under conditions for resource consent DW-2016-107113-01 and WS-2016-107114-01 and the list of the 2020 monitoring reports fully complies (*fully complies*):

▪ Golder 2020. Gisborne MAR Stage 3 Injection Trial – Interim Monitoring Report – August 2020. Letter-report 1898725_7403-012-LR-Rev1. August 2020.

▪ Golder 2020. Gisborne MAR Stage 3 Injection Trial – Interim Monitoring Report – December 2020. Letter-report 1898725_7403-013-L-Rev0. December 2020.

4.0   FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

4.1   Groundwater System and Trends

Golder draws several key conclusions following a review of geological information and groundwater level and water quality data, and completion of catchment-wide numerical groundwater modelling:

■ The shallow fluvial deposit and Te Hapara sands form one aquifer (i.e., they are not laterally separated by a low permeability layer, although there are some differences in hydraulic conductivity) which is recharged mainly from rainfall recharge, and some inflow from infiltrating streams that run off from the western and eastern hills. The Waipaoa, Makauri and Matokitoki aquifers are recharged predominantly

from the Waipaoa River in the upper catchment around the Kaitaratahi township, and some rainfall recharge through the uppermost aquifer near the hill sides. This is where the confining layers are much thinner, and the aquifers come closer to the surface. There is also evidence of deep inflow into the Poverty Bay Flat aquifer system along its north-eastern boundary (near the eastern hills), from transmissive fault zones in the structural geology that comprise the eastern hills.

- The Poverty Bay Flat aquifers are likely to extend beneath the bay area where they 'pinch out' a few hundred metres to a few kilometres offshore. This is supported by bore logs of several near-coastal wells. Therefore, all three aquifers discharge into the sea beneath the Poverty Bay, but some Waipaoa and Makauri aquifer water could seep into coastal streams and rivers, such as the Waikanae Creek and Taruheru River.

- Abstraction predominantly for irrigation has a significant influence on groundwater levels in the summer, effectively forming a large 'sump' in the central area during summer. Groundwater is gradually drawn towards the area in the summer, although cessation of pumping over winter and natural groundwater recharge restore the groundwater levels to its unmodified flow pattern. Current abstraction from the Poverty Bay Flat aquifer system is in the order of 1 Mm^3/year, but this varies from year to year driven by seasonal weather conditions (i.e., evapotranspiration rates).

- Various researchers have investigated the long-term trends in aquifer water levels. Barber (1993) and White et al (2012) conclude there is a long-term decline in aquifer levels in the Poverty Bay Flat. Williams (2019) also acknowledges a decline for some periods in the past but concludes the groundwater levels are generally stable in the last few years. Golder considers it would be more useful to consider groundwater level trends over a longer term than a few years. A long-term decline of Makauri Aquifer water levels in past few decades does not appear to be disputed.

- Groundwater quality appears to be gradually changing in the Poverty Bay aquifer system, in particular the salinity. Groundwater salinity is gradually increasing in most Makauri aquifer wells to the south and west of the main irrigation area (i.e., saline intrusion), where some freshening seems to occur to the southeast. It is likely the heavy abstraction for irrigation in the central area has caused or at least exacerbated the ongoing increasing salinity trends. If these trends continue, it is anticipated that a much larger part of the Makauri aquifer beneath the Poverty Bay Flat would become more saline.

- By infiltrating river water into the Makauri aquifer, a full-scale Managed Aquifer Recharge (MAR) application is expected to compensate for the over-abstraction and mitigate the deterioration of abstracted groundwater quality. However, a full-scale MAR system layout needs to be optimally designed to achieve the desired outcome and ensure the best cost-benefits are achieved. This is particularly crucial if a water quality improvement is a key objective.

4.2   MAR Injection Trial Results

Following an injection trial in 2017 to assess the technical feasibility of MAR to augment the Makauri Aquifer, another injection trial was completed in winter 2019 and in autumn to spring 2020. No injection has been undertaken in the winter 2018 between cessation of the 2017 trial Stage 1 on the 13 September 2017 and the start of the Stage II injection trial on 7 August 2019. Additional monitoring wells were installed, and a monitoring programme was developed to collect data and information required to assess effects on groundwater levels, flows and water quality of the 2017, 2019 and 2020 injection trials. Key conclusions from the MAR injection trial are as follows:

- A total of 39,881 m^3 was injected in 2019, which is less than the 73,180 m^3 injected in 2017. Temporary cessation of injection for well backwashing was required for all three trials in 2017, 2019 and 2020. However, during the most recent in 2019 and 2020 trials both injection pressure and turbidity

downstream of the Arkal filter bank triggered several backwashing cycles, mainly due to stricter trigger level conditions. This limited the injection period and thus total amount that could be injected in particular for the 2019 trial. Nonetheless, the MAR injection system performed as expected and some changes to the operational procedures (e.g., revising injection pressure trigger levels upwards to avoid frequent unnecessary triggering, injection at end of irrigation season when aquifer water levels are low allows for higher injection pressures and thus higher rates) could achieve higher average injection rates and total injection volume.

■ The 2019 and 2020 MAR injection causes groundwater levels to clearly rise in all four monitoring wells and in the injection well itself, similar to the rises observed in the 2017 injection trial. It is estimated that the distance from the injection well in which a noticeable rise would occur to be about 1.5 km.

■ The injection of river water into the Makauri Aquifer during the MAR trials will result in a localised change in groundwater quality as the river water has a different composition as the ambient groundwater in the Makauri Aquifer. An injection plume forms around the injection well. The lateral extent and shape of the injection plume will gradually change under the influence of nearby irrigation, which modifies groundwater flow directions. This is reflected in observed fluctuations of groundwater salinity levels (recorded as EC) in the designated monitoring wells. As such, EC forms a good indicator for plume tracking.

■ Hydrogeochemical reactions in response to injecting river water and mixing this with Makauri Aquifer have been assessed. Well clogging from degassing of CO_2 (carbon dioxide) or CH_4 (methane) either of the injection well or downgradient water supply wells does not appear to be a significant risk at this site. There is no evidence of the mobilisation of arsenic, and this does not appear to pose a risk to water quality. Overall, it is concluded that the river water injection improves the Makauri aquifer water quality be making it fresher and less corrosive than ambient groundwater.

■ Where pathogens are clearly present at high levels in Waipaoa River water, this is not the case in the groundwater monitoring wells located within the 2017, 2019 and 2020 river water injection plume, although some pathogens tested positive at low levels within groundwater near to the injection well. It is concluded that the pathogens are likely to die off rapidly once injected into the groundwater system.

■ GDC has tested Waipaoa River water and injection plume groundwater for several groups of 'emerging contaminants' including dioxins, personal care products & pharmaceuticals (PCP&P's), pesticides and some other chemicals. Parameters tested positive (i.e., above detection limit) in the July to September 2020 period were caffeine, cotinine, paracetamol, triclosan, carbamazepine, lamotrigine, metaprolol, norcotinine, sulfamethoxazole, trimethoprim, diltiazem, glyphosate, AMPA, fluoxetine, and venlafaxine. If emerging contaminants are present in the MAR source water (Waipaoa River) they will enter groundwater. With the Waipaoa River being a major natural source of recharge for the Makauri Aquifer it is inevitable that emerging contaminants will eventually enter the groundwater system via natural processes as well and are likely to already be present in ambient groundwater. The presence to emerging contaminants in wells GPD115 and GPG060, both located outside of the MAR injection plume, confirm this.

■ Inspection of the injection well and pump on 26 April 2019, showed material had formed on the injection well screen after the well had been idle for almost 2 years. This could potentially lead to reduced well performance due to clogging. The material is most likely formed by iron sulphide deposition associated with corrosion of the well and pump, and this process is not likely to occur in the aquifer. The well was subsequently redeveloped with airlifting. Well performance testing showed that the redeveloped was largely successful at improving performance of the well.

■ However, well clogging by sediments in the source water does appear to affect well performance during the 2019 and 2020 injection periods. Well backwashing between periods of injection during 2019 and 2020 appear to have temporarily increased the well performance followed by an initially rapid decline and then a more stable well performance. The results underpin the importance of controlling turbidity levels in the injection water (i.e., source water) to maintain well performance during injection and minimise risks of aquifer clogging. Further improvement of sediment removal by improving the Arkal filter performance or other options (including the use of sedimentation ponds) for pre-treatment of source water, is recommended.

■ All injection trial test results have been reviewed and compliance with resource consent has been assessed. It is concluded that the 2019 injection trial generally complied with the conditions of consent. The 2020 injection period did not fully comply during the initial stages, but generally complied thereafter.

4.3   Recommendations

Golder recommends expanding the Gisborne MAR project by investigating different MAR options and how these could achieve the desired water management outcomes. This should include testing various concept by modelling, but also further physical MAR trials are recommended. Specific recommendations are as follows:

■ Derive the optimal MAR scheme layout via further stakeholder engagement to meet the desired outcomes of a scheme including water quality, quantity, and stream and spring flows enhancement. This is also recommended to ensure candidate options take into account cultural values of local Iwi.

■ Further investigation to manage high turbidity of source river water, thus minimising risks to abstraction infrastructure and groundwater quality, and enable more water to be injected.

■ Targeted geological investigations, such as core drilling and geophysical exploration to confirm the extent and thicknesses of the aquifers and confining layers. This would better inform the ability of various MAR options (passive infiltration basins versus extraction wells) to augment the aquifers.

■ Determination of the sediment reactivity would better predict the rates of hydrogeochemical changes in the aquifer. A more comprehensive hydrogeochemical analysis (i.e., a 'Stuyfzandt classification' based on aquifer water quality data) would confirm and quantify ongoing saline intrusion and freshening processed in the Poverty Bay Flat aquifers. This can be used to better understand how a full-scale MAR scheme can be implemented and managed to achieve the desired water quality outcomes.

■ To develop and implement a well maintenance programme to ensure the MAR injection well performance is sustained. To minimise the risks of well clogging, periodic backflushing is recommended during the irrigation season when the well would be idle.

■ All three the 2017, 2019 and 2020 injection plumes are still present near the MAR injection well, and the hydraulic and water quality responses within the aquifer continuous to evolve. Water level and water quality monitoring should continue to confirm potential effects.

■ Undertake modelling-based assessment of identified candidate MAR scheme layout options and associated cost-benefit and net present value analysis allowing for capital and operational costs. This could be extended to include comparisons to conventional centralised storage dam and on-site storage options.

■ Reconsider using the Waipaoa Augmentation Plant for further MAR injection trials and potential upscaling of the Gisborne MAR project. The water treatment facilities at this plant could be used to improve source water quality prior to injection.

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APPENDIX A

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APPENDIX B

Gisborne Groundwater Model
Description

Software

The Gisborne groundwater model is constructed as a MODFLOW-2005 model using the Groundwater Vistas V7 modelling package. Groundwater Vistas was developed by Environmental Simulations Inc (1996 - 2011). The MODFLOW source code was developed by the USGS (1988). This is a widely used, industry standard, three-dimensional numerical groundwater modelling tool.

The 3D geological model was developed with MAPTEK Vulcan developed by MAPTEK, a widely used geological modelling tool in the mining industry.

Model State

The groundwater model (see Figure B1 below) has been designed and structured to simulate a steady state and transient flow field through the area of interest that reflects the observed groundwater gradients, interpreted groundwater sources and outflow zones from the model. The Gisborne groundwater model has been updated in 2019, resulting in version 4 ('V4') which has been used for the MAR trials investigations. The following updates have been applied:

- Layer refinement in the uppermost lithological units, from a 5 to a 6-layer model.

- Rainfall recharge is discretised based on land use categories.

- The geological model has been updated with additional bore log information (i.e., from newly installed monitoring wells for the Gisborne MAR project), and a reinterpretation of various bores logs has been made to better represent geological conditions.

- The deep groundwater inflow from the eastern hills into the Matokitoki and Makauri aquifers has been incorporated into the model.

- A further optimisation of the model has been undertaken to improve the accuracy of groundwater level and flow simulations.

Apart from the Waipaoa River, the surface water boundary conditions (i.e., other rivers, streams, land drains and the sea) applied to the model do not reflect seasonal variations, but rather represent an average condition for each boundary. On this basis, the model does not fully simulate catchment-wide dynamic groundwater and surface water interaction, but rather a simulation set up specifically for the purpose of evaluating groundwater flow directions within the Waipaoa River coastal catchment on the Poverty Bay Flat.

Model Area and Grid Structure

The model area is shown in the overview map presented in Figure B1. It covers an area of approximately 29 km by 16 km (totalling 168,099,113 m^2). The model cell sizes vary from 67.5 m by 67.5 m in the outer areas to 10 m by 10 m in the area around the Gisborne MAR injection well GPE066. The model has a total of 696,156 active cells.

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Figure B1: Gisborne groundwater model area.

Model Layers

The model has 6 layers that represent the local aquifers as follows:

■ Layer 1: Unconfined aquifer: combines the Te Hapara sand / shallow fluvial aquifers as well as the 1st confining layer, forming the uppermost lithological units.

■ Layer 2; Waipaoa gravel aquifer.

■ Layer 3: Aquitard: 2nd confining layer separating the Makauri Aquifer from overlying aquifers.

■ Layer 4: Makauri gravel aquifer.

■ Layer 5: Aquitard: 3rd confining layer separating the Makauri Aquifer from the underlying aquifer.

■ Layer 6: Matokitoki gravel aquifer.

The top of layer 1 represents ground level. Elevations for the top of Layer 1 have been derived from LiDAR data from the Gisborne area. The base elevations for Layers 1 to 6 are derived from the 3D geological model.

Boundary Conditions

Three types of boundary conditions have been defined in the model to simulate the effects of surface water:

■ Rivers: rivers are special forms of the head-dependent boundary condition. In a head-dependent boundary, the model computes the difference in head between the boundary and the model cell where the boundary is defined. The head difference is then multiplied by a conductance term to get the amount of water flowing into or out of the aquifer (Environmental Simulations 2007). All major streams and rivers that receive water from hill catchments are defined as a river boundary:

  ▪ Waipaoa River has an assumed average stage of 28 m RL at the northern boundary of the model near Kaitaratahi. The stage gradually falls to mean sea level near the coast, where the Waipaoa River flows out into the Poverty Bay.

  ▪ Taruheru River has an assumed average stage of 16.6 m RL near Waihirere and this falls to mean sea level near the coast in Gisborne.

  ▪ Whakaahu Stream has an assumed average stage of 13.5 m RL near Patutahi and this falls to 4.5 m RL at the confluence with the Waipoao River.

  ▪ Te Arai River has an assumed average stage of 1.5 m RL near Papatu Road and this falls to 0.5 m RL at the confluence with the Waipoao River.

  For most of the Waipaoa River and all other rivers, the streambed conductance is calculated by the groundwater model, assuming an average width of 60 m and length of 10 m, a hydraulic conductivity of 1 m/day, and a bed thickness of 1 m. The optimised hydraulic conductivity for the northern reaches is 10 m/day. This enhances infiltration up-catchment and improves calibration results.

■ Drains: Drains are similar to rivers except that drains will only remove water from the model. If the head in the model cell drops below the drain elevation, the drain will not inject water into the model. Under these conditions, the drain becomes inactive (Environmental Simulations 2007). All spring-fed streams and land drains in the Poverty Bay Flats are modelled as a drain:

  ▪ Waikanae Creek has an assumed average stage of 2.8 m RL near Gisborne Airport and this falls to mean sea level near the coast at Gisborne.

  ▪ Upper reaches of the Taruheru River and tributary drains have various stage elevations.

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- ▪ Awapuni Drains have an assumed average stage elevation of mean sea level.

- ▪ Network of land drains across the Poverty Bay Flats area maintained by GDC.

  The streambed conductance for drains is calculated by the groundwater model, assuming an average width of 60 m and length of 10 m, a hydraulic conductivity of 2 m/day, and a bed thickness of 1 m.

- ■ General Head Boundaries: A general head boundary (or GHB) is a generic form of the head-dependent boundary condition. GHB's are normally used along the edge of the model to allow groundwater to flow into or out of the model under a regional gradient (Environmental Simulations 2007). The sea, which forms the southern model boundary, is defined as a general head boundary with a water level at mean sea level. Furthermore, deep groundwater inflow from the eastern hills into the Matokitoki and Makauri aquifers are simulated as a GHB.

The location of rivers, streams and land drains is based on information from NIWA's hydrology database REC2_V4. All surface water levels are estimated from LiDAR data from the Gisborne area. Waipaoa River water depths are assumed to be 3 m across the model. For other rivers and land drains a water depth of 1 m is assumed. It is acknowledged that this may not be accurate for smaller streams and drains and more accurate site specific data would be required to better simulate the interaction between surface water and shallow groundwater. However, for the purpose of this study, which is understanding and tracking the MAR injection trials in the Makauri Aquifer, the data used is considered sufficient.

For the steady state calibration using September – October 2016 groundwater levels data, sea level has been assumed to be 0.2 m RL, to reflect mean sea level conditions. All elevations and levels are expressed in m RL expressed as height above a local datum (Gisborne 1926 – Gisborne Vertical Datum, GVD) and those are comparable to the topographical information (LIDAR data). For transient modelling, the 1992 – 2018 period has been used, with seasonal changes in rainfall recharge incorporated.

Groundwater Recharge

The groundwater recharge (i.e., the land surface recharge) is applied to all active cells in Layer 1. The annual rainfall recharge is assumed to occur in full in the winter season, with no recharge occurring in summer.

Calibration of the previous version of the Gisborne Groundwater Model (version V3) indicated a better fit with observed aquifer levels could be obtained if it is assumed that 50 % of the annual rainfall represents the annual groundwater recharge, with all of this occurring in the winter season. In the Gisborne Groundwater Model V4, rainfall recharge has been further discretised based on land use categories (see table B1 and Figure B2).

Table B1: Rainfall Recharge Zones in Gisborne Groundwater Model.

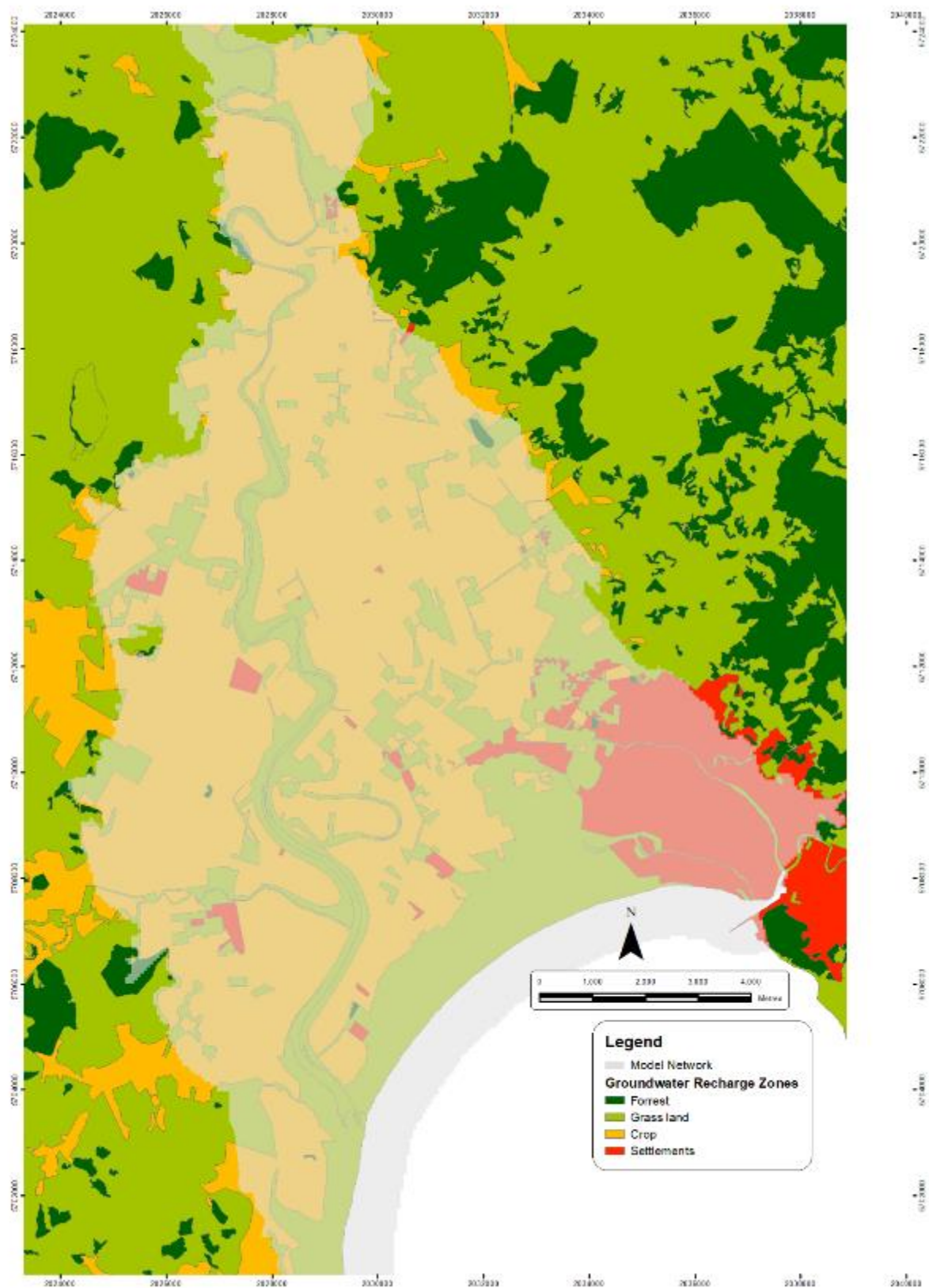| Zone	% of Winter Rainfall	Winter Recharge Rate (mm/day)*
Grass Land	42 %	1.71
Forrest	38 %	1.55
Crop	53 %	2.15
Settlements (urban areas)	27 %	1.08
*Rainfall recharge is assumed to only occur in winter		

Figure B2: Groundwater recharge land use zones.

For the steady state model, the recharge is based on the average annual recharge of 868 mm in 2016. For the transient model, the groundwater recharge changes based on annual rainfall from 1992 to 2019. For future time steps and average annual rainfall of 1000 mm is assumed.

Groundwater Abstraction

Groundwater abstraction information for the period 2009 – 2017 provided by GDC has been incorporated into the transient model during the irrigation season only. The information includes location of active water supply wells, their seasonal flow rates, and pumped aquifer for 70 wells. No data has been made available for abstractions beyond that period and 'synthetic' abstraction rates have been incorporated. These have been derived from the relationship between potential evapotranspiration rates and recorded groundwater abstractions.

Aquifer Properties and Model Calibration

The optimised hydraulic properties of the aquifers and confining layers following calibration (next section) are listed in Table B2.

Model Layer 1 is a 'lumped' aquifer, representing the Te Hapara Sand / Shallow fluvial aquifer and the first confining layer. Conductivity zones have been assigned to Layer 1 in the model based on thickness distribution of these two formations, as shown in Figure B3. For all other model layers the conductivity values listed in Table B2 are applied uniformly over the modelled area.

Table B2: Optimised hydraulic properties.

| Layer	Aquifer	Horizontal Hydraulic Conductivity (m/day)	Vertical Hydraulic Conductivity (m/day)	Specific Yield (-)	Specific Storage (-)
1	Te Hapara Sand / Shallow Fluvial Aquifer and Confining Layer 1	2 to 18	0.001 to 7	0.05	-
2	Waipaoa Aquifer	30	3	-	0.0001
3	Confining layer 2	0.001	0.001	-	0.0001
4	Makauri Aquifer	190	190	-	0.0001
5	Confining layer 3	0.001	0.001	-	0.0001
6	Matikotiko Aquifer	50	50	-	0.0001
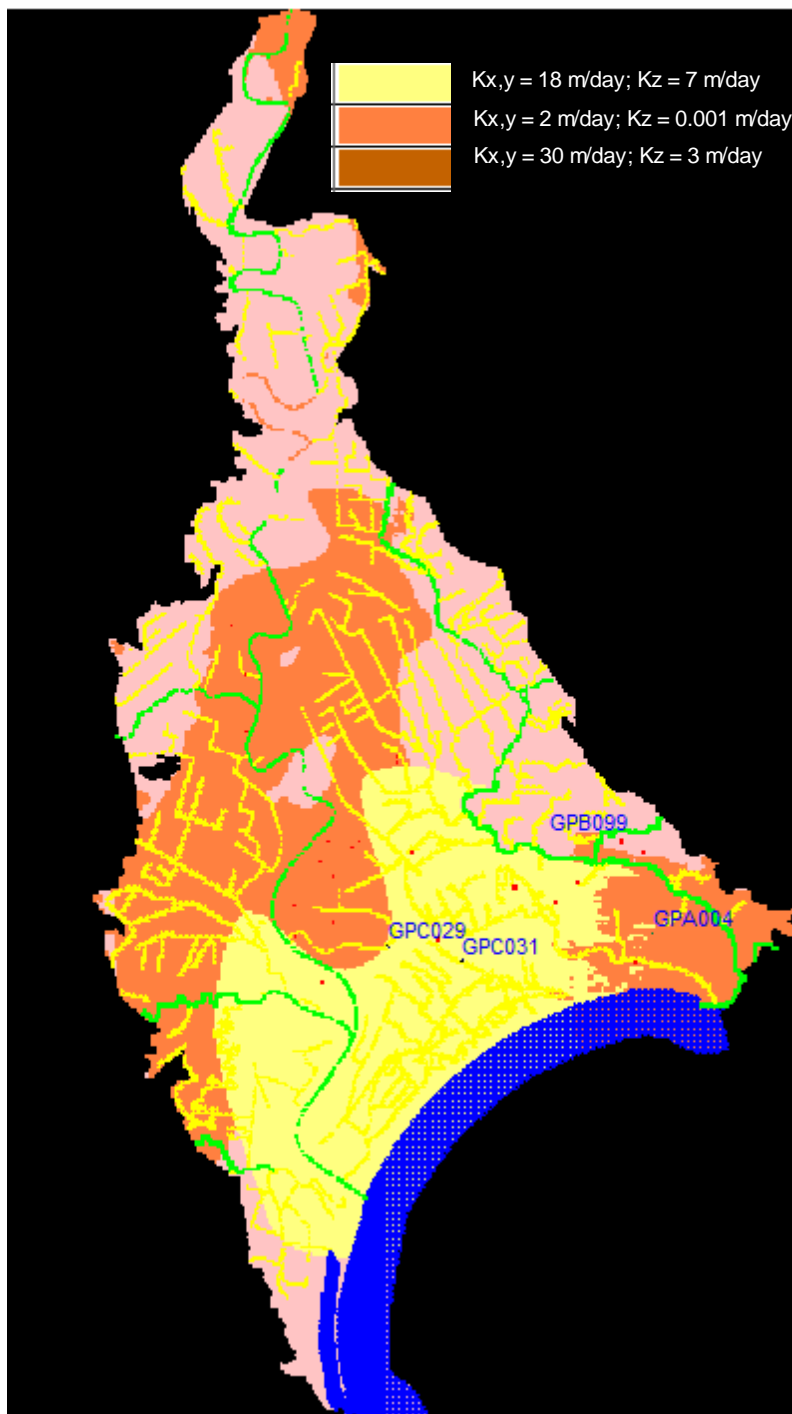
Figure B3: Layer 1 conductivity zones in Gisborne groundwater model.

Calibration and Verification

The Gisborne groundwater model V4 has been calibrated, to ensure the model is suitable to assess groundwater flows near the MAR site. The calibration was done for steady-state conditions based on September – October 2016 groundwater level data. Hydraulic conductivity values have been optimised during the calibration, through a combination of manual and automatic calibration in PEST.

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The following checks have been undertaken:

■ A review of the differences between the modelled and observed groundwater levels for the model area (Figure B4) indicates the modelled and observed levels are similar across most of the model. Groundwater model calibration statistics are presented in Table B3, which shows the root mean square (RMS) is low (i.e., 277 m) and scaled root mean square (SRMS) is less than 5 %.

■ A review of the groundwater balance (Table B4) for the steady state model indicates the difference between water introduced to the model through the various simulated boundaries and water leaving the model through other boundaries is very similar. The water balance error is less than 0.01 %, which is very small and indicates the model numerical calculations have converged to a numerically valid result.

■ A review of the flow paths from up-gradient water sources (boundary conditions) through the model to down-gradient groundwater discharge areas (boundary conditions) indicated that these flow paths reasonably reflect our knowledge of the groundwater system in the area simulated.
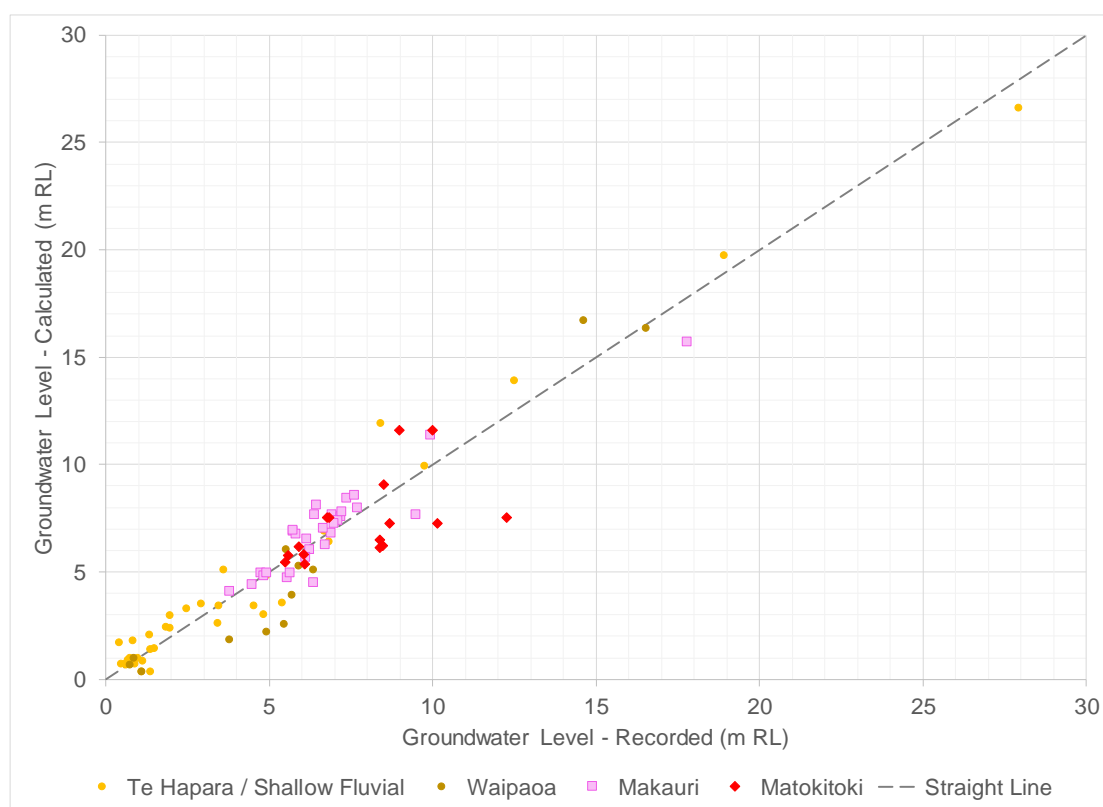

Figure B4: Recorded versus modelled groundwater levels – steady state model.

Table B3: Groundwater model calibration statistics.

Parameter	Value
Residual Mean (m)	0.13
Absolute Residual Mean (m)	0.95
Residual Standard Deviation (m)	1.32
Sum of Squares (m^2)	166
Root Mean Square (RMS) Error (m)	1.33
Minimum Residual (m)	-3.51
Maximum Residual (m)	4.76
Number of Observations (-)	94
Range in Observations (m)	27.52
Scaled Residual Std. Deviation	4.8%
Scaled Absolute Residual Mean	3.4%
Scaled RMS Error	4.8%
Scaled Residual Mean	0.5%

Table B4: Steady state groundwater model water balance.

Description	Inflow (m³/day)	Outflow (m³/day)
Recharge	217,566	-
Constant Head	575	12,605
River	14,041	107,971
Drain	-	114,449
GHB	2,841	-
Total	**235,024**	**235,025**
Error	**>0.01 %**	

Transient modelling calculations have also been undertaken for the 1992 – 2018 period, to inform the optimisation process. The transient calibration simulation covers a period of 4 years and starts in March 2016 (beginning of winter 2016) until mid-March 2020. All stress periods are of different length, mainly capturing the winter recharge and the irrigation seasons during the summer months with particular refinement during the 2017 and 2019 winter injection trials periods.

The numerical groundwater flow model simulates the hydraulic responses to stresses on the aquifers at any location and depth. For the transient calibration we have compared the response to recorded groundwater levels in designated monitoring well GPE065 which has the longest period of observations (Figure B5). Note that most other wells used for groundwater level observation across the Poverty Bay Flat are pumped wells and summer water levels in these wells are influenced by well loss from pumping and do not represent aquifer water levels.

General modelled responses to stresses (i.e., rainfall recharge, MAR injection trials and summer groundwater abstraction) reasonably fit well with the recoded water levels in GPE065. However, uncertainty about timing, rates and volumes in the many different irrigation abstraction wells across the area limits the fit of modelled and recorded summer water levels. Accurate information about these factors was largely unavailable and have been estimated based on a synthetic time series, which were adjusted during model optimisation in order to capture the amplitude of the associated drawdown during the irrigation seasons. A further optimisation was undertaken in 2020 by assuming the groundwater abstraction for irrigation was 1.7 times higher than derived with the synthetic time series (i.e., synthetic time series are based on a relationship between recorded groundwater abstraction and recorded evapotranspiration rates; the data used was from 2009 to 2014 and this may no longer be valid as irrigated land area may have increased ever since).

Specific Storage (SS) has been optimised on the transient calibration and optimised value is included in Table B2.
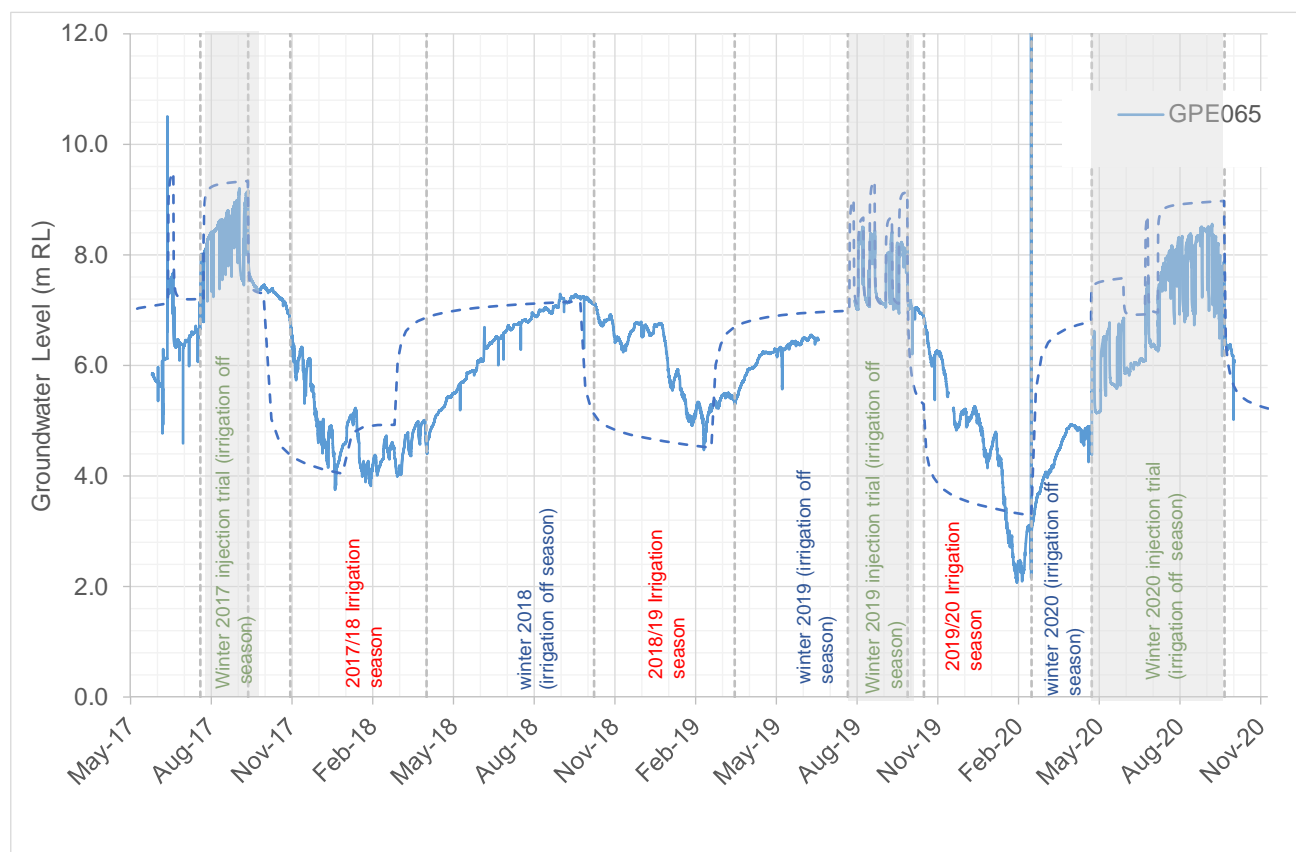
Figure B5: Observed (line) versus modelled (dashed) water levels at monitoring well GPE065.

To summarise, the model is capable to accurately simulate responses of various stresses and we consider the model to be suitable for investigation of responses to MAR injection trials. It is noted that more accurate irrigation abstraction data would further improve the model's accuracy.

Solute Transport Modelling (Groundwater Quality)

Changes in salinity from injecting fresh river water into the mineralized Makauri Aquifer have been modelled with MT3DMS within the Gisborne groundwater model. For modelling various MAR layout scenarios, the following assumptions were made:

- EC levels were modelled assuming injection water (i.e., river water) has an EC of 500 uS/cm. Ambient groundwater was assumed to have 1,450 µS/cm.

- Only advective transport was assumed and no reactivity or dispersion activated in the model. However, some numerical dispersion occurs in the model which to some extent would reflect what occurs naturally.

- Steady state conditions where assumed with average annual abstraction (about 1.1 Mm3/year), recharge and injection (about 0.9 Mm3/year) incorporated. The model was run for a 20 year period.

References

Environmental Simulations 2007. Guide to Using Groundwater Vistas, Version 5.

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Hydrogeochemical Processes and Plume Tracking during Injection Trials

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Introduction

The injection of river water into the Makauri Aquifer during the MAR trials will result in a localised change in groundwater quality as the river water has a different composition as the ambient groundwater in the Makauri Aquifer. The change in groundwater quality is the result of various processes, which can be grouped as follows:

■ Displacement: the injection water displaces the ambient groundwater and forms a plume around the injection well. This plume remains present to some degree after injection stops and will gradually flow downgradient under the influence of groundwater throughflow in the aquifer. Every time the groundwater flow direction changes, the injection plume will also change. At the Gisborne MAR site this occurs each change of season, where flow in the winter is generally south-eastwards, and the summer flow is eastwards due to abstraction for irrigation.

■ Dispersive mixing: the injection plume will disperse at the edges and mainly at the downgradient front of the plume, where it mixes with ambient groundwater. This is referred to as dispersive mixing.

■ Hydrogeochemical processes: various biological and chemical processes can cause a change in water quality when waters of different composition mix, or when water comes into contact with aquifer material as it flows through the aquifer.

These various processes described above can be traced by the targeted monitoring (which includes frequent water quality sampling and testing) in the four monitoring wells screened in the Makauri Aquifer surrounding the MAR injection well, which injects into the Makauri Aquifer (described in Section 3.2 and locations shown in Figure 11 in the main body of the report). Furthermore, the chemical composition of the material that comprise the Makauri Aquifer and overlying confining layer were tested to assess their reactivity.

Injection Plume Tracking

The lateral extent and shape of the injection plume will gradually change under the influence of changing groundwater flow directions. In winter the groundwater will flow generally in south-eastern direction, but this changes to an eastern direction in summer, because of irrigation abstraction in the central area of the Poverty Bay Flat. During injection, the groundwater flow will be generally south to southeast away from the injection well and the plume will continue to expand as long as injection continues.

It is important to understand what changes in groundwater quality can be attributed to changes in the lateral extend and shape of the injection plume, and not to hydrogeochemical responses. Golder has therefore tracked the plume in two different ways:

■ Assess the migration of the plume by interpreting monitoring data for 'conservative' chemical parameters (i.e., parameters that are not influenced by chemical reactions in the aquifer);

■ Groundwater and solute transport modelling using the Gisborne groundwater model was used to better understand plume breakthrough in various monitoring wells and enable improvement of the predictive value of the groundwater model.

Golder has used the difference in water quality signature of ambient groundwater and Waipaoa River water (i.e., the injection source water) to track the plume in the 4 designated monitoring wells described in Section 0 and locations shown in Figure 11 in the main body of the report.

Plume Tracking Based on Monitoring Results

Field testing results of the July 2019 sampling rounds before commencing the 2019 injection trial listed in Table C1, show a clear difference in water quality in all four monitoring wells, with GPE065 most akin to the

injected Waipaoa River water and GPE069 representing ambient groundwater in the Makauri Aquifer at this site. Irrigation wells GPD115 and GPD189 both located south of the MAR site, are most akin to GPE069, but show that the ambient water quality composition in the Makauri Aquifer is variable.

Table C1: Field testing results and plume tracking.

Monitoring well	Sample date	Temperature (°C)	DO (%)	DO (mg/L)	EC (uS/cm)	pH (-)	Turbidity (NTU)
Pre-injection trial (May 2017)							
GPE065	17-05-17	-	-	-	1,347	-	-
GPE066 (injection)	08-05-17	-	-	-	1,302	-	-
Post 2017 injection trial but pre-2019 trial (July 2019)							
GPE066 (injection)	22-07-19	13.1	2.4	0.25	-	6.81	0.34
GPE065	15-07-19	14.7	0.2	0.02	-	7.58	0.31
GPE067	15-07-19	14.7	0.9	0.09	736	7.11	0.36
GPE069	16-07-19	14.8	0.2	0.02	1,460	8.27	0.74
GPE068	15-07-19	15.2	1.3	0.13	766	7.08	0.38
GPD115	18-07-19	15.2	12.9	1.23	1,370	7.38	0.68
Waipaoa River (source water)	22-07-19	8.6	99.7	11.6	415	8.27	0.2
Post-2019 Injection trial (September 2019)							
GPE066 (injection)	-	-	-	-	-	-	-
GPE065	24-09-19	14.8	2.8	0.27	474	7.59	22.4
GPE067	24-09-19	15	1.6	0.16	773	7.2	5.16
GPE069	-	-	-	-	-	-	-
GPE068	24-09-19	15.3	2.6	0.26	906	7.22	5.68
GPD115	-	-	-	-	-	-	-
Waipaoa River (source water)	24-09-19	15.3	99.4	9.96	478	8.14	31
Lab test results							

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EC levels prior to the winter 2017 MAR injection trial in GPE065 and GPE066 (injection well) are similar to those recorded in GPE069 in all sampling before commencing the 2019 injection trial, suggesting the 2017 injection plume has not reached GPE069. The other two wells (GPE067 and GPE068) show various degrees of dispersive mixing between injected river water and ambient groundwater.

Oxygen (O_2) concentrations in all four monitoring wells (GPE065, GPE067, GPE068 and GPE069) are low (i.e., EC less than 1 mg/L) and this reflects the reactiveness of organic matter present in the ambient groundwater causing oxygen within the injected water to be quickly consumed, as expected.

Field measurements of oxygen levels are known to be sensitive to contamination by oxygen in the atmosphere (~21 %) which may explain the levels recorded in the field on 5 March in GPD189 (21.8 %) and on 18 July 2019 in GPD115 (12.9 %).

When plotting the Bromide (Br) against the Chloride (Cl) concentrations (see graph below), the progressive dispersive mixing is also apparent (Figure C1). The dotted line in the graph represents mixing between river water and ambient groundwater which have very different compositions of Cl and Br. For components that are not subject to chemical reactions (which is the case for Br and Cl), any degree of mixing between these two water types will result in a mixture with a Br and Cl levels that plots on this line. Any deviation from this line may point to ongoing biological or chemical reactions causing depletion or enrichment of either component. No such deviation is indicated from the results for Br and Cl in any of the monitoring rounds between October 2018 to September 2019.

A shift in water quality signature is observed in GPE067 in comparison to GPE068. A higher degree of dispersive mixing was observed in GPE067 than in GPE068 prior to March 2019, although GPE068 is at greater distance from injection well then GPE067. This has changed since November 2018, with GPE067 gradually becoming more akin to the injection water and GPE068 shifting to the water quality signature of ambient groundwater. This shift in water quality signature of GPE067 is caused by a change in direction of the 2017 injection plume due to summer abstraction for irrigation to the east of the MAR site. GPE067 was at the fringe of the injection plume in winter and spring 2018, but this shifted as the injection plume was drawn eastwards. During the 2019 and 2020 injection trials water quality in GPE067 becomes increasingly fresher and more so than GPE068. These processes are conceptually depicted in Figure C2.

The graph also suggests that irrigation well GPD189 at approximately 1 km southeast of injection well GPE066 has a different water quality signature then ambient groundwater recorded in GPE069. The modelled extend of the injection plume as per December 2020 is shown as EC levels (in µS/cm) in Figure 18 in the main body of this report. The injection plume is approaching the general area of irrigation well GPD189 since the 2020 injection trial, however, this well is likely screened in the underlying Matokitoki Aquifer and will not receive injection plume water.

Irrigation well GPD115 at 1.5 km distance southwest of the injection well has similar water quality as GPE069 representing ambient groundwater.

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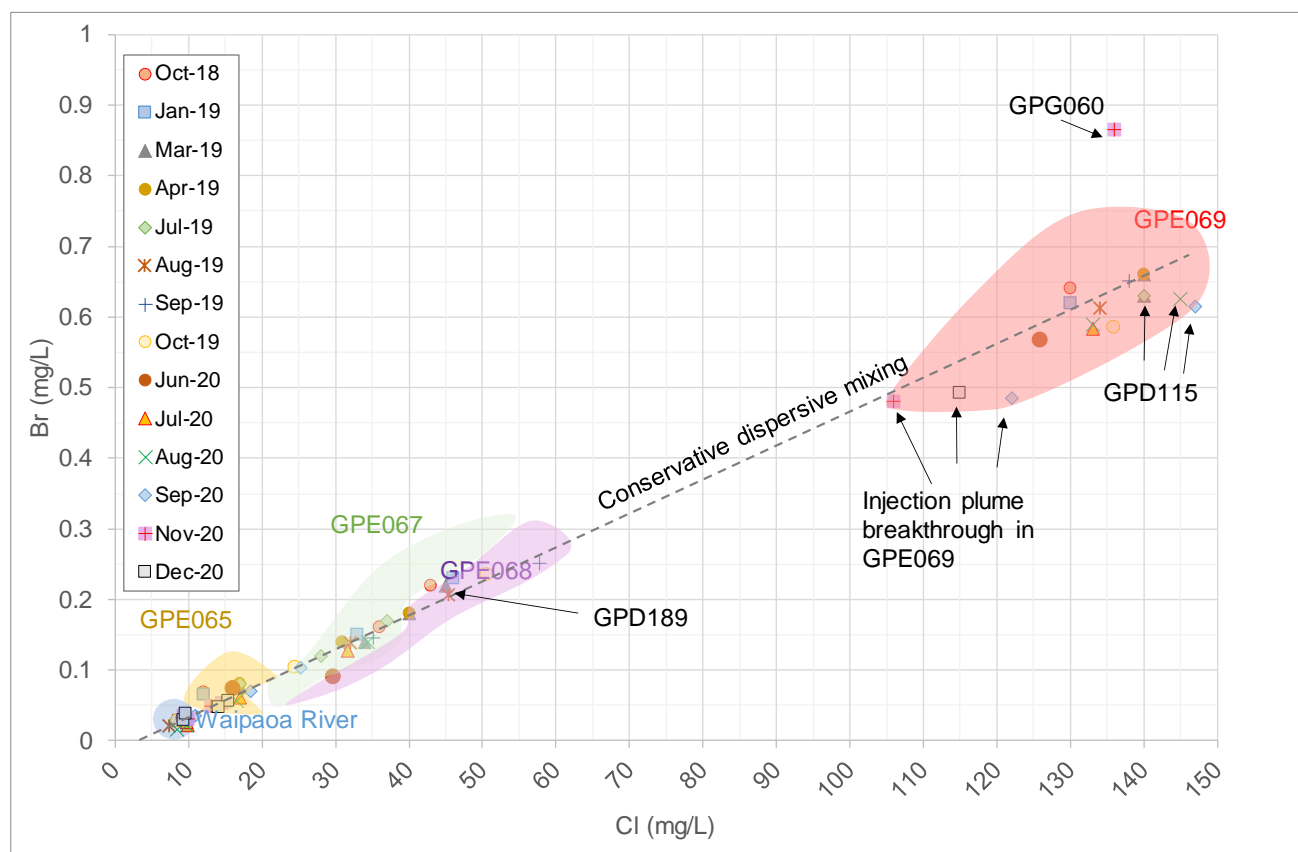
Figure C1: Bromide and Chloride ratio in recorded water quality.
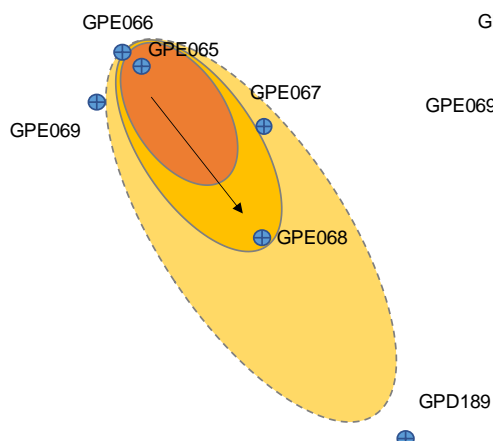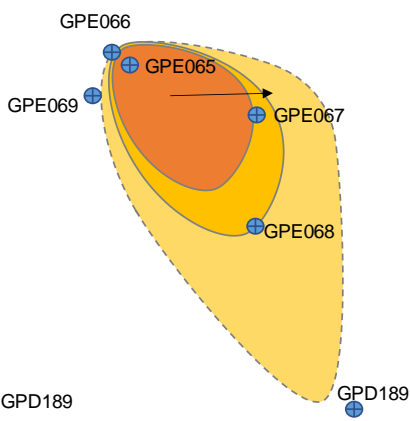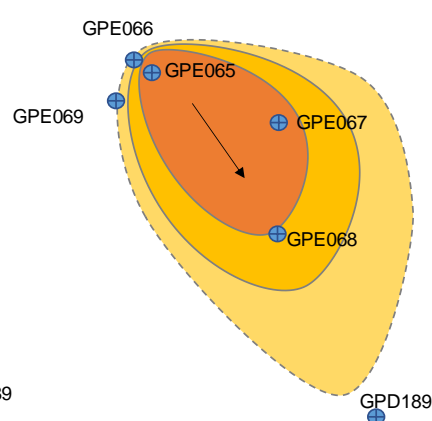

Figure C2: Schematic representation of injection plume development following the 2017 to 2020 injection trials (colour-shading indicatively represents concentration contours influenced by dispersive mixing).

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Plume Tracking by Groundwater and Solute Transport Modelling

Golder has also attempted to model the development of the injection plume throughout the whole injection trial period between 2017 and 2020. Golder's Gisborne groundwater model has recently been updated (Appendix B) and used to assess the hydraulic and water quality response to the 2017, 2019 and 2020 injection trials, caused by plume migration.

Of particular interest at this stage is injection plume tracking and understanding how the migration of the plume influences the water quality signature in the various monitoring wells. This assists in evaluating the water quality and well clogging risks of the river water injection. Breakthrough in nearby irrigation wells can also be predicted and followed. The results have subsequently been used to improve the accuracy of the Gisborne Groundwater Model and increase the predictive value.

The Gisborne groundwater model couples MODFLOW and MT3DMS that is designed and widely used to simulate 3D groundwater flow coupled with solute transport. The plume migration was modelled by simulating the breakthrough of salinity, measured as Electrical Conductivity (EC). The following processes and initial conditions were incorporated in the model:

■ Background groundwater EC from recorded observations remains below 1,500 µS/cm with a median value used for the solute transport modelling of 1,320 µS/cm from wells GPE065 and GPE066 (March to May 2017). It is notes that background EC levels vary and in GPE069 they appear to be higher than they were for GPE065.

■ From the Waipaoa River at the Infiltration Chamber water EC median values of 390 µS/cm and 490 µS/cm were recorded and used for injection concentration modelling, respectively for the 2017 and 2019 trials.

■ Dispersive mixing is included in the model as longitudinal and transversal dispersivity (α). No reactive transport was assumed.

■ The model grid is locally refined to 10 m spacing allowing injection process at GPE066 to be simulated at a fine scale.

■ Field and automated records of EC at GPE065, GPE067, GPE068 and GPE069 are available from May 2018 to December 2020 which includes the 2019 and 2020 injection trials. Very limited EC data is available for the pre- and post-2017 trial.

Figure C3 below shows the recorded and modelled breakthrough in all four wells. The comparison between observations and modelled EC is difficult for the 2017-2018 period due to the lack of EC records. The model fit is poor prior to 2019 injection trial, mainly because accurate regional abstraction data is not available, which would have strongly influenced flow field and plume breakthrough. Abstraction rates and volumes during the irrigation season are based on synthetic time series and rough estimations.

However, the shift in GPE067 (i.e., from edge of plume to inside of plume) and GPE068 (i.e., from inside plume to edge of plume) does appear to be modelled, as graphs cross prior to 2019 injection trial. Therefore, the model is suitable to assess general trends. Of interest is that the model does not predict that the plume has broken through at monitoring well GPD189 as per October 2019. It is therefore not certain if the water quality signature observed in GPD189, which deviates from ambient groundwater, represents the injection plume.

The model is more capable of simulating the initial response to the 2019 injection trial in the August to October 2019 period and the subsequent period until December 2020. This suggests the model is sufficiently accurate

to simulate MAR injection plume development, but for assessing very localised effects, much more accurate and detailed abstraction information is required.
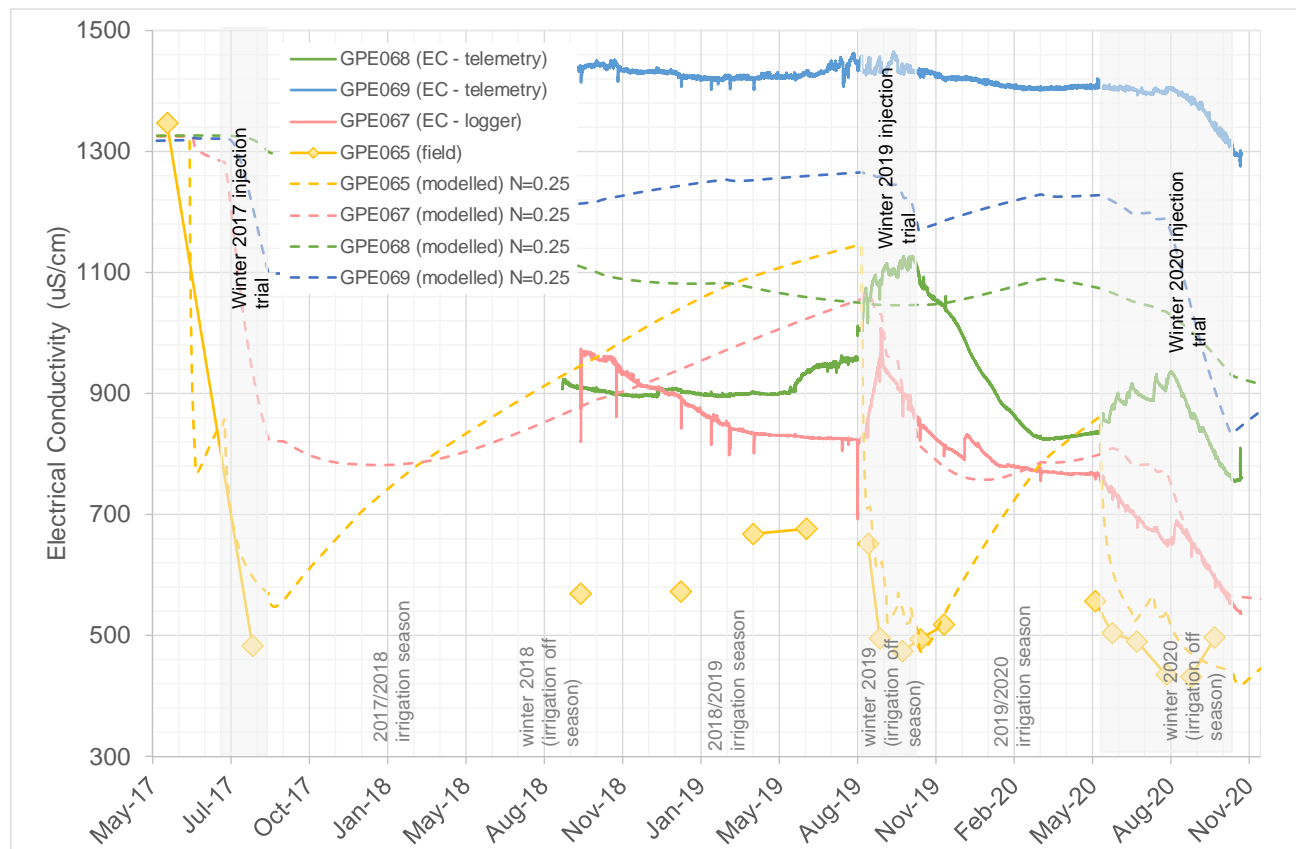

Figure C3: Modelled injection plume breakthrough and EC level changes in monitoring wells in response to the 2017, 2019 and 2020 injection trials.

Dispersivity and porosity were varied in the model to assess their sensitivity to the amplitude and timing of plume breakthrough in the three monitoring wells that have received the plume (GPE069 has not shown to ever have received the plume). The results for each of those three monitoring wells are shown in the three graphs in Figure C4 below. Note that the sensitivity analysis was undertaken with the previous model version that did not include the irrigation abstraction volume optimisation described above.

Dispersivity is very sensitive meaning that slight changes will result in notable changes in breakthrough. In general, a lower dispersivity results in the best fit between modelled and recorded EC levels. Porosity governs the breakthough timing, and in general higher values show a better fit between modelled and observed EC levels.

GPE068 is located beyond the area in which grid refinement was introduced, and this impedes the model to accurately assess the breakthrough in this well.

Overall a better fit is obtained for 2019 injection trial with high porosity (n=0.3) and low dispersivity (<50 m) for GPE 065 and GPE067.
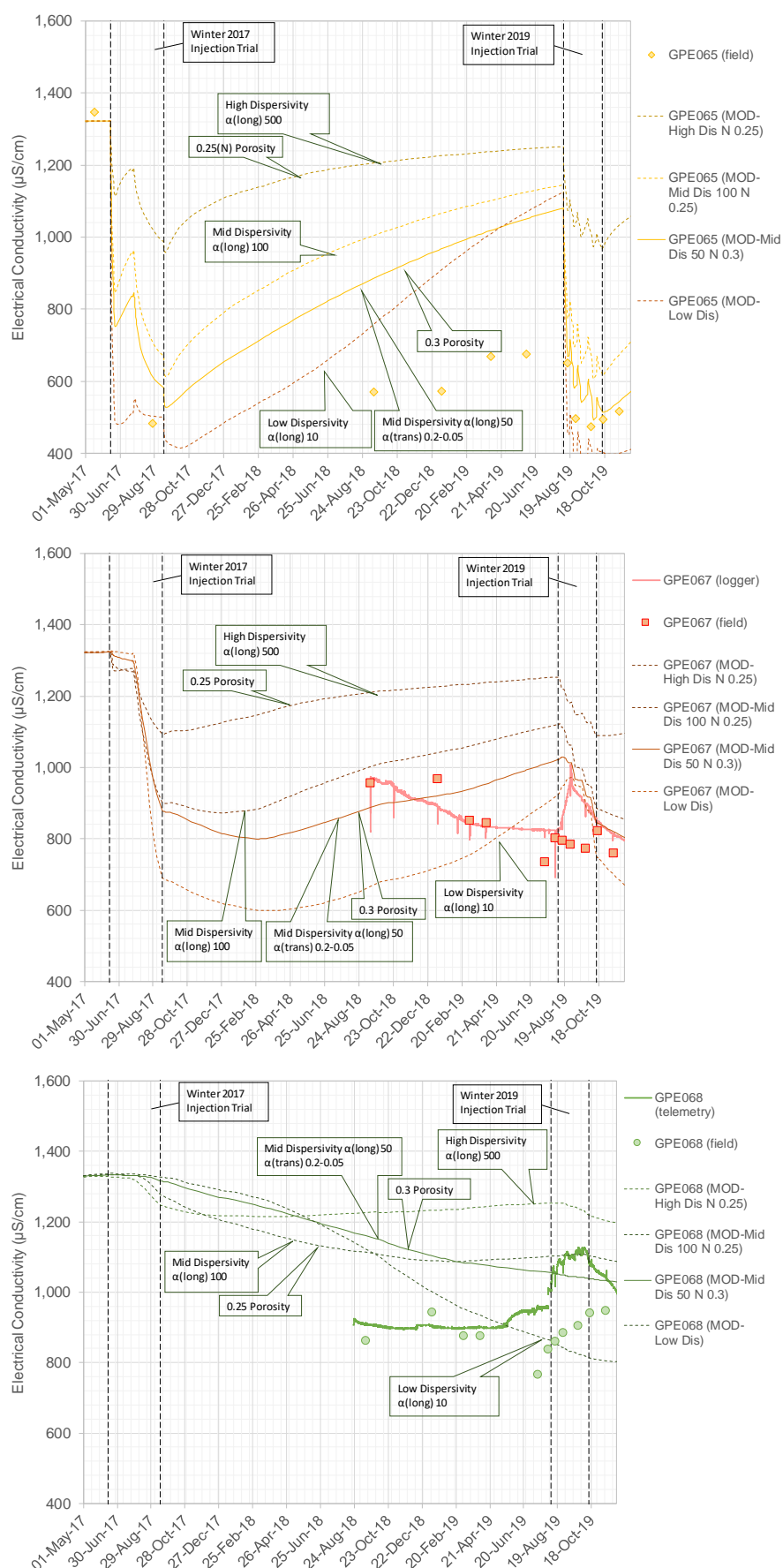
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Figure C4: Results of solute transport model sensitivity analysis.

Aquifer Material Testing Analysis

Aquifer material samples retrieved from drill cuttings during installation of the new monitoring wells have been tested for organic matter and carbonate content (Table C2). In addition, various elements have been tested by XRF testing. The results are listed in Table C3.

Table C2: Results aquifer material testing for organic matter and carbonate content.

Sample	Lithological description	Total Organic Carbon (%)	Carbonate Alkalinity (as $CaCO_3$) (mg/kg)
GPE069 (27-28 m depth)	Gravels - Waipaoa Aquifer	0.5	140
GPE069 (66-67 m depth)	Blue clay - confining layer above Makauri	4.7	78
GPE068 (67-68 m depth)	Blue clay - confining layer above Makauri	0.6	56
GPE068 (70-71 m depth)	Gravels - Makauri Aquifer	<0.1	41

The results indicate the Makauri Aquifer material has low organic matter content compared to the overlying confining layer. It is acknowledged that organic matter, in the form of wood fragments, within gravel deposits is recorded in approximately 5 % of Poverty Bay Flat bore logs, mainly in the Waipaoa and Matokitoki aquifers. However, the vast majority of the bore logs show no wood fragments in gravel deposits. The reduction of organic matter (i.e., methanogenesis) in the confining layers is likely to be the principal source of methane encountered during the injection well drilling in 2017. This would suggest the injected river water will not become methanic over time, as the injected water passes through the Makauri Aquifer that holds little organic matter and little methanogenesis occurs.

It is noted that some organic matter is present in Makauri Aquifer water, as Total Organic Carbon (TOC) levels are 3.3 to 3.9 mg/L within the injection plume and 6.9 mg/L in GPE069, which represents ambient groundwater.

Table C3: Results of XRF element composition testing of aquifer material.

Sample Name	GPE069 (27-28 m depth)	GPE069 (66-67 m depth)	GEP068 (67-68 m depth)	GPE068 (70-71 m depth)
Lithological description	Gravels - Waipaoa Aquifer	Blue clay - confining layer above Makauri	Blue clay - confining layer above Makauri	Gravels - Makauri Aquifer
Measurement Finished	04-09-18 13:54	04-09-18 16:48	04-09-18 19:41	04-09-18 22:35
Calibration Method	Geotraces - Majors by Fusion			
Sc (PPM)	9	13	10	12

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Sample Name	GPE069 (27-28 m depth)	GPE069 (66-67 m depth)	GEP068 (67-68 m depth)	GPE068 (70-71 m depth)
Lithological description	Gravels - Waipaoa Aquifer	Blue clay - confining layer above Makauri	Blue clay - confining layer above Makauri	Gravels - Makauri Aquifer
V (PPM)	68	106	75	60
Cr (PPM)	49	78	119	64
Co (PPM)	15	18	11	9
Ni (PPM)	29	45	38	25
Cu (PPM)	18	37	16	14
Zn (PPM)	49	114	54	43
Ga (PPM)	12	17	13	9
As (PPM)	7	12	7	4
Rb (PPM)	63	87	66	52
Sr (PPM)	112	179	153	327
Y (PPM)	10	16	15	11
Zr (PPM)	126	162	185	120
Nb (PPM)	4	6	5	4
Mo (PPM)	4	4	4	4
Sn (PPM)	0	25	3	1
Sb (PPM)	0	0	1	2
Cs (PPM)	3	2	1	8
Ba (PPM)	990	563	970	718
La (PPM)	0	11	6	3
Ce (PPM)	26	47	36	28
Nd (PPM)	16	18	17	16
Tl (PPM)	0	2	0	0
Pb (PPM)	8	71	9	7
Th (PPM)	5	9	6	5

Sample Name	GPE069 (27-28 m depth)	GPE069 (66-67 m depth)	GEP068 (67-68 m depth)	GPE068 (70-71 m depth)
Lithological description	Gravels - Waipaoa Aquifer	Blue clay - confining layer above Makauri	Blue clay - confining layer above Makauri	Gravels - Makauri Aquifer
U (PPM)	3	3	3	3
SiO2 (%)	76.1	63.98	74.91	62.37
Al2O3 (%)	8.92	13.64	9.84	7.29
TiO2 (%)	0.428	0.655	0.48	0.374
MnO (PPM)	304	555	340	611
Fe2O3 (%)	3.39447	4.86431	3.55768	2.89162
Na2O (%)	1.379	2.177	1.736	1.257
MgO (%)	1.243	1.805	1.102	0.987
K2O (%)	1.506	2.112	1.516	1.176
CaO (%)	1.588	2.781	2.364	11.965
P2O5 (%)	0.074	0.122	0.134	0.096
S (PPM)	26533	10587	2436	744
F (PPM)	418	771	795	612
Cl (PPM)	390	5580	403	311
CO2 (%)	5.18	7.86	4.44	11.75
Sum (%)	102.75	101.91	100.67	100.54
Compton (%)	98.958	101.129	99.964	100.243

Hydrogeochemical Processes

Redox state

As mentioned above, the dissolved oxygen (DO) concentration in the aquifer is less than 1 mg/L which suggests most oxygen has been consumed in the generally anoxic Makauri Aquifer.

In the graphs below (Figure C5) the nitrate-N (NO_3) and sulphate (SO_4) (Figure C6) have been plotted against the chloride (Cl) concentration. Median values for Waipaoa River water and GPE065 water prior to the 2017 injection have been included in the graph as well. Both the concentration of NO_3 and SO_4 fall more strongly than what would be expected from conservative dispersive mixing.
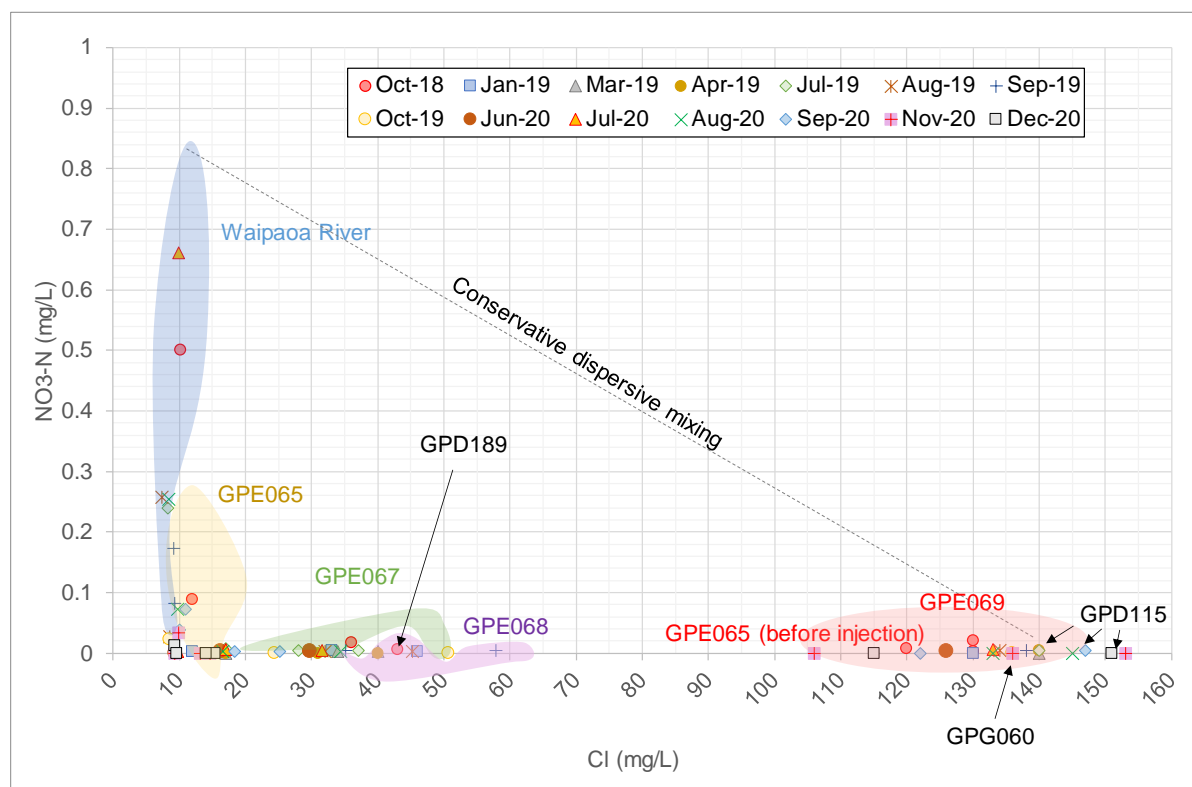
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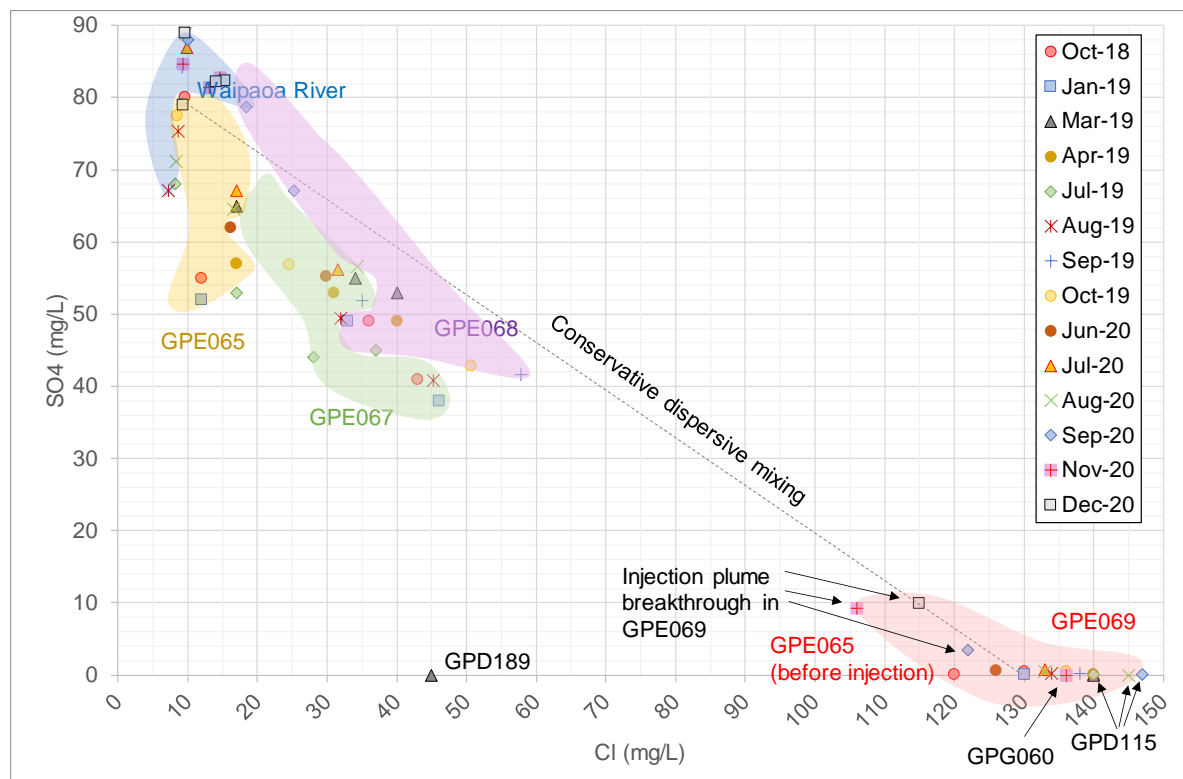**Figure C5: Nitrate and Chloride ratio in recorded water quality.**

Figure C6: Sulphate and Chloride ratio in recorded water quality.

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Furthermore, NO_3 shows a sharper fall than SO_4 and appears to be entirely depleted in all monitoring wells in the sampling rounds between January 2019 and August 2020. These trends are consistent with reduction processes in which NO_3 is typically targeted first (i.e., denitrification) followed by iron and manganese oxides (i.e., iron reduction) and then SO_4 (i.e., sulphate reduction). A slight increase of NO_3 is again observed in GPE065 after the 2019 injection trial starts and this is expected to gradually decline again now that the 2019 injection trial has ceased. However, continuous injection could eventually deplete all organic matter around the injection well and NO_3 concentrations could rise and become similar to Waipaoa River water.

Pyrite oxidation would have resulted in a sulphate (SO_4) increase, and this does not seem to occur in any of the monitoring rounds, as this would have shown some of the points on the plot above the dispersive mixing line. The same shift in GPE067 water quality signature towards injection water, as explained above can be observed in these graphs.

The same shift in GPE067 and GPE068 water quality signature towards injection water, as explained above can be observed in these graphs. As observed in the Br/Cl graph above GPE069 appears to depart from the low SO_4 concentrations observed in ambient groundwater quality as the plume breaks through.

Iron concentrations (Fe) are plotted against chloride (Cl) in the graph in Figure C7 below. Iron concentrations in GPE067 and GPE068 for the October 2018 to July 2019 period appear to be influenced by seasonal changes in groundwater flow direction described above. More recent sampling results including from the recent monitoring rounds between July and September 2020 show a gradual shift of both the GPE067 and GPE068 water quality signature towards that of GPE065 and river water. The changes in iron concentrations appear to be mainly associated with changes in groundwater flow direction and the progressive expansion of the injection plume as described above, and to a lesser extent due to hydrogeochemical reactions. A slight increase in Fe concentration (i.e., present as Fe^{2+} ions) is apparent as all samples from GPE067 and GPE068 plot above the conservative dispersive mixing line. This is likely due to the reduction of iron oxides in aquifer material which releases Fe^{2+} ions, as also mentioned above.

Significant arsenic mobilisation (a concern with pyrite oxidation) does not seem to occur, as suggested by the graph below. Concentrations are highest in GPE069 which has a composition similar to ambient groundwater for the other parameters. The low arsenic concentration in GPE068 in the January 2018 round appears to be inconsistent with previous and subsequent arsenic concentrations recorded in that wells. It is considered that the variability in arsenic concentrations recorded in GPE065, GPE067 and GPE068 are a result of the variability in arsenic concentrations of the ambient groundwater, reflected by the results for GPE069. There is no indication of arsenic release by hydrogeochemical processes associated with the injection trial.
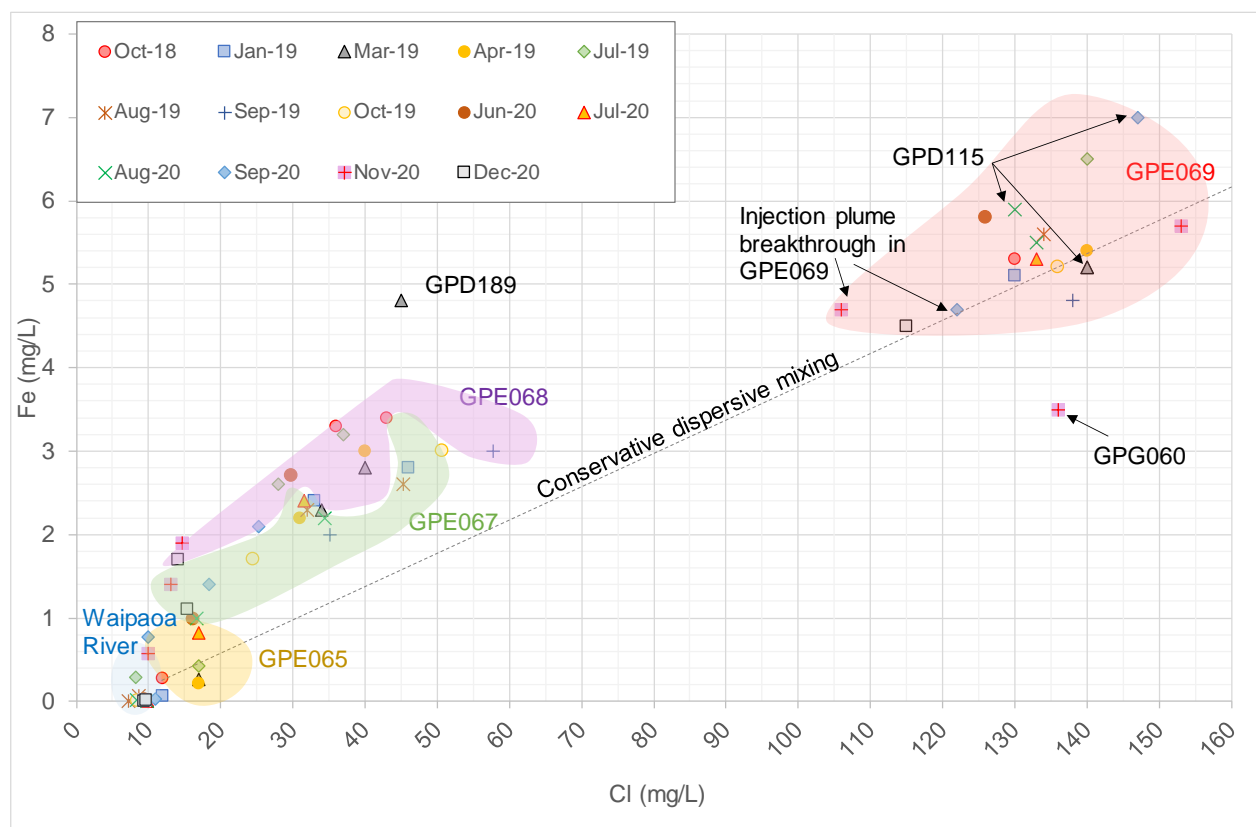
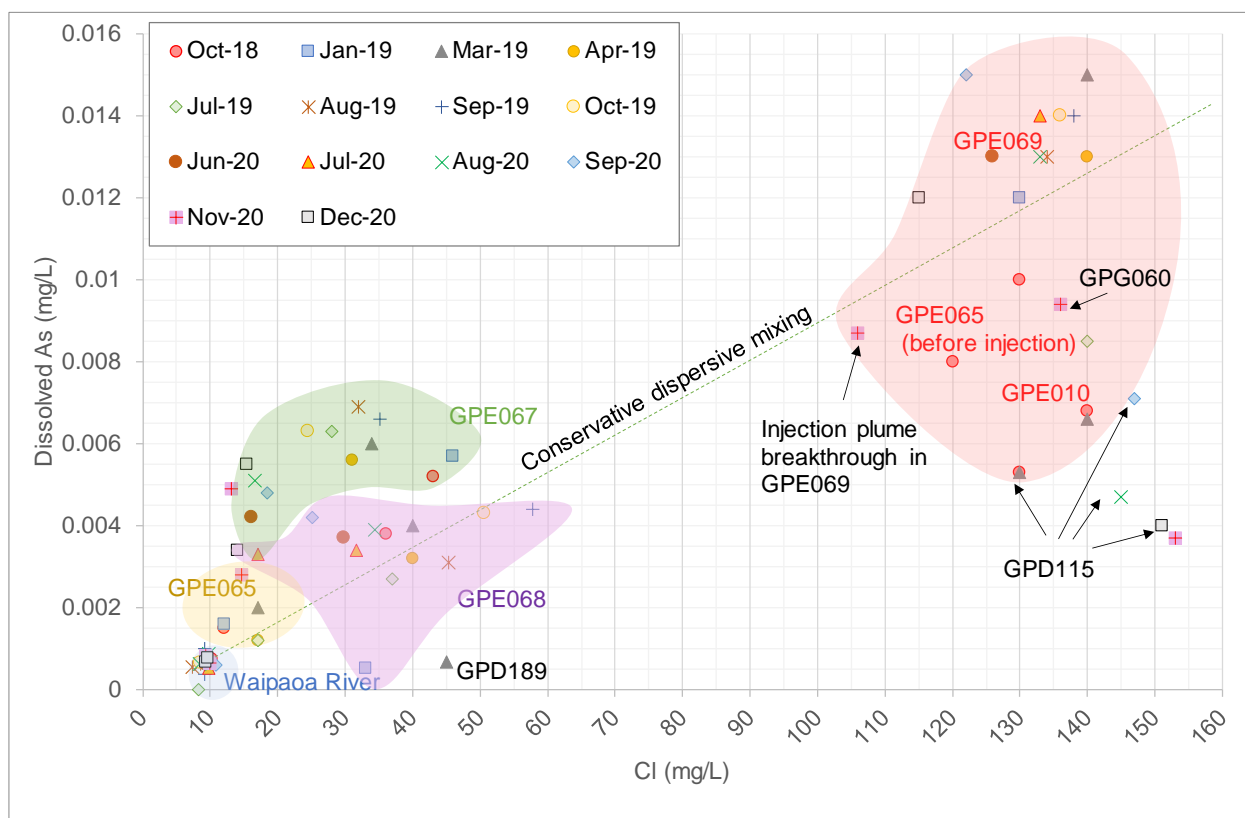**Figure C7: Iron and Chloride ratio in recorded water quality.**

Figure C8: Arsenic and Chloride ratio in recorded water quality.

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Cation Exchange

In the graph below (Figure C9) the sodium (Na) concentration is plotted against the chloride (Cl) concentration. The sodium appears to increase more readily than would be expected from 'conservative' dispersive mixing (e.g., Br/Cl relationship). This is due to the high calcium concentration in injected river water compared to the concentration in ambient groundwater. Cation exchange will result in calcium ions replacing sodium ions within exchange complexes in the sediments, which are subsequently released to the groundwater. This process is referred to as 'freshening' and the data from all monitoring rounds suggest this process is ongoing.

Of interest is the Na/Cl ratio in the September 2019 round for GPE068, which shows this well has since become more akin to ambient groundwater. It would appear the new injection plume since winter 2019 has pushed ambient groundwater towards this well causing the shift.
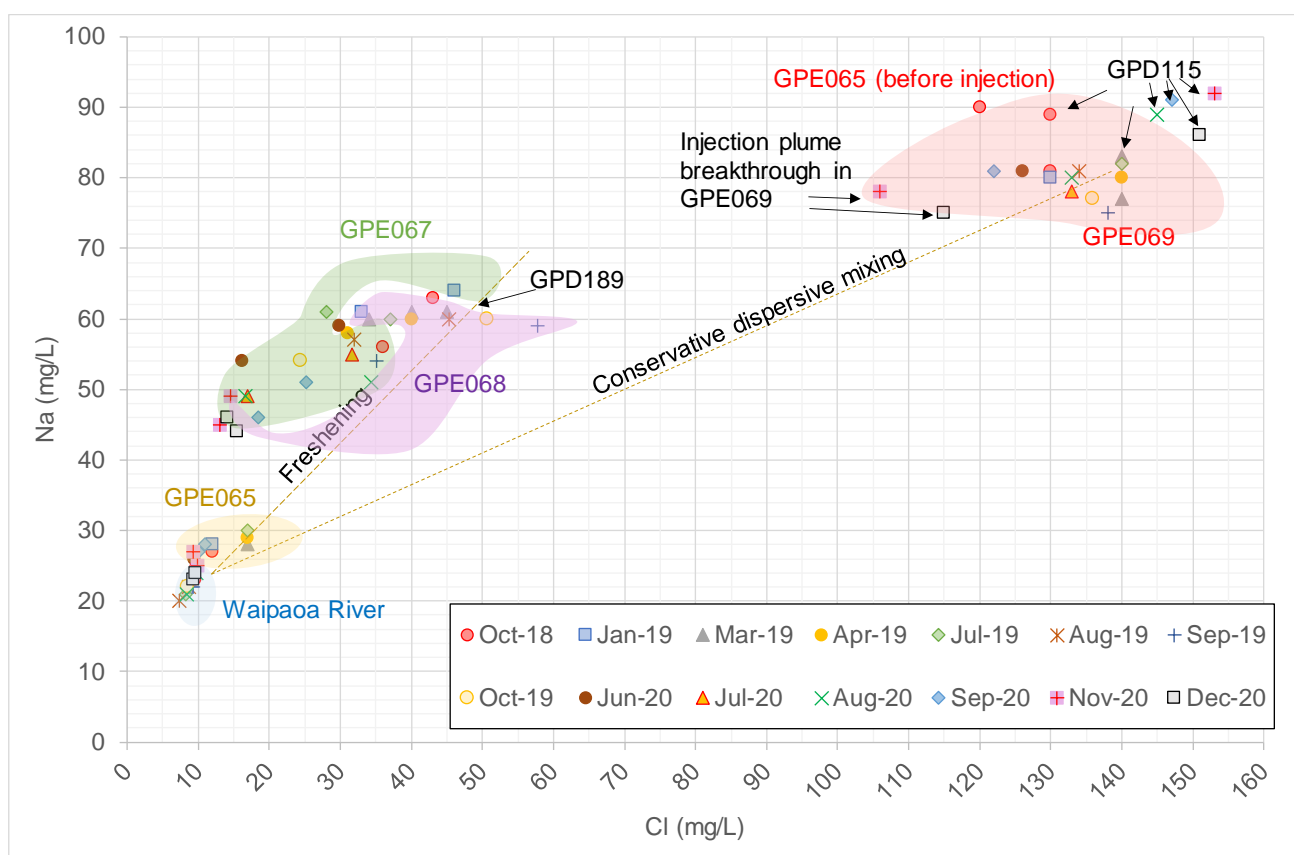
Figure C9: Sodium and Chloride ratio in recorded water quality.

Carbonates and Carbon Dioxide

In the graph below the calcium (Ca) concentration is plotted against the total alkalinity. The injection of river water results in an increase of both parameters in all monitoring rounds for GPE067 and GPE068 in particular. It is considered that this is not the result of dispersive mixing but of calcite carbonate reactions. Carbon dioxide (CO_2) is produced from the oxidation of organic matter by oxygen in the infiltrated river water. This shifts the calcite dissolution reaction indicated in the graph to the right (calcium carbonate stoichiometric relationship represented by the straight line), and both calcium and alkalinity (expressed as HCO_3^-) will increase. However, CO_2 pressures within the injection plume appear to remain well below those present in the ambient groundwater, as shown by the distinctively higher Ca/Alkalinity concentrations in GPE069.

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The specific capacity for abstraction (i.e., the flow rate per metre drawdown) differs from the specific capacity for injection (i.e., the flow rate per metre rise) for most wells. Both can be tracked over time to review changes in well performance. To compare results, the specific capacity test has to be undertaken at similar flow rates and length of time.
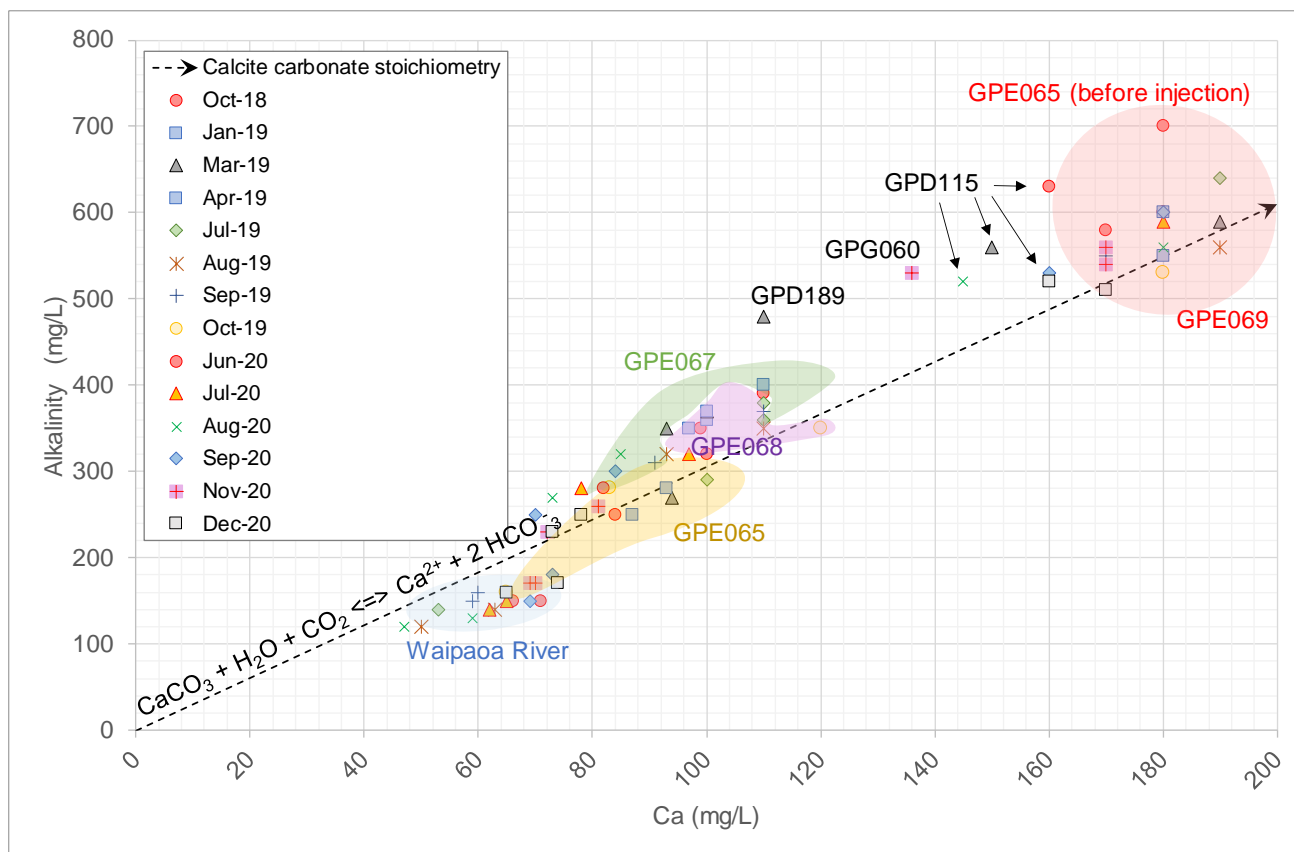
Figure C10: Alkalinity and Calcium ratio in recorded water quality.

Possible scaling and/or corrosion has affected the telemetry probe installed in GPE065 (see photo below to the left). The probes have been supplied by Scott Tech and are CS451 Campbell Scientific transducers made of 316L stainless steel. Although the logger in GPE068 also appears to have been affected, the nature of the scaling seems different from that observed on the GPE065 logger (see photo below to the right). The scaling on the GPE068 probe appears to be similar to that observed on the well screen and well pump (described in Section 3.5 in the main body of the report), but no pitting has occurred at the GPE068 logger.

GPE068 logger

It is unclear from the GPE065 logger photo whether corrosion or scaling on the logger occurs. If pitting has occurred, as noted by GDC, then corrosion may have affected the logger to some degree. Since the ambient groundwater has a relatively high background salinity, and high carbon dioxide (CO_2) pressures are present in the groundwater, corrosion in this environment can occur rapidly with certain steel qualities. This will produce hydrogen gas and result in iron carbonate precipitation. Since there might still be oxygen in the injected water at GPE065, any reduced iron (Fe(II)) remaining or incorporated in scales may become oxidised and cause discoloration. This type of scaling could however also occur due to degassing of the local groundwater when being exposed to atmospheric pressures during drilling.

APPENDIX D

Groundwater Salinity Long-term Trend Analysis

Trend Analysis Approach

Electrical conductivity (EC) data of groundwater in a large amount of water supply wells listed in GDC's Hill Top database has been analysed with TimeTrend software from NIWA and Jowett (2017) using Mann-Kendall trend analysis.

For most wells the long-term data is from approximately the late 1988 to 2018. The results are listed in the table below and includes the mean EC level in 2015.

Site	Aquifer	Samples used	Sampling period	Mean EC Level in 2015	Percent annual change	Probability	Trend
GPA004	SFD/Te Hapara	93	6-Sep-89-26-Oct-17	478	-0.36	1.00	Decreasing
GPA036	SFD/Te Hapara	69	11-Mar-88-20-Apr-16	730	-1.99	1.00	Decreasing
GPB042	SFD/Te Hapara	76	12-Jul-88-10-Aug-17	1,162			No significant trend
GPB099	SFD/Te Hapara	101	6-Jul-88-29-Mar-18	388			No significant trend
GPB100	SFD/Te Hapara	94	25-Mar-88-16-Feb-18	2,440	0.05	1.00	Increasing
GPC026	SFD/Te Hapara	97	27-Jul-88-10-Jul-18	1,195	0.68	1.00	Increasing
GPC027	SFD/Te Hapara	56	19-Jan-94-19-Jun-14				No significant trend
GPC028	SFD/Te Hapara	67	19-Jan-94-9-Apr-18	953			No significant trend
GPC029	SFD/Te Hapara	38	19-Apr-02-10-Jul-18	540			No significant trend
GPC030	SFD/Te Hapara	67	19-Jan-94-9-Apr-18	518	-1.55	1.00	Decreasing
GPC031	SFD/Te Hapara	67	19-Jan-94-9-Apr-18	873			No significant trend
GPC050	SFD/Te Hapara	47	15-May-89-7-Sep-17	1,150	0.55	1.00	Increasing
GPC051	SFD/Te Hapara	65	19-Jan-94-9-Apr-18	1,731	3.19	1.00	Increasing
GPC053	SFD/Te Hapara	75	20-Dec-88-31-Mar-15	754			No significant trend
GPC061	SFD/Te Hapara	56	8-Nov-94-14-Sep-17	1,348			No significant trend
GPC062	SFD/Te Hapara	58	8-Nov-94-9-Apr-18	938			No significant trend
GPC072	SFD/Te Hapara	63	4-Sep-89-22-Jan-13		-1.24	1.00	Decreasing
GPC078	SFD/Te Hapara	72	10-Apr-90-21-Sep-17	725	1.43	1.00	Increasing
GPD139	SFD/Te Hapara	61	15-Aug-89-7-Mar-17	579			No significant trend
GPD146	SFD/Te Hapara	58	27-Apr-94-25-Jan-18	1,087	0.62	1.00	Increasing

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Site	Aquifer	Samples used	Sampling period	Mean EC Level in 2015	Percent annual change	Probability	Trend
GPE006	SFD/Te Hapara	65	20-Dec-89-17-Nov-17	647	-0.12	0.98	Decreasing
GPG019	SFD/Te Hapara	64	27-Mar-91-17-Nov-17	690	1.01	1.00	Increasing
GPH022	SFD/Te Hapara	77	7-Jun-89-25-Aug-17	792	-0.08	0.96	Decreasing
GPH028	SFD/Te Hapara	47	7-Dec-88-14-Jul-17	854			No significant trend
GPH030	SFD/Te Hapara	59	16-Mar-94-2-Nov-17	507			No significant trend
GPJ081	SFD/Te Hapara	59	16-Feb-94-25-May-18	971	0.47	1.00	Increasing
GPO004	SFD/Te Hapara	63	16-Mar-94-2-Nov-17	574			No significant trend
GPO028	SFD/Te Hapara	63	16-Mar-94-2-Nov-17	578	0.12	0.98	Increasing
GPC094	SFD/Te Hapara	54	27-Jun-96-9-Oct-18	1,440	-0.49	0.98	Decreasing
GPC097	SFD/Te Hapara	17	27-Jun-96-21-Nov-17	40,200	1.32	1.00	Increasing
GPC100	SFD/Te Hapara	18	27-Jun-96-23-Apr-18	544			No significant trend
GPC105	SFD/Te Hapara	18	27-Jun-96-23-Apr-18	1,270			No significant trend
GPB009	Waipaoa	65	19-May-88-8-Jan-13		-0.31	1.00	Decreasing
GPB039	Waipaoa	77	12-Jul-88-29-Mar-18	1,255	0.38	1.00	Increasing
GPB049	Waipaoa	68	28-Apr-88-27-Apr-18	2,463	0.67	1.00	Increasing
GPB111	Waipaoa	41	14-Mar-88-22-Jan-18	1,109			No significant trend
GPB125	Waipaoa	91	27-Jun-88-4-Dec-17	1,100	-0.16	1.00	Decreasing
GPB129	Waipaoa	73	17-Dec-91-10-Aug-17	1,173	-0.19	1.00	Decreasing
GPG076	Waipaoa	40	16-Mar-94-10-Apr-15	111	-0.90	1.00	Decreasing
GPG077	Waipaoa	66	6-Jul-89-2-Nov-17	595			No significant trend
GPJ005	Waipaoa	77	16-Feb-94-25-May-18	1,940	-0.29	0.99	Decreasing
GPJ070	Waipaoa	58	28-Apr-89-5-Oct-17	909	-0.48	1.00	Decreasing
GPJ078	Waipaoa	57	24-May-89-24-Aug-17	3,158	-0.49	1.00	Decreasing
GPO052	Waipaoa	32	17-Oct-01-23-Jul-13		-0.40	1.00	Decreasing
GPB135	Makauri	81	4-Apr-90-29-Mar-18	3,773	-0.04	0.97	Decreasing

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Site	Aquifer	Samples used	Sampling period	Mean EC Level in 2015	Percent annual change	Probability	Trend
GPC112	Makauri	64	9-Nov-94-1-May-18	1,981	-0.88	1.00	Decreasing
GPD039	Makauri	66	11-Jan-88-27-Apr-18	1,148	0.17	1.00	Increasing
GPD111	Makauri	71	29-Mar-88-22-Jan-18	701	0.04	0.98	Increasing
GPD115	Makauri	72	21-Mar-90-22-Jan-18	1,305	1.03	1.00	Increasing
GPD116	Makauri	74	11-Dec-91-4-Dec-17	1,425	0.13	1.00	Increasing
GPF071	Makauri	30	13-Mar-91-12-May-15	1,030	-0.73	1.00	Decreasing
GPF095	Makauri	81	19-Jul-89-4-Dec-17	798	0.11	1.00	Increasing
GPF106	Makauri	70	19-May-88-4-Dec-17	2,042	0.15	0.97	Increasing
GPG026	Makauri	52	7-Aug-91-15-Nov-11		0.25	1.00	Increasing
GPG058	Makauri	88	25-May-88-16-Feb-18	1,428			No significant trend
GPI032	Makauri	67	8-Aug-90-20-Apr-16	1,393	-0.64	1.00	Decreasing
GPJ033	Makauri	63	16-Feb-94-25-May-18	688			No significant trend
GPJ040	Makauri	86	26-May-88-25-May-18	1,645	1.25	1.00	Increasing
GPJ069	Makauri	59	6-Sep-89-24-Nov-15	1,894	0.30	1.00	Increasing
GPB102	Matokitoki	90	19-May-88-16-Feb-18	1,106	-0.01	0.96	Decreasing
GPB126	Matokitoki	102	12-Jul-88-4-Dec-17	1,103	-0.12	1.00	Decreasing
GPB128	Matokitoki	73	10-Jul-91-29-Mar-18	120	-0.06	1.00	Decreasing
GPC003	Matokitoki	69	3-Jun-92-23-Feb-18	2,202	-1.16	1.00	Decreasing
GPD129	Matokitoki	96	12-Apr-88-27-Apr-18	3,457	0.06	0.98	Increasing
GPD130	Matokitoki	91	12-Apr-88-27-Apr-18	1,377	-0.06	1.00	Decreasing
GPD132	Matokitoki	77	12-Apr-88-25-Jan-18	2,621	0.38	1.00	Increasing
GPD134	Matokitoki	94	29-Mar-88-29-Sep-15	2,635			No significant trend
GPD147	Matokitoki	57	28-Apr-92-25-Sep-17	2,530	0.56	1.00	Increasing
GPE040	Matokitoki	74	25-May-88-2-Mar-18	977	-0.66	1.00	Decreasing
GPE041	Matokitoki	73	11-May-88-2-Mar-18	1,252	-0.47	1.00	Decreasing

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Site	Aquifer	Samples used	Sampling period	Mean EC Level in 2015	Percent annual change	Probability	Trend
GPE059	Matokitoki	65	12-May-93-2-Mar-18	1,183			No significant trend
GPF056	Matokitoki	88	11-May-88-4-Dec-17	800	-0.17	1.00	Decreasing
GPF117	Matokitoki	78	7-Mar-90-4-Dec-17	995	-0.29	1.00	Decreasing
GPG059	Matokitoki	88	25-May-88-16-Feb-18	1,300	-0.45	1.00	Decreasing
GPG088	Matokitoki	64	30-Mar-94-16-Feb-18	1,621	-0.08	1.00	Decreasing
GPH008	Matokitoki	59	7-Jun-89-16-Feb-18	694	-0.22	1.00	Decreasing
GPI026	Matokitoki	80	23-Nov-88-10-Jul-18	1,207	0.20	1.00	Increasing
GPJ080	Matokitoki	74	7-Aug-91-25-May-18	1,050	-0.48	1.00	Decreasing

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