Report

Gisborne MAR Stage 2 Injection Trial

Monitoring Period 2018 - 2020

Submitted to:

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Distribution List

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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 injection trialling for the Gisborne MAR project, water is injected into the Makauri Aquifer via an injection well, headworks and filtering system. A MAR site was selected approximately 13 km north west of Gisborne, on the Kaiaponi farmland, south of Waerengaahika (Figure 1). The source water is 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.

Two injection trials have been completed since, being the Stage 1 injection trial in the winter of 2017 and a Stage 2 injection trial in winter 2019. Stage 1 of the Gisborne MAR trial was undertaken between June and September 2017 during the irrigation offseason and the results are reported by Golder (2017a). Key conclusions from the 2017 Stage 1 injection trial were as follows:

- Augmentation of the Makauri Aquifer is technically viable, with 73,180 m^3 being injected in a single well over a time period of 55 days in winter 2017. 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.

In 2018 GDC commissioned Golder Associates (NZ) Ltd (Golder) to provide technical assistance with the Stage 2 Gisborne MAR injection trial. The Stage 2 injection trial included ongoing monitoring of the migration of the 2017 injection plume still present in the area around the injection well, by targeted monitoring in four designated monitoring wells. This was followed by another injection trial and groundwater monitoring between August and November 2019. A total of 39,881 m^3 of water was injected during the 2019 injection trial over a period of 69 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 hydro geochemistry 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 and 2019 injection trials, and;
3) optimise injection infrastructure to give operational efficiencies and reduced running costs.

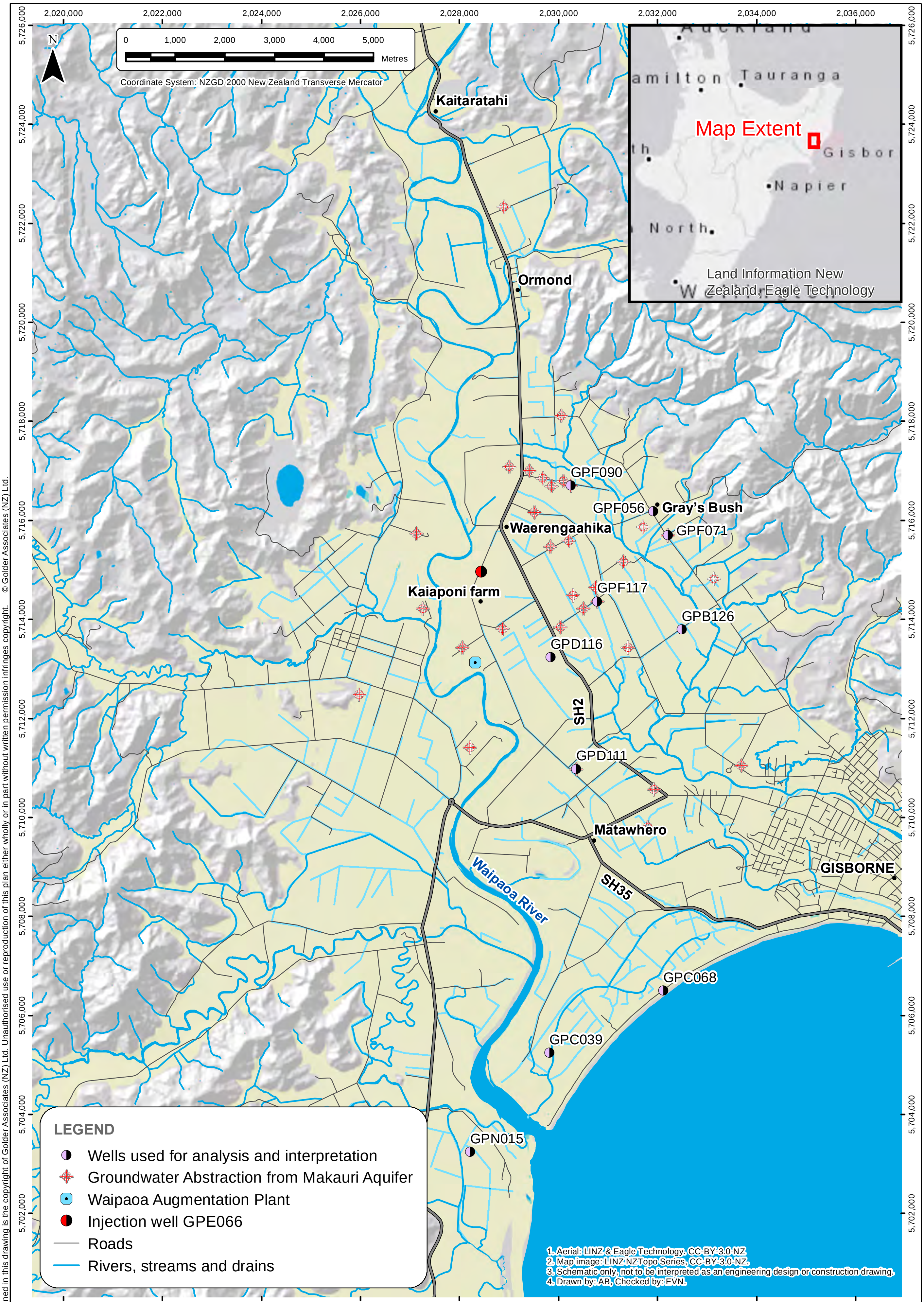
In addition, Golder has further assessed the water management challenges of the Poverty Bay Flat aquifer system and explored how MAR solutions could achieve a catchment-wide improvement of aquifer water quality and yield. This analysis has not been included in this report.

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 2019 injection trial, and the hydraulic and water quality response to the 2019 injection trial.
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 trials 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 injection trial 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 2 of the Gisborne MAR pilot project, and present options and considerations for future MAR developments in Gisborne.



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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) 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. The lateral extent derived from geological modelling is shown in Figure 2.

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.

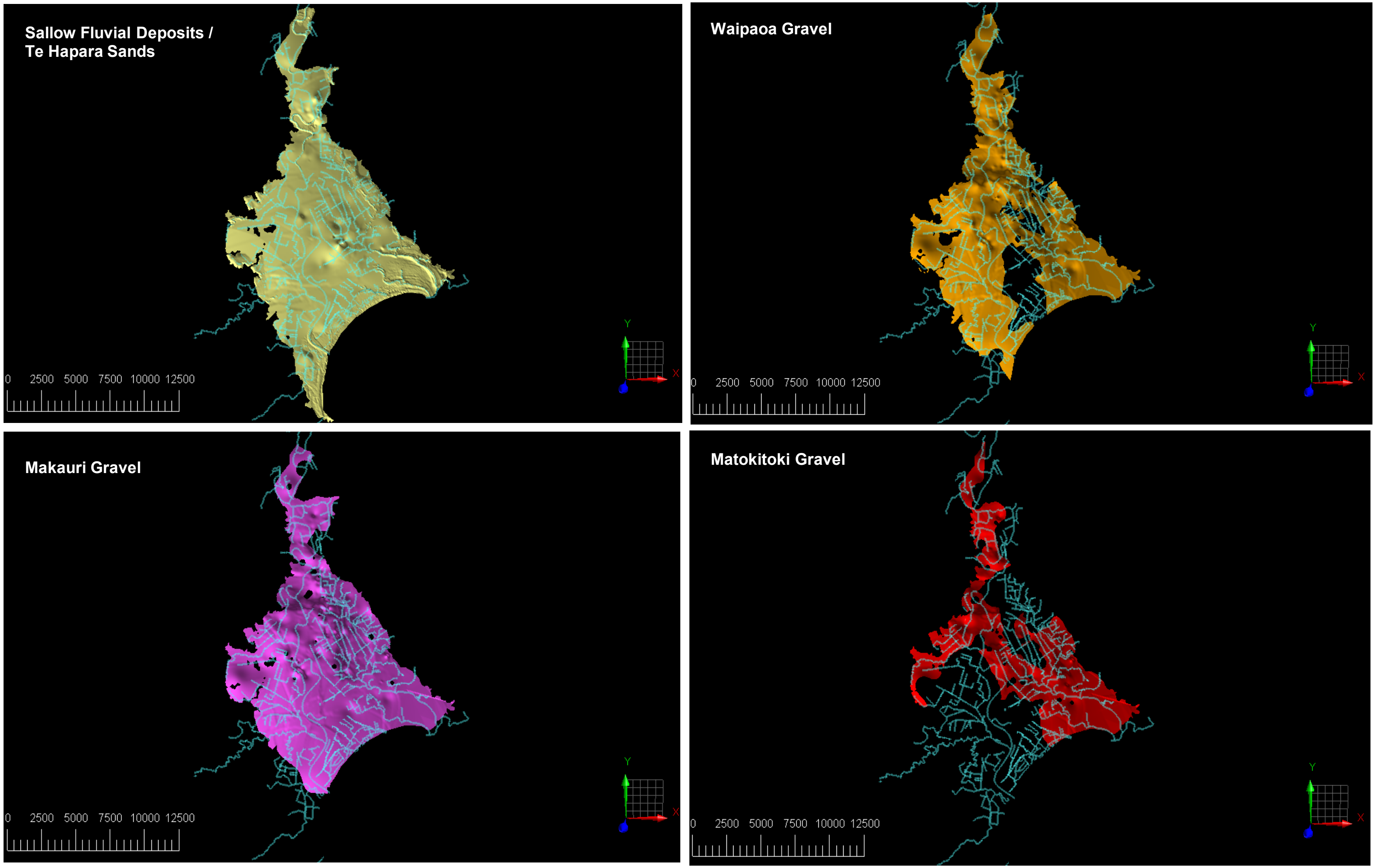


Figure 2: Modelled lateral extent of Poverty Bay Flat aquifers (indicative).

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

Aquifer	Current allocation (m^3)	Estimated abstraction and use in Oct 2016 to Oct 2017 (m^3)**
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 Mm^3 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 groundwater level drawdown in summer which were notably higher than average over that 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 3. Abstraction predominantly for irrigation has a significant influence on groundwater levels in the summer as shown in the bottom pane of Figure 3, 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 4.

Figure 4 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.

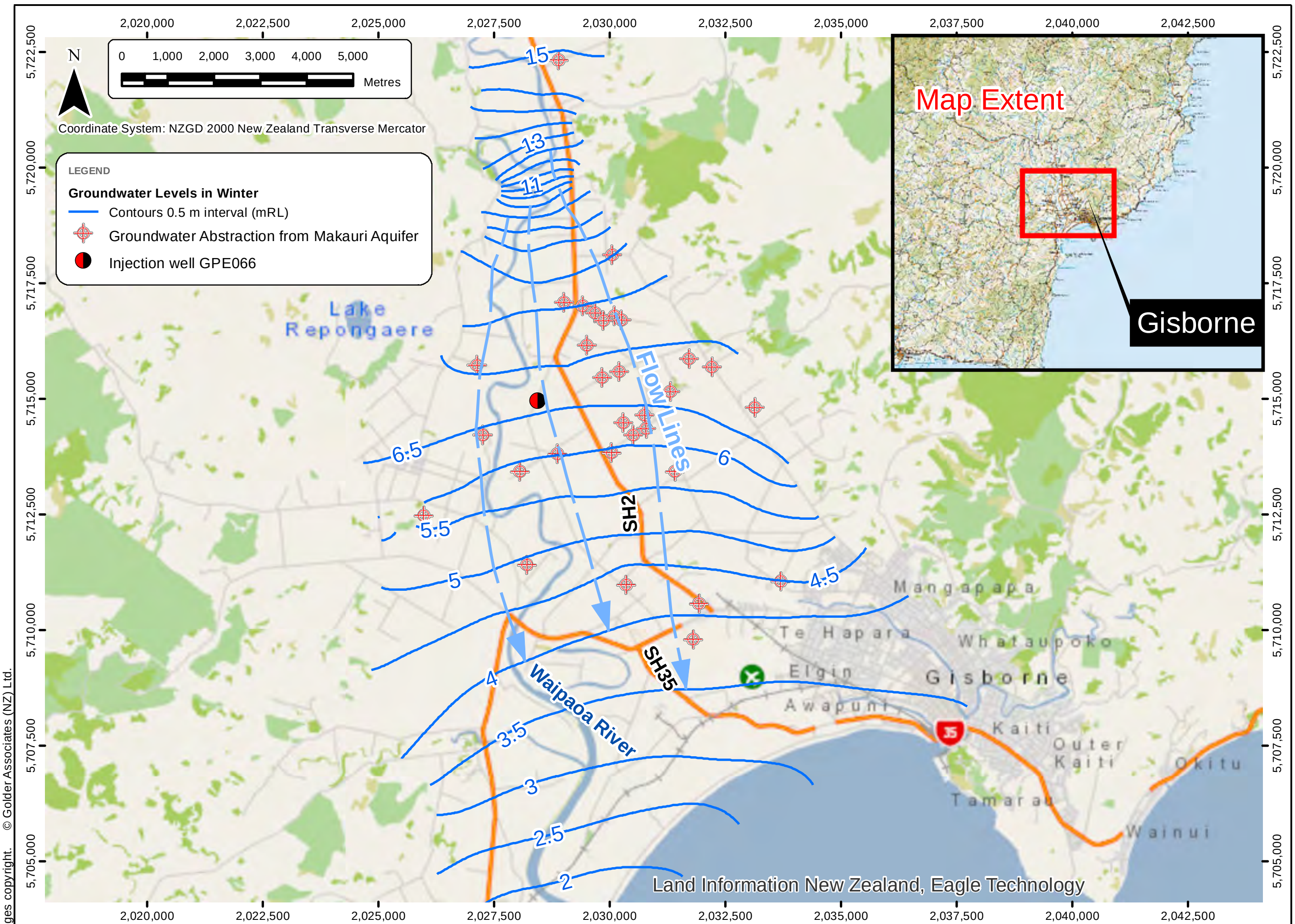
- The Waipaoa, Makauri and Matokitoki aquifers are recharged predominantly from the Waipaoa River in the upper catchment around the Kaitaratahi township, and some inflow from rainfall recharge through the uppermost aquifer along the hills sides where the confining layers are much thinner and the aquifers 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 likely to be screened in the Matokitoki Aquifer[1]. About 600 m southeast is well GPF071 which is screened in the overlying Makauri Aquifer but is not flowing artesian. 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 Matokitoki Aquifer. Taylor (1994) also suggested possible inflow into the Makauri and Matokitoki Aquifers from the eastern hills.

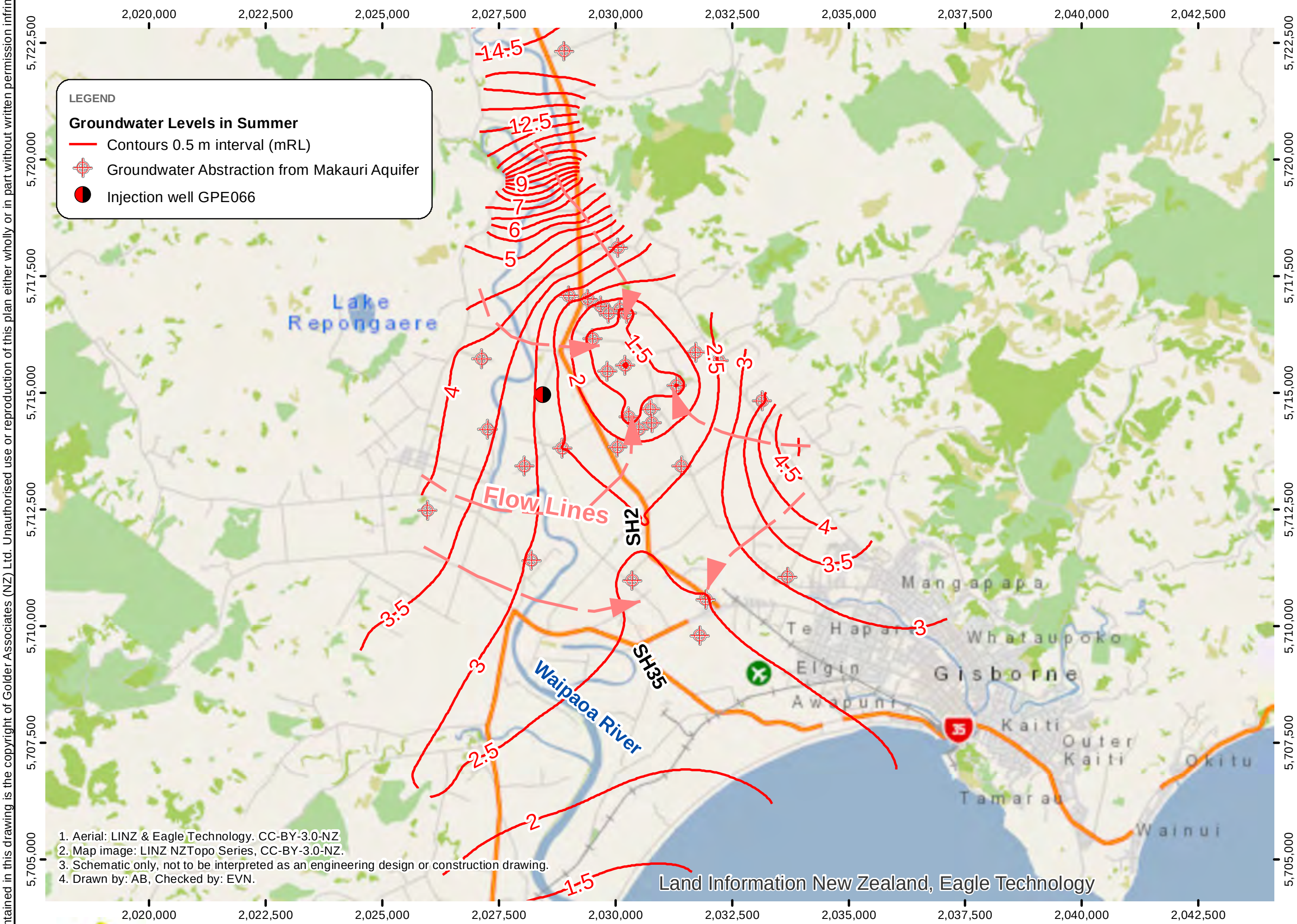
Taylor (1994) suggests a Makauri Aquifer throughflow of 1.25 Mm^3 per year, based on age dating and average thickness of the aquifer of 10 m, but no abstraction. Groundwater modelling (Appendix B) indicate some 2.6 Mm^3/year of throughflow if abstraction of approximately 0.9 Mm^3/year is incorporated. 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.

[1] Whilst well GPF056 is listed on GDC's database as being 111 m deep but screened 11 to 14 m bgl, Golder notes this well is flowing artesian of up to 3 m above ground level, and has a tritium ratio akin to older Makauri and Matokitoki aquifer water according to Taylor (1994). In our view the water quality and water level of well GPF056 does not represent the shallow aquifer, but more likely that of deeper aquifers.





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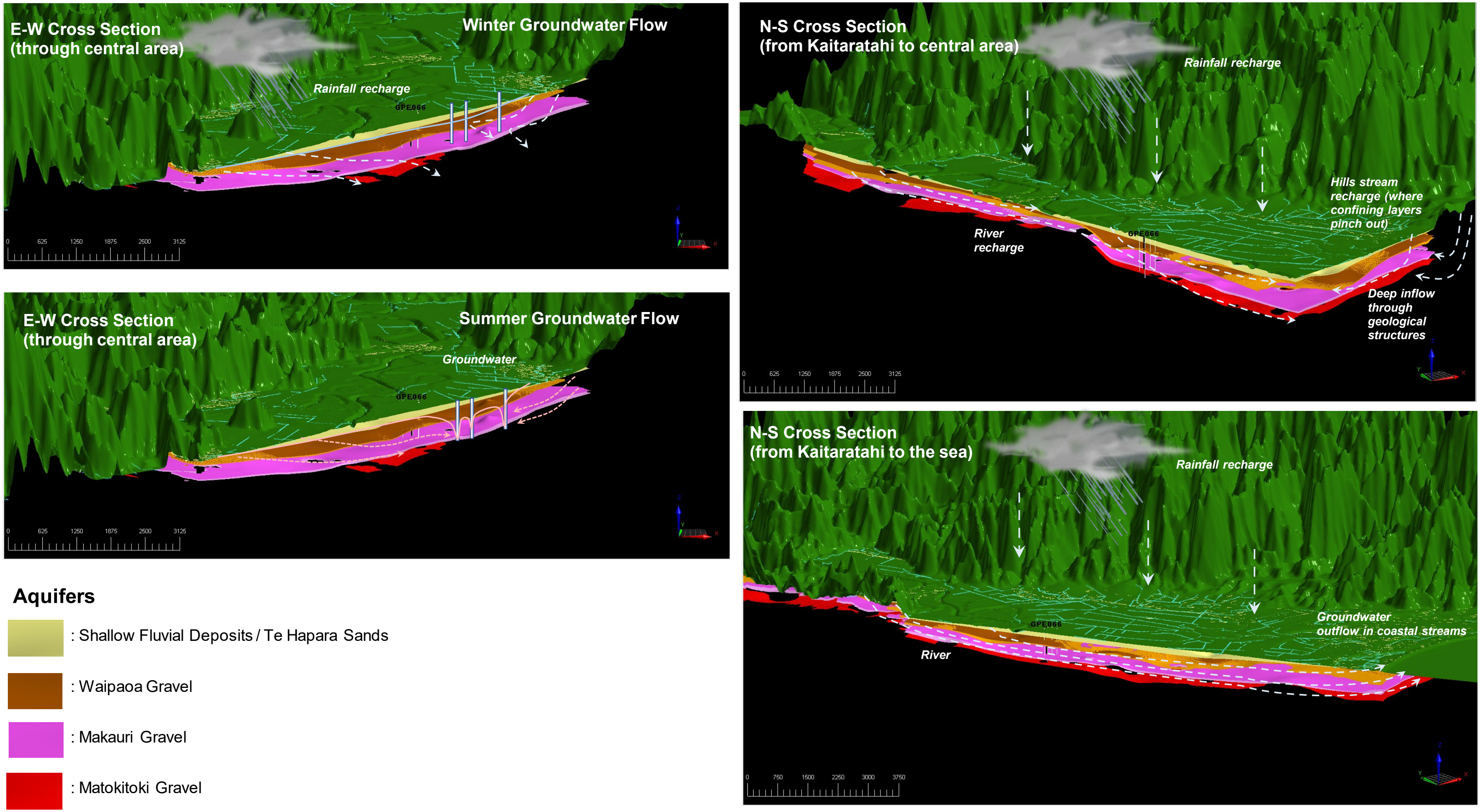


Figure 4: Conceptual model of Poverty Bay Flat groundwater system (confining layers separating the aquifers are not shown).

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 suggest ongoing saline intrusion within this aquifer near the coast.

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. These represent the typical water quality types that can be encountered in the Makauri and Matokitoki aquifers.

Table 3: Various groundwater quality types across the Poverty Bay Flat (chemical composition listed as median values of 2009 - 2019 period).

Well ID	GPJ040	GPD116	GPF056	GPF090	Waipaoa River*
Ground Elevation (m RL)	10.7	7.4	9.8	11.0	-
End Depth (m)	80	76.2	111	51.8	-
Aquifer	Makauri	Makauri	Matokitoki	Makauri	-
Water type	Anoxic mineralised 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	1,420	792	795	407
Major Ions					
Calcium (mg/L)	180	190	120	105	63
Magnesium (mg/L)	22	25	12	12	7
Sodium (mg/L)	158	97	30	63	23
Potassium (mg/L)	7.1	6.3	5.3	5.2	2.7
Bicarbonate (mg/L)	670	840	410	497	208
Chloride (mg/L)	220	65	26	35	11
Sulfate (mg/L)	0.5	0.5	30.0	1.0	68.1
Nutrients					
Ammoniacal-Nitrogen (mg/L)	1.30	1.35	0.31	0.57	0.05
Nitrate-Nitrogen (mg/L)	0.005	<0.002	0.005	0.03	0.16
Metals					
Iron (total) (mg/L)	5.6	9.5	5.0	0.4	0.9
Manganese (total) (mg/L)	0.7	0.7	1.5	0.8	0.2
**Average values for the September 2018 to October 2019 period.*					

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 statistically significant increasing trends. 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 5, 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).

A comparison of the 1993 and 2015 EC contours shown Figure 5 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 6 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.

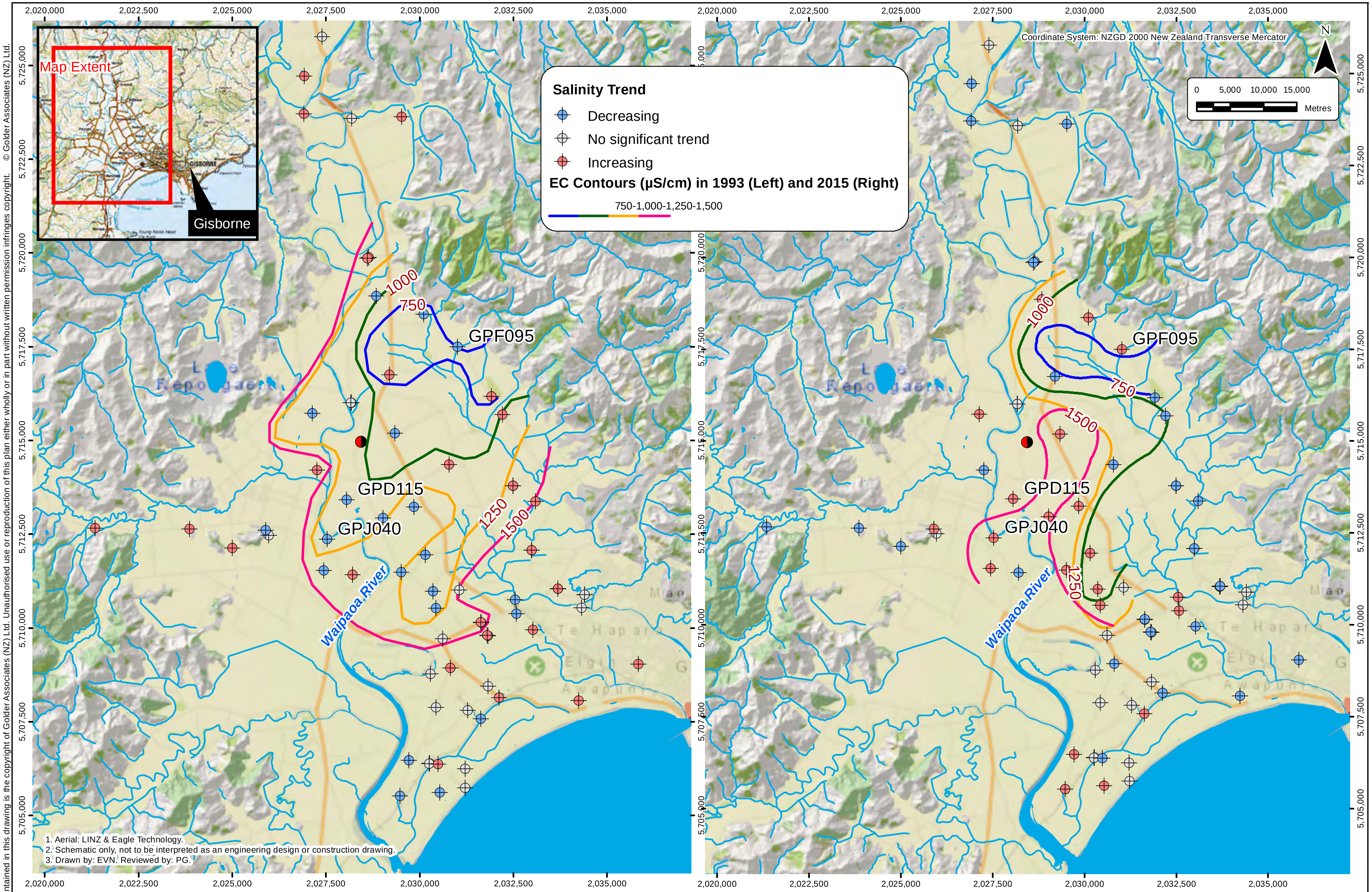
If these trends continue, Golder anticipates a much larger part of the Makauri aquifer beneath the Poverty Bay Flat may become more saline. It is likely the heavy abstraction for irrigation in the central area has caused or at least exacerbated the ongoing increasing salinity trends by drawing connate 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.



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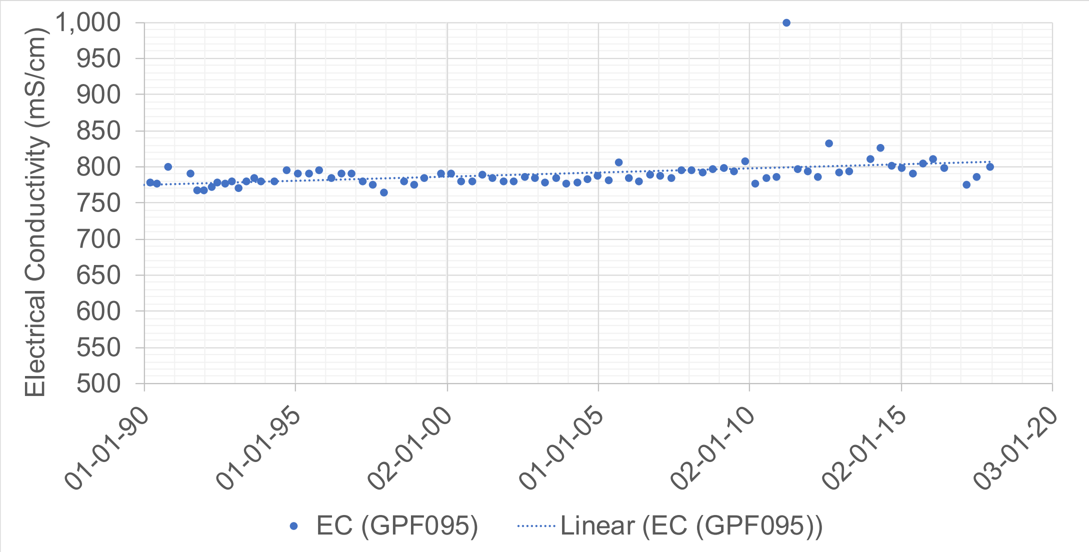
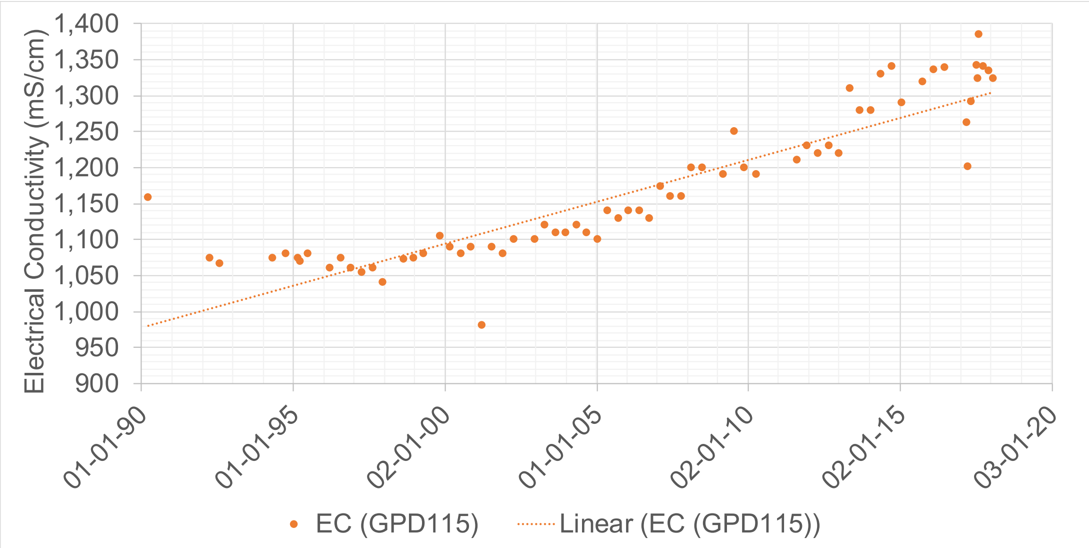




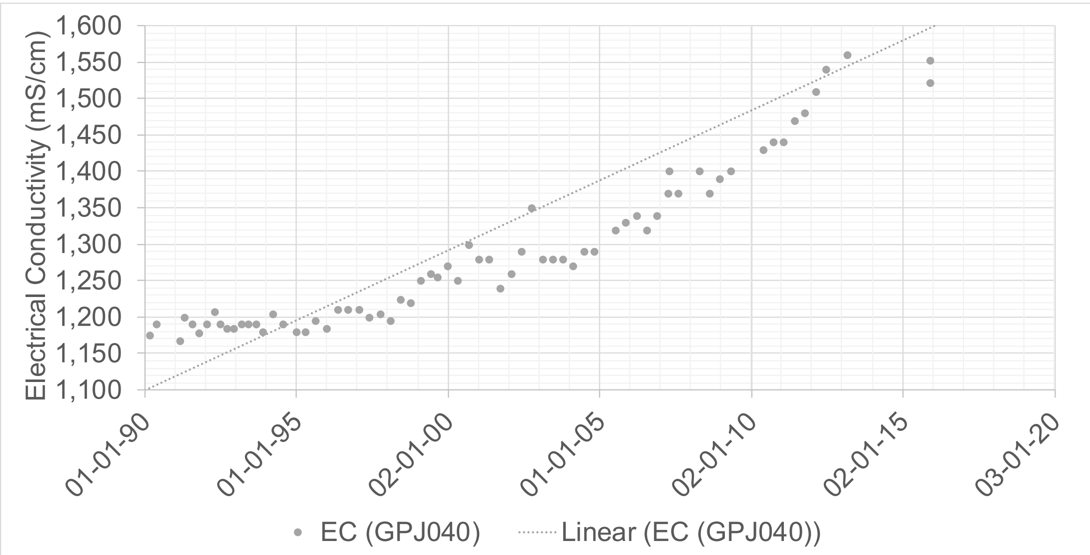


Figure 6: Examples of increased groundwater salinity (EC levels) in water supply wells across the Poverty Bay Flat in the past 30 years.

3.0 MAR INJECTION TRIAL SETUP AND RESULTS

3.1 MAR Injection Trial Setup

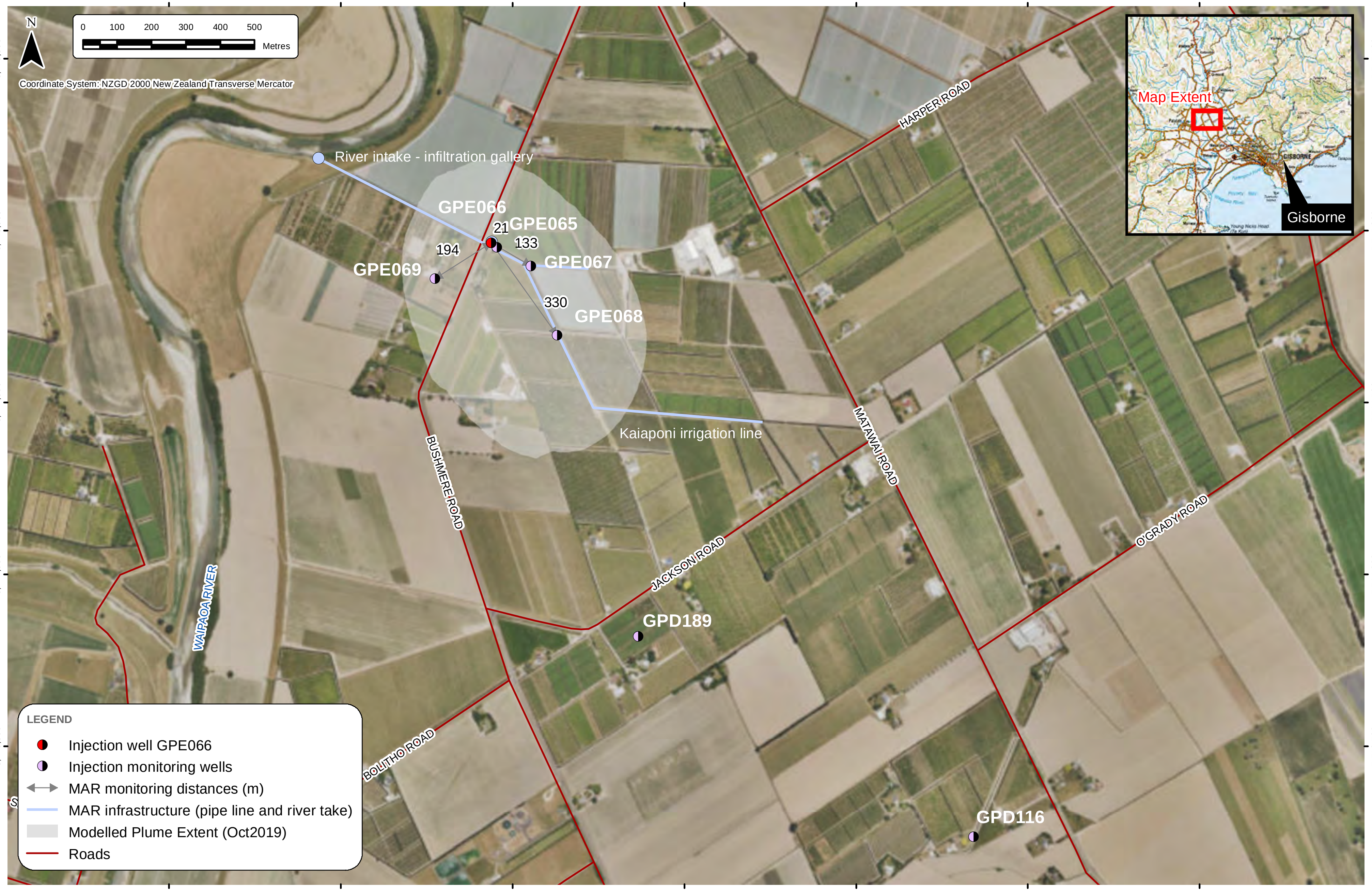
The type of MAR technology used in the Poverty Bay MAR pilot project is referred to as Aquifer Storage Transfer and Recovery (ASTR). ASTR entails the injection of water into an aquifer through an injection well and the recovery of this water some distance downgradient, after the injection water has passed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

The water for injection is 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. 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. Photos of the Waipaoa River intake and the injection well and headworks are included in Figure 7. An overview map of the MAR infrastructure layout and injection trial monitoring wells is included in Figure 8.

Figure 7: Photos of the Waipaoa River intake (left photo) and MAR injection well GPE066 (right photo).

Golder (2019) 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.



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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.

3.2 Injection and Monitoring Program

Injection trails were undertaken in 2017 and 2019 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 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 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 9. 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.

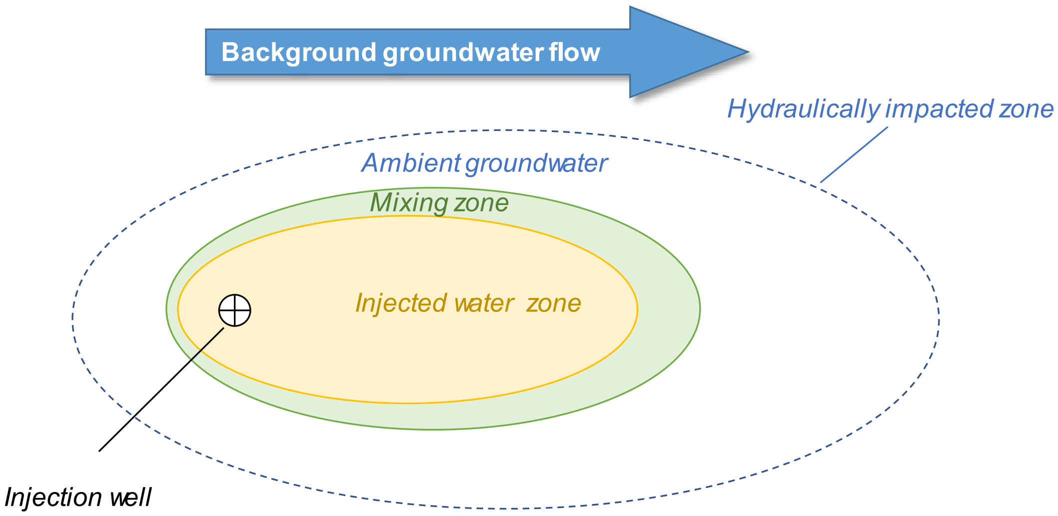

Figure 9: Schematic representation of injection plume development.

Four new monitoring wells (Table 4) were used to monitor the aquifer responses and track the injected plume migration. The locations of the monitoring wells are included in the overview map in Figure 8. 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) can be monitored prior to, during and after the 2019 river water injection.

Table 4: 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
GPE066	Injection well (300 mm steel with 250 mm PVC liner)	2028438	5714964	12.89	0	72.0
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
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
**Golder understand GPD089 has been decommissioned and replaced by GPD189. It is assumed this well is screened in the same aquifer and the well installed at the same location as the previous well. However, no confirmation has been received.*						

An overview of all groundwater level, flow and water quality monitoring that was undertaken prior to, during and after the injection trial in 2019 is included in Table 5. 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. 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, and during the 2019 injection trial. This is also planned to continue following the cessation of the wate injection programme in 2019. This is described in Section 3.5.

Table 5: 2019 Injection trial monitoring programme – September 2018 to October 2019.

Monitoring site	Telemetry data collection	Water quality sampling and testing
Waipaoa infiltration chamber and headworks (source water)	(none)	■ Suite 1: 2x and Suite 2: 1 x ■ 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

3.2.2 Injection programme

Injection rates, volumes and timing of both the 2017 and 2019 injection trials are given in Table 6. No injection has been undertaken in the winter 2018 between cessation of the 2017 trial Stage 1 on the 13 September 2017 and recommencing the Stage II trial on 7 August 2019.

Table 6: 2017-2019 injection trials details.

Injection Details	Winter 2017 Injection Trial	Winter 2019 Injection Trial
Trial period	20 July 2017 to 13 September 2017	5 August 2019 to 13 October 2019
Total injection period (days)	52	69
Total volume injected (m3)	73,180	39,881
Average injection rate (L/s)	14	14
Maximum injection rate (L/s)	19	20

Temporary cessation of injection for well backwashing was required for both the 2017 and 2019 injection trials. However, during the most recent in 2019 both injection pressure and turbidity downstream of the Arkal filter bank triggered several backwashing cycles and cessation of water injection. A stricter turbidity trigger level of 50 NTU is required under the current resource consent for the Stage 2 trial (in 2019), where this was 100 NTU for the Stage 1 trial (2017). This limited the injection period and thus the total amount of water that could be injected in 2019. Nonetheless, lower turbidity levels (less than 10 NTU) were injected during the 2019 trial and this would have reduced the risk of well clogging from sediment. The 2019 injection trial stop and start times are listed in Table 7.

Table 7: Injection periods in 2019 of Stage 2 injection trial.

# Injection (2019)	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

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 10. 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).

In Figure 11 the groundwater level response during the 2019 injection trial is shown, together with the injection flow rates. 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).

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.

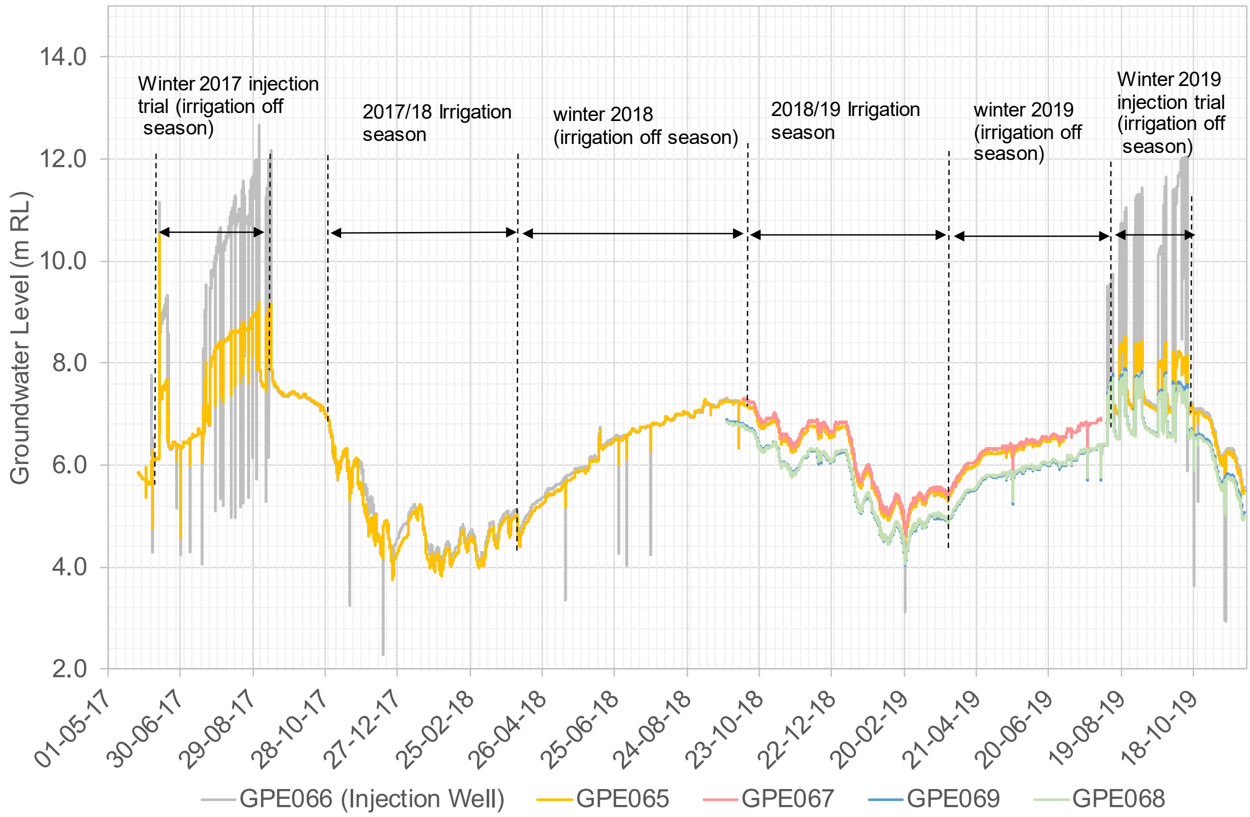

Figure 10: Water levels 2017-2020 monitoring.

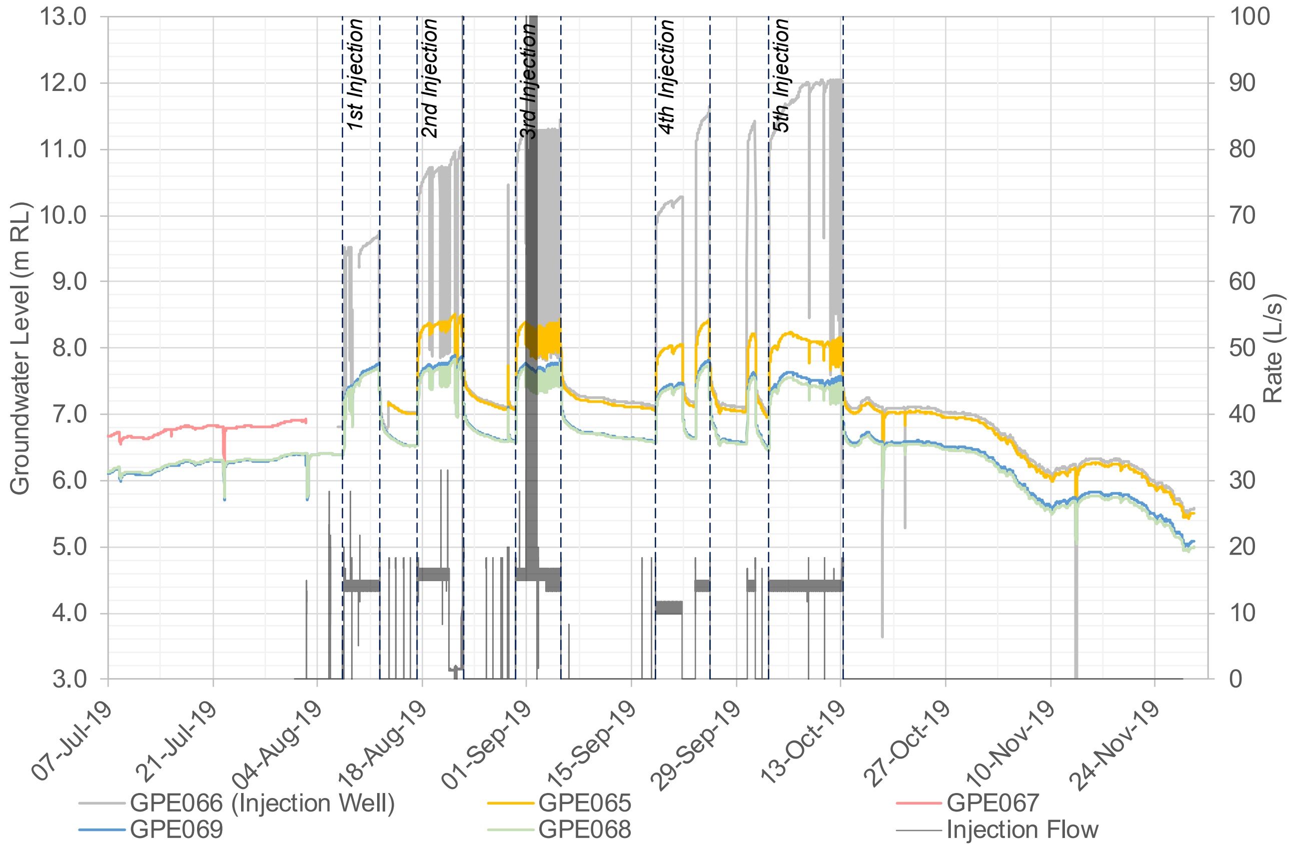

Figure 11: Water levels and flow monitoring.

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 8). 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. 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.

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 12). 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 12. This clearly shows the injection plume is still present near GPE066 (injection well) and nearest monitoring well GPE065, but may have never reached GPE069. GPE067 and GPE068 have gradually become fresher after the 2017 injection and this process seems to be ongoing. At the start of the 2019 injection trial, 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.

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 March 2019, with GPE067 now more akin to the injection water and GPE068 is 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. Irrigation well GPD189 may currently be at the fringe of the injection plume. Concentration contours are conceptually depicted in Figure 13 below.

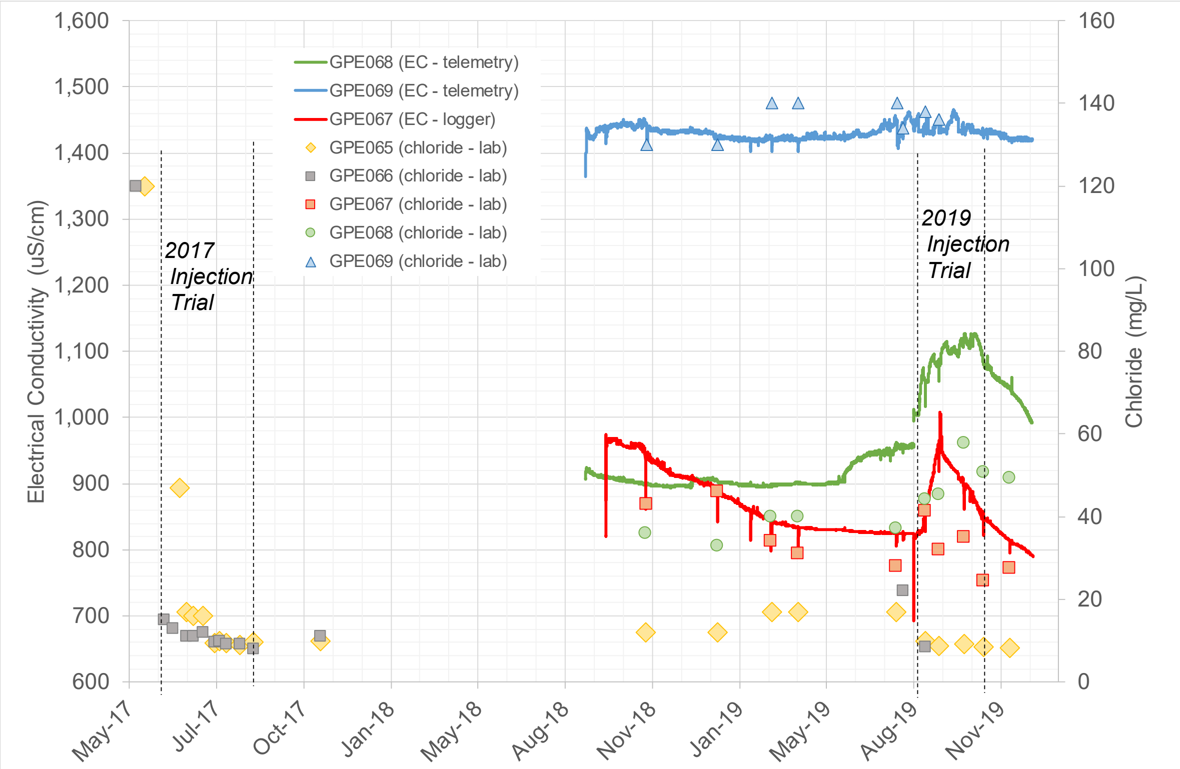

Figure 12: Gradual change in salinity expressed as EC and chloride - plume tracking.

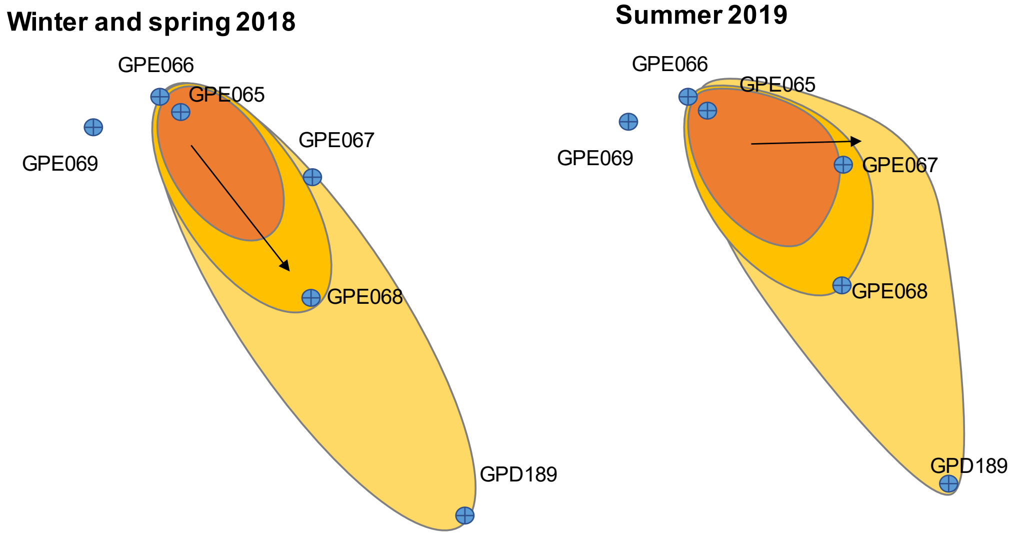

Figure 13: Schematic representation of injection plume development following the 2017 to 2019 injection trials (colour-shading indicatively represents concentration contours influenced by dispersive mixing).

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 result in lowering that 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.

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 sulfate observed, but instead a decrease that corresponds with the mixing of the river water with the sulfate-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 both the 2017 and 2019 injection trial. 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 NZ, 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 injection trial. The results are included in Table 8.

The results indicate the pathogens are present at significant levels in Waipaoa River water abstracted by the Kaiaponi irrigation infrastructure. GPE065, the nearest monitoring well, was tested positive for Enterococci and Somatic coliphages (indictor for viruses) before the 2019 injection trial and during the 28 August 2019 sampling run, after a few weeks of injection. No bacterial contamination has been recorded in GPE067 and GPE068 although injection plume water from the 2017 injection trial would have arrived in these wells. Viruses were detected in GPE067 on a single occasion before the 2019 injection trial.

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 and 2019 injection plume although some pathogens test positive in groundwater at low levels and near the injection well. It appears the pathogens die off rapidly once injected.

Emerging contaminants

GDC has tested Waipaoa River and 2017 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 were caffeine, cotinine, paracetamol and triclosan in several water sampling rounds as indicated in Table 9. Cotinine is found in tobacco and both paracetamol and triclosan are pharmaceuticals. All other tested parameters were below detection limit.

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. However, they could also have come from river injection water of 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.

No conclusions can be drawn from these initial test results other than that emerging contaminants if present in source water will enter the receiving aquifer. Golder recommends a further review when more data is available across the wider catchment, including that of the Waipaoa River water.

Table 8: Pathogens test results.

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 trial						
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 trial						
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	-
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	-

Table 9: Emerging contaminants test results.

	Sample Date/Time	Caffeine (ng/L)	Cotinine (ng/L)	Paracetamol (ng/L)	Triclosan (ng/L)
Prior to 2019 MAR injection trial					
GPE066 (headworks)	15-07-19	<0.5	<0.5	<2	<0.5
GPE065	15-07-19	<0.5	<0.5	<2	<0.5
GPE067	15-07-19	<0.5	<0.5	<2	<0.5
GPE068	15-07-19	<0.5	27	9	<0.5
GPE069	16-07-19	<0.5	24	6	5
During 2019 MAR injection trial					
GPE066 (headworks)	14-08-19	7.4	<0.5	<2	<0.5
GPE065	14-08-19	2.3	<0.5	<2	<0.5
GPE067	14-08-19	9	<0.5	<2	<0.5
GPE068	14-08-19	<0.5	<0.5	<2	<0.5
GPE069	15-08-19	3.4	<0.5	<2	<0.5
GPE066 (headworks)	28-08-19	1.9	<0.5	<2	<0.5
GPE065	28-08-19	3.9	2.8	<2	<0.5
GPE067	28-08-19	4.3	2.3	<2	<0.5
GPE068	28-08-19	<0.5	<0.5	<2	<0.5
GPE069	28-08-19	2.8	4.9	<2	<0.5
GPE066 (headworks)	24-09-19	<0.5	<0.5	<2	<0.5
GPE065	24-09-19	<0.5	<0.5	<2	<0.5
GPE067	24-09-19	24	<0.5	27	<0.5
GPE068	24-09-19	<0.5	<0.5	23	<0.5
GPE069	24-09-19	<0.5	<0.5	<2	<0.5
GPE066 (headworks)	14-10-19	<0.5	<0.5	<2	<0.5
GPE065	14-10-19	149	6.8	58	<0.5
GPE067	14-10-19	19	9.4	1.7	<0.5
GPE068	14-10-19	<0.5	<0.5	<2	<0.5
GPE069	14-10-19	25	8.3	3.4	<0.5

3.5 Injection Well Performance

3.5.1 Injection well inspection and maintenance

Prior to the 2019 injection trial the injection 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 14). 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.

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 Makuari 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 14: 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 Honour 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.

3.5.2 2017 Injection well performance

The well performance was re-assessed following the well-redevelopment in May 2019. The results were compared to those obtained from the initial well performance testing, which was undertaken in 2017 following installation of the injection well.

Performance testing was carried out on the injection well in May 2017, shortly after construction of the injection well, in the form of a stepped rate test and constant rate test. Golder (2017b) documents the testing which consisted of four 120-minute steps at flow rates of 7 L/s, 10 L/s, 13 L/s and 16 L/s). Table 10 presents the results of the step rate test including drawdown and specific capacity. 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.

Table 10: Golder 2017 Step 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	

3.5.3 Specific capacity testing

No stepped rate testing was undertaken following the well-redevelopment in May 2019. Instead, well performance was assessed with specific capacity testing.

Reductions in well performance from clogging can also 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):

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

The specific capacity can be tested by pumping 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.

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.

Abstraction specific capacity testing

The 2019 injection trial has ceased mid-October 2019, which provided an opportunity in the ideal period to undertake well performance testing to assess the performance of the injection well. Three separate pumping tests were performed over the reporting period which are summarised in Table 11. In each of the tests, abstraction rates in the well were kept constant for at least 2 hours at approximately 15 L/s. Drawdown data and flow rates were obtained for each test from the telemetry data.

Table 11 provides results of the specific capacity testing. There is a notable difference between the results from the August testing (prior to the injection trial) and those testing in October and November. Average abstraction specific capacity of the August test was 5.41 L/s/m compared with the October and November tests which average 4.2 L/s/m and 4.32 L/s/m respectively (Figure 15). The November results are comparable to the October results suggesting no reduction of well performance over this time period. Over the duration of each test abstraction specific capacity steadily declines, this is likely due to greater drawdown occurring within the well.

Comparing these results to Golder's 2017 step test results, it appears well performance of the injection well has improved since the previous testing. It appears the recent re-development by airlifting to remove the clogging material has been largely successful at improving performance of the well.

Table 11: Well Performance Testing 2018 – 2020.

Date	Duration (mins)	Average Rate (L/s)	Average Specific Capacity (L/s/m)
02/08/2019	120	15.2	5.41
18/10/2019	130	14.6	4.46
13/11/2019	130	15.6	4.58

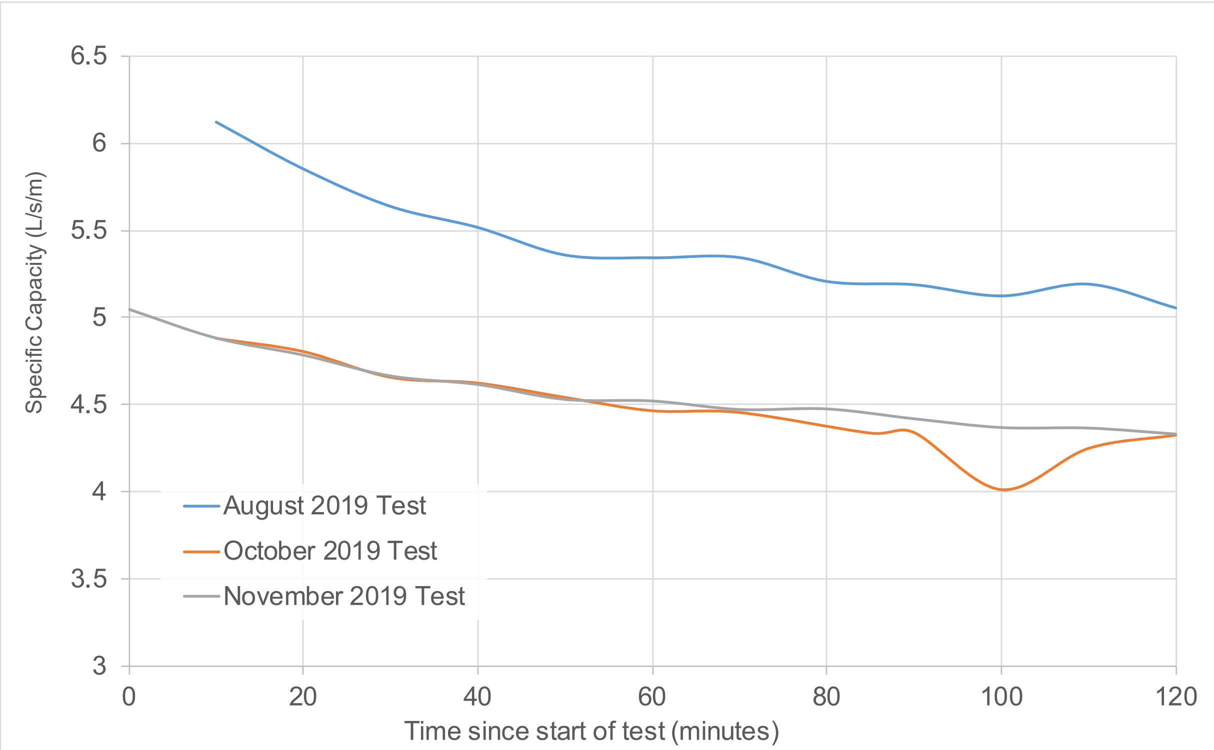

Figure 15: Abstraction specific capacity testing of GPE066.

Injection specific capacity testing

The performance of the injection well was also assessed by deriving specific capacity data from telemetered recordings of the 15-minute flow data. Given injection testing was undertaken over a period of several months, water level from the well needs to be corrected to remove the natural increase of water level rise caused during the winter recharge. Nearby monitoring wells showed a small increasing background trend of 0.002 m/day over the injection period. This background trend was removed from the water level data and the specific capacity over the entire trial period was plotted in Figure 16, together with the well turbidity data (1 minute data). The results suggest the following:

- 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 16 (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.

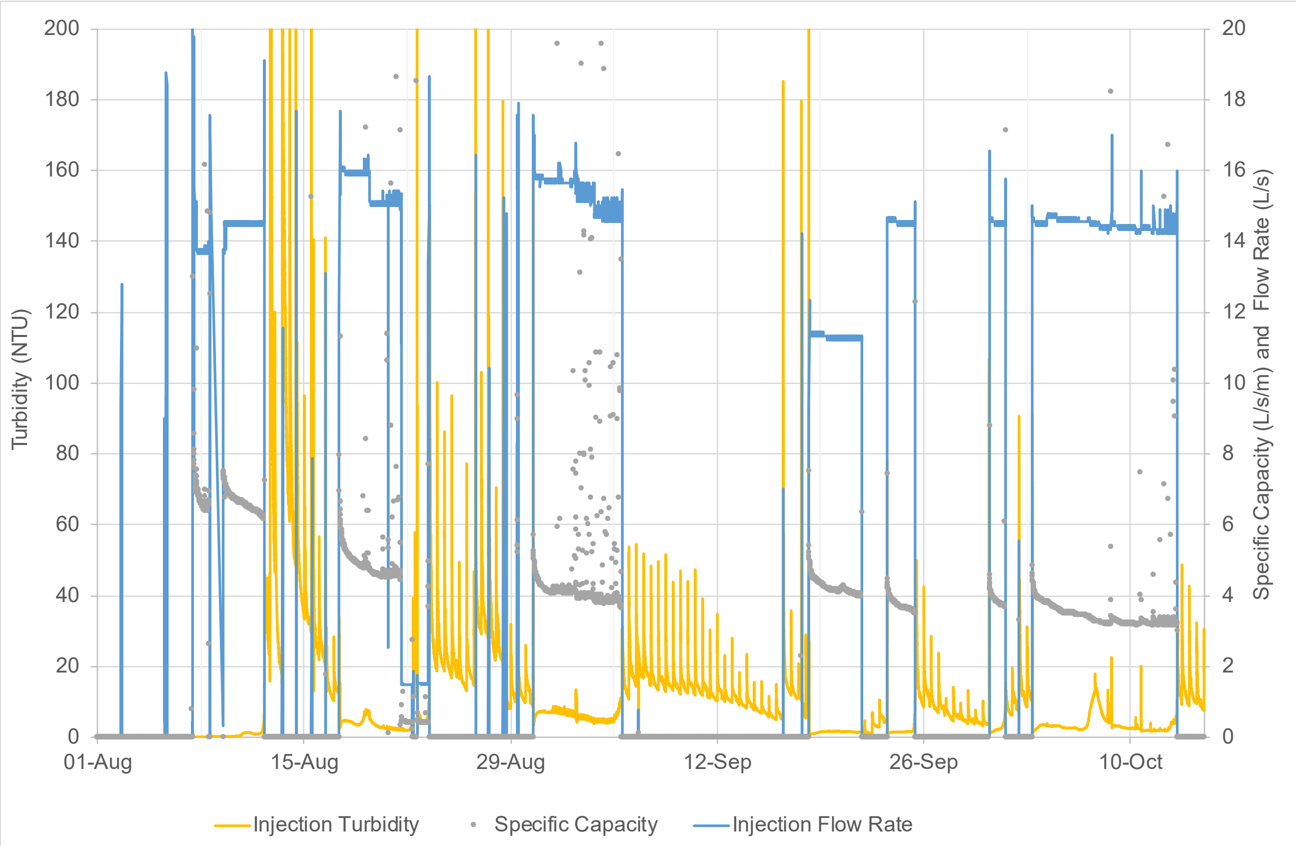

Figure 16: Injection specific capacity testing, August – October 2019.

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). 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.

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 hills 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. 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 and 2019 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 both the 2017 and 2019 injection trials. However, during the most recent in 2019 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 2019. 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 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 and 2019 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 and 2017 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 were caffeine, cotinine, paracetamol and triclosan in several water sampling rounds. No conclusions can be drawn from these initial test results other than that emerging contaminants if present in source water will enter the receiving aquifer.
- 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 lead to reduced well performance due to clogging. The clogging material is most likely formed by iron sulphide deposition. 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 injection trial. Over the five periods of injection during the 2019 trial, well backwashing between these periods of injection appear to have temporarily increased the well performance followed by rapid decline. The results underpin the importance of controlling turbidity levels in the injection water to maintain well performance during injection.
- 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.

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 managed 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.
- Both the 2017 and 2019 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.

5.0 REFERENCES

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APPENDIX A

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Report Limitations

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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.

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.

- 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*		

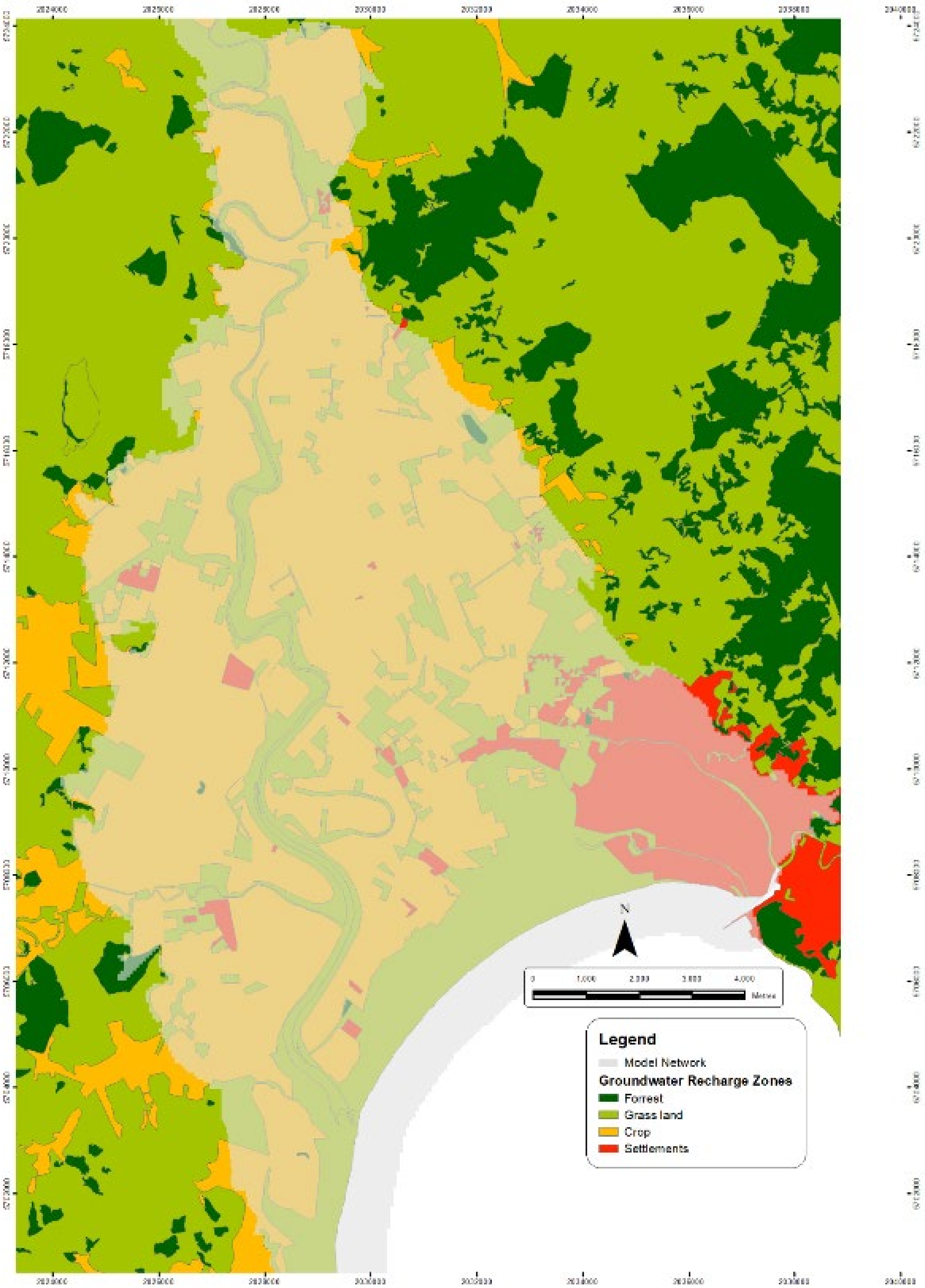


Figure B2: Groundwater recharge land use zones.

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

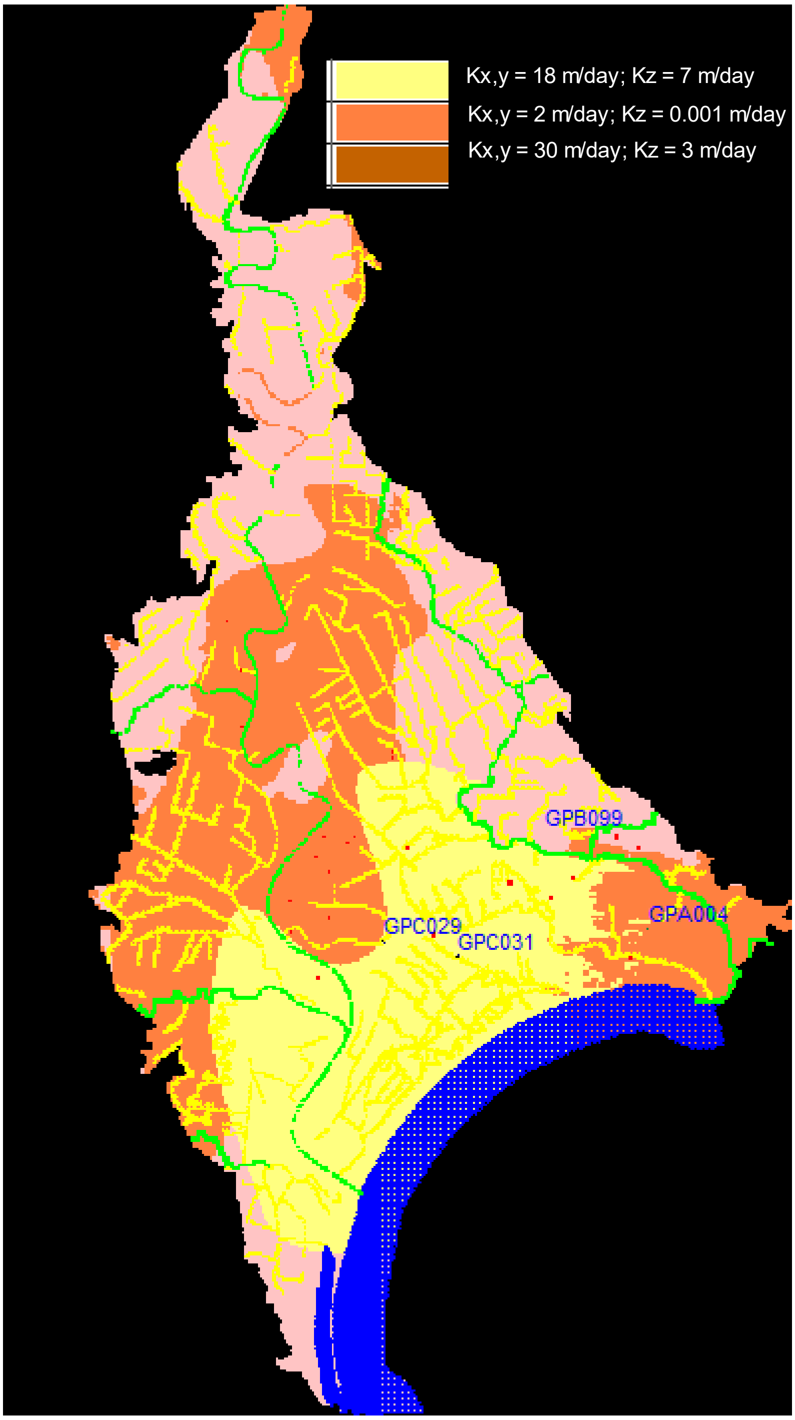


Figure B3: Layer 1 conductivity zones in Gisborne groundwater model.

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.

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.

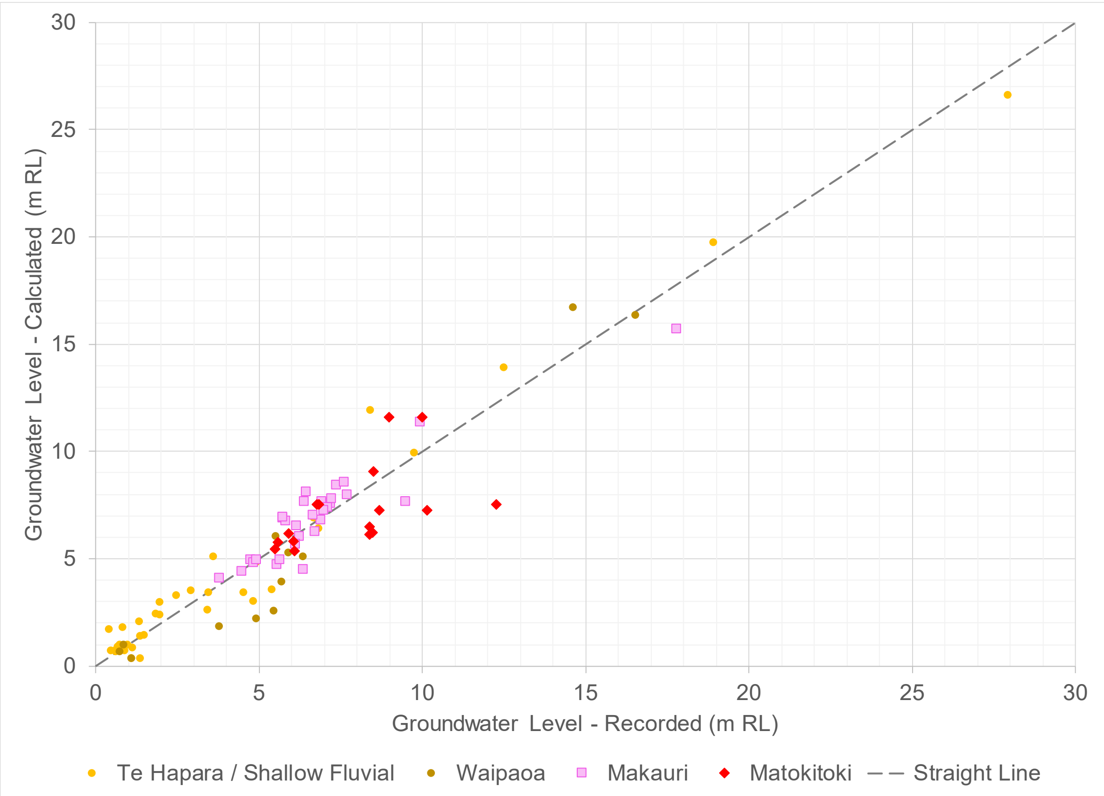


Figure B4: Recorded versus modelled groundwater levels – steady state model.

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 (m^3/day)	Outflow (m^3/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. Specific Storage (SS) has been optimised on the transient calibration and optimised value is included in Table B2.

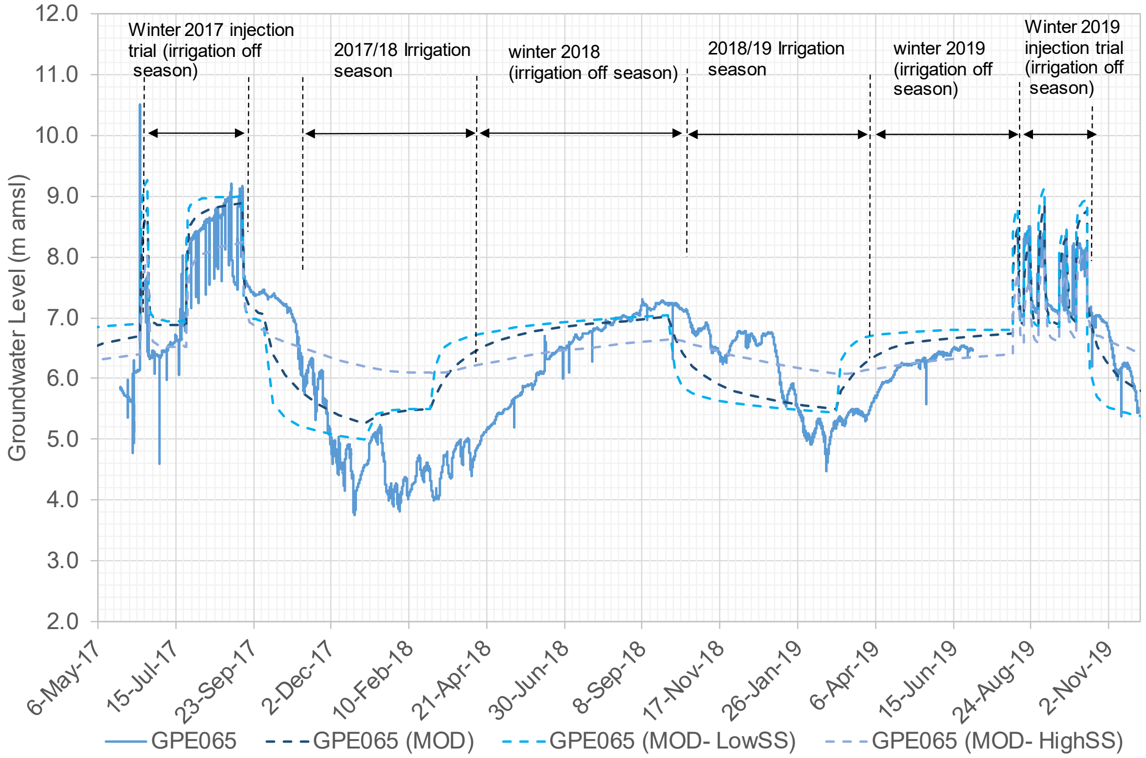


Figure B5: Observed (line) versus modelled (dashed) water levels at monitoring well GPE065.

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.

APPENDIX C

Hydrogeochemical Processes and Plume Tracking during Injection Trials

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 8 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 southeastern 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 3.4 and locations shown in Figure 8 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 the table below, 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.

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 %).

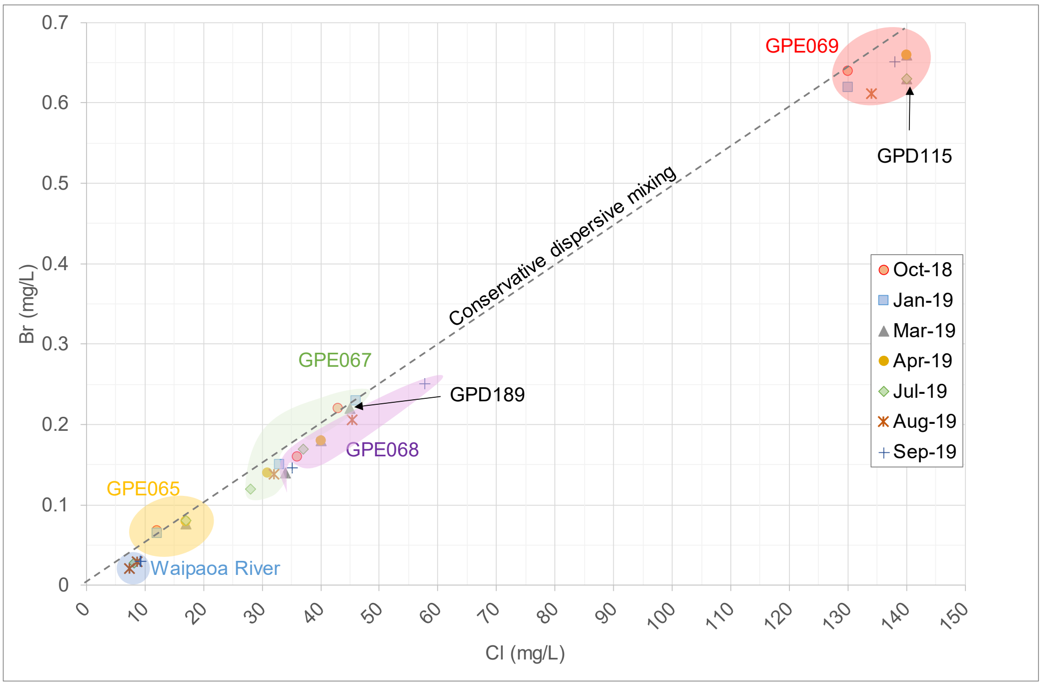
Table C1: Field testing results and plume tracking.

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*							

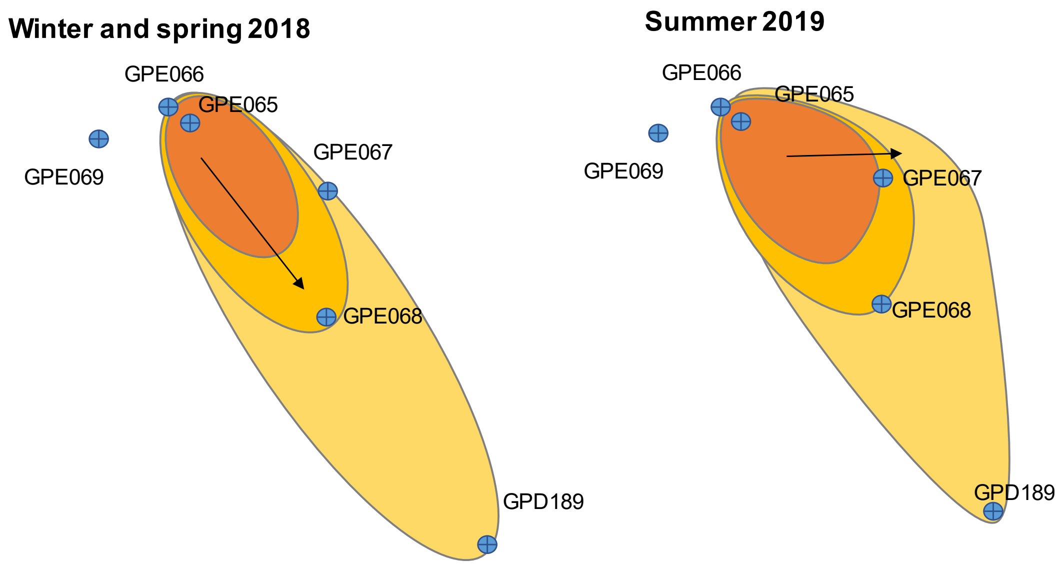
When plotting the Bromide (Br) against the Chloride (Cl) concentrations (see graph below), the progressive dispersive mixing is also apparent. The dotted line in the graph represents mixing between river water and ambient groundwater which have very different compositions of Cl and Br. For components 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 March 2019, with GPE067 now more akin to the injection water and GPE068 is shifting to the water quality signature of ambient groundwater.

The graph also suggests that irrigation well GPD189 at approximately 1 km southeast of injection well GPE066 receives water similar to river water, and possibly received the 2017 MAR injection plume water at least since March 2019. Irrigation well GPD115 at 1.5 km distance southwest of the injection well has similar water quality as GPE069 representing ambient groundwater.



The 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. Irrigation well GPD189 may currently be at the fringe of the injection plume. Concentration contours are conceptually depicted in the figure below.



Plume tracking by groundwater and solute transport modelling.

Golder has also attempted to model the plume extend at different times prior to, during and after the 2019 injections trial, as the 2017 injection plume is still present around the injection well. Golder's Gisborne groundwater model has recently been updated (Appendix B) and used to assess the hydraulic and water quality response to the 2017 and 2019 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:

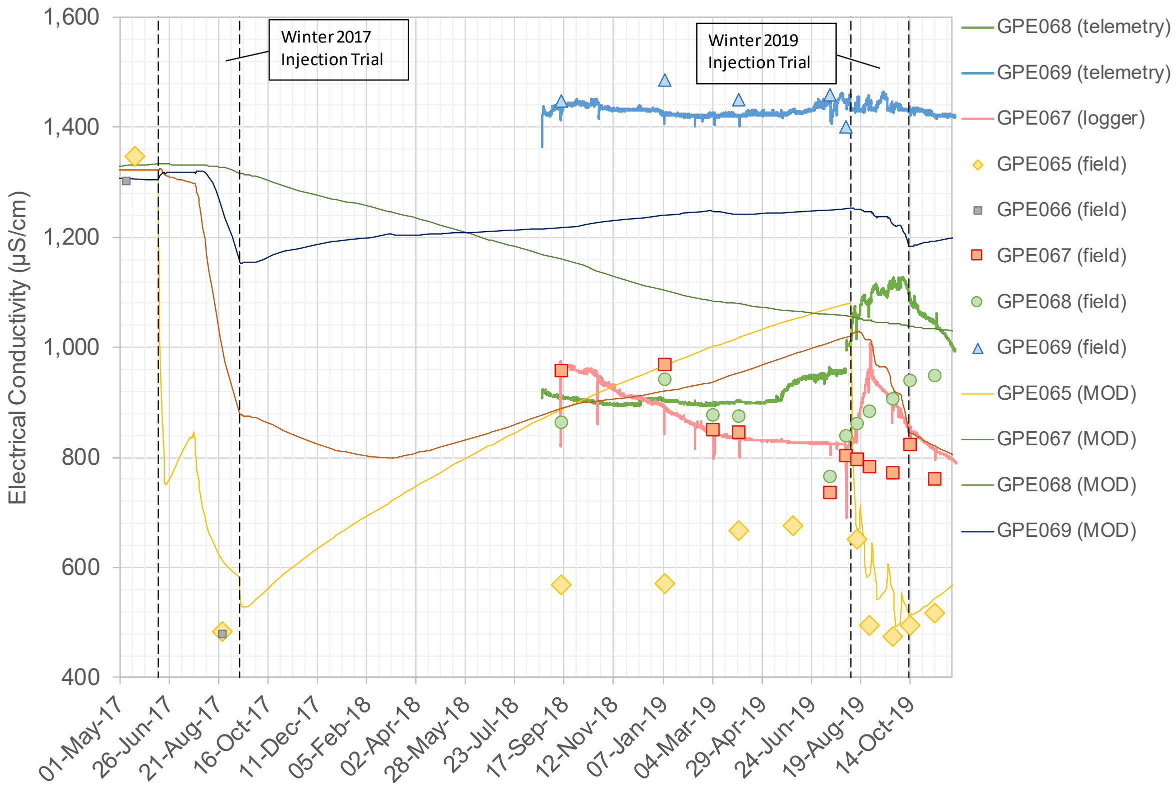
- Background groundwater EC from recorded observations remains below 1,500 µS/cm with a median value used for the solute transport modelling of 1,320 µS/cm from wells GPE065 and GPE066 (March to May 2017).
- From the Waipaoa River at the Infiltration Chamber water EC median values of 390 µS/cm and 490 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 up to 1 year prior to 2019 injection plume and post-trial. Very limited EC data is available for the pre- and post-2017 trial.

The first graph 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 this 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, which occurred during winter with no significant abstraction from irrigation. 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.

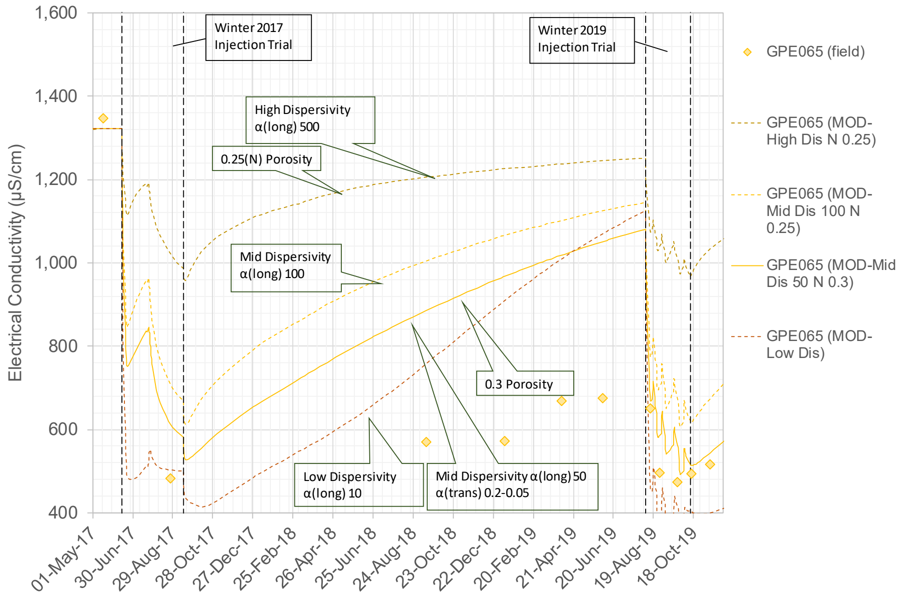


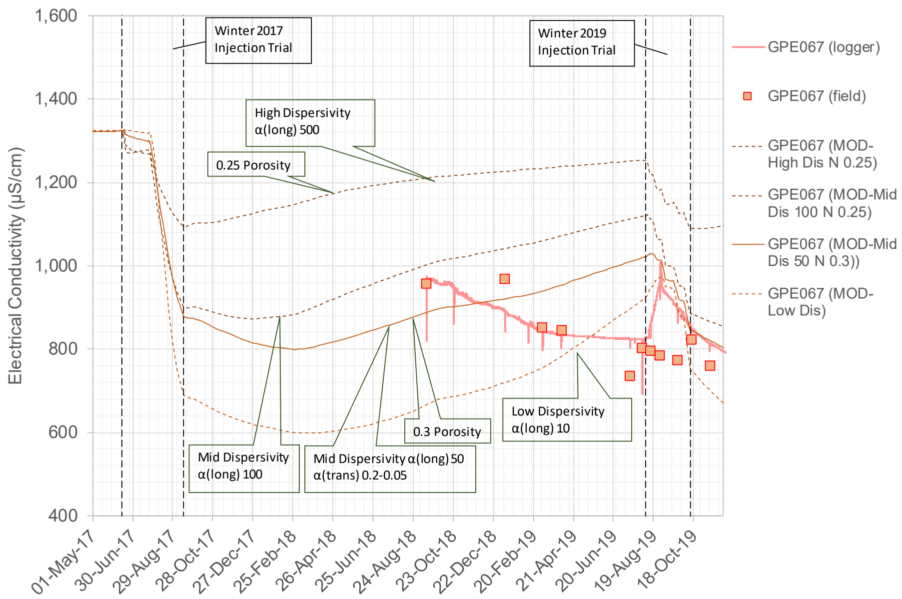
Dispersivity and porosity were varied in the model to assess their sensitivity to the amplitude and timing of plume breakthrough in the three monitoring wells that have received the plume (GPE069 has not shown to ever have received the plume). The results for each of those three monitoring wells are shown in the three graphs below.

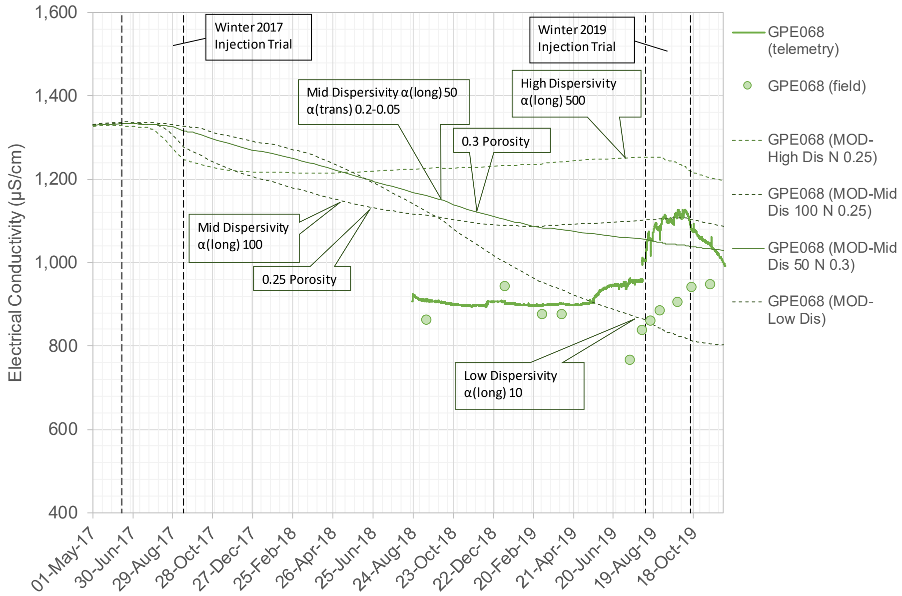
Dispersivity is very sensitive meaning that slight changes will result in notable changes in breakthrough. In general, a lower dispersivity results in the best fit between modelled and recorded EC levels. Porosity governs the breakthough timing, and in general higher values show a better fit between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







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
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

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
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
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

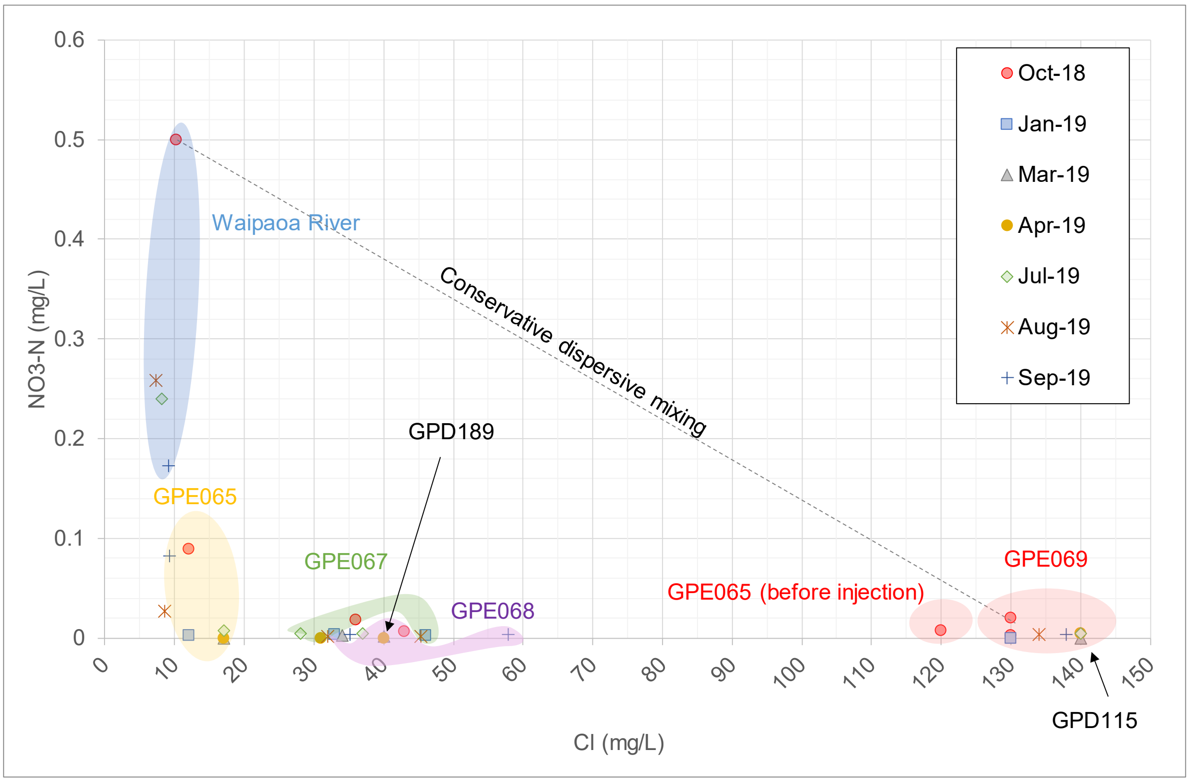
Hydrogeochemical Processes

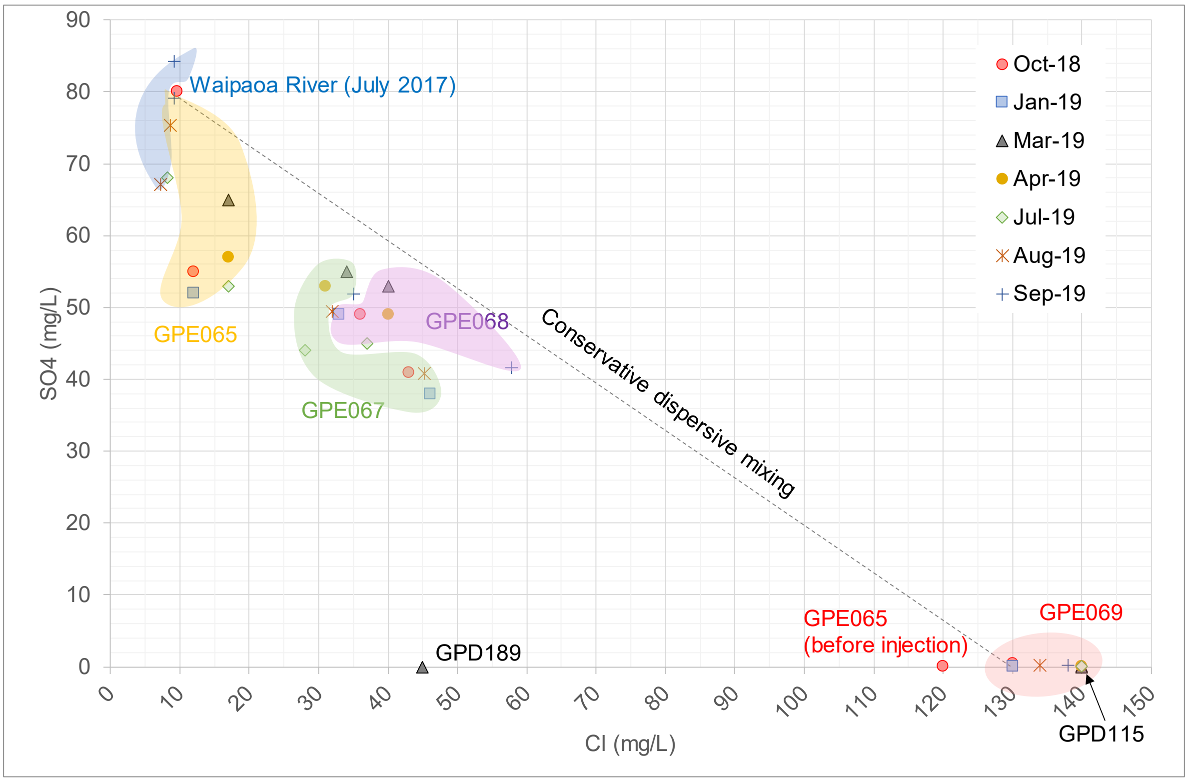
Redox state

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.

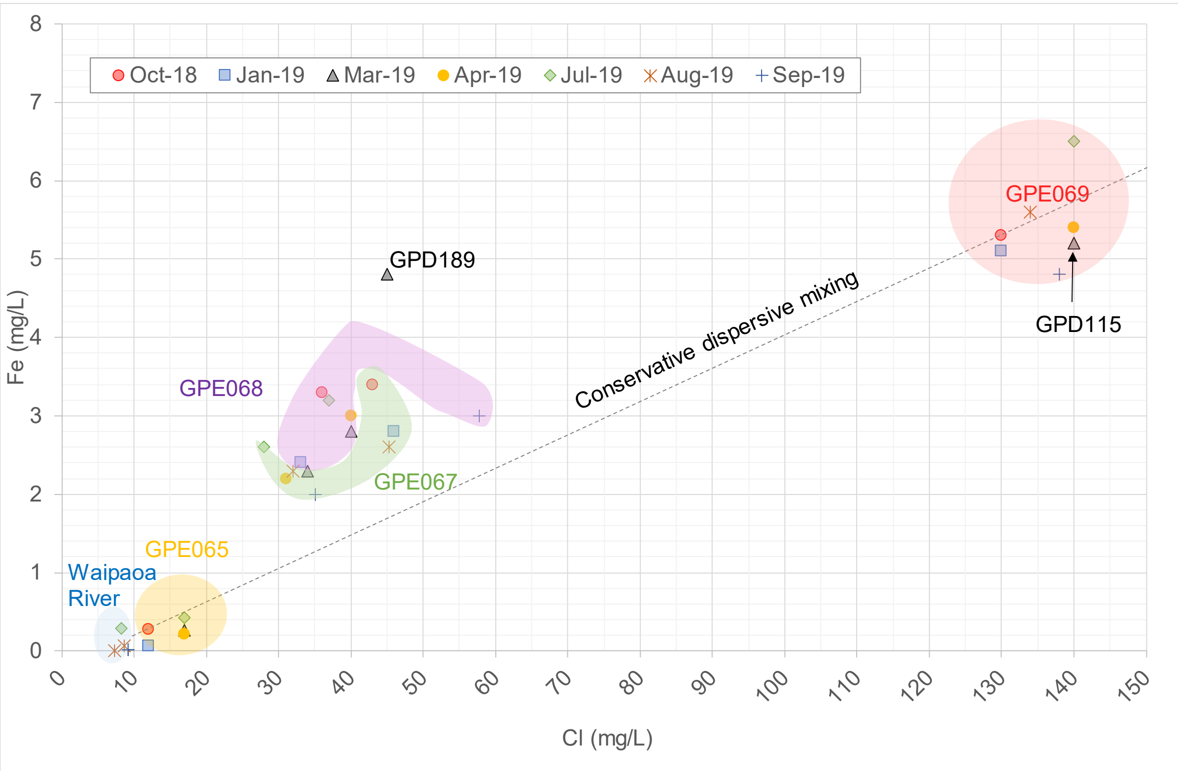
In the graphs below the nitrate-N (NO_3) and sulphate (SO_4) have been plotted against the chloride (Cl) concentration. Median values for Waipaoa River water and GPE065 water prior to the 2017 injection have been included in the graph as well. Both the concentration of NO_3 and SO_4 fall more strongly than what would be expected from conservative dispersive mixing. 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 and July 2019. 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, nut this is expected to gradually decline again now that the 2019 injection trial has ceased.

Pyrite oxidation would have resulted in a sulphate 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.

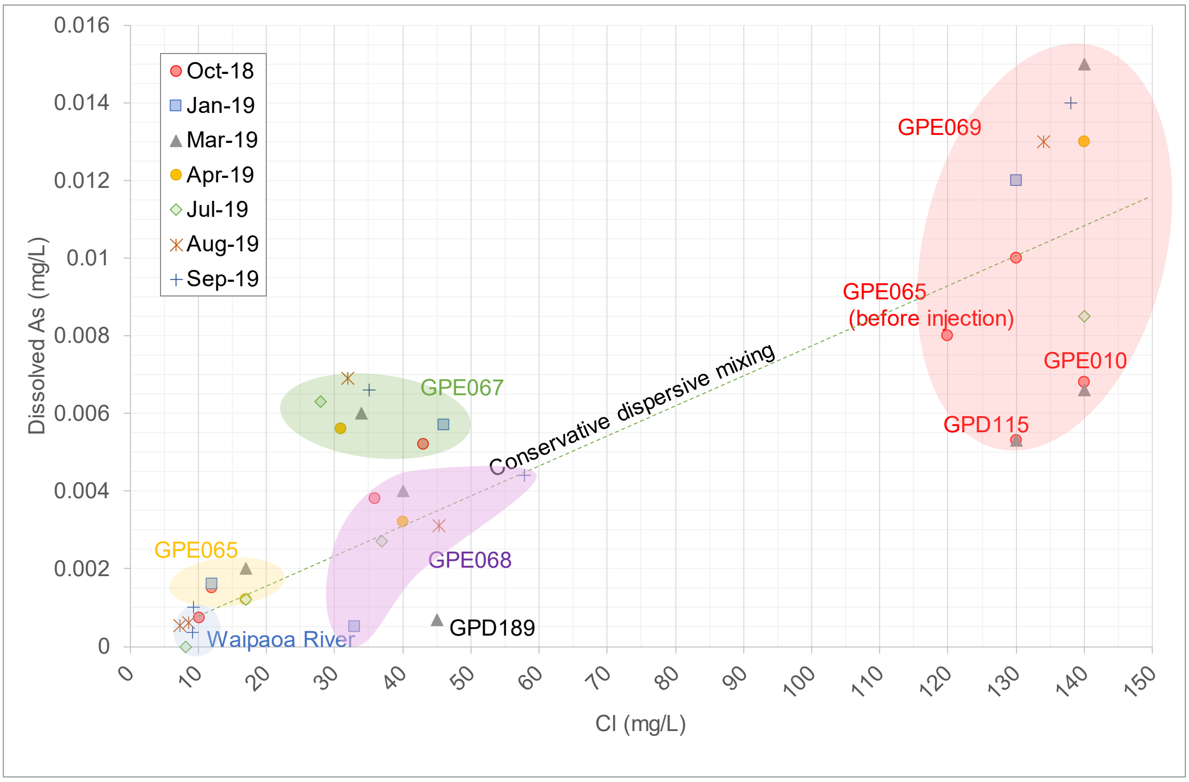




Where iron concentrations appeared to decrease in GPE067 and GPE068 in the March 2019 monitoring round relative to the October 2018 and January 2019 rounds, this trend seems to have reversed in the April to September 2019 sampling rounds. The changes in iron concentrations appear to be associated with changes in groundwater flow direction as described above, and not due to hydrogeochemical reactions.



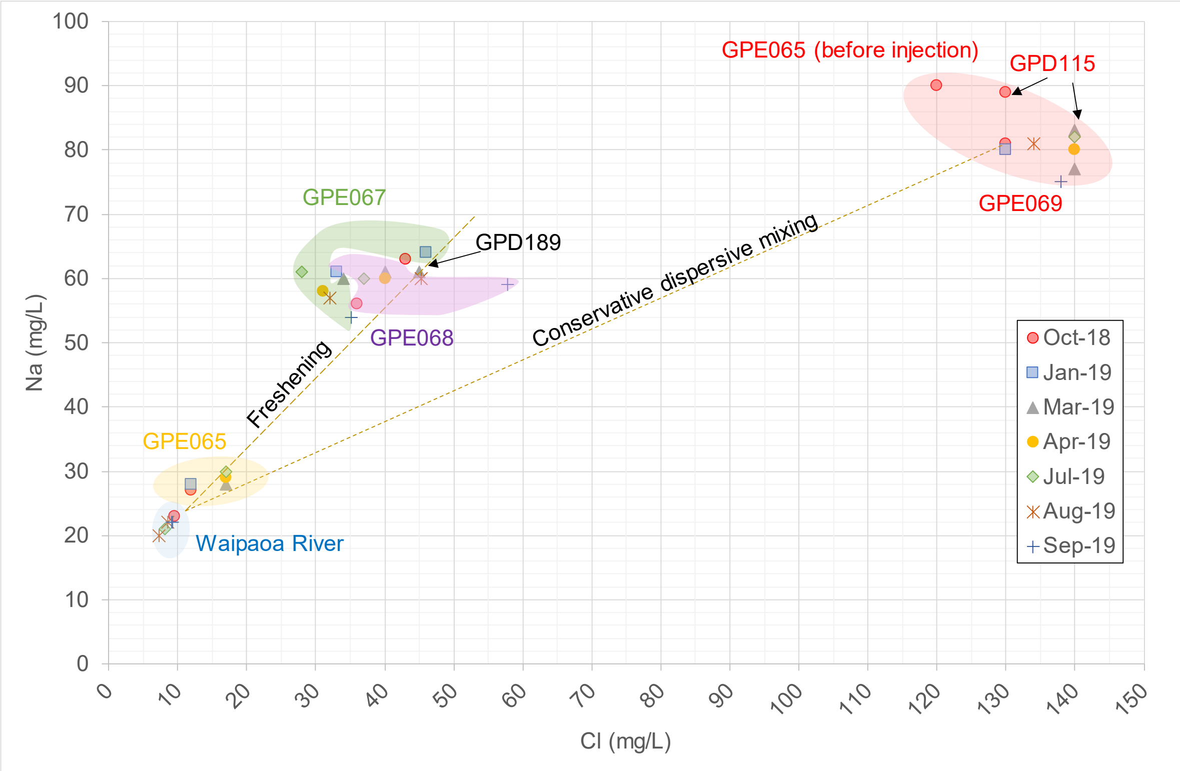
Significant arsenic mobilisation (a concern with pyrite oxidation) does not seem to occur, as suggested by the graph below. Concentrations are highest in GPE069 which has a composition similar to ambient groundwater for the other parameters. The low arsenic concentration in GPE068 in the January 2018 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.



Cation Exchange

In the graph below 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.

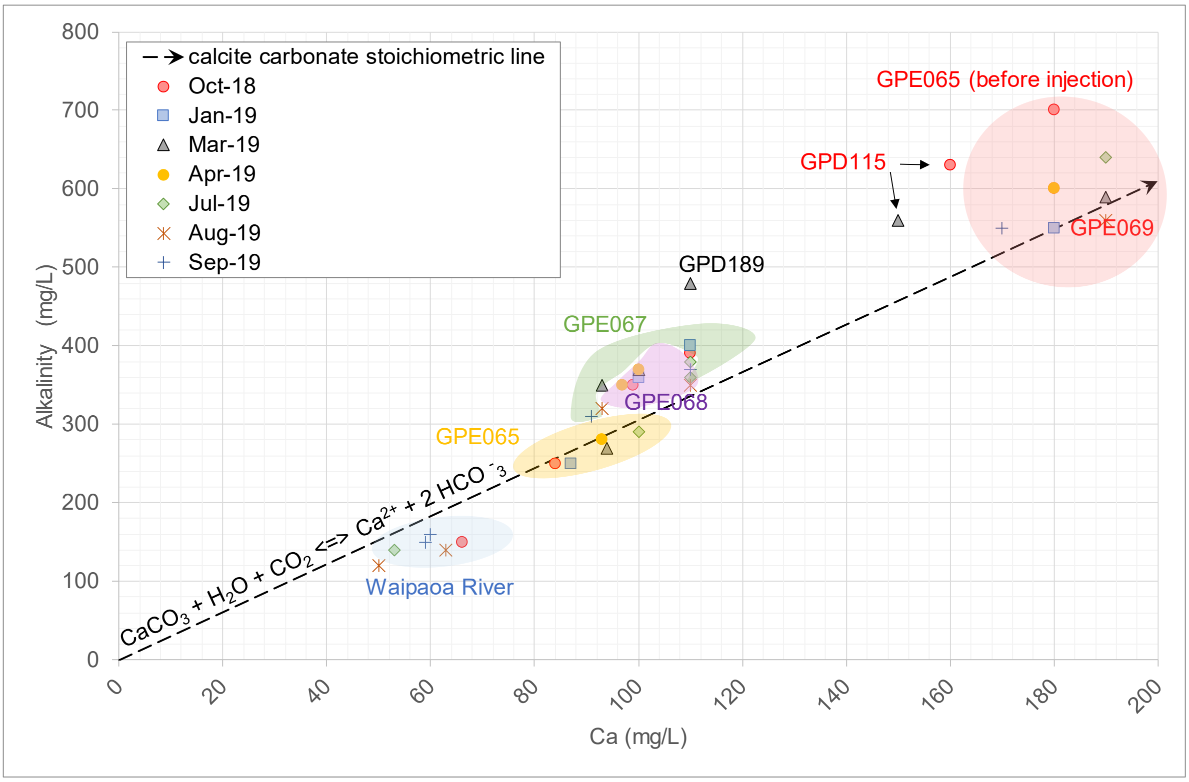
Of interest is the Na/Cl ratio in the September 2019 round for GPE068, which shows this well has since become more akin to ambient groundwater. It would appear the new injection plume since winter 2019 has pushed ambient groundwater towards this well causing the shift.



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.

The monitoring data shows some change in Ca/alkalinity ratio in all wells but most notably in GPE069 (i.e., ambient groundwater), suggesting variability in the ambient groundwater composition.



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.

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

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

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

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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