APPENDIX A

Poverty Bay Flats Aquifers Environmental Setting

1.0 INTRODUCTION

Golder has developed a numerical GoldSim model titled *Poverty Bay Flats Groundwater Management Tool* that simulates the groundwater water balance of the Poverty Bay Flats area. This appendix has been produced to summarise the information evaluated to derive appropriate groundwater input factors for the conceptual water balance model. Golder's interpretation of the information is also summarised in this appendix.

The data analysed to support the development of the GoldSim model simulating the groundwater water balance of the Poverty Bay Flats area have been primarily derived from the GDC environmental and consents database. Those data not directly sourced from the database have been derived from pumping test reports held by the GDC and published reports and papers from various sources. Where appropriate, these documents are referred to, with the reference list provided in the body of the main report.

A preliminary quality control process has been undertaken to check the validity and correctness of the data. The process has not been exhaustive as this was outside the scope of the project and unnecessary for the purposes of model development. This quality control process is summarised at the end of this appendix.

2.0 MAKAURI AQUIFER PROPERTIES

2.1 Introduction

Five main aquifers have been delineated within the Quaternary deposits of the Poverty Bay Flats. These include:

- Three shallow aquifers which are hydraulically linked to surface water bodies: Shallow Fluvial Aquifer, Waipaoa Gravel Aquifer, Te Hapara Sand.
- Two deeper aquifers: Makauri Gravel Aquifer and Matokitoki Gravel Aquifer.

Of these, the Makauri Aquifer is the most extensive and the most accessed for water supplies.

The Makauri Aquifer system consists of a complex braided system of gravel and sand river channel deposits beneath the Poverty Bay Flats. This aquifer is also interpreted to extend northward beneath the terraces of the Waipaoa River valley upstream from the Flats (Barber 1993).

2.2 Geometry

2.2.1 Lateral Boundaries

The Makauri Aquifer appears to terminate against Tertiary claystones and siltstones that form the hills to northeast and southwest of the flats area. As the Quaternary sediments were deposited in a pre-existing valley, the extent of the Makauri Aquifer is somewhat less than the extent of the flats themselves (refer to Figure 3 in body of main report).

Past interpretation (Barber 1993) suggests the Makauri Aquifer may not extend more than perhaps 2 km to the west of the Waipaoa River. This interpretation is consistent with a recent evaluation that indicates that the basement Tertiary rocks are located at relatively shallow depths to the west of the river (White et al. 2012). There is however known to be an aquifer containing relatively saline water to the west of the river, which may correspond to the Makauri Aquifer. Golder understands this aquifer is not generally accessed for water supplies due to the degree of salinity and its continuity with the Makauri Aquifer and full extent is unclear.

The Makauri Aquifer extends up the Waipaoa River valley to the north. The northern limit of the aquifer is not yet closed out through drilling.

Exploratory drillholes have found no evidence of the Makauri gravel aquifer continuing out to sea (Barber 1993). Drillhole data from GDC confirm the aquifer approaches to within 3 km of the coast. The lack of deep bores closer to the coast means the southern extent of the aquifer is poorly defined.

2.2.2 Depth

Beneath the Poverty Bay Flats, the Makauri Aquifer has been described as being located at depths varying between approximately 45 m and 80 m (Barber 1993). A selective assessment of depth to the Makauri Aquifer has been completed through the quality control process outlined in Section 3.0. This assessment was based on bores monitored by GDC and on pumping tests where the test could be shown to affect bores screened in the Makauri Aquifer.

The depth to the Makauri Aquifer beneath the central and southern sections of the Poverty Bay Flats based on this assessment is presented in Figure A1. The outcome from this assessment confirms a tendency for the aquifer to increase in depth toward the south and west. Within this area the aquifer depths ranged from 35 m in the northeast to slightly over 75 m. Beneath the Waipaoa River terraces, in the vicinity of Ormond and as far north as Kaitaratahi, the depth to the Makauri Aquifer is approximately 45 m to 70 m (Figure A1).

2.2.3 Thickness

Presentation of thickness data for the Makauri Aquifer derived directly from the GDC database (Figure A2) indicates almost all of the aquifer exceeds 4 m in thickness and much of the aquifer exceeds 6 m in thickness. Some drillhole logs suggest the aquifer locally exceeds 20 m thick. This large thickness may be a consequence of intersecting river channel deposits at different elevations (and therefore ages).

An early interpretation of drillhole data (Barber 1993) indicated the Makauri aquifer is approximately 7 m thick at Kaitaratahi, 12 m thick in the Makauri area and 3 m thick at Matawhero. White et al. (2012) also indicate that the aquifer in the middle of the Poverty Bay Flats is approximately 20 m thick. The information presented in Figure A2 however, suggests the aquifer thickness in the Makauri area is more consistently less than 8 m thick.

The thickness contours set out in Figure A2 indicate very thin (< 4 m) or thick (> 12 m) areas of the aquifer are predominantly derived from data from single isolated drillholes. In some cases the identification of areas with low aquifer thickness is the result of linear interpolation between drillholes rather than a geological interpretation of the depositional environment. A quality control process has not been undertaken to validate the aquifer thickness data as this is not likely to be a critical factor in the model.

Beneath the Waipaoa River terraces in the vicinity of Ormond the drillhole data indicates the Makauri Aquifer ranges in thickness from approximately 4 m to approximately 12 m. One bore (GPH016) intersected an aquifer thickness exceeding 25 m in this area however this thickness is not considered to be representative of the wider aquifer in the Ormond area.

For the purposes of this project a thickness of 6 m has been applied to the Makauri Aquifer beneath the Poverty Bay Flats. A thickness of 6 m to 8 m has been applied to the Makauri Aquifer beneath the Waipaoa River terraces in the vicinity of Ormond.

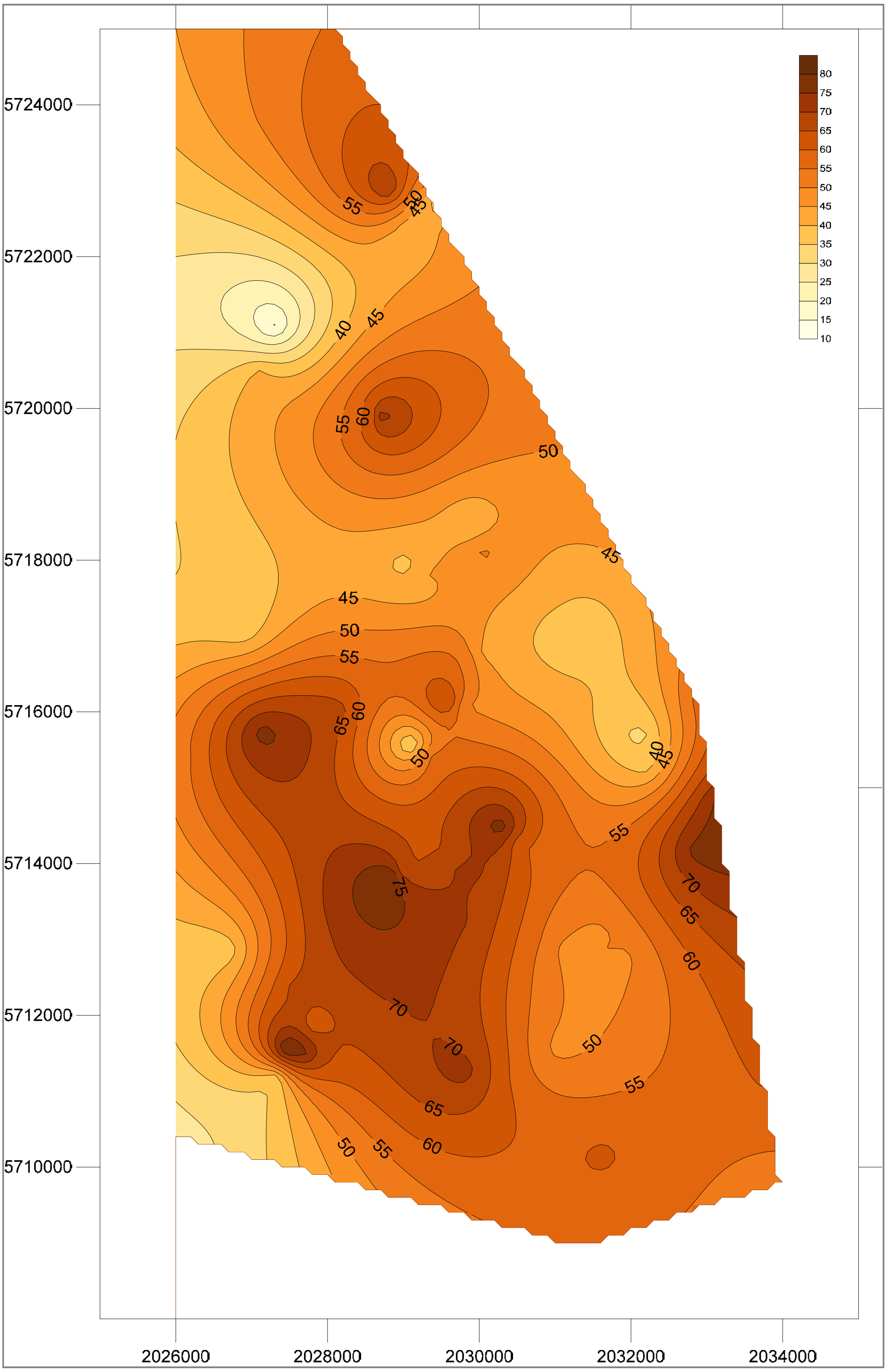

Figure A1: Makauri Aquifer depth beneath Poverty Bay Flats – selected bores (metres bgl).

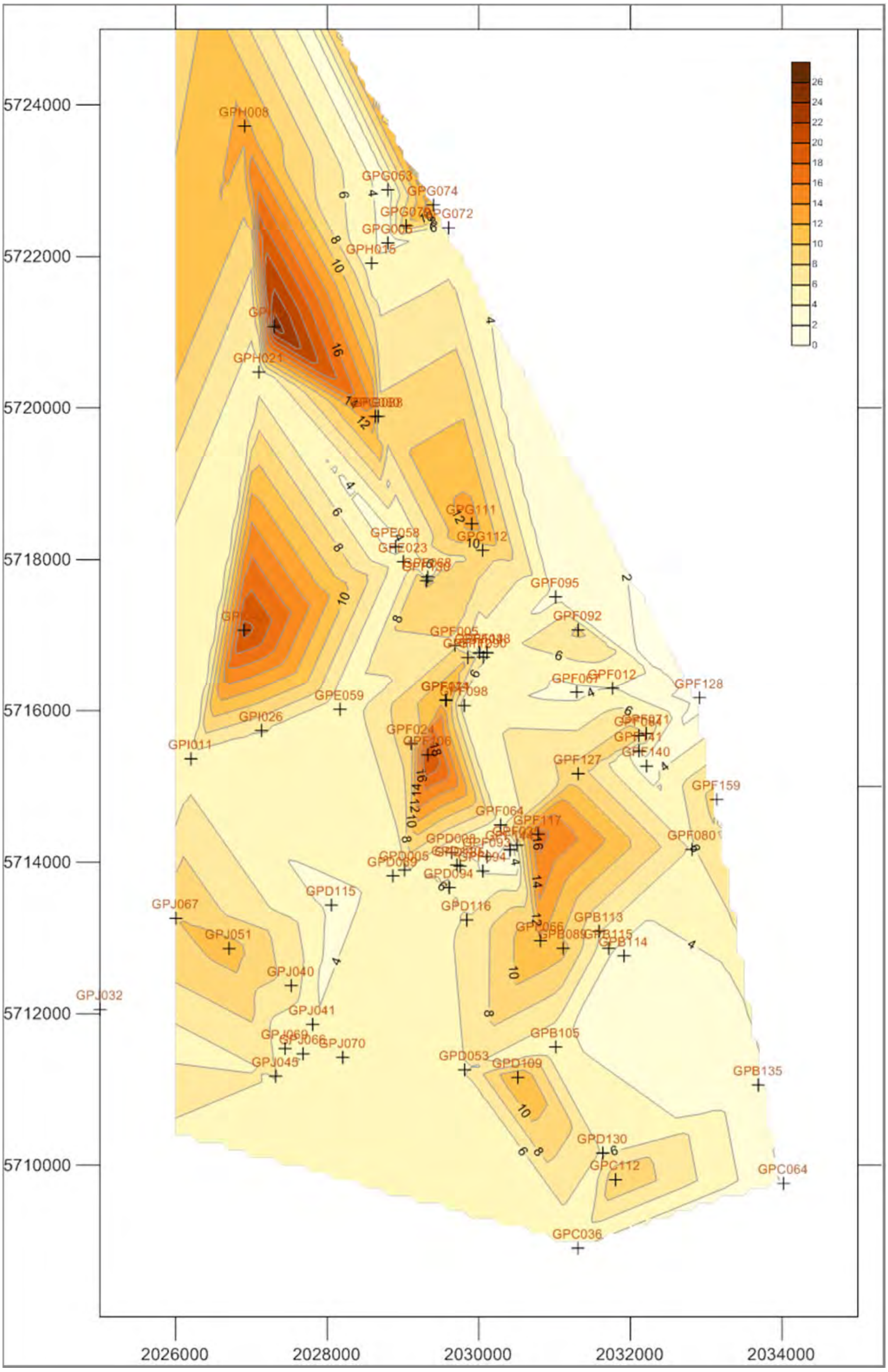

Figure A2: Makauri Aquifer thickness – all GDC data.

2.3 Hydraulic Properties

2.3.1 Transmissivity and hydraulic conductivity

Of the bores screened in the Makauri Aquifer, pumping tests have been performed on 22. Transmissivity results are available for each of these tests (Table A1). The lack of monitoring well data from the pumping test or data on aquifer thickness for some of these wells means hydraulic conductivity and storage coefficients are not available for all of the tested bores.

Table A1: Makauri Aquifer hydraulic properties.

Bore ID	Easting	Northing	Thickness	Transmissivity (m^2/day)	Hydraulic conductivity (m/day)	Storage coefficient (-)
GPB039	2034406	5710893		42		
GPB082	2034620	5712466		26		1×10^{-4}
GPD007	2029609	5714365		383		1.7×10^{-5}
GPD008	2029641	5714126	4.0	680	170	2.79×10^{-5}
GPD089	2028866	5713819	4.5	1,155	257	1.2×10^{-3}
GPD115	2028054	5713434	3.5	456	130	
GPD135	2029753	5713948	5.8	424	73	2.70×10^{-4}
GPE034	2028831	5714327	4.0	1,280	320	
GPF024	2029107	5715567	9.2	235	26	
GPF035	2030505	5714222	6.0	945	158	1.70×10^{-4}
GPF064	2030287	5714491	5.0	1,380	276	1.50×10^{-4}
GPF068	2029327	5717771	4.5	1,053	234	
GPF074	2029569	5716136	12.1	2,312	191	2.70×10^{-4}
GPF092	2031310	5717071	8.6	75	9	
GPF109	2029307	5716068		1,620		
GPF111	2029564	5716141	12.1	1,839	152	1.05×10^{-3}
GPF112	2029856	5716706	10.0	2,500	250	8.10×10^{-4}
GPF117	2030783	5714369	17.0	1,048	62	1.90×10^{-4}
GPF147	2029507	5716168		2,326		3.08×10^{-4}
GPF159	2033140	5714827	9.0	1,000	111	
GPI040	2026902	5717067	21.0	500	24	1.90×10^{-3}
GPJ066	2027681	5711472	6.1	1,006	165	

The transmissivity data for the Makauri Aquifer beneath the Poverty Bay Flats has been mapped and interpolated. The interpolated transmissivity isolines presented in Figure A3 do not take into account any geological interpretation of the aquifer structure. For this reason, the isolines presented in this figure should be considered as indicative only.

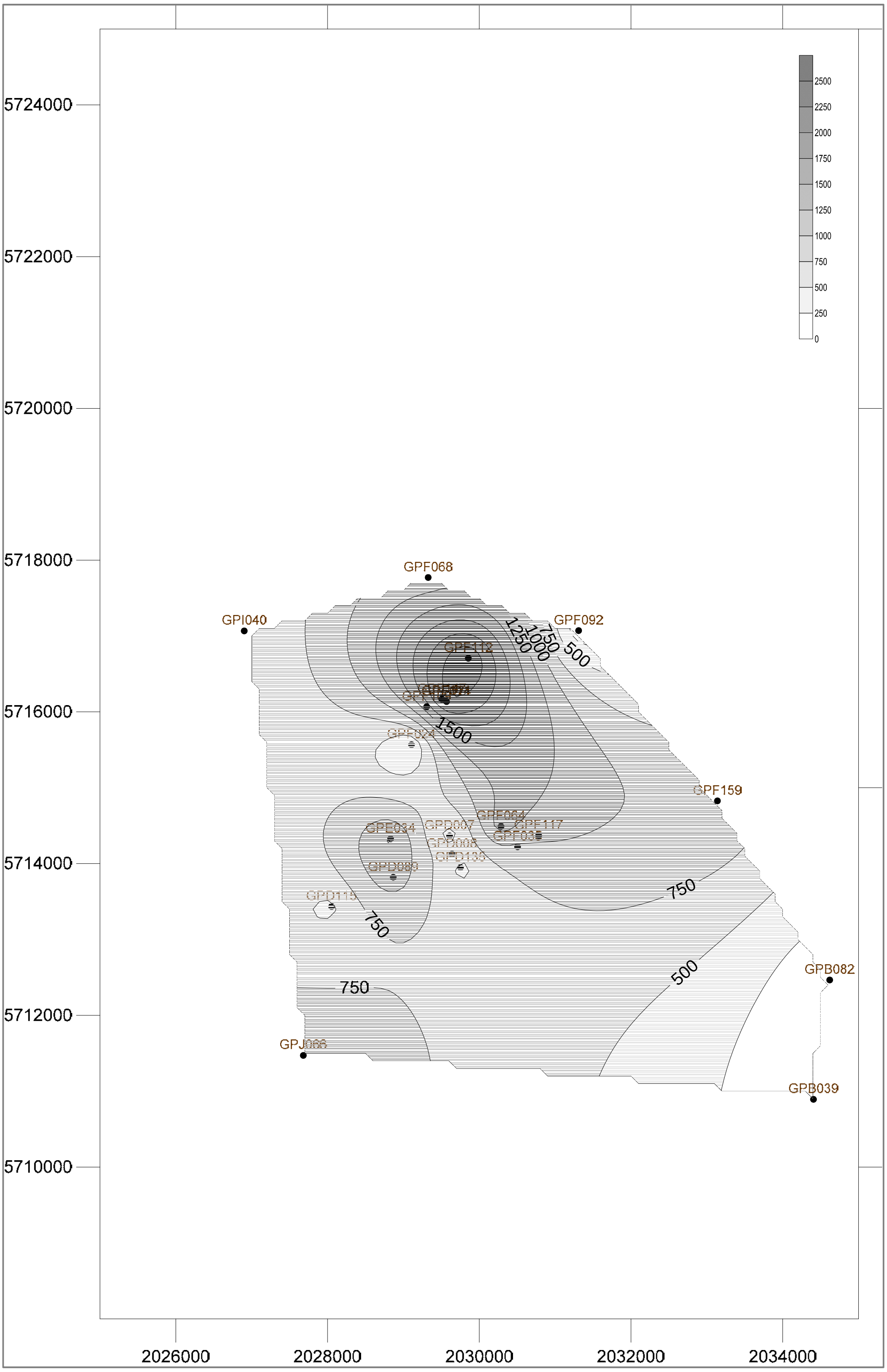

Figure A3: Transmissivity distribution within the Makauri Aquifer.

On the basis of this interpolation perhaps 80 % of the Makauri Aquifer beneath the Poverty Bay Flats may be characterised by a transmissivity range of 500 m^2/day to 1,500 m^2/day (Figure A3). Less than 50 % of the test results however fall within this range (Figure A4). The reasons for this discrepancy are:

- The higher transmissivity values tend to be derived from bores that are located close together.
- Tests on several isolated bores toward the edges of the aquifer produced low transmissivity results and these results influence the interpolation across relatively large areas of the aquifer.

Provided artificial recharge is not undertaken close to the edges of the aquifer, it is likely the aquifer transmissivity near the recharge bore will be within or above the range indicated.

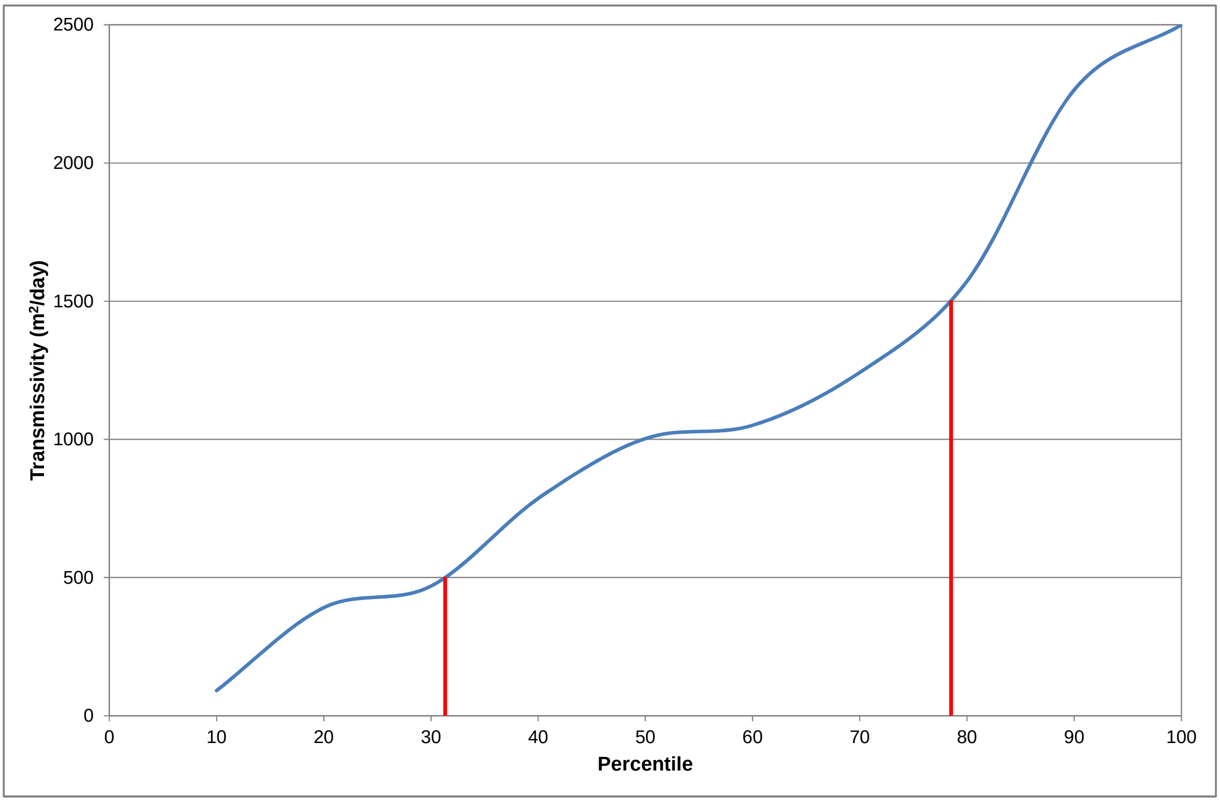

Figure A4: Makauri Aquifer transmissivity percentile distribution.

2.3.2 Storage coefficients

Analysis of the data from thirteen pumping tests carried out on bore screened in the Makauri Aquifer produced the storage coefficients presented in Table A1. For the most part, these results indicate a fully confined or leaky confined aquifer. In the case of an unconfined gravel aquifer the results would tend to exceed 0.01.

The storage coefficient data for the Makauri Aquifer beneath the Poverty Bay Flats have been mapped and interpolated. On the basis of this interpolation, the central area of the Makauri Aquifer is expected to be characterised by a storage coefficient of between 0.001 and 0.0001. Approximately 70 % of the test results are within this range (Figure A5).

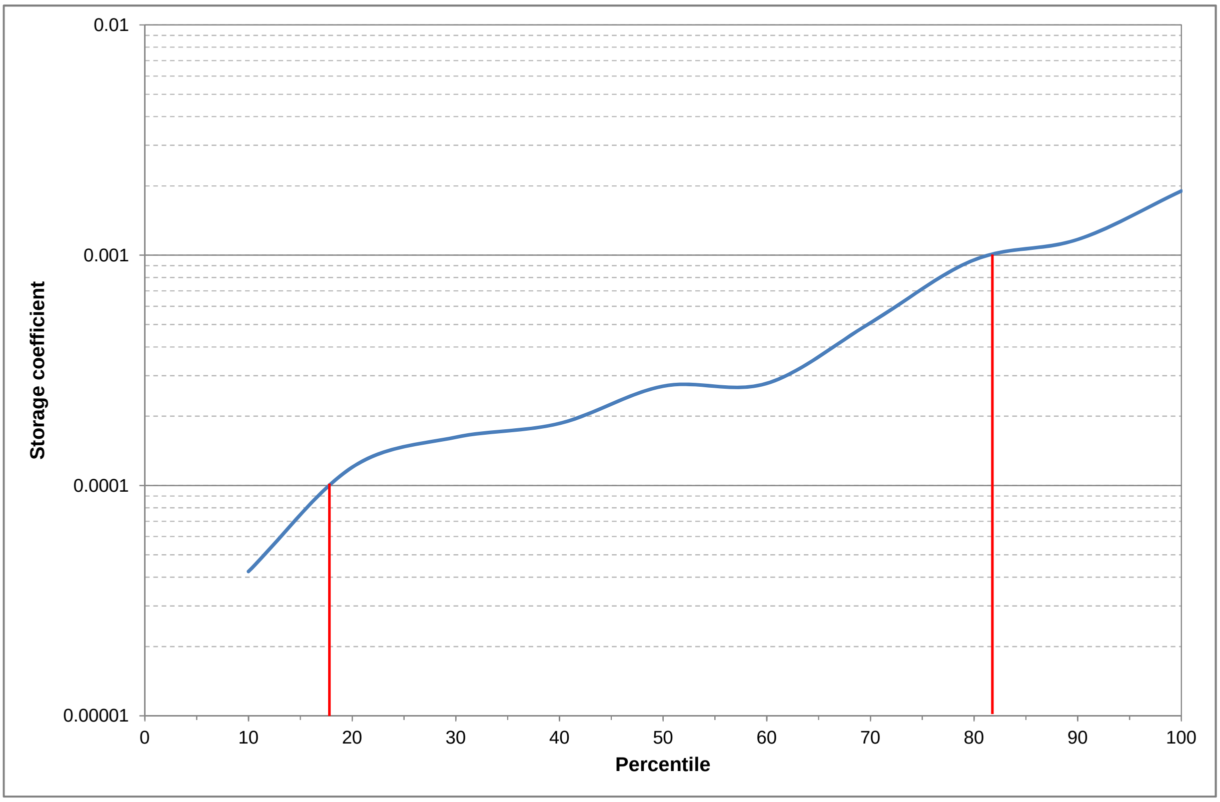

Figure A5: Makauri Aquifer storage coefficient percentile distribution.

2.3.3 Leakance

Beneath the Poverty Bay Flats the Makauri Aquifer deposits are overlain and underlain by silt and clay sediments. The aquifer behaves as a confined or leaky confined aquifer. The leakage capacity for the aquitards beneath the overlying the aquifer cannot be calculated individually from the data available. For the purposes of this project, it has therefore been assumed that leakage is primarily between the Makauri Aquifer and the overlying shallow aquifers.

Leakage capacity (leakance) is represented in terms of the vertical hydraulic conductivity of the overlying aquitard (K’) and the thickness of the aquitard (b’). Leakance is defined as K’/b’. These values can be derived from extended constant rate pumping tests, provided data from at least one observation well is also available in addition to that from the production well.

Records from 44 pumping tests carried out on bores across the Poverty Bay Flats were provided by the GDC. A review of the pumping tests was undertaken. None of the tests had been analysed to provide leakance information. The data from most of the tests were not useful for this purpose for one or more of the following reasons:

- The test was not carried out on the Makauri Aquifer.
- Only a short term stepped rate test was performed.
- Changes in groundwater levels were not recorded at nearby observation wells.
- The frequency of measurements recorded at either the production well or the observation well was not sufficient to enable an analysis of leakance.

Data from two tests was reanalysed and leakance parameters derived from these tests. The bores tested were GPF074 and GPF147, both of which are located in the central area of the Poverty Bay Flats. Both tests were for a pumping duration of approximately 24 hours, with a comparable recovery period recorded. These periods are at the lower end of what would normally be used for leakance assessment, so the outcomes are indicative only. The results from analysis of each of these tests differed from observation well to observation well; the average outcomes are presented in Table A2.

Table A2: Makauri Aquifer indicative leakance.

Parameter	Units	GPF074	GPF147
Leakance (K'/b')	m/day/m or 1/day	0.0005	0.00005
Aquitard thickness (b') [(1)]	M	40	50
Aquitard vertical hydraulic conductivity (K')	m/day	0.02	0.002

Note: 1) Approximated from drillhole log attached to the pumping test.

2.4 Hydraulic Behaviour

2.4.1 Seasonal groundwater level variation

Groundwater levels within the Makauri Aquifer vary both spatially and temporally. The spatial variations are primarily a consequence of local changes in the geometry, proximity of abstraction bores and hydraulic characteristics of the aquifer. The temporal variations are primarily due to:

- Climate related differences in recharge to the aquifer through the year.
- Seasonal variations in water demand and therefore groundwater abstraction from the aquifer.

Groundwater levels have been monitored in 42 bores scattered across the Poverty Bay Flats since approximately 1981. Of these bores, 29 are interpreted as being screened in the Makauri Aquifer. This constitutes a groundwater level database exceeding 30 years. For this entire period, a clear seasonal pattern in groundwater level changes has been recorded (Figure A6). This seasonal pattern is consistent across the full extent of the Makauri Aquifer. To emphasise the consistency, the record from each individual bore has been normalised against the mean groundwater level in that bore (Figure A7). This process enables seasonal variations to be visually compared between many bores, without needing to consider the hydraulic gradient across the aquifer.

Overprinted on this seasonal groundwater level pattern are localised drawdowns generated during the summer irrigation season. Many of the records from individual bores show the influence of operational pumps installed in the monitored bore, or in a bore very close by (Figure A6). Large drawdowns recorded from individual production wells during the irrigation season are however not necessarily useful in evaluating the hydraulic behaviour of the aquifer. For this reason, the deepest water levels recorded from many of the bores are outside the level ranges presented in both Figure A6 and Figure A7. This aspect of groundwater drawdown is examined in greater detail in Section 2.4.2.

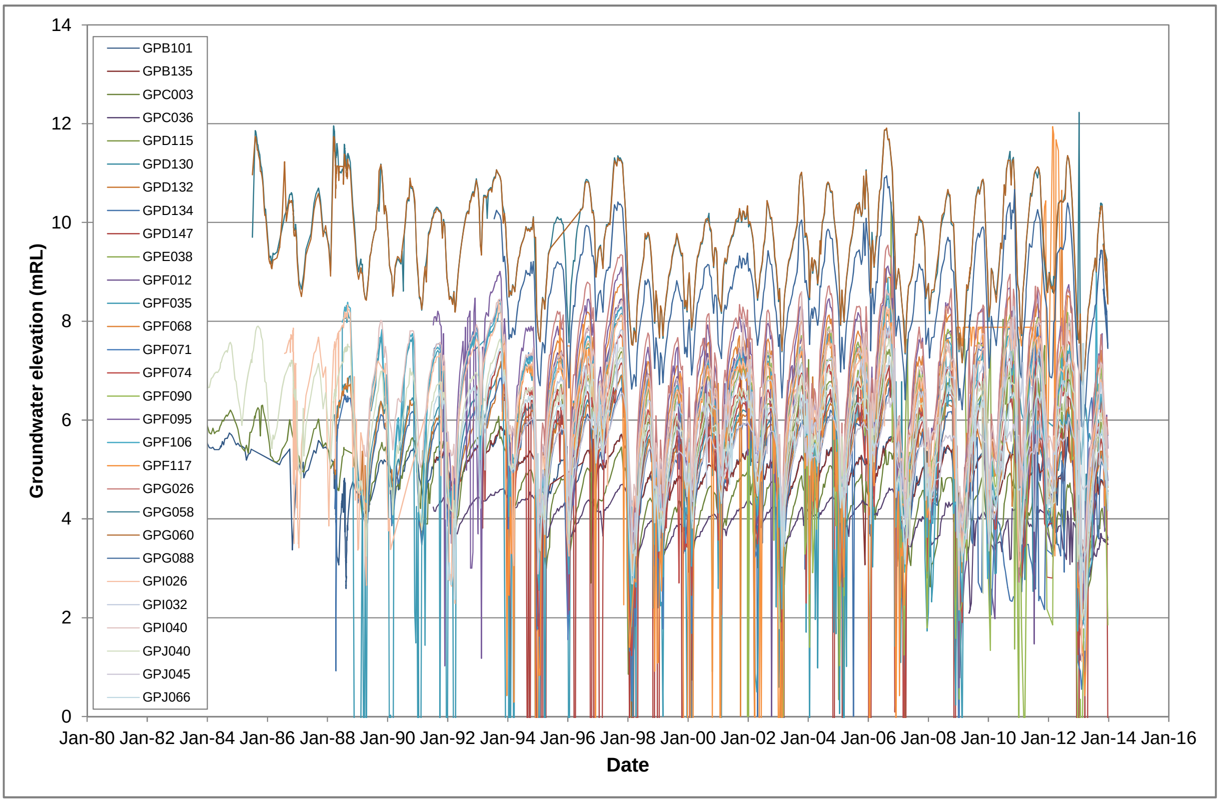

Figure A6: Makauri Aquifer groundwater elevations.

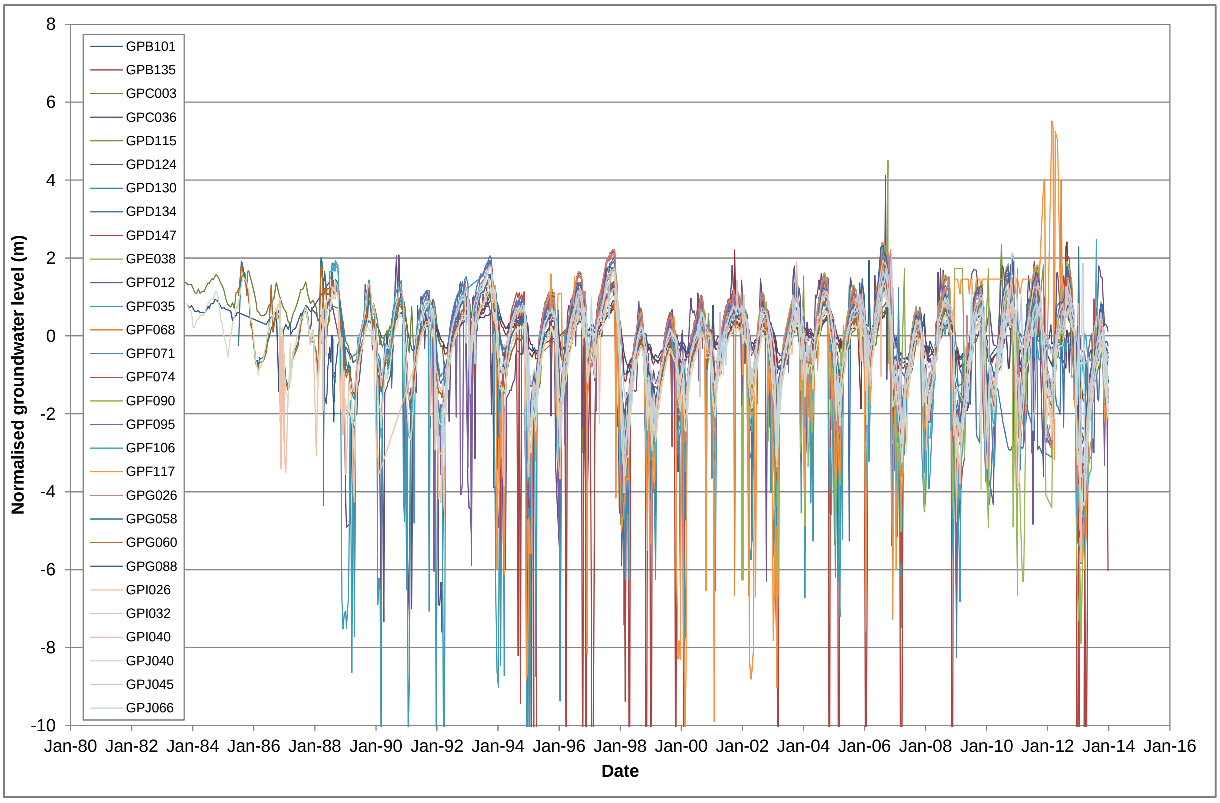

Figure A7: Makauri Aquifer normalised groundwater levels.

If one ignores large localised drawdowns generated through pumping from operational bores, the seasonal fluctuation in water level in the Makauri Aquifer is generally between 2 m and 6 m. This magnitude of fluctuation is clear when the records most influenced by large drawdowns from operational bores are removed from the chart (Figure A8).

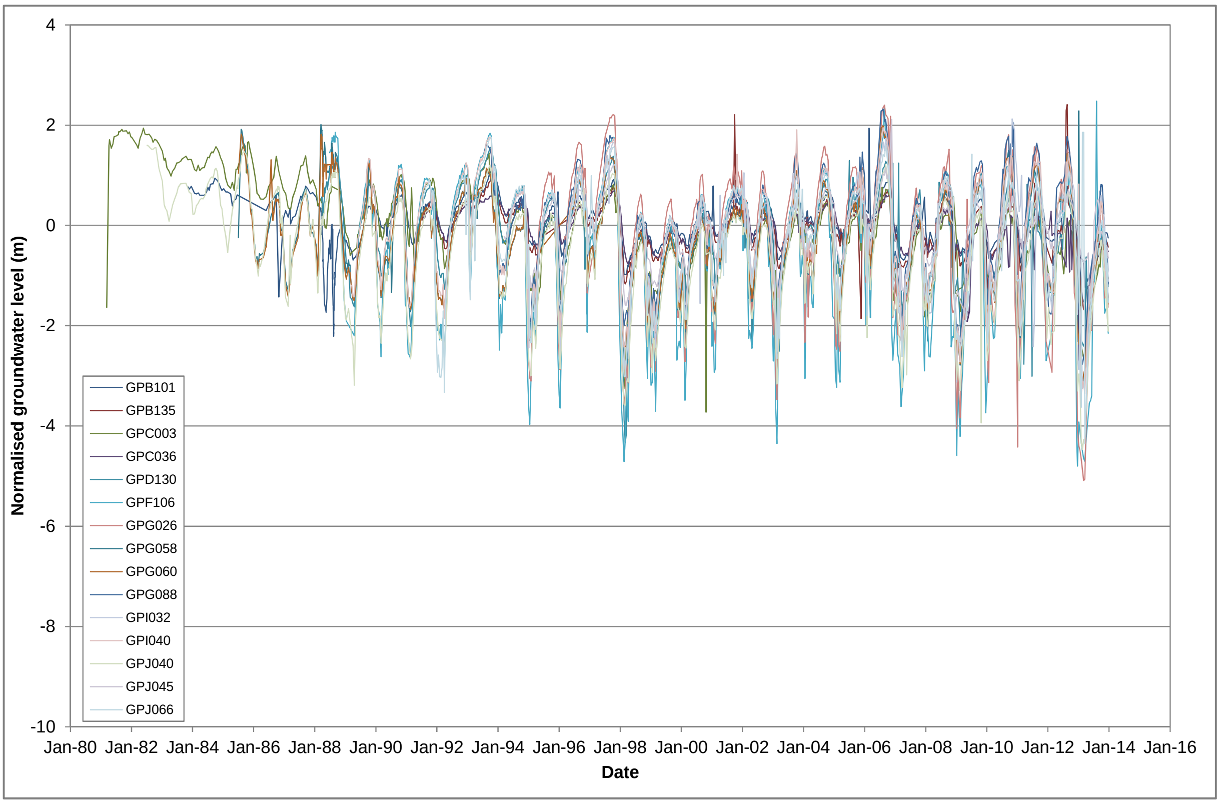

Figure A8: Makauri Aquifer normalised groundwater levels – selected records.

2.4.2 Hydraulic gradients – lateral

Hydraulic gradients across the Poverty Bay Flats also vary both spatially and temporally, for the same reasons that the groundwater levels vary (refer Section 2.4.1). If possible, an assessment of hydraulic gradients across the Flats therefore needs to:

- Cover both a high groundwater period during winter and a low groundwater level period during the summer irrigation period.
- Have all the water level records taken on the same day for each of the above periods.
- Have the water level trends as consistent as possible between the groundwater monitoring well records.
- Avoid substantial drawdowns relating to one or two individual bores.

A review of the groundwater level records presented in Figure A7 indicated the data collected on two dates would suit the purposes: 25 August 2008 and 7 January 2009 (Table A3). As two of the groundwater level records from January 2009 were anomalously high (Figure A9), the values applied from these bores have been taken from other slightly earlier dates. These two data sets have been mapped and the spatial trends interpolated (Figure A10 and Figure A11).

The groundwater levels on the two dates above are considered to be indicative of winter and summer levels over the most of the monitored period. For this reason, the levels measured on these two dates have also been used to calculate:

- Groundwater flows into the aquifer during winter (refer Section 2.4.3).
- Changes in seasonal groundwater storage within the Makauri Aquifer (refer Section 2.4.4).

Table A3: Makauri Aquifer groundwater elevation data for hydraulic gradient analysis.

Bore ID	Easting	Northing	Groundwater elevation (mRL)	
			25/08/2008	7/01/2009
GPB101	2033685	5711056	5.43	4.52
GPB135	2033688	5711060	5.49	4.5
GPC003	2033120	5709928	4.83	4.24
GPC036	2031307	5708906	4.34 (1)	3.63
GPD115	2028054	5713434	6.76	3.13
GPD130	2031636	5710161	6.38	4.42
GPD132	2030157	5711956	6.32	3.59
GPD134	2031081	5711034	6.16	3.41
GPD147	2029020	5712946	6.52	3.55
GPF012	2031765	5716297	7.76	1.45
GPF035	2030505	5714222	7.43 (2)	-1.26
GPF068	2029327	5717771	8.07	2.26
GPF071	2032209	5715700	7.65	-1.86
GPF074	2029569	5716136	7.07	1.77
GPF090	2030059	5716712	7.84	0.35
GPF095	2031013	5717507	8.36	0.58
GPF106	2029328	5715415	7.63	1.94
GPF117	2030783	5714369	7.64	
GPG026	2029926	5718385	8.16	3.09
GPG060	2028635	5719888	10.67	7.43
GPG088	2028672	5719889	9.7	6.4
GPI026	2027133	5715738	7.46	2.16
GPI032	2027259	5714224	7.04	3.05
GPI040	2026902	5717067	7.41	3.88
GPJ040	2027525	5712371	6.98	3.36
GPJ066	2027681	5711472	6.69	3.42

Notes: 1) Measurement date 9/8/2008.
2) Measurement date 30/7/2008.

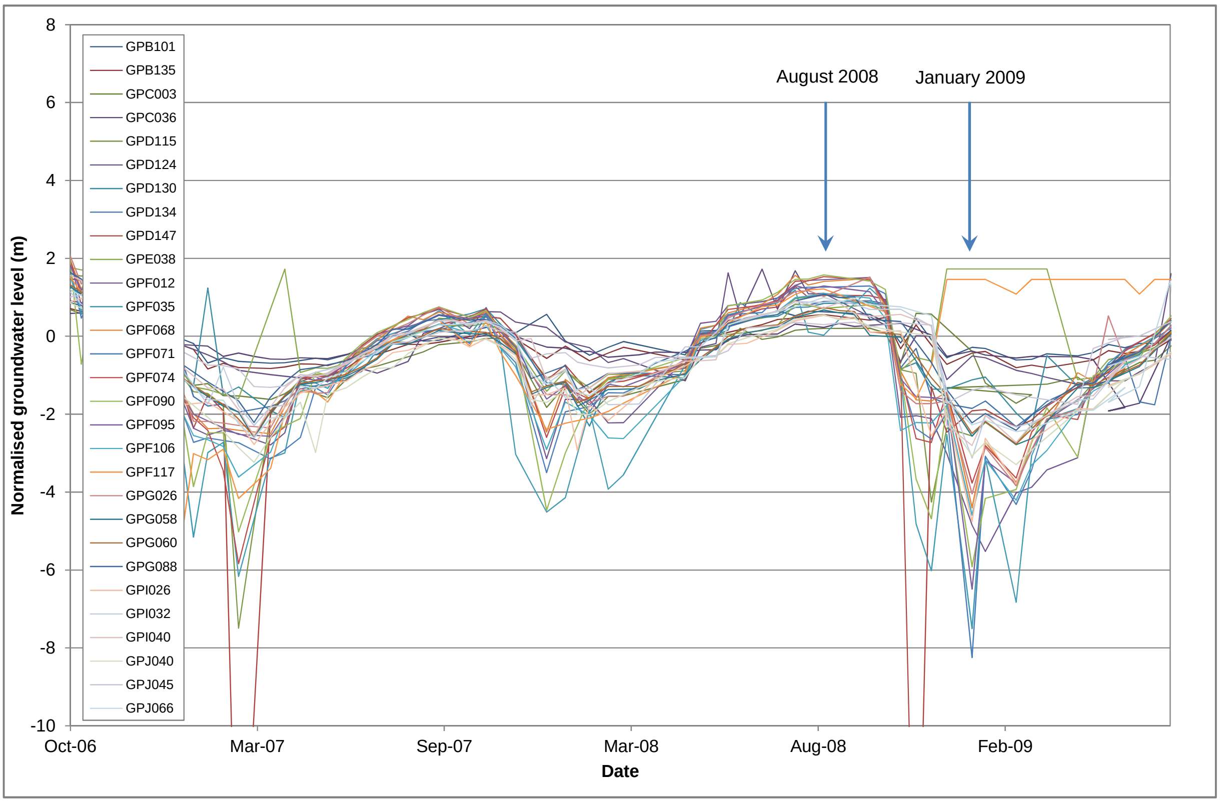

Figure A9: Normalised groundwater level records from Makauri aquifer bores – 2006 to 2009.

During the 2008 winter period, groundwater flowed southward from the narrow section of the Makauri Aquifer in the area of Ormond, across the Poverty Bay Flats and continued at least as far south as Gisborne airport. Hydraulic gradients at the northern end of the Flats were steeper than across the Flats themselves, which is likely due to the widening of the aquifer to the south from Ormond (Table A4).

During the early 2009 summer period, the hydraulic gradient south from Ormond was not only steeper than during the previous winter but this gradient continued further south into the main area of the Flats. Groundwater drawdown, which was not exceptionally large in 2009 compared to other summer periods, resulted in a reversal of the hydraulic gradient between King Road and Gisborne airport (Table A5).

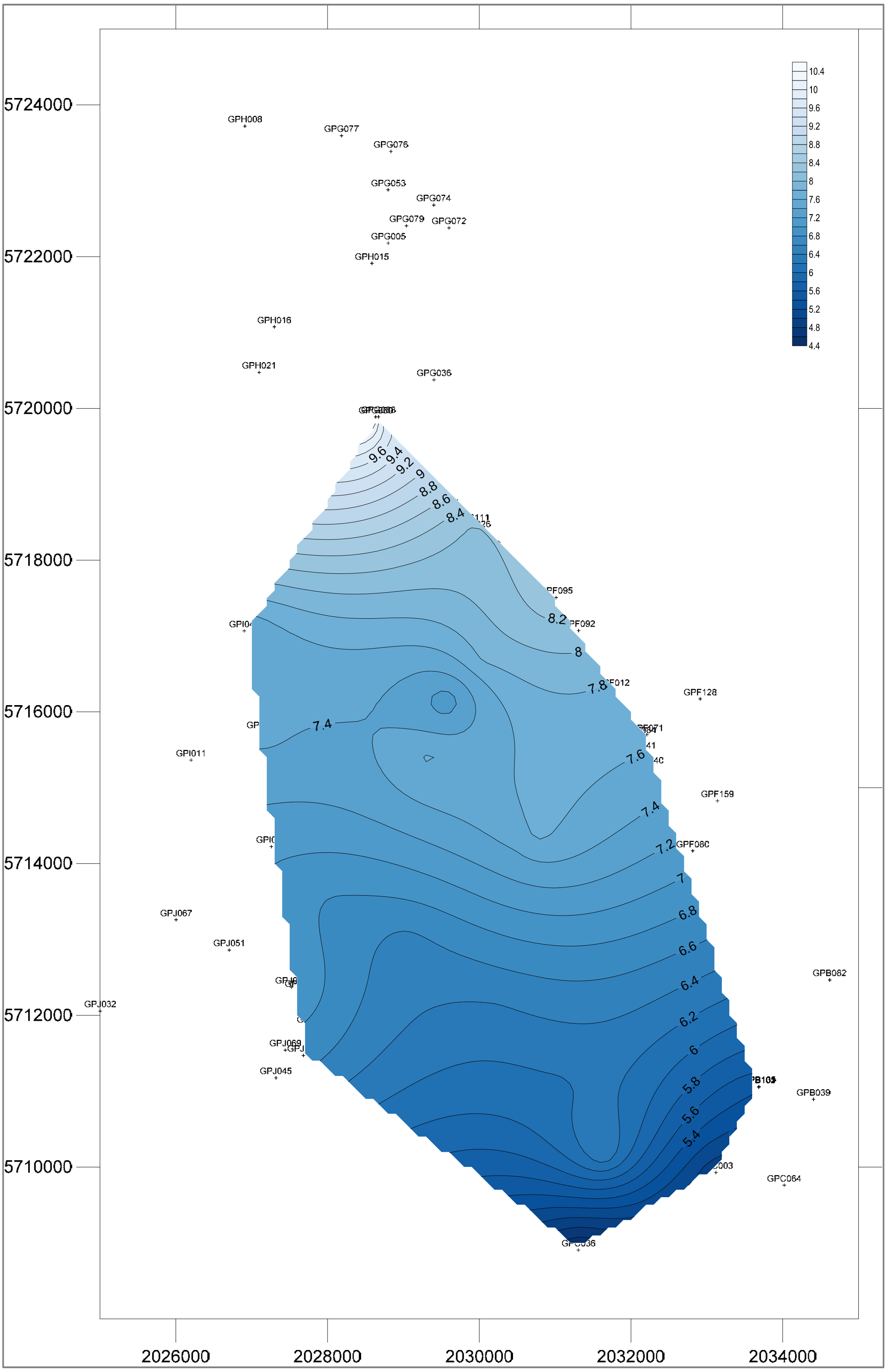

Figure A10: Makauri Aquifer lateral hydraulic gradient – 25 August 2008.

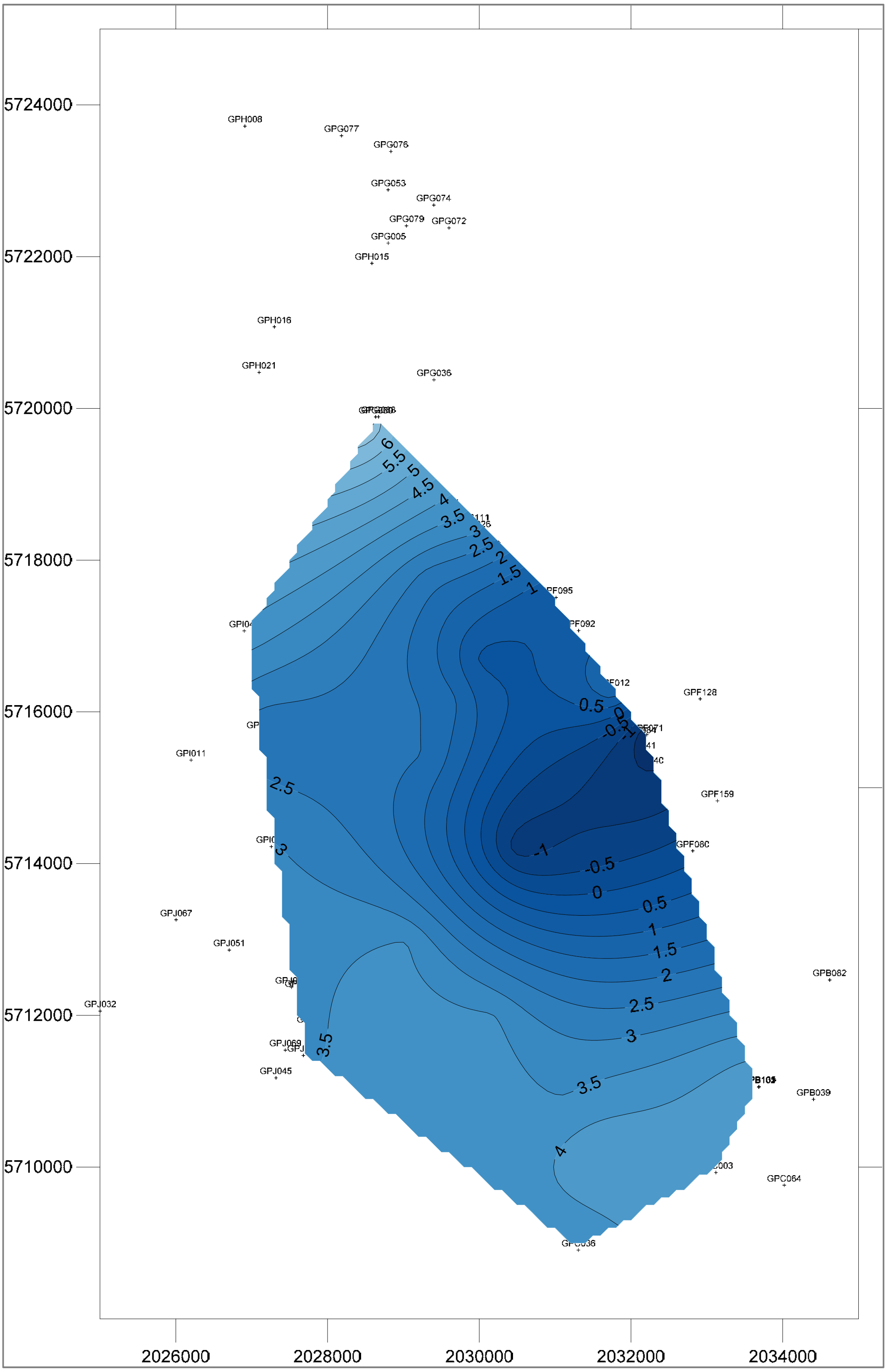

Figure A11: Makauri Aquifer lateral hydraulic gradient – 7 January 2009.

Table A4: Makauri Aquifer hydraulic gradients.

Area	August 2008			January 2009		
	dH (m)	dL (m)	dH/dL (m/m)	dH (m)	dL (m)	dH/dL (m/m)
Ormond to Harper Road	1.8	1,700	0.0011	5.5	2,750	0.0020
King Road to Matawhero	1.8	3,700	0.0005	-4.5	3,100	-0.0015
Matawhero to Gisborne airport	1.0	1,300	0.0008	-0.5	1,800	-0.0003

Notes: dH = head change over measured horizontal distance; dL = measured distance
Negative numbers indicate hydraulic gradient away from coast.

2.4.3 Groundwater flow

A simple groundwater flow calculation has been made to estimate groundwater flow from the section of the Makauri Aquifer beneath the Waipaoa River terraces at Ormond to the wider Makauri Aquifer beneath the Poverty Bay Flats (Table A5). As the aquifer is fully saturated all year, the transmissivity of the aquifer does not change seasonally. The width of the flow section is also constant throughout the year so the only variable in the calculation is the hydraulic gradient. Seepage flows through this section of the Makauri Aquifer doubled between August 2008 and January 2009. This increase in flow resulted from the drawdown in aquifer pressures beneath the Flats due to groundwater abstraction.

Table A5: Groundwater flow estimates in Makauri Aquifer from Waipaoa Valley to Poverty Bay Flats.

Parameter	Units	August 2008	January 2009
Flow section width (1)	m	1,400	1,400
Hydraulic gradient	m/m	0.001	0.002
Transmissivity	m^2/day	1,000	1,000
Volumetric flow rate	m^3/day	1,400	2,800
Range (2)	m^3/day	1,100 – 2,000	2,200 – 4,000

Note: 1) Width of aquifer in the valley may be as great as 2,000 m. The width was reduced to allow for bedrock geometry.
2) Transmissivity in this area may range from 800 m^2/day to 2000 m^2/day. This range taken into account in the flow range.

The Makauri Aquifer in the area of Ormond appears to be subject to groundwater drawdown in a similar manner to the aquifer areas toward the middle of the Flats. The magnitude of the drawdown is however less than observed further south, potentially reflecting the availability of groundwater inflows from further up the valley.

At the southern end of the Makauri Aquifer, close to the coast, the data indicates the hydraulic gradient reverses seasonally as a result of groundwater abstraction (Table A6). This reversal does not however necessarily mean that seawater is seasonally being drawn into the aquifer. It simply means that the drawdown cone generated by groundwater abstraction extends past the monitored bores that are located approximately 3 km from the coast.

2.4.4 Groundwater storage change

The change in groundwater stored in the Makauri Aquifer between August 2008 and January 2009 can be estimated. The difference in groundwater pressure is calculated for each unit of aquifer area; one unit being 100 m by 100 m (Figure A12). This drawdown is then totalled across the monitored area of the aquifer. The total drawdown is multiplied by the storage coefficient to provide the change in stored water volume.

Within the monitored area, which totals approximately 4,400 ha, the total drawdown in pressure is approximately 2.1 x 10^8 m^3. Multiplying that drawdown by storage coefficient within the range of 0.001 and 0.0001 produces a change in stored groundwater of between 210,000 m^3 and 21,000 m^3.

Table A6: Groundwater flow estimates in Makauri Aquifer in Matawhero / Gisborne airport area.

Parameter	Units	August 2008	January 2009
Flow section width	m	5,000	5,000
Hydraulic gradient	m/m	0.0008	-0.0003 (1)
Transmissivity	m^2/day	250	250
Volumetric flow rate	m^3/day	1,000	-300
Range (2)		250 – 2,000	-60 – -600

Note: 1) Negative number indicates flow direction inland away from the coast.
2) Transmissivity in this area may range from 50 m^2/day to 500 m^2/day. This range taken into account in the flow range.

This calculation has been based on interpolated data only and consequently does not cover the full extent of the Makauri Aquifer. The change in stored water volume does not equate to the volume of water pumped out of this area of the aquifer during this period because inflows from above and the sides of the monitored area contribute to the aquifer water balance.

2.5 Recharge

2.5.1 Introduction

Recharge to the Makauri Aquifer is potentially derived from:

- Direct recharge to any unconfined section of the Makauri Aquifer, upriver from Ormond
- Leakage from the overlying Waipaoa Aquifer and the Waipaoa River upriver from Ormond
- Leakage from overlying aquifers and the Waipaoa River in the Poverty Bay Flats area
- Lateral recharge from the southwestern, northeastern and southern boundaries of the aquifer.
- Upward leakage from the underlying Matokitoki Aquifer.

Not all of these components are likely to be significant and several cannot be quantified from the data available. For this reason, several assumptions regarding the recharge to and discharge from the Makauri Aquifer have been made:

1) There is no lateral recharge or discharge where the aquifer contacts the underlying Tertiary siltstones and claystones along its southwestern and northeastern boundaries.
2) The hydraulic characteristics of the Matokitoki Aquifer, its extent and the hydraulic characteristics of the overlying aquitard are not well understood. Groundwater monitoring records from bores in the area of Gisborne indicate the hydraulic gradient between the Matokitoki Aquifer and the Makauri Aquifer is generally upward. At this stage, it has been assumed that the seepage contribution from the Matokitoki Aquifer to the Makauri Aquifer is minimal.

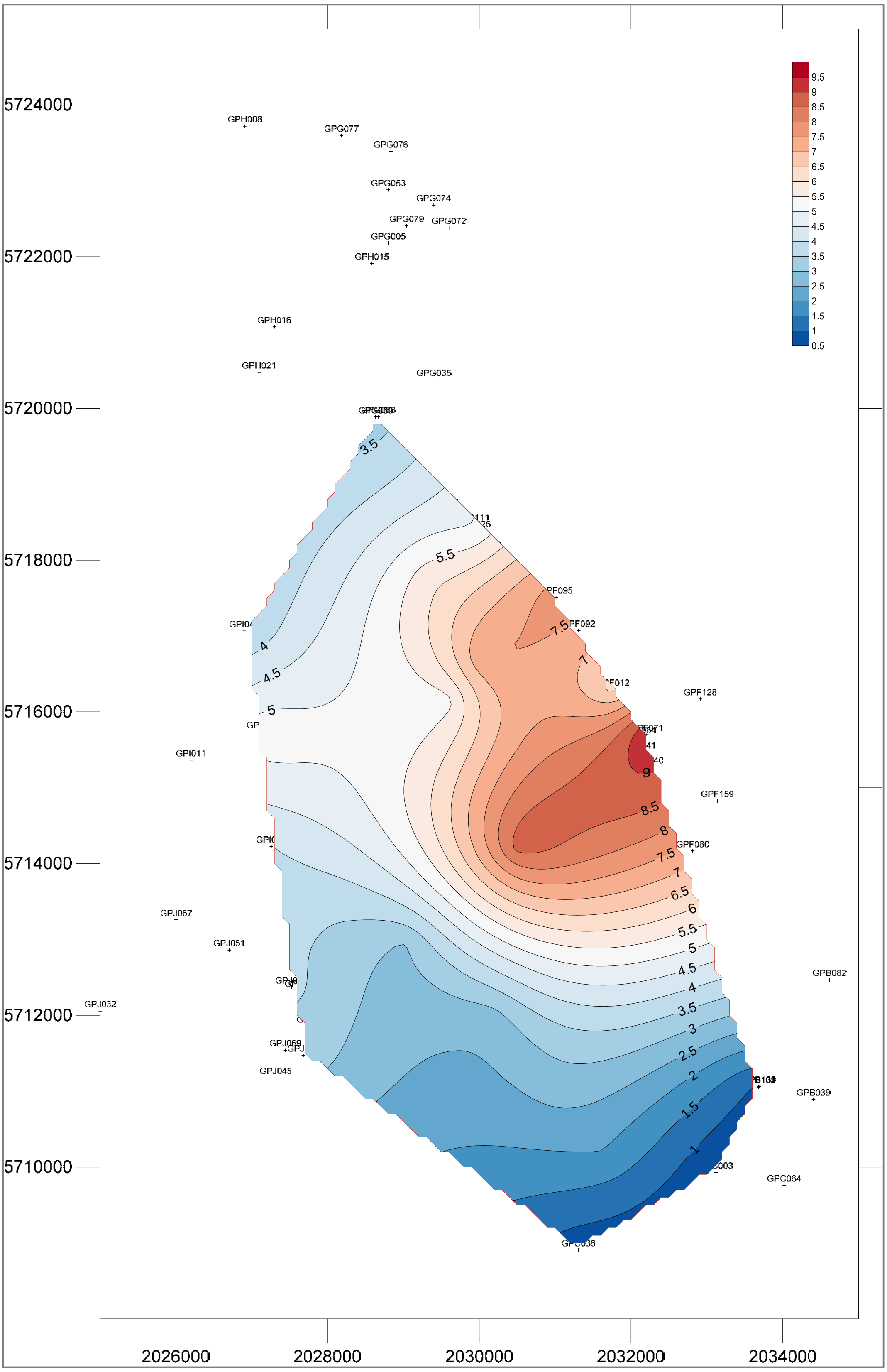

Figure A12: Makauri Aquifer decline in groundwater elevation between 28 August 2008 and 7 January 2009.

2.5.2 Waipaoa Aquifer and Waipaoa River

The Waipaoa Aquifer at the northern end of the Poverty Bay Flats and north of Ormond is hydraulically connected to the Waipaoa River although it may not be fully unconfined. The groundwater pressure records from bores screened in the Waipaoa Aquifer are very similar (Figure A13). When each record is normalised about its mean and plotted against the stage level for the Waipaoa River at Kaiteratahi, there are clear correlations between the records (Figure A14).

The Waipaoa Aquifer groundwater pressure records show different characteristics to those from bores screened in the Makauri Aquifer (Figure A15 and Figure A16). The Waipaoa Aquifer records generally show upward spikes in winter groundwater levels with subsequent tail off as levels decline during the summer. This pattern is a subdued and attenuated reflection of the seasonal river level patterns.

In contrast, the Makauri Aquifer records are characterised by downward spikes in groundwater levels during the summer, followed by an upward recovery during the winter. These downward spikes reflect summer abstraction. The winter spikes in groundwater levels shown by the Waipaoa Aquifer are attenuated in the Makauri Aquifer, as reflected in the records from 2002 and 2006 (Figure A15 and Figure A16).

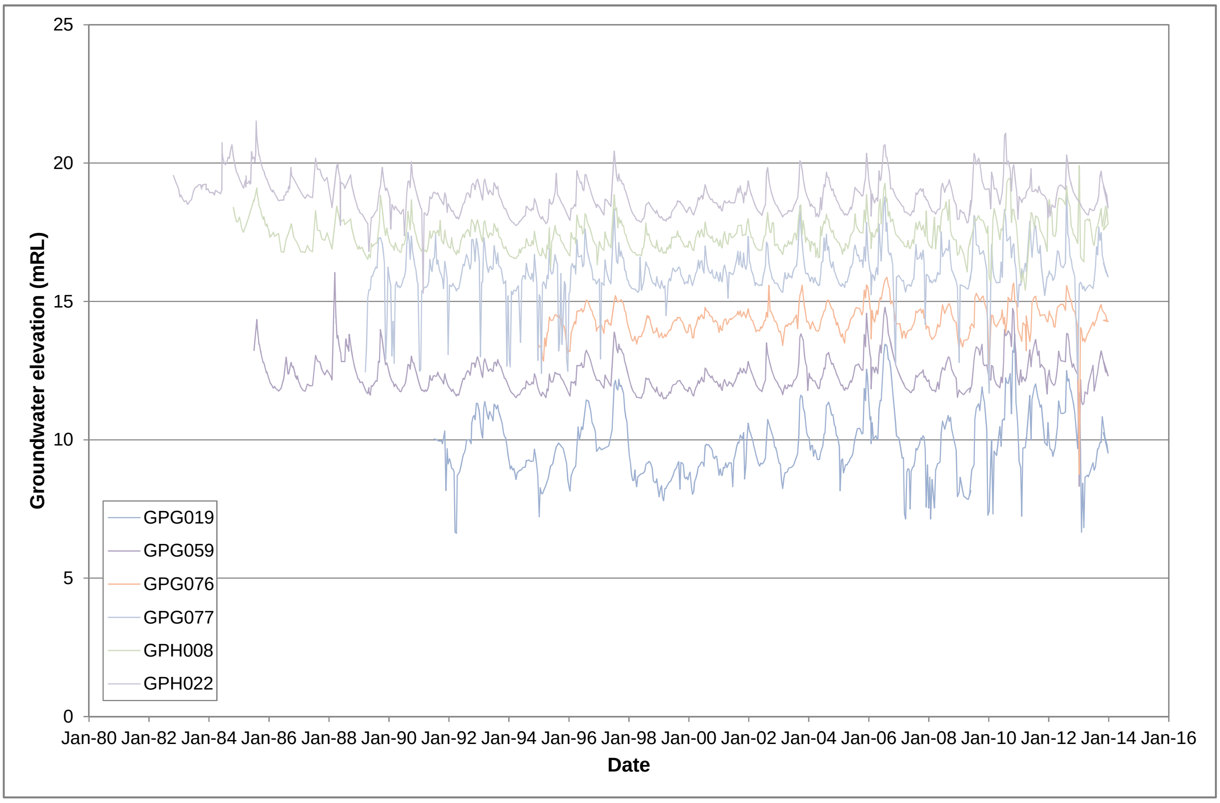

Figure A13: Waipaoa Aquifer groundwater elevations.

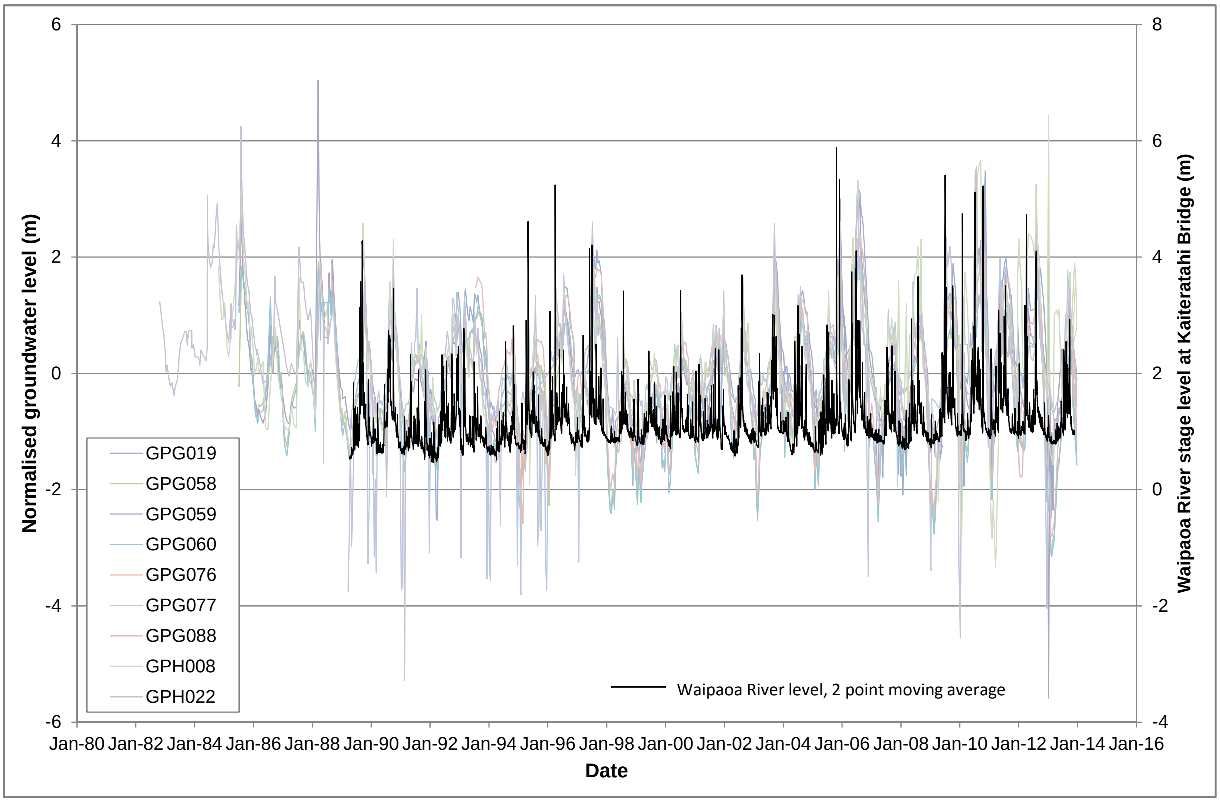

Figure A14: Waipaoa Aquifer normalised groundwater level and Waipaoa River stage record.

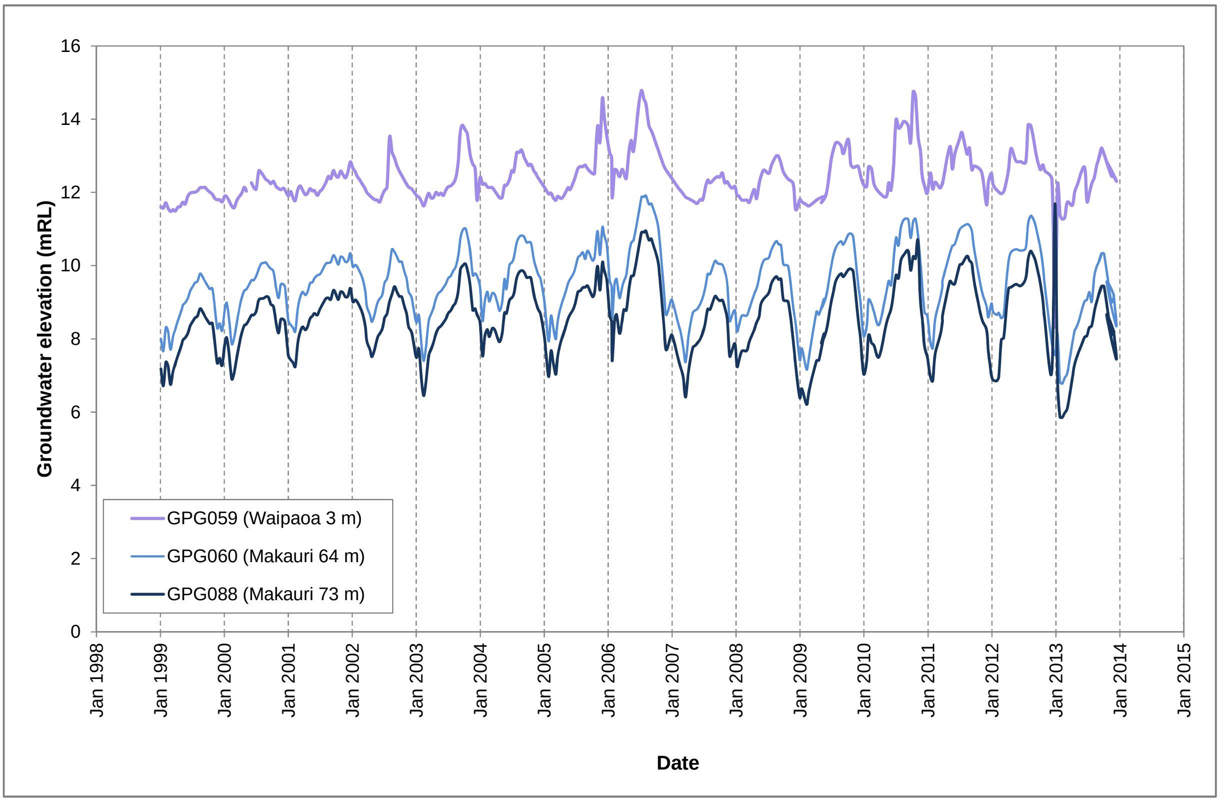

Figure A15: Caesar Road GDC monitoring well groundwater level records.

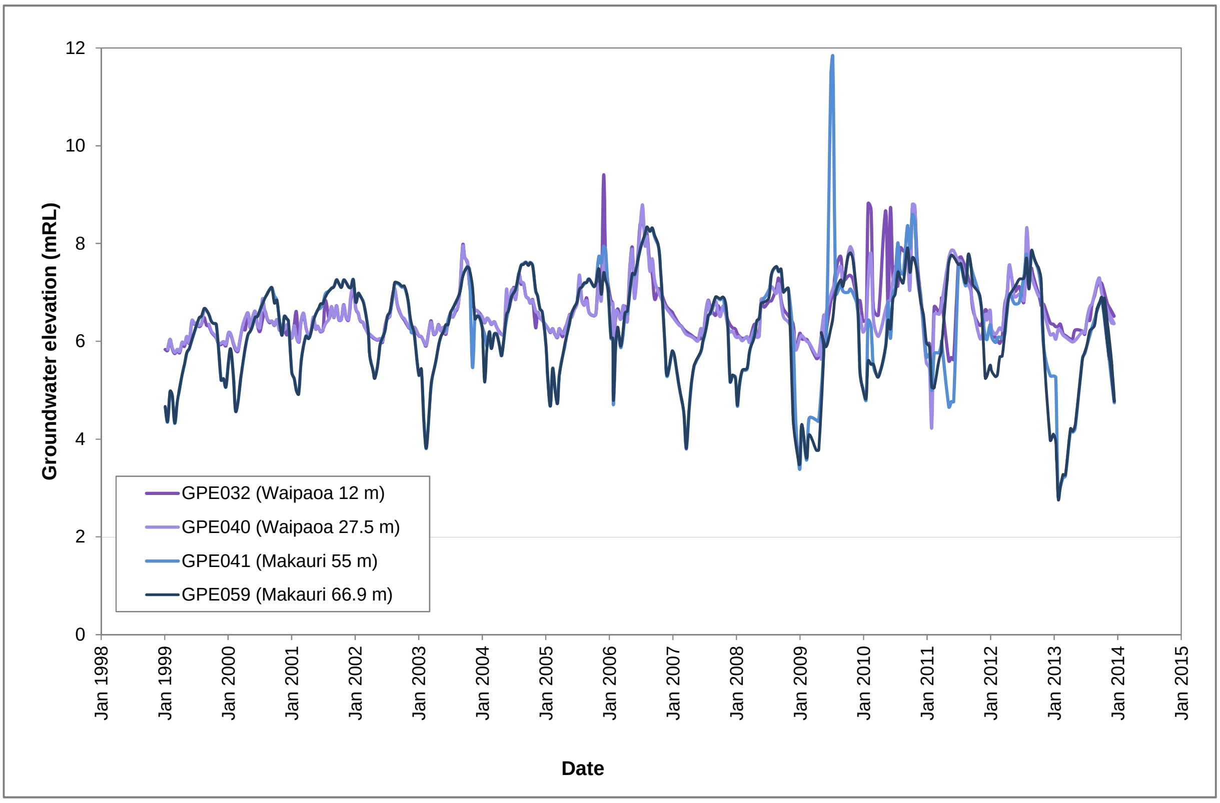

Figure A16: Ferry Road GDC monitoring well groundwater level records.

Groundwater level records from monitoring wells at Caesar Road, close to Ormond (Figure A15) have been used to estimate leakage from the Waipaoa Aquifer to the Makauri Aquifer in this area. The hydraulic gradients are consistently downward indicating continual recharge to the Makauri Aquifer. The calculated recharge rate for August 2008 (winter) was approximately twice the January 2009 (summer) value (Table A7).

Leakage from the confining layer overlying the Makauri Aquifer has been estimated from vertical hydraulic gradients and the leakance values documented in Section 2.3.3. These leakage calculations have been provided for guidance purposes only. The calibration process for the Makauri Aquifer water balance modelling should provide more reliable leakage estimates across the aquifer.

In the area of Ferry Road, winter groundwater levels are very similar in the Waipaoa and Makauri aquifers, with little leakage between the two (Table A8). Drawdown of the Makauri Aquifer pressures during the summer leads to similar leakage rates to those calculated for the Caesar Road area.

In the area of Cameron Road, the hydraulic gradients between the unconfined Te Hapara Aquifer and the Makauri Aquifer have changed over time (Figure A17). During the 2008 to 2009 period there was very little leakage calculated between these two aquifers (Table A9). Since then however, a clear downward hydraulic gradient between the aquifers has developed, leading to recharge to the Makauri Aquifer in this area.

Table A7: Estimated leakage from Waipaoa Aquifer to Makauri Aquifer at Caesar Road.

Parameter	Units	Low leakance		High leakance	
Date		August 2008	January 2009	August 2008	January 2009
Groundwater Waipaoa Aquifer	mRL	12.99	11.8	12.99	11.8
Groundwater Makauri Aquifer	mRL	10.67	7.43	10.67	7.43
Pressure difference (dH)	m	2.32	4.37	2.32	4.37
Base Waipaoa Aquifer	mRL	-10	-10	-10	-10
Top Makauri Aquifer	mRL	-45	-45	-45	-45
Aquitard thickness (dL)	m	35	35	35	35
Vertical hydraulic gradient (dH/dL)	m/m	0.07	0.13	0.07	0.13
Aquitard hydraulic conductivity (K')	m/day	0.02	0.02	0.002	0.002
Leakage per hectare	**m^3/day/ha**	**13**	**25**	**1.3**	**2.5**

Table A8: Estimated leakage from Waipaoa Aquifer to Makauri Aquifer at Ferry Road.

Parameter	Units	Low leakance		High leakance	
Date		August 2008	January 2009	August 2008	January 2009
Groundwater Waipaoa Aquifer	mRL	6.977	6.06	6.977	6.06
Groundwater Makauri Aquifer	mRL	7.531	3.48	7.531	3.48
Pressure difference (dH)	m	-0.55	2.58	-0.55	2.58
Base Waipaoa Aquifer	mRL	-14	-14	-14	-14
Top Makauri Aquifer	mRL	-69	-69	-69	-69
Aquitard thickness (dL)	m	55	55	55	55
Vertical hydraulic gradient (dH/dL)	m/m	-0.01	0.05	-0.01	0.05
Aquitard hydraulic conductivity (K')	m/day	0.02	0.02	0.002	0.002
Leakage per hectare	**m^3/day/ha**	**-2.0**	**9.4**	**-0.2**	**0.9**

Table A9: Estimated leakage from Waipaoa Aquifer to Makauri Aquifer at Cameron Road.

Parameter	Units	Low leakance		High leakance	
Date		August 2008	January 2009	August 2008	January 2009
Groundwater Te Hapara Aquifer	mRL	5.43	4.83	5.43	4.83
Groundwater Makauri Aquifer	mRL	4.83	4.5	4.83	4.5
Pressure difference (dH)	m	0.6	0.33	0.6	0.33
Base Te Hapara Aquifer	mRL	-14	-14	-14	-14
Top Makauri Aquifer	mRL	-53	-53	-53	-53
Aquitard thickness (dL)	m	38	38	38	38
Vertical hydraulic gradient (dH/dL)	m/m	0.02	0.01	0.02	0.01
Aquitard hydraulic conductivity (K')	m/day	0.02	0.02	0.002	0.002
Leakage per hectare	**m^3/day/ha**	**3.2**	**1.7**	**0.3**	**0.2**

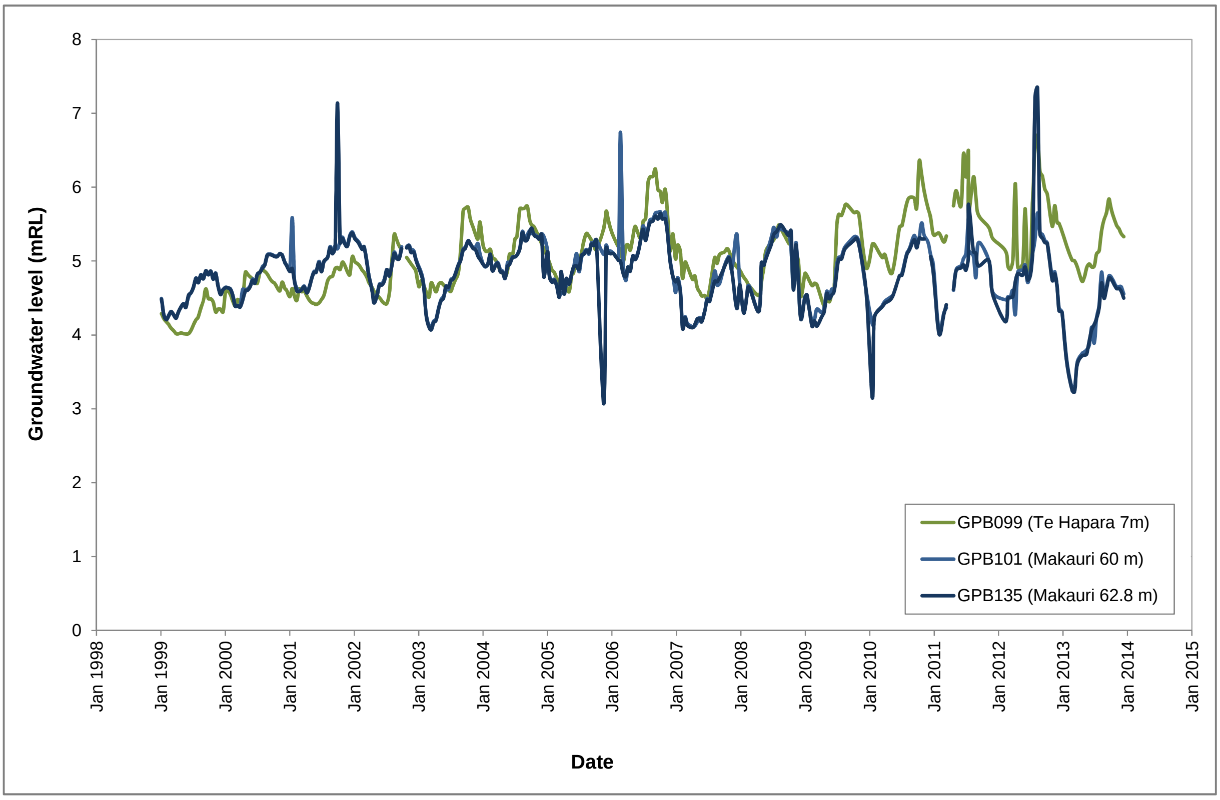

Figure A17: Cameron Road GDC monitoring well groundwater level records.

3.0 DATA SOURCE AND QUALITY CONTROL PROCESS

The quality control process has entailed:

1) Identifying critical bores which have either long term water level monitoring records, pumping test records or water quality records.

2) Reviewing the data from these bores to identify those with comparable hydraulic behaviour since about 1980. Bores with similar behaviour were grouped and initially assigned to the same aquifer.

3) Where pumping tests are available, the bores tested and the monitoring bores influenced by the test were also grouped together. This was done when at least one of the bores monitored in the test had a long term groundwater level record assigned to one of the groups previously defined, or the bores could be confidently assigned to one specific aquifer.

4) The geological logs from the bores and GDC records of bore screen elevations were reviewed. Aquifer elevations for the bores in each of the groups defined above were compared to confirm general elevation trends for individual aquifers across the Poverty Bay Flats area. Anomalous elevations were resolved. The bore groups were assigned to specific aquifers.

5) Where water quality records are available for bores within specific groups, these were also compared to confirm the water quality of the aquifer. Bores with anomalous water quality were compared and the anomaly resolved, if necessary through designation of the bore to a different aquifer.

As the quality control process was not intended to be exhaustive, the data from many bores listed in the GDC database were not reviewed. For the purposes of this project, data that have not been reviewed and validated have been excluded from model development. Exclusion of data from the modelling process does not imply that the data were incorrect. The quality control process provided a clear understanding of the hydraulic characteristics and behaviour of the MAR target aquifers.

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APPENDIX B

Groundwater Management Tool

1.0 INTRODUCTION

This appendix documents the model design, calibration and functionality of the Poverty Bay Flats Groundwater Management Tool (PBGMT) developed for Gisborne District Council (GDC). The purpose of the PBGMT is to provide a tool to support the GDC in assessing potential future groundwater resource trends and the benefits of developing a MAR groundwater replenishment scheme to increase the sustainable yield from the Poverty Bay Flats aquifer system.

As discussed in Appendix A, pumping for irrigation purposes has resulted in summer groundwater levels in the Makauri Aquifer becoming increasingly drawn down over time. The objective of a Groundwater Replenishment scheme would be to:

1) Stabilising the declining trends in groundwater levels

2) Restoring groundwater levels to a range identified through community consultation

3) Manage the aquifer at a sustainable yield, also defined through consultation with the community.

The purpose of the PBGMT is to:

- Enable an increased understanding of the Makauri Aquifer water budget and how this budget influences historic and future groundwater level trends.
- Support an assessment of groundwater management options and basic economic benefits of MAR.

It is important to recognise that the PBGMT is a highly adaptable tool that remains under development. As knowledge of the Poverty Bay aquifer system increases, the tool can be adapted correspondingly.

The key model outputs are therefore groundwater levels in the Makauri Aquifer over time and a water budget for the aquifer.

This appendix is structured as follows:

- Section 2.0 introduces the PBGMT platform
- Section 3.0 documents the water balance model domain and spatial discretisation
- Section 4.0 documents the water balance model temporal discretisation
- Section 5.0 summarises the water balance model logic and input parameters
- Section 6.0 summarises the water balance model calibration process and outcomes
- Section 7.0 documents the limitations applicable to the water balance model and the PBGMT
- Section 8.0 provides a user guide to the PBGMT Player file provided to the GDC

2.0 MODEL PLATFORM

The model has been developed using GoldSim Pro (Version10.50) software. GoldSim is a graphical object-oriented modelling environment with the capacity to carry out dynamic probabilistic simulations. Originally developed by Golder in the early 1990's, GoldSim is now commercially supported by a separate entity to Golder. GoldSim is used internationally in a decision-support role for a wide range of water balance, water quality and water resource fields.

A GoldSim water balance model is a computer-based representation of the essential features of a natural hydrological system. The model represents the environmental system simulated to a level of detail suitable to achieve the intended objectives. GoldSim models are used to support decision and risk analysis by simulating future performance while quantitatively representing the uncertainty and risks inherent in all complex systems. The software enables users to construct models by adding “elements” that represent data, equations, processes or events, and link them together into graphical representations. Visual representations and hierarchical structures help users to build large, complex models that can still be clearly explained to interested stakeholders (e.g., government regulators, elected officials, and the public) (GoldSim 2014).

The principal components of the PBGMT are a control panel, the model logic, model inputs and results. These components are set out in more detail below.

3.0 GOLDSIM MODEL DOMAIN AND SPATIAL DISCRETISATION

The GoldSim model in its current state of development is structured to calculate groundwater level fluctuations and water balance within the Makauri Aquifer. The model has been discretised (split) in the horizontal and vertical directions and also temporally (into time steps) to focus the assessment on key areas of interest and to provide model results at an adequate resolution.

Five main aquifers have been delineated within the Quaternary deposits. These include three shallow aquifers hydraulically linked to surface water bodies (Shallow Fluvial Aquifer, Waipaoa Gravel Aquifer, Te Hapara Sand) and two deeper leaky confined aquifers (Makauri Aquifer and Matokitoki Aquifer). Individual representation of the shallow aquifers is not required for the purposes of evaluating the hydrogeological behaviour of the Makauri Aquifer. The shallow aquifers are therefore treated as a single aquifer in the water balance model.

The Makauri Aquifer is the key groundwater source unit of interest for the PBGMT and is therefore the focus of the water balance model. The deeper Matokitoki Aquifer is of less interest within the scope of this project, due to its limited extent and relatively small number of users. In addition, the likely low seepage rates between the Matokitoki and Makauri Aquifers cannot be clearly differentiated from seepage between the shallow aquifers and the Makauri Aquifer. For these reasons the Matokitoki Aquifer is not specifically incorporated in the water balance model at this stage of development.

The Poverty Bay Flats aquifer system has been divided laterally into five slices (Figure B1). Each of the slices is henceforth referred to as a cell. This division has been incorporated to provide the model with sufficient sensitivity to simulate groundwater levels changes generated from a Groundwater Replenishment scheme focused on a single cell. Both the shallow aquifer and the deep aquifer have been laterally divided in this manner.

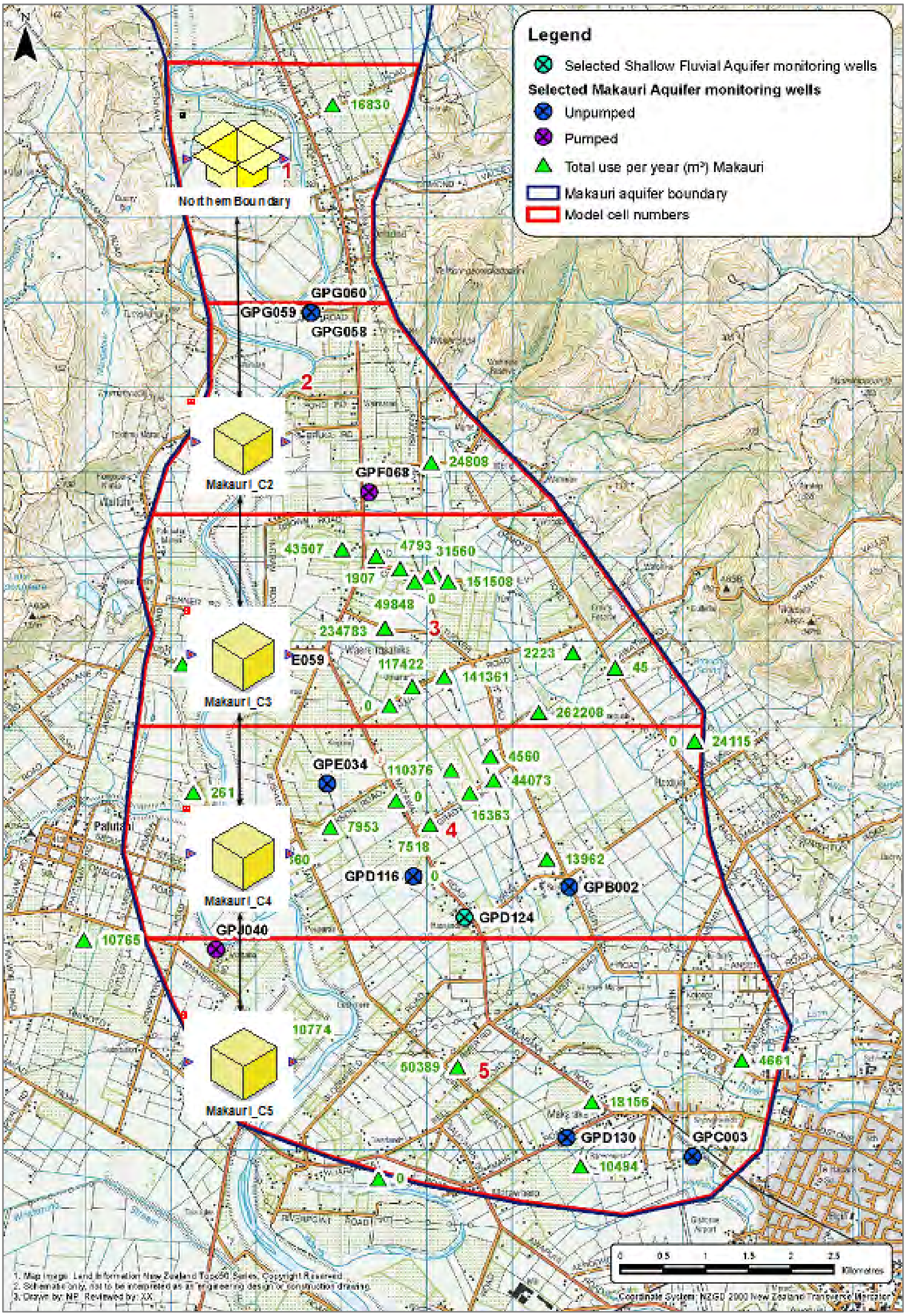

Figure B1: Makauri Aquifer Cell Layout (screen capture from water balance model).

4.0 TEMPORAL DISCRETISATION

The model has been developed for transient simulations, using historical data to simulate changing groundwater levels and water balance elements over time. Transient models discretise the simulation period into individual time steps, with model variables (e.g., groundwater abstraction) being constant within each time step. Criteria for the selection of time step length are:

- Data availability: If data is only available on an annual or seasonal basis, this limits the potential for short time steps to be applied with any validity. In this case the groundwater abstraction data for many consented takes is available on monthly or quarterly basis.

- Model requirements and calibration: A daily time step would be required to simulate minimum groundwater levels on a peak abstraction day. A monthly time step adequately simulates general seasonal water level trends. A yearly time step could only be used to simulate long term groundwater level trends.

In order to calibrate the model reservoir capacity (aquifer volume x storativity), simulation of seasonal water level variations is required and on this basis quarterly or monthly time steps are required. For the purposes of this model, a monthly time step has been adopted.

Data availability: groundwater use data is limited to annual volumes whilst groundwater level data is available at daily (or higher) resolution.

5.0 MODEL LOGIC AND INPUTS

5.1 Model logic

The core of the model logic is a series of five aquifer reservoir elements or cells that represent the Makauri Aquifer groundwater resources of the Poverty Bay Flats. Each cell has an individually specified water storage capacity and hydrogeologic properties. These are defined by the model builder and cannot be changed by a Player file user.

The model calculates the volume of water stored in these reservoirs over time, based on inflows and outflows. Some inflows and outflows are defined by the model builder. Others can be varied by the Player file user, within limits specified by the model builder. An example of the influences on one of the reservoirs is presented in Figure B2.

Vertical and lateral groundwater flows were calculated using Darcy's Law which describes the rate of flow of a fluid through a permeable medium (Equation 1).

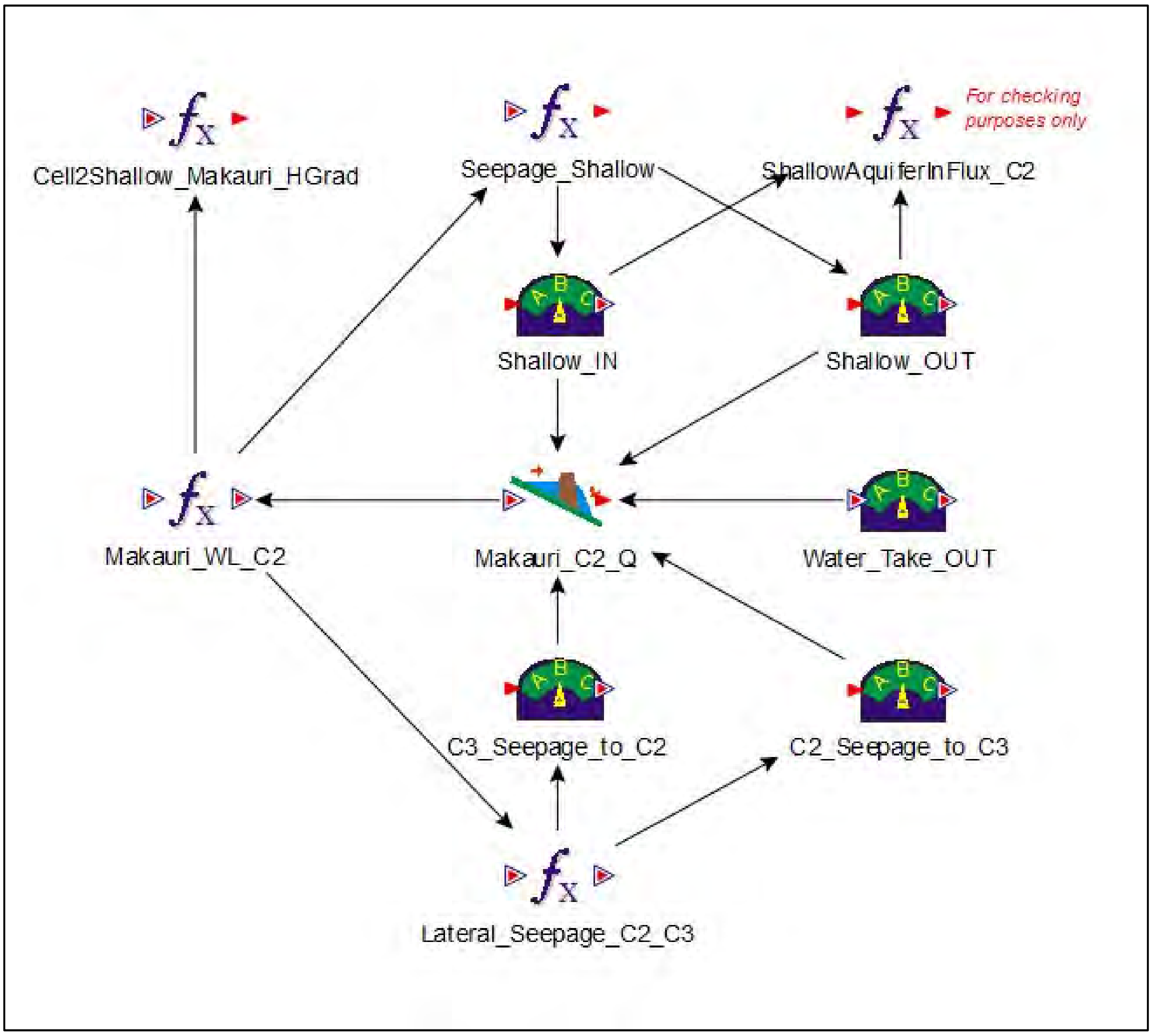

Figure B2: Influence diagram of inflows and outflows on the Makauri Aquifer Cell 2 reservoir, Makauri_C2_Q (screenshot from PBGMT).

Equation 1

$$Q = -K_v A \frac{(h_b - h_a)}{L}$$

or

$$Q = -Tb \frac{(h_b - h_a)}{L}$$

where:

Q	=	flow (m^3/day)
K	=	vertical hydraulic conductivity (m/day)
A	=	cross sectional area of the flow boundary (m^2)
T	=	lateral transmissivity (m^2/day)
B	=	width of the flow boundary (m)

$h_b - h_a$ = the drop in pressure head (m)

L = the distance over which the pressure drop occurs (m)

Pressure heads in the overlying shallow gravel aquifer were derived from historical monitoring records values, as described below. Pressure heads in the Makauri Aquifer constituent cells were derived by dividing the volume of water stored in the cell reservoir by its respective area and storativity (Equation 2).

Equation 2

$$h_a = \frac{V}{AS}$$

Where:

h_a	=	pressure head (m)
V	=	volume (m^3)
A	=	area (m^2)
S	=	storativity ($m^3/m^2/m$)

We have assumed in applying storativity to Equation 2 that the Makauri Aquifer would remain fully saturated across the entire breadth of the Poverty Bay Flats, even during a substantial drought year associated with a large water demand.

The values applied to various cells in the model for aquifer transmissivity and storativity and the vertical hydraulic conductivity for the overlying aquitard vary, as described in Section 5.2.3.

5.2 Model inputs

5.2.1 Allocation Limits

The allocation limit record was synthetically extended through interpolation between available annual allocation limit data points (Figure B3). The first allocation record has been set at zero for the year 1960, when groundwater allocation limits were not yet enforced within the Poverty Bay Flats catchment.

5.2.2 Water Takes

Documented water use records compiled from 32 wells connecting to the Makauri Aquifer were synthetically extended through a regression analysis of the relationship between monthly Penman Evapotranspiration (PET), derived from NIWA's virtual climate station (VCS) data, and the recorded monthly water use data for the years 2009 to 2013 provided by GDC.

Two synthetic water take records were developed (Figure B4), a static record for calibration runs (Scenario 1) and a modifiable record which allows the user to run future projections (Scenarios 2 and 3). The Scenario 1 water take record consists of two parts:

- 2009-2013: recorded data from monitored pumped wells intersecting the Makauri Aquifer
- Pre-2009: the same synthetic record as for Scenarios 2 and 3, modified to reflect the expectation that increases in water use with time would mirror the increases in allocation. This was achieved by adjusting for the catchment wide allocation limit for the current year as a fraction of the 2013 catchment wide allocation limit.

The base water take records for Scenario 2 and Scenario 3 are completely synthetic records derived using the regression equation. The synthetic water take records for each scenario have been applied to each Makauri Aquifer cell, in proportion to the recorded volumes taken from each area during the 2009 to 2013 period.

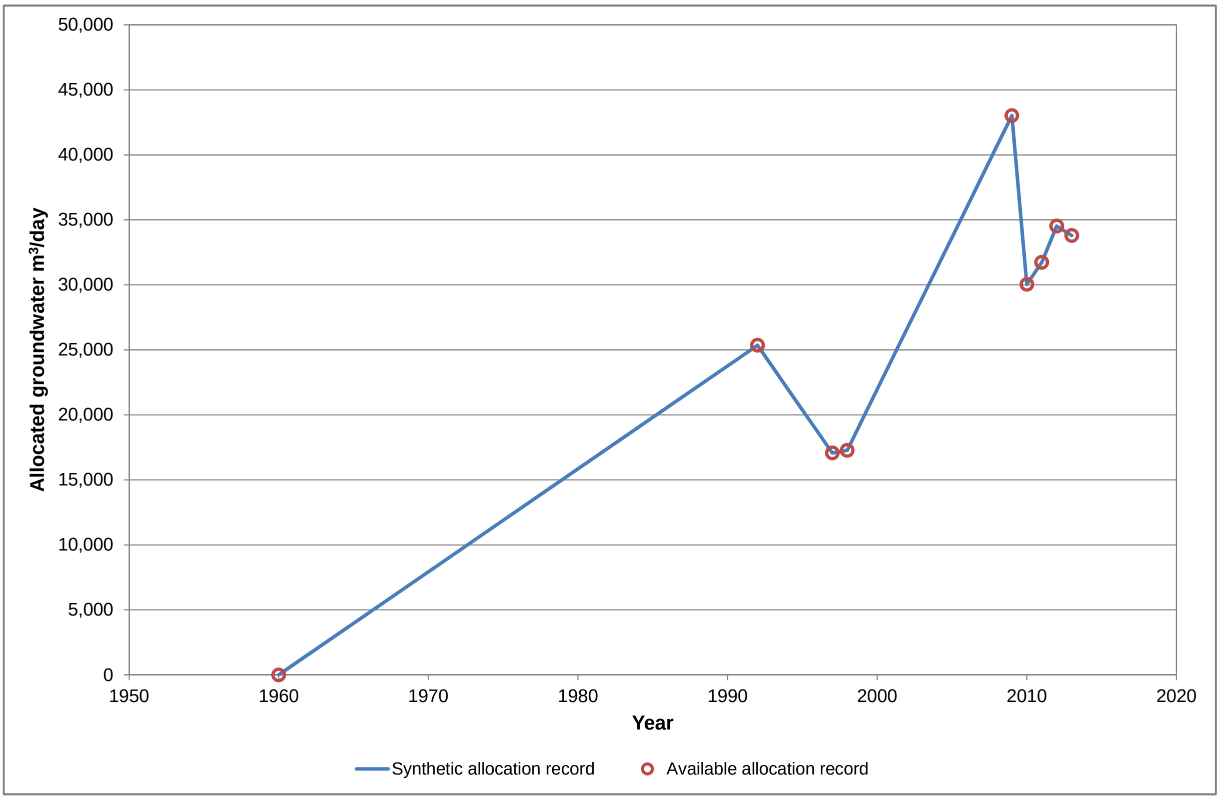

Figure B3: Graph of recorded allocation limits and synthetic allocation record.

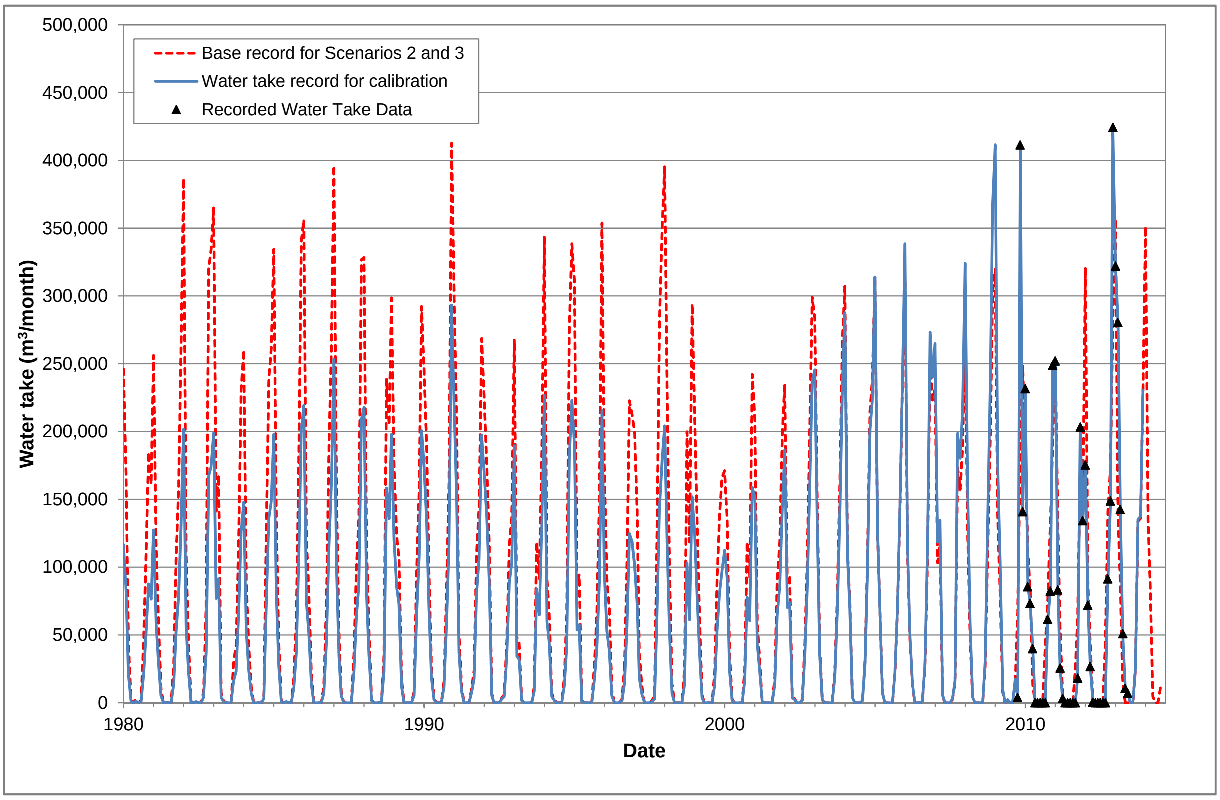

Figure B4: Synthetically extended water take records.

The shallow aquifer head boundary for each cell is calculated based on water level records from bores contacting the overlying shallow fluvial aquifer. The water level records from wells GPG059, GPE032, GPD124 and GPA004 (Refer to Figure 3 in the main report) were used in the model to calculate seepage rates between the shallow overlying aquifer and the Makauri Aquifer cells two, three, four and five.

The calculated water levels for the Makauri Aquifer's constituent cells were each checked against one or more long term water level records from selected Makauri Aquifer monitoring wells (separate to the 32 wells used to develop the water use record). Wells GPG060, GPF068, GPE034 and GPJ040, used to calibrate water levels in cells one, two, three and four, respectively, are presented in Figure 3 in the body of the report.

5.2.3 Physical Parameters

The physical parameters defined for each aquifer cell in the model consist of:

- Storativity (S),
- Capacity,
- Hydraulic conductivity (K_h) and transmissivity (T) (hydraulic conductivity of the aquifer multiplied by the aquifer thickness)

In addition, a vertical hydraulic conductivity (K_v) value is specified for the aquitard layer overlying each cell.

The geometry for each Makauri Aquifer cell was based on the inferred Makauri Aquifer boundary laid out in Barber (1993). The expected ranges of values were developed based on analysis of measured hydrogeological data (refer Appendix A). These ranges provided initial constraints during the model calibration process. The development of the final ranges of values for the above parameters is described further in Section 6.0.

The physical parameter values cannot be altered by the PBGMT end-user at this stage of model development. Further development of the Player file and the control dashboard may enable end users to vary the physical aquifer parameters within previously specified ranges if required.

6.0 MODEL CALIBRATION

The physical aquifer characteristics listed in Section 5.2.3 were adjusted in the water balance model calibration process. During this process the model outputs for groundwater levels in each Makauri Aquifer cell were compared to recorded water levels for the 2005 to 2013 period.

A calibrated set of aquifer parameters through the use of an objective function built into the model. The objective function in this case has been defined as the sum of the cumulative error in groundwater levels for the Makauri Aquifer cells. This function is calculated through squaring the difference between the modelled and the observed water levels for each cell and totalling the results over time. GoldSim has an internal optimiser function which enables the user to specify the goal (minimise or maximise), the function to optimise, the precision (number or scenarios to run) and the desired variables requiring optimisation.

The calibration objective during model development was to minimise the objective function (as described above) by adjusting the values for vertical hydraulic conductivity (K_v), transmissivity (T), storativity (S) and the northern boundary recharge rate.

Table C1: Constraints and optimised values for the Makauri Aquifer physical parameters.

Parameter	Spatial Extent	Constraint Values	Optimised Values
K_v (m/day)$^{(1)}$	Cells 1 – 3	0.00036	0.00057
	Cells 4 – 5	0.00036	0.0023
T (m^2/day)$^{(1)}$	Cell 1	864	10 $^{(3)}$
	Cells 2 – 3	1,800	2,500
	Cells 4 – 5	1,000	1,500
	Coastal boundary	2.5	2.7
S (m^3/m^2/m)$^{(2)}$	Makauri Aquifer	0.0008	Minimum = 0.0001 Maximum = 0.001
Northern boundary inflow (m^3/day)	Northern boundary	838	2,937

Notes: 1) Constraint and calibrated values presented as the mean of a uniform distribution.
2) Constraint value presented as the mean of a uniform distribution. Calibrated values are the minimum and maximum of a uniform distribution.
3) For further information refer to text in Section 6.0.

The transmissivity values applied to each aquifer cell are used to model the groundwater seepage rate across the boundary between adjacent cells. In general the mean transmissivity of the adjacent cells is used in calculating seepage between these cells. The transmissivity between Cell 1 and Cell 2 was however represented as a weighted average to account for the different distances between the centroid for each call and the boundary between the two cells. The transmissivity applied to Makauri Aquifer Cell 1 however applies to the full width of the northern boundary.

The calibrated transmissivity value applied to the Makauri Aquifer Cell 1 is substantially less that would be expected, given the transmissivity values identified from pumping tests in other areas of the aquifer. This low value was applied to throttle back on seepage rated from the north and therefore enable realistic seasonal variability in Makauri Aquifer groundwater levels to be achieved. This requirement suggests further work is required in simulating inflows through the northern boundary of the model.

Validation of the model over the period from 1985 to 2005 was checked by comparing the water level outputs from each cell to the water levels recorded in wells from spatially comparable locations. The respective plots for cells 1, 2, 3, 4 and 5 can be seen below in Figure B5, Figure B6, Figure B7, Figure B8 and Figure B9.

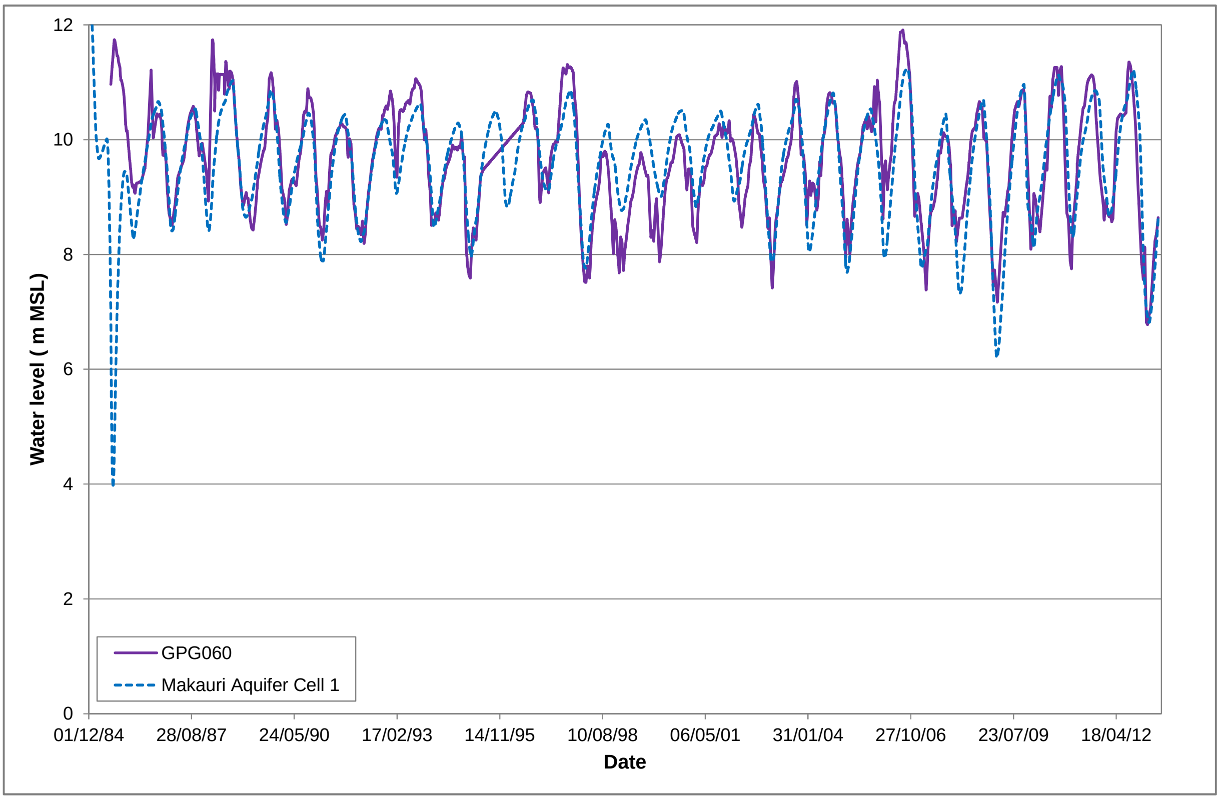

Figure B5: Makauri Aquifer Cell 1 validation plot.

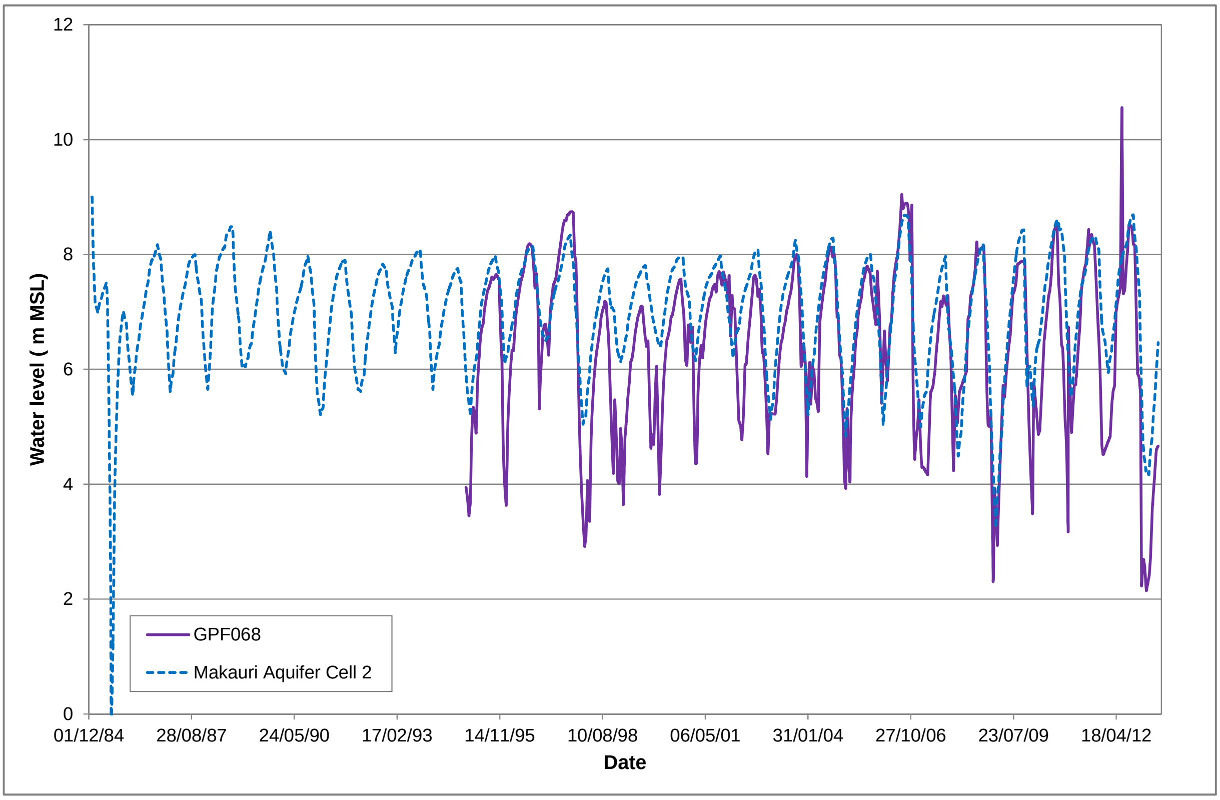

Figure B6: Makauri Aquifer Cell 2 validation plot.

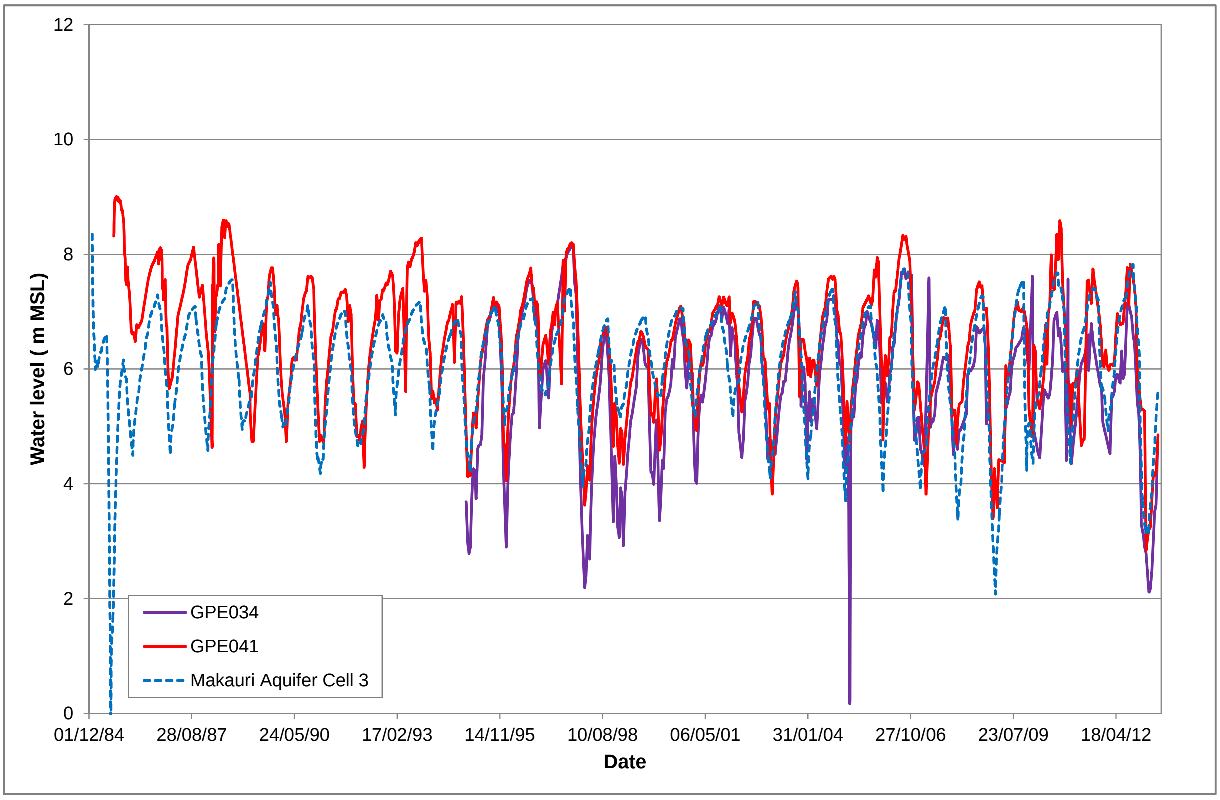

Figure B7: Makauri Aquifer Cell 3 validation plot.

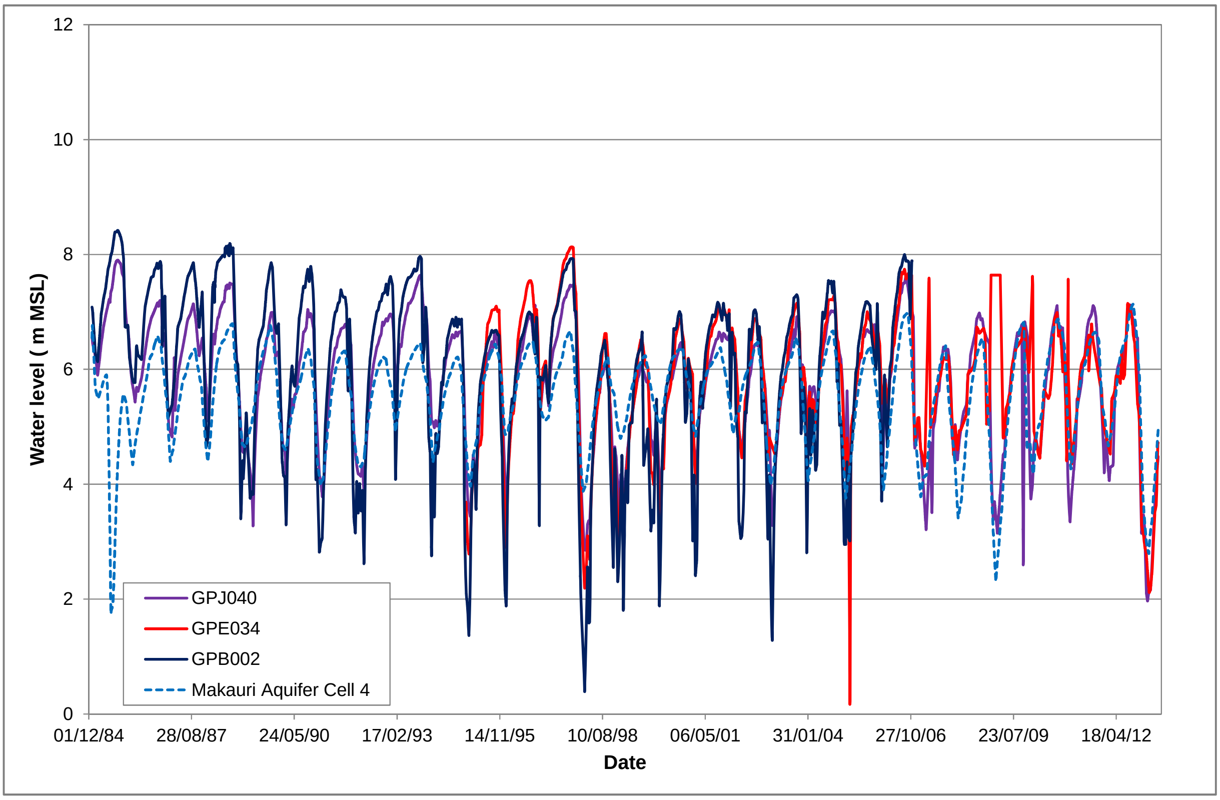

Figure B8: Makauri Aquifer Cell 4 validation plot.

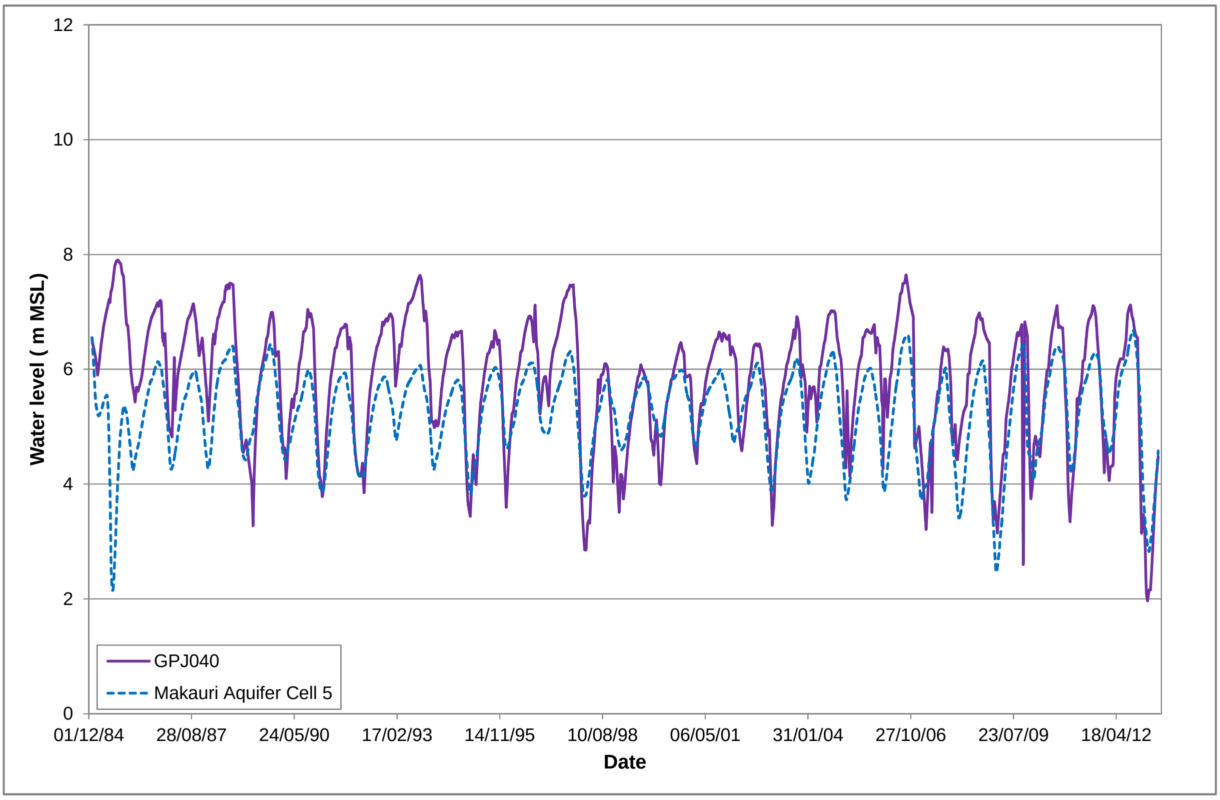

Figure B9: Makauri Aquifer Cell 5 validation plot.

7.0 MODEL LIMITATIONS

It is important to recognise that the water balance model is still under development. Some aspects of the model may change as knowledge of how the aquifer reacts under specific circumstances increases. The model structure and the outcomes from the model calibration process (Table C1) do not represent a unique solution to simulating the Makauri Aquifer behaviour.

The model does not incorporate hydrostatic pressure decline in the aquitard overlying the Makauri Aquifer, shallow aquifer water level reduction or surface water depletion. Model shallow aquifer water levels are represented using historic water level data, so although model water levels in this unit vary seasonally and in response to longer term climatic trends, shallow aquifer water level decline cannot be simulated under the current model configuration. This means that the model may over-predict Makauri Aquifer recovery rates. Future Makauri Aquifer water pressure declines could be greater than model results indicate if increased abstraction cased water level declines in the shallow aquifer. During further development the model may be reconfigured so that the shallow aquifer is represented as a series of reservoirs with a constant through flow, calibrated against groundwater level monitoring records. This would allow for shallow groundwater level declines and any associated reduction in recharge of the Makauri Aquifer.

Water is supplied to the northern model boundary based on the assumption of a constant head zone in the aquifer several kilometres to the north of the model. In effect, this assumes the presence of a recharge zone in the Waipaoa River valley several kilometres to the north of Ormond. Although it is possible that this is a reasonable representation of how recharge to the Makauri Aquifer occurs, it is also possible that the available water from the north could decrease over time in response to increased abstraction from the Makauri Aquifer. If this is the case, the simulation of seepage flows into the model from the north during the late summer may be overstated by the model.

Model optimisation results indicated that an acceptable calibration to measured groundwater level data could be achieved with a higher Makauri Aquifer coastal zone transmissivity. The upward seepage losses and downward seepage gains from the shallow aquifer system were replaced by coastal discharge in this scenario, and the future increased water use scenarios resulted in intrusion of water from the coastal boundary to the Makauri Aquifer. Although the Makauri Aquifer is thought to be blind at the coast, with limited hydraulic connectivity, it is not certain that this is the case and hence the possibility of coastal boundary water intrusion in response to future increased abstraction cannot be ruled out entirely at this stage.

In summary, the current model provides only one possible outcome, and other outcomes are possible whilst still achieving a reasonable model calibration against measured groundwater level trends. The GoldSim model could be developed further to determine the full range of aquifer parameter inputs that provide an acceptable match to measured data. The model could then be run in probabilistic mode to estimate the range of possible long term groundwater level trends for each scenario, and the probability that any given outcome will occur.

8.0 MODEL USER GUIDE

8.1 Introduction

The Player File version of the PBGMT allows users to access the model functionality and view the underlying model structure via a free Player File software download[1]. The Player File version of the model will be sent electronically to the end user. The Player File is set up to export water level results from the 5 Makauri Aquifer cells, the daily water budget and daily average water fluxes to an Excel spreadsheet named “ModelExports”. During the first model run, GoldSim will generate the Excel workbook within the folder to which the player file is saved. Further simulations will export to the same workbook, overwriting the existing results.

The overall PBGMT model structure cannot be modified when using a Player File. The input values that may be applied by the user are limited to a realistic potential range. Inputs that are available for modification are accessed via the “Scenarios dashboard”, a user-friendly interface designed specifically to enable model end-users to define appropriate parameters to simulate operational management of the potential GWR scheme.

The “Results dashboard” presents a selection of the graphical model outputs which enable the user to quickly view the consequences of the selected scenario and parameters on groundwater supply reliability projections. The user is also able to explore and view the time history outputs of any other function element within the wider model by left-clicking on the elements output arrow, then right-clicking on the output of interest and selecting “Time Histories”.

This version of the PBGMT is a work in progress and is not intended to be used at this stage for detailed design work.

[1] http://www.GoldSim.com/forms/playerdownload.aspx

8.2 Scenario Settings

The three groundwater take scenarios built into the model are:

Scenario 1: Calibration

> Projections made using this scenario represent current groundwater abstraction and recharge patterns continuing into the future. This scenario was used to calibrate the model through comparison of modelled and measured groundwater levels, as described in Section 6.0.

Scenario 2: Annual growth

> This scenario allows the model user to define an annual percentage increase in groundwater abstraction rate, above those defined for the status quo (zero growth). This scenario can be used, through combination with user-defined inflows, to assess the impact on groundwater levels associated with a range of MAR management options and water demand growth scenarios.

Scenario 3: Percentage of allocation limit

> This scenario can be selected to show the expected decline in groundwater levels if all existing groundwater takes were operated at a user-defined percentage of their consented limits on peak drought days. This scenario can be used, through combination with user-defined inflows, to assess the impact on groundwater levels associated with a range of MAR management options and water demand scenarios. Currently, on peak drought days, water demand in the catchment peaks at 30% of the total allocated limit.

The scenario is chosen via a drop down box on the main control dashboard. The desired growth rate for scenario 2 is entered by the user into an input box as a percentage annual growth. The proportion of the allocation limit used on peak drought days as a percentage is selected by the user via a slider on the main control dashboard.

8.3 Managed Aquifer Recharge Settings

The total volume of water injected into the aquifer over the course of a recharge season is entered by the user into an input box on the main control dashboard. The volume specified by the user is assumed to be injected at a steady rate into the Makauri Aquifer Cell 3 reservoir over the period 01 May to 30 September each year. The volume of water injected into the aquifer over the course of the recharge season can also be linked to the growth rate of water use, if the model is run under scenario 2.

8.4 General Settings

All settings may be changed while the simulation is paused; for example adjusting the volume of water injected during the recharge season. This enables changes in future use or recharge scenarios to be applied from a specified point in the future.

This capability includes switching the selected scenario, for example if one wished to model a 10% growth rate for the first 10 years (scenario 2), followed by a jump in water use to 100% of the allocation limit on peak drought days (scenario 3). The simulation may be accurately paused by decreasing the speed of the simulation using the slider at the bottom right of the GoldSim Run Controller and selecting the pause/play button once the desired date is displayed.

8.5 Model Extensions

The model structure has been designed to accommodate additional modules if required during later phases of the MAR project, such as a financial module and a water quality module. The financial module can provide estimates of GWR capital and operating costs and economic benefits (e.g., revenue associated with increased irrigated area) for a given operational scenario. A water quality module could be developed to indicate possible water quality changes in the aquifer due to recharge of water from the various potential water sources.

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APPENDIX C

Groundwater Quality

1.0 INTRODUCTION

1.1 Background

The GDC is considering the use of a MAR system to provide increased reliability of supply to groundwater users across the Poverty Bay Flats area. One component of this feasibility study is an assessment of the effects of a MAR system on aquifer water quality and on the properties of the aquifer itself.

For the purposes of this water quality effects evaluation, it has been assumed that:

- The water to be recharged to the aquifer is sourced from the Mangapoike dams.
- The recharge water is to be injected into the Makauri Aquifer.

A general overview of water quality for the aquifers of the Poverty Bay Flats area, as well as potential recharge source water alternatives, was provided in Golder (2014).

1.2 Appendix Structure

This appendix is set out into the following sections.

- Section 2.0 summarises the receiving water quality of the Makauri Aquifer.
- Section 3.0 summarises the quality of the water available for use as artificial recharge to the Makauri Aquifer.
- Section 4.0 describes the likely water chemistry effects of mixing the two different waters and summarises management measures available to mitigate potential environmental effects.
- Section 5.0 summary.

All documents referred to in this appendix are listed in the reference list of the main report.

2.0 RECEIVING WATER QUALITY

For the purpose of the MAR feasibility assessment, it has been assumed that the Makauri Aquifer will be the target for direct injection of recharge water. Based on 5-year medians (2008 to early 2014) of water quality data from bores screened in this aquifer, the following observations have been made:

- No data on oxygen concentrations (or reducing-oxidising potential) are available. However, relatively high concentrations of dissolved iron, dissolved manganese and ammoniacal nitrogen suggest the aquifer is anoxic (i.e., no oxygen is present).
- Analysis of water from the Makauri Aquifer bores monitored by GDC indicates the groundwater in this aquifer has concentrations of iron elevated above ANZECC (2000) guidelines for long-term irrigation (>1.0 g/m^3). Iron concentrations are greatest in the southern half of the aquifer (Figure B1a) with the highest median recorded in water from bore GPD147 (24 g/m^3).
- Concentrations of manganese measured in water from the Makauri Aquifer bores were elevated above ANZECC (2000) guidelines for manganese (>1.0 g/m^3) in bores to the northeast of Makaraka (bores GPD132, GPD 134 and GPD147), particularly bore GPD132 (Figure B1**Error! Reference source not found.**b), but were below the guideline value elsewhere.

- Ammoniacal nitrogen concentrations in water from the bores in the western and southern margins of the Makauri Aquifer (Figure B2a) exceeded ANZECC (2000) guidelines for nitrogen in long-term irrigation water.
  - Total nitrogen concentrations were not measured, so it is possible that the use of ammoniacal nitrogen as a proxy for all nitrogen species underestimates nitrogen concentrations throughout the aquifer.
  - The ANZECC (2000) nitrogen guideline is for the prevention of bacterial growth in irrigator machinery. It is therefore likely that, given relatively elevated concentrations throughout the catchment, bacterial growth within existing bores is limited by phosphorus (if at all).
  - Dissolved reactive phosphorus concentrations were typically low, and the results for all of the monitored bores were below the ANZECC (2000) guidelines for long-term irrigation (0.05 g/m^3).
- The electrical conductivity of water from the monitored bores increased from north (0.67 dS/m) to south-west (3.67 dS/m). Bores in the south-western corner of the aquifer have been less suitable for the irrigation of saline-intolerant crops (e.g., grapes) than elsewhere (ANZECC 2000); Figure B2b).

In summary, the Makauri Aquifer bores with better water quality are located in the eastern half of the aquifer while bores to the south had poorer water quality.

On the basis of this assessment, two bores were selected for further consideration. Bore GPF068 to represent “best available” bore water quality, and bore GPD147 to represent “worst case” bore water quality (high iron, moderate salinity, moderate ammoniacal nitrogen). Iron was considered to be the primary element of concern for the worst case assessment.

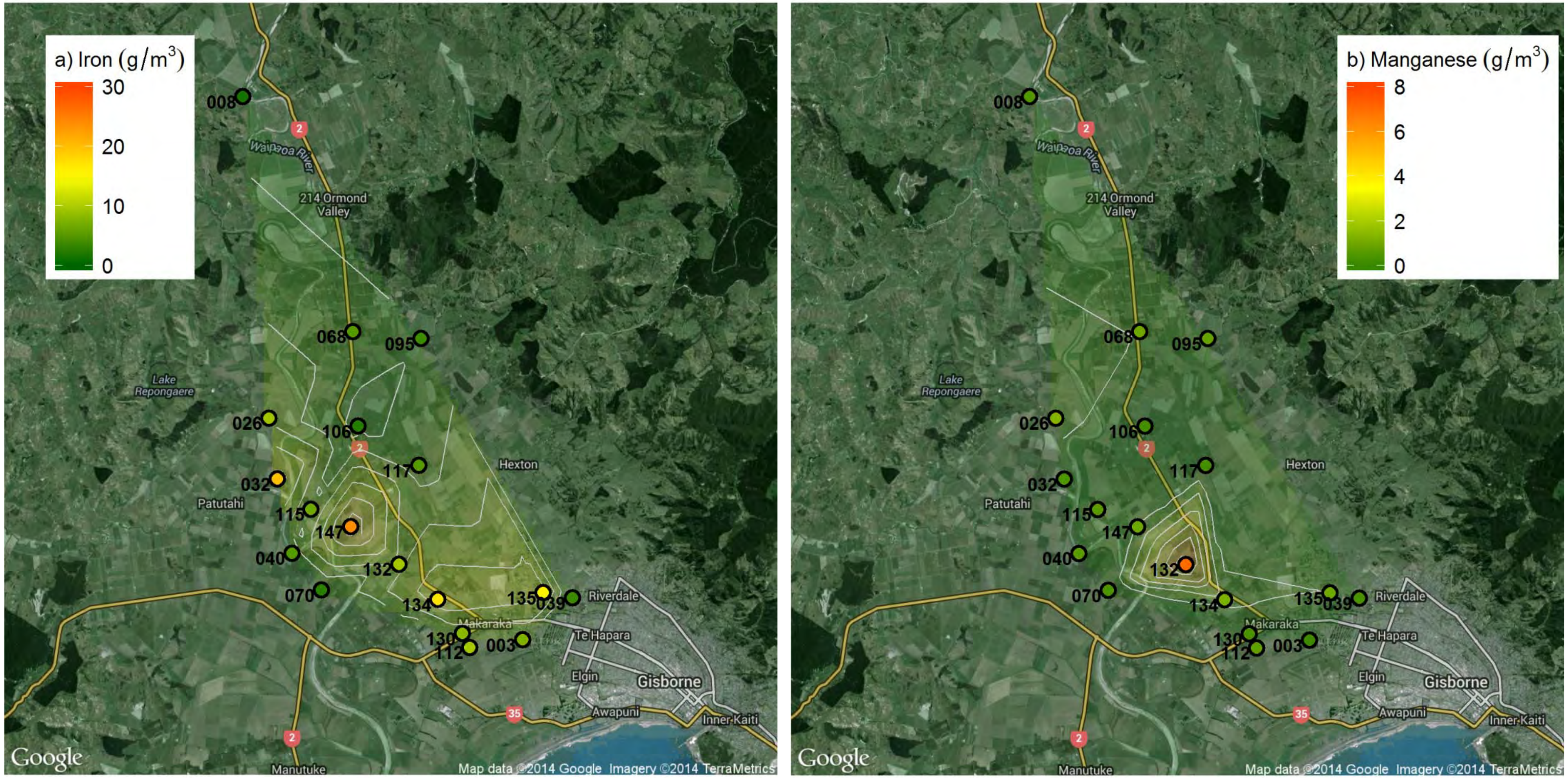

Figure B1: 5-year medians for a) iron and b) manganese in the Makauri aquifer.

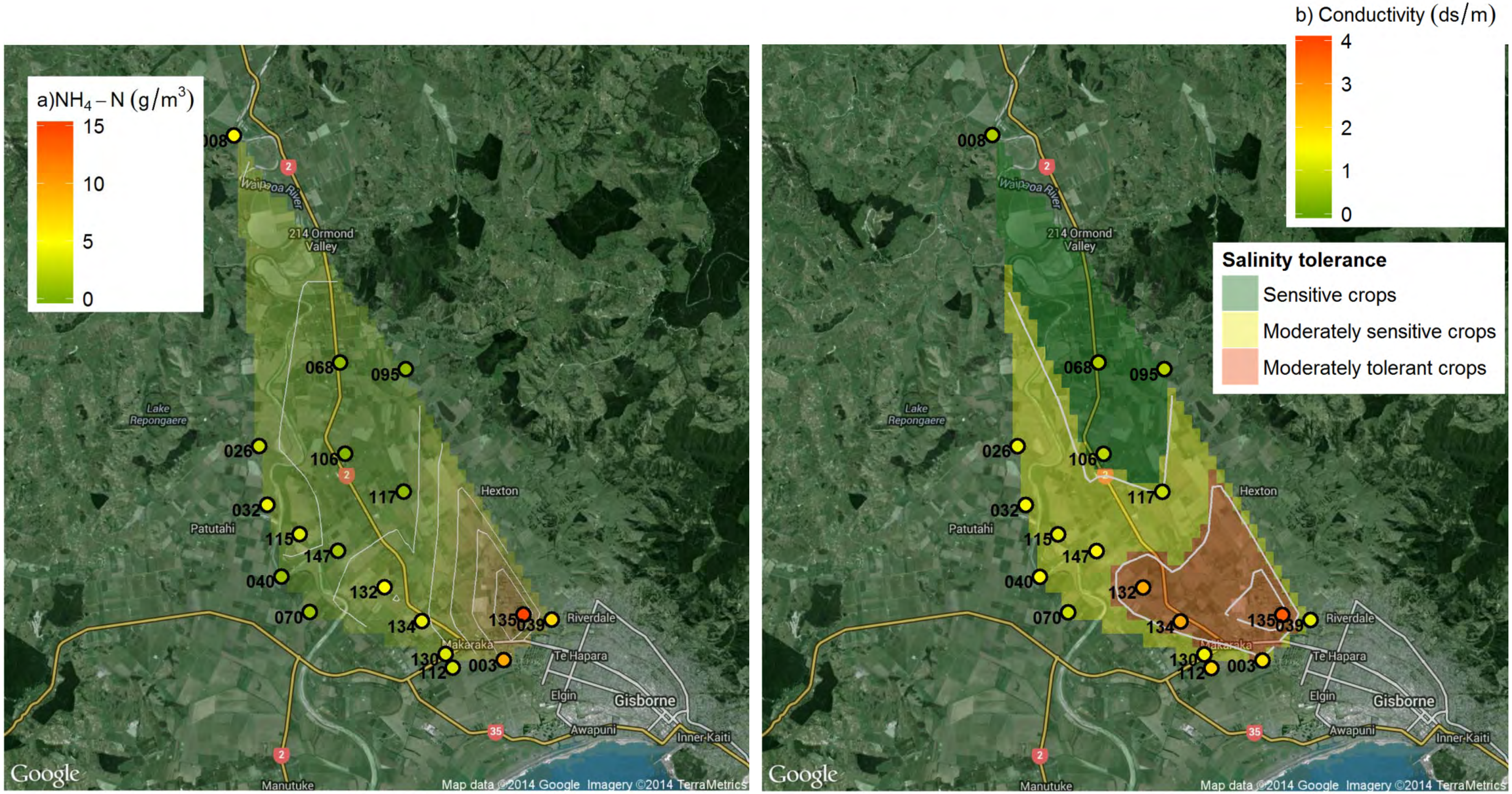

Figure B2: 5-year medians for a) ammoniacal nitrogen and b) salinity in the Makauri aquifer.

3.0 POTENTIAL SOURCE WATER

The quality of water in the dams that feed into the Waingake treatment plant is generally very good. Measured concentrations of nitrogen, phosphorus, iron and manganese in this water are all below laboratory limits of reporting. In comparison to mean data for 5-year median data for the two feasibility bores, concentrations of all parameters of significance were low (Table B1). It is thus considered that the use of Waingake dam water for reinjection has the potential to improve the overall quality of the Makauri aquifer.

The Waingake dam water has low concentrations of suspended sediments (turbidity <0.6 NTU). It is assumed that water from the Waingake dams is oxygen-saturated.

Table B1: Comparison of Makauri Aquifer and untreated dam water quality.

Parameter(1)	Dam water quality	GPF068(2) (Makauri)	GPD147(3) (Makauri)	LTV(4)
pH (unitless)	7.6	7.2	7.3	-
Salinity (dS/m)	0.0078	0.72	1.6	0.95
Chloride	Not measured	21	220	350
Sodium	6.2	29	130	115
SAR (unitless)	0.55	0.92	2.8	2
Ammoniacal nitrogen	<0.010	0.76	1.5	5
Dissolved reactive phosphorus	<0.004	<0.004	<0.004	0.05
Aluminium(5)	<0.003	0.0031 (2)	0.0063	5
Iron	<0.02	5.2	24	0.2
Manganese	<0.0005	0.98	1.0	0.2

Notes:
1) All units g/m^3 unless otherwise stated.
2) Median data 2010-2014, n=6 except for Fe (n=5) and Al (n=2).
3) Median data for 2008-2014, n=5.
4) ANZECC (2000) long-term values for irrigation; values are for sensitive crops.
5) Included because, although low compared to iron and manganese, aluminium can also precipitate as an oxyhydroxide.

4.0 CHEMICAL PRECIPITATION

4.1 Introduction

The primary geochemical aspect considered for the feasibility study was the potential for the precipitation of amorphous metal oxides and hydroxides to occur. Such precipitation may occur because the injected water will contain oxygen, whereas the receiving water will not. The mixing of high oxygen water with low oxygen water can cause a change in the oxidising-reducing potential of a system (i.e., redox potential, the general flow of electrons in chemical reactions), which in turn affects whether minerals will dissolve or precipitate in water.

It should be noted that one of the pioneering uses of MAR was to induce such precipitation to remove iron and manganese from groundwater. The amorphous precipitates form colloids, which can congeal into flocs. These flocs have the potential to clog the bore screens and affect the permeability of the aquifer about the injection area (e.g., Boochs & Barovic 1981). This phenomenon has been recognised for at least thirty years.

Other factors that will need to be considered at a later stage include:

- Effects associated with the ion-exchange (i.e., whether clays may swell or contract as a result of significant differences in the SAR of the injection water compared to the receiving water).
- Effects associated with the presence of iron (or other metals) oxidising bacteria

These factors were not considered to be a priority because:

- The ionic strength of the proposed injection water is low. The source of larger cations (e.g., calcium) that may exchange with smaller cations (e.g., sodium) in clays, thereby causing swelling, is limited.
- The management of injection to prevent colloid formation should also mitigate the effects of ion-exchange.
- Where precipitation is already identified as an issue, the principal effect of bacterial processes will be to enhance the rate of colloid formation. Therefore the mitigation of colloid formation should also lessen the risk of effects from bacterial processes.

4.2 Conceptual model

In order to understand the effects of geochemical precipitation induced by direct injection, a geochemical model was developed in the software package PHREEQC[1] (Parkhurst & Appelo 1999). PHREEQC is an ion-balance model that predicts saturation indices (i.e., the tendency of minerals to precipitate or dissolve) using thermodynamic and chemical speciation data.

The model was designed to provide answers to the following questions:

- Will the injection of oxygen-rich surface water into an oxygen-depleted groundwater result in the formation of amorphous iron, manganese and / or aluminium precipitates?

If so:

- What is the maximum amount of precipitate that could be produced?
- What are the drivers of this precipitation?

To answer these questions, a mixing model in PHREEQC was set-up. In this model:

- Injection water was equilibrated with atmospheric conditions (to entrain oxygen)
- This water was then mixed into the aquifer at a fixed proportion and then allowed to equilibrate with amorphous iron-oxyhydroxide, amorphous manganese oxide, and amorphous aluminium oxyhydroxide.
  - These minerals are the precursors to geologically more significant minerals, such as ferrihydrite or goethite, and so effectively limit the formation of these non-amorphous minerals
- The model was repeated with different mixing proportions (2 % intervals between 0 % and 100 % injection)
- Results for iron, manganese and aluminium concentrations were reported, along with pH and pe (a measurement of redox potential)

As stated previously, two scenarios were considered:

[1] The default PHREEQC database was used for the model.

1) Injection into an aquifer characterised by water quality similar to that measured from bore GPF068 ("good" water quality" scenario)

2) Injection into an aquifer characterised by water quality similar to that measured from bore GPD147 ("poor water quality" scenario)

4.3 Caveats and assumptions

Scenarios considered

The model only considered a direct injection scenario. Surface recharge was not modelled because it was assumed that natural processes will consume oxygen as the water is transported into the deeper aquifer. As a result any changes in redox potential under a surface recharge scenario should be minimal.

Existing conditions

Minerals already over-saturated in the bore water were ignored. For example, the model indicated that calcite was oversaturated in the GPF147 bore water, but it was assumed that the precipitation of calcite in the bore was retarded by (unidentified) chemical kinetics that would not be affected by any injection process.

Model limitations

No kinetic restraints were considered, i.e., all reactions were instantaneous. The model result should therefore be treated as "worst-case" or maximum likely potential results. In "real-world" conditions, the net rate of precipitation may be slow enough that subsequent dispersion and dilution results in fewer precipitates forming than projected.

The model only accounts for dissolved elements. Effects associated with suspended sediments or physical processes were not considered. These factors can be successfully managed separately when designing the pilot trial or a full scale Groundwater Replenishment scheme.

4.4 Model results

The results for the two modelled scenarios are presented in Figure B3. Higher amounts of precipitation were predicted in the poor water quality scenario (GPD147) than in the good water quality scenario (GPF068), with a maximum of >20 g precipitate per m^3 of mixed water. However, less injected water was required to produce precipitation in the GPF068 bore. Precipitation occurred at 6 % injection into the GPF068 bore, whereas 8 % injection was required to induce precipitation in the GPD147 bore.

The driver for precipitation in the model was the introduction of oxygen into the system, leading to a shift in redox potential (pe) from negative (reduction reactions favoured) to positive (oxidising reactions favoured). This shift causes the reduced form of iron (Fe^{2+}) to oxidise into Fe^{3+}, which has a tendency to precipitate in neutral pH conditions.

The precipitation also consumes hydroxyl (OH^-) ions, so there is a decrease in pH as precipitation occurs. This decrease affects other reactions, and as the pe of the system increases with increasing proportions of injection water, further changes in system dynamics occur. The combination of shifts in pH and pe means that maximum potential precipitation occurs at 18 % mixing for the GPD147 scenario, and 10 % mixing for the GPF068 scenario.

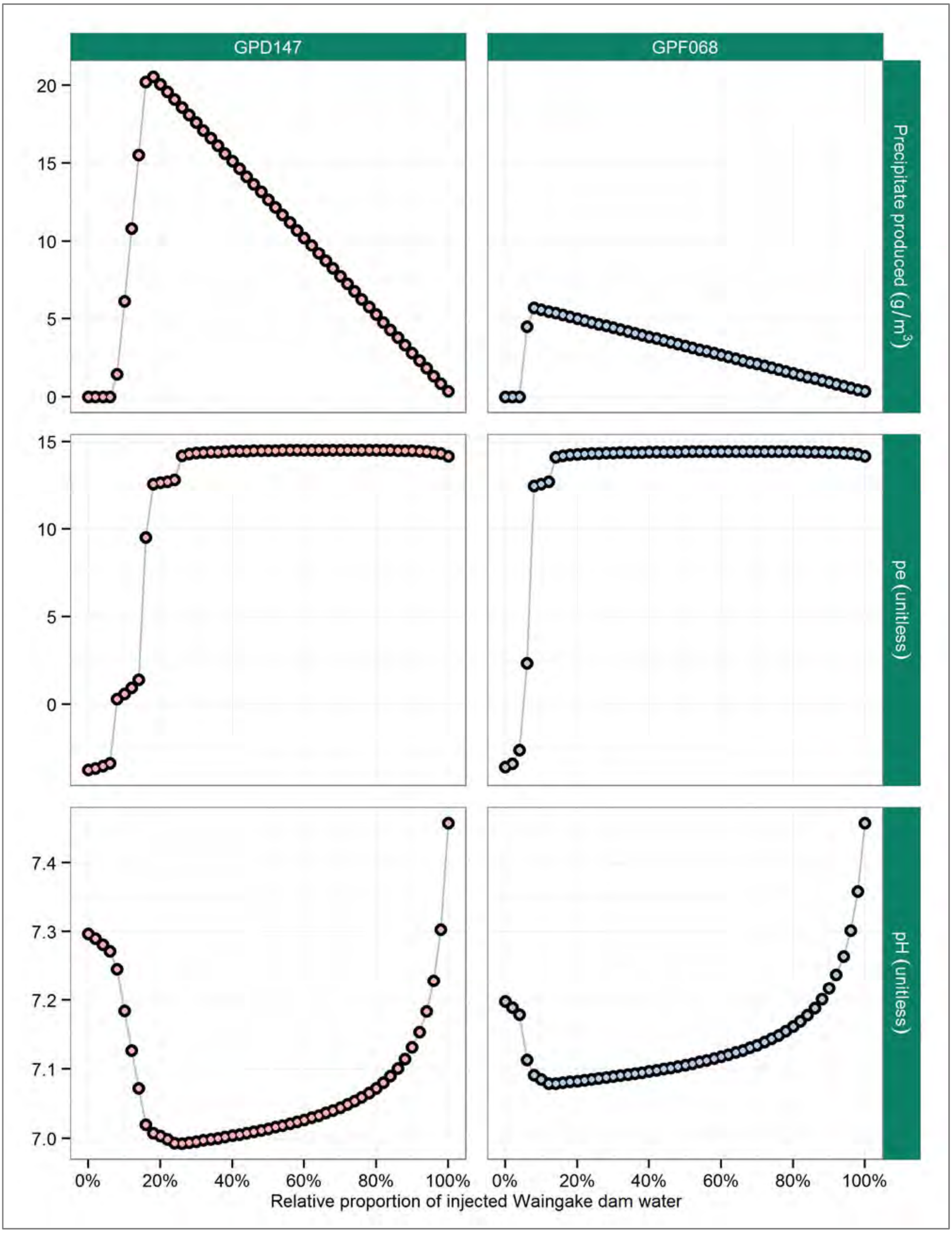

Figure B3: Results of PHREEQC modelling for two injection scenarios.

Amorphous iron was the dominant precipitate, particularly when considering water from bore GPD147 (Figure B4). The results presented in Figure B4 also indicate that the precipitation of manganese is driven solely by the addition of sufficient oxygen and is not affected by pH (within the range assessed). No amorphous aluminium precipitates were predicted in either scenario.

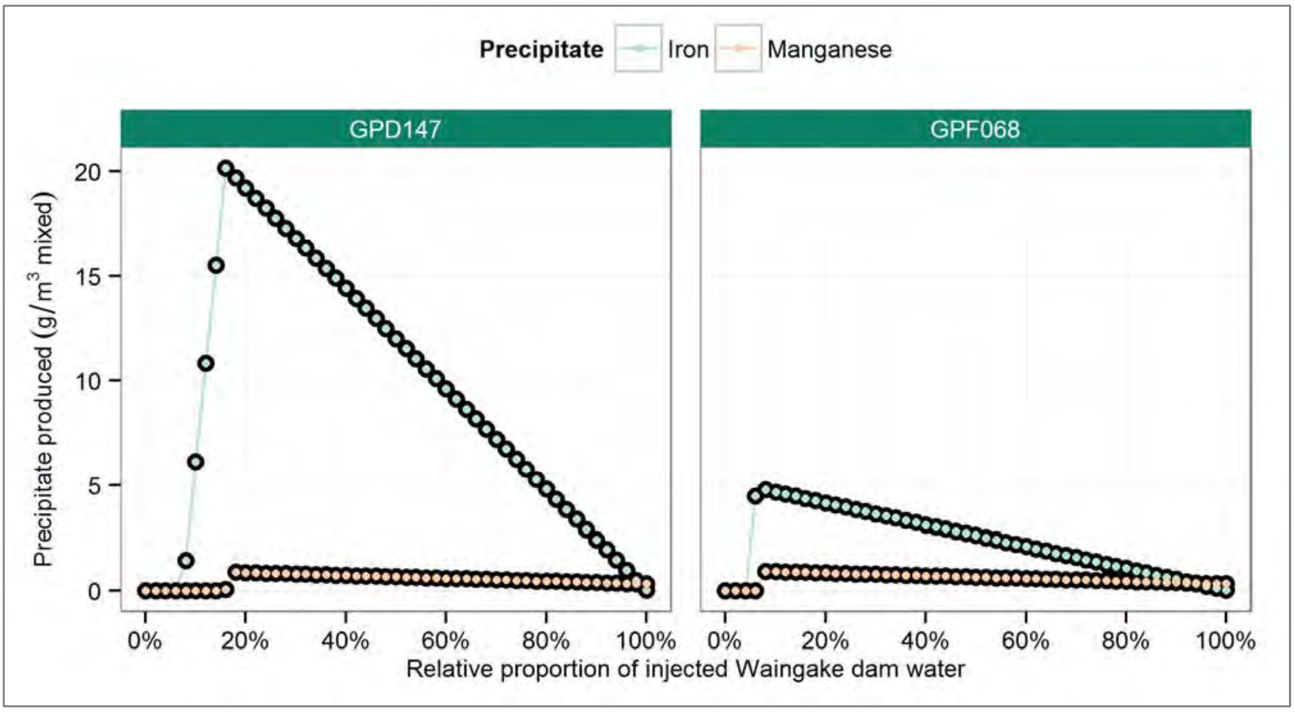

Figure B4: Types of precipitates produced in modelled scenarios

4.5 Management

4.5.1 Options

The results of the PHREEQC modelling work indicate that precipitation of metal hydroxides is likely to occur as a result of injecting water from the Waingaka dam into the Makauri Aquifer. This applies regardless of what part of the Makauri Aquifer is targeted for reinjection.

The amount of precipitation that occurs will be primarily controlled by:

1) Ambient iron concentrations in the aquifer water
2) The amount of water injected
3) The dissolved oxygen concentrations in the injected water
4) The extent of the zone where waters of different qualities mix

Management of the effects of geochemical precipitation can generally be achieved through managing one or more of the above factors. There are a range of mitigation (and prevention) solutions that may be applied to minimise the risk of clogging associated with the predicted precipitation.

These options, which can be considered separately or in combination, include:

- Distributing injected water
- The creation of a buffer zone
- Pre-treatment of injection water

4.5.1.1 Distributing injected water

The injection of recharge water may be distributed between a series of bores. This distributed recharge system would result in the injected water being distributed widely within the aquifer. The cumulative mixing zones resulting from injecting at numerous sites would normally be considerably larger that the mixing zone resulting from injecting the same volume at a single point.

The objective of distributed injection is to encourage mixing of the injected and ambient water, leading to widely distributed precipitation of iron from the aquifer water. The concept is that, over time, the water quality across much of the aquifer would improve, without having flocculants focused at any particular point or area.

This process is used in some remediation projects to improve water quality in contaminated aquifers. A complex injection system of this type is however not appropriate for most trial projects.

4.5.1.2 Buffer zone creation

Water may be injected at a single point in a manner that creates a buffer zone (often referred to as a “bubble”) in the aquifer around the injection well. The use of buffers is not novel and has been well documented in the scientific literature (e.g., Brown & Misut, 2010).

In summary, injected water displaces the existing ambient groundwater. This displacement results in a buffer zone around the injection bore where injected water dominates the pre-existing ambient groundwater. Within this bubble the aquifer water quality is therefore similar to the injected water quality (in the case of the Makauri project, low iron, manganese, etc.,). Correct management of injection cycles should enable a buffer zone or bubble to be created, maintained and expanded over time. The maintenance of an injected water bubble is more easily achieved where water is injected using a sole purpose bore rather than through a bore that is also used for seasonal water production.

A conceptual example of the cyclic development of a buffer zone or bubble at a dual use bore is shown in Figure B5. The buffer zone can be expanded through consecutive injection-abstraction cycles for two reasons:

- When anoxic groundwater is pulled back into the well during abstraction, (dissolved) Fe^{2+} can adsorb (stick) onto freshly precipitated iron oxyhydroxides created during the initial injection period. By alternating the process, the zone of iron hydroxide precipitation and iron adsorption can be pushed deeper into the aquifer each cycle.
- A little less water may be pumped out seasonally than is injected.

This approach is considered to be viable for a Makauri Aquifer MAR trial system, especially as a sole use injection well is proposed for the trial.

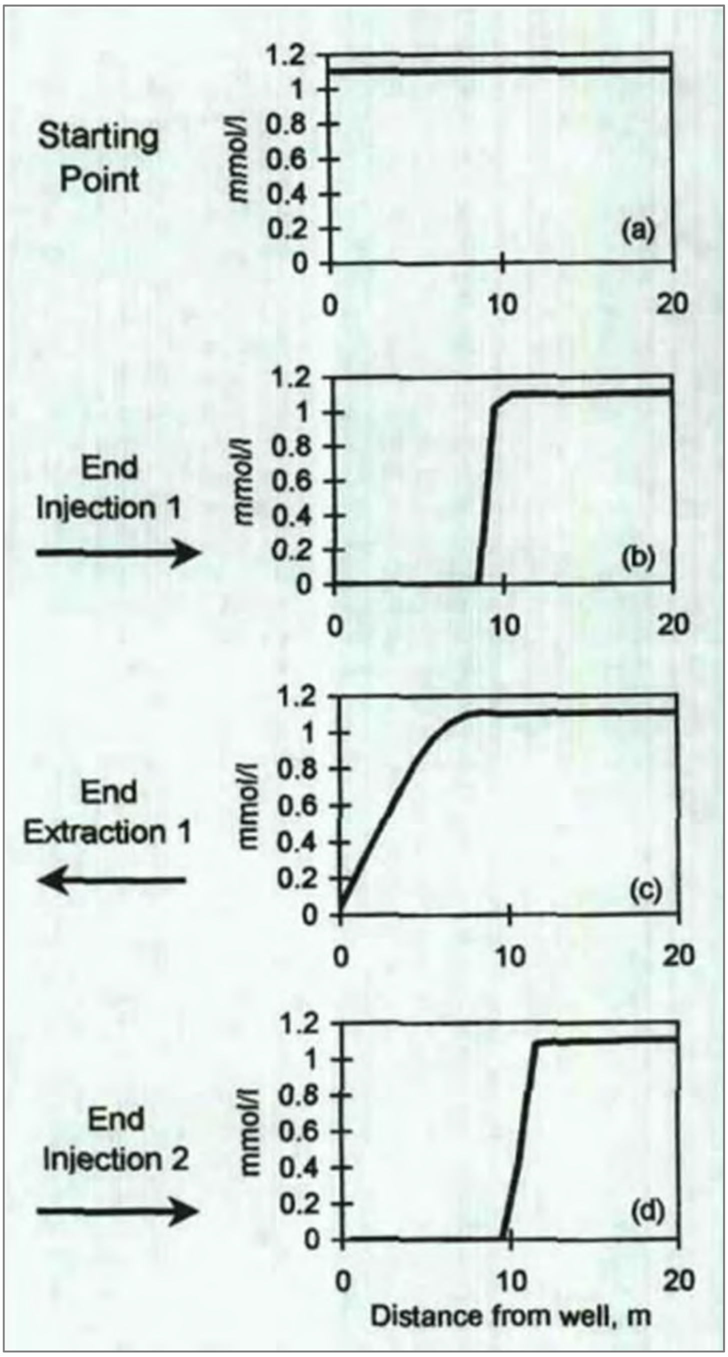

Figure B5: Effects of injection/abstraction (extraction) cycle on concentrations of Fe^{2+} (from Appelo et al. 1999).

4.5.1.3 Pre-treatment

The potential precipitation of iron oxyhydroxides can also be managed through pre-treatment of the injected water to remove oxygen. The injection of anoxic water into the Makauri Aquifer should not induce metal oxide precipitation, because oxygen has been identified as the primary driver of any precipitation reactions that may occur as a result of injection.

The pre-treatment of water prior to its injection may however incur ongoing operational costs. Chemical dosing is often the only practicable option to achieve this purpose, but, for the Makauri aquifer, alternatives are available. For example, water could be allowed to stagnate in large holding containers before injection. This alternative method is much slower than chemical dosing and there are risks associated with the process, such as bacterial contamination.

On balance, given the likely costs associated with setting up a temporary water treatment system for this purpose, pre-treatment of the water is probably not a practicable option for the water to be used for the trial.

5.0 SUMMARY

The modelled results indicate precipitation would be induced upon injection of Waingake dam water into the Makauri Aquifer. The amount of precipitation that may be expected will depend on several factors including the amount of water injected and the quality of the ambient aquifer water.

The potential for the precipitation of amorphous iron, manganese and aluminium minerals that could lead to well and aquifer clogging was considered using a relatively simple mixing model. Two scenarios were considered, “good” receiving water quality, and “poor” receiving water quality.

Precipitation management options include distributing injected water widely within the aquifer, developing buffer zones about dedicated injection wells and pre-treatment of injection water. Of these options, the development of a buffer zone is likely to be the most cost effective and practical option for a MAR pilot trial. This conclusion would however be reviewed during the design of a MAR pilot project.

APPENDIX D

Makauri Aquifer Direct Injection Complexity Rating Matrix

Attribute	Question	Outcome of the PFA	Project complexity rating
1. Source-water quality with respect to groundwater environmental values	Does source water meet the water-quality requirements for the environmental value of ambient groundwater?	Yes	Low Risk: Recharge water quality is a better quality than receiving waters
2. Source-water quality with respect to recovered water end-use environmental values	Does source water meet the water-quality requirements for the environmental values of the intended end uses of the water on recovery?	Yes	Low Risk: Recharge water quality is better than existing groundwater and surface water
3. Source-water quality with respect to clogging	Does source water have low quality; for example: Total suspended solids (TSS) >10 mg/L; Total organic carbon >10 mg/L; or Total nitrogen >10 mg/L?	 No No No	Low Risk: TSS- Values not well documented, likely to be variable depending on state of the Rangitata River.
	Is the soil or aquifer free of macro-pores?	Stage II	Low Risk: Aquifer is highly porous
4. Groundwater quality with respect to recovered water end-use environmental values	Does ambient groundwater meet the water quality requirements for the environmental values of intended end uses of water on recovery?	Yes	Low Risk: as source water quality is generally better than existing groundwater
5. Groundwater and drinking water quality	Is either drinking water supply, or protection of aquatic ecosystems with high conservation or ecological values, an environmental value of the target aquifer?	Stage II	Low Risk: the Makauri Aquifer is a semi-confined system with no clear connections to surface water bodies with high ecological values. A few bores may be used for drinking water supply purposes.
6. Groundwater salinity and recovery efficiency	Does the salinity of native groundwater exceed either of the following: 10,000 mg/L; or The salinity criterion for uses of recovered water?	 No No	Low Risk: Salinity generally not an issue in New Zealand.
7. Reactions between source water and aquifer	Is redox status, pH, temperature, nutrient status and ionic strength of groundwater similar to that of source water?	No	Moderate Risk: The issue of iron precipitation resulting from injection of oxygenated water is recognised and would require management.
8. Proximity of nearest existing groundwater users, connected ecosystems and property boundaries	Are there other groundwater users, groundwater-connected ecosystems or a property boundary within 100 to 1,000 m of the MAR site?	Stage II	Low Risk: the trial can be designed to minimise risk to other groundwater users.

APPENDIX E

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