Rainfall, River Flow, and Groundwater Level State and Trends in Tāmaki Makaurau / Auckland 2010-2019. State of the Environment Reporting

Kolt Johnson

February 2021 Technical Report 2021/06

Research and Evaluation Unit RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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Executive summary

Auckland Council operates long-term hydrological monitoring programmes for river flows and aquifer water levels throughout the region. Hydrological data is used to determine the current state and long-term trends, identify environmental management issues, inform the review and development of the Auckland Unitary Plan (AUP), and to assess the effectiveness of current plan provisions. This report describes patterns and trends in rainfall, river flow, and groundwater level and makes observations about the impacts of resource use where data were available (for groundwater) and the effectiveness of the current monitoring programmes to deliver on the stated objectives.

Climate drivers were investigated to provide context for the state and trends in this report. The Interdecadal Pacific Oscillation was predominantly increasing, and El Niño Southern Oscillation was predominantly decreasing, however there was not a clear relationship between climate oscillations and observed rainfall. No monotonic trends in rainfall could be established with confidence, however there was higher than normal rainfall in 2011 and 2016-2018. Trends in the number of high stream flows could not be established with confidence, however, there was a clear pattern of decreasing numbers of high flow events in urban catchments and increasing numbers of high flow events in rural catchments. High rainfall years were also reflected in fewer minimum flow days.

The magnitude of annual low stream flows had increasing trends at two-thirds of flow monitoring sites, but only two sites had trends that could be established with confidence. Increasing trends in low stream flows did not reflect a pattern in location, catchment size, or land cover, indicating that rainfall is the primary driver of streamflow trends. This is consistent with rainfall patterns observed over the period of analysis. The frequency of low flows below the MALF had decreasing trends (less days below) at all five minimum flow monitoring sites, however, the rate of change could not be established with confidence.

Increasing trends were calculated for most groundwater monitoring sites for both mean monthly (75%) and annual maximum groundwater level (62%). The spatial distribution of increasing trends did not show a pattern in location or aquifer characteristics. Several aquifers were found to be influenced by groundwater abstraction, leading to both decreased water levels (Omaha Waitematā and Glenbrook Kaawa aquifers) and increased water levels (Waiwera geothermal, Parakai geothermal). These cases were not representative of monotonic trends, but rather step-changes in the annual water level pattern. All sites with decreasing annual minimum groundwater levels did not have a corresponding trend in the annual maximum, indicating that groundwater abstraction did not affect winter recharge to aquifers. The decreasing summer groundwater levels observed in some aquifers are temporary in duration and followed by full recovery of groundwater levels over winter. Normal winter recharge in these aquifers suggests long-term sustainability. However, the link between water use and groundwater level in some aquifers (Omaha Waitematā, Waiwera and Parakai geothermal, and Glenbrook Kaawa aquifers) highlights the importance of continued monitoring to inform ongoing management.

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1 Introduction

The Auckland region has an estimated 19,000km of permanent rivers and streams and many productive aquifers. Surface water and groundwater are vital sources for both municipal supply and agricultural water use, including livestock drinking, rural domestic supply, and irrigation of valuable crops. It is recognised that the contribution of groundwater irrigation to the New Zealand economy is significant (estimated at $2 billion per annum) (Corong et al. 2014). The combined surface and groundwater use in the Auckland region was estimated at approximately 10% of the national average and the 12th out of 15 regions analysed in magnitude of use (Booker and Henderson 2019). However, Auckland was 6th in the nation for the number of groundwater take consents in 2010, the start of the period of analysis for this report (Aqualink, 2010). The Auckland region supports a nationally significant horticulture industry in the Franklin area (Crowcroft and Smaill 2001, Deloitte 2018) and other areas like the Okahukura Peninsula are experiencing increasing horticultural development, which require water sourced from streams or aquifers.

The purpose of this report is to assess stream flows and aquifer groundwater levels for changes or patterns over time and aid the understanding of how those changes may affect the long-term sustainability of Auckland's water supply resources.

1.1 National and regional directives

The National Policy Statement for Freshwater Management (NPS-FM) sets requirements for regional councils to protect freshwater ecosystems and provides additional direction for local decision-making under the Resource Management Act 1991 (RMA). These requirements include management of discharges, water supply and allocation, and land use. The data collected and analysed via the State of the Environment (SOE) groundwater network directly informs the objectives, policies, and rules that govern water allocation in the Auckland region.

Section 35 of the RMA requires regional councils to report on the effectiveness of plans in achieving objectives set for resource management. A key component to this is to identify any relevant trends in hydrological indices that relate to council management objectives, to determine whether the rules governing resource use are enabling these objectives to be achieved.

The Auckland Unitary Plan (OP) specifies several objectives for the management of freshwater resources, including:

- Water in rivers and aquifers is available for use provided the natural values of water are maintained and established limits are not exceeded.
- Water resources are managed within limits to meet current and future water needs for social, cultural, and economic purposes.
- Freshwater resources available for use are managed and allocated in order of priority to provide for domestic and municipal water supplies, animals, and economic development.

- Water resources are managed to maximise the efficient allocation and efficient use of available water.

Policies specific to streams:

- Minimum flows in rivers and streams are established to protect instream ecological values.
- Flow variability is maintained in rivers, streams, and springs.

Policies specific to aquifers:

- Maintain baseflow to connected streams.
- Avoid subsidence.
- Avoid saltwater intrusion.

This report addresses the state and trends observed in rainfall, river flows, and groundwater levels to compare against past analyses and to aid the assessment of environmental outcomes against management objectives. As part of an ongoing State of the Environment programme, this report will provide a comparison point for past and future reporting to track environmental change.

1.2 Auckland streams

Auckland has a diverse range of streams from small spring-fed streams in urban catchments to large rivers in rural areas. Many Auckland streams have small catchments with a short distance to the sea. The connection to groundwater systems also varies considerably, from high-baseflow spring-fed streams in volcanic geology, to low-baseflow streams in allochthonous marine-derived sediments.

Streams in urban centres tend to show 'flashy' characteristics due to the high percentage of impervious cover causing high stormwater runoff. Spring-fed streams sourced from volcanic aquifers tend to be very stable, or 'flat' throughout the year due to consistently high groundwater baseflow. Other streams show variations in flow patterns between these extremes, which are governed by topography, land use, geology, and other related factors (assuming climate is similar across all catchments).

Water takes from streams have immediate impacts on flow that can be quickly seen in the field and on hydrographs (charts of water level or flow over time). Taking water from a stream results in an instantaneous reduction in flow. This is important to consider because aquatic plant and animal communities rely on the amount of flow in a stream. Changes in flow have impacts on depths and velocities in a stream, which in turn have effects on instream biota that rely on those physical habitat characteristics (Jowett et al. 2005). A reduction in flow can cause a reduction in the amount of habitat for flow demanding species, so the flow at any given point in time is important for the management of streams to protect stream ecology. This is particularly applicable to low flows. Physical water quality characteristics are also affected by low flows, including temperature and dissolved oxygen, which impact on instream biota. This report presents trends in stream flows for both high and low flow conditions.

1.3 Auckland aquifers

Aquifers are formations of sediments or rock that are saturated and sufficiently permeable to transmit an economic quantity of water (Fetter, 2001). Groundwater is water that is held within the pores between grains of sand and rock or cracks in rocks underground below the water table. Connections between the pore spaces and cracks allow water to flow through the material. Aquifers with many well-connected pores or cracks have more flow and are more useful to us as a source of water.

The Auckland region does not have many large rivers, so the availability of surface water for abstraction is more limited in Auckland than other regions of New Zealand. Many areas of Auckland use groundwater for domestic water supply, stock drinking water, and irrigation. Groundwater provides an essential part of the freshwater resource for the region.

Groundwater takes use wells to pump water from 10s to 100s of metres below ground for various uses including irrigation of crops and drinking water. Aquifer characteristics like porosity and fracturing influence the degree to which groundwater levels react to pumping a groundwater well. This means that the effects of taking water from aquifers are highly variable in the magnitude, extent, and timing of the impacts. This often results in delayed impacts from groundwater takes than can range from hours to years and spread over many hundreds of metres.

Taking groundwater can also have impacts on streams by reducing baseflow, which is groundwater that normally discharges into the streambed. The degree of impacts on baseflow is again related to the physical properties of aquifers. The limits on water availability from aquifers are intended to ensure that baseflow to streams is maintained. Groundwater level trends can be an analogue for baseflow to streams, e.g. decreases in groundwater levels could indicate a reduction in baseflow. This report addresses trends in monthly groundwater levels and annual maximum and minimum groundwater levels.

1.4 State of the Environment report series

This report has been produced concurrently with several others pertaining to the freshwater and marine environments in the Auckland region, including:

- *Auckland river water quality: annual reporting and National Policy Statement for Freshwater Management current state assessment,* 2019 – TR2021/11
- *Coastal and estuarine water quality 2019 annual report* – TR2020/016
- *Coastal and estuarine water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/02
- *Groundwater quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/03
- *Lake water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/04

- *Marine ecology state and trends in Tāmaki Makaurau / Auckland to 2019. State of the environment reporting* – TR2021/09[1]
- *Marine sediment contaminant state and trends in Tāmaki Makaurau / Auckland 2004-2019. State of the environment reporting* – TR2021/10[1]
- *River ecology state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/05
- *River water quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/07

The authors in this series have worked collectively to analyse state and trend data over the same period (2010-2019). This is a new approach adopted by the Research and Evaluation Unit (RIMU) and aims to better identify potential linkages between disciplines and inform the overall State of the Environment five-yearly reporting in a more consistent manner.

All related reports (past and present) are available on Auckland Council's Knowledge Auckland website: www.knowledgeauckland.org.nz. Time series data used in this report are available for download at https://evironmentauckland.org.nz.

Specific data requests, further enquiries, and requests for summary analysis outputs from this report (Excel format) can be directed to environmentaldata@aucklandcouncil.govt.nz.

[1] Analyses for coastal benthic ecology and coastal sediment contaminants were completed for all data on record, not 2010-2019 as with the rest of the series.

2 Methods

Auckland Council collects data on rainfall depth, river flows, and groundwater levels to inform a wide variety of council programmes, community initiatives, and general interest. The data are published in Environment Auckland, the data portal maintained by council's Research and Evaluation Unit (RIMU): www.environmentauckland.govt.nz. These data form time series that can be analysed for trends to indicate environmental changes. This report presents surface water and groundwater level trends for the calendar year period 2010-2019, inclusive.

2.1 Rainfall

2.1.1 Monitoring network

Rainfall is a key metric in the assessment of water resources of the region as it is the source of freshwater to rivers and aquifers. Auckland Council currently operates 78 rain gauges across the region. This analysis used records from 54 sites that had greater than 20 years of data (Appendix 1). The rainfall sites were grouped into five sub-regional areas for reporting: North, Central, West, East, and South (Figure 1). The sub-regional grouping was solely based on location, however land use differences between the sub-regional groups are apparent. Most notably, the Central group includes most of the Auckland urban area, while the other groups are predominantly rural. North and South groups comprise most of the region's productive rural land and East and West are representative of large forest parks in the Waitakere and Hunua ranges.

Rainfall records were transformed to a monthly time series based on a 30-day total rainfall depth. The mean annual rainfall total was calculated for each sub-regional group.

Long-term mean and interquartile range (IQR) were calculated for the 20-year period 2000-2019. These long-term statistics were used to compare the annual rainfall totals for the reporting period (2010-2019) within each sub-regional group. The difference between the annual total and the long-term mean and IQR was used to indicate a dry/normal/wet condition for the year and sub-region. Trend analysis was run on the monthly rainfall total time series for each sub-region for the period 2010-2019.

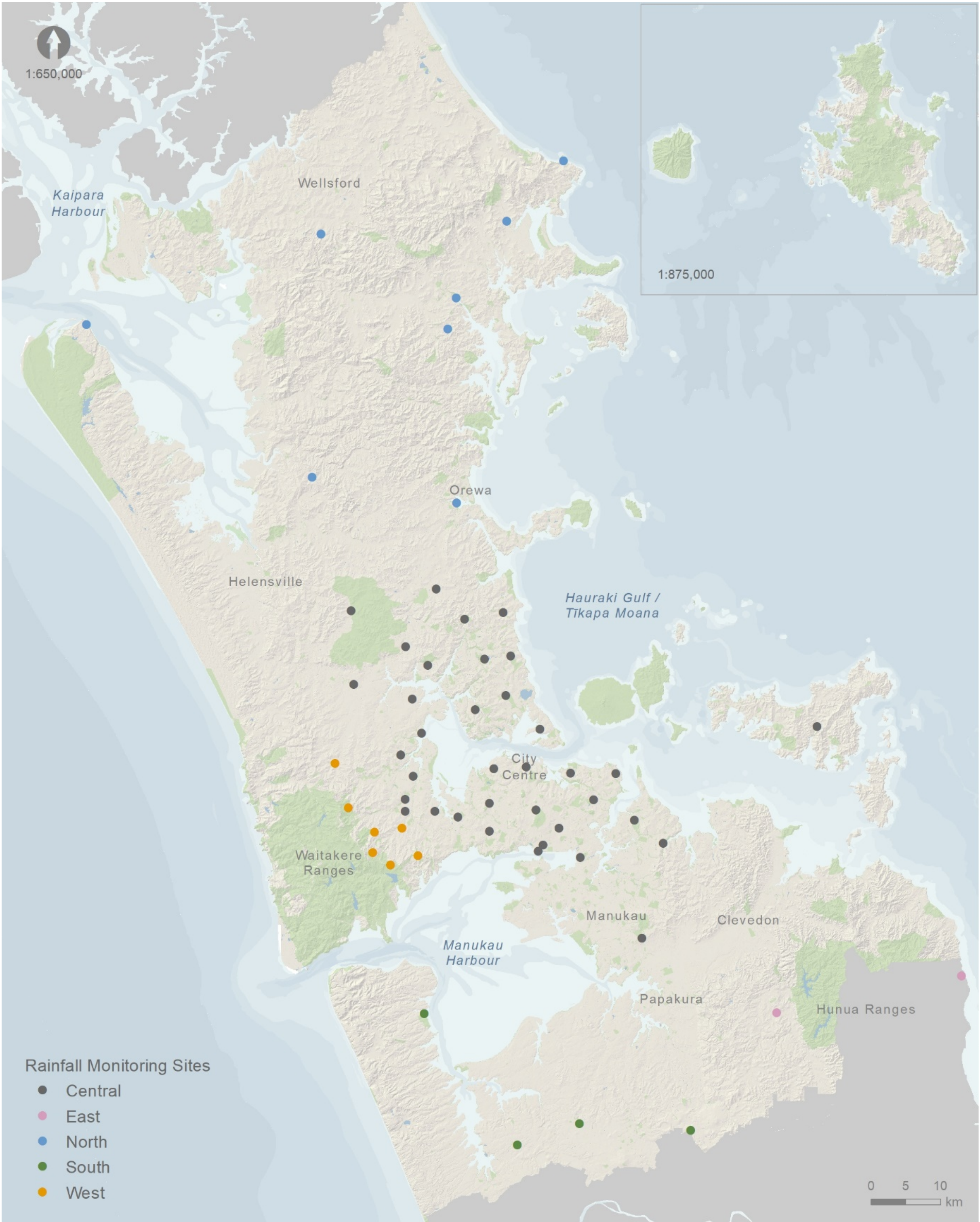

Figure 1: Auckland Council rainfall monitoring site locations, grouped by sub-regional area.

2.2 Streams

2.2.1 Monitoring network

This report assesses flow data from 39 telemetered stream flow monitoring sites in the region (Figure 2). The sites are distributed throughout catchments with land cover ranging from rural to urban and inform both resource management and flood management initiatives. Flow monitoring sites cover a range of catchment sizes, from 1km^2 to 276km^2. The median catchment size monitored in the network is approximately 11km^2. Fifteen of the 39 sites monitor catchment areas less than 5km^2, demonstrating the relatively small size of many Auckland streams. Council has monitored stream flow at 26 of the 39 sites for 20 years or more, which is 67% of the stream network analysed in this report. Site details are provided in Appendix 2.

Figure 2: Auckland Council State of the Environment stream flow monitoring site locations.

2.2.2 Annual stream high flows

High flows have impacts on instream ecology primarily through disturbance-related changes to physical habitat, but also through changes to water quality via increased sedimentation, entrainment of contaminants washed from the land surface, and dilution of contaminants from point-source discharges. Physical disturbance of stream channels is necessary to maintain physical habitat variability and to flush systems of nuisance algae and macrophytes.

The frequency of occurrence of high flows has been shown to be an ecologically significant metric with which to classify high flow regimes of New Zealand streams. Three-times the median flow was found to approximate bed-disturbance flows, thus constituting a change to physical habitats in a river (Clausen and Biggs, 1997). The number of times that three times the median flow (3XMedian) occurs is known as the FRE_3. This metric describes the number of times per year that high flow events disturb instream biota and is a metric commonly used in New Zealand (MfE, 1998). Each stream has unique characteristics which govern flood flows and their ability to disturb instream biota, but 3XMedian provides a useful approximation of this level of disturbance that can be used to analyse many streams without the need for detailed, long-term, and costly field work.

The number of times per year that a flow of 3XMedian occurs is a useful way to estimate the number of channel scour events that ‘reset’ the physical habitat of streams. Some streams flood often, so the physical habitat is changed often. Others have a more stable flow regime with less frequent high flows so habitat is not changed very often. These different stream types will naturally be colonised by a unique assemblage of organisms that are well adapted to that unique environment (Clausen and Biggs, 1997). It follows that a change in high flow statistics like the FRE_3 over time indicates that the unique high flow environment of a stream is changing. This could in turn impact the unique group of organisms that inhabit the stream.

FRE_3 was selected for trend analysis to investigate if recent urbanisation in parts of Auckland led to changes in the high flow regimes of streams. Increased runoff due to increased impervious surface of urban land cover can occur if water sensitive design isn’t adequately incorporated into the built environment.

The state of high flows was reported by comparing the FRE_3 across three periods: five-year (2015-2019, the ‘current state’), 10-year (2010-2019), and the long-term record, (all years). Trend analysis was run using the Mann-Kendall trend test on the FRE_3 dataset (2010-2019) to determine if the high flow component of the flow regime changed over the reporting period.

2.2.3 Annual stream low flows

Many native fish species in New Zealand have lifespans of multiple years and reproduce annually, so periodic low flows are important to quantify in relation to fish life histories. Flows represented by the mean annual low flow, or MALF (with a return period of approximately two years) are likely to impact fish populations at some point in their lifespan (McDowall 2000). The MALF is thus a limiting factor on the instream life that a stream can sustain (Jowett, 1990; Clausen and Biggs, 1997; Jowett et al. 2005; Booker & Graynoth 2008[1 & 2]). The natural flow of a river can be significantly affected by water takes, particularly during the dry months of the year when flows are typically at their lowest. Water takes have been found to cause significant reductions in key statistics like the MALF (Wilding 2018).

Council allocates and manages water takes from streams based on the MALF. This metric has ecological significance and is easy to apply in a water allocation framework (Franklin et al. 2012). The MALF is calculated by averaging the lowest seven-day rolling mean flow for each year on record[2]. MALF represents the typical lowest flows in a river system for the year, usually observed during late summer.

An analysis of the lowest flows of each year was completed to identify any changes in low-flow hydrology. A dataset was compiled which contains the lowest seven-day rolling mean flow for each of the last 10 years for all sites with continuous flow records. Trend analysis was run using the Mann-Kendall test on the annual low flow datasets (2010-2019) to show whether annual low flows were getting higher or lower over time.

State was reported by comparing the MALF of the last five years (2015-2019, the 'current state') to the MALF of the last 10 years and the long-term MALF (all years).

2.2.4 Statutory minimum flows

Minimum flows are established in Appendix 2 of the Auckland Unitary Plan (AUP) to limit the cumulative impact of multiple surface water takes when streamflow is very low and ecosystems, particularly fish, are at their most vulnerable. The AUP Appendix 2 can be read online at https://unitaryplan.aucklandcouncil.govt.nz. Minimum flow conditions require water takes to cease when the flow in a stream drops below the minimum flow. The intended result is that streams revert to natural flows during these periods of water stress. The cessation of water takes will not always prevent a stream from naturally receding below the minimum flow. However, cessation of takes at least provides a greater opportunity for instream biota to survive until flows increase. The frequency of minimum flows can give an indication of the severity of impact on water users each year. Because the AUP sets the minimum flow as a proportion of the mean annual low flow (MALF), the number of days below the long-term MALF was also analysed for context.

Analysis of low flow duration was completed for council monitored sites that also have a minimum flow established in AUP Appendix 2. The sites included in this analysis were:

- Mahurangi River at Argonaut
- Wairoa River at Tourist Road
- Puhinui Stream at Drop Structure
- Ngakoroa Stream at Mill Road
- Waitangi Stream at SH1

Trend analysis was run using the Mann-Kendall test on the total number of days below the MALF and the minimum flow per year, respectively. This analysis showed if there were any trends in the number of days that flows were below the minimum flow.

[2] This process does not include the addition of water takes back into the flow record, known as "naturalisation". The naturalised MALF is often used for flow setting where the flow regime is significantly affected by water takes.

2.3 Aquifers

2.3.1 Monitoring network

Council currently operates 56 monitoring wells in the region, which includes 40 wells that are dipped manually each month and 16 wells that are equipped for automatic groundwater level recording and telemetry. The aquifer types represented in the region include weakly cemented sands, basaltic volcanics, shell beds of the Kaawa formation, sandstones of the Waitemata Group, geothermal centres, and greywacke basement rocks of the Waipapa Group. Monitoring wells measure groundwater levels in 27 of the 121 aquifer management areas (AMAs) across the Auckland region. This report details analysis of 47 of the 56 monitoring wells that had sufficiently complete datasets (Figure 3). Site details are provided in Appendix 3.

2.3.2 Groundwater level analysis

Groundwater level data were analysed in three ways to examine the data for trends and possible connections to anthropogenic and environmental influences. The groundwater level records were first averaged to produce 30-day mean datasets. This averaging accomplishes several functions:

- Produces a smoothed dataset that removes short-term and localised influences (e.g. from abstraction) which is representative of longer-term, larger-scale aquifer dynamics.
- Produces an even time-step with records that have varying data recording frequencies, i.e. monthly manual dips and 15-min automatic telemetered data.
- Produces a dataset that is easily analysed by statistical applications.

Three aspects of groundwater levels were analysed in this report. The entire 30-day mean water level dataset, the annual maximum (based on the 30-day mean dataset), and the annual minimum (based on the 30-day mean dataset).

The 30-day mean monthly dataset characterises the full year of aquifer water levels. This dataset is seasonal, with high water levels in the winter/spring, followed by lower water levels in the summer/autumn.

The annual maximum groundwater level (30-day mean) was isolated for analysis to serve as a proxy for the annual recharge, i.e. the highest water level of the year can be used as in indicator for the level of recharge to the aquifer. While not a perfect description of aquifer dynamics, this provides a useful way to assess how water levels rebound after the driest parts of the year. In this analysis, only the highest water level for each year was used. Changes to annual highs could indicate a change in the amount of water recharging the aquifer or could indicate a change in aquifer storage (e.g. a decrease in storage due to excessive groundwater abstraction). The results of this analysis are helpful to direct attention to further analysis of aquifer recharge and/or aquifer storage over time.

The annual minimum groundwater level (30-day mean) was isolated for analysis to serve as a proxy for pressure on the groundwater resource, both environmental (to supply stream baseflow, recharge to other connected aquifers, etc.) and anthropogenic (via groundwater abstraction). While not a perfect description of aquifer dynamics, this provides a useful way to assess how water levels are drawn down during the driest parts of the year, which also coincides with the highest demand for groundwater abstraction. In this analysis, only the lowest water level value for each year was used. Changes to the annual low water level could indicate a change in the amount of water discharging from the aquifer, or a change in the annual recharge. The results of this analysis are helpful to direct attention to further analysis of abstractive water use and/or aquifer recharge over time.

Where decreasing trends were observed in groundwater level records, hydrographs were inspected for patterns to better describe the trend. The effects of groundwater abstraction were discussed in context of trend analysis to better contextualise the results and implications for water resource management.

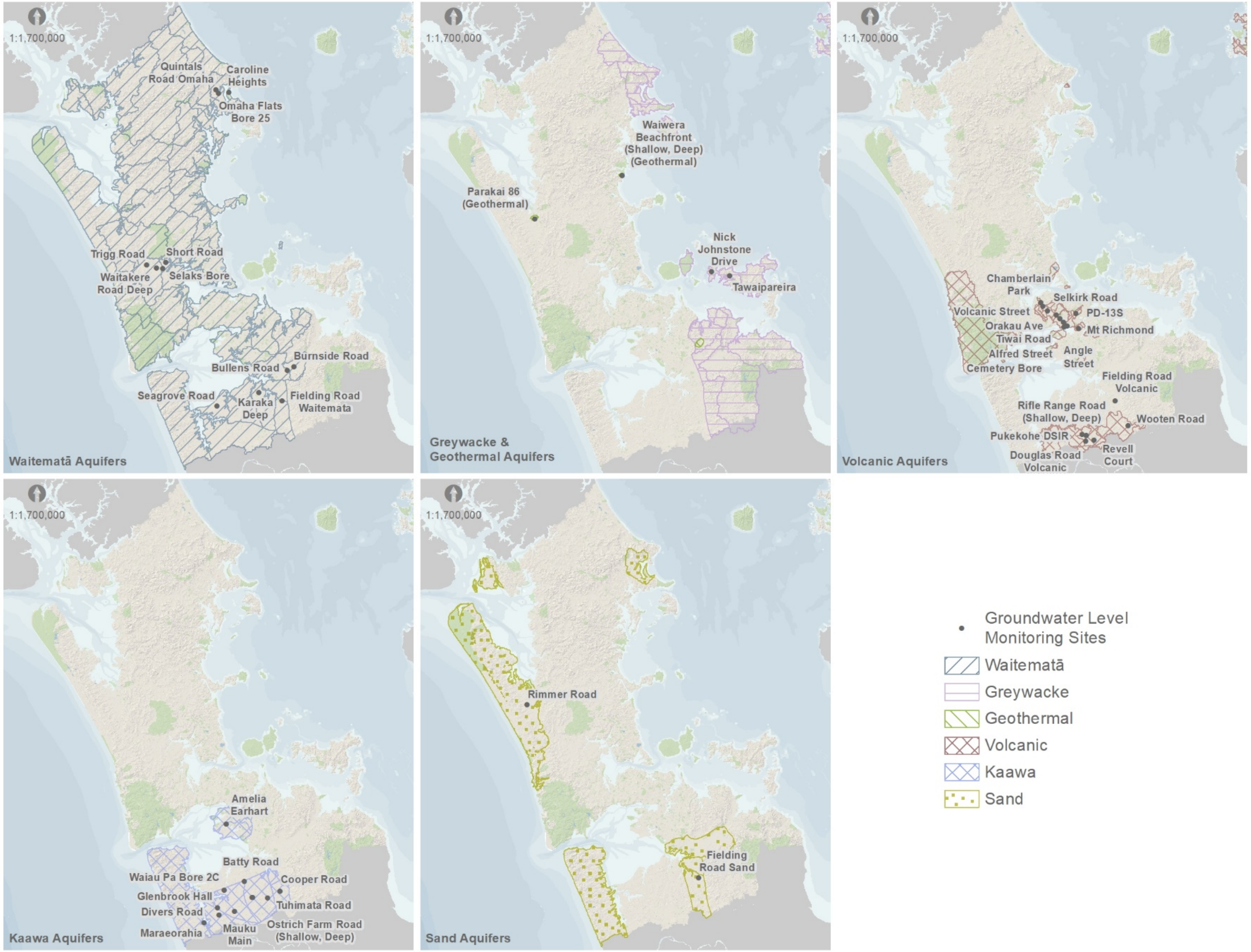

Figure 3: Auckland Council State of the Environment monitoring well locations.

2.4 Trend tests

2.4.1 Previous state of the environment trend analyses

Statistical trend analysis for surface water hydrology has not yet been reported for Auckland streams under the State of the Environment programme. Comparative analysis for streams has been completed in previous reports (Stansfield and Holwerda 2015), e.g. comparison of number of days below minimum flow in 2013 vs 2012.

Water level trend analysis was completed for the groundwater monitoring network in 2017 using data for the period 2006-2015, inclusive (Kalbus, et al. 2017). Groundwater level trends were reported as 'environmentally meaningful' if they were both statistically significant at $p<0.05$ and the annual rate of change was greater than 5% of the inter-quartile range of the groundwater levels. This method followed that used by Environment Southland (Wilson, 2011). The justification for this criterion was that at a 5% rate of change, the lowest water level would become the highest after 20 years. The list of environmentally meaningful trends is presented in Table 1. Only 9 of the 33 environmentally meaningful trends were negative, i.e. declining water levels over time.

Table 1: Trends reported as environmentally meaningful by Kalbus et al. 2017.

Site name	Site number	Aquifer	2017 trend direction	2017 trend magnitude (Sen slope, m/yr)
Quintals Road	6437005	Omaha Waitematā	Declining	-0.045
Caroline Heights	6437087	Omaha Waitematā	Declining	-0.048
Parakai Bore 86	6464007	Parakai geothermal	Declining	-0.055
Parakai Bore 87	6464009	Parakai geothermal	Declining	-0.019
Delamore Drive 105m	6479005	Waiheke West greywacke	Declining	-0.051
Tanner Reserve	6498011	Mt Wellington volcanic	Declining	-0.081
Karaka North #2	7419119	Karaka Waitematā	Declining	-0.055
Seagrove Road	7417021	Waiau Pa Waitematā	Declining	-0.154
Seagrove Road Observation	7417023	Waiau Pa Waitematā	Declining	-0.163
Waiwera Beachfront Deep	6457041	Waiwera Geothermal	Increasing	0.110
Waiwera Beachfront Shallow	6457097	Waiwera Geothermal	Increasing	0.110
Trigg Road	6475005	Kumeu West Waitematā	Increasing	0.051
Short Road	6475157	Kumeu East Waitematā	Increasing	0.984
Delamore Drive 55m	6479003	Waiheke West greywacke	Increasing	0.660

Site name	Site number	Aquifer	2017 trend direction	2017 trend magnitude (Sen slope, m/yr)
Nick Johnstone Drive	6479007	Waiheke West greywacke	Increasing	0.211
Mt Richmond	6494001	Mt Richmond volcanic	Increasing	0.123
Selwyn Street	6497011	Onehunga volcanic	Increasing	0.003
Angle Street	6498003	Mt Wellington volcanic	Increasing	0.017
Lambie Drive (Puhinui)	6498035	Manukau City Waitematā	Increasing	0.079
Oneroa Bowling Club 29m	6570003	Waiheke West greywacke	Increasing	0.104
Oneroa Bowling Club 54m	6570005	Waiheke West greywacke	Increasing	0.228
Oneroa Church 39.5m	6570009	Waiheke West greywacke	Increasing	0.080
View Road	6570011	Waiheke Central West greywacke	Increasing	0.129
Mako Road	6570013	Waiheke West greywacke	Increasing	0.042
Tuhimata Road	7419003	Pukekohe Kaawa	Increasing	0.043
Cooper Road	7419011	Bombay-Drury Kaawa	Increasing	0.196
Pukekohe DSIR	7428043	Pukekohe central volcanic	Increasing	0.069
Rifle Range Deep	7428103	Pukekohe central volcanic	Increasing	0.260
Rifle Range Shallow	7428105	Pukekohe central volcanic	Increasing	0.173
Jenkin Road	7428109	Pukekohe central volcanic	Increasing	0.193
Douglas Road	7429013	Pukekohe central volcanic	Increasing	0.058
Clevedon Rd	7500001	Clevedon East Waitematā	Increasing	0.074
Wooten Road	7510005	Bombay volcanic	Increasing	0.096

2.4.2 Trend analysis for 2010-2019

All trend analyses for this report were completed using TimeTrends v6.4 software. Trends in the 30-day mean groundwater level were analysed using the Seasonal Kendall test applied to four seasons. The seasonal test was applied because this dataset had a seasonal pattern of water levels reflective of seasonal rainfall recharge. The Mann-Kendall test was used for all other datasets, which had a single statistic per year, thus no seasonality. Sites were excluded from mean monthly groundwater analysis if the number of data points was less than 36 (90% of 40 total seasonal values from 2010-2019). Sites were excluded from all other analyses if the number of data points was less than 10.

Trends were assessed based on the direction (increasing or decreasing) and magnitude of change. The trend direction and confidence were calculated using the Kendall test (seasonal and non-seasonal) based on the probability of the trend. The probability derived from the

Kendall test was interpreted based on the categories used by the Intergovernmental Panel on Climate Change which was simplified into five categories by Fraser and Snelder (2018) (Table 2). The categories are used for national-level environmental reporting in New Zealand by Land Air Water Aotearoa (LAWA).

Table 2: Trend categories by probability and colour code.

Trend categories	Probability (%)
Very likely increasing	90-100 (with positive Kendall S)
likely increasing	67-90 (with positive Kendall S)
Indeterminate	0-67
Likely decreasing	67-90 (with negative Kendall S)
Very likely decreasing	90-100 (with negative Kendall S)

The magnitude of the trend is characterised by the slope of the trend line using the Sen slope estimator (SSE) (or the seasonal version (SSSE)). The SSE is the median of all possible inter-observation slopes. Some trends, though statistically valid, may have a Sen slope less than the margin of error associated with various data collection techniques, so the rate of change cannot be reported with confidence. Trend magnitude can only be estimated with confidence for *very likely* trends (probability exceeding 0.9).

Trend magnitude was assessed in this report relative to the measurement precision for each parameter following the approach in Fraser and Snelder (2018). Trends were considered to be established with confidence if the trend was *very likely* (probability >0.9) and:

- Median Sen slope exceeded the measurement accuracy of:
    - Streams: 8% of measured discharge or 0.001 m^3/s, whichever is higher.
    - Groundwater: 0.02 m (positive or negative).

For groundwater, water level measurements are recorded by both manual measurement and using automatic recording methods. Sites with automatic water level recorders are calibrated by field measurements to within 0.020 m.

For streams, the calculated flow is based on continuous water level measurements that are fitted to a rating which calculates flow based on water level, known as the ‘rated flow’. Flow ratings are continually updated based on measured flow in the field to ensure that the calculated flow via the rating accurately matches the true flow of the stream. The requirement for continuous flow records is that the rated flow is within 8% of measured flow.

However, small streams frequently have very low flows, which are difficult to measure accurately in the field. A review of the gauging files of Auckland streams showed that for telemetered sites with ratings, the measured flow frequently exceeded 20% error when flow was less than 10 l/s. Not all gaugings at very low flows have large errors against the rating, but the preponderance of large errors at low flows requires a pragmatic criterion for trend assessment. For this reason, a conservative threshold of 1 l/s (0.001 m^3/s) was applied as a second criteria for stream flows. Thus, a trend with a Sen slope greater than 8% of the lowest flow in the dataset but less than 0.001 would fail to be established with confidence.

3 Results: Rainfall

3.1 State and trends

The mean annual rainfall total was compared to the long-term mean for each sub-regional group by plotting the departure from the mean (Figure 4). This highlighted years with greater or less rainfall that are difficult to discern from hydrographs alone.

The lowest mean annual total in the 20-year long-term record was measured in the North in 2019 and Central in 2010. The highest long-term mean annual rainfall total was recorded the following year (2011) in all the sub-regional groups, excluding the East. Rainfall was consistently high for all five areas in the years 2016-2018 and the East recorded a long-term maximum in 2017. Annual statistics by year and sub-regional area are provided in Table 3.

No monotonic trends could be established with confidence for the sub-regional monthly rainfall totals over the period of analysis (2010-2019). The probability of trends was less than 0.9 and the Sen slope was less than 1mm/year for all five sub-regional areas. This is consistent with the pattern in rainfall observed in the deviation from the long-term mean, which indicates the reporting period had very wet years (2011, 2016-2018) and very dry years (2010 and 2019) with no consistent trend in one direction.

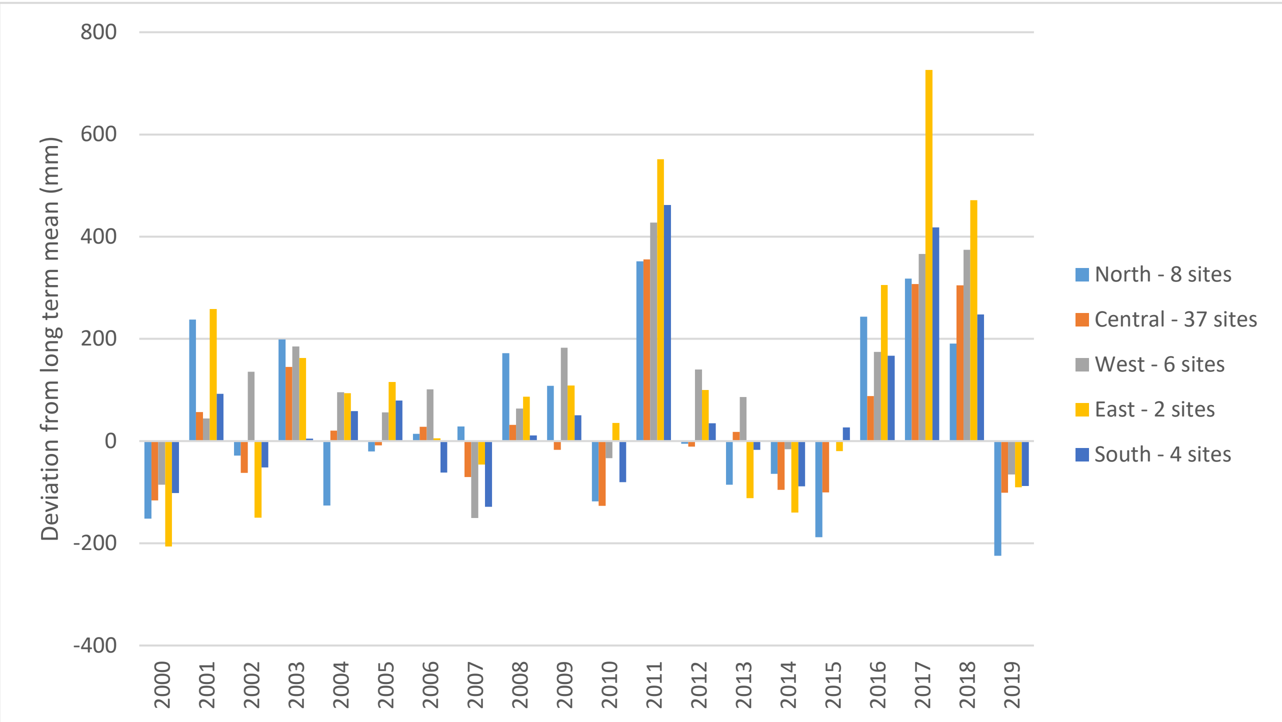

Figure 4: Rainfall deviation from long-term mean for rain gauge groups (average value per group).

Table 3: Comparison of mean annual rainfall totals to the 20-year mean for each sub-regional group. Cells highlighted orange are less than the long-term 25th percentile, blue highlighted cells are greater than the 75th percentile. Red text is the lowest annual rainfall total in the period 2000-2019, purple text is the highest.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
North	1181	**1651**	1294	1214	1235	1111	1543	1617	1490	**1075**
Central	**1089**	**1571**	1205	1234	1121	1115	1304	1523	1521	1115
West	1547	**2008**	1720	1666	1564	1580	1754	1946	1954	1515
East	1395	1912	1460	1249	1220	1340	1666	**2087**	1831	1270
South	1212	**1755**	1328	1276	1204	1320	1460	1711	1541	1205

4 Results: Streams

4.1 Annual high stream flows

4.1.1 State

The comparison of the median number of high flow events between the last five years (2015-2019), the last 10 years (2010-2019) and the full record (all years) showed little variation between the periods of analysis (Table 4). More high flow events were recorded in the last five years than in the last 10 years at 27 sites (69%) versus 12 sites which had fewer high flow events (31%).

The largest decrease between the last five years and the last 10 years was 5.26% at the Waitangi Stream in Waiuku (0.5 less high flow events per year on average). The largest increase in the number of events was from 21 to 24 events for the Whau Stream. The largest proportional increase was 22.22% for the Kaipara River in Waimauku (2 more high flow events per year on average).

Table 4: Comparison of the number of high flow events (3XMedian flow) for full record, 10-year, and 5-year periods.

Site name	Long-term median	10-year median	5-year median	Last 5 years as % of 10-year median	Last 5 years as % of long-term median
Tamahunga Stream	15	14.5	15	103.45%	100.00%
Mahurangi River	14.5	14.5	15	103.45%	103.45%
Orewa Stream	13	10.5	10	95.24%	76.92%
West Hoe Stream	14.5	14	15	107.14%	103.45%
Vaughan Stream	16	16.5	17	103.03%	106.25%
Mairangi Bay Stream	21	21	22	104.76%	104.76%
Taiaotea Stream	20	20	19	95.00%	95.00%
Awaruku Stream	21	21.5	21	97.67%	100.00%
Taiorahi Stream	21	19	21	110.53%	100.00%
Wairau Creek at Motorway	21	21	21	100.00%	100.00%
Wairau Creek at Chartwell Rd	22	22.5	22	97.78%	100.00%
Eskdale Stream	20	21	21	100.00%	105.00%
Kaipatiki Stream	23	23	23	100.00%	100.00%
Rangitopuni River	12	9	9	100.00%	75.00%
Oteha Stream	20	21.5	23	106.98%	115.00%
Lucas Creek	21	21.5	21	97.67%	100.00%
Alexandra Stream	20	20.5	22	107.32%	110.00%
Opanuku Stream at Candia Road	17	17	17	100.00%	100.00%
Swanson Stream	18	16	16	100.00%	88.89%
Oratia Stream	20	19	20	105.26%	100.00%

Site name	Long-term median	10-year median	5-year median	Last 5 years as % of 10-year median	Last 5 years as % of long-term median
Opanuku Stream at Vintage Reserve	20	20.5	20	97.56%	100.00%
Whau Stream	21	21	24	114.29%	114.29%
Motions Stream	26	25.5	25	98.04%	96.15%
Meola Stream	24	24	23	95.83%	95.83%
Newmarket Stream	19	17.5	18	102.86%	94.74%
Otara Stream	20	20.5	20	97.56%	100.00%
Tamaki Stream Tributary	20	20	20	100.00%	100.00%
Mangemangeroa Stream	15	13.5	14	103.70%	93.33%
Wairoa River	13	11.5	12	104.35%	92.31%
Mangawheau Stream	14	14	16	114.29%	114.29%
Waitangi Stream	10	9.5	9	94.74%	90.00%
Papakura Stream	15	17.5	20	114.29%	133.33%
Puhinui Stream	22	22.5	24	106.67%	109.09%
Ngakoroa Stream	14	13.5	14	103.70%	100.00%
Kaipara River	12	9	11	122.22%	91.67%
Ararimu River	12.5	10	10	100.00%	80.00%
Kaukapakapa Stream	11	10	10	100.00%	90.91%
Hoteo River	12	11.5	11	95.65%	91.67%
Waiteitei River	12	11.5	11	95.65%	91.67%

4.1.2 Trends

The Taiaotea Stream was the only stream with a *very likely* trend category (*very likely decreasing*, median Sen slope = -0.875 events/year). The remainder of sites had trend categories of *likely decreasing* (9), *likely increasing* (11) and *indeterminate* (18), but none were established with confidence. Site location, trend direction, and trend confidence is mapped for all sites in Figure 5.

Figure 5: Trend results for the annual frequency of high stream flows (>3XMedian) over the period 2010-2019.

4.2 Annual low stream flows

4.2.1 State of annual low flow magnitude

The comparison of the MALF between the last five years (2015-2019), the last 10 years (2010-2019), and the full record (all years) showed consistently higher flows in recent years than later years (Table 5). Thirty-two of the 39 sites had higher MALFs for the last five years than the last 10 years (82%).

A threshold of 85% MALF was used to identify sites where a reduction in the MALF may have impacts on instream biota. This threshold is necessarily arbitrary because it does not relate to specific flow management objectives for each river. However, the 85% threshold relates to default minimum flow guidelines established in Appendix 2 of the Auckland Unitary Plan, so a change beyond the threshold indicates that the generalised flow management objectives of the AUP may not be achieved. Two sites had MALF values in the last five years that were less than 85% of the previous 10-year MALF: Wairau Creek (at the Chartwell Road site) and the Rangitopuni Stream. These two sites are discussed further in Section 5.2.

Table 5: Comparison of the 7-day mean annual low flow for full record, 10-year, and 5-year periods. Highlighted rows indicate a reduction in MALF of more than 15% between the last 10 and 5 years of analysis.

Stream	Record mean (m^3/s)	10-year mean (m^3/s)	5-year mean (m^3/s)	Last 5 years as % of 10-year mean (m^3/s)	Last 5 years as % of long-term mean (m^3/s)
Tamahunga Stream	0.0075	0.0077	0.0074	96.10%	99.15%
Mahurangi River at Argonaut	0.0832	0.0832	0.0944	113.46%	113.46%
Orewa Stream*	0.0008	0.0001	0.0002	200.00%	23.64%
West Hoe Stream	0.0016	0.0014	0.0012	85.71%	73.85%
Vaughan Stream	0.0005	0.0004	0.0004	100.00%	80.00%
Mairangi Bay Stream	0.0018	0.0019	0.0022	115.79%	125.71%
Taiaotea Stream	0.0030	0.0028	0.0028	100.00%	93.33%
Awaruku Stream	0.0015	0.0016	0.0018	112.50%	122.73%
Taiorahi Stream	0.0025	0.0026	0.0026	100.00%	105.63%
Wairau Creek at Motorway	0.0155	0.0198	0.0232	117.17%	149.32%
Wairau Creek at Chartwell Rd	**0.0054**	**0.0034**	**0.0026**	**76.47%**	**48.15%**
Eskdale Stream	0.0076	0.0081	0.0088	108.64%	116.23%
Kaipatiki Stream	0.0028	0.0030	0.0038	126.67%	133.51%
Rangitopuni Stream	**0.0317**	**0.0278**	**0.0190**	**68.35%**	**59.93%**
Oteha Stream	0.0151	0.0193	0.0228	118.13%	150.99%
Lucas Creek	0.0075	0.0080	0.0092	115.00%	122.04%
Alexandra Stream	0.0030	0.0040	0.0052	130.00%	173.33%
Opanuku Stream at Candia Road	0.0443	0.0433	0.0524	121.02%	118.26%
Swanson Stream	0.0256	0.0358	0.0324	90.50%	126.37%
Oratia Stream	0.0728	0.0756	0.0848	112.17%	116.48%
Opanuku Stream at Vintage Reserve	0.0541	0.0524	0.0528	100.76%	97.60%
Whau Stream	0.0104	0.0107	0.0092	85.98%	88.83%
Motions Stream	0.1230	0.1324	0.1390	104.98%	112.97%
Meola Stream	0.0467	0.0484	0.0516	106.61%	110.57%
Newmarket Stream	0.0031	0.0034	0.0040	117.65%	130.00%
Otara Stream	0.0168	0.0269	0.0332	123.42%	197.44%
Tamaki Stream Tributary	0.0082	0.0080	0.0082	102.50%	100.57%
Mangemangeroa Stream	0.0014	0.0012	0.0012	100.00%	87.69%
Wairoa River	0.4399	0.3998	0.4150	103.80%	94.35%
Mangawheau Stream	0.0876	0.0837	0.0870	103.94%	99.34%
Waitangi Stream	0.0422	0.0425	0.0468	110.12%	110.88%
Papakura Stream	0.0499	0.0573	0.0614	107.16%	123.06%
Puhinui Stream	0.0199	0.0236	0.0258	109.32%	129.95%
Ngakoroa Stream	0.0111	0.0108	0.0132	122.22%	119.17%
Kaipara River	0.1653	0.1199	0.1174	97.91%	71.03%
Ararimu River	0.0738	0.0694	0.0760	109.51%	103.05%
Kaukapakapa Stream	0.0236	0.0198	0.0192	96.97%	81.45%

Stream	Record mean (m^3/s)	10-year mean (m^3/s)	5-year mean (m^3/s)	Last 5 years as % of 10-year mean (m^3/s)	Last 5 years as % of long-term mean (m^3/s)
Hoteo River	0.5032	0.4588	0.4860	105.93%	96.59%
Waiteitei River	0.1494	0.1253	0.1310	104.55%	87.69%

*Orewa Stream frequently dries (i.e. zero flow) throughout the historical record, so this site is not considered for further analysis.

4.2.2 Trends in low flow magnitude

Eight of 39 sites had *very likely increasing* trends in the 7-day annual low flow over the period 2010-2019, however only the Otara Stream had a trend that was established with confidence (Table 6). Eighteen sites had *likely increasing* trends. Nine sites had *indeterminate* trends and four sites had *likely decreasing* trends. No sites had *very likely decreasing* trends. Site location, trend direction, and trend confidence is presented for all sites in Figure 6.

Figure 6: Trend results for annual low flows over the period 2010-2019.

Table 6: Trends in annual low flows with *very likely* probability (>0.9).

Site name	Site #	Kendall statistic	Median Sen slope (annual)	Probability	2010-2019 SOE trend category
Wairau Creek Motorway	7604	23	0.0008	0.9775	very likely increasing*
Kaipatiki Stream	7719	20	0.0003	0.9667	very likely increasing*
Newmarket Stream	8176	14	0.0000	0.9261	very likely increasing*
Otara Stream	**8208**	**19**	**0.0025**	**0.952**	**very likely increasing**
Tamaki Stream Tributary	8222	16	0.0001	0.9262	very likely increasing*
Mangemangeroa Stream	8304	15	0.0001	0.9074	very likely increasing*
Wairoa River	8516	19	0.0073	0.9477	very likely increasing*
Ngakoroa Stream	43829	20	0.001	0.956	very likely increasing*

*Trends were not established with confidence (did not meet the Sen slope criterion: >0.001).

4.2.3 Analysis of low flow frequency

The total number of days below MALF appears to decrease over the period 2010-2019 (Figure 7). The years of 2010 and 2013-2015 had more days below the MALF than other years. There were no days below MALF in any of the five streams analysed in the years 2012 and 2018 and generally few days below minimum flow in the years 2011 and 2016-2017. These reflect the years with high rainfall previously described in Section 3.1.

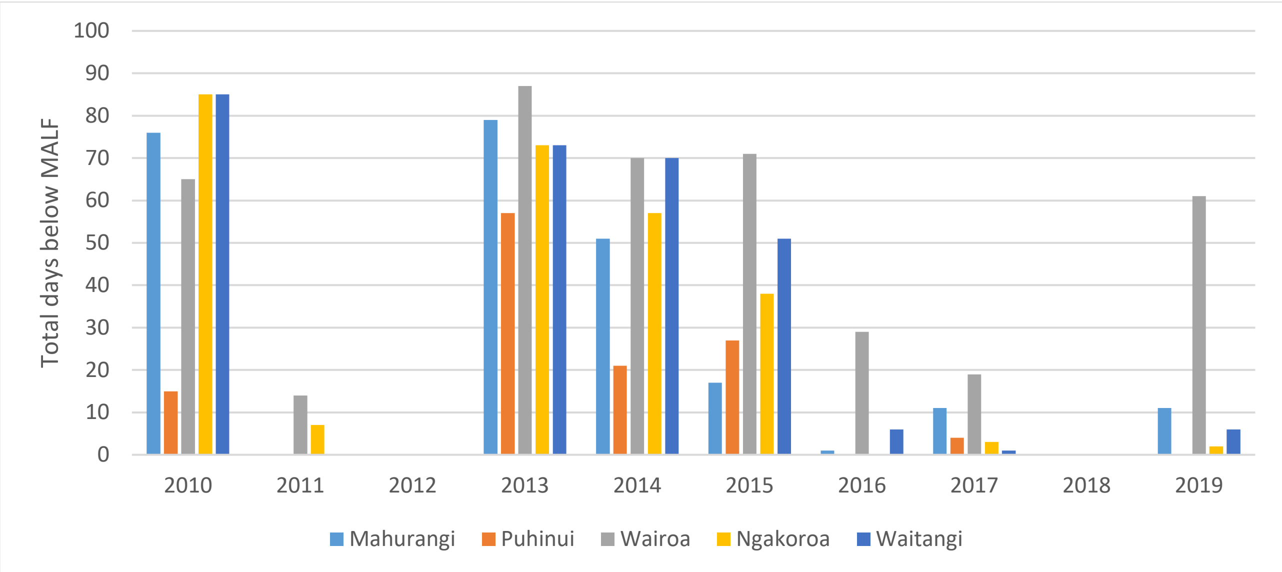

Figure 7: Days below the 7-day mean annual low flow over the period 2010-2019.

Trend analysis of the total number of days below MALF showed that only the Waitangi Stream had a decreasing trend that could be established with confidence (Table 7). The other sites generally showed trends in a decreasing direction. A decreasing trend equates to fewer days below the MALF over time (i.e. more water instream).

Table 7: Trend analysis of days below the 7-day mean annual low flow.

Site name	Site number	Kendall statistic	Median Sen slope (annual)	Probability	2010-2019 SOE trend category
Mahurangi River	6863	-11	-2.0014	0.8671	likely decreasing
Wairoa River	8516	-6	-1.9998	0.7352	likely decreasing
Puhinui Stream	43602	-13	-3.9991	0.8991	likely decreasing
Ngakoroa Stream	43807	-9	0	0.8317	Indeterminate*
Waitangi Stream	43829	-20	-7.0048	0.9717	very likely decreasing

*Sen slope = 0 resulted from several zero values in the period of analysis; indicates no monotonic trend.

The duration of flows below the AUP specified minimum flow was plotted (Figure 8). The Mahurangi River was also the only site to have no flows below the minimum flow in all years except 2013. A review of the data showed that all sites had multiple years with zero days below the AUP minimum flow, so a trend analysis was excluded for this data (Table 8).

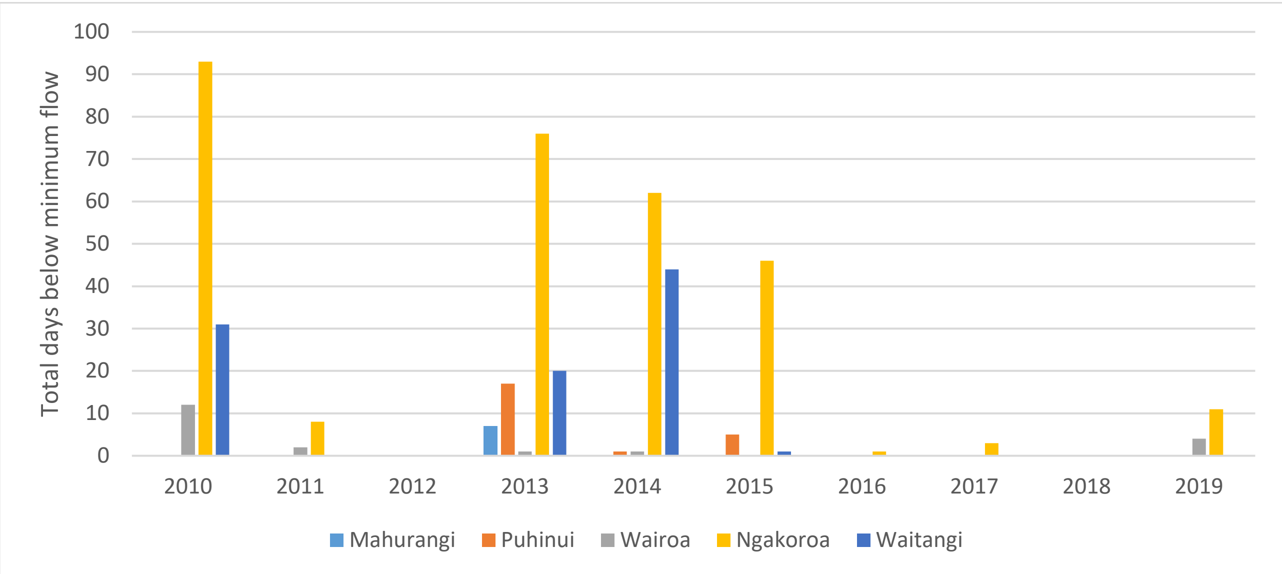

Figure 8: Days below the AUP minimum flow over the period 2010-2019.

Table 8: Days below the AUP minimum flow for monitored AUP minimum flow sites.

Year	Mahurangi River	Puhinui Stream	Wairoa River	Ngakoroa Stream	Waitangi Stream
2010	0	0	12	93	31
2011	0	0	2	8	0
2012	0	0	0	0	0
2013	7	17	1	76	20
2014	0	1	1	62	44
2015	0	5	0	46	1
2016	0	0	0	1	0
2017	0	0	0	3	0
2018	0	0	0	0	0
2019	0	0	4	11	0

5 Results: Aquifers

5.1 Mean monthly groundwater level

5.1.1 State

Mean monthly groundwater level was analysed for basic statistics: maximum, median, minimum, interquartile range (IQR), and standard deviation for the period 2015-2019 (Appendix 4). The median groundwater level ranged from 156.87 mRL at Wooten Road to -4.81 mRL at Mt Richmond. The largest groundwater level variations were observed at Waitakere Road #2 (Kumeu West Waitematā aquifer) with an interquartile range of 6.68 metres. The second and third largest groundwater level variations were observed at Short Road (Kumeu East Waitematā aquifer, IQR = 3.17 m) and Fielding Road Sand (Bombay-Drury sand aquifer, IQR = 3.16 m). Table 9 provides a comparison of the median groundwater level for three periods of analysis: the most recent 5 years 2015-2019 (i.e. current state), the most recent 10 years 2010-2019, and the full record.

Table 9: Comparison of median groundwater level for three periods of analysis: current state 2015-2019, 2010-2019, and the full record. All values in metres above sea level, NZVD 2016.

Site name	Site number	Median 2015-2019	Median 2010-2019	Median full record
Quintals Road Omaha	6437005	7.022	7.239	7.229
Omaha Flats Bore 25	6437021	4.350	4.293	4.504
Caroline Heights	6437087	1.310	0.791	0.764
Waiwera Beachfront Deep	6457041	1.598	1.232	0.413
Waiwera Beachfront Shallow	6457097	1.549	1.221	0.845
Parakai 86	6464007	3.081	2.507	2.427
Rimmer Road	6464089	4.566	4.475	4.476
Waitakere Road #2	6474003	19.874	19.533	18.826
Selaks Bore	6475003	24.196	23.880	23.480
Trigg Road	6475005	21.247	20.956	20.330
Short Road	6475157	18.246	14.209	8.176
Nick Johnstone Drive	6479007	31.026	30.725	29.992
Volcanic Street	6487001	38.239	38.255	38.507
Selkirk Road	6487007	19.113	19.093	18.982
Leslie Road	6487009	28.312	28.039	27.865
Chamberlain Park	6487021	11.206	11.209	11.176
PD-13S	6488045	21.638	21.347	21.630
Alfred Street	6497007	3.288	3.412	3.462
Cemetery Bore	6497013	1.776	1.763	1.823
Orakau Ave	6497015	39.744	39.866	39.863
Amelia Earhart	6497017	3.324	3.275	3.095
Tiwai Road	6497019	15.837	15.730	15.646

Site name	Site number	Median 2015-2019	Median 2010-2019	Median full record
Angle Street	6498003	2.511	2.468	2.322
Tawaipareira	6570015	2.771	2.699	2.664
Mt Richmond	6594001	-4.815	-4.832	-4.619
Burnside Road	7409001	28.004	28.304	28.282
Bullens Road	7409011	22.863	23.028	22.697
Glenbrook Hall	7417001	8.317	8.317	8.276
Seagrove Road	7417021	4.658	4.294	5.299
Waiau Pa Bore 2C	7418003	12.659	12.519	12.247
Batty Road	7418013	22.523	22.476	22.358
Ostrich Farm Road #2	7418023	20.496	20.453	20.362
Ostrich Farm Road Observation	7418027	20.533	20.483	20.483
Tuhimata Road	7419003	23.997	23.953	23.540
Fielding Road Sand	7419007	9.622	9.682	9.109
Fielding Road Volcanic	7419009	15.269	15.200	15.013
Cooper Road	7419011	18.009	17.765	17.531
Fielding Road Waitemata	7419013	12.068	12.068	12.266
Karaka #2	7419119	4.457	4.415	4.866
Divers Road	7427003	12.207	12.167	12.608
Maraeorahia	7427005	2.463	2.475	2.589
Pukekohe DSIR	7428043	49.728	49.174	48.966
Mauku Main	7428047	27.406	26.977	26.974
Rifle Range Deep	7428103	49.362	48.360	45.877
Rifle Range Shallow	7428105	57.797	57.450	56.531
Revell Court	7429011	63.320	63.320	62.962
Douglas Road Volcanic	7429013	51.194	50.322	50.251
Wooten Road	7510005	156.874	156.639	156.304

5.1.2 Trends

Trends were calculated for the period 2010-2019. The results for mean monthly groundwater level had 25 sites with *very likely increasing* trends (52%) and 11 sites had *likely increasing* trends (23%). Only four sites had *very likely decreasing* trends (8%) (Table 10). These included Quintals Road (Omaha Waitematā aquifer), Alfred Street and Orakau Avenue (Onehunga volcanic aquifer) and Burnside Road (Clevedon East Waitematā aquifer). All sites with *very likely* trends met the criteria to be established with confidence. Site location, trend direction, and category are presented for all sites in Figure 9.

Table 10: Trends in mean monthly groundwater level with very likely probability (>0.9).

Site name	Aquifer	Sen slope (annual)	Probability	Trend category
Quintals Road Omaha	Omaha Waitematā	-0.034	0.929	very likely decreasing
Caroline Heights	Omaha Waitematā	0.076	0.987	very likely increasing
Waiwera Beachfront Deep	Waiwera geothermal	0.103	1	very likely increasing
Waiwera Beachfront Shallow	Waiwera geothermal	0.082	0.999	very likely increasing
Parakai 86	Parakai geothermal	0.092	0.981	very likely increasing
Rimmer Road	Kaipara sand	0.038	1	very likely increasing
Waitakere Road #2	Kumeu West Waitematā	0.443	0.95	very likely increasing
Selaks Bore Kumeu	Kumeu East Waitematā	0.256	0.999	very likely increasing
Trigg Road	Kumeu West Waitematā	0.146	1	very likely increasing
Short Road	Kumeu East Waitematā	2.031	1	very likely increasing
Nick Johnstone Drive	Waiheke West greywacke	0.207	1	very likely increasing
Selkirk Road	Western Springs volcanic	0.022	0.902	very likely increasing
PD-13S	Mt Wellington volcanic	0.130	0.995	very likely increasing
Alfred Street	Onehunga volcanic	-0.029	0.967	very likely decreasing
Orakau Avenue	Onehunga volcanic	-0.068	0.925	very likely decreasing
Amelia Earhart	Mangere-Manurewa Kaawa	0.029	0.99	very likely increasing
Tiwai Road	Onehunga volcanic	0.050	0.980	very likely increasing
Angle Street	Mt Wellington volcanic	0.021	1	very likely increasing
Tawaipareira	Waiheke Central West greywacke	0.04	0.984	very likely increasing
Burnside Road	Clevedon East Waitematā	-0.076	0.931	very likely decreasing
Seagrove Road	Waiau Pa Waitematā	0.121	1	very likely increasing
Batty Road	Glenbrook Kaawa	0.033	0.979	very likely increasing
Ostrich Farm Road Observation	Pukekohe Kaawa	0.03	0.985	very likely increasing
Fielding Road Waitemata	Bombay-Drury Waitematā	0.036	0.958	very likely increasing
Pukekohe DSIR	Pukekohe central volcanic	0.274	1	very likely increasing
Mauku Main	Glenbrook Kaawa	0.144	1	very likely increasing
Rifle Range Deep	Pukekohe central volcanic	0.559	1	very likely increasing
Rifle Range Shallow	Pukekohe central volcanic	0.11	0.977	very likely increasing
Douglas Road Volcanic	Pukekohe central volcanic	0.296	1	very likely increasing

Figure 9: Trend results for mean monthly groundwater levels over the period 2010-2019.

5.2 Annual maximum groundwater level

Most sites across the region showed *likely increasing* (29%) or *very likely increasing* (33%) trends in maximum groundwater level. Few sites had decreasing trends (8%) in maximum groundwater level and only one site had a *very likely decreasing* trend. All sites with *very likely* trends also met the criteria to be established with confidence (Table 11). Short Road (Kumeu East Waitematā aquifer) had a median Sen slope of approximately 1 order of magnitude larger than all other sites at 1.4203 m/year and is discussed further in Section 5.3. Site location, trend direction, and trend confidence is mapped for all sites in Figure 10.

Table 11: Sites with very likely trend results for annual maximum groundwater level over the period 2010-2019.

Site name	Aquifer	Median Sen slope (annual)	Probability	2010-2019 SOE trend category
Caroline Heights	Omaha Waitematā	0.056	0.929	very likely increasing
Waiwera Beachfront Deep	Waiwera geothermal	0.169	0.990	very likely increasing
Waiwera Beachfront Shallow	Waiwera geothermal	0.166	0.997	very likely increasing
Parakai 86	Parakai geothermal	0.123	0.978	very likely increasing
Rimmer Road	Kaipara sand	0.027	0.978	very likely increasing
Selaks Bore	Kumeu East Waitematā	0.198	0.976	very likely increasing

Site name	Aquifer	Median Sen slope (annual)	Probability	2010-2019 SOE trend category
Trigg Road	Kumeu West Waitematā	0.134	1	very likely increasing
Short Road	Kumeu East Waitematā	1.420	0.998	very likely increasing
Nick Johnstone Drive	Waiheke West greywacke	0.250	0.934	very likely increasing
Alfred Street	Onehunga volcanic	-0.037	0.920	very likely decreasing
Tiwai Road	Onehunga volcanic	0.138	0.915	very likely increasing
Seagrove Road	Waiau Pa Waitematā	0.08	0.966	very likely increasing
Batty Road	Glenbrook Kaawa	0.048	0.932	very likely increasing
Pukekohe DSIR	Pukekohe central volcanic	0.282	0.999	very likely increasing
Mauku Main	Glenbrook Kaawa	0.160	0.997	very likely increasing
Rifle Range Deep	Pukekohe central volcanic	0.491	0.998	very likely increasing
Douglas Road Volcanic	Pukekohe central volcanic	0.291	0.998	very likely increasing

Figure 10: Trend results for annual maximum groundwater levels over the period 2010-2019.

5.3 Annual minimum groundwater level

Trends in annual minimum groundwater level showed that more sites exhibited increasing trends in the last 10 years than decreasing trends; 33% *very likely increasing* and 31% *likely increasing* versus 10% *likely decreasing* and 10% *very likely decreasing*. *Indeterminate* trends were calculated for 15% of sites. *Very likely decreasing* trends were calculated for four aquifers: Omaha Waitematā, Onehunga volcanic, Glenbrook Kaawa, and the Waiuku Kaawa aquifers. These are discussed further in Section 5.3.

All *very likely* trends met the criterion for Sen slope > 0.02 m/year (Table 12). Site location, trend direction, and trend confidence is mapped for all sites in Figure 11.

Table 12: Sites with very likely trend results for annual minimum groundwater level over the period 2010-2019.

Site name	Aquifer	Median Sen slope (annual)	Probability	Trend category
Quintals Road Omaha	Omaha Waitematā	-0.127	0.983	very likely decreasing
Omaha Flats Bore 25	Omaha Waitematā	-0.237	0.974	very likely decreasing
Waiwera Beachfront Deep	Waiwera geothermal	0.072	0.972	very likely increasing
Waiwera Beachfront Shallow	Waiwera geothermal	0.061	0.911	very likely increasing
Selaks Bore	Kumeu East Waitematā	0.435	0.942	very likely increasing
Trigg Road	Kumeu West Waitematā	0.145	0.998	very likely increasing
Short Road	Kumeu East Waitematā	2.466	1	very likely increasing
Nick Johnstone Drive	Waiheke West greywacke	0.191	0.981	very likely increasing
Leslie Road	Western Springs volcanic	0.152	0.931	very likely increasing
PD-13S	Mt Wellington volcanic	0.147	0.967	very likely increasing
Orakau Avenue	Onehunga volcanic	-0.142	0.978	very likely decreasing
Angle Street	Mt Wellington volcanic	0.025	0.999	very likely increasing
Glenbrook Hall	Glenbrook Kaawa	-0.031	0.949	very likely decreasing
Seagrove Road	Waiau Pa Waitematā	0.157	0.955	very likely increasing
Ostrich Farm Road Observation	Pukekohe Kaawa	0.042	0.946	very likely increasing
Diver Road	Waiuku Kaawa	-0.810	0.998	very likely decreasing
Pukekohe DSIR	Pukekohe central volcanic	0.359	0.999	very likely increasing
Mauku Main	Glenbrook Kaawa	0.158	0.991	very likely increasing
Rifle Range Deep	Pukekohe central volcanic	0.619	0.969	very likely increasing
Rifle Range Shallow	Pukekohe central volcanic	0.236	0.953	very likely increasing
Douglas Road Volcanic	Pukekohe central volcanic	0.327	0.994	very likely increasing

Figure 11: Annual minimum groundwater level trends over the last 10 years.

6 Discussion

6.1 Rainfall

6.1.1 Climate Oscillations

The results presented in Sections 3 to 5 showed increases in hydrological metrics (i.e. rainfall, river flow, and groundwater level) for most areas in the region over the period of analysis (2010-2019). Decreases in hydrological metrics, particularly groundwater levels, were predominantly associated with changes to seasonal water use rather than a reduction in natural water quantity. This indicates that there has generally been increasing water in the Auckland environment over the last 10 years. The widespread increases across multiple metrics indicates a climatic driver which can be put in context using data on climate oscillations.

Long- and short-term climate oscillations including the Interdecadal Pacific Oscillation (IPO) and the El Niño Southern Oscillation (ENSO), can affect hydrometric cycles for New Zealand. IPO is associated with decadal climate variability (Pearce et al., 2020, Salinger et al. 2001) whereas ENSO affects climate on interannual cycles (Pearce et al., 2020, Folland et al. 2002). Climate oscillations like IPO and ENSO cannot fully account for observed changes in rainfall, e.g. ENSO accounts for less than 25 per cent of annual variation in rainfall (NIWA, 2020), but climate oscillations can provide valuable context to changes or trends in hydrometric data.

The IPO positive phase is associated with stronger west to southwest winds and more rain in the west of NZ and the negative phase is associated with greater influence from the northeast with more rain in the north and east of NZ. The IPO showed a strong positive phase from 1980 to 1998, shifting to a negative phase until 2014.

The period of analysis for this report (2010-2019) falls within a period of mostly increasing IPO (Figure 12). The pattern of IPO does not match well with rainfall observations which show positive deviations from normal averages in 2011 and again in 2016-2018, however the overall weighting of increased rainfall to the latter half of the period of analysis coincides with increasing IPO.

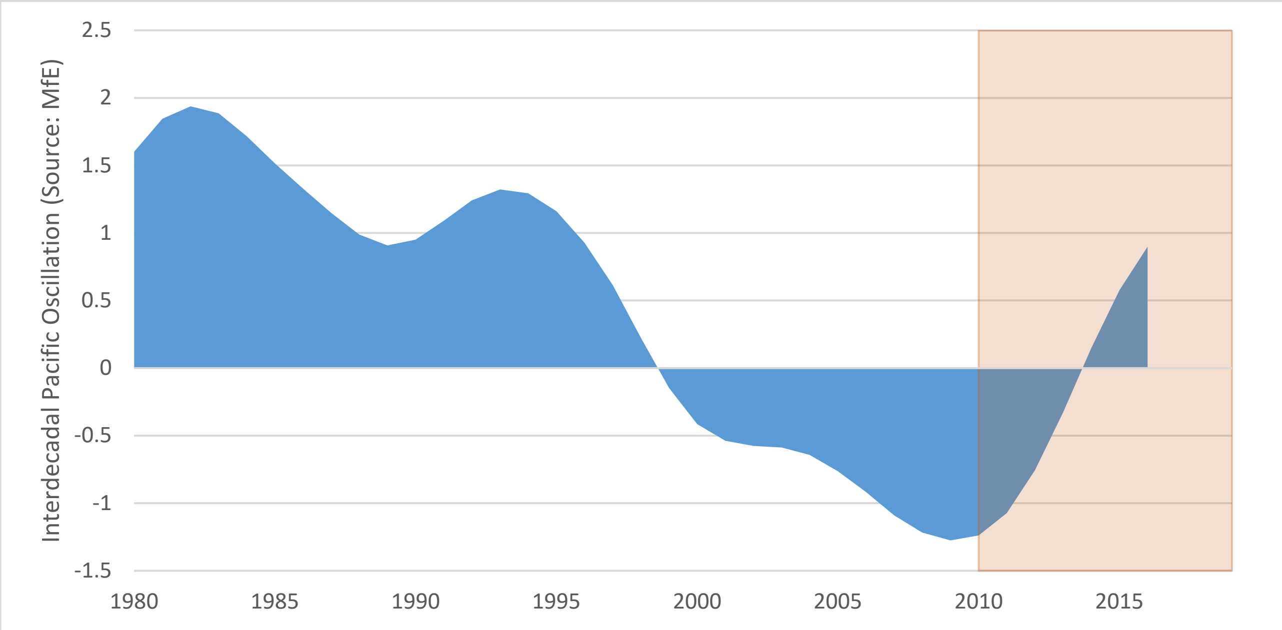

Figure 12: Interdecadal Pacific Oscillation (annual values). Period of analysis highlighted (2010-2019). Source: Ministry for the Environment.

The ENSO index values for the period of analysis (2010 to 2019) show a marked decrease from strong positive values in 2010/11 to strong negative values in 2015/16 (Figure 13). This is consistent with a shift from La Niña to El Niño conditions. The period from 2016 through 2019 was more neutral (closer to zero) but decreasing with two values below -1 observed in 2019.

The pattern of ENSO does not match well with the rainfall observations, but some inferences can be drawn between the two datasets. The strong La Niña in 2011 coincided with high rainfall observed in the region. The strong El Niño event in 2015/16 also coincided with higher than normal rainfall in the Auckland region, an opposite relationship to 2011. The period of "neutral" ENSO values from 2012 to 2015 coincided with either normal or below normal rainfall (within or below the interquartile range). The years 2016-2018 had higher than normal rainfall, but with ENSO values in the "neutral" range.

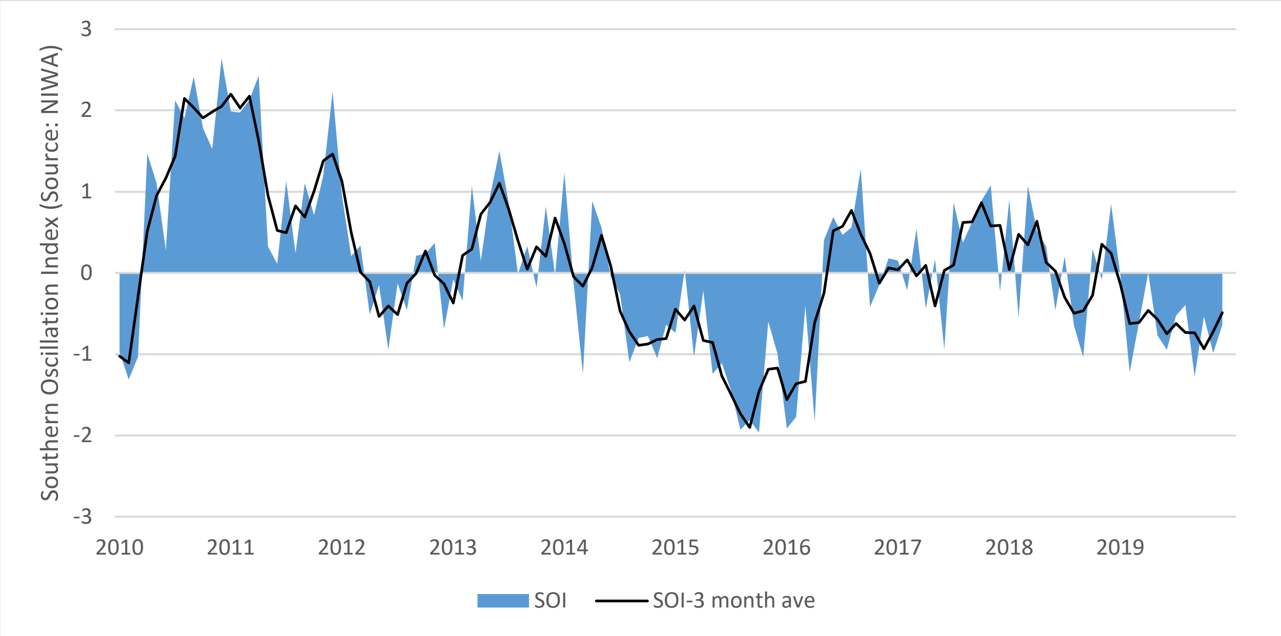

Figure 13: Southern Oscillation Index (monthly values) during the reporting period. Source: NIWA.

6.2 Annual high flows

The comparison of the current state (2015-2019) to the period of analysis (2010-2019) and the long-term record (2000-2019) revealed that only two sites showed a significant change in the number of high flow events. More high flow events were recorded in the last five years than in the last 10 years at 27 sites (69%) versus 12 sites which had fewer high flow events (31%). This reflects the three consecutive years with rainfall exceeding the 75th percentile from 2016-2018 and the general pattern observed in climate oscillations.

This report presents the first statistical trend analysis for the number of annual high flow events (as evidenced by 3XMedian flow) for Auckland streams. This analysis was conducted to determine if there were any clear indications that changes in land cover had an impact on the number of high flow events.

Trend analysis found only one site that had a trend in annual high flows that could be established with confidence: Taiaotea Stream (Browns Bay) with a decreasing trend and magnitude of -0.875 events/year. Analysis completed by McKerchar (2020) showed corroborating results with no statistical difference in flood frequency between pre-1999 and 2000-2018 periods for 8 of 14 sites. The remainder of sites were analysed further and shown to be influenced by non-normally distributed data and infrequent very large events, i.e. the data do not show significant differences indicative of a monotonic trend.

However, 90 per cent of sites with decreasing trend directions were in predominantly urban catchments and 70 per cent of sites with increasing trend directions were in predominantly rural catchments (Table 13).

Table 13: Dominant land cover by trend category for annual high stream flows assessment (land cover data source: LCDB v5.0)

Dominant land cover	Decreasing trends	Increasing trends
Urban	9	2
Native forest	1	1
Rural	0	7

The higher percentage of impervious cover in urban areas is usually associated with frequent peaks of stream flow following rainfall due to runoff being directed to streams via short-pathway systems (e.g. stormwater infrastructure). Rural catchments tend to have comparatively less frequent flow peaks due to more pervious area with high infiltration and entrainment in the landscape. The trends observed show less frequent high flow events in urban areas and more frequent high flow events in rural areas. The distinction between the results by land cover suggests that changes in the natural and built environment may be a controlling factor on the observed trends.

Approximately 90% of sites with decreasing trends in the number of high flow events were in catchments with predominantly urban land cover. Urban sites are constrained as to the amount of development that can occur; however, recent policy initiatives have been enacted to manage stormwater in these catchments. Twelve streams in this analysis are within Stormwater Management Areas for Flow (SMAF) catchments, which cover the North Shore of Auckland from Okura to the north, Lucas Creek to the west, and south to the Waitematā Harbour. SMAF catchments have specific regulations regarding stormwater management for new developments. Six of the 12 streams in SMAF areas had decreasing trends in the number of high flow events per year. The remaining six streams in SMAF areas had indeterminate trends. The SMAF regulations on stormwater management came into effect in 2016, so only apply to the last three years in the period of analysis. Only 50% of sites in SMAF areas showed a decreasing trend in high flows, so SMAF regulations are unlikely to have influenced high flow hydrology over the reporting period.

6.3 Low flow magnitude and frequency

This report presents the first statistical trend analysis for annual low flows. Analyses addressed magnitude of low flows, as evidenced by the 7-day annual low flow, and frequency, as evidenced by the number of days flows were lower than the long-term 7-day MALF and the AUP minimum flow.

Eight of 39 sites had *very likely increasing* trends in the magnitude of low flows, i.e. trending towards higher flows. Only the Otara Stream had an increasing trend that could be established with confidence. There was no distinct difference in trend direction between dominant land cover categories. Urban and rural land cover comprised approximately half of the sites with both increasing and decreasing trends (Table 14).

The state and trend analysis of low flow frequency indicates that there were less low flow days within the reporting period than in the past, although not as a monotonic trend. The number of days below the minimum flow relates well to the patter of annual rainfall, with no or few days below the minimum flow when rainfall was above the 75th percentile for the year.

Table 14: Dominant land cover by trend category for annual low stream flows (land cover data source: LCDB v5.0)

Dominant land cover	Decreasing trends	Increasing trends
Urban	2	14
Native forest	1	0
Rural	1	12

6.3.1 Influence of water takes on trend analysis outcomes

Trends in stream low flows are unlikely to be impacted by water use as evidenced by the lack of a difference in trend direction between rural streams (with relatively high water abstraction) and urban streams (with relatively low water abstraction). However, the potential for major stream takes to influence recorded stream flows is still relevant to support the conclusion.

Water use data were unavailable for analysis in this report; however the potential influence of stream takes on surface flows can be addressed based on location of flow monitoring sites within the catchments. Flow measurements at sites located at the upstream extent of catchments will be less influenced by water takes than flows measured at downstream sites as the number and cumulative effects of water takes increase with distance downstream. A trend result which may misrepresent actual conditions could arise from sites where flow monitoring is upstream of major water takes, and is particularly important where the result could be a change in the trend direction from increasing to decreasing.

Most flow monitoring sites in the Auckland region are located below most surface water takes. There are two sites in the network that were identified as being upstream of major takes or in the upper catchment:

- Mahurangi River at Argonaut: above the municipal supply take for Warkworth.
- Ngakoroa Stream at Mill Road: upper reaches of catchment above most takes.

The two sites had trend results of *likely increasing* and *very likely increasing*, respectively. An analysis of water takes alongside the trend results for low flows (magnitude and frequency) will help to determine the impact of takes on the flow regime in future reporting.

6.4 Groundwater levels

6.4.1 Groundwater trend comparisons

The trend analysis completed for this work addressed three components of the groundwater hydrograph: the monthly mean, the annual maximum, and annual minimum water levels. These components of the hydrograph help to focus investigation of the likely drivers of the trends, e.g. increased summer abstraction for irrigation causing declines in summer groundwater levels.

Eleven of the 47 sites (23%) had *very likely increasing* trends across all three analyses (monthly mean, annual maximum, and annual minimum). No sites had *very likely decreasing* trends in all three trend analyses. Only three sites had *very likely decreasing* trends in two of the three analyses.

6.4.2 Comparison to previous work

The trend results for 2010-2019 included 47 sites total. Of the 47 sites, 35 sites were also analysed by Kalbus et al. (2017). The 35 sites were compared to highlight any sites with changes in trend direction or magnitude (Table 16). The comparison shows consistent trends between the two reporting periods at 77% of the sites for both trend direction and magnitude, indicating consistent hydrogeological conditions (including water abstraction) in many of the aquifers in the region.

Eleven sites of the 47 analysed (23%) had a change in trend direction between the two periods of analysis:

- Six sites with previously decreasing trends in mean monthly groundwater level had increasing trends from 2010-2019 (one of the increasing trends was not *very likely*).
- Two sites with a previously indeterminate trend had an increasing trend from 2010-2019.
- Three sites with a previously indeterminate trend had a decreasing trend from 2010-2019.

Potential abstraction effects were recognised in several hydrographs that showed both increased and decreased groundwater levels, likely via reduced or increased abstraction, respectively (Table 15). These sites are discussed further in Section 5.3. The remaining sites that show a change in trend direction between the two periods of analysis that cannot be attributed to abstraction effects are also addressed in Section 5.3.

Sites that showed a consistent increasing trend between the two periods of analysis are not discussed further in this report.

Table 15: List of groundwater sites with obvious pumping effects or changes in trend direction.

Site	Aquifer	Obvious pumping effects?
Quintals Road	Omaha Waitematā	Yes
Omaha Flats Bore 25	Omaha Waitematā	Yes
Waiwera Beachfront Deep	Waiwera geothermal	Yes
Parakai Bore 86	Parakai geothermal	Yes
Diver Road	Glenbrook Kaawa	Yes
Caroline Heights	Omaha Waitematā	Yes
Rimmer Road	Kaipara sand	No
Selaks	Kumeu East Waitematā	No
Short Road	Kumeu East Waitematā	No
Selkirk	Western Springs volcanic	No
PD-13s	Mt Wellington volcanic	No
Alfred Street	Onehunga volcanic	No
Orakau Avenue	Onehunga volcanic	No
Burnside Road	Clevedon East Waitematā	No
Seagrove Road	Waiau Pa Waitematā	No

Table 16: Comparison of trend results for mean monthly groundwater level between 2006-2015 and 2010-2019 (only includes sites analysed in both reports). Highlighted rows indicate a change in trend direction between 2006-2015 and 2010-2019.

Site name	Site number	Aquifer	2006-2015 trend direction	2006-2015 trend magnitude (Sen slope, m/yr)	2010-2019 trend direction	2010-2019 trend magnitude (Sen slope, m/yr)
Quintals Road	6437005	Omaha Waitematā	Decreasing	-0.045	Decreasing	-0.034
Caroline Heights	**6437087**	**Omaha Waitematā**	**Decreasing**	**-0.048**	**Increasing**	**0.076**
Parakai Bore 86	**6464007**	**Parakai geothermal**	**Decreasing**	**-0.055**	**Increasing**	**0.092**
Seagrove Road	**7417021**	**Waiau Pa Waitematā**	**Decreasing**	**-0.154**	**Increasing**	**0.121**
Karaka North #2	**7419119**	**Karaka Waitematā**	**Decreasing**	**-0.055**	**Increasing****	**0.025**
Rimmer Road	**6464089**	**Kaipara Sand**	**Decreasing***	**0.013**	**Increasing**	**0.038**
PD-13S	**6488045**	**Mt Wellington volcanic**	**Decreasing***	**-0.079**	**Increasing**	**0.130**
Waiwera Beachfront Deep	6457041	Waiwera Geothermal	Increasing	0.11	Increasing	0.103
Waiwera Beachfront Shallow	6457097	Waiwera Geothermal	Increasing	0.11	Increasing	0.082
Trigg Road	6475005	Kumeu West Waitematā	Increasing	0.051	Increasing	0.146
Short Road	6475157	Kumeu East Waitematā	Increasing	0.984	Increasing	2.031
Nick Johnstone Drive	6479007	Waiheke West greywacke	Increasing	0.211	Increasing	0.207
Mt Richmond	6494001	Mt Richmond volcanic	Increasing	0.123	Increasing**	0.092
Angle Street	6498003	Mt Wellington volcanic	Increasing	0.017	Increasing	0.021
Tuhimata Road	7419003	Pukekohe Kaawa	Increasing	0.043	Increasing**	0.025
Cooper Road	7419011	Bombay-Drury Kaawa	Increasing	0.196	Increasing**	0.036
Pukekohe DSIR	7428043	Pukekohe central volcanic	Increasing	0.069	Increasing	0.274
Rifle Range Deep	7428103	Pukekohe central volcanic	Increasing	0.26	Increasing	0.559
Rifle Range Shallow	7428105	Pukekohe central volcanic	Increasing	0.173	Increasing	0.11
Douglas Road	7429013	Pukekohe central volcanic	Increasing	0.058	Increasing	0.296
Wooten Road	7510005	Bombay volcanic	Increasing	0.096		Indeterminate
Waitakere Road #2	6474003	Kumeu West Waitematā	Increasing*	0.249	Increasing	0.443

Site name	Site number	Aquifer	2006-2015 trend direction	2006-2015 trend magnitude (Sen slope, m/yr)	2010-2019 trend direction	2010-2019 trend magnitude (Sen slope, m/yr)
Batty Road	7418013	Glenbrook Kaawa	Increasing*	0.02	Increasing	0.033
Diver Road	7427003	Waiuku Kaawa	Increasing*	0.049	Decreasing**	-0.031
Mauku Main	7428047	Glenbrook Kaawa	Increasing*	0.03	Increasing	0.144
Selaks Bore	**6475003**	**Kumeu East Waitematā**	**Decreasing not statistically significant**		**Increasing**	**0.256**
Selkirk Road	**6487007**	**Western Springs volcanic**	**Decreasing not statistically significant**		**Increasing**	**0.022**
Alfred Street	**6497007**	**Onehunga volcanic**	**Decreasing not statistically significant**		**Decreasing**	**-0.029**
Orakau Avenue	**6497015**	**Onehunga volcanic**	**Decreasing not statistically significant**		**Decreasing**	**-0.068**
Amelia Earhart	6497017	Manukau Kaawa	Not statistically significant		Increasing	0.029
Tiwai Road	6497019	Onehunga volcanic	Not statistically significant		Increasing	0.050
Tawaipareira	6570015	Waiheke Central West greywacke	Not statistically significant		Increasing	0.04
Burnside Road	**7409001**	**Clevedon East Waitematā**	**Decreasing not statistically significant**		**Decreasing**	**-0.076**
Glenbrook Hall	7417001	Glenbrook Kaawa	Not statistically significant		Increasing**	0.016
Ostrich Farm Road Observation	7418027	Pukekohe Kaawa	Not statistically significant		Increasing	0.03
Fielding Road Waitematā	7419013	Bombay-Drury Waitematā	Not statistically significant		Increasing	0.036

* statistically significant but not environmentally meaningful (from Kalbus et al. 2017)

** probability less than 0.9; does not establish trend with confidence

6.5 Potential groundwater abstraction effects

6.5.1 Omaha Waitematā aquifer

The Omaha Waitematā aquifer is an important source of water for a regionally significant fruit and vegetable industry. The aquifer also provides for livestock drinking, domestic, and industrial supply.

The Quintals Road monitoring well is located within the central area of the Omaha Waitemata aquifer. It is also located near the Omaha Flats Bore 25. Both sites are proximal to the main horticulture area. Increased abstraction starting at the end of 2016 has led to much lower summer groundwater levels in all successive seasons. Summer groundwater levels were approximately 1m lower after 2016 (Figure 14). Water level recovery over winter returned to levels in the normal range (i.e. within interquartile range of winter highs) even after the lower summer water levels from 2016 onwards.

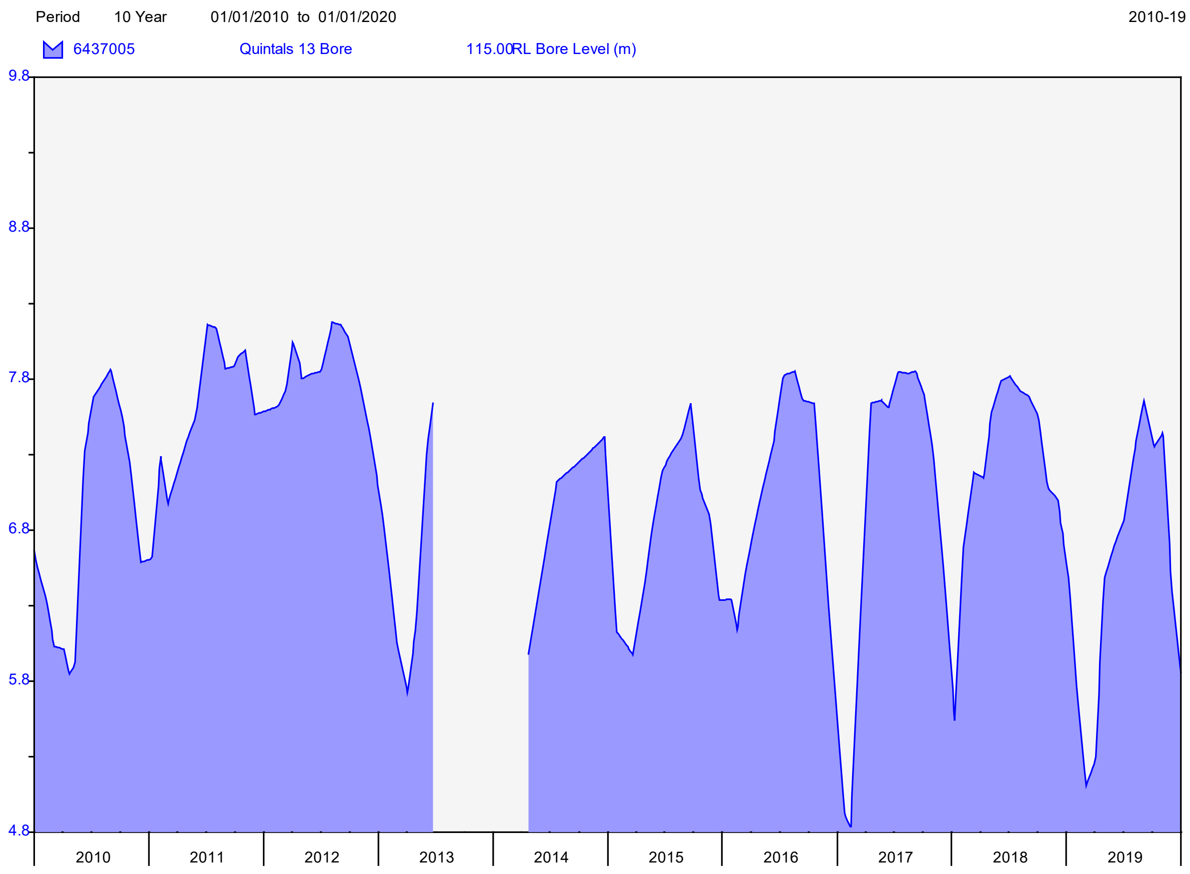

Figure 14: Groundwater level hydrograph at Quintals Road in the Omaha Waitematā aquifer.

Section 4.3 showed a decreasing trend in summer water levels for the aquifer at Omaha Flats Bore 25. A review of the groundwater level hydrograph reveals a change in the pattern of summer water levels, starting in 2016, rather than a gradual downward trend. This corresponds directly with increased water allocation in the aquifer starting in 2016. The Omaha Flats Bore 25 exhibits pumping effects and recent increases in water allocation from the aquifer are reflected in significant drops in groundwater level over the summer period (Figure 15). The site was monitored via monthly manual measurements until early 2016 when it was upgraded to automatic water level recording which was initiated to gain better resolution data following the increased abstraction from the aquifer.

Summer abstraction from the aquifer has lowered groundwater levels below sea level for the last three seasons. The abstraction regime only lasts for a portion of the day; therefore, groundwater levels can partially recover prior to the next days' abstractions. As a result, the daily average groundwater level has not dropped below sea level.

Winter groundwater levels recover to the normal range (within 1 standard deviation) for the full period 2012-2019.

Lower water levels over summer do not necessarily equate to environmental degradation. The Omaha Waitematā aquifer was found to be at least partially confined by impermeable marine muds within the Omaha Flats area (Kelly, 1992) which would limit the upward flow of water as baseflow discharge. However, Kelly (1992) also notes the exposure of Waitematā Group rocks at the higher elevation margins of the catchment. Baseflow discharge is most likely to occur in these higher elevation areas where Waitemata Group rocks outcrop in the stream valleys. The Tamahunga Stream is the largest stream within the aquifer management area (3rd order) and its catchment is entirely outside the Omaha Flats, where most irrigation activity occurs. Abstraction within Omaha Flats (the confined to semi-confined part of the aquifer) is unlikely to affect water levels within the marginal extent of the aquifer (and thus relationship to baseflow), however the effect has not been quantified.

The new water abstraction regime will likely carry on for the foreseeable future and thus a 'new normal' of very low groundwater levels in summer can be expected. Careful attention is needed to monitor the recovery of water levels, both short-term (daily) and long-term (over winter). Short-term monitoring is typically actioned as a condition of consent and managed via the consent/compliance process. Long-term monitoring will be actioned through the State of the Environment groundwater programme.

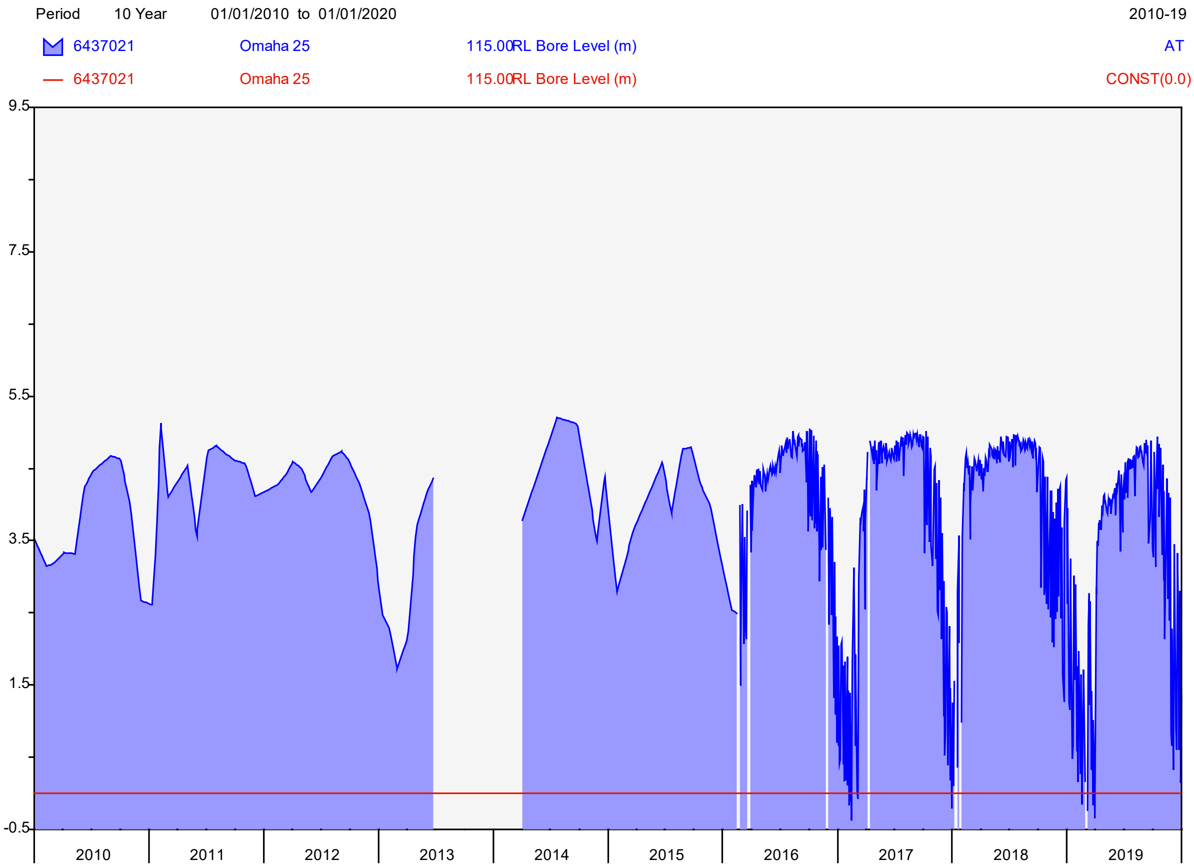

Figure 15: Groundwater level hydrograph for Omaha Flats Bore 25 in the Omaha Waitematā aquifer. Red line indicates sea level (0.0m RL).

The water level at Caroline Heights in the Omaha Waitematā aquifer had an increasing trend from 2010-2019 (Sen slope 0.076). An inspection of the hydrograph shows a change in the pattern at this monitoring well, starting at the end of 2016 (Figure 16). The inter-annual amplitude reduced, showing very little seasonal variation after the first few months of 2017. The change in the hydrograph confirms that there is not a monotonic trend in groundwater levels at this location.

The cause of the change is unconfirmed but is likely linked to cessation of the only consented groundwater take in the area. A review of the water meter readings submitted to council shows the take essentially ceased in January 2017, which coincides with the change in water level patterns showing no more summer drawdowns (Figure 17).

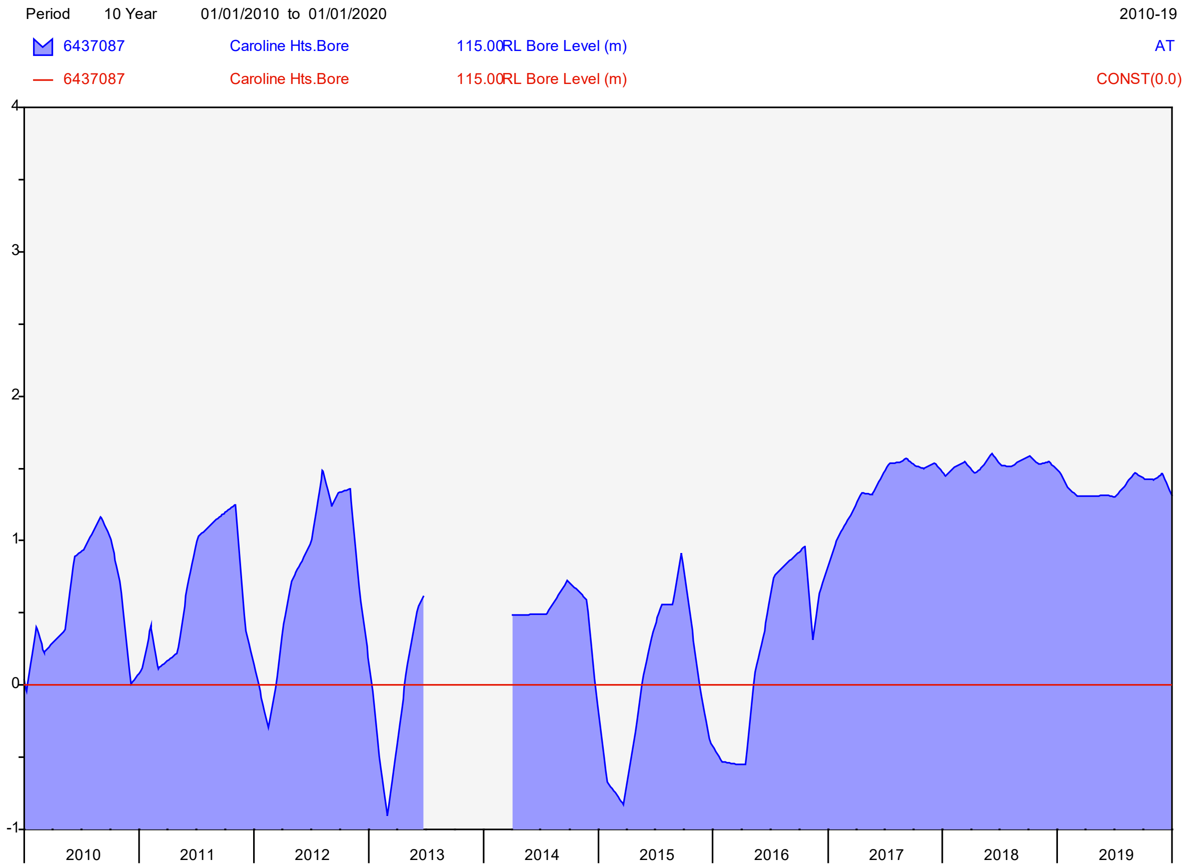

Figure 16: Groundwater level hydrograph for Caroline Heights in the Omaha Waitematā aquifer. Red line indicates sea level (0.0m RL).

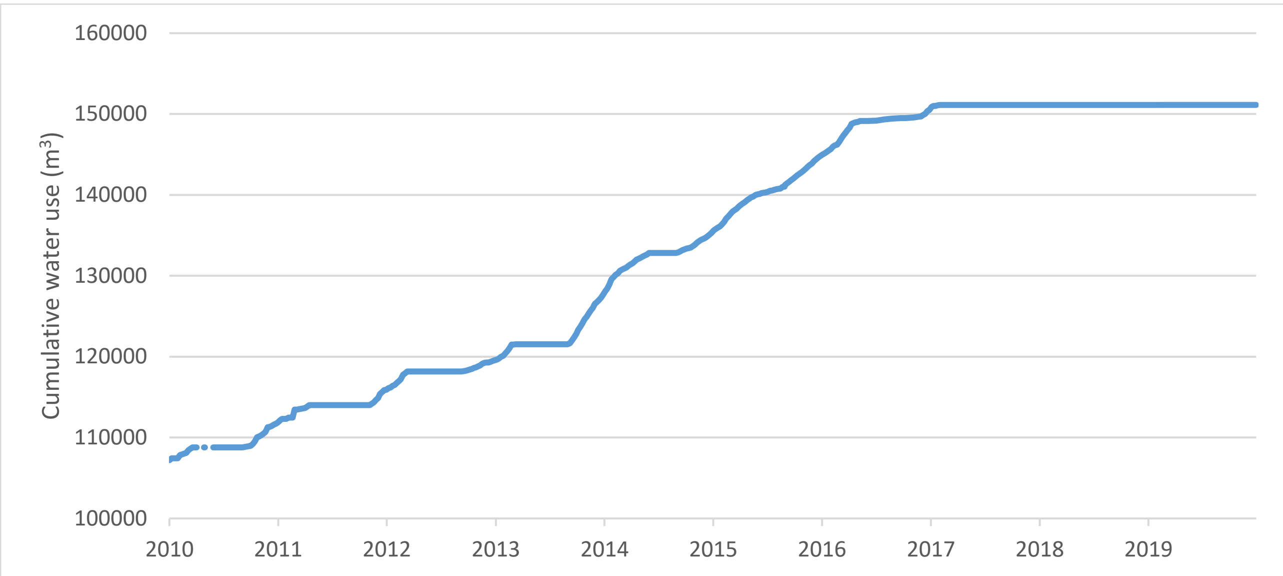

Figure 17: Water meter readings from a groundwater take near the Caroline Heights groundwater monitoring site.

6.5.2 Waiwera geothermal aquifer

Trend analysis of groundwater levels in the Waiwera geothermal aquifer show an increasing trend for all analyses (monthly means, annual maximum, and annual minimum). The trend results are influenced primarily by two events; the rapid water level rise caused by the Kaikoura earthquake in 2016 (Khün and Schöne 2018) and increases in water level after the Waiwera thermal spa and water bottling complex ceased taking water in February 2018. The hydrograph of groundwater levels in the deep monitoring bore is shown in Figure 18.

Following cessation of take by the thermal resort, groundwater levels began to rise and by 21 December 2018, had risen above ground level, causing artesian flow of geothermal water from wells in the area. The two council monitoring wells in Waiwera were retrofitted with extended casing to contain the artesian flow and reinstate water level monitoring. Groundwater levels in the geothermal aquifer have been elevated ever since closure of the thermal spa complex and overflow from some private wells continues.

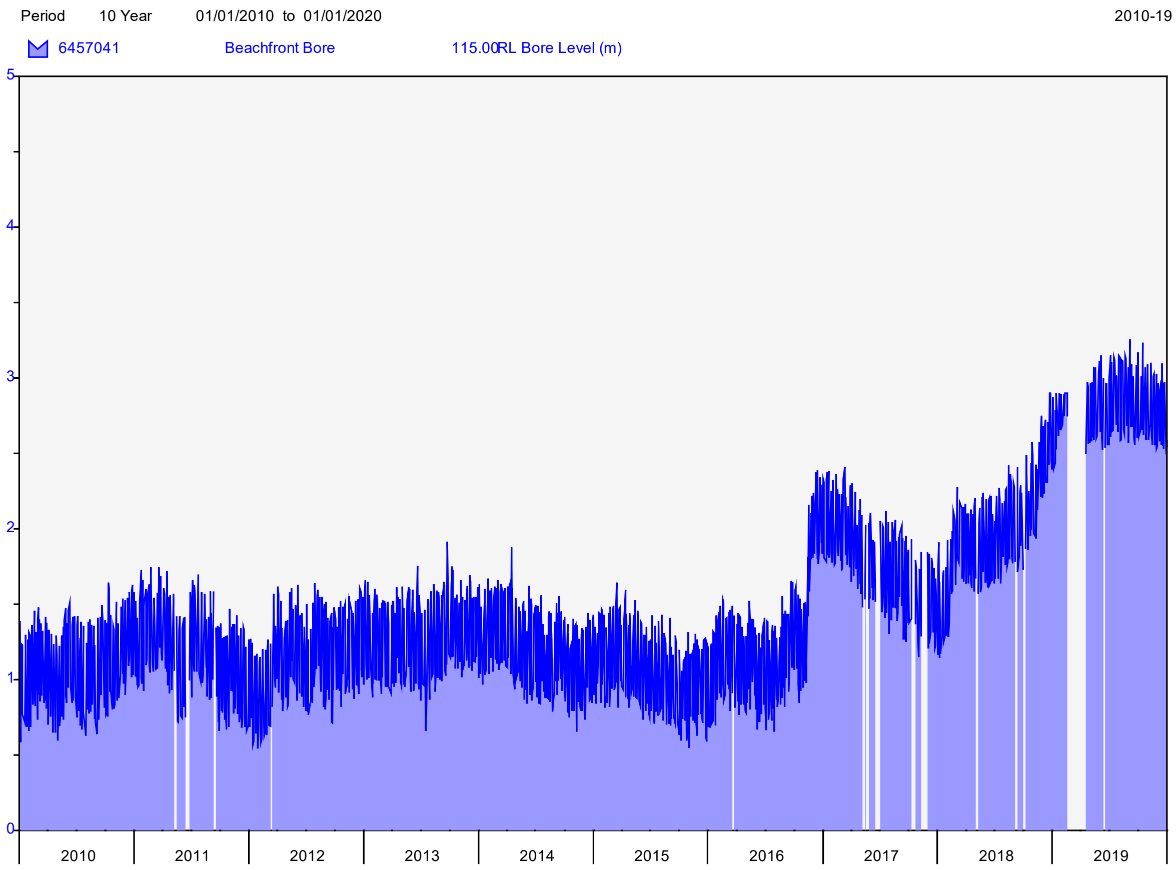

Figure 18: Groundwater level hydrograph for Waiwera Beachfront deep in the Waiwera geothermal aquifer.

What appears to be natural geothermal springs have been observed emanating from the base of the southern seawall and from fractures in the seabed on Waiwera beach since approximately September 2019. This appears to be a result of a cessation in abstraction from geothermal wells in February 2018. An estimate of the flow of geothermal water that is naturally rising to the surface through fissures has not been calculated to date and there is considerable difficulty in accounting for the total aquifer discharge at the surface.

Researchers from Potsdam University visited Waiwera in October 2019 to investigate the structural geology of the geothermal aquifer. Thermal images were taken of the beach at low tide at approximately 5:00 am on October 3, 2019. Cold overnight air temperatures (down to approximately 5°C) allowed for sharp contrast images to be taken, which indicate that geothermal water was rising through fissures in the seabed (Figure 19). The seabed at the southern end of the beach surrounding the geothermal fissures was also at an elevated temperature from the northern part of the beach. This supports the hypothesis that natural hot springs are re-occurring at Waiwera.

The long-term existence of natural geothermal springs is expected to be directly related to the abstraction regime for geothermal wells. Some wells in Waiwera do not have sealed headworks. As a result, overflows are possible if the water level in the aquifer is higher than the top of the well. This is currently occurring for some wells in the township. The overflowing geothermal water is currently being directed to stormwater drains and then to the coast. This is visible in the thermal image, with overflows from a geothermal well entering a stormwater catchpit and then overflow exiting at the beach via a culvert.

Capping of geothermal wells would prevent waste of the geothermal water resource and potentially increase pressure within the aquifer, potentially allowing for increased natural spring activity at the beach. Reinstatement of historical abstraction volumes will likely lower the piezometric head of the aquifer, thus reversing the presumed natural geothermal spring activity as currently observed.

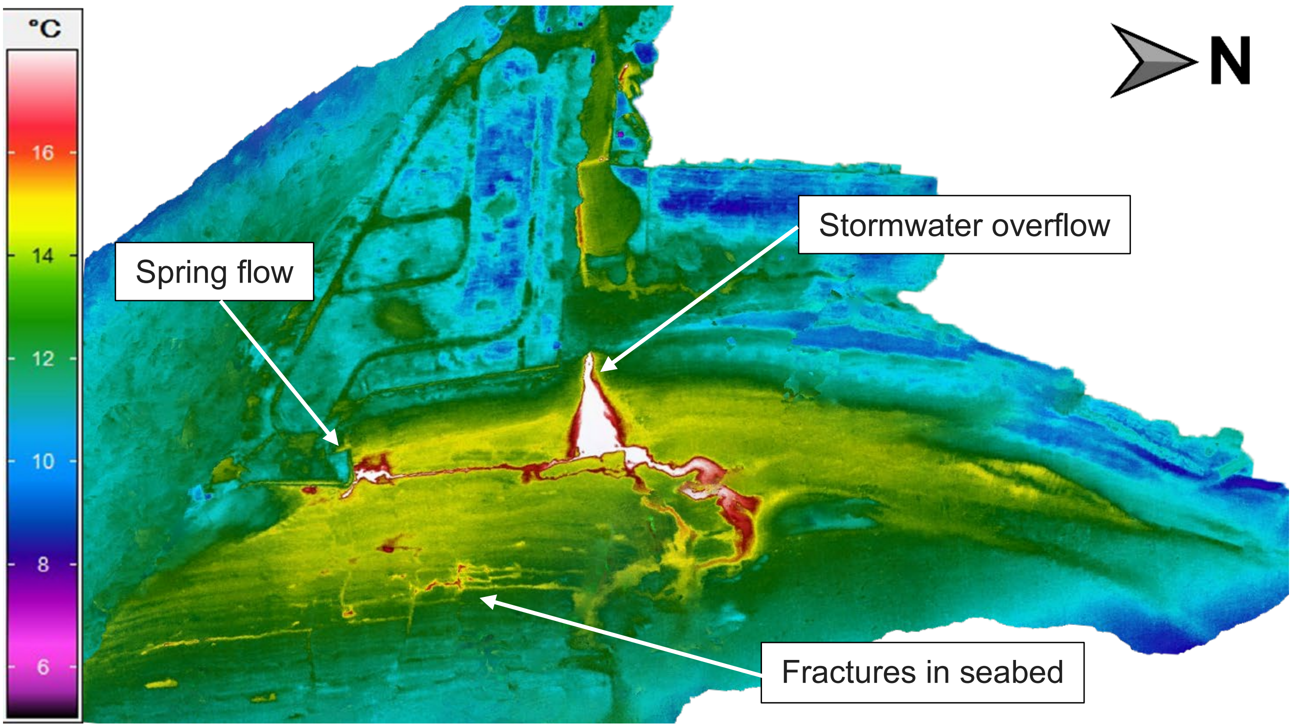

Figure 19: Thermal image of Waiwera beachfront showing thermal water emanating from springs and fissures in the seabed and from overflowing geothermal wells via a stormwater outfall. Taken 13/10/2019.

6.5.3 Parakai geothermal aquifer

Trend analyses from Sections 4.1 and 4.2 showed an increasing trend in the monthly mean and annual maximum groundwater levels. However, the water levels were in a long-term decline (Kalbus et al. 2016) until 2016 when a significant upward shift occurred (Figure 20). From 2016 to present, water levels have begun to decrease toward pre-2017 levels. This demonstrates that there was not an increasing monotonic trend in the data.

Water take data for one large take in the Parakai aquifer was available for review. This data provides a possible explanation for the water level patterns observed. Exceedances of consented water allocation were noted starting in August 2013 and then ceased in April 2016 (Figure 21). The sharp increase in water levels in the aquifer coincide with the cessation of take. No further meter data are available for this water take for the period 2016-2019 to confirm if water use has re-commenced. A full review of water take records is necessary to understand the link between abstraction and long-term water level response in the Parakai Geothermal aquifer.

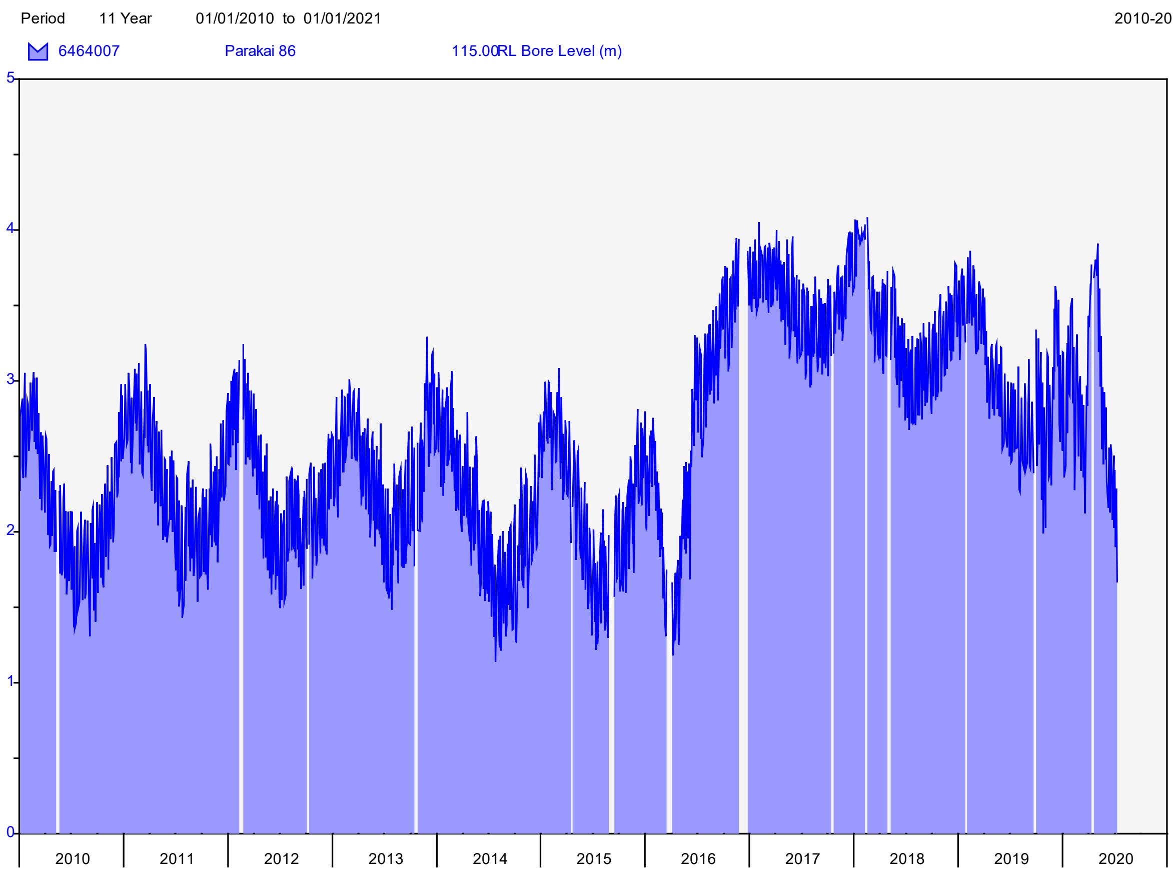

Figure 20: Hydrograph of groundwater levels in the Parakai geothermal aquifer.

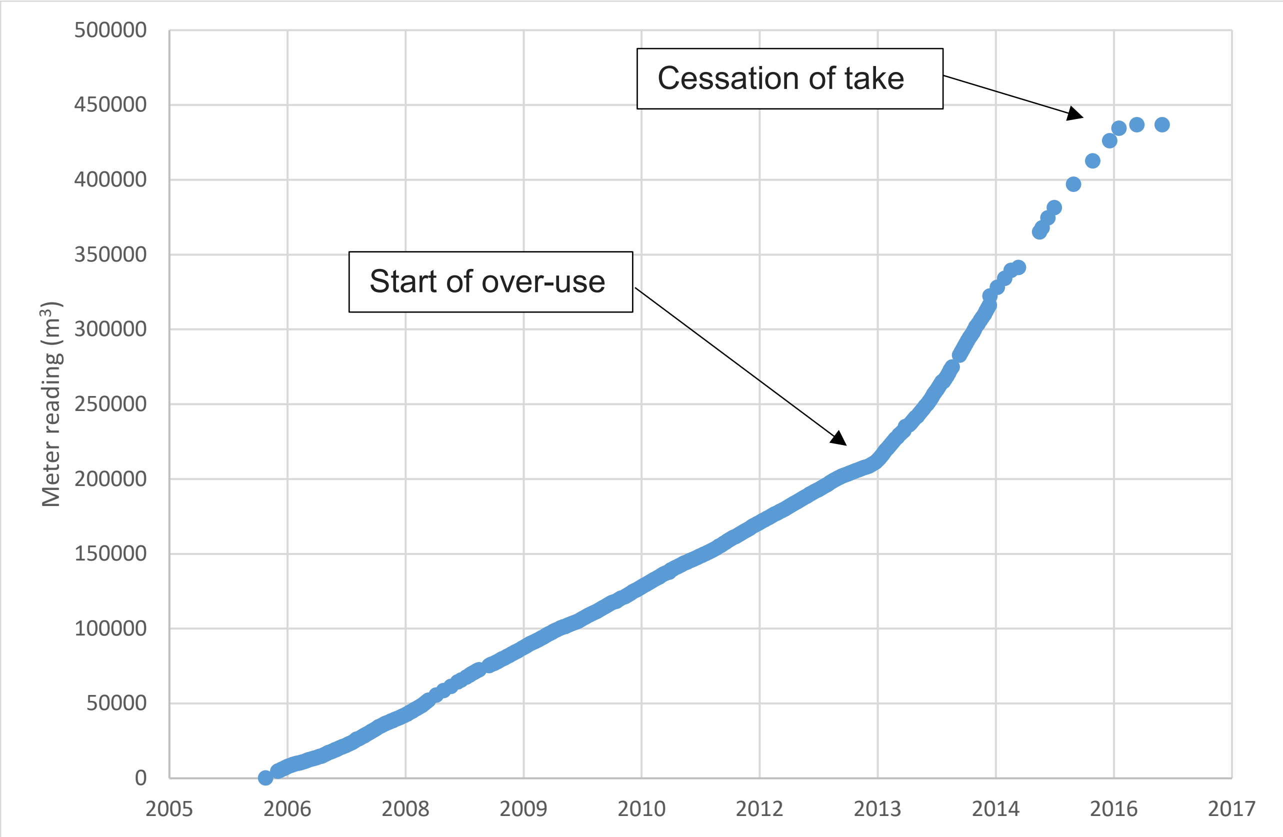

Figure 21: Water use record for one water take from the Parakai Geothermal aquifer.

6.5.4 Rimmer Road, Kaipara sand aquifer

The trend in groundwater level at Rimmer Road from 2010-2019 was *very likely increasing*. The hydrograph for Rimmer Road shows a consistent seasonal pattern throughout the period of analysis, with a slightly decreased inter-annual amplitude from 2016 onwards (Figure 22). Large magnitude, but short duration decreases in water level are visible in 2015 and 2019 but these events exhibit rapid, full recovery of water levels that resemble pumping tests. The hydrograph does not show any large, abrupt, and permanent features that indicate extraneous factors may be influencing the trend result for 2010-2019.

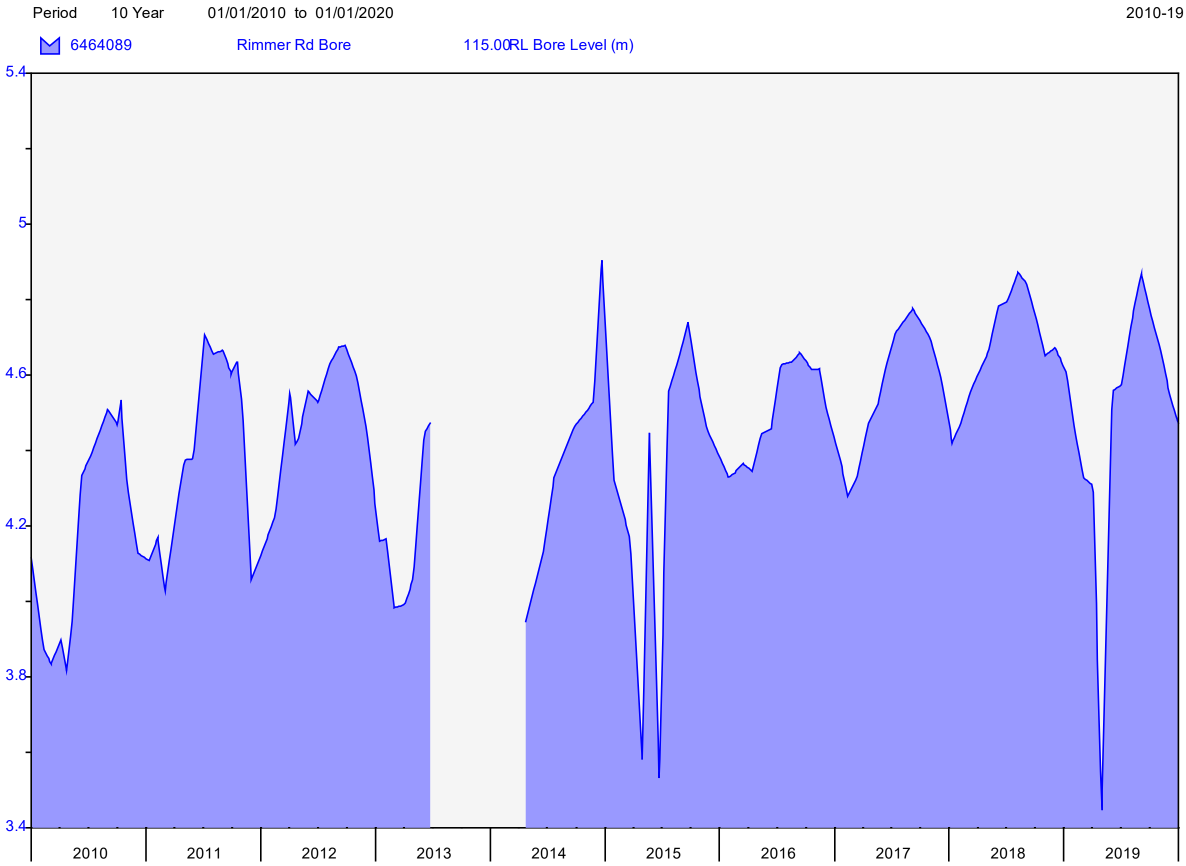

Figure 22: Groundwater level hydrograph for Rimmer Road in the Kaipara Sand aquifer.

6.5.5 Kumeu East Waitematā

The Kumeu East Waitematā aquifer is used for irrigation by the local viticulture and horticulture industry. Trend analysis by Kalbus et al. (2017) found an indeterminate trend for Selaks over the period 2006-2015. The trend from 2010-2019 was very likely increasing with an annual Sen slope of 0.256 m/year. The seasonal pattern is consistent from 2014 onwards, but with generally increasing levels through successive years (Figure 23). This supports the increasing trend result.

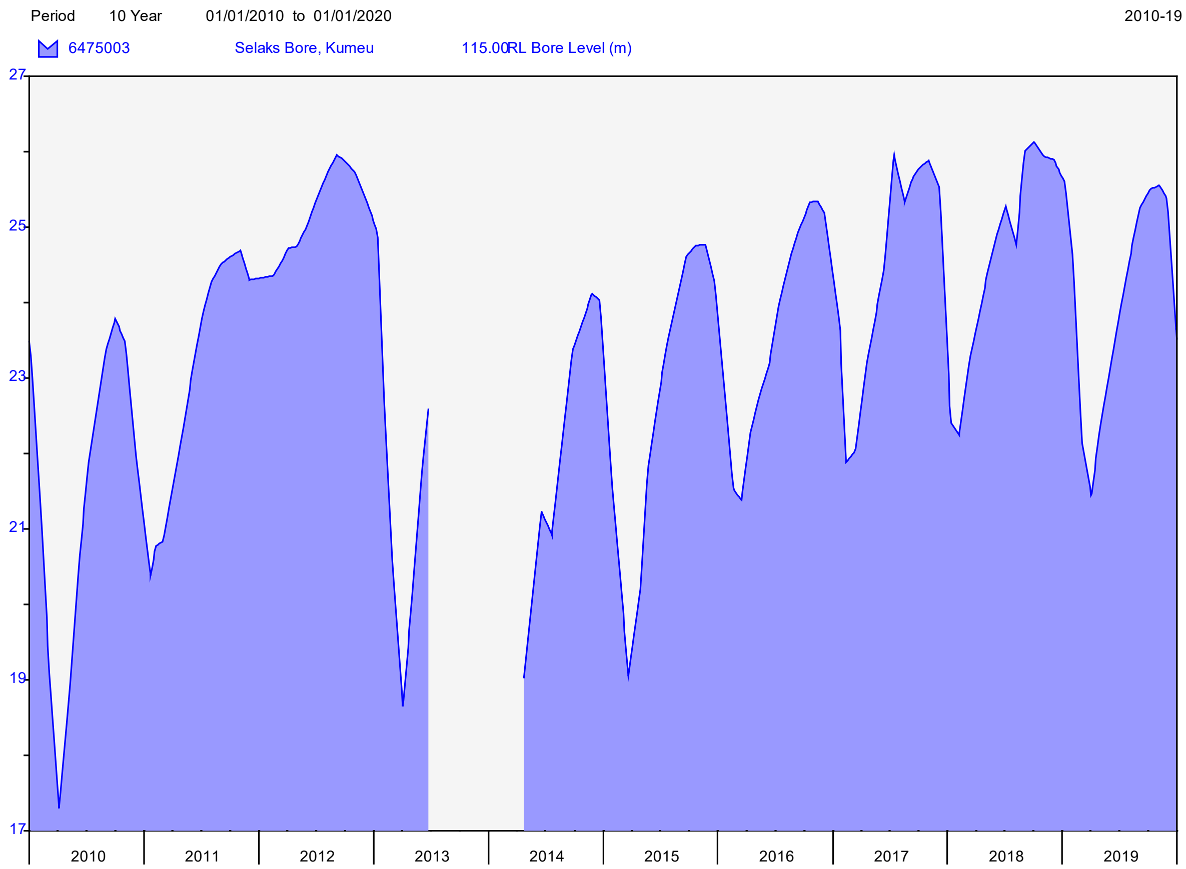

Figure 23: Groundwater level hydrograph for Selaks Bore in the Kumeu East Waitematā aquifer.

The Short Road monitoring well had an increasing trend over the period 2010-2019 that was an order of magnitude higher than any other site (Sen slope = 2.031 m/year). This hydrograph was inspected to visualise the pattern of water level change (Figure 24). The pattern exhibited in the hydrograph was of a marked change between 2011 and 2012 and a steep, but gradual increase in water level. Over the period of analysis, water levels increased and the inter-annual amplitude between high and low water levels also decreased. The highest annual water level of 2010 and 2011 was approximately the lowest annual water level in 2012 then increased steadily throughout successive years (acknowledging the seasonal pattern superimposed on the overall increasing water levels).

The major change from 2011 to 2012 suggests that reduced water take from the aquifer may have occurred sometime in 2011. A review of infrastructure details shows that the reticulated water supply network in Riverhead, Kumeu, and Huapai was installed in June 2012. It is possible that uptake of reticulated mains supply from 2012 onwards resulted in reduced domestic groundwater use and aquifer water level recovery. A review of groundwater take data will be conducted in the future to provide evidence as to the likely cause of increasing groundwater levels.

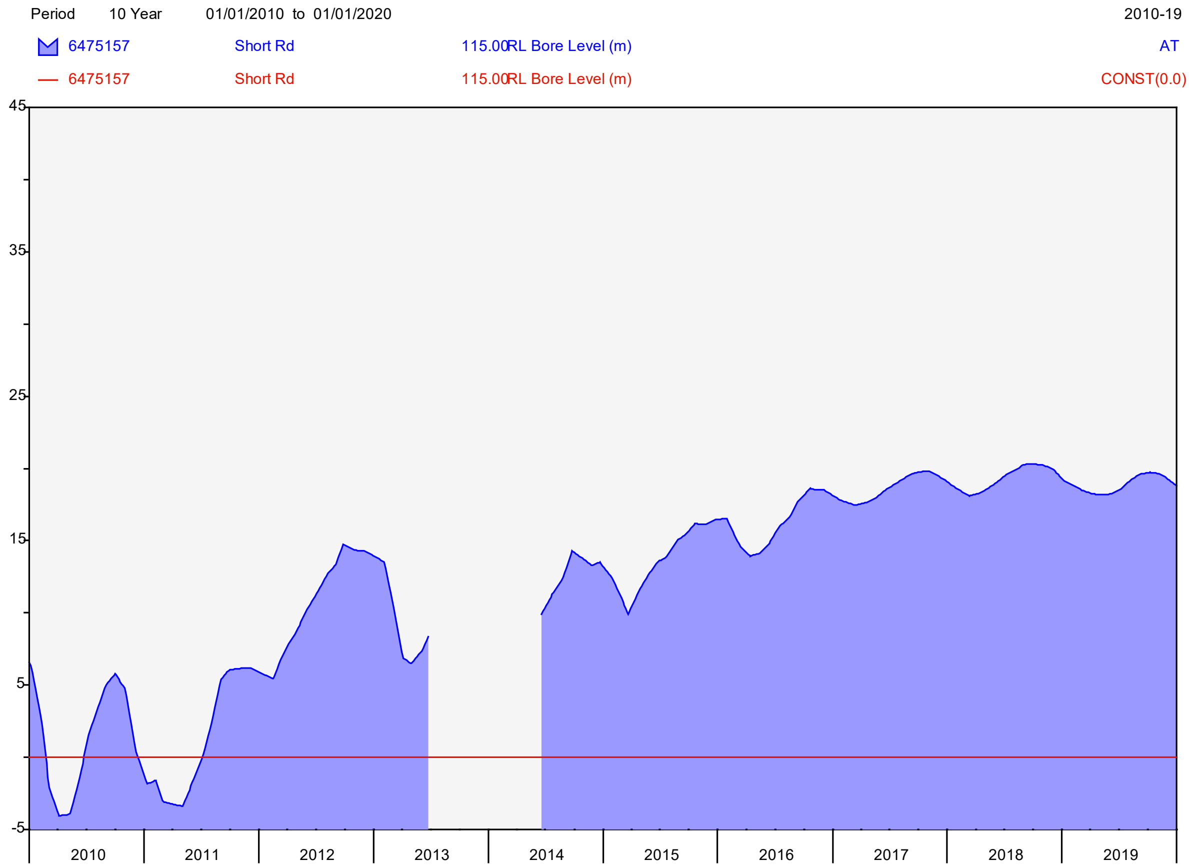

Figure 24: Groundwater level hydrograph for Short Road in the Kumeu East Waitematā aquifer. Red line indicates sea level (0.0m RL).

6.5.6 Selkirk Road, Western Springs Volcanic Aquifer

Trend analysis by Kalbus et al. (2017) found an indeterminate trend for the Selkirk Road site over the period 2006-2015. The trend from 2010-2019 was *very likely increasing* but with an annual Sen slope of 0.022 m/year, which is just over the magnitude threshold criteria based on measurement precision.

The calculated increasing trend is not obvious in the water level hydrograph (Figure 25). The long-duration, low water levels during summer/autumn of 2010-2014 are likely the primary factor for the trend direction calculated for the monthly mean dataset. The annual max and annual minimum trend analyses did not yield a *very likely* trend.

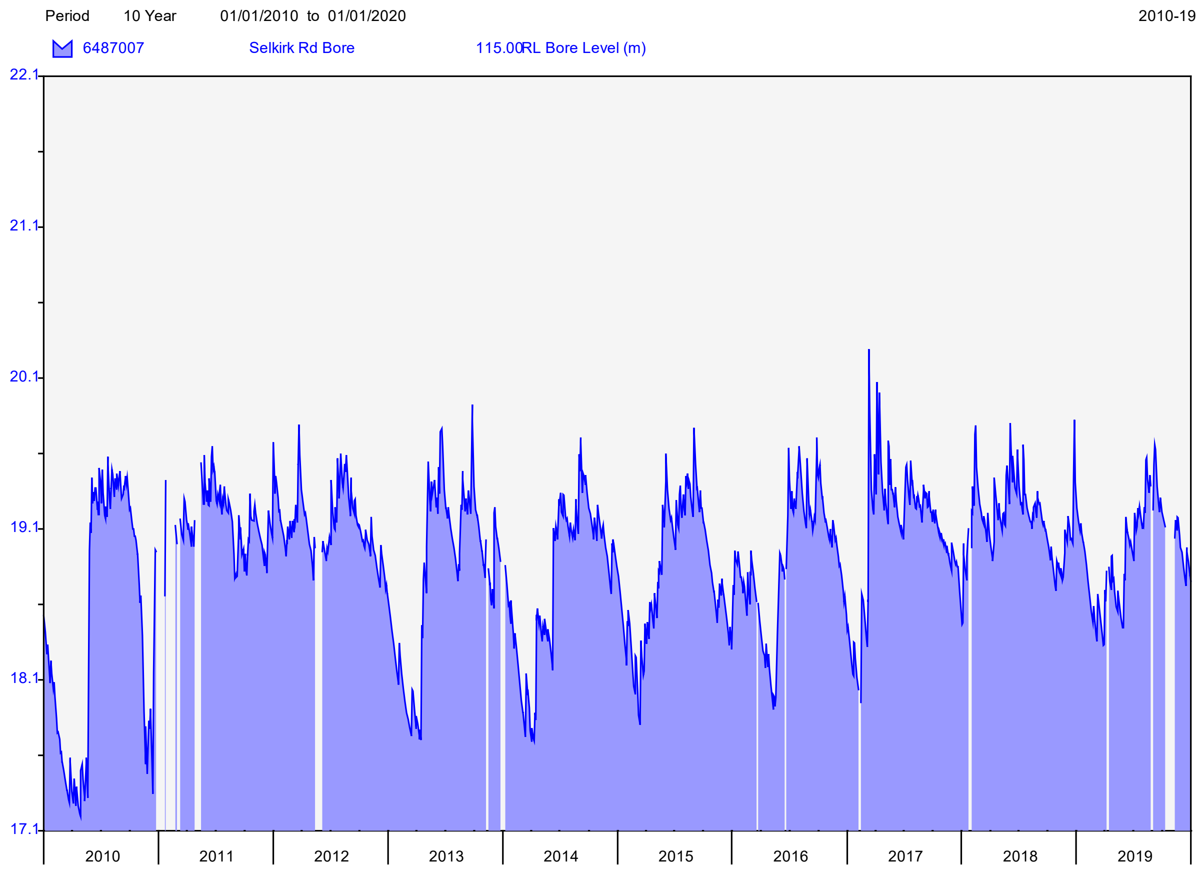

Figure 25: Groundwater level hydrograph at the Selkirk Road monitoring bore in the Western Springs volcanic aquifer.

6.5.7 Onehunga volcanic aquifer

The Onehunga aquifer is the source of drinking water for the Onehunga area, thus constituting an important resource for Auckland's municipal supply network. The groundwater levels in the Onehunga volcanic aquifer are measured in four monitoring wells. Two monitoring wells had a change in trend from the last state of the environment report: Orakau Avenue and Alfred Street. These sites both had decreasing trends in mean monthly groundwater level over the period 2010-2019.

Orakau Avenue had a decreasing trend in mean monthly groundwater level of -0.068 m/year. This site was also the only groundwater site in the network that had a decreasing trend in annual minimum groundwater level that could be reported with confidence (Sen slope -0.142 m/year). The hydrograph clearly shows higher annual minima from 2010-2012 and a significantly lower summer water level for 2019, which was the lowest water level on record up to that date (Figure 26).

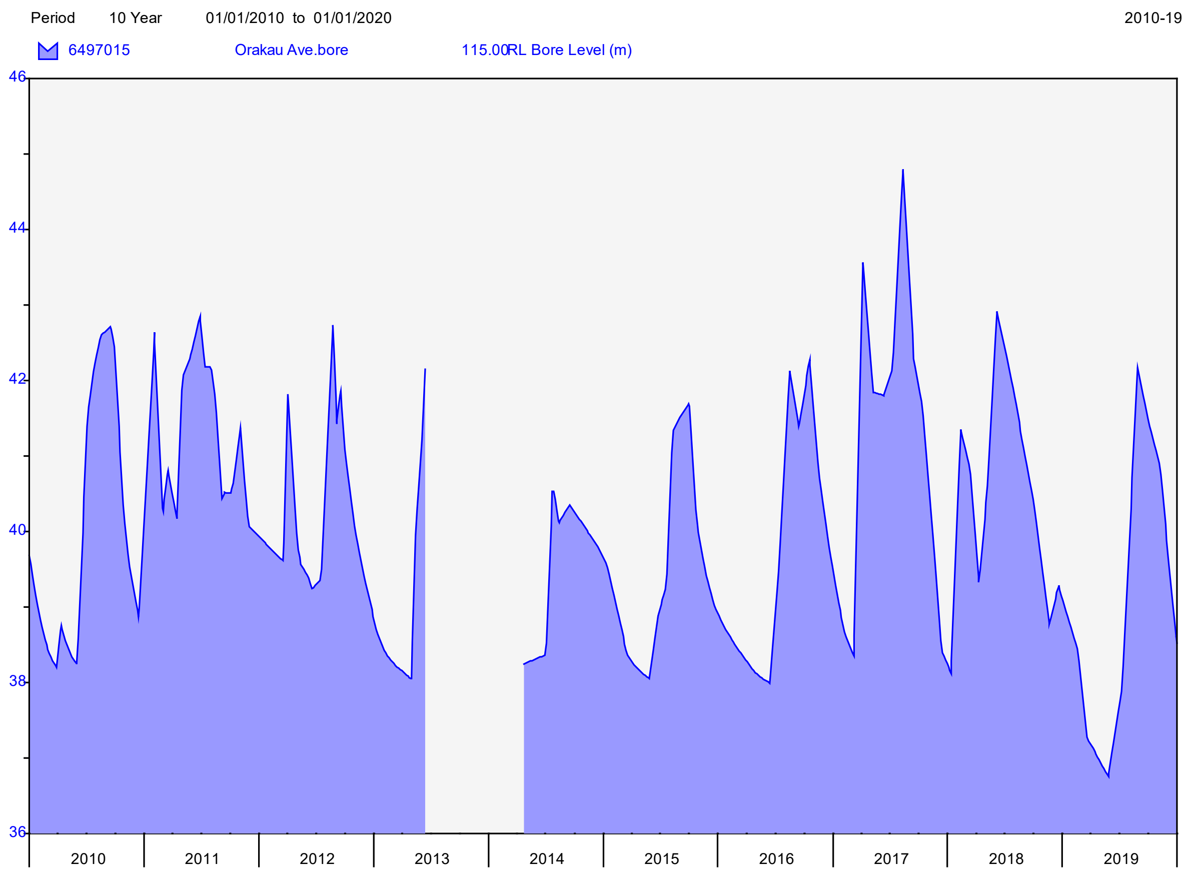

Figure 26: Groundwater level hydrograph for Orakau Ave in the Onehunga volcanic aquifer.

Albert Street had lower magnitude trends than Orakau Avenue. The monthly mean groundwater level trend from 2010-2019 was *very likely decreasing* with an annual Sen slope of -0.029 m/year, which just meets the criteria to be established with confidence (Sen slope >0.02 m/year).

The hydrograph for Alfred Street shows the annual highs generally decrease over time (Figure 27). This is confirmed by a *very likely decreasing* trend calculated for the annual maximum groundwater level at this site (Sen slope -0.037). The analysis of annual minimum groundwater levels resulted in an indeterminate trend, thus, the annual maximum is the most likely driver of the trend in the monthly mean dataset. Alfred street was the only groundwater monitoring site with a *very likely decreasing* trend in the annual maximum water level. A discussion paper addressing aquifer recharge in Onehunga is planned to be completed to address potential land cover impacts on recharge for this aquifer.

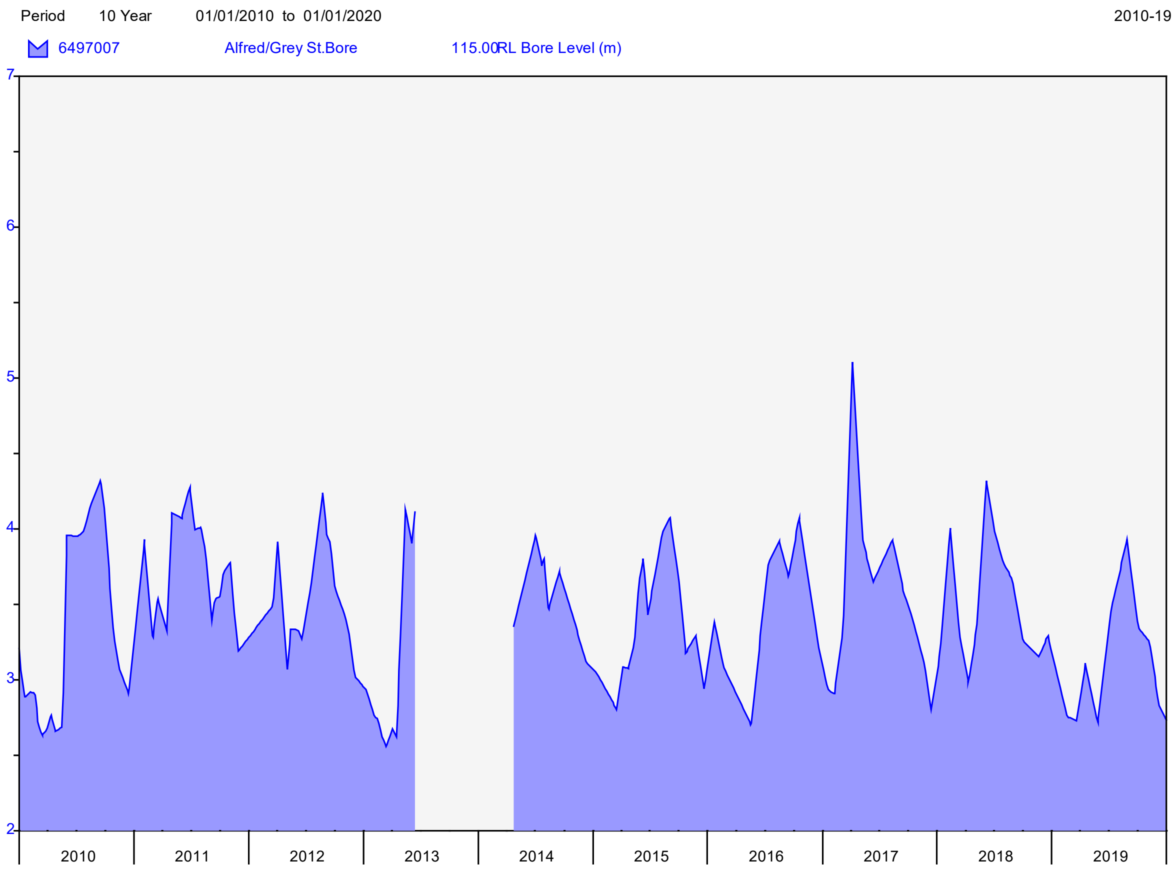

Figure 27: Groundwater level hydrograph for Alfred Street in the Onehunga volcanic aquifer.

6.5.8 Burnside Road, Clevedon East Waitematā aquifer

Burnside Road had an indeterminate trend result for the period 2006-2015 (Kalbus et al., 2017). The trend result for the period 2010-2019 showed a *very likely decreasing* trend at -0.076 m/year. A review of the hydrograph shows high groundwater levels throughout the seasonal range for 2011 and 2012 and a very low water level in early 2019 (Figure 28). Trend analysis of the annual max and annual min also resulted in decreasing trends, but at probabilities less than 0.9.

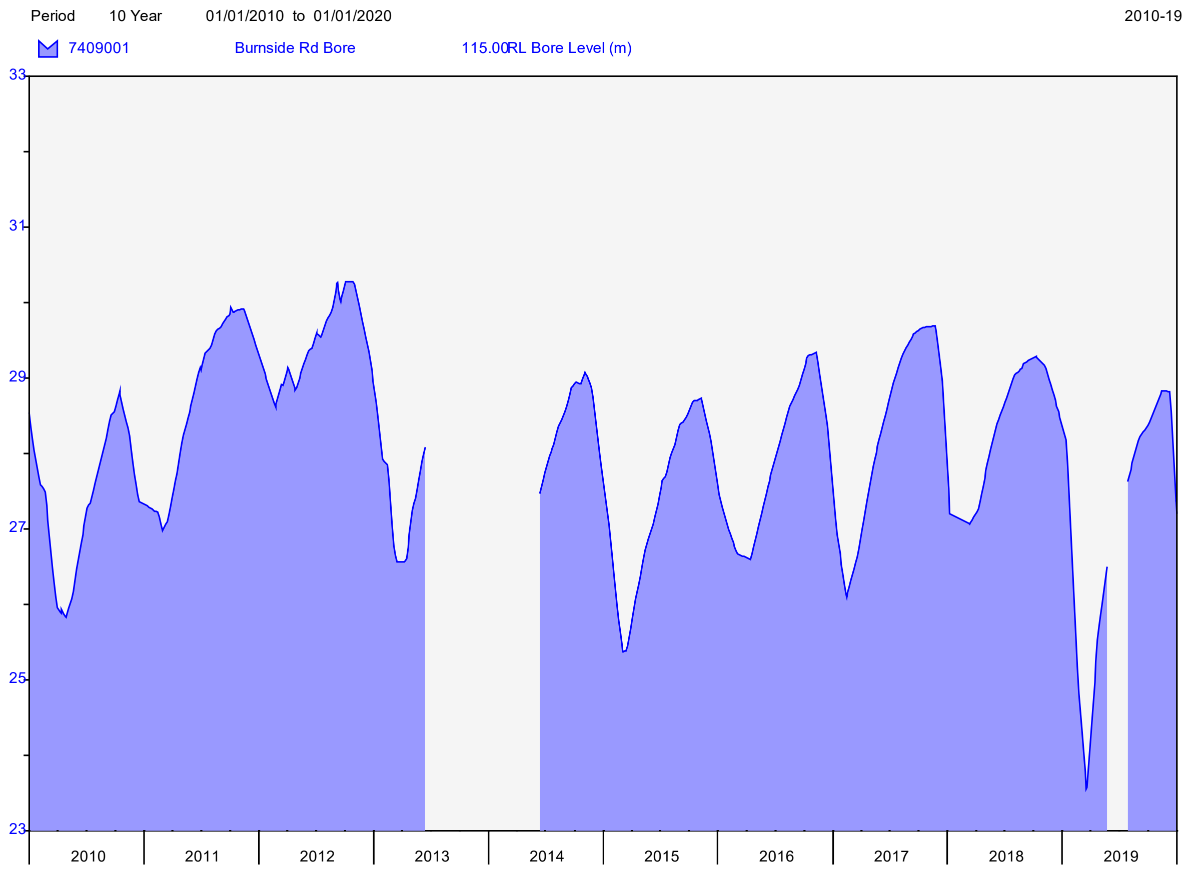

Figure 28: Groundwater level hydrograph for Burnside Road, Clevedon East Waitematā aquifer.

6.5.9 Seagrove Road, Waiau Pa Waitematā

Water level declines at Seagrove Road have been the subject of study by Auckland Council since 2010. Council staff noticed declining water levels at this site and initiated a study to better understand the drivers of the trend. The results of the study were inconclusive, with potential drivers identified as a reduction in aquifer recharge and increases in water allocation (SKM, 2010). More recent work suggests that the long-term declines are less likely a result of climatic drivers and more likely a result of water allocation and use (White, 2020).

The trend analysis of Seagrove Road by Kalbus et al. (2017) showed a decreasing trend over the period 2006-2015 of -0.154 m/year. The trend for the period 2010-2019 showed a *very likely increasing* trend with Sen slope of 0.080. Inspection of the hydrograph shows a gradual increase in water levels, particularly the annual minimum levels from 2015-2018 and also the annual maximum levels in 2017 and 2018 (Figure 29). The recent higher groundwater levels are contrary to the hypothetical connection between declining water level trends and increased water allocation.

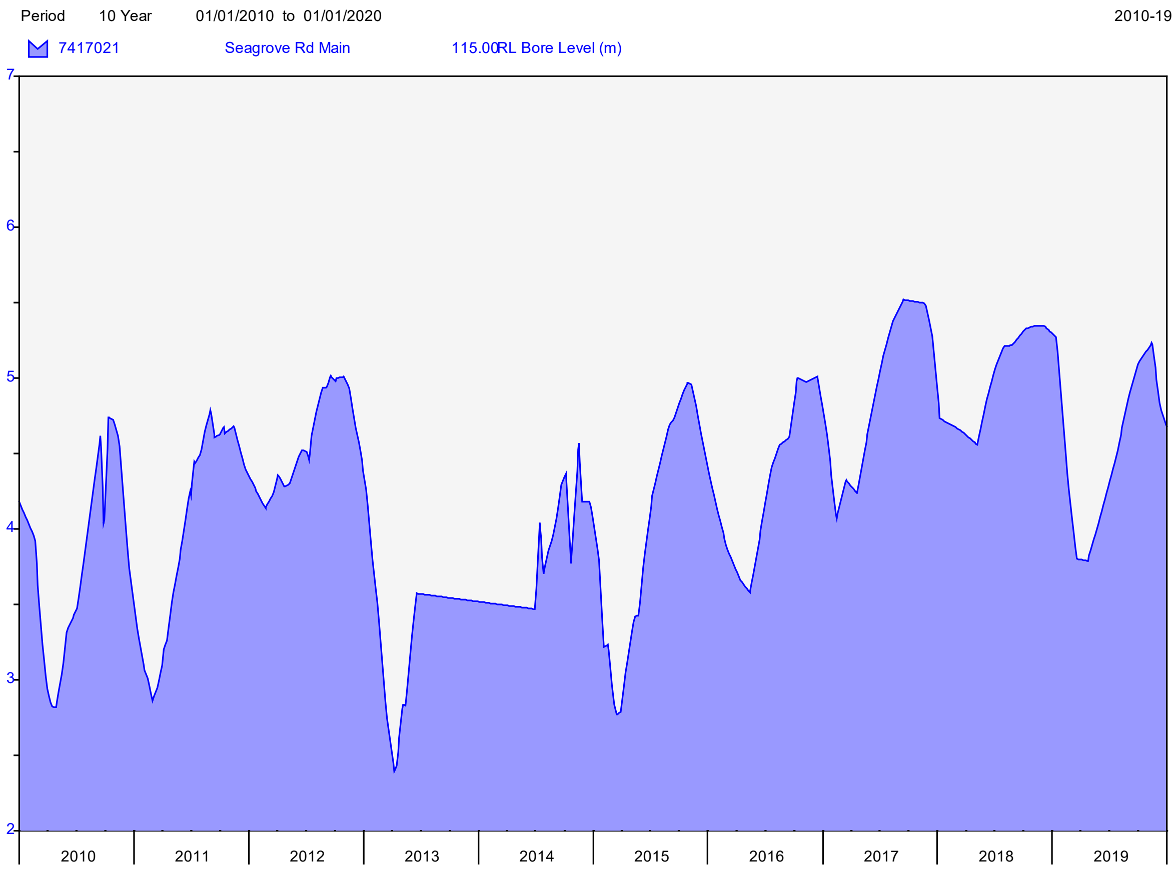

Figure 29: Groundwater level hydrograph for Seagrove Road, Waiau Pa Waitematā aquifer.

6.5.10 Diver Road, Glenbrook Kaawa aquifer

The Glenbrook Kaawa aquifer is an important water source for vegetable cropping in South Auckland and provides for rural domestic water supply and stock drinking water. This highly transmissive shell bed aquifer provides water to many growers in the area. Section 4.3 showed a decreasing trend in water level for the Glenbrook Kaawa aquifer at Diver Road. A review of the groundwater level hydrograph reveals a similar pattern to the Omaha Waitematā aquifer with a step-change of significantly lower summer water levels starting in 2016.

The water level data show that water levels were within the normal range for years prior to 2016, excluding the period of no data between June 2013 and May 2014. The comment files for Diver Road note the effects of a new water take on the groundwater level in the aquifer, starting in June 2015. The effect of the take is clearly seen in the groundwater level hydrograph following establishment of the water take (Figure 30).

A consistent pattern has been established with a new lower water level regime over summer. The winter recovery of water levels at Diver Road is at the top of the normal range (approx. +1 standard deviation), even for years with significantly lower summer water levels, indicating full winter recharge is occurring despite the decreasing trend in annual minimum water levels.

Lower water levels over summer do not necessarily equate to environmental degradation. The Kaawa does not provide direct baseflow to streams because of its confined nature, so reduced water levels in summer are unlikely to affect stream flows. Careful attention is required to monitor winter recovery and long-term water level patterns.

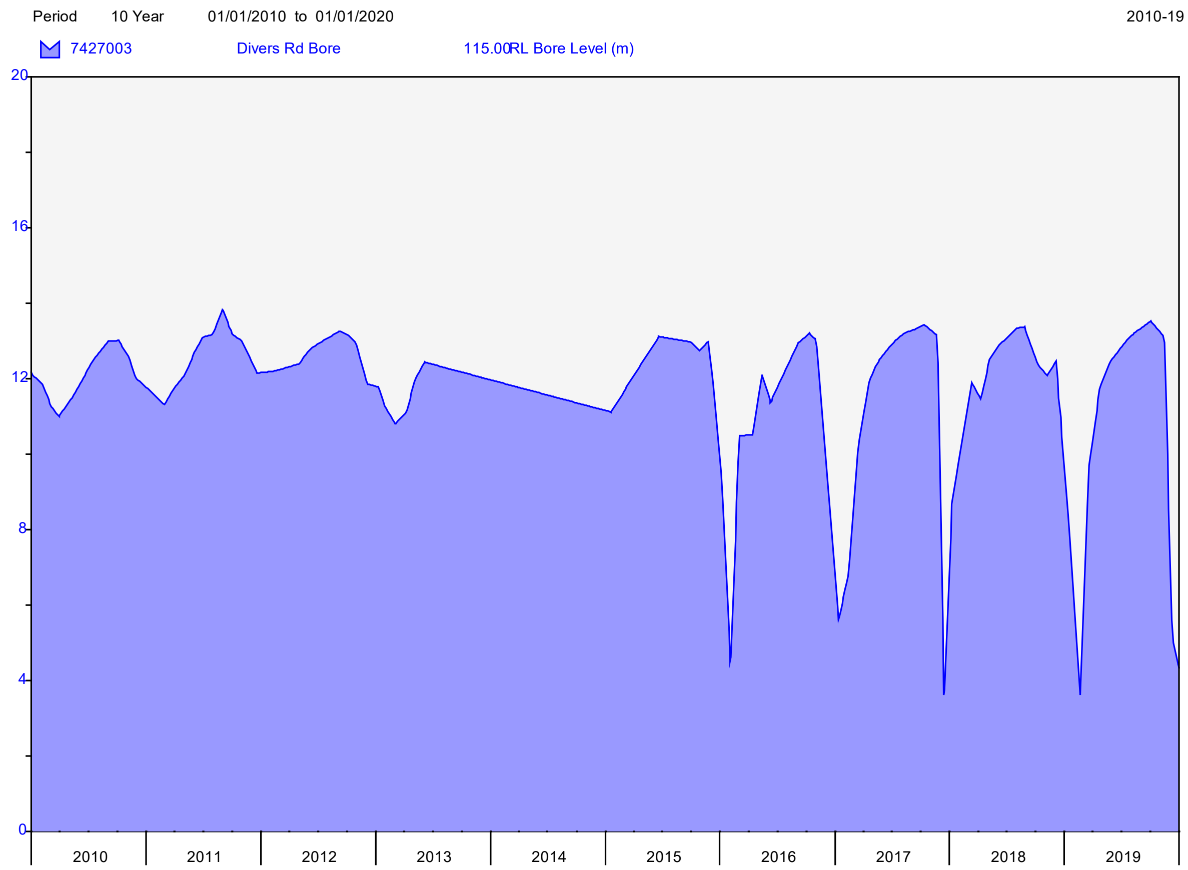

Figure 30: Groundwater level hydrograph for Diver Road in the Glenbrook Kaawa aquifer.

7 Conclusions

7.1 Rainfall

The analysis of rainfall data showed that rainfall in the years 2010 and 2019 was low (<15th percentile). Rainfall for years 2011 and 2016-2018 was high (>75th percentile). There was not a monotonic trend in the dataset that could be reported with confidence. This indicates that there was not a consistent trend in the overall climate of the region. This is supported by data on climate oscillations (IPO and ENSO), which did not show a consistent pattern with observations in rainfall. However, high rainfall years were predominant in the second half of the reporting period, including three consecutive years exceeding the 75th percentile. These high rainfall years are a likely contributing factor to the preponderance of increasing trends in river low flows and groundwater levels.

7.2 Streams

Approximately the same number of increasing and decreasing trends were calculated for high flows in streams. However, the trend results were generally not at a sufficiently high confidence level to report a rate of change. The comparison between increasing and decreasing trends showed a clear association with land cover. Catchments with urban land use had decreasing trends in the number of high flow events in 90% of cases. Stormwater management policy is a possible driver in the reduction of high flow events in urban areas, but the proportion of sites in areas with recent stormwater management initiatives does not conclusively support this hypothesis. Catchments with rural land use had increasing trends in the number of high flow events in 70% of the cases.

Low flow magnitude (7-day annual low flow) showed increasing trends at 26 of 39 sites (67%), but only two sites met the criteria to be established with confidence. Increasing trends were widespread, showing no pattern in location or catchment size. There were almost the same number of sites in rural areas as urban areas, indicating land cover was not a major driver for changes in low flows.

Analysis of low flow frequency, i.e. the number of days below the MALF and the AUP minimum flow, showed that there were less days below the MALF and AUP minimum flows for all five minimum flow sites over the last 10 years. This was consistent with predominantly increasing trends in low flow magnitude. The pattern of high and low numbers of days below minimum flow closely reflected the rainfall patterns observed, with high rainfall associated with few or no days below minimum flow and low rainfall associated with multiple days below minimum flow. The Mahurangi River showed the largest discrepancy between number of days below the MALF and number of days below the AUP minimum flow. This reflects the very low minimum flow level relative to the MALF (Mahurangi minimum flow = 42% MALF).

Rural water use and rainfall generally have an inverse relationship as the demand for water decreases when rainfall is abundant, however the degree to which water use impacts stream flows is an important consideration for the sustainable management of riverine water resources. The impacts of water use on stream flow were not presented here due to data limitations, however this is a priority for future work.

7.3 Aquifers

Increasing trends were calculated for most sites for both mean monthly (75%) and annual maximum groundwater level (62%). The distribution of wells with increasing trends did not show any pattern in location or aquifer characteristics. Higher groundwater levels may be linked to greater recharge to aquifers over the period of analysis and the widespread distribution of the trends with no pattern in location or aquifer type indicate an overall climatic driver. This is supported by the results of the rainfall analysis which showed high rainfall in the years 2011 and 2016-2018.

The analysis of annual maximum and annual minimum groundwater level proved useful to differentiate the effects of summer water use from other drivers. This showed that although annual low water levels were much lower for some wells in recent years, the annual high groundwater levels fully recovered following the summer irrigation season with a *likely increasing* trend over the same period. Using mean monthly groundwater level alone would not have revealed these patterns.

Analysis of annual minimum groundwater levels showed a strong connection of some monitoring wells with groundwater abstraction effects. Clear changes in annual minimum levels that corresponded to abstraction patterns were visible in groundwater hydrographs. Groundwater pumping effects on annual minima ruled out monotonic trends.

Monitoring wells used for the State of the Environment groundwater programme are becoming increasingly affected by summer groundwater pumping. This is evidenced clearly by Omaha Flats Bore 25 (Omaha Waitemata aquifer) and Diver Road (Glenbrook Kaawa aquifer) where the annual water level pattern changed markedly following additional pumping and installation of a new water supply well, respectively. The use of monitoring wells affected by groundwater pumping remains useful as the effects of winter recharge can still be captured. Data from wells impacted by groundwater pumping may provide new insights for future long-term reporting related to key aquifer characteristics like storativity.

7.4 Consented water allocation

Work is underway to collate a comprehensive list of water take consents data for the purposes of accounting and analysis. Several sections in this report address the potential effects of water takes that require a detailed analysis of water take data. This analysis will provide valuable context for stream flow and water level trends, particularly where decreasing trends have been observed though time.

7.5 Reporting gaps

7.5.1 Minimum flow monitoring

Auckland Council's water management regime sets limits on water use to protect the life supporting capacity of streams and other water bodies. This is accomplished through establishment of minimum flows in the Auckland Unitary Plan. Surface water abstraction must cease if flows drop below the minimum flow.

Appendix 2 of the AUP includes 11 streams with 15 minimum flows (four of the streams have two minimum flow sites, one upper catchment site, one lower). Council monitors flows in five of these streams as part of the long-term state of the environment monitoring programme. Several SOE flow monitoring sites across the region are used as a proxy for minimum flows on streams with no monitoring sites. This is detailed in individual resource consent conditions with specified correlations between flow sites. The SOE programme does not include monitoring of minimum flows for the purposes of individual consents. This function is solely the responsibility of the consent holder.

The AUP also specifies that for all other streams not specified, a minimum flow of 85% of MALF applies. The list of streams with minimum flows in the AUP is provided below. For context, the AUP minimum flow for specified streams in AUP Appendix 2 is stated as a percentage of MALF. All minimum flows in the AUP are less than the default 85% MALF level. This reflects the longer history of minimum flow setting in the Auckland region and the complexity of competing values in each catchment.

- **Waitangi Stream – actively monitored by NIWA. Min flow = 71% of MALF**
- Upper Mauku Stream
- Lower Mauku Stream
- Upper Whangamaire Stream
- Whangamaire Stream
- Whangapouri Stream (at Paerata Road)
- Whangapouri Stream (at Blackbridge Road)
- **Upper Ngakoroa Stream (at 139b Mill Road) – actively monitored by AC. Min flow = 100% of MALF**
- Lower Ngakoroa Stream (at Runciman Road)
- Hingaia Stream (at Great South Road)
- Waihoihoi Stream
- Tutaenui Stream
- **Mahurangi River – actively monitored by AC. Min flow = 42% of MALF**
- **Wairoa River – actively monitored by AC. Min flow = 77% of MALF**
- **Puhinui Stream – actively monitored by AC. Min flow = 70% of MALF**
- Hoteo River (at 47 Wilson Road)

AC actively monitors five of the sites as part of the State of the Environment programme. The Waitangi River monitoring site is maintained by NIWA with data telemetered to council.

The Hoteo River is monitored by AC, but at a site approximately 23 kilometres downstream, which is not tied to the minimum flow condition in AUP Appendix 2.

7.5.2 Physical gaps: streams

There are several stream catchments that are not currently represented in the stream flow monitoring programme. These are predominantly located in rural or coastal areas with historically less resource use pressures. As water resources become further utilised, it may be necessary to include additional sites within the SOE programme. A pragmatic trigger point might be applied whereby a stream is added to the monitoring network after a portion of the total availability is taken up.

Catchments not currently monitored for flow:

- Aotea (Great Barrier Island) streams
- Waiheke Island streams
- Poutawa Stream (Tomarata)
- Pakiri River (Pakiri)
- All South Head Peninsula streams
- Okiritoto Stream (Muriwai, West Coast)
- Anawhata Stream (West Coast)
- Piha Stream (West Coast)
- Karakare Stream (West Coast)
- Whatipu Stream (West Coast)
- Araparera River (Kaipara Harbour)
- Makarau River (Kaipara Harbour)
- Puhoi River (Hibiscus Coast)
- Waiwera River (Hibiscus Coast)
- Taitaia River (Clevedon)
- Orere River (Southeast Coast)
- Hingaia Stream (Bombay/Drury)
- Whangapouri Stream (Pukekohe)
- Whangamaire Stream (Pukekohe)
- Awhitu Peninsula streams

7.5.3 Physical gaps: aquifers

A detailed internal review of the SOE Groundwater Monitoring Network was completed in July 2020 (Johnson 2020). The review identified gaps in the network and made recommendations for reinstatement of 11 closed wells and installation of 22 new wells (Table 17). Several of the aquifers represented by the new well recommendations are now fully allocated, including all three Okahukura aquifers and the Mahurangi Waitematā.

Table 17: Recommendations for additional wells for the SOE groundwater monitoring programme, including reinstated and new wells.

Reinstated wells	New wells	
Mt Eden Volcanic	Okahukura Waitematā (2 wells)	Okahukura Kariotahi Sand
Three Kings Volcanic	Tomarata Waitematā	Okahukura Awhitu Sand
Newmarket Volcanic	Hoteo Waitematā	Franklin Southwest Waitematā
Waiheke West Greywacke (3 wells)	Mahurangi Waitematā	Kaipara Sand
Bombay-Drury Kaawa	Mahurangi East Waitematā	Mt Roskill-Mt Albert Volcanic
Bombay West Waitematā	Whangaparaoa Waitematā	Waiheke Central West Greywacke
Karaka Waitematā	Papakura West Waitematā	Te Hihi North Waitematā
Glenbrook Kaawa	Paerata Waitematā	Te Hihi South Waitematā
Glenbrook Volcanic	Pukekohe North Volcanic	Awhitu Sand
	Pukekohe South Volcanic	Awhitu Waitematā
	Pukekohe West Volcanic	Papakura Kaawa

References

Ballentine, D. J. (2012). Water quality trend analysis for the Land and Water New Zealand website (LAWNZ). NIWA Client Report HAM2012-080. Prepared for Horizons Regional Council, Palmerston North.

[1]Booker, D. J and Graynoth, E. (2008). Instream habitat and flow regime requirements in the Lower Selwyn River. Prepared for Environment Canterbury. NIWA Client Report ENC08510. ISBN:978-1-86937-778-6.

[2]Booker, D. J and Graynoth, E. (2008). Instream habitat and flow regime requirements for Birdlings Brook, the Halswell River, Harts Creek, and the Lee River. Prepared for Environment Canterbury. NIWA Client Report U08/51 ISBN:978-1-86937-913-1.

Booker, D. J and Henderson, R. D. (2019). National water allocation statistics for environmental reporting; Prepared for Ministry for the Environment. NIWA Client Report No. 2019049CH. March 2019.

Clausen, B and Biggs, B. J. F. (1997). Relationships between benthic biota and hydrological indices in New Zealand streams. Freshwater Biology 38: 327-342.

Corong, E., Hensen, M., Journeaux, P. (2014). Value of irrigation in New Zealand: and economy-wide assessment: NZ Institute of Economic Research Inc and AgFirst Consultants NZ Ltd. Final report to the Ministry for Primary Industries. Wellington (NZ). Institute of Economic Research. 64p.

Crowcroft, G and Smaill, A. (2001). Auckland. In: Rosen, M. R. and White, P. A., editors. Groundwaters of New Zealand. Wellington (NZ): New Zealand Hydrological Society. p. 303-313.

Fetter, C. W. (2001). Applied Hydrogeology (fourth edition). pp.598. Prentice Hall, Inc. Upper Saddle River, New Jersey.

Folland, C. K., Renwick, J. A., Salinger, M. J., Mullan, A. B. (2002). Relative influences of the Interdecadal Pacific Oscillation and ENSO on the South Pacific Convergence Zone. Geophysical Research Letters. Volume 29. Issue 13. Pp 21-1 to 21-4.

Franklin, P. A., Snelder, T. H., Diettrich, J and Booker, D. J. (2012). Simulating consequences of allocation limits for the Auckland region. Prepared by the National Institute of Water and Atmospheric Research for Auckland Council. Auckland Council technical report, TR2012/043.

Fraser, C and Snelder, T. (2018) State and trends of river water quality in the Manawatū-Whanganui Region: For all records up to 30 June 2017. LWP Client Report 2018-08.

Johnson, K. (2020). Groundwater State of the Environment Monitoring: A Review of Auckland's Groundwater Monitoring Network. Auckland Council internal report. July 2020.

Jowett, I. G. (1990). Factors related to the distribution and abundance of brown and rainbow trout in New Zealand clear-water rivers. New Zealand Journal of Marine and Freshwater Research 24:429-440.

Jowett, I .G., Richardson, J., Bonnet, M. L. (2005). Relationship between flow regime and fish abundances in a gravel-bed river, New Zealand Journal of Fish Biology. 66, 1419-1436.

Kalbus, E., Buckthought, L., Perks, A and Boyle, J. (2017). State of the environment: groundwater state and trends in the Auckland region 2016. Auckland Council technical report, TR2017/034.

Kelly, T. (1992). Omaha Groundwater Allocation and Management Plan 1992. Auckland Regional Council technical publication, TP06 June 1992.

Khün, M and Schöne, T. (2018). Investigation of the influence of earthquakes on the water level in the geothermal reservoir of Waiwera (New Zealand). Adv. Geosci., 45, 235-241.

McDowall, R. M. (2000). The Reed Field Guide to New Zealand Freshwater Fishes. Reed Publishing New Zealand (NZ) Ltd. 222p.

McKerchar. (2020). Flood frequency analysis; Auckland flows and levels. National Institute of Water and Atmospheric Research Ltd. Prepared for Environmental Services Limited. January 2020.

Ministry for the Environment (MfE). (1998). Flow Guidelines for Instream Values. Volume B Technical Background.

[1]NEMS. (2013). Open Channel Flow Measurement. Measurement, Processing and Archiving of Open Channel Flow Data. Version 1.1. June 2013.

[2]NEMS. (2019). Water Level. Water Level Field Measurement Standard. Version 3.0.0. July 2019.

[3]NEMS. (2019). Rating Curves. Construction of stage-discharge and velocity-index ratings. Version 2.0.0. November 2019.

Pearce, P., Bell, R., Bostock, H., Carey-Smith, T., Collins, D., Fedaeff, N., Kachhara, A., Macara, G., Mullan, B., Paulik, R., Somervell, E., Sood, A., Tait, A., Wadhwa, S., Woolley, J-M. (2020). Auckland Region climate change projections and impacts. Revised September 2020. Prepared by the National Institute of Water and Atmospheric Research, NIWA, for Auckland Council. Auckland Council technical report, TR2017/030-3

Salinger, M. J., Renwick, J. A., Mullan, A. B. (2001). Interdecadal Pacific Oscillation and South Pacific climate. International Journal of Climatology. Volume 21, Issue 14. pp1705-1721.

Scarsbrook, M. R (2006). State and trends in the National Water Quality Network (1989-2005). NIWA Client Report HAM2006-131. Prepared for Ministry of the Environment, Wellington.

SKM. (2010). Karaka North – Review of Hydrogeology. Report prepared for Auckland Regional Council. 22p.

Stansfield, B and Holwerda, N. (2015). State of the environment monitoring: Auckland water quantity statement 2012/2013. Prepared by EIA Ltd for Auckland Council. Auckland Council technical report, TR2015/005.

White, P. A., Moreau, M., Mourot, F., White, J., Johnson, K., Hill, M. (2019). Groundwater in the Franklin area. Wairakei (NZ): GNS Science. 105 p. Consultancy Report 2019/81.

White, P. A. (2020). The Waitemata Formation aquifer in South Auckland. GNS Letter Report prepared for Auckland Council. October 2020.

Wilding, T. (2018). Addendum to fish habitat modelling for the Ngaruroro and Tutaekuri rivers. Hawkes Bay Regional Council Report No. 4990 – RM 18-09. April 2018.

Wilson, K. W (2011). State of the Environment: Groundwater Quantity Technical Report. Environment Southland, Invercargill.

Appendix 1: Rain gauge site table

Name	Sub-region	Site	Easting	Northing	Start date
Leigh Rainfall	North	642701	1761548	5984703	1/01/1971
Tamahunga at Quintals Road	North	643713	1755540	5978303	18/05/1977
Hoteo at Oldfields	North	643510	1735747	5976946	25/10/1977
Mahurangi at Warkworth STP	North	644626	1750128	5970131	5/07/1921
Mahurangi at Satellite Dish	North	644616	1749240	5966835	3/07/1982
Folded Hills Farm	North	645519	1734801	5951101	3/12/1967
Orewa at Treatment Ponds	North	646619	1750205	5948366	30/11/1979
Kaipara Heads	North	644211	1710813	5967291	3/11/1971
Cutler Park	Central	649637	1748027	5939181	21/12/1999
Ararimu at Zanders	Central	647510	1738983	5936876	9/11/1978
Torbay at Glamorgan School	Central	647739	1755131	5936696	4/07/1997
Albany at Heights Road	Central	647618	1751033	5935988	21/12/1998
Rangitopuni at Walkers	Central	647614	1744793	5933070	13/09/1978
School at Mairangi Bay	Central	647737	1755968	5932097	18/05/1997
Oteha at Rosedale Ponds	Central	647727	1753163	5931755	1/06/1984
School at Paremoremo	Central	647619	1747144	5931081	1/09/1997
Kumeu at Maddrens	Central	647513	1739266	5929066	31/07/1977
Wairau at Testing Station	Central	647722	1755440	5927857	13/05/1973
Whenuapai at Airbase	Central	647601	1745482	5927516	1/09/1945
Inwards Reserve	Central	647738	1752153	5926391	18/05/1997
Hauraki Gulf at Waiheke Island	Central	A65812	1788556	5924566	3/05/1914
Plymouth Reserve	Central	648732	1759057	5924306	18/05/1997
Constable Lane	Central	648625	1746459	5923880	20/12/1999
Lincoln Park Avenue	Central	648613	1744264	5921576	12/12/1990
Albert Park	Central	648719	1757591	5920276	3/09/1962
Cox's Bay Park	Central	648733	1754176	5920115	26/08/1999
Okahu Bay Bowling Club	Central	648817	1762302	5919634	31/12/1993

Churchill Park	Central	648816	1767115	5919583	24/03/1993
Te Pai Park	Central	648626	1745568	5919279	20/12/1999
Keeling Road	Central	648612	1744707	5916831	12/12/1990
Colin Maiden Park	Central	648851	1764753	5916809	3/03/1995
Mt Albert Grammar	Central	648717	1753704	5916402	11/10/1991
Waitakere Filter Station	Central	648513	1738676	5915966	20/07/1993
Alexandra Park Runway	Central	648718	1758617	5915704	23/04/1992
Harmel Road Pump Station	Central	648614	1747875	5915584	23/01/1991
Opanuku at Candia Road	Central	648517	1744707	5915567	17/12/1999
Avondale Racecourse	Central	648615	1750345	5914938	24/08/1992
Park Village	Central	649842	1769089	5914636	24/09/1995
Anns Creek	Central	649818	1763345	5910654	21/05/1992
Rowe Street	Central	649723	1759380	5911995	7/10/1988
Harbour Road Reserve	Central	649714	1758856	5911346	21/12/1992
Bassant Reserve	Central	649836	1761088	5913759	6/03/2001
Mangemangeroa	Central	649941	1772195	5912158	8/10/2001
Botanical Gardens	Central	740945	1769930	5902091	27/03/1983
Mt Roskill Substation	Central	649713	1753684	5913432	11/09/1991
Waitakere Domain	West	648516	1737267	5920662	16/12/1999
Oratia Cemetery Oratia	West	649636	1744379	5913777	10/12/1999
Forrest Hill Road	West	649517	1741480	5913372	14/12/1999
Reservoir Bush Road	West	649516	1741261	5911171	10/12/1999
Huia Filter Station	West	649641	1746104	5910847	14/12/1990
Arataki Visitors Centre	West	649514	1743146	5909847	22/01/1975
Waharau Regional Park	East	750213	1803921	5898062	9/04/1983
Wairoa at Hunua Nursery	East	750010	1784237	5894142	6/12/1979
Awhitu at Brook Road	South	741611	1746752	5894063	31/12/1989
Whangamaire	South	741813	1763274	5882381	22/06/1992
Ngakoroa at Donovans	South	742914	1775123	5881674	22/10/1980
Waitangi at Diver Road	South	742736	1756667	5880110	30/11/1993

Appendix 2: Streams site table

Site name	Site number	Easting	Northing	Upstream catchment area (km^2)	Commenced
Tamahunga Stream	6501	1755631	5978391	8.31	23/02/1978
Mahurangi River	6863	1748589	5970087	47.20	21/04/2009
Orewa Stream	7202	1748294	5948507	9.73	20/06/1980
West Hoe Stream	7206	1748302	5950580	1.30	25/02/2003
Vaughan Stream	7506	1755422	5938731	2.79	1/09/1998
Mairangi Bay Stream	7514	1756356	5932536	1.03	9/08/2003
Taiaotea Stream	7515	1755362	5935169	2.34	9/08/2003
Awaruku Stream	7516	1755674	5937597	2.38	14/05/2004
Taiorahi Stream	7519	1756374	5933485	1.39	27/03/2006
Wairau Creek at Motorway	7604	1756064	5928087	11.33	17/03/1978
Wairau Creek at Chartwell Road	7607	1754730	5927652	2.06	14/04/1980
Eskdale Stream	7706	1752367	5926880	3.18	8/05/2005
Kaipatiki Stream	7719	1752666	5927948	1.61	8/12/2006
Rangitopuni River	7805	1744587	5933077	81.50	16/05/1975
Oteha Stream	7811	1751328	5933522	12.31	13/12/1979
Lucas Creek	7830	1751468	5934510	6.47	11/10/2006
Alexandra Stream	7834	1752378	5932435	3.52	14/12/1979
Opanuku Stream at Candia Road	7904	1742162	5915566	16.13	8/08/2006
Swanson Stream	7907	1743783	5919897	23.20	3/02/1994
Oratia Stream	7911	1745527	5916175	28.80	22/06/1999
Opanuku Stream at Vintage Reserve	7912	1744587	5917203	24.60	23/06/1999
Whau Stream	8006	1751679	5913591	4.36	9/09/2005
Motions Stream	8104	1753745	5918720	3.55	27/03/1990
Meola Stream	8106	1753197	5918529	14.89	3/04/1998
Newmarket Stream	8176	1759168	5918606	6.86	9/05/2006
Otara Stream	8208	1767628	5908076	18.94	28/04/1992
Tamaki Stream Tributary	8222	1764880	5912818	2.99	14/04/2006

Site name	Site number	Easting	Northing	Upstream catchment area (km^2)	Commenced
Mangemangeroa Stream	8301	1772887	5908834	4.43	14/07/2000
Wairoa River	8516	1782663	5901676	150.60	13/02/1979
Mangawheau Stream	8529	1783781	5891411	30.93	15/06/1988
Waitangi Stream	43602	1755195	5878315	18.48	1/04/1966
Papakura Stream	43803	1769579	5899729	41.40	16/06/1969
Puhinui Stream	43807	1766420	5904316	12.86	6/12/1978
Ngakaroa Stream	43829	1775153	5881619	4.95	28/03/1980
Kaipara River	45311	1733345	5930348	155.30	6/10/1978
Ararimu River	45326	1734999	5932630	66.80	14/12/1983
Kaukapakapa Stream	45415	1735809	5945031	62.30	4/07/1994
Hoteo River	45703	1735424	5972357	276.56	10/06/1977
Waiteitei River	45705	1742460	5985481	80.86	21/02/1996

Appendix 3: Groundwater site table

Site name	Site number	Easting	Northing	Aquifer	Total depth (m)	Casing depth (m)	Casing Ø (mm)	Record start	Confine-ment	Recording	Freq.
Quintals Road Omaha	6437005	1755760	5978227	Omaha Waitematā	129.6	94	200	3/02/1977	confined	manual	monthly
Omaha Flats Bore 25	6437021	1756485	5977154	Omaha Waitematā	90	34	100	7/12/1977	confined	automatic	15-minute
Caroline Heights	6437087	1759338	5977414	Omaha Waitematā	188	131	100	31/05/1993	confined	manual	monthly
Waiwera Beachfront Deep	6457041	1752868	5954102	Waiwera geothermal	407		100	30/11/1976	confined	automatic	15-minute
Waiwera Beachfront Shallow	6457097	1752873	5954101	Waiwera geothermal	52	30	100	10/12/1997		automatic	15-minute
Parakai Bore 86	6464007	1728297	5941883	Parakai geothermal	249	100	200	13/06/1984	confined	automatic	15-minute
Rimmer Road	6464089	1726124	5939301	Kaipara sand	63.5	49.5	100	15/04/1997	unconfined	manual	monthly
Waitakere Road #2	6474003	1739082	5927989	Kumeu West Waitematā	150	78	100	5/08/1998	confined	automatic	15-minute
Selaks Bore	6475003	1740754	5927896	Kumeu East Waitematā	299	101	100	12/02/1986	confined	manual	monthly
Trigg Road	6475005	1736310	5928959	Kumeu West Waitematā	248	71	100	11/01/1989	confined	manual	monthly
Short Road	6475157	1741716	5929638	Kumeu East Waitematā	242	91.5	100	10/09/1996	confined	manual	monthly
Nick Johnstone Drive	6479007	1778056	5926955	Waiheke West greywacke	88.5	42	100	11/03/2006		manual	monthly
Volcanic Street	6487001	1755313	5915915	Onehunga volcanic	10.5	7	50	14/11/1996	unconfined	manual	monthly
Selkirk Road	6487007	1754021	5917236	Western Springs volcanic	25.5			13/11/1996		automatic	15-minute
Leslie Road	6487009	1754679	5917291	Western Springs volcanic	24.3	18.3	50	13/11/1996	unconfined	automatic	15-minute
Chamberlain Park	6487021	1753511	5918278	Western Springs volcanic				15/06/1998		manual	monthly
PD-13S	6488045	1763376	5915230	Mt Wellington volcanic	23.5	22.5	50	11/12/1991	unconfined	manual	monthly
Alfred Street	6497007	1759789	5912783	Onehunga volcanic	40	24	50	6/06/1989		manual	monthly
Waikaraka Cemetery	6497013	1759920	5911507	Onehunga volcanic	15.9	9.9	50	21/06/1993	unconfined	manual	monthly
Orakau Avenue	6497015	1757832	5914770	Onehunga volcanic	47.8	41.8	50	14/11/1996		manual	monthly

Site name	Site number	Easting	Northing	Aquifer	Total depth (m)	Casing depth (m)	Casing Ø (mm)	Record start	Confine-ment	Recording	Freq.
Amelia Earhart	6497017	1758649	5905851	Mangere-Manurewa Kaawa	50.6	42.6	50	25/03/1997		manual	monthly
Tiwai Road	6497019	1758791	5913752	Onehunga volcanic	58.53	46.53	50	8/04/1997		manual	monthly
Angle Street	6498003	1760820	5911670	Mt Wellington volcanic	25	9.78	100	6/06/1989	unconfined	automatic	15-minute
Mako Road	6570013	1779254	5927093	Waiheke West greywacke	117	106	25	16/03/2006	confined	manual	monthly
Tawaipareira	6570015	1783160	5925794	Waiheke Central West greywacke	60	53.5	100	12/02/2007	confined	automatic	15-minute
Mt Richmond	6594001	1764001	5911038	Mt Richmond volcanic	42.6	30.27	150	9/08/2001		manual	monthly
Burnside Road	7409001	1777680	5900303	Clevedon East Waitematā	169	154.2	100	10/07/1985	confined	manual	monthly
Bullens Road	7409011	1775849	5899165	Clevedon West Waitematā	75	38.9	100	21/06/1993	confined	manual	monthly
Glenbrook Hall	7417001	1756247	5882259	Glenbrook Kaawa	103.7		115	16/03/1970	confined	manual	monthly
Seagrove Road	7417021	1756024	5889134	Waiau Pa Waitematā	201	97.8	100	8/08/1991	confined	manual	monthly
Waiau Pa Bore 2C	7418003	1758131	5887101	Glenbrook Kaawa	43.8	34.7	200	18/04/1980	confined	manual	monthly
Batty Road	7418013	1763756	5889684	Glenbrook Kaawa	50	41.4	100	20/12/1985	confined	manual	monthly
Ostrich Farm Road #2	7418023	1766027	5885160	Pukekohe Kaawa	47.6	46	80	20/12/1985	confined	manual	monthly
Ostrich Farm Road Observation	7418027	1766016	5885089	Pukekohe Kaawa	84	68	80	20/12/1985	confined	manual	monthly
Tuhimata Road	7419003	1770320	5884982	Pukekohe Kaawa	114.2	67.6	100	3/12/1986	confined	manual	monthly
Fielding Road Sand	7419007	1774443	5890653	Bombay-Drury sand	64	57	100	4/04/1989	semi-confined	manual	monthly
Fielding Road Volcanic	7419009	1774447	5890664	Bombay-Drury volcanic	46.7	16.3	150	4/04/1989	unconfined	manual	monthly
Cooper Road	7419011	1773758	5886862	Bombay-Drury Kaawa	120.6	108.4	100	16/01/1990	confined	manual	monthly
Fielding Road Waitemata	7419013	1774438	5890637	Bombay-Drury Waitematā	273	157	100	24/04/1991	confined	manual	monthly
Karaka #2	7419119	1767829	5892996	Karaka Waitemata	207	91.2	100	12/03/1992	confined	automatic	15-minute
Diver Road	7427003	1756683	5880119	Waiuku Kaawa	218	173	100	27/08/1985	confined	manual	monthly

Site name	Site number	Easting	Northing	Aquifer	Total depth (m)	Casing depth (m)	Casing Ø (mm)	Record start	Confine-ment	Recording	Freq.
Maraeorahia	7427005	1752381	5877971	Awhitu Kaawa	62	51.5	100	5/01/1987	confined	automatic	15-minute
Pukekohe DSIR	7428043	1765111	5881260	Pukekohe central volcanic	96.3	73	150	26/04/1979	confined	manual	monthly
Mauku Main	7428047	1760994	5881217	Glenbrook Kaawa	194.7	156	150	17/04/1985	confined	automatic	15-minute
Rifle Range Deep	7428103	1766258	5880972	Pukekohe central volcanic	90	78	50	24/04/1997	confined	manual	monthly
Rifle Range Shallow	7428105	1766250	5880967	Pukekohe central volcanic	42	30	50	24/04/1997	unconfined	manual	monthly
Revell Court	7429011	1768376	5879583	Pukekohe central volcanic	54.6	10.4	150	14/08/1979	unconfined	automatic	15-minute
Douglas Road Volcanic	7429013	1766160	5879366	Pukekohe central volcanic	108.2	71	100	6/06/1980	confined	automatic	15-minute
Wooten Road	7510005	1778058	5883662	Bombay volcanic	76.5	58.3	100	15/12/1991		manual	monthly

Appendix 4: Groundwater state summary statistics (2015-2019)

Site name	Site number	Minimum	Maximum	Mean	Median	95th percentile	75th percentile	25th percentile	5th percentile	Standard deviation	Inter-quartile range
Quintals Road Omaha	6437005	5.024	7.843	6.924	7.022	7.813	7.568	6.354	5.424	0.740	1.215
Omaha Flats Bore 25	6437021	0.951	4.911	3.905	4.350	4.873	4.712	3.470	1.086	1.101	1.242
Caroline Heights	6437087	-0.773	1.574	0.896	1.310	1.556	1.506	0.467	-0.599	0.745	1.040
Waiwera Beachfront Deep	6457041	0.926	2.872	1.690	1.598	2.856	2.046	1.112	0.960	0.649	0.934
Waiwera Beachfront Shallow	6457097	0.931	2.81	1.646	1.549	2.800	2.009	1.120	0.958	0.591	0.889
Parakai 86	6464007	1.639	3.949	2.951	3.081	3.748	3.467	2.634	1.678	0.620	0.833
Rimmer Road	6464089	3.823	4.861	4.511	4.566	4.817	4.674	4.383	3.947	0.244	0.291
Waitakere Road #2	6474003	6.851	28.089	19.156	19.874	26.341	23.040	16.356	10.301	4.979	6.684
Selaks Bore	6475003	19.422	26.056	23.885	24.196	25.877	25.205	22.594	21.014	1.594	2.611
Trigg Road	6475005	20.215	22.006	21.236	21.247	21.992	21.596	20.856	20.424	0.475	0.740
Short Road	6475157	10.482	20.282	17.338	18.246	20.076	19.210	16.035	12.026	2.515	3.176
Nick Johnstone Drive	6479007	29.847	32.812	31.126	31.026	32.589	31.971	30.298	29.901	0.914	1.673
Volcanic Street	6487001	37.714	39.722	38.408	38.239	39.343	38.921	37.836	37.721	0.584	1.085
Selkirk Road	6487007	18.062	19.489	18.983	19.113	19.453	19.267	18.736	18.242	0.369	0.531
Leslie Road	6487009	25.905	29.187	27.952	28.312	29.046	28.637	27.336	26.339	0.878	1.301
Chamberlain Park	6487021	10.6	11.526	11.138	11.206	11.473	11.314	10.925	10.693	0.242	0.389
PD-13S	6488045	19.56	25.565	21.819	21.638	24.203	22.698	20.721	19.877	1.386	1.978
Alfred Street	6497007	2.753	4.497	3.392	3.288	4.085	3.741	3.064	2.842	0.414	0.677
Cemetery Bore	6497013	0.986	2.276	1.761	1.776	2.053	1.927	1.629	1.395	0.227	0.298
Orakau Ave	6497015	36.868	44.043	39.975	39.744	42.678	41.359	38.590	37.389	1.661	2.769
Amelia Earhart	6497017	2.686	3.713	3.276	3.324	3.676	3.485	3.074	2.773	0.274	0.411
Tiwai Road	6497019	14.63	17.942	15.807	15.837	17.172	15.982	15.445	15.067	0.568	0.537
Angle Street	6498003	2.343	2.672	2.512	2.511	2.634	2.561	2.453	2.376	0.079	0.108
Tawaipareira	6570015	2.016	3.432	2.796	2.771	3.350	3.116	2.571	2.088	0.375	0.545
Mt Richmond	6594001	-6.906	-2.979	-5.033	-4.815	-3.136	-3.992	-6.523	-6.870	1.350	2.531

Site name	Site number	Minimum	Maximum	Mean	Median	95th percentile	75th percentile	25th percentile	5th percentile	Standard deviation	Inter-quartile range
Burnside Road	7409001	23.997	29.67	27.805	28.004	29.499	28.707	27.017	25.600	1.243	1.690
Bullens Road	7409011	21.145	23.892	22.844	22.863	23.820	23.265	22.411	21.620	0.615	0.854
Glenbrook Hall	7417001	7.594	9.093	8.290	8.317	9.007	8.557	8.112	7.656	0.369	0.445
Seagrove Road	7417021	2.886	5.512	4.555	4.658	5.443	5.021	4.140	3.342	0.639	0.881
Waiau Pa Bore 2C	7418003	8.994	14.216	12.439	12.659	13.977	13.389	11.608	10.459	1.176	1.781
Batty Road	7418013	21.877	23.167	22.515	22.523	23.100	22.747	22.278	21.926	0.361	0.469
Ostrich Farm Road #2	7418023	19.613	21.824	20.507	20.496	21.067	20.726	20.240	19.887	0.421	0.486
Ostrich Farm Road Observation	7418027	19.883	21.105	20.522	20.533	21.020	20.801	20.261	19.979	0.332	0.540
Tuhimata Road	7419003	23.057	24.672	23.968	23.997	24.563	24.276	23.664	23.275	0.401	0.613
Fielding Road Sand	7419007	5.611	12.463	9.521	9.622	12.131	11.102	7.939	6.767	1.795	3.163
Fielding Road Volcanic	7419009	13.672	16.339	15.213	15.269	16.272	15.893	14.608	14.120	0.717	1.285
Cooper Road	7419011	13.663	27.049	18.322	18.009	22.906	18.965	16.950	15.328	2.303	2.015
Fielding Road Waitemata	7419013	11.388	12.51	12.031	12.068	12.444	12.298	11.775	11.483	0.312	0.522
Karaka #2	7419119	3.441	5.069	4.376	4.457	4.992	4.769	3.984	3.532	0.465	0.785
Divers Road	7427003	4.953	13.441	11.407	12.207	13.361	12.953	10.812	6.043	2.209	2.142
Maraeorahia	7427005	1.385	2.826	2.358	2.463	2.801	2.704	2.063	1.569	0.417	0.641
Pukekohe DSIR	7428043	48.553	51.133	49.829	49.728	51.011	50.409	49.231	48.734	0.731	1.178
Mauku Main	7428047	25.761	28.237	27.287	27.406	28.109	27.747	26.867	26.243	0.585	0.880
Rifle Range Deep	7428103	44.709	51.079	49.193	49.362	50.714	49.995	48.492	47.427	1.134	1.503
Rifle Range Shallow	7428105	55.535	59.178	57.562	57.797	58.898	58.201	56.884	55.818	0.931	1.317
Revell Court	7429011	61.808	64.781	63.344	63.320	64.462	63.997	62.721	62.081	0.752	1.276
Douglas Road Volcanic	7429013	49.029	52.547	51.050	51.194	52.421	51.794	50.335	49.393	0.959	1.459
Wooten Road	7510005	154.232	158.807	156.935	156.874	158.536	157.892	156.099	155.663	1.019	1.793

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