Groundwater Quality State and Trends in Tāmaki Makaurau / Auckland 2010-2019. State of the Environment Reporting

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February 2021

Technical Report 2021/03

Research and Evaluation Unit
RIMU

Auckland Council
Te Kaunihera o Tāmaki Makaurau

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ISSN 2230-4525 (Print)
ISSN 2230-4533 (Online)

ISBN 978-1-99-002288-3 (Print)
ISBN 978-1-99-002289-0 (PDF)

This report has been peer reviewed by the Peer Review Panel.
Review completed on 5 February 2021 Reviewed by two reviewers
Approved for Auckland Council publication by: Name: Eva McLaren Position: Manager, Research and Evaluation (RIMU)
Name: Jonathan Benge Position: Manager, Water Quality (RIMU)
Date: 5 February 2021

Recommended citation
Foster, C and K Johnson (2021). Groundwater quality state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting. Auckland Council technical report, TR2021/03

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Fielding Road – Bombay Drury Sand aquifer, groundwater quality monitoring well. Photograph by Courtney Foster

Executive summary

Auckland Council regularly monitors groundwater quality (physical, chemical and microbiological parameters) within some of the region's aquifers as part of its State of the Environment programme. The primary purpose of the groundwater quality monitoring programme is to regularly assess and report the current state and long-term trends for groundwater quality in aquifers across the region.

This reporting is driven by requirements under the Resource Management Act 1991 and the National Policy Statement for Freshwater Management 2020 (NPS-FM, 2020). Water quality is reported against all relevant New Zealand standards. Results relating to the Drinking Water Standards New Zealand do not comprise a compliance-level assessment but are provided for a comprehensive assessment of the current state of groundwater resources. The results from State of the Environment monitoring are used to inform management of potable drinking water supplies and rural productive land use activities, for evidencing the efficacy of urban stormwater and wastewater management, and to inform the management of the flow-on effects on ecosystem health of streams with high groundwater baseflow.

Sites in the Auckland Council groundwater quality monitoring network are grouped by aquifer type and primary water quality stressor. Urban shallow volcanic aquifers are predominantly affected by stormwater and wastewater, and aquifers in the Franklin (shallow volcanic and shallow and deep sedimentary aquifers) and Kumeu (shallow and deep sedimentary aquifers) areas are predominately affected by rural activities such as fertiliser leaching.

Shallow volcanic aquifers in the Franklin area are affected by high nitrate relating to horticultural land use. The National Policy Statement for Freshwater Management 2020 does not include a National Objectives Framework (NOF) for nitrate in groundwater, however the surface water NOF is relevant to aquifers which provide baseflow to streams. Six groundwater sites in the Franklin area had nitrate levels above the surface water NOF grade D ('Acute'), these sites are in shallow oxygenated volcanic aquifers that contribute high baseflow to nearby streams. Long-term trends (10 years, 2010-2019) for nitrate show *very likely* improving trends at four of these sites and *likely* to *very likely* degrading trends at the other two sites. Three further sites in the Franklin area, representing deeper aquifers with less oxygenated waters, have no signs of nitrate contamination.

Two sites in the Kumeu West Waitematā aquifer had generally good groundwater quality. Results showed that groundwater in this aquifer was below guideline values for human consumption and did not pose a risk to ecosystem health. Nitrate was very low (five-year median of 0.01 mg/L); however, one site had a *likely* degrading trend. Ammonia levels were low and trends in ammonia were *very likely* improving at both sites.

Nitrate exceeded expected natural conditions in the Three Kings Volcanic aquifer, which suggests land use practices are impacting the aquifer. The Three Kings Aquifer is the baseflow source for Western Springs Lake and Motions Stream and likely to be one source of nitrate contamination in surface waters. *E. coli* (a faecal indicator bacteria) was present

in groundwater samples for the Three Kings volcanic aquifer, most likely linked to stormwater and wastewater leakage in urban areas. The long-term trend in *E. coli* was *likely* degrading, which indicates faecal bacterial contamination is likely increasing in this aquifer.

Zinc concentrations in the Three Kings Volcanic aquifer exceeded the Australia and New Zealand Environmental Conservation Council (ANZECC) ecosystem health trigger value for surface water, suggesting that groundwater baseflow to Motions Stream may contribute zinc contamination to the stream. Reporting in 2017 showed no zinc exceedances at this site, suggesting potentially increasing zinc contamination over recent years. Previous reporting showed median zinc values in other Auckland isthmus aquifers (Onehunga Volcanic and Mt Richmond Volcanic) also exceeded ANZECC ecosystem health guidelines for surface water, indicating a link between urban sites and zinc contamination.

Overall, results from the groundwater quality monitoring programme indicate that nitrate is the foremost contaminant of concern for shallow volcanic aquifers in the Auckland region. High nitrate observed in groundwater coincides with both horticultural and urban land uses. The levels of nitrate observed exceeded expected concentrations for natural conditions, New Zealand drinking water standards, and the NOF national bottom line for surface water ecosystem health. Trends in nitrate were predominantly improving in the Franklin shallow volcanic aquifers, but degrading trends were observed in the Bombay Volcanic and Drury Volcanic aquifers. These aquifers provide baseflow to streams, suggesting that groundwater baseflow contributes to nitrate contamination in Franklin streams.

Additional monitoring sites will be added to the programme over the next three years to improve coverage of Auckland's Aquifer Management Areas and further strengthen our understanding of the effects of land use, climate change, and water abstraction on groundwater quality.

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1 Introduction

Auckland's freshwater environments are valued by the people of Auckland. Wai (water) holds special significance to Māori. Mana whenua whakapapa to significant water bodies and have kaitiaki obligations to protect them. This is part of the customary practice of taonga tuku iho (protecting treasures or taonga passed down from previous generations).

The availability of groundwater as a water source depends on many factors including climate (rainfall) and geology. Formations of sand or rock that hold a usable amount of groundwater are known as aquifers. Groundwater is water that is held within the tiny pores between grains of sand and cracks in rocks underground. 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 people as a source of water.

The geology of the Auckland region comprises greywacke basement rocks overlain by a succession of marine sedimentary formations, overlain by a thin sequence of terrestrial and shallow marine sediments found mainly in coastal and lowland areas, and intrusive volcanic rocks (Ballance, 1976). In much of the Auckland region, Miocene marine sedimentary rocks form the functional basement (where depth to greywacke exceeds 1000m). Intermittent volcanic activity formed much of the Waitākere Ranges, Aotea/Great Barrier Island, Te Hauturu-o-Toi/Little Barrier Island, the South Auckland Volcanic Field, and the Auckland (Isthmus) Volcanic Field (Edbrooke, 2001).

Except for localised basalt and shell bed deposits, aquifers in the Auckland region are low yielding compared with other parts of New Zealand (Crowcroft & Smaill, 2001), yet they are an important water source for many rural areas and for some industries. Groundwater can be the sole source of water to some rivers, streams, and wetlands across the region for extended periods. Intensification or change in land use poses a potential threat to the sustainability of groundwater resources for both water quantity and water quality.

Every three months Auckland Council samples 16 groundwater wells in specific parts of the region where groundwater quality is thought to be potentially at risk, or as part of the National Groundwater Monitoring Programme (Rosen, 1989). The state and trends in Auckland's groundwater resource were last reported by Auckland Council in 2017 for groundwater quality data collected up until 2013 (Kalbus et al., 2017). This report provides an updated assessment of groundwater quality using data for the most recent 10-year period from 2010 to 2019.

1.1 Purpose and objectives

Auckland Council's groundwater quality monitoring programme supports the following objectives:

- Meet council's obligations under section 35 of the Resource Management Act 1991 (as amended) to monitor and report on the state of the environment, with specific regard to groundwater quality.
- Provide evidence of how the council is maintaining and enhancing the quality of Auckland's groundwater environments (Local Government Act, 2002). Specifically, evidence for the Environment and Cultural Heritage component of the Auckland Plan 2050. A key direction for the region is to manage the effects of growth and development on our natural environment.
- Help inform the efficacy and efficiency of council policy initiatives and strategies.
- Assist with the identification of large scale and/or cumulative impacts of contaminants associated with different land uses and disturbance regimes and correlative links to specific activities.
- Provide regionally specific baseline data to underpin sustainable management through resource consenting and associated compliance monitoring for groundwater environments.
- Help identify the possible standard of future groundwater quality in Auckland.
- Continuously increase the knowledge base for Aucklanders and promote awareness of regional groundwater quality issues and their subsequent management.

1.1.1 Supporting reports

Previous reports are available on Auckland Council's Knowledge Auckland website, www.knowledgeauckland.org.nz.

Supplementary data files of the trend analysis outputs presented in this report are also available on Knowledge Auckland. For further enquiries and data supply, email environmentaldata@aucklandcouncil.govt.nz.

Microbiological contamination of beaches and recreational water quality are monitored through the Safeswim programme, www.safeswim.org.nz.

This report is one of a series of publications prepared in support of the State of the Environment report for Tāmaki Makaurau / Auckland. Reports on aspects of freshwater and coastal water quality and ecology include:

- *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
- *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
- *Marine sediment contaminant state and trends in Tāmaki Makaurau / Auckland 2004-2019. State of the environment reporting* – TR2021/10
- *Rainfall, river flow, and groundwater level state and trends in Tāmaki Makaurau / Auckland 2010-2019. State of the environment reporting* – TR2021/06
- *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.

2 Groundwater quality programme

2.1 Current groundwater quality network

The Auckland region is divided into Aquifer Management Areas (AMA) for water allocation purposes. AMAs act as a proxy for independent groundwater bodies, allowing each AMA to be managed independently based on water availability and water use. AMAs thus represent the areal extent of aquifers as they are managed for allocation purposes. AMAs were defined based on known geological boundaries, measured or modelled groundwater levels and flow paths, and/or surface water catchment boundaries (surface water catchment boundaries were used where aquifers are widespread, e.g., Waitematā group aquifers). The aquifers in the Auckland region (and those included in the SOE monitoring programme) are used for many purposes including industry, irrigation, stock drinking water, and domestic supply.

Auckland Council's groundwater quality monitoring programme was established in 1998 and was designed to detect long-term changes across the Auckland region. The programme comprised 27 sites across the region including National Groundwater Monitoring Programme (NGMP) sites managed by Geological and Nuclear Science (GNS). Groundwater samples were taken from bores at 24 sites (representing 18 aquifers) and from three groundwater fed surface springs.

The groundwater quality monitoring programme was suspended in June 2013 due to budget constraints. In mid-2014, an interim plan for groundwater quality was enacted and monitoring resumed.

This interim monitoring plan simplified the programme to:

- prioritise monitoring in aquifers where change in groundwater quality was suspected (e.g., unconfined or semi-confined shallow aquifers)
- standardise the water quality parameter test profile across all aquifers
- align the frequency of sampling, to test all aquifers on a quarterly basis, which aligns with the frequency of samples required for the NGMP[1] undertaken by GNS Science.

Site selection at that time was based on the following criteria:

- continued monitoring of sites required by GNS for the National Groundwater Monitoring Programme
- retention of monitored aquifers exhibiting change or interpreted as being under pressure, generally relying on knowledge of land use activities at the time; namely aquifers in Franklin known to be impacted by horticultural activities (as summarised in Meijer et al., 2016), and urban sites susceptible to stormwater/wastewater infiltration with potentially high metal and microbial concentrations (Lewis, et al., 2015).

[1] RIMU staff collect water quality samples from these aquifers and send them to GNS for testing at the Wairakei Analytical Laboratory

Auckland Council currently monitors groundwater quality in eight aquifers which are represented by 16 sites, three of which are surface springs (see Table 2-1 for aquifer details). The 16 sites monitored include six wells that are shared with the NGMP (GNS). Of the 10 dedicated SOE sites, results for nine are reported here, as sampling was only initiated at the tenth site (Alfred St – Onehunga Volcanic aquifer) at the end of 2019 and this site does not have a sufficient data record to be analysed at this time.

The groundwater quality monitoring network was reviewed more recently in mid-2020 (Johnson, 2020). As a result of this review, monitoring of additional aquifers will be phased in over the next three years to improve spatial representation of groundwater quality across the region and to gather evidence to support our understanding of land use pressures on the water quality component of these resources over the longer term.

Figure 2-1 shows current groundwater quality monitoring locations split into Long-term Baseline (LTB), and National Groundwater Monitoring Programme (NGMP) sites. Further site details can be found in Appendix A (GPS coordinates, site numbers and commencement date of monitoring).

Table 2-1 Summary site details for aquifers monitored for groundwater quality in the Auckland region.

Dominant land use pressure	Aquifer Geology	Aquifer Management Area	Site	Aquifer type	Aquifer depth	Spring/bore (screen depth)
Franklin agricultural sites	Franklin Volcanics	Drury Volcanic	Fielding Road Volcanic	Unconfined	Shallow	Bore (16-47 m)
			Hillview Springs	Unconfined	Shallow	Spring
		Bombay Volcanic	BP Bombay	Unconfined	Shallow	Bore (62-79 m)
		Pukekohe Volcanic	Hickey Springs	Unconfined	Shallow	Spring
			Rifle Range Road Deep	Unconfined	Deep	Bore (90 m)
			Rifle Range Road Shallow	Confined	Shallow	Bore (42 m)
			Patumahoe Spring	Unconfined	Shallow	Spring
			Gun Club Road	Unconfined	Shallow	Bore (27 m)
	Franklin Kaawa	Pukekohe Kaawa	Ostrich Farm Road Shallow	Confined	Shallow	Bore (46-48 m)
			Ostrich Farm Road Deep	Confined	Deep	Bore (84 m)
	Bombay Drury Sand	Drury Sand	Fielding Road Sand	Semi-confined	Shallow	Bore (57-64 m)
	Waitematā	Waiau Pa Waitematā	Seagrove Road	Confined	Deep	Bore (201 m)
Kumeu agricultural sites	Waitematā	Kumeu West Waitematā	Waitakere Road Deep	Confined	Deep	Bore (150 m)
			Waitakere Road Shallow	Semi-confined	Shallow	Bore (15 m)
Central Isthmus Urban site	Auckland Isthmus Volcanics	Three Kings Volcanic	Watson Ave	Unconfined	Shallow	Bore (32-38 m)

Figure 2-1 Groundwater quality monitoring site locations across the Auckland region, split into LTB (Long-term baseline) and NGMP (National Groundwater Monitoring Programme) sites.

Figure 2-2 Locations of aquifer types and associated groundwater quality monitoring sites.

2.1.1 Franklin volcanic aquifers geology

The Franklin volcanic aquifers are comprised of three main eruptive centers in Bombay, Pukekohe, and Glenbrook. Two major periods of volcanic activity are represented by older Bombay basalts and younger Pukekohe basalts, separated by silts and clays (Auckland Regional Water Board and Waikato Valley Authority, 1977). The eruptive volcanic deposits form distinctive landforms in this part of the Auckland region, namely Pukekohe Hill and Bombay Hills (White et al., 2019) (Figure 2-3). The rocks comprising the Franklin volcanic aquifers include basalt lava flows, scoria cones, and tuff rings composed of exploded bedrock, tephra and ash (Auckland Regional Water Board and Waikato Valley Authority, 1977 and Auckland Regional Council, 1996).

The rock type and physical characteristics of the basalts are heterogeneous but generally characterized by high transmissivity and high groundwater throughflow (Auckland Regional Council, 1996 and Viljevac, 2002). Three-dimensional geological modelling visualised the major volcanic aquifer divisions in the area (White et al., 2019).

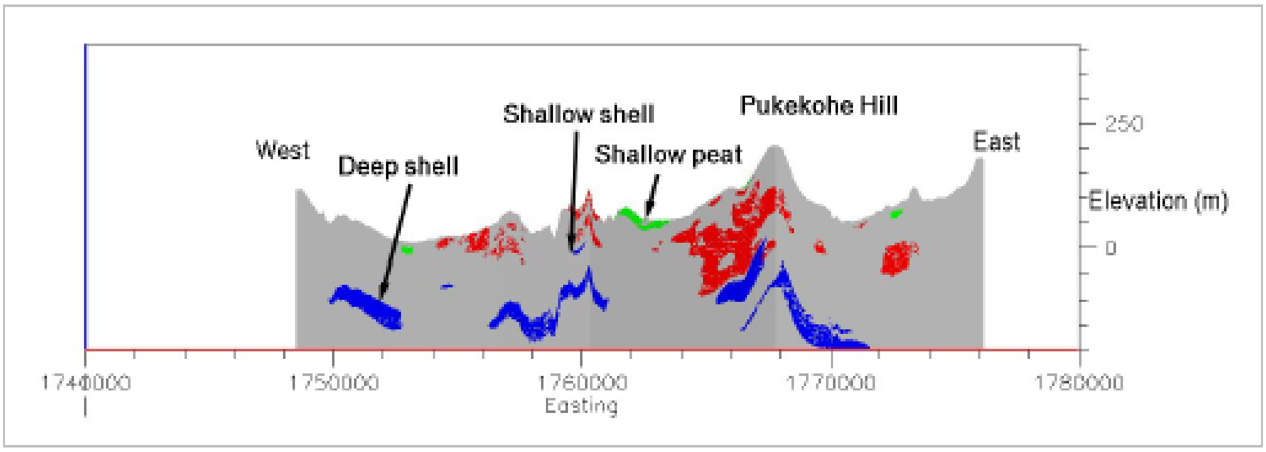

Figure 2-3 Cross section west to east: volcanic aquifers (red), peat aquifers (green), and shell aquifers (blue), through the area where the monitored Franklin volcanic aquifer sites are positioned (adapted from White et al., 2019).

Recharge to the basalts is predominantly via rainfall infiltration in the unconfined areas of the aquifers and by vertical leakage and throughflow to the lower and confined aquifers (Auckland Regional Council, 1996 and White et al., 2019). Recharge rates to the volcanic aquifer in Pukekohe were estimated at 680 mm/year (Viljevac et al., 2002). Actual rainfall recharge was measured at the Karaka lysimeter site at 819, ±121 mm/year (White et al., 2019). Groundwater residence time in the Franklin basalts was found to be generally less than 50 years in the shallow basalts and greater than 50 years in the deep basalts, with age also increasing at distance from the recharge zone (van der Raaij, 2015). Groundwater quality sites within the Franklin Volcanic aquifers can be found in Figure 2-2.

In general, these two basalt aquifer groups can be identified by their water chemistry (particularly, nitrate-N, dissolved oxygen, and iron):

- Shallow, oxic groundwater with nitrate-N concentrations that discharges to springs and
- Deep, anoxic groundwater that flows to the deeper Kaawa Formation (White et al., 2019).

2.1.2 Franklin Kaawa Shell aquifer geology

The Pliocene-age Kaawa formation consists of weakly cemented, fractured marine sandstone containing shell horizons that form important aquifers in the Franklin area (Viljevac et al., 2002). The Kaawa underlies the basalts of the Franklin Volcanic Field and is recharged via vertical leakage from the basalts and to a lesser extent from the overlying sedimentary rocks where basalt is not present (Figure 2-4). Recharge rates to the Kaawa were estimated as 176 mm/year in Viljevac et al. (2002), and 273 ±108 mm/year in White et. al. (2019). The hydraulic properties of the Kaawa aquifer vary considerably with transmissivity (T) and storativity (S) ranging from 13 to 500 m^2/day and 10^{-2} to 10^{-5} (no units apply to storativity), respectively (Auckland Regional Water Board, 1989 and Viljevac et al., 2002). Transmissivity is generally highest near Pukekohe and decreases towards the proximal extent of the shell deposits (Viljevac et al., 2002). Groundwater residence time has not been assessed for the Kaawa aquifer; however, it is expected to be greater than 50 years due to recharge from overlying units that have residence times exceeding 50 years. Sites within the Kaawa aquifer are shown in Figure 2-2.

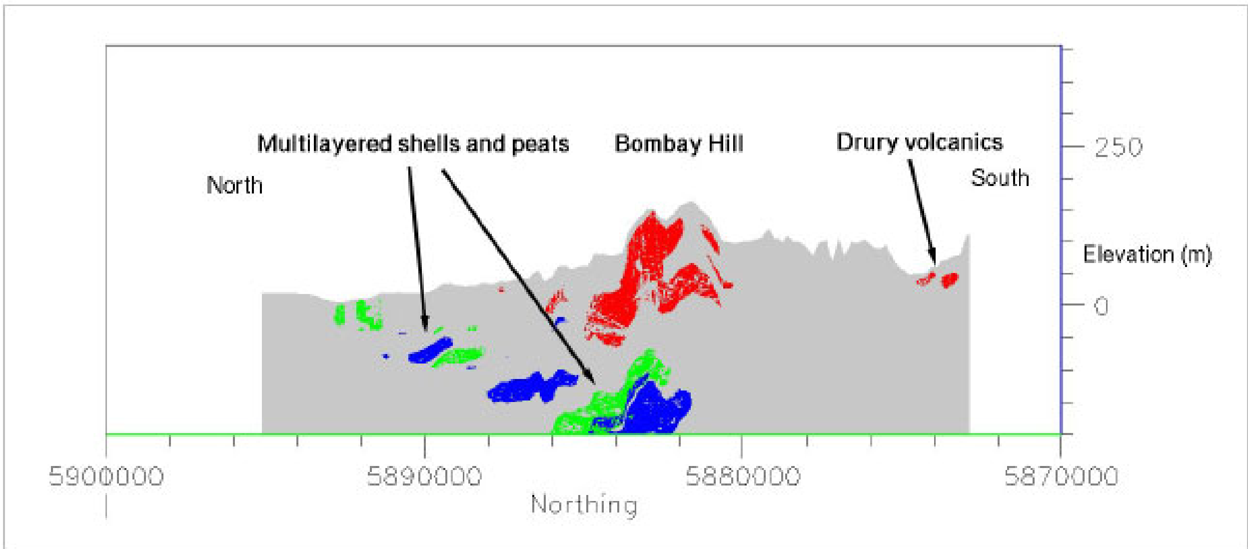

Figure 2-4 Cross section north to south: volcanic aquifers (red), peat aquifers (green) and shell aquifers (blue) (adopted from White et al., 2019).

2.1.3 Bombay-Drury sand aquifer

The Bombay-Drury sand aquifer is comprised of semi-confined sands of the Pleistocene age Tauranga Group, which includes Puketoka Formation alluvium (Murphy, 1991 and Edbrooke, 2001). The Tauranga Group forms a regional aquitard that confines the underlying Kaawa Formation (Viljevac et al., 2002), however, localized aquifers are present in the Drury and Clevedon areas, as evidenced by bore logs from water take consents. Recharge rates to the Puketoka sands have been reported as approximately 10 per cent of annual rainfall in resource assessments supporting consent applications. Groundwater residence time in the Bombay-Drury sands has not been assessed. Figure 2-2 shows the sites within the Bombay-Drury Sand aquifer.

2.1.4 Waitematā aquifers geology

The Waitematā aquifers are situated within the Waitematā Group sedimentary rocks and are comprised of alternating sandstones and mudstones, with some sand, silt, shells and minor clay and gravel locally (Balance, 1976 and White et al., 2020). Thickness of the sandstone beds varies throughout the Auckland region, total thicknesses range from a few meters to over 1000m (Crowcroft & Smaill, 2001).

The Waitematā Group rocks form the majority of the Auckland region's local basement, excluding a few locations in the Hunua Ranges, areas of Onerahi rocks in the north, and some Hauraki Gulf Islands (Balance, 1976). Waitematā aquifers are characterised by fine-grained sediment matrices with relatively low permeabilities, but the Waitematā Group includes fracturing, jointing and faults that can improve local permeability.

In general, Waitematā aquifers are low yielding. Transmissivity values in Waitematā aquifers range from 5-120 m^2/day, with aquifer recharge rates of 4-76 mm/year (Earthtech, 2018). The Kumeu West and the Waiau Pa Waitematā are monitored as part of the Auckland Council groundwater quality network; sites within these aquifers are shown in Figure 2-2.

Horizontal permeability is far greater than vertical due to strong horizontal bedding and vertical constriction from mudstone horizons (White et al., 2020). In some aquifers (e.g., Kumeu West Waitematā), Council monitors both the shallow and deep extents of the aquifer due to different hydraulic and groundwater chemistry characteristics. In the case of the Kumeu Waitematā, there is not a clear demarcation between deep and shallow aquifers and as a result, the aquifer is not divided into shallow and deep management areas. However, the observed differences in water quality justify inclusion of both shallow and deep monitoring. Groundwater monitoring sites located in the Waitematā aquifers are shown in Figure 2-2.

2.1.5 Auckland Isthmus Volcanic aquifers geology

The Three Kings Volcanic aquifer comprises several eruption phases made up of basalt lava, scoria and roughly bedded tuffs (volcanic ash) with larger bombs throughout (Searle, 1962 and PDP, 2017) which sit atop the erosional surface of the underlying Waitematā and Tauranga Group sedimentary rocks. Infiltration rates and groundwater residence times are likely similar to other basalt aquifers like those in Pukekohe as described above. The basalts are generally characterized by high transmissivity via secondary porosity and fracturing (Namjou et al., 2006). The basalt aquifers have high infiltration rates and throughflow, contributing to their important role in stormwater discharge via soakage (Namjou et al., 2006 and PDP, 2017). The use of the isthmus aquifers for stormwater discharge is a key consideration of the groundwater quality monitoring programme for this aquifer. The Three Kings aquifer and associated monitoring site (Watson Ave) is shown in Figure 2-2.

3 Methods

3.1 Data collection

Each monitored site is sampled quarterly by council's Research and Evaluation Unit (RIMU), using the National Environmental Monitoring Standards (NEMS) for groundwater quality (NEMS, 2019). Several variables are measured directly while in the field (Table 3-1). All sensors are calibrated/validated in accordance with NEMS and additionally follow a stricter Auckland Council internal calibration protocol (RIMU, 2019).

Table 3-1 Parameters collected in the field and stabilisation criteria for sample collection.

Field parameter	Abbreviation	Unit	Stabilization criteria (NEMS, 2019)
Dissolved oxygen	DO	mg/L	± 0.3
pH		pH	± 0.1
Temperature		ºC	± 0.2
Oxygen reducing potential	ORP	mV	NA
Turbidity		FNU	± 10%
Electrical conductivity	EC	mS/cm	± 3%

Samples collected from bores are collected using the 3-purge volume method. This is to remove stagnant water from the bore before samples are collected. Field measurements are logged at every purged volume to ensure stabilization of parameters, the last two logs must be within the stabilization criteria (Table 3-1). Samples collected from springs are collected once field measurements have stabilized using the same criteria in Table 3-1.

The Auckland Council LTB samples are sent to RJ Hill Laboratories in Hamilton for analysis of nutrients, microbes, and dissolved metals. Samples are freighted promptly to ensure microbial samples are processed within 24 hours (NEMS, 2019). Details on laboratory reported variables and methods for their analysis are provided in Appendix B and C.

NGMP samples are collected, preserved, and sent to the GNS Wairakei Laboratory to be analysed. Details on parameters and methods for analysis can be found in Appendix D.

3.2 Data processing

Pre-processing took place prior to analysis and outliers were removed based on several criteria: identified field equipment failure, outliers that were an order of magnitude out from more than 90 per cent of the site data, and where further investigation gave reason to remove them from the dataset, for example sample arrival temperatures exceeding NEMS recommendations for *E. coli* testing.

Sample results were also excluded when greater than five per cent error was detected in the charge balance. This quality assurance measure ensures that the electroneutrality of a sample is verified.

3.3 Selection of water quality parameters to report

The process to choose which parameters to report was based on the following criteria:

1) the quality of the dataset (e.g., some gaps exist, inconsistent parameters have been analysed through time, changes in laboratory methods, short analyses records for some parameters and multiple detection limit changes through time).

2) consistency in reporting similar parameters to the last groundwater quality state and trends report (Kalbus et al., 2017).

3) Only parameters on the current analyte list were chosen.

Parameters that are reported here are outlined in Table 3-2. The full list of parameters that have been analysed are in Appendix B and C and NGMP sites in Appendix D. Further descriptions of each parameter and what indicators they are used for are in Appendix F.

Table 3-2 Groundwater quality parameters analysed.

Parameter type	Parameter	Units	Parameter type	Parameter	Units	Parameter type	Parameter	Units	Parameter	Units
Nutrients	Ammoniacal – nitrogen*	mg/L	Microbial	*E. coli*	cfu/100 ml	Other	pH*	-	Chloride	mg/L
	Nitrite – nitrogen	mg/L	Metals	Soluble iron*	mg/L		Alkalinity	mg/L	Total hardness	mg/L
	Nitrate – nitrogen*	mg/L		Soluble manganese*	mg/L		Dissolved oxygen	mg/L		
	Dissolved reactive phosphorus	mg/L		Soluble sodium*	mg/L		Electrical conductivity	mS/cm		
				Soluble zinc	mg/L		Total dissolved solids	mg/L		
				Soluble copper	mg/L		Sulphate*	mg/L		

**Parameters also analysed for NGMP sites.*

3.4 Data analysis

3.4.1 Censored values

Values that are below laboratory detection limit for a parameter are referred to as "left censored" values. Censored values were replaced by imputation for the purposes of calculating the five-year state statistics. Left censored values were replaced with imputed values generated using ROS (Regression on Order Statistics; Helsel, 2012). The ROS procedure produces estimated values for the censored data that are consistent with the distribution of the uncensored values, and it can accommodate multiple censoring limits.

For trend analysis, censored values were replaced with a value half the detection limit, this ensures that any value equal to the detection limit is being treated as larger than any value that is less than the detection limit i.e., a measured concentration of 0.2 mg/L is larger than a value recorded as <0.2 mg/L. This process ensures the difference between two censored values is not measurable and treated as zero.

Detection limits have differed over time for some analyses due to changes in laboratory providers and/or laboratory methods. The data are presented as-is relative to the detection limit applied, rather than replacing all lower detection limit values with the highest detection limit overall. This ensures that observations obtained with more sensitive laboratory analytical measurements are not lost under an umbrella of older water quality observations with poor resolution.

3.4.2 Guidelines used for current state assessment

Current groundwater quality state has been assessed against various guidelines:

- Drinking Water Standards – New Zealand (MoH, 2019), Maximum Acceptable Values (MAV) and Aesthetic guideline values.
- Expected Concentrations for Natural Conditions (ECNC) (Morgenstern & Daughney, 2012) – nitrate only.
- Australian & New Zealand Guidelines for Fresh & Marine Water Quality (ANZECC, 2000) – dissolved reactive phosphorus, soluble zinc and copper, comparison to surface water trigger values.

There are currently no National Objective Framework (NOF) attributes for groundwater quality in the National Policy Statement for Freshwater Management (NPS-FM, 2020).

Guidelines for groundwater quality variables are outlined in Table 3-3. Variables not listed do not have guideline values but can be useful indicators of contaminant leaching into groundwater or other hydrogeological processes.

Summary statistics were calculated for each monitored site (median, min, max, 5^{th}, 95^{th}). The median (or 50^{th} percentile) value for the period 2015-2019 was used to assess the current state of each parameter against guideline values (Table 3-3). The median is a more robust measure than the mean as it is not affected by outliers. Below are explanations of each guideline and how the value was determined.

3.4.2.1 Maximum acceptable values – Drinking Water Standards-New Zealand (DWS-NZ)

A maximum acceptable value (MAV) is generally the maximum value of a chemical that is considered, based on current knowledge, not to cause any significant risk to the *health* of a consumer over 70 years of drinking 2L of water a day (MoH, 2019).

MAV is set differently for nitrate, nitrite and *E. coli*. For nitrate and nitrite, the MAV is a short-term exposure limit established to protect bottle-fed infants against methemoglobinemia (blue baby syndrome). Public health experts recommend applying this value to bottle-fed babies less than six months old and to pregnant women. *E. coli* concentrations above the

MAV may cause a significant risk of contracting a waterborne disease. MAVs are used here as a screening assessment of groundwater quality for drinking water supply, but do not imply a compliance level assessment.

3.4.2.2 Aesthetic based guideline values (AGV) – DWS-NZ

Exceedances of aesthetic guideline values do not pose a human health risk but can create nuisances with water purification equipment, taste, staining, and scum build up with certain soaps. Reporting against aesthetic guidelines uses median concentrations.

3.4.2.3 Expected concentration for natural conditions (ECNC)

The expected concentration for natural conditions (ECNC) for nitrate-nitrogen is currently thought to be <2.5 mg/L in groundwater. Measured values above 2.5 mg/L indicate the potential impact of human activities (Morgenstern & Daughney, 2012).

3.4.2.4 Trigger value (TV) – ANZECC

Australia and New Zealand Environmental Conservation Council (ANZECC) have guidelines for fresh and marine water quality, including trigger values for some parameters. Reporting against trigger value guidelines uses median concentrations. The trigger values are not absolute and should only be used as guides to provide a framework for protecting water quality and associated ecosystems, human health, and food production. The guidelines should be used to refine regional or local trigger values for each parameter and provide evidence for further action. ANZECC surface water guidelines for filterable reactive phosphorus (equivalent to dissolved reactive phosphorus), soluble zinc, and copper are used to assess shallow volcanic aquifer groundwater quality in the context of their potential baseflow supply into surface waters (rivers) (ANZECC & ARMCANZ, 2000).

Table 3-3 Guideline values used to assess groundwater quality state.

Parameter type	Parameter	Value	Guideline	Reference
Physical	pH	7.0-8.5 pH	Aesthetic GV	DWS-NZ (2019)
Nutrients	Nitrate – N* short term	11.3 mg/L[2]	MAV – human health	DWS-NZ (2019)
	Nitrate – N	2.5 mg/L	ECNC – ecosystem	(Morgenstern & Daughney, 2012)
	Nitrite *short term	0.91 mg/L[3]	MAV	DWS-NZ (2019)
	Nitrite *long term	0.061 mg/L[4]	PMAV	DWS-NZ (2019)
	Ammonia – N	1.5 mg/L	Aesthetic GV – odor threshold	DWS-NZ (2019)
	Dissolved reactive Phosphorus (DRP)	0.01 mg/L	Trigger Value for slightly disturbed surface water systems	ANZECC (2000)
Metals	Soluble iron	0.2 mg/L	Aesthetic GV	DWS-NZ (2019)
	Soluble sodium	200 mg/L	Aesthetic GV – taste threshold	DWS-NZ (2019)
	Soluble manganese	0.4 mg/L	MAV – human health Taste threshold 0.1 mg/L	DWS-NZ (2019)
	Soluble copper	2 mg/L 0.0014 mg/L[5]	MAV – ATO[6] human health TV – ecosystem health	DWS-NZ (2019) ANZECC (2000)
	Soluble zinc	2 mg/L 0.008 mg/L[7]	MAV – ATO human health TV – ecosystem health	DWS-NZ (2019) ANZECC (2000)
Microbial	*E. coli*	<1 cfu/100 mL	MAV – human health	DWS-NZ (2019)
Other	Chloride	250 mg/L	Aesthetic GV – taste threshold	DWS-NZ (2019)
	Total hardness	200 mg/L	Aesthetic GV Taste threshold 100-300 mg/L <100 may be more corrosive	DWS-NZ (2019)
	Total dissolved solids	1000 mg/L	Aesthetic GV	DWS-NZ (2019)
	Sulphate	250 mg/L	Aesthetic GV – taste threshold	DWS-NZ (2019)

[2] Conversion from NO_3 50 mg/L
[3] Conversion from NO_2 3 mg/L
[4] Conversion from NO_2 0.2 mg/L
[5] Conversion from 1.4 µg/L
[6] ATO – Concentrations of the substance at or below the health-based guideline value that may affect the waters appearance, taste, or odour
[7] Conversion from 8 µg/L

3.4.3 Groundwater 10-year trend analysis

Monotonic trends were assessed for the 10-year period from January 2010 to December 2019, inclusive. Minimum data requirement rules required 65 per cent of the total possible number of observations per parameter, per site, slightly lower than the 75 per cent required by national level reporting on the Land, Air, Water Aotearoa (LAWA) website. This was an intentional choice to enable inclusion of more site and parameter combinations in the overall regional analysis undertaken here. Any site and parameter combinations that did not meet these data requirements are not reported here.

Analyses were undertaken using a purpose-built script designed for analysing quarterly water quality trends. The general analyses are described by Larned et al. (2018) and were performed using the R statistical package (R Core Team, 2020). The base script was obtained from Land Water People (LWP) and is readily available at https://landwaterpeople.co.nz/pdf-reports/. Previous Auckland Council groundwater quality reporting used the NGMP Calculator (Daughney, 2010) to undertake this analysis.

Data were assessed for seasonality (split into the four seasons/quarters), using the Kruskal Wallis test (Helsel & Hirsch, 2002), which determined the type of test subsequently used in the trend analysis step (Seasonal or Non-Seasonal). Seasonal tests compare observations within each quarter over time while non-seasonal tests compare all observations over time.

Monotonic trends across sites were analysed by assessing the direction of a trend, i.e., what is the likelihood the parameter is increasing or decreasing? The confidence in the trend direction is calculated using the Kendall (or seasonal Mann-Kendall) test based on the probability that the trend was decreasing. An overarching assumption of the first step of the trend analysis is that there are always differences between observations (McBride, 2019). The calculated probability is then interpreted based on the categories used by the Intergovernmental Panel on Climate Change (Snelder & Fraser, 2019) and further aggregated to five categories for simplicity as per LAWA (e.g., Cawthron Institute 2019) (see Table 3-4).

For most parameters, a decreasing trend is interpreted as an improvement in water quality and an increasing trend is a degradation in groundwater quality. For “other” parameters (Table 3-2) the likelihood of the direction of the trend is reported as increasing or decreasing, with no associated value assessment (i.e., improving or degrading). A trend is classified as indeterminate when there is insufficient evidence to determine if the data is trending in a particular direction.

Table 3-4 Trend confidence category levels used to determine the direction of trends.

Trend categories		Probability (%)
Very likely improving	Very likely decreasing	90-100
Likely improving	Likely decreasing	67-90
Indeterminate	Indeterminate	33-67
Likely degrading	Likely increasing	10-33
Very likely degrading	Very likely increasing	0-10

If a degrading trend is *likely*, further investigation of the nature of the trend is necessary. This includes assessment of the likelihood of the trend, the magnitude of the trend, the risk of adverse ecological outcomes (in relation to the known current state), and consideration of whether the current state is with a reflection of naturally occurring processes.

The magnitude of the trend was also assessed, i.e., how much is a parameter increasing or decreasing? 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)), which robustly handles typical groundwater quality data (Moreau, 2019). The SSE is the median of all possible inter-observation slopes. The 90 per cent confidence intervals of this median estimate are also calculated.

While a trend may be very likely improving or degrading, the smaller the Sen slope, or rate of change, the longer it would take to be reflected in assessments of the current state, assuming a linear rate of change. Trend magnitude is therefore assessed in this report relative to the limit of precision (i.e., the measurement resolution) for each parameter following the approach in Fraser & Snelder (2018). The magnitude of a trend is only reported if the rate of change exceeded the precision limit. Trend magnitude can only be estimated for *very likely* trends.

The estimation of the magnitude of the trend (Sen slope) decreases in reliability as the proportion of censored values increases. The LWP script specifically identifies where the trend slope was calculated from data with censored observations. In these instances, the magnitude of the trend is considered imprecise and is not reported here. Only magnitudes of change that meet all the above criteria (i.e., very likely trend, exceeding the measurement resolution, and are not calculated from censored observations) are presented in the report.

3.4.3.1 Long-term trend analyses exclusions and warnings

- Gun Club Rd (Pukekohe Volcanic aquifer) did not meet the minimum number of observations to be analysed for metals and is therefore not included in these analyses.
- No sites had enough observations for long-term manganese trend analysis because it has been intermittently measured, but current state could be evaluated.

- Soluble iron had a detection limit change from 0.002 to 0.2 mg/L when changing analytical laboratories in 2017, this is likely to induce a trend and should be viewed with caution.
- Soluble copper had a detection limit change from 0.002 to 0.005 mg/L in 2017, long-term trends are not reported due to obvious induced trends because of this detection limit change.
- Some aquifers did not have enough observations for “other” parameters and therefore do not have long-term trends reported here.

4 Results and discussion

Aquifers are grouped in this section by three geographic areas across Auckland: Franklin, Kumeu, and Auckland Isthmus. LTB and NGMP sites are grouped together for a more complete discussion of the groundwater quality across the Auckland region, noting that NGMP sites did not have the full parameter suite analysed. Refer to Table 3-2 in Section 3 for the list of parameters. Results and discussion are synthesised into an assessment of current state (2015-2019) and long-term trends (2010-2019) for each parameter type (nutrients, metals, microbial indicators and other parameters).

Trend reporting follows a stepped process. Trends are firstly split into the proportions of degrading and improving trends. Then, *very likely* trends are discussed. Lastly, only *very likely* trends that exceeded the limit of precision for each parameter are further considered. Differences between the trends in this report and those reported by Kalbus et al. (2017) are discussed in each respective aquifer section. All three geographic areas are integrated at the end of this section to discuss overall groundwater quality of the Auckland region.

4.1 Franklin aquifers

Franklin aquifers are used primarily for horticultural irrigation, but also provide for municipal drinking water, stock drinking water, and domestic use. Of the Franklin aquifers, the Pukekohe volcanics are shallow and high yielding, however susceptible to contamination from land use activities.

The Pukekohe horticultural growing area has some of the highest production yields in the country (Deloitte, 2018) and sits at the headwaters of several streams in the Franklin area. Nitrogen fertilisers are used to sustain production yields, but excess water-soluble nitrate can either enter streams directly after high rainfall via surface flow or enter shallow aquifers through leaching from overlying soils and subsequently entering streams via groundwater baseflow. The existence of nitrate contamination in shallow groundwater in the Franklin region is well known (Cathcart, 1995, Moreau et al., 2016, Meijer et al., 2016, Kalbus et al., 2017, White et al., 2019).

Groundwater residence times in Franklin volcanic aquifers range from 16 to 99 years, with shallow aquifers characterised by residence times less than 50 years and deeper aquifers greater than 50 years (van der Raaij, 2015). Groundwater discharge to streams as baseflow is thus the product of multiple years of aquifer throughflow following initial recharge through the soil. This is commonly known as the groundwater “lag effect”. Understanding this lag time from recharge to baseflow is essential to the effective management of land use activities, particularly in areas where nutrient enrichment is occurring, or has the potential to occur with future land use activity change (Morgenstern et al., 2015).

4.1.1 Groundwater quality current state in Franklin (2015-2019)

4.1.1.1 Nutrients

Nitrate-N is the dominant nitrogen form measured at six of the eight sites used to monitor conditions in the Franklin volcanic aquifers (Table 4-1, except for Drury Volcanic and Pukekohe Volcanic – deep). Ammonia was the dominant form for all other monitored aquifers including Bombay Drury Sand, Waiau Pa Waitematā, and Franklin Kaawa aquifers. In 2019, the six nitrate-dominated bores had five-year median NO_3-N concentrations between 9.1 and 26 mg/L (Pukekohe Volcanic – shallow).

Nitrogen species occur naturally in groundwater from nitrogen-rich bedrock and natural soil leaching; however, an elevated concentration of nitrogen potentially indicates the impact of land use activities on groundwater quality (e.g., from sewage discharge or fertiliser application) (Morgenstern & Daughney, 2012 and Moreau, 2019). For six of the Franklin shallow volcanic aquifer sites, the current state for nitrate reported here is above expected groundwater concentrations (>2.5 mg/L, Morgenstern & Daughney, 2012). Four of the Franklin volcanic aquifer sites were also above New Zealand drinking water guidelines maximum acceptable value (MAV); however, it is noted that the 95th percentile for BP Bombay (12.73 mg/L) does exceed MAV (Table 4-1).

Table 4-1 Five-year medians (2015-2019) for nutrients in groundwater for the Franklin aquifers. Values in bold and red are above guideline values, values in bold and yellow are above ECNC for nitrate.

	Parameter	Ammonia -N (NH_3+NH_4)	Nitrite N (NO_2)	Nitrite N (NO_2)	Nitrate N (NO_3)	DRP
	Guideline	*Aesthetic GV (1.5 mg/L)*	*MAV short term (0.91 mg/L)*	*PMAV long term (0.061 mg/L)*	*MAV short term (11.3 mg/L), ECNC (2.5 mg/L)*	*ANZECC Surface Trigger Value (0.01 mg/L)*
Franklin Volcanics	Drury Volcanic - Fielding Rd Volcanic	0.029	0.0018**	0.0018**	0.006	**0.034**
	Drury Volcanic – Hillview Spring (surface)	0.005**	0.0015**	0.0015**	**15.1**	**0.056**
	Bombay Volcanic – BP Bombay	0.005**	0.0015**	0.0015**	**11#**	**0.096**
	Pukekohe Volcanic – Hickey Spring (surface)	0.005**	0.0015**	0.0015**	**17**	**0.024**
	Pukekohe Volcanic – Rifle Range Road Shallow	0.003 ($NH_{3\ only}$)	NA	NA	**9.1**	NA
	Pukekohe Volcanic – Rifle Range Road Deep	0.2 ($NH_{3\ only}$)	NA	NA	0.01	NA

	Parameter	Ammonia -N (NH_3+NH_4)	Nitrite N (NO_2)	Nitrite N (NO_2)	Nitrate N (NO_3)	DRP
	Guideline	*Aesthetic GV (1.5 mg/L)*	*MAV short term (0.91 mg/L)*	*PMAV long term (0.061 mg/L)*	*MAV short term (11.3 mg/L), ECNC (2.5 mg/L)*	*ANZECC Surface Trigger Value (0.01 mg/L)*
	Pukekohe Volcanic-Patumahoe Spring (surface)	0.005**	0.0015**	0.0015**	**24**	**0.021**
	Pukekohe Volcanic-Gun Club Rd	0.005**	0.0011**	0.0011**	**26**	**0.019**
Franklin Waitematā	Waiau Pa Waitematā – Seagrove Road	0.22 ($NH_{3\ only}$)	NA	NA	0.01	NA
Franklin Kaawa	Pukekohe Kaawa-Ostrich Farm Road Shallow	0.13	0.002**	0.002**	0.0024	**0.014**
	Pukekohe Kaawa-Ostrich Farm Road Deep	0.22 ($NH_{3\ only}$)	NA	NA	0.001	NA
Bombay Drury Sand	Bombay Drury Sand – Fielding Rd Sand	0.68	0.0015**	0.0015**	0.002**	**0.179**

*** >50% of observations were below the laboratory detection limit for this parameter.*

 # Whilst this median value for the Bombay Volcanic aquifer does not exceed the short-term nitrate MAV, we note that the 95th percentile of 12.73 mg/L does exceed the New Zealand drinking water guideline MAV. In contrast, the 95%ile for the Pukekohe Volcanic aquifer – shallow does not currently exceed the short-term nitrate MAV.

Fertiliser application is common in the horticulture growing areas of Franklin, along with frequent soil tilling, which leads to a loss of soil carbon. Soil carbon is an indicator of soil organic matter (SOM), which directly impacts the structural stability of soils and the availability of nitrogen and carbon for use by microbes and plants. Soils with poorer structure are more susceptible to erosion and nutrient leaching, particularly nitrate in the Franklin area (Curran-Courane, 2020).

The Bombay Volcanic aquifer site (BP Bombay) is currently just below the short-term nitrate drinking water guideline MAV of 11.3 mg/L, with a median of 11.0 mg/L. Of note is that the 95th percentile for this site is 12.73 mg/L, suggesting that the short-term MAV is exceeded greater than five per cent of the time.

Franklin Kaawa, Bombay Drury Sand, and Waiau Pa Waitematā aquifers had nitrate concentrations below both guideline values, reflecting strongly reducing groundwater conditions (low oxygen, high reduced Fe concentrations). Nitrate concentrations <0.4 mg/L can be expected, irrespective of land use intensity, due to natural denitrification processes (Rissmann, 2012). This is confirmed by monitored data for the six aquifers that are above expected concentration for natural conditions which have high dissolved oxygen (i.e., >70 per cent), whilst Franklin Kaawa, Drury Volcanic (Fielding Road Volcanic only) and Bombay Drury Sand aquifers have very low dissolved oxygen (i.e., <2 per cent).

All Franklin aquifers have median ammonia values below the aesthetic GV for drinking water. Five sites had ammonia values below the current laboratory limit of detection for this parameter. Ammonia concentrations in the Drury Volcanic aquifer Fielding Road site nearly halved from 0.050 mg/L in 2013 to 0.029 mg/L in 2019. Similarly, ammonia nearly halved in the Pukekohe Kaawa Aquifer (Ostrich Farm Road Shallow) from 0.20 mg/L in 2013 to 0.13 mg/L in 2019. The Bombay Drury Sand Aquifer had similar ammonia concentrations to those reported in 2017.

All aquifers had nitrite concentrations well below both the short and long-term maximum acceptable value (MAV & PMAV) guidelines for human health (Table 4-1), and all sites had most values below the laboratory limit of detection for this parameter. Most aquifers had greater than 50 per cent censored values for these parameters meaning that median concentrations cannot be well elucidated as current laboratory methods are not able to detect these very low concentrations.

All aquifers are above the ANZECC threshold (surface water – ecosystem health) for dissolved reactive phosphorus (Table 4-1). Elevated concentrations in groundwater >0.05 mg/L can be an indication of the following: naturally occurring concentrations associated with dissolution of volcanic rocks through time (Morgenstern & Daughney, 2012 and Morgenstern et al., 2015), land use change, on-site septic systems, dairy farms, and fertiliser use (McDowell et al., 2015 and McDowell et al., 2019). It is difficult to determine the predominant source of phosphorus in volcanic aquifers. It has been identified that sand aquifers under largely dairying catchments, can become enriched in phosphorus, this might explain the higher median values in the Bombay Drury Sand aquifer (McDowell et al., 2015) (Table 4-1). Of note is that horticultural soils in the Franklin area are heavily saturated with Olsen P, (a measure of plant available phosphate in the soil), at 109 mg/kg (mean values for 1995-2017) and have the highest Olsen P values of all land use types monitored by Auckland Council's soil quality monitoring programme (Curran-Courane, 2020).

4.1.1.2 Metals

All Franklin volcanic aquifers have concentrations lower than NZDWS guideline values for manganese, sodium, and copper (Table 4-2). Oxidising processes reduce soluble iron and manganese concentrations, and this can be seen in five of the Franklin volcanic sites. Fielding Rd Volcanic (Drury Volcanic aquifer) has low dissolved oxygen (0.12 mg/L Table 4-4) and higher iron and manganese concentrations (Table 4-2) than other monitored volcanic aquifers.

Concentrations of soluble manganese in the Franklin Kaawa aquifer do not exceed the MAV but do exceed the “taste” value for drinking water guidelines. Franklin Kaawa and Bombay Drury Sand aquifers exceed the aesthetic guideline value for iron (Table 4-2). This is consistent as iron and manganese are redox indicators of anoxic conditions (Table 4-4 for dissolved oxygen values) (White et al., 2019). A national groundwater quality study undertaken by Daughney (2003) found that aquifers in basalt, shellbed and sandstone are the least likely to have high concentrations of iron and manganese, and aquifers comprising of gravel and sand are more likely to have higher concentrations of these metals. Although there is no MAV, iron and manganese can potentially pose a health risk and become an issue for corrosion of equipment and staining of laundry (Daughney, 2003 and MoH, 2019).

Two sites (Hillview Springs – Drury Volcanic and BP Bombay – Bombay Volcanic) exceeded the ANZECC (2000) surface water trigger value for zinc. Gadd et al. (2019) developed and proposed Auckland-specific ecosystem health attributes for copper and zinc. When compared to these regional surface water guidelines, Hillview Springs falls into band B of the zinc ecosystem health grading (Table 4-2). This indicates a potential impact on five per cent of senstive species from groundwater baseflow (Gadd et al., 2019), although instream dilution could reduce this effect. The zinc value for the Bombay Volcanic aquifer exceeds band D (>0.031 mg/L), which approaches an acute impact level, i.e. risk of death to sensitive instream fauna (Gadd et al., 2019). The Bombay Volcanic aquifer discharges into Ngakora Stream. The Ngakaroa Stream is monitored as part of Auckland Council's river water quality monitoring programme. Groundwater quality results indicate that baseflow to streams may impact on ecosystem health.The interconnected nature of ground and surface waters in this region requires careful consideration when trying to identify the naturally occurring states for surface waterbodies with a high baseflow component.

Table 4-2 Five-year median (2015-2019) for metals in groundwater for the Franklin aquifers. Values in bold and red are above MAV or GV guidelines and cells highlighted in yellow and bold are above "taste" values.

	Parameter	Soluble iron (Fe)	Soluble manganese (Mn)	Soluble sodium (Na)	Soluble copper (Cu)	Soluble zinc (Zn)
	Guideline	**Aesthetic GV** (0.2 mg/L)	**MAV** (0.4 mg/L)	**Aesthetic GV** (200 mg/L)	**MAV** (2 mg/L) Surface Trigger Value ANZECC (0.0014 mg/L)	**MAV** (2 mg/L) Surface Trigger Value ANZECC (0.008 mg/L)
Franklin Volcanics	Drury Volcanic - Fielding Rd Volcanic	0.11	0.0153	26	0.0002**	0.001**
	Drury Volcanic – Hillview Spring (surface)	0.014	0.0005**	17.95	0.0002**	**0.008, Band B***
	Bombay Volcanic – BP Bombay	0.016	0.0005**	17	0.0002**	**0.062, Band D***
	Pukekohe Volcanic – Hickey Spring (surface)	0.011	0.0005**	20.5	0.0002**	0.001**
	Pukekohe Volcanic – Range Road Shallow	0.01	0.003	15.6	NA	NA
	Pukekohe Volcanic – Range Road Deep	0.03	0.02	27	NA	NA
	Pukekohe Volcanic-Patumahoe Spring (surface)	0.02	0.0005**	24	0.0002**	0.001**

	Parameter	Soluble iron (Fe)	Soluble manganese (Mn)	Soluble sodium (Na)	Soluble copper (Cu)	Soluble zinc (Zn)
	Guideline	**Aesthetic GV** (0.2 mg/L)	**MAV** (0.4 mg/L)	**Aesthetic GV** (200 mg/L)	**MAV** (2 mg/L) Surface Trigger Value ANZECC (0.0014 mg/L)	**MAV** (2 mg/L) Surface Trigger Value ANZECC (0.008 mg/L)
	Pukekohe Volcanic- Gun Club Rd	0.02	0.0006	24	0.0002**	0.019
Franklin Waitematā	Waiau Pa Waitematā – Seagrove Road	0.05	0.006	89	NA	NA
Franklin Kaawa	Pukekohe Kaawa-Ostrich Farm Road Shallow	**3.4**	**0.1045**	20	0.0002**	0.001**
	Pukekohe Kaawa-Ostrich Farm Road Deep	0.13	0.06	21	NA	NA
Bombay Drury Sand	Bombay Drury Sand – Fielding Rd Sand	**0.425**	0.0430	40.5	0.0002**	0.001**

**Table 3-4 – Band B and D – Developing Auckland-specific ecosystem health attributes for copper and zinc (Gadd, et al., 2019). Conversion from µg/L to mg/L. Total hardness modifications were not done but it is noted that this can affect zinc toxicity.*

*** >50% of observations were below the laboratory detection limit for this parameter.*

NA – these parameters are not monitored by the national groundwater monitoring programme.

4.1.1.3 Microbial indicators

The microbial assessment of groundwater for drinking water safety focuses on levels of *Escherichia coli* (*E. coli*) as an indicator organism for pathogenic contamination. The New Zealand drinking water guidelines MAV for *E. coli* is set as below detection level guideline for faecal contamination of groundwater, i.e., presence of *E. coli* at any concentration does not meet the MAV criterion.

An assessment of the current state of *E. coli* in Auckland council LTB monitored aquifers against the DWS-NZ (2018) can only be reported for a 2.5-year period (July 2017 to Dec 2019), and as such should be considered as a provisional state assessment (Table 4-3). Prior to this the *E. coli* laboratory detection limit was <1.6 cfu/100mL which is greater than the DWS-NZ guideline value. In mid-2017, Auckland Council changed laboratory providers and this change altered the detection limit to 1 cfu/100 ml. The approach taken here is to report on the proportion of samples that exceeded this *E. coli* MAV over the defined period. Aquifers monitored for the NGMP do not include reporting of *E. coli* as an indicator of faecal pathogens.

Sampling of springs is expected to be influenced by surface water flows in terms of monitored *E. coli* levels and should not be directly compared to shallow groundwater aquifers.

Table 4-3 Two-and-a-half-year median (Jul 2017 to Dec 2019) for *E. coli* in groundwater in Franklin aquifers.

	Parameter	*Well depth*	*Sample size (n)*	*% exceedance*	*Maximum exceedance*
	Guideline		MAV **(<1 cfu/100ml)**		(cfu/100 ml)
Franklin Volcanics	Drury Volcanic - Fielding Rd Volcanic	16-47 m	10	10	140
	Drury Volcanic – Hillview Spring (surface)	N/A	10	20	2
	Bombay Volcanic – BP Bombay	62-79 m	10	0	-
	Pukekohe Volcanic – Hickey Spring (surface)	N/A	10	40	5
	Pukekohe Volcanic-Patumahoe Spring (surface)	N/A	10	70	920
	Pukekohe Volcanic-Gun Club Rd	27 m	9	11	2
Franklin Kaawa	Pukekohe Kaawa-Ostrich Farm Rd Shallow	46-48 m	10	10	1
Bombay Drury Sand	Bombay Drury Sand – Fielding Rd Sand	57-64 m	10	0	-

4.1.1.4 Other water quality parameters

All three springs of the Franklin aquifers, Rifle Range Shallow, and Gun Club Rd (Pukekohe and Volcanic aquifer), and Seagrove Road (Waiau Pa Waitematā aquifer) had pH values outside the aesthetic GV (7.0-8.5 pH) for drinking water (Table 4-4).

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) can be a useful indicator of changes in abstraction, saltwater intrusion, or for interpreting results from deep aquifers. Although electrical conductivity results for the Franklin aquifers are low compared to surface waters (0.286-0.369 mS/cm), the Auckland region has some of the highest conductivites nationally (0.307-0.455 mS/cm from Auckland NGMP sites), alongside Northland and Whanganui-Manawatu (Table 4-4). These higher electrical conductivity values can be attributed to aquifers with highly reduced conditions, due to longer groundwater residence times (Moreau et al., 2016).

The Waiau Pa Waitematā aquifer had elevated sodium and chloride relative to other monitored sites (Na = 89 mg/L Table 4-2, and Cl = 36 mg/L Table 4-4). These values are consistent with values observed since the early 1990s and are indicative of increased residence time in sedimentary aquifers (Auckland Regional Council, 1993). The inland volcanic aquifers of the Franklin area have lower values for sodium and chloride (Na ranging between 15.6-40.5 mg/L Table 4-2, Cl ranging between 17-28 mg/L Table 4-4). However, none of the Franklin sites breach the drinking water aesthetic GVs for these parameters.

All Franklin volcanic aquifers fall into the moderately soft category of hardness. Elevated levels of hardness can cause depositions in pipes, hot water cylinders and kettles. Water with low hardness (<100 mg/L, DWS-NZ, 2019) can sometimes contribute to corrosion of plumbing fittings and metals that come into contact with groundwater. The Drury Volcanic (Fielding Road Volcanic) and the Pukekohe Volanic aquifer (Patumahoe Spring and Gun Club Rd) had total hardness values above the aesthetic GV "taste" threshold (Table 4-4).

Table 4-4 Five-year median (2015-2019) for other parameters in groundwater in the Franklin aquifers. Values in bold and red are above guideline values and values in yellow and bold are above "taste" values.

	Parameter	pH	Alkalinity (mg/L)	DO (mg/L)	EC (mS/cm)	Chloride (Cl)	Total Hardness	TDS	Sulphate (SO_4)
	Guideline	AGV (7.0-8.5)	NA	NA	NA	Aesthetic GV (250 mg/L)	Aesthetic GV (200 mg/L)	Aesthetic GV (1000 mg/L)	Aesthetic GV (250 mg/L)
Franklin Volcanics	Drury Volcanic - Fielding Road Volcanic	8.2	138	0.12	0.326	21	**109**	200	3.3
	Drury Volcanic – Hillview Spring (surface)	**6.6**	46	9.08	0.294	22	91	235	2.5
	Bombay Volcanic – BP Bombay	7.1	64	7.92	0.286	20	93	220	2.1
	Pukekohe Volcanic – Hickey Spring (surface)	**6.3**	36	8.57	0.3	23	86	240	3.6
	Pukekohe Volcanic – Rifle Range Road Shallow	**6.9**	NA	NA	NA	17	NA	NA	NA
	Pukekohe Volcanic – Rifle Range Road Deep	**8.4**	NA	NA	NA	23	NA	NA	NA
	Pukekohe Volcanic-Patumahoe Spring (surface)	**6.3**	32	8.44	0.352	27	**101**	280	3.1
	Pukekohe Volcanic-Gun Club Rd	**6.4**	32	8.58	0.369	28	**107**	290	3.1

	Parameter	pH	Alkalinity (mg/L)	DO (mg/L)	EC (mS/cm)	Chloride (Cl)	Total Hardness	TDS	Sulphate (SO_4)
	Guideline	AGV (7.0-8.5)	NA	NA	NA	Aesthetic GV (250 mg/L)	Aesthetic GV (200 mg/L)	Aesthetic GV (1000 mg/L)	Aesthetic GV (250 mg/L)
Waitematā	Waiau Pa Waitematā	**8.9**	NA	NA	NA	36	NA	NA	NA
Franklin Kaawa	Pukekohe Kaawa-Ostrich Farm Road Shallow	7.1	120	0.12	0.302	20	98	220	0.5
Franklin Kaawa	Pukekohe Kaawa-Ostrich Farm Road Deep	8.0	NA	NA	NA	21	NA	NA	NA
Bombay Drury Sand	Bombay Drury Sand – Fielding Rd Sand	7.8	161	0.07	0.359	19	91	250	0.5

4.1.2 Ten-year trends in water quality for Franklin aquifers (2010-2019)

In comparison to the last trend reporting (data to 2013, Kalbus et al., 2017) where both Hillview Springs (Drury Volcanic aquifer) and Gun Club Road (Pukekohe Volcanic aquifer) had shorter periods of data on record than the other sites, this current trend reporting is over a similar length of time for all sites (nominally 10 years), which makes trend comparison between sites more robust.

4.1.2.1 Nutrients

Nine of the Franklin aquifers had *very likely* improving trends in ammonia (six Franklin Volcanic, two Franklin Kaawa and the Waiau Pa Waitematā sites), and the Bombay Drury Sand aquifer had a *very likely* degrading trend in this parameter (Figure 4-1). Of the aquifers that had *very likely* improving trends, only four had magnitudes of change that exceeded the limit of precision for this parameter (>0.001 mg/L). The Waiau Pa Waitematā aquifer had the greatest magnitude of improvement with an estimated rate of 0.01 mg/L per annum (Figure 4-2).

Bombay Drury Sand had the greatest rate of change for ammonia (Figure 4-2), which was *very likely* degrading at an estimated rate of 0.029 mg/L per annum (confidence intervals of 0.01-0.04 mg/L per annum), this is coupled with the highest ammonia state value of any of the Franklin aquifers.

As stated in Section 4.1.1.1, shallow volcanic aquifers in the Franklin area are contaminated with nitrate due in part to high levels of nitrogen fertiliser, poor soil structure, and low soil carbon, which ultimatly leads to nutrient leaching from horticultural activities. Although nitrate concentrations are generally high, some aquifers are exhibiting improving trends.

Seven of the Franklin sites had improving trends and four had degrading trends in groundwater nitrate. The six sites that had *very likely* improving trends were: four sites in the shallow Pukekohe Volcanic aquifer (Hickey Springs, Patumahoe Springs, Gun Club Road, and Rifle Range Road Shallow), one site in the Drury Volcanic aquifer (Fielding Road Volcanic) and one site in the Franklin Kaawa aquifer (Ostrich Farm Road Shallow) (Figure 4-1). Of all the *very likely* improving trends the annual rate of change only exceeded the limit of precision (for this parameter, ≥0.001 mg/L) for the Pukekohe Volcanic aquifer sites (Figure 4-3). The Drury Volcanic and Franklin Kaawa sites did not meet this criterion. Rifle Range Road Shallow (Pukekohe Volcanic aquifer) had the greatest magnitude of improvement of all sites over the period of analysis at 0.681 mg/L per annum (confidence intervals of 0.292-0.541 mg/L per annum), and a median current state of 9.7 mg/L. This trend direction for nitrate was opposite to that reported by Kalbus et al., 2017, and reflects the most recent 10-year period, which does not include much lower nitrate concentrations recorded to mid-2010. We are unable to identify the reason for the step change in nitrate concentrations recorded at this site.

Improving trends in groundwater nitrate concentrations in shallow volcanic aquifers over the last 10 years may indicate there have been changes in land management practices in recharge zones that support this aquifer. However, small annual rates of change (Rifle Range Road Shallow as an exception) coupled with long groundwater residence times (~50 years) suggest that nitrate concentrations will not drop below national drinking water or instream ecosystem health guidelines for many years to come. High-nitrate groundwater will continue to discharge into streams via baseflow in the interim.

Of the four sites with degrading trends (Figure 4-1), two had *very likely* degrading trends (Bombay Volcanic and Waiau Pa Waitematā), and two had *likely* degrading trends; Hillview Springs (Drury Volcanic) and Ostrich Farm Road Deep (Pukekohe Kaawa). Of the *very likely* degrading trends BP Bombay had the greatest magnitude of degradation at a rate of 0.120 mg/L per annum (with a current median state of 11 mg/L) (Figure 4-3). Although the Waiau Pa Waitematā aquifer had a *very likely* degrading trend, the sen slope was influcened by two or more censored values and was not considered further for magnitiude of degradation. The degrading nitrate trend at BP Bombay was consistent with that previously reported by Kalbus et al. (2017). Hillview Springs showed degrading nitrate concentrations, an opposite trend in nitrate to that identified from a smaller three-year dataset analysed by Kalbus et al. (2017).

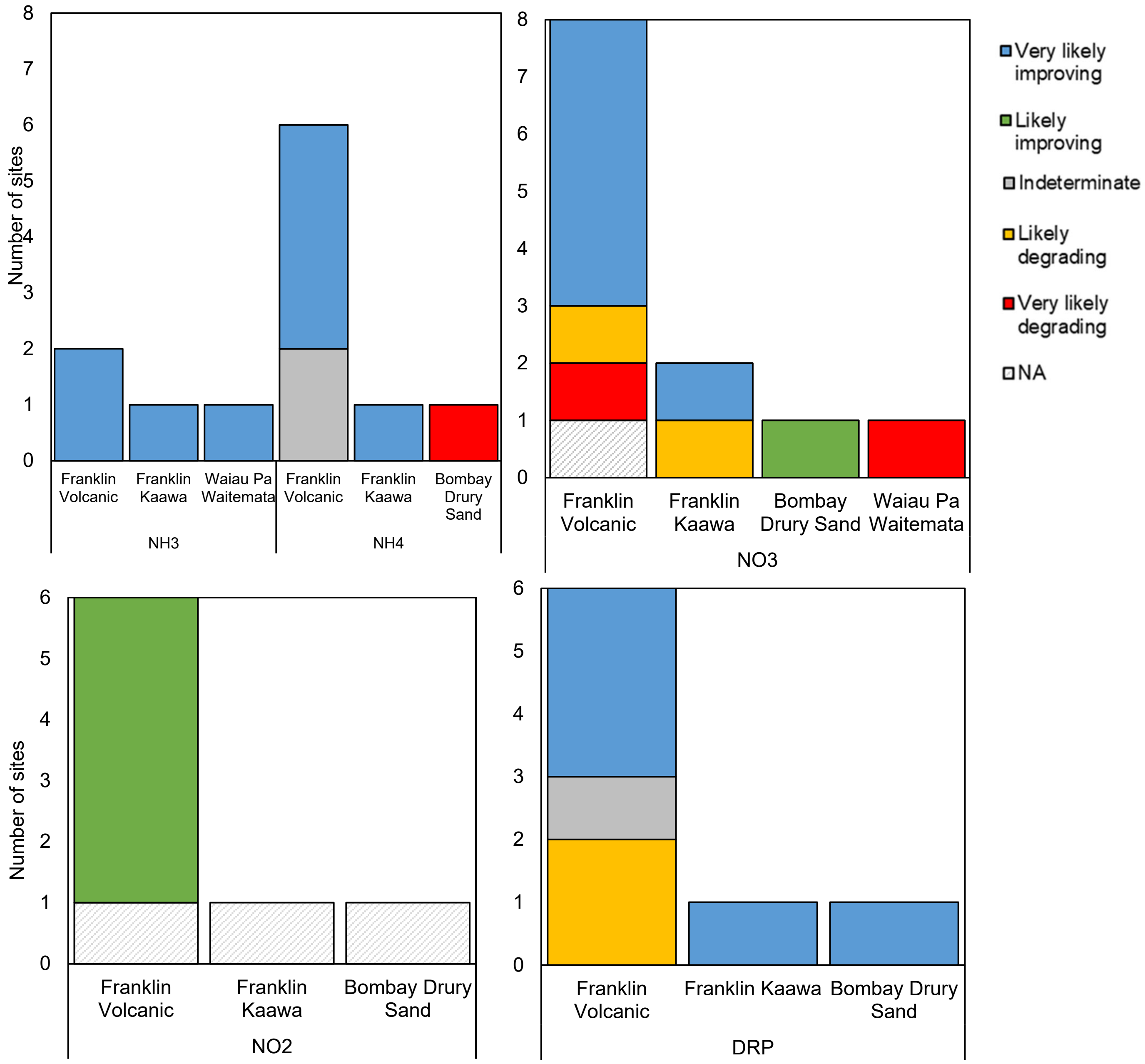

Figure 4-1 Summary of 10-year (2010-2019) trends in nutrient concentrations for Franklin aquifers, showing the number of sites per trend category by parameter.

Only eight of the 12 monitored Franklin sites could be assessed for trends in nitrite as this is not monitored by the NGMP. Most of the nitrite trends were *likely* improving for the Franklin Volcanic aquifers and the remaining trends were not assessed due to too many tied data points and not enough unique values (Figure 4-1).

Only eight of the 12 monitored Franklin sites could be assessed for trends in DRP due to intermittent DRP analyses for the NGMP sites. The Pukekohe Volcanic, Franklin Kaawa, and Bombay Drury Sand aquifers all had *very likely* improving trends for DRP (Figure 4-1). The volcanic aquifers had the smallest magnitude rates of change that were close to the limit of precision (≥0.001 mg/L), estimated rates of change were ~ 0.002 mg/L per annum. Of note, the Drury Sand aquifer had the worst DRP state value (0.179 mg/L, Table 4-1) but had the greatest estimated rate of annual improvement 0.004 mg/L with a wide confidence interval (0.003-0.004 mg/L) (Figure 4-4).

Although the state for these sites exceeded the ANZECC surface water trigger value, long-term trends are showing improvement. This may be due to decreases in phosphorus fertilisers and therefore decreases in soil Olsen P that can make its way into groundwater.

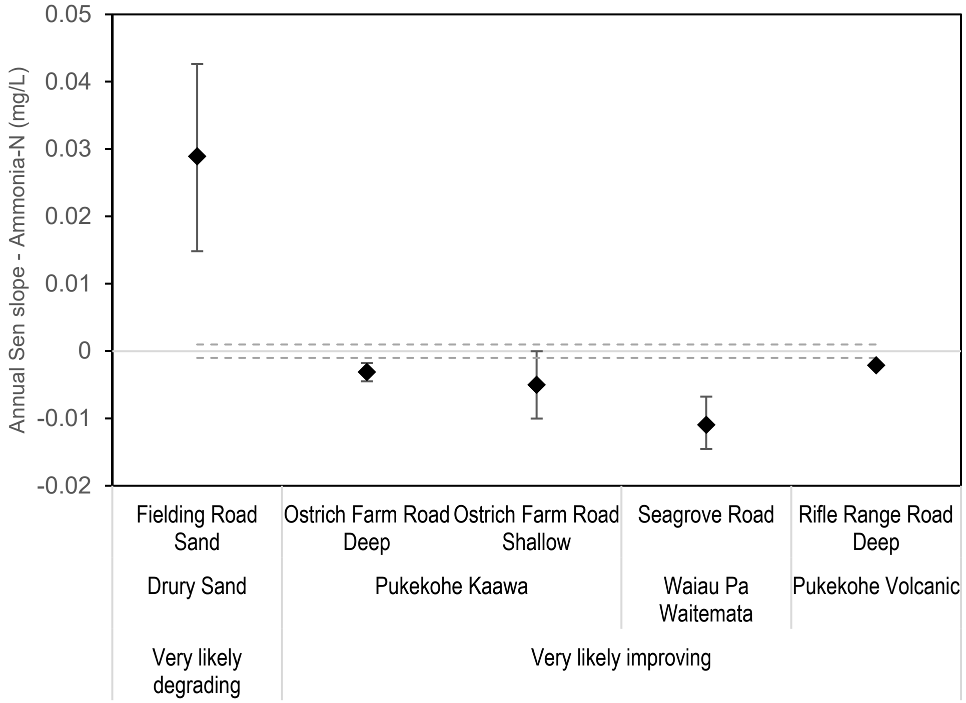

Figure 4-2 The estimated annual Sen slope (in units of parameter) for Ammonia-N for the Franklin aquifers with *very likely* trends. The limit of precision is displayed by the dashed lines. Error bars are 95% confidence intervals of the slope estimate.

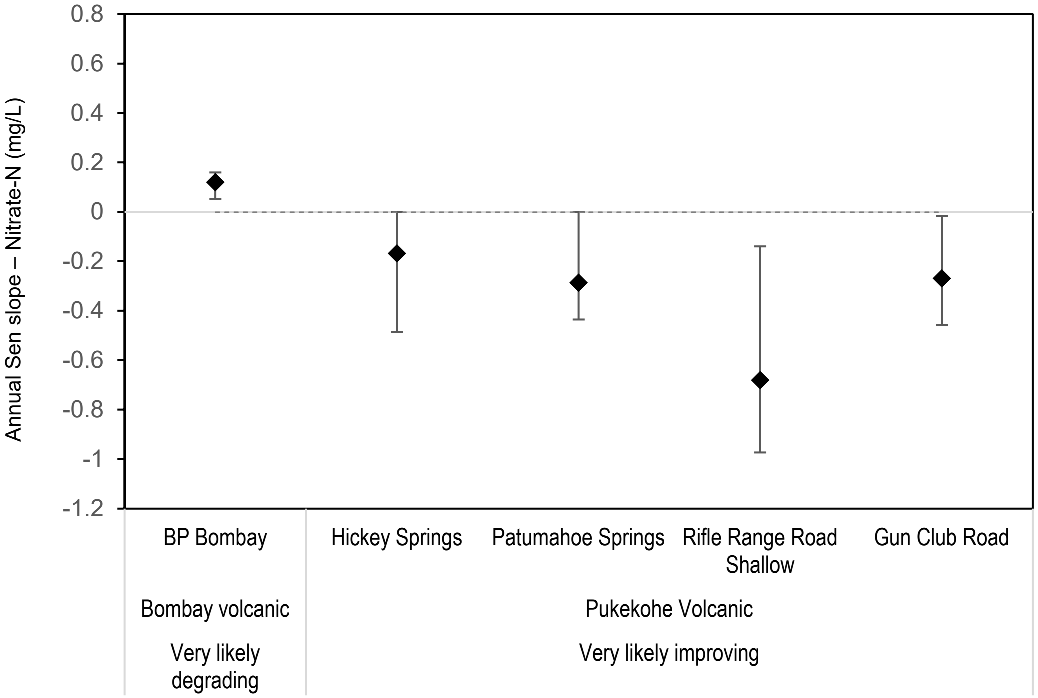

Figure 4-3 The estimated annual Sen slope (in units of parameter) for Nitrate-N for the Franklin aquifers with very likely trends. The limit of precision (≥0.001 mg/L) is too small to be displayed at this scale. Error bars are 95% confidence intervals of the slope.

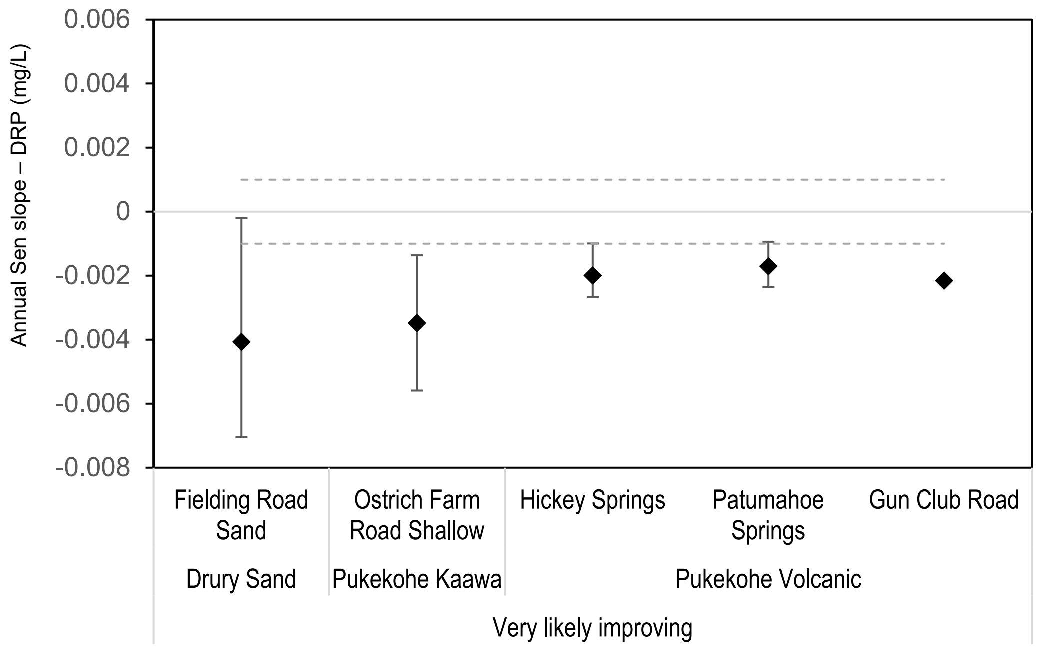

Figure 4-4 The estimated annual Sen slope (in units of parameter) for DRP for the Franklin aquifers with very likely trends. The limit of precision is shown with dashed lines. Error bars are 95% confidence intervals of the slope estimate.

4.1.2.2 Metals

Soluble zinc, manganese, and copper were analysed for all Auckland Council monitored Franklin aquifers, but trend analysis could not be undertaken because of the high percentage of censored values for these sites, or alternatively, they did not meet the required observations cut off.

For soluble iron, two of the Franklin sites had improving trends and four had degrading iron trends (Figure 4-5), while three sites had indeterminate trends. One site in the Drury Volcanic aquifer (Hillview Springs), and one site in the Pukekohe Volcanic aquifer (Rifle Range Road – Deep) (Figure 4-5) had *very likely* improving trends, however, neither of these sites had trends with magnitudes greater than the limit of precision for this parameter (≥0.001 mg/L). Fielding Road Volcanic (Drury Volcanic aquifer) and Ostrich Farm Road Shallow (Pukekohe Kaawa) had *very likely* degrading trends, both with a trend magnitude which exceeded the limit of precision for this parameter. Ostrich Farm Road Shallow had the greatest magnitude of change with an estimated rate of 0.027 mg/L per annum (Figure 4-6).

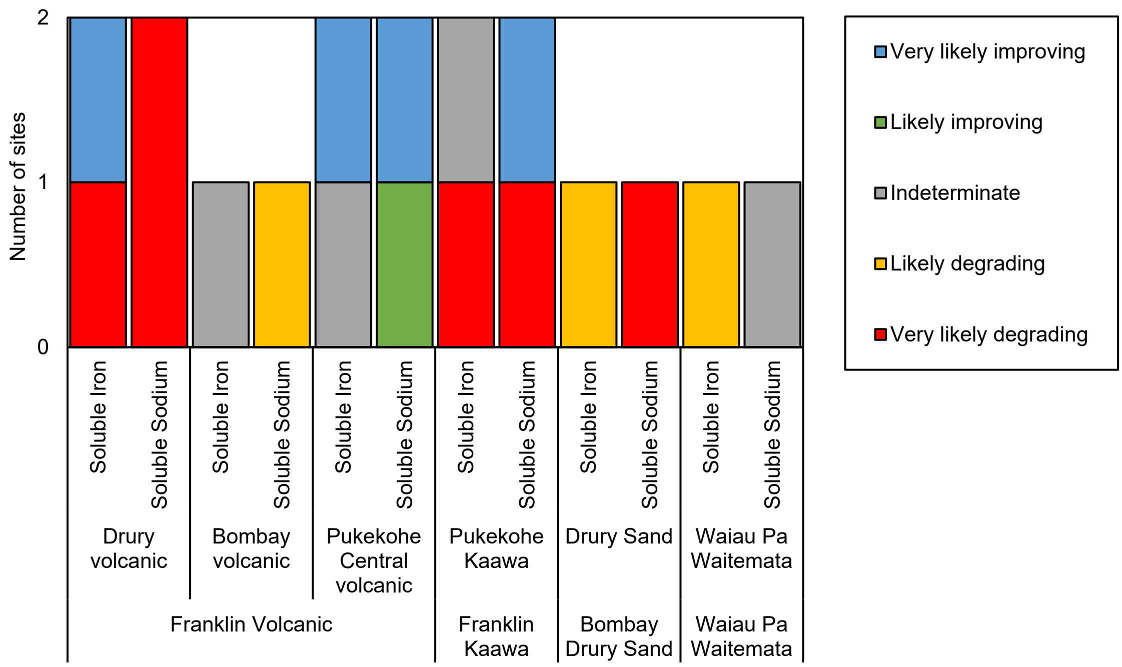

Figure 4-5 Summary of 10-year (2010-2019) soluble iron and sodium trends in groundwater for the Franklin aquifers, showing the number of sites per trend category.

The Drury and Bombay Volcanics, Pukekohe Kaawa (Ostrich Farm Road Shallow) and Bombay Drury sand aquifers all had degrading trends in soluble sodium. The Pukekohe Volcanic and Ostrich Farm Road Deep (Pukekohe Kaawa) aquifers had improving trends in sodium (Figure 4-5). No aquifers with *very likely* trends (Drury Volcanic, Pukekohe Kaawa and Bombay Drury Sand) exceeded the limit of precision for this parameter (≥1 mg/L).

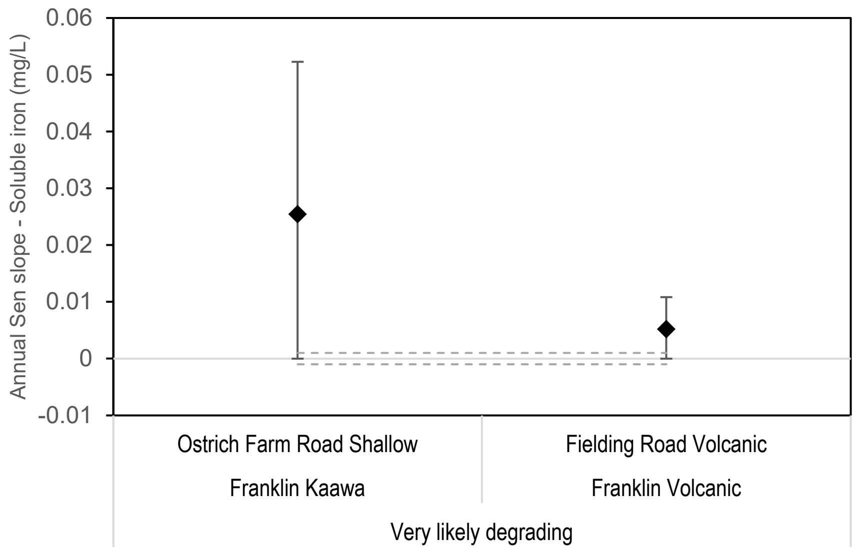

Figure 4-6 The estimated annual Sen slope (in units of parameter) for soluble iron for the Franklin aquifers with *very likely* trends. The measurement precision limit is shown with dashed lines. Error bars are 95% confidence intervals of the slope estimate.

4.1.2.3 Microbial indicators

Only Auckland Council monitored sites could be analysed for microbial trend analysis, as NGMP sites are not monitored for *E. coli*. Hickey Springs, Patumahoe Springs and Gun Club Road did not meet the required number of observations (26/40 for the 10-year period) to be analysed for trends in *E. coli*. Of the five remaining Franklin sites that had the required number of observations, only Hillview Springs was analysed for trends, as the remaining sites had too many tied values. This site returned a *likely* improving trend which was potentially induced by changes in detection limits.

4.2 Kumeu West Waitematā aquifer

The Kumeu West Waitematā aquifer represents another important horticulture growing area in the Auckland region that has been utilised for groundwater abstraction for at least the last 75 years. Horticultural water users have been attracted to Kumeu because of the proximity to Auckland city, soils suitable for horticulture and the ready supply of high-quality groundwater (Scoble & Millar, 1995).

4.2.1 Groundwater quality current state of the Kumeu West Waitematā aquifer

The only measured parameter of note for the groundwater quality state of the Kumeu West Waitematā aquifer was iron, both shallow and deep sites are above the aesthetic guideline value (as has been reported previously by Scoble & Millar, 1995). Iron is naturally occurring in groundwater due to weathering of the surrounding geology, however, it can become an issue for corrosion of equipment and staining of laundry (Daughney, 2003 and MoH, 2019) (Table 4-5). Of the nitrogen species, ammonia nitrogen is the most common form found in this aquifer (Table 4-5). The chloride and sodium results for the Waitakere Road Deep site are similar with that of the Waiau Pa Waitematā aquifer, where the geology is comprised of ocean derived sedimentary rocks that have naturally higher sodium and chloride concentrations (Mullaney et al., 2009).

Table 4-5 Five-year medians (2015-2019) for all parameters in the Kumeu West Waitematā aquifer. Values in bold and red are above guideline values.

Parameter	Guideline	Waitakere Road Deep	Waitakere Road Shallow
Ammonia N	Aesthetic GV (1.5 mg/L)	0.3	0.15
Nitrate N	MAV short term (11.3 mg/L) ECNC (2.5 mg/L)	0.01	0.01
Soluble iron	Aesthetic GV (0.2 mg/L)	**1.1**	**6.2**
Soluble manganese	MAV (0.4 mg/L)	0.06	0.12
Soluble sodium	Aesthetic GV (200 mg/L)	36	21
pH	Aesthetic GV (7.0 - 8.5)	7.5	**6.7**
Cl	Aesthetic GV (200 mg/L)	71	26
Soluble Sulphate	Aesthetic GV (250 mg/L)	0.03	0.03

4.2.2 Ten-year trends in water quality of the Kumeu West Waitematā aquifer (2010-2019)

4.2.2.1 Nutrients

Ammonia was *very likely* improving in both the shallow and deep Kumeu West Waitematā aquifers (Figure 4-7), with a median state of 0.16 and 0.33 mg/L respectively. Both sites have trends which exceed the limit of precision for this parameter (≥0.001 mg/L) and the estimated rates of change are very small, 0.003 and 0.008 mg/L per annum respectively (Figure 4-8).

Waitakere Road Deep had a likely degrading trend for nitrate and Waitakere Road Shallow was not analysed due to the dataset containing less than three unique values. Nitrate concentrations in the Waitakere Road Deep site are very low (long-term median value of 0.005 mg/L).

4.2.2.2 Metals

Waitakere Road Shallow had improving trends for all metals, iron and sodium had *very likely* improving trends (Figure 4-7). The estimated Sen slope for iron exceeded the limit of precision (≥0.001 mg/L) and had an estimated rate of improvement of 0.072 mg/L per annum (confidence interval of ±0.05 mg/L) (Figure 4-8). The estimated Sen slope for sodium did not exceed the level of precision (≥1 mg/L). The current state of iron in the shallow extent of the aquifer was above the NZDWS aesthetic GV but 10-year trends suggest improvement.

Waitakere Road Deep had a *likely* degrading trend in manganese and a *very likely* improving trend in sodium (this trend did not meet the limit of precision for further analysis). Soluble iron returned an indeterminate trend.

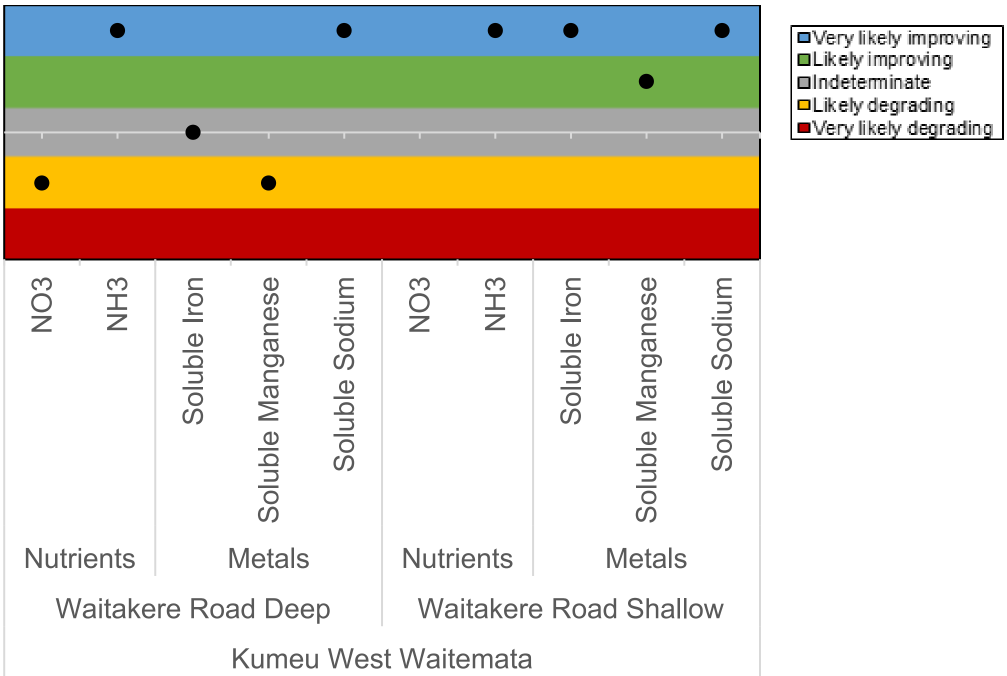

Figure 4-7 Summary of 10-year trends (2010-2019) for nutrient and metal parameters for the Kumeu West Waitemata aquifers.

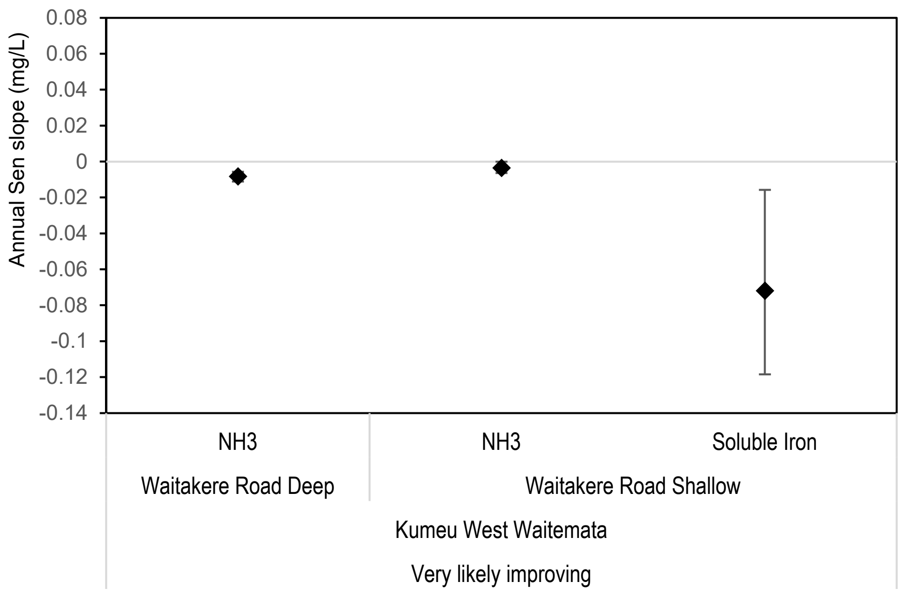

Figure 4-8 The estimated annual Sen slope (in units of parameter) for ammonia (NH3) and iron, for the Kumeu West Waitemata aquifers with very likely trends. Error bars are 95% confidence intervals of the slope estimate.

4.3 Auckland Isthmus – Three Kings Volcanic aquifer

Stormwater is one of the main pressures on the Three Kings Volcanic aquifer. Stormwater runoff in an urban environment can contain elevated concentrations of nutrients, metals (zinc and copper), and organic contaminants. Soakage devices (including bores and soak pits) have been installed over the last 60 years to prevent urban stormwater runoff from entering directly into streams in the surrounding catchments (Meola and Western Springs). Soakage devices with rock bores discharge stormwater directly to the underlying aquifer. Treatment of stormwater to the relevant standard is necessary to protect water quality in groundwater receiving environments (Strayton & Lillis, 2013). Some stormwater treatment may be accomplished via sediment chambers and raingardens.

Groundwater flows through the fractured basalt aquifer and discharges into Western Springs. If groundwater quality is compromised it can then impact surface water through baseflow provision (Hong et al., 2001). Recharge of the aquifer has doubled post-urbanisation due to the use of stormwater soak holes (Viljevac et al., 1999 and Rosen et al., 2000). A study on the effects of stormwater infiltration in this fractured rock aquifer was undertaken by Rosen and colleagues in 2000 and they concluded that the relatively high quality of the water in the wells monitored may be attributed to the ability of the accumulated sediment in the soak holes and the aquifer fractures to trap contaminants (Rosen et al., 2000). Water quality sampling in the Three Kings Volcanic aquifer allows ongoing monitoring of the effects of stormwater soakage on this groundwater receiving environment.

Auckland Council adopted a water sensitive design approach in 2015 to manage stormwater quality (additional to the existing 'low impact design' approach at the time) and minimise the effects on aquatic ecosystems (this document is commonly known as GD04 – Water Sensitive Design for Stormwater, Lewis et al., 2015). Pre-treatment of stormwater is required (in areas of high sediment loading) before it enters soakage areas to minimise adverse effects on groundwater quality. Soakage infiltration devices have been constructed with the Auckland Isthmus Volcanic aquifers receiving environment to remove excess contaminants and sediment (see Section 5.4 Soakage Infiltration Devices: *Stormwater Disposal via Soakage in the Auckland Region*, Strayton et al., 2013). The Watson Ave groundwater quality site in the Three Kings Volcanic aquifer is directly down-gradient from several soak holes in Balmoral. The current groundwater state and trends as reported here for the Three Kings Aquifer provides an indication of the efficacy of the water sensitive design principles and adequacy of soakage infiltration devices with respect to groundwater quality.

4.3.1 Groundwater quality current state in an urban aquifer (2015-2019)

4.3.1.1 Nutrients

Although the Three Kings Volcanic aquifer is not used for drinking water supply, groundwater quality parameters are compared to these guidelines for consistency with reporting of previous aquifers. Ammonia and nitrite were below aesthetic and human health drinking water guideline values with multiple nitrite levels below the limits of detection for the laboratory method (Table 4-6). The median nitrate concentration was 3.75 mg/L (Table 4-6), indicating some anthropogenic input (i.e., > 2.5 mg/L, Morgenstern & Daughney, 2012). This was similar to that previously reported by Kalbus et al., 2017 at 4.00 mg/L. Nitrate was above the National Bottom Line (NBL) for river surface waters, >2.4 mg/L, which was recently set to protect 95 per cent of instream species, (MfE, National Policy Statement for Freshwater Management, 2020). The Three Kings aquifer discharges down gradient into Western

Springs lake and as such contributes groundwater to this ecosystem. Nitrate concentrations are elevated above presumed natural levels; however elevated nitrate has been observed for nearly 100 years. Rosen et al. (2000) note that nitrate concentrations in this aquifer had not changed significantly from 1925 to 1999 (at around 5 mg/L). This indicates that either background nitrate is naturally higher in the Western Springs volcanic aquifer or that anthropogenic effects have occurred for a long time.

The Three Kings Volcanic aquifer was above the surface water ANZECC DGV (0.01 mg/L) for dissolved reactive phosphorus (DRP) with a median value of 0.065 mg/L (Table 4-6). The phosphorus concentrations were most likely naturally derived; groundwater interacts with volcanic rock and phosphorus increases via dissolution of volcanic glass (Morgenstern & Daughney, 2012, and Morgenstern et al., 2015).

Table 4-6 Five-year median (2015-2019) for all parameters in the Three Kings Volcanic aquifer (Auckland Isthmus), as assessed against guideline values. Values in bold and red are above various guideline values.

Parameter	Guideline	Auckland Isthmus (Three Kings Volcanic)
Ammonia N	Aesthetic GV (1.5 mg/L)	0.009
Nitrite N	MAV short term (0.91 mg/L)	0.001**
Nitrate N	MAV short term (11.3 mg/L) ECNC (2.5 mg/L)	**3.75**
Dissolved Reactive Phosphorus (DRP)	ANZECC surface water Trigger Value (0.01 mg/L)	**0.065**
Soluble iron	Aesthetic GV (0.2 mg/L)	0.047
Soluble manganese	MAV (0.4 mg/L)	0.010
Soluble sodium	Aesthetic GV (200 mg/L)	22
Soluble zinc	MAV (2 mg/L), ANZECC surface water Trigger Value (0.008 mg/L)	**0.012, *Band C**
Soluble copper	MAV (2 mg/L), ANZECC surface water Trigger Value (0.0014 mg/L)	0.0008, #Band A
pH	Aesthetic GV (7.0 - 8.5)	**6.89**
Alkalinity	NA (mg/L)	48
DO	NA (mg/L)	6.55
EC	NA (mS/cm)	0.214
Cl	Aesthetic GV (200 mg/L)	18
Total Hardness	Aesthetic GV (200 mg/L)	44
Total Dissolved Solids (TDS)	Aesthetic GV (1000 mg/L)	140
Soluble Sulphate	Aesthetic GV (250 mg/L)	12.85

** Table 3-4 – Band C – Developing Auckland-specific ecosystem health attributes for copper and zinc. Conversion from µg/L (> 8 ≤31) to mg/L (>0.008 ≤0.031). Total hardness modifications were not done but it is noted that this can affect zinc toxicity.*

 # Table 3-3 – Band A – Developing Auckland-specific ecosystem health attributes for copper and zinc. Conversion from µg/L (≤1) to mg/L (0.001 mg/L).

*** >50% of observations were below the limit of detection for this parameter*

4.3.1.2 Metals

The current state of manganese and iron concentrations was below aesthetic and human health drinking water guideline values in the Three Kings volcanic aquifer. This is characteristic of an oxygenated aquifer (White et al., 2019). Zinc and copper are monitored as potential indicators of urban stormwater contaminants and both parameters were below drinking water guideline values.

The current state of metals was compared to ANZECC (2000) Trigger Values because the Three Kings aquifer discharges into surface water bodies. Zinc exceeded the ANZECC limit and was within Band C of the Auckland-specific regional zinc ecosystem health attribute table for surface water (Gadd et al., 2019). The median zinc concentration tripled from 0.004 mg/L in 2013 (Kalbus et al., 2017) to 0.012 mg/L in 2019; and was of a similar magnitude to that previously reported for other Central Isthmus volcanic aquifers.

4.3.1.3 Microbial Indicators

Three Kings Volcanic aquifer was consistently impacted by microbial contamination of faecal origin, as evidenced by all monitored observations exceeding the *E. coli* MAV of 1 cfu/100 mL over the last two and half years. Values ranged between 34-270 cfu/100 ml (Table 4-7).

Table 4-7 Two-and-a-half-year median (Jul 2017 to Dec 2019) for *E. coli* in groundwater in the Three Kings volcanic aquifer.

	Parameter	***Well depth***	***Sample size (n)***	***% exceedance***	***Maximum exceedance***
	Guideline		MAV **(<1 cfu/100ml)**		(cfu/100 ml)
Auckland Isthmus	Three Kings Volcanic – Watson Ave	**32-38 m**	**10**	**100**	**270**

4.3.1.4 Other

The Three Kings Volcanic aquifer had a median pH value of 6.89 which was slightly outside the pH New Zealand drinking water aesthetic GV bounds (Table 4-6). This aquifer is shallow and comprises permeable basalt making it highly influenced by rainfall, stormwater, atmospheric and soil interactions. Electrical conductivity provides a measure of total dissolved solids in the aquifer and is a useful indicator of abstraction and recharge mechanisms. There are no human health or ecosystem health indicators for electrical conductivity, but this aquifer had the lowest measured electrical conductivity of all monitored Auckland aquifers. The Three Kings Volcanic aquifer also had the softest water of all monitored sites (44 mg/L $CaCO_3$). Values below 100 mg/L are more corrosive (DWS-NZ, 2019). Total dissolved solids were also low compared to drinking water guidelines and were comparable to levels reported previously by Kalbus et al. (2017).

4.3.2 Ten-year trends in water quality in an urban aquifer (2010-2019)

4.3.2.1 Nutrients

Ammonia concentrations were *likely* degrading through time (Figure 4-9); and the median value was well below the aesthetic GV (1.5 mg/L). Trends in nitrite were unable to be determined because of the large number of values reported below the laboratory detection limit. Nitrate was *very likely* improving in the Three Kings aquifer at an estimated rate of 0.066 mg/L per annum (confidence interval of ±0.040 mg/L) (Figure 4-10). This was greater than the precision limit of ≥0.001 mg/L for this parameter. Although nitrate was showing improvement, the estimated magnitude of change was very small, suggesting that nitrate concentrations may not drop below natural groundwater conditions (<2.5 mg/L) for years to come, as influenced by groundwater residence times (inferred ~50-year residence times in Section 2.1.5).

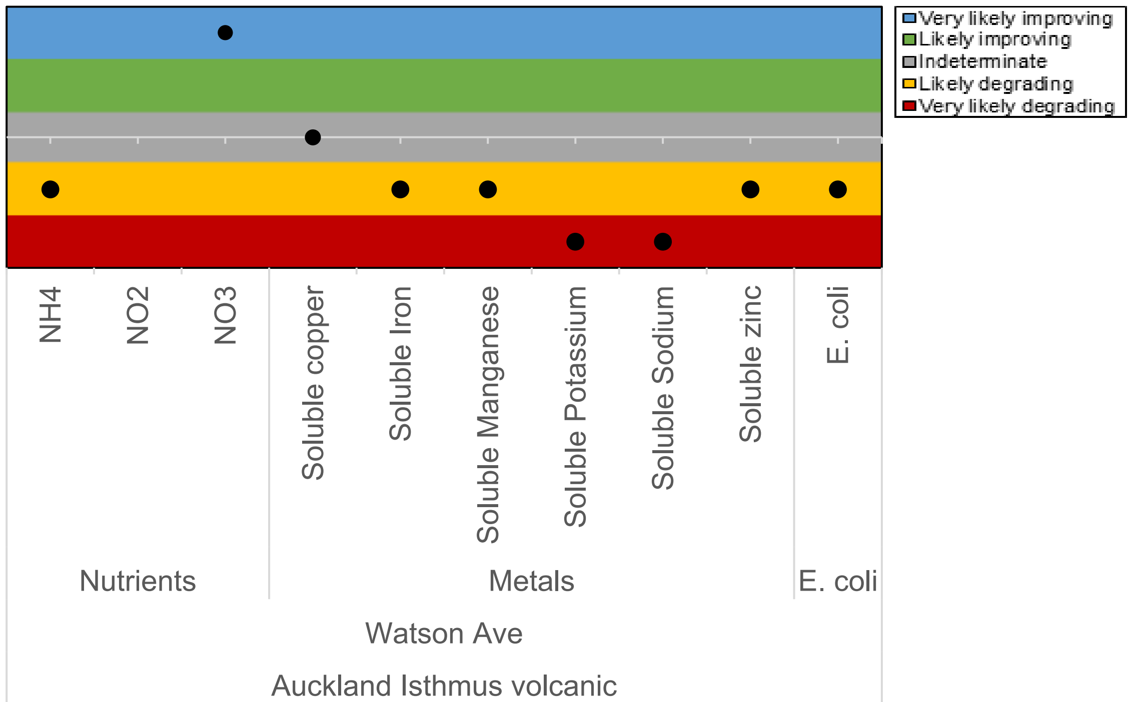

Figure 4-9 Summary of 10-year trends (2010-2019) for nutrients, metals, and microbial parameters for the Three Kings Volcanic Aquifer – Auckland Isthmus.

4.3.2.2 Metals

All metals for the Three Kings Volcanic aquifer had degrading trends, except for soluble copper which had an indeterminate trend (Figure 4-9). The degrading zinc trend direction was the same as established by Kalbus et al. (2017), suggesting that trends in zinc concentrations should be further evaluated through time.

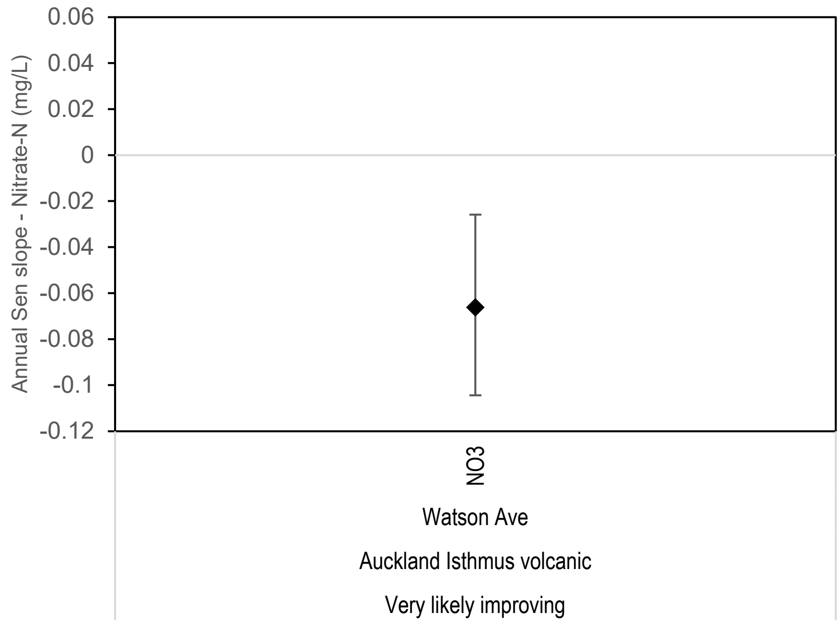

Figure 4-10 The annual Sen slope (in units of parameter) for nitrate for the Three Kings Volcanic aquifer where *very likely* trends were detected. The measurement limit of precision is 0.001 mg/L. Error bars are 95% confidence intervals.

4.3.2.3 Microbial indicators

The current state of *E. coli* in the Three Kings Volcanic aquifer in combination with the *likely* degrading trend suggests that faecal contamination may be worsening in this aquifer. This aquifer is not used as a drinking water source.

4.4 Water quality of all monitored aquifers

This section is a summary of the state and trends for parameters that are compromising the water quality for all monitored aquifers. A synopsis used to identify the overall water quality of the Franklin aquifers, Kumeu West Waitematā and Three Kings Volcanic aquifers.

4.4.1 Groundwater quality for the Franklin area

Six of the twelve monitored sites in shallow Franklin aquifers had nitrate levels above ECNC and four were above MAV. All six sites belong to the shallow Franklin Volcanic aquifers. Franklin Kaawa, Waiau Pa Waitematā and Bombay Drury Sand aquifers showed no sign of nitrate contamination. The Pukekohe Volcanic aquifer (Hickey Springs, Patumahoe Springs, and Gun Club Rd) had *very likely* improving trends in nitrate but nitrate levels were above safe human consumption guidelines and were above ecosystem health guideline levels for connected surface water receiving environments (Table 4-8).

High nitrates in water (>11.3 mg/L) can cause methemoglobinemia in bottle fed babies (<6 months old), and pregnant woman are also advised to avoid drinking this water (MoH, 2019). Fielding Rd Volcanic showed no contamination of nitrates. The redox conditions are different between Fielding Road and Hillview Springs. Although the two sites belong to the same aquifer management unit (Drury volcanic aquifer), the two sites are not connected by contiguous volcanic geology and thus are not hydraulically linked.

Franklin Kaawa and Bombay Drury Sand aquifers had median values over the aesthetic guideline for iron and *likely* to *very likely* degrading long-term trends, however, iron was above the drinking water aesthetic guideline value (Table 4-8).

Table 4-8 Water quality of the Franklin aquifers, a summary of state (2015-2019) and 10-year trends (2010-2019).

Aquifer zone	AMA	Site	State	Long-term trends	Safe to drink**	Overall water quality
Franklin Volcanics	Drury Volcanic	Fielding Road Volcanic	**No values above guidelines**	***Very likely* improving nitrate trend**	**Yes**	**Good**
		Hillview Springs	**Nitrate exceeded both guidelines**	***Likely* degrading nitrate trend**	**No**	**Poor**
	Bombay Volcanic	BP Bombay*	**Nitrate exceeds ECNC**	***Very likely* degrading nitrate trend**	**No**	
	Pukekohe Volcanic	Hickey Springs	**Nitrate exceeded both guidelines**	***Very likely* improving nitrate trend**	**No**	
		Rifle Range Deep	**No values above guidelines**	**No degrading trends of note**	**Yes**	**Good**
		Rifle Range Shallow	**Nitrate exceeds ECNC and close to MAV**	***Very likely* improving nitrate trend**	**No**	**Poor**
		Gun Club Road	**Nitrate exceeded both guidelines**	***Very likely* improving nitrate trend**	**No**	
		Patumahoe Springs	**Nitrate exceeded both guidelines**	***Very likely* improving nitrate trend**	**No**	
Franklin Kaawa	Pukekohe Kaawa	Ostrich Farm Road Deep	**No values above guidelines**	***Likely* degrading nitrate trend**	**Yes**	**Good**
		Ostrich Farm Road Shallow	**Iron exceeded aesthetic guideline**	***Very likely* degrading iron trend**	**Yes**	**Good**
Franklin Sand	Bombay Drury Sand	Fielding Road Sand	**Iron exceeded aesthetic guideline**	***Likely* degrading iron trend**	**Yes**	**Good**
Franklin Waitematā	Waitematā	Waiau Pa Waitematā	**No values above guidelines**	***Very likely* degrading nitrate trend**	**Yes**	

*** The status of groundwater for drinking outlined here is only undertaken at a broad level and does not replace a compliance level assessment against the NZDWS for community supply.*

4.4.2 Groundwater quality for the Kumeu West Waitematā aquifer

Water quality for the Kumeu West Waitematā aquifer had no exceedances of drinking water guidelines or trends indicating a risk to human or ecosystem health (Table 4-9).

Table 4-9 Water quality of the Kumeu West aquifers, a summary of state (2015-2019) and 10-year trends (2010-2019).

AMA	Site	State	Long-term trends	Safe to drink	Overall water quality
Kumeu West Waitematā	Waitakere Road Deep	**Iron exceeded aesthetic guideline**	***Likely* degrading nitrate trend**	**Yes**	**Good**
	Waitakere Road Shallow	**Iron exceeded aesthetic guideline**	***Very likely* improving iron trend**	**Yes**	**Good**

4.4.3 Groundwater quality for the Three Kings Volcanic aquifer

Median nitrate values were above the ECNC for state, indicating human-induced impacts on the groundwater quality of the Three Kings Aquifer. However, long-term trends were *very likely* improving. Nitrate was not above the drinking water MAV but this aquifer will continue to be monitored for nitrates due to observed nitrate concentrations exceeding 2.5 mg/L.

Zinc breached the ANZECC surface water Trigger Value for state and had a *likely* degrading trend. The Three Kings Volcanic aquifer discharges into Western Springs and degraded water quality of baseflow has the potential to impact sensitive species. The remaining reported metals had values below guidelines for state but the long-term trends for all metals except copper suggested they were *likely* to *very likely* degrading over time.

The Three Kings aquifer had *E. coli* values above the MAV and had a *likely* degrading trend (Table 4-10). *E. coli* is used as an indicator species of faecal bacteria and in an urban environment this can be attributed to aquifer recharge from wastewater or stormwater discharges, especially after heavy rainfall.

Table 4-10 Water quality of the Auckland Isthmus aquifer, a summary of state and long-term trends across all parameters.

Parameter type	State	Long-term trends	Safe to drink	Overall water quality
Nutrients	**Nitrate above ECNC**	***Very likely* improving nitrate trend**	**Yes**	**Poor**
Metals	**Zinc above ANZECC surface water Trigger Value**	***Likely* degrading trends for zinc**	**Yes**	
Microbial	***E. coli* exceeded guidelines**	***Likely* degrading *E. coli* trend**	**No**	

5 Franklin nitrates – case study

5.1 Surface water and groundwater interaction

Three streams in the Franklin area are monitored for river water quality. In a recent analysis all three sites were above the National Bottom Line for nitrate (> 2.4 mg/L nitrate-nitrogen) (Ministry of the Environment, 2020). The National Bottom Line refers to the minimum state for each attribute that councils must meet or work towards meeting over time for the National Objectives Framework under the National Policy Statement for Freshwater Management 2020 (NPS-FM) (Ministry of the Environment, 2020). The nitrate attribute for the NPS-FM reflects the toxic effects of nitrate to instream species and is a measure of ecosystem health. Althouth the National Objectives Framework does not apply to groundwater, the groundwater quality monitoring sites indicate that baseflow to these streams via shallow volcanic aquifers (Table 5-1) is above the following; suface water National bottom line, the expected concentration for natural conditions, and the Drinking Water Standards – New Zealand guidelines for nitrate.

The Whangamarie Stream has been identified as having a *very likely* improving nitrate trend for the period 2010-2019 (Ingley, 2021), which is consistent with the Pukekohe Volcanic aquifer trend results identified in this report, however, the current state of nitrate in these two water bodies is still very high. The groundwater baseflow index (BFI – the ratio of baseflow to total streamflow volume) is high for the Whangamaire (Table 5-1) and residence times of the Pukekohe Volcanic aquifer are approximately 50 years. This suggests that decades old water will still be discharging into the stream for years to come (Tesoriero et al., 2013). Increased understanding of the nitrogen loads being applied in the recharge zones for these aquifers will enable a more robust assessment of land use activities on aquifer nitrate levels in the future and the subsequent delivery of nitrate to streams.

Similarly, the Ngakoroa Stream recieves baseflow from the Bombay Volcanic aquifer. Both aquifer and stream waters had elevated nitrate concentrations (current state) and both had increasing 10-year trends for nitrate. A better understanding of current and future land use activities will enable an improved management approach for this shallow aquifer.

Table 5-1 Summary of nitrate state and trends for Auckland Council surface water and groundwater quality monitoring sites. Aquifer baseflow source and residence times are provided to assist interpretation of the connectivity of groundwater and surface water in the Franklin District.

Stream Site	**Groundwater site**	**Aquifer baseflow source**	**BFI** (Eckhardt, 2005)	**Residence time** (van der Raaij, 2015)	**State of stream (median value, NOF band) (mg/L)**	**State of groundwater (median value) (mg/L)**	**Long-term trends in stream nitrate**	**Long-term trends in groundwater nitrate**
Whangamaire	Patumahoe Springs and Gun Club Rd	Pukekohe Volcanic	0.84	<50 years	**12.95 (D)***	**24-26 mg/L**	***Very likely* improving***	***Likely* improving trend**
Ngakoroa	BP Bombay	Bombay Volcanic	0.61	<50 years	**3.1 (C)***	**11**	***Very likely* degrading***	***Very likely* degrading**

**Results from River Water Quality State and Trends Report* (Ingley, 2021).

5.2 How can we understand these groundwater systems better?

The Research and Evaluation Unit at Auckland Council has trialled continuous nitrate sensors at Hickey Springs (Pukekohe Volcanic aquifer) and Whangapouri Stream for a one-month period. The project's aim was to identify if short-term rainfall events have an impact on nitrate concentrations in surface and groundwater. The preliminary results show delayed effects of rainfall on nitrate concentrations at the Hickey Springs site over the space of a few weeks, compared to an instant response in the Whangapouri stream. The residence time of the Pukekohe Volcanic aquifer is approximately 50 years, therefore rainfall recharge and leaching of nitrate is mixed and dispersed along the pathway to entering the stream as baseflow. In this way aquifer groundwater tends to provide a composite of the nitrate concentrations derived from multiple rainfall events.

The surface water site had an immediate nitrate response after rainfall events. Nitrate entered the stream from quick flow, observed through an instant spike in nitrate, then nitrate became diluted as water was still draining from surface runoff. Once the surface water component slowed, the high baseflow element (0.81 BFI, White, et al., 2019) dominated and nitrate concentrations increased again. Although these are preliminary results, we have identified a direct coupling of rainfall, quick flow of nitrates, and the effects of high baseflow on streams once quick flow has subsided.

The use of continuous nitrate sensors to allow us to capture "real time" data to build a more nuanced understanding of the effects of rainfall events and nitrate leaching from various land use practices, or at various positions in a catchment, will enable a refined management response in the Franklin area. Additional work will also be undertaken by Auckland Council in 2021 to update our understanding of groundwater residence times in the Franklin region.

6 Summary

The groundwater quality monitoring programme was established in 1998 to detect long-term changes across the Auckland region. Auckland Council currently monitors nine aquifers, split into three geographical areas (Franklin, Kumeu and Auckland Isthmus), which are represented by 16 sites. Six wells are shared through the NGMP, sampled by Auckland Council and analysed by GNS. Results for 15 sites are reported here (one Long-term Baseline site had insufficient data records to undertake state and trend analyses).

State was determined for the period 2015-2019. There are currently no National Objectives Framework attributes for groundwater quality in the National Policy Statement for Freshwater Management, therefore median groundwater quality values were assessed against multiple national guidelines (DWSNZ – MAVs and Aesthetic GVs, and ANZECC – TVs) and the expected concentration of natural conditions (ECNC) for nitrate only (Morgenstern & Daughney, 2012). The results did not comprise a compliance level assessment but are provided here for a comprehensive assessment of the current state of groundwater resources.

Trends were assessed for the period 2010-2019 and where possible compared to the previous state and trend report (Kalbus et al., 2017). Trends were split into the proportions of degrading and improving, *very likely* trends were discussed, and only *very likely* trends that exceeded the limit of precision for each parameter were considered further.

The groundwater quality state of the shallow Franklin Volcanic aquifers is predominantly affected by high nitrate which is well documented through time (Cathcart 1995, Moreau et al., 2016, Meijer et al., 2016, Kalbus et al., 2017, White et al., 2019). Six of the 12 monitored Franklin sites were above ECNC (Hillview Springs – Drury Volcanic, BP Bombay – Bombay Volcanic, and Hickey Springs, Patumahoe Springs, Gun Club Road, and Rifle Range Shallow – Pukekohe Volcanic), and four sites were above DWSNZ – MAV (BP Bombay – Bombay Volcanic and Rifle Range Road Shallow – Pukekohe Volcanic were not). Fielding Road Volcanic showed no signs of nitrate contamination, although it belongs to the same aquifer management area as Hillview Springs (Drury Volcanic); the geological unit is not contiguous with the Hillview Springs site, i.e. the two sites represent different water bodies in the same management unit. Redox conditions are the likely cause of differing nitrate outcomes at these sites. Franklin Kaawa, Bombay Drury Sand and Waiau Pa Waitematā showed no signs of nitrate contamination. Nitrate was *very likely* improving at the four Pukekohe volcanic aquifer sites (Hickey Springs, Patumahoe Springs, Gun Club Road, and Rifle Range Shallow). Hillview Springs (Drury Volcanic) and Bombay Volcanic were *likely* and *very likely* degrading in nitrate concentrations, respectively.

Although some groundwater nitrate trends showed improvement, this does not mean that groundwater is safe for human consumption (e.g., high nitrate can cause methemoglobinemia) or that receiving ecosystems with high base flow surface waters are not impacted. The three monitored surface water sites (Whangamaire, Ngakoroa and

Waitangi Streams) in the Franklin area (with high baseflow) indicate nitrate contamination (above nitrate NBL > 2.4 mg/L). This is likely impacted by high-nitrate groundwater from shallow volcanic aquifers (e.g., Pukekohe Volcanic). The groundwater residence times of these aquifers (~50 years) suggest that decades old water will be discharging into these streams for years to come. Further understanding of nitrate loads being applied in the recharge zones will enable a more refined management approach.

Although the iron aesthetic GV was exceeded at both Kumeu West Waitematā aquifer sites, the water quality was generally good, below relevant drinking water standards, and did not pose a risk to ecosystem health.

The Three Kings Volcanic aquifer showed anthropogenic impacts, indicated by >2.5 mg/L nitrate and the presence of *E. coli*. All monitored observations for *E. coli* (July 2017-December 2019, due to change in laboratory detection limits), exceeded MAV and the long-term trend (analysis period 2010-2019) was *likely* degrading. Zinc concentrations exceeded the ANZECC TV and were within band C of the Auckland-specific regional zinc ecosystem health attribute (Gadd, et al., 2019). The long-term trend for zinc was *likely* degrading.

The groundwater quality monitoring network is not currently representative of all quality-sensitive aquifers across the region. However, a programme review was completed in July 2020 to assess the effectiveness of the current programme and its ability to meet continual dynamic requirements of national and regional level directives including the NPS-FM and the Auckland Unitary Plan (AUP) (Johnson, 2020). Recommendations in the report called for the reinstatement of all wells monitored in 2013 and the addition of 25 sites to the current network. New groundwater sites will be phased in over the next three years to enhance spatial coverage and further strengthen knowledge on land use, saltwater intrusion, climate change, and the effects of abstraction. A further 18 Aquifer Management Areas (AMAs) will be covered by the addition of new sites: Waiheke West Greywacke, Manukau South-east Kaawa, Clevedon West and East Waitematā, Kaipara Sand, Kumeu East Waitematā, Bombay West Waitematā, Glenbrook Kaawa, Waiuku Kaawa, Karaka Waitematā, Awhitu Kaawa, Bombay Drury Kaawa, Mt Eden, Newmarket, Mt Wellington, Mt Richmond Volcanics, Omaha Waitematā and Omaha Sand.

7 Acknowledgements

Auckland Council's groundwater quality monitoring network has benefited from several legacy and current staff members through the inception of the programme, continual enhancements, reviews, and monitoring. Thank you to all staff members who have contributed towards the continual development of this programme.

Thank you to Coral Grant, Rhian Ingley and Jane Groom for technical support, Jade Khin for data management and continual improvement to databases, and to Ange Chaffe and Tarn Drylie for report discussions and comments that helped to improve this report. Thank you to Grant Lawrence for providing maps.

Thank you to Watercare Services Ltd and RJ Hill Laboratories for providing water quality analysis for the LTB sites and GNS analytical laboratory for analysis of the NGMP samples. A huge thanks to Magali Moreau (GNS) for providing technical support and a full NGMP dataset for Auckland which contributed to this report.

Thank you to peer reviewers for discussion and providing comments that improved this report.

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Appendices

Appendix A – Groundwater quality monitoring site details

Table A. Auckland Council groundwater quality monitored sites, location, year of commencement and site type. LTB (long-term baseline) and NGMP (National Groundwater Monitoring Programme).

Site No.	Site name	NZTM X	NZTM Y	Year	Site type
7419121	BP Bombay	1775891	5881877	1994	LTB
7419007	Fielding Rd – Sand	1774435	5890642	1998	LTB
7419009	Fielding Rd – Volcanic	1774435	5890642	1998	LTB
7419127	Hickey Springs	1768720	5882057	1994	LTB
7419126	Hillview Springs	1776245	5884311	2010	LTB
7418023	Ostrich Farm Rd No 2	1766052	5885143	1998	LTB
43915	Patumahoe Springs	1764114	5889239	1998	LTB
6487015	Watson Ave	1754847	5916559	1997	LTB
7428031	Gun Club Rd	1764324	5880929	1990	LTB
7428105	Rifle Range Rd – Shallow	1766295	5880987	1997	NGMP
7428103	Rifle Range Rd – Deep	1766295	5880987	1998	NGMP
7418027	Ostrich Farm Rd No 1	1766043	5885027	1994	NGMP
7417021	Seagrove Rd	1755957	5889239	1996	NGMP
6475015	Waitakere Rd – Shallow	1739213	5928139	1996	NGMP
6474003	Waitakere Rd – Deep	1739005	5927973	1996	NGMP

Appendix B – Reported parameters

Table B. Laboratory methods and current detection limits for reported LTB parameters.

Parameter	Group	Method	Detection limit	Units
Electrical conductivity	Physical	EXO sonde, Field		mS/cm
pH	Physical	EXO sonde, Field		pH
DO	Physical	EXO sonde, Field		mg/L
Total dissolved solids mg/L Laboratory	Physical	APHA 2540 C (modified drying temperature of 103 – 105 ◦C used rather than 180 ± 2◦C) 23rd ed. 2017	10	mg/L
Ammonium-N mg/L Laboratory	Nutrients	APHA 4500-NH_3 H 23rd ed. 2017	0.005	mg/L
Nitrite-N mg/L Laboratory	Nutrients	APHA 4500-NO_3^- I (modified) 23rd ed. 2017	0.0010	mg/L
Nitrate-N mg/L Laboratory	Nutrients	Calculation: (Nitrate-N + Nitrite-N) NO2N – Hills Laboratory In-house	0.0010	mg/L
Soluble P mg/L Laboratory	Nutrients	APHA 4500-P G 23rd ed. 2017	0.0010	mg/L
Total alkalinity mg/L (CaCO3) Laboratory	Physical	APHA 2320 B (modified for Alkalinity <20) 23rd ed. 2017		
Total hardness mg/L (CaCO3) Laboratory	Physical	Calculation from Calcium and Magnesium. APHA 2340 B 23rd ed. 2017	1.0	mg/L
Soluble potassium mg/L Laboratory	Metals	APHA 3125 B 23rd ed. 2017	0.05	mg/L
Chloride mg/L Laboratory	Physical	APHA 4110 B (modified) 23rd ed. 2017	0.5	mg/L
Soluble iron mg/L Laboratory	Metals	APHA 3125 B 23rd ed. 2017	0.02	mg/L
Soluble manganese mg/L Laboratory	Metals	APHA 3125 B 23rd ed. 2017		
Soluble sodium mg/L Laboratory	Metals	APHA 3125 B 23rd ed. 2017	0.2	mg/L
Sulphate mg/L Laboratory	Physical	APHA 4110 B (modified) 23rd ed. 2017	0.5	mg/L
E. coli	Microbial	APHA 9222 I 23rd ed. 2017	1	cfu/ 100 ml
% difference in ion balance	Ions	Formula from sum of anions and sum of cations. APHA 1030 E 23rd ed. 2017	0.10	%

Appendix C – Parameters analysed but not reported (LTB only)

Table C. Parameters analysed but not reported, laboratory methods and current detection limits.

Parameter	Current laboratory analytical method	2019 Detection limits	Units
Hydroxide alkalinity	APHA 4500-CO_2 D 23rd ed. 2017	1.0	mg/L
Total iron	APHA 3125 B 23rd ed. 2017	0.021	mg/L
Soluble lead*	APHA 3125 B 23rd ed. 2017	0.00010	mg/L
Fluoride	APHA 4500-F C 23rd ed. 2017	0.05	mg/L
Carbonate alkalinity	APHA 4500-CO_2 D 23rd ed. 2017	1.0	mg/L
Total phosphorus	APHA 4500-P B & E (modified from manual analysis and modified to include a reductant to reduce interference from any arsenic present in the sample) 23rd ed. 2017. NWASCO, Water & soil Miscellaneous Publication No. 38, 1982.	0.004	mg/L
Turbidity (laboratory)	APHA 2130 B 23rd ed. 2017.	0.05	NTU
Turbidity (field)	EXO sonde, field		FNU
Soluble magnesium	APHA 3125 B 23rd ed. 2017.	0.02	mg/L
Soluble calcium	APHA 3125 B 23rd ed. 1 2017.	0.05	mg/L
Calcium as hardness as CaCO3	Calculation from Dissolved Calcium.	1.0	mg/L
Magnesium hardness as CaCO3	Calculation from Magnesium.	1.0	mg/L
Bicarbonate HCO3	APHA 4500-CO2 D 23rd ed. 2017.	1.0	mg/L
Water temperature	EXO sonde, field		◦C
Salinity	EXO sonde, field		Ppt
Soluble silica	APHA 4500-SiO2 F (modified from flow injection analysis) 23rd ed. 2017.	0.1	mg/L
Oxygen reduction potential – ORP	EXO sonde, field		mV
Dissolved oxygen saturation	EXO sonde, field		%

*Soluble lead was not analysed as part of this report. Most values are below the laboratory detection limit and all values are below DWS-NZ., 2019 (0.01 mg/L) and ANZECC., 2000 (protection of 95% of freshwater species, 0.0034 mg/L) guidelines.

Appendix D – Parameters analysed for NGMP sites

Table D. National Groundwater Monitoring Programme (NGMP) parameter list and laboratory methods. Parameters in bold are reported on here.

Parameter	Units	NGMP analytical method
Alkalinity (total, as HCO_3)	mg/L as $CaCO_3$	Titration APHA 2320B
Ammonia as NH3 (preserved)	**mg/L**	**FIA APHA 4500-NH3H**
Bromide	mg/L	Ion Chromatography APHA 4110B
Soluble Calcium	mg/L	Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B
Soluble Chloride	mg/L	Ion Chromatography APHA 4110B
Soluble Fluoride	mg/L	Iron Chromatography APHA 4110B
Soluble Iron	**mg/L**	**Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B**
Soluble Magnesium	mg/L	Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B
Soluble Manganese	**mg/L**	**Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B**
Nitrate – N	**mg/L**	**Iron Chromatography APHA 4110B**
Soluble Potassium	mg/L	Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B
Soluble Sodium	**mg/L**	**Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B**
Soluble Sulphate	**mg/L**	**Iron Chromatography APHA 4110B**
Soluble Silica (as SiO2)	mg/L	Induced coupled Plasma – Optical Emission Spectrometry, APHA 3120B
pH (lab)	**pH**	**APHA 4500-H+**

Appendix E – Description of groundwater quality parameters

Nutrients

Ammoniacal-nitrogen

Ammoniacal nitrogen (NH_3), or ammonia, is one form of nitrogen that can occur naturally in soil from the degradation of organic matter. Ammonia is an essential nutrient for plants and is taken up by plants and surrounding soils. Excess ammonia can be nitrified further into nitrite and nitrate. High naturally occurring groundwater ammonia levels may reflect peat aquifers, or generally older more evolved groundwater. Natural levels of ammonia in groundwater are usually below 0.2 mg/L (The Water Security Agency – Canadian Government, 2019). Groundwater ammonia concentrations can be higher from the decay of organic matter and at very high levels (>>2.0 mg/L) it can be an indicator of faecal contamination.

Nitrite-nitrogen

Specialised ammonia- and nitrite-oxidising microbes utilise ammonia (NH_3) and produce nitrite (NO_2-) by the process of nitrification/oxidation. Nitrite is naturally found in soils and commonly found in groundwater. Nitrite can pose a short-term risk to human health at high concentrations in drinking water.

Nitrate-nitrogen

Nitrate-nitrogen is the final product of the nitrogen cycle. However, nitrate is highly soluble in water and is rapidly leached from soil during high rainfall events to streams, lakes, and groundwater. Although nitrate is naturally occurring in groundwater (<2.5 mg/L), land use intensification (irrigation and application of nitrogen fertilisers) may raise nitrate concentrations in groundwater, and this can have adverse effects on the ecological health of connected receiving environments. High nitrate concentrations imply poor groundwater quality and are deemed unsafe for human consumption without appropriate treatment. The short-term exposure MAVs for nitrate and nitrite in drinking water have been established to protect against methemoglobinemia in bottle-fed infants.

Dissolved reactive phosphorus (DRP)

Phosphorus occurs naturally in rocks, minerals, and soils which can be made bio-available by the weathering of these substances. There is no DWS (NZ) for phosphorus. The leaching of phosphorus from soils and aquifer materials is generally attenuated by sorption and filtration in the shallow vadose zone. However, drainage into aquifers with low anion storage capacity (e.g., sand and gravel aquifers), can lead to groundwaters becoming phosphorus-enriched and thereby supply enriched baseflow to connected streams (McDowell et al., 2019).

Metals

Iron and Manganese

Iron and manganese are naturally occuring in groundwater due to the weathering of aquifer materials (sediments and rocks) and are characteristic markers of aquifer type and groundwater quality (Langdon and Nath, 2010).

Sodium

Sodium is naturally occurring in soils and can be enriched in groundwater dependent on the type of soils and land use at the recharge site. Coupled sodium and chloride concentrations can give an indication of the main source of these parameters and can be either sourced through recharge or aquifer geochemistry.

Zinc and copper

Zinc and copper are used as indicators of industrial and municipal pollution and can cause acute impacts on sensitive species in aquatic environments (Rosen et al., 2000 and Malecki et al., 2016). Soak holes in the Three Kings aquifer receive storm water and sediment runoff from the surrounding urban environment, these parameters are measured to determine potential impacts on the groundwater quality and where recharge to surface water may affect ecosystem health.

Microbial indicators

Escherichia coli

Escherichia coli (*E. coli*) is used as the preferred bacterial indicator group for the occurrence of faecal micro-organisms in groundwater. They are a marker of faecal contamination from animals or human waste. Presence of *E. coli* can lead to rapid and/or major outbreaks of illness. In 2017, Auckland Council changed laboratory providers and this process reduced the detection limit from 1.6 cfu/100 ml to 1 cfu/100 ml.

Other parameters

pH

Field pH has been preferentially reported here as we have found that pH increases slightly on transportation of water samples to the laboratory. pH is a measure of acidity and basicity in aqueous solutions. Natural variation in pH is common, although extremes can be detrimental to living organisms. pH can also be useful to interpret ammonia, hardness, and alkalinity results.

Alkalinity

Alkalinity is the measure of buffering capacity, i.e., water’s ability to neutralise acids. The key elements contributing to alkalinity are bicarbonate and carbonate. The two main sources of alkalinity are the interaction of water and carbon dioxide or reactive by-products from reducing processes. Alkalinity is controlled predominantly by bicarbonate, carbonate, and carbonic acid. Laboratory analysis for the SOE groundwater quality programme reports alkalinity in milligrams per litre of calcium carbonate ($CaCO_3$).

Dissolved oxygen

Dissolved oxygen (DO) is the measure of oxygen concentrations in water. Groundwater DO can be influenced by rate of groundwater movement, aquifer porosity, and water temperature. Dissolved oxygen has a direct influence on biotic assemblages that can be found aquifers (microbes, biofilms, and stygofauna). Redox conditions are influenced by DO, which in turn affects concentrations of other parameters such as nutrients and metals. All results for DO are standardised with temperature and barometric pressure at the time of calibration.

Electrical conductivity

Electrical conductivity (EC) is an indicator of ionic concentration in groundwater and it can be used to interpret total dissolved solids and saltwater intrusion. All results for EC are standardised to temperature at 25°C by default.

Chloride

Chloride is naturally occurring in groundwater due to dissolution of chloride minerals from soils and aquifer materials. High chloride levels can indicate saltwater intrusion or the presence of connate water (water retained in aquifer materials at or near the time of formation).

Total hardness

Total hardness measures the amount of dissolved calcium and magnesium minerals as $CaCO_3$. Water hardness does not affect human health, it is seen as an aesthetic quality of water.

Total dissolved solids

Total dissolved solids (TDS) are used as an indicator of overall water quality (alongside electrical conductivity) mineralisation and used to compare groundwater quality through time.

Sulphate

The presence of sulphate in groundwater can be an indicator of oxidation of minerals in aquifer materials or leaching from land use activities (e.g., application of gypsum fertilisers).

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