Groundwater Quality

State of the Environment Monitoring
2015-2020

Technical Report 2022-87

Working with people | caring for Taranaki

Taranaki
Regional Council

Taranaki Regional Council
Private Bag 713
Stratford

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Executive summary

Regional councils have responsibilities under the Resource Management Act (1991) to monitor the state of the environment (SEM) within their region. The Taranaki Regional Council (the Council) monitors the state and trends across the region's groundwater systems using a number of measures, including chemical and microbial water quality, groundwater levels and water usage. The focus of this report is on regional groundwater quality.

Minerals, salts and contaminants can easily be dissolved into, and transported by water. Aquifers close to the Earth's surface are more at risk of contamination from land use activities given the shorter, or more direct, pathways to them. Deeper aquifers, or those separated from the Earth's surface by geological material that restrict the flow of water (an aquitard), are at less risk from surface contamination although can be contaminated via poorly secured bores and wells. In addition to potential contamination by activities on the land surface, the quality of groundwater can also be adversely impacted by the rocks and sediments in the aquifer through which it flows. In some instances, these natural process can also affect the suitability of groundwater for certain uses.

The Council has routinely monitored groundwater quality across the region since 1994. We do this in order to gain a better understanding of how groundwater quality varies across the region and to assess how its quality is changing over time. We examine how our groundwater systems are being impacted by land use activities and how suitable groundwater is for various uses (such as drinking water). Because groundwater provides a pathway from land to surface water, we also assess the risk groundwater may pose to the health of sensitive environments such as streams, lakes and estuaries.

Our current Groundwater Quality Monitoring Programme (GQMP) network includes a total of 32 wells and bores. These sites are sampled every three months and analysed for a number of physical and chemical indicators of water quality. For this report, analysis of state and temporal trends was conducted on GQMP site data for 12 key indicators of groundwater quality. Data from 2015 to 2020 was used to assess current state, with results compared to accepted levels for environmental or human health, including attribute limits set-out in the National Policy Statement for Freshwater Management (NPS-FM) and the Drinking-water Standards for New Zealand 2018 (DWSNZ). Trends were assessed using data collected over the ten year period from 2010 to 2020.

Monitoring by the Council over the last five years shows *Escherichia coli* bacteria (*E. coli*), nitrate nitrogen (nitrate), ammoniacal nitrogen (ammonia), iron and manganese are occasionally found at levels considered unsafe for humans or stock to drink, or at levels that can make the water look or taste unpleasant.

People using private groundwater supplies are most at risk of drinking groundwater with *E. coli* bacteria and elevated levels of nitrate. Overall, median nitrate and *E. coli* levels in Taranaki groundwater are comparable to other regions across Aotearoa where intensive agriculture is the predominant land use. Human activities and animal and industry wastewater discharged to land locally are both common sources of bacteria and nitrate. Poorly constructed wells and bores, or those that are not adequately isolated from direct sources of contamination, or surface runoff, are more likely to display elevated levels of *E. coli*.

At certain concentrations, nitrate can pose a health risk to babies and breastfeeding mothers. The DWSNZ sets a maximum acceptable value (MAV) for nitrate intended to protect against these risks. There is some discussion in the science community presently around whether a more stringent MAV should be set to protect our health, although there is not yet a strong consensus in New Zealand as to whether the science supports further limits on nitrate levels in groundwater. In Taranaki, there was only one site where median levels of nitrate were found to exceed the MAV for drinking water. Median nitrate concentrations were less than half of the MAV at 27 of 32 sites monitored (84%).

The presence of *E. coli* is used as an indicator of the potential presence of pathogens that can make us sick. Monitoring during 2015 to 2020 showed that *E. coli* were detected on at least one occasion at 21 of the 25 sites (84%) located in aquifers most at risk from *E. coli* contamination. At a number of sites the presence of *E. coli* is related to poor bore or well construction, which allows for the ingress of overland runoff into groundwater. *E. coli* concentrations found in purpose designed monitoring wells installed following good drilling practices are consistently low. These results highlight the importance of the proper construction of bores and treating groundwater prior to using it for household drinking water.

The presence of iron, manganese and ammonia in groundwater is mostly due to the local geology and natural processes that occur in aquifers with low levels of oxygen. The concentration of these contaminants in water at some locations can cause the staining of plumbing fixtures, clogging of pipes or result in the taste or look of groundwater being unpleasant, making the water unsuitable for certain uses. Iron concentrations are a particularly common challenge for those utilising groundwater in Taranaki.

Between 2015 and 2020, 12 of 32 monitored sites (38%) were found to have concentrations of iron and/or manganese exceeding an aesthetic or heath related standard set out in the DWSNZ. A further three sites (9%) had exceedances of the aesthetic standard for ammonia.

Test results show that pesticides and heavy metals are generally not an issue in groundwater throughout Taranaki, although there have been isolated instances where contamination by chemical substances and herbicides/fungicides has been detected.

There was sufficient data available to assess trends in groundwater quality at ten of the 32 sites monitored. In most cases, individual water quality indicators at these sites have shown little change over the last ten years, or are changing at an insignificant rate. Meaningful changes were only detected in three bores, with levels of nitrate considerably improving in one bore (10%) and deteriorating in two others (20%).

The Council is currently reviewing its regional policy and plans to cater for new guidance and thresholds for freshwater quality and health. Monitoring of groundwater quality in Taranaki may also need to change to help the Council meet rules in the new policy and plans, especially where relationships between groundwater and surface water may exist.

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1. Introduction

Groundwater in the Taranaki region is mostly used for stock and domestic water supply and is generally abstracted at low volumes and pumping rates. Other significant uses of groundwater include industrial purposes, community water supply, and pastoral and horticultural irrigation.

Groundwater provides base flow to rivers, streams and wetlands, or forms natural springs or seeps where it discharges at the ground's surface. Careful management of the quality and quantity of groundwater is required to protect both groundwater aquifers (from occurrences like saltwater intrusion and aquifer collapse or contamination), and surface water ecosystems dependent on groundwater.

Regional councils, under Section 35(2)(a) of the Resource Management Act (RMA) 1991, must monitor the state of the environment (SEM) within their region. Monitoring and reporting on the state of the environment informs decision-making around the sustainable management of the region's natural resources and provides an understanding of the state or health of the environment overall.

Policies and plans, developed and enforced by the Council, aim to protect, enhance and/or maintain the quality of the region's groundwater systems by avoiding, remedying or mitigating adverse impacts on groundwater aquifers. Key policy documents include the 2010 Regional Policy Statement for Taranaki (RPS), and the 2001 Regional Freshwater Plan for Taranaki (RFWP).

The 2010 RPS advocates for the sustainable management of the region's groundwater quality under: Freshwater Issue 6.3 - *Maintaining groundwater flows and quality at sustainable levels*.

The 2001 RFWP provides polices, methodologies and rules for the management of groundwater quality under: Issue 6.4 – *Adverse effects on the environment from the taking and use of groundwater*; and, Issue 6.5 - *Adverse effects on groundwater quality from the discharge of contaminants to land and water*.

Human activities that have an effect on the environment or use natural resources, are required to meet the standards and conditions outlined in regional policy and plans. If activities cannot meet these requirements, then a resource consent (permit) is required. Often discharges to the environment (either to water or to land) or water abstraction will require a resource consent from the Council under the 2001 RFWP.

The Taranaki Regional Council (the Council) monitors the state and trends across the region's groundwater systems using a number of measures, including physiochemical and microbial water quality variables, groundwater levels and usage. State and trend analysis of groundwater quality in the Taranaki region is usually conducted on a biennial basis. The last report was prepared in 2017 and assessed monitoring data collected between 1 July 2002 and 30 June 2016 from 35 groundwater monitoring sites.

This report provides an overview of groundwater quality state and trends in the Taranaki region based on monitoring data from 32 groundwater sites sampled between 1 July 2010 and 30 June 2020, along with discussion around the suitability of groundwater in Taranaki for particular uses, like stock and potable supply, highlighting where groundwater contamination may pose a risk to aquatic ecosystem health. The report complements the recently released report: Groundwater Quantity: State of Environment Monitoring Triennial Report 2017-2020 which discusses the allocation and use of groundwater in the region.

2. Groundwater quality monitoring in the Taranaki Region

Groundwater quality has been routinely monitored in the Taranaki region at a select number of sites since 1994. The Council historically sampled groundwater sites separately under the SEM Groundwater Chemical Quality and the SEM Nitrates in Shallow Groundwater monitoring programmes. In 2011, a series of external and internal reviews of the groundwater quality network initiated an amalgamation of all SEM groundwater quality programmes into a single Groundwater Quality Monitoring Programme (GQMP) in 2013. Monitoring results from sites sampled in the revised GQMP were first reported in 2017 (TRC 2017).

The GQMP has three primary objectives:

1. To characterise the state of groundwater quality at a selected number of sites across the region;
2. Enable the assessment of groundwater quality against relevant guidelines and standards; and
3. Identify spatial and temporal trends in groundwater quality arising as a result of natural and/or anthropogenic influences.

This information is used to measure how effective the Council's management practices, policies and rules are at maintaining the quality of the region's groundwater, and if environmental outcomes for groundwater quality are being achieved.

The current GQMP comprises 32 groundwater wells and bores, located throughout the Taranaki region (Figure 1). Site details are included in Appendix I. Sites were selected for GQMP largely based on location, depth and aquifer representation. Sampling is carried out at three monthly intervals, generally in March, June, September and December, with the intention of capturing seasonal variations in groundwater quality.

Sites sampled for the GQMP are classified into two subset networks for the purpose of this report. There are 24 groundwater wells which are less than 15 m in depth[1] and collectively form the shallow groundwater monitoring (SGWM) network. The Council also undertakes groundwater sampling at a further eight sites on behalf of the Institute of Geological and Nuclear Sciences (IGNS) for the National Groundwater Monitoring Programme (NGMP). These sites are a mixture of wells and bores, collectively referred to as the NGMP network.

The GQMP attempts to sample a diverse and regionally representative range of groundwater sites. However, Figure 1 illustrates that majority of GQMP monitoring sites are shallow wells located within unconfined aquifers in the Taranaki Maunga volcanic ring plain or Marine Terrace geological units, and in areas of intensive land use. The remaining five GQMP sites are deeper bores screened within the Tertiary geological formations that extend from the Eastern Hill Country, where land use is a mix of high and low intensity (grassland – low producing) land use. As such, the GQMP is more representative of groundwater quality in unconfined aquifers, i.e. those most susceptible to land use impacts.

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[1] The Regional Freshwater Plan 2001 defines all bores and wells less than 20 m depth as wells and all bores and wells greater than 20 m depth as bores.

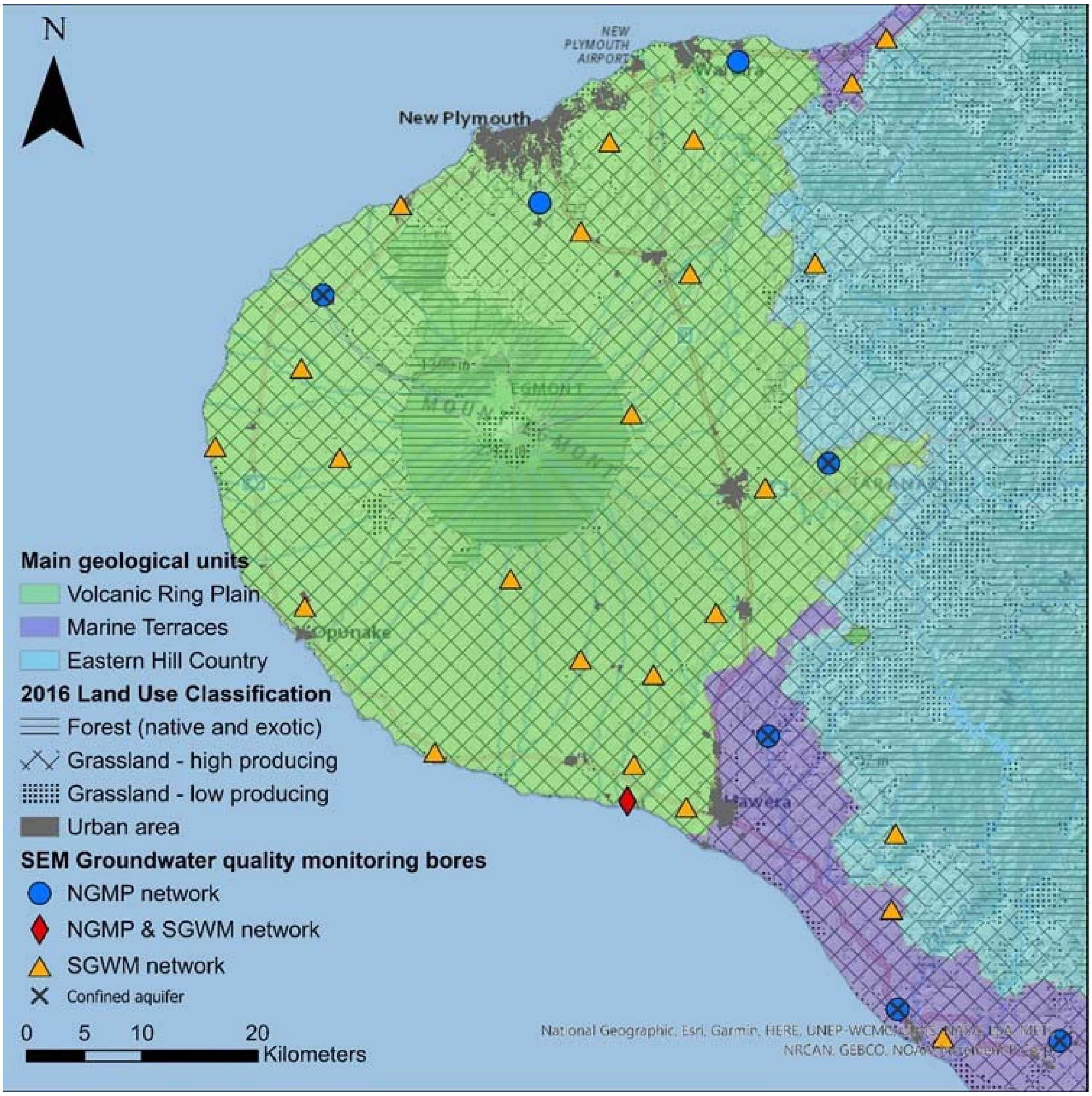

Figure 1 Location of the 32 groundwater sites monitored as part of the Taranaki Groundwater Quality network

Note: *Sub networks include the National Groundwater Monitoring Programme (NGMP) and the Shallow Groundwater Monitoring (SGWM) networks. The main geological units and land use are also detailed here.*

Wells in the SGWM network are constructed using a range of drilling methodologies. The most common method of construction is to excavate shallow wells by hand or machine (referred to as a "Dug Well"). The well is either lined with precast wide diameter concrete rings (c.900 mm to 1,200 mm in diameter) or left unlined. Other well construction methods include auger or rotary drilling rigs. Wells may or may not be lined and/or screened, within the water bearing aquifer. Bores in the NGMP network tend to be constructed by drilling deeper and screening bores within a single aquifer. However, two of the NGMP bores are open ended casing (no bore screen) (Appendix I). Figure 2 illustrates examples of the various construction types in the Taranaki region.

Figure 2 Examples of the well construction types in Taranaki

(Top left: Dug and lined well GND1098, Top right: Dug - unlined well GND1082, Bottom left: Example of internal well lining in dug well GND1095, Bottom right: drilled and screened well GND2484 (being sampled with a peristaltic pump)

2.1. Monitoring variables and methods

Groundwater quality is assessed by measuring different variables including: pH, conductivity, faecal indicator bacteria (*E. coli*), dissolved nutrients (including nitrogen and phosphorus), redox potential, and some major ions. Groundwater samples are collected in accordance with the Council's Groundwater Sampling Procedure (TRC, 2015). The rationale for monitoring select variables, together with details on variable analysis methodology is provided in Appendix II.

At present, the SGWM and NGMP networks do not test groundwater samples for the same number of variables. The NGMP network analyses for most major and minor ions, providing a general overview of hydrochemistry in the region. Meanwhile, the SGWM network tests variables that are more likely to be associated with aquifers influenced by anthropogenic activity. Table 1 provides a list of chemical analytes tested for under each groundwater monitoring network. Appendix II details changes to the testing regime since groundwater quality monitoring began in Taranaki.

Until 30 June 2018, SGWM samples were tested by the Council's onsite IANZ accredited laboratory. The SGWM programme samples are currently tested by RJ Hill Laboratories in Hamilton. Samples collected for the NGMP programme are tested by IGNS for a more comprehensive range of water quality variables (see Table 1). The results of all sample analyses are stored in the Council's LAB database.

Table 1 Routine laboratory testing and sample analysis details

Analyte	SGWM network	NGMP network
Temperature (Field)	💧	💧
pH (Field)	💧	💧
Electrical conductivity (Field)	💧	💧
Dissolved oxygen (Field)	💧	💧
pH (Lab)	💧	💧
Electrical conductivity (Lab)	💧	💧
E.coli	💧	-
Bicarbonate (as HCO_3)	💧	💧
Chloride (Cl)	💧	💧
Sodium (Na)	💧	💧
Total dissolved solids (TDS)	-	💧
Nitrate (as NO_3-N)	💧	💧
Nitrite (as NO_2-N)	💧	💧
Ammoniacal Nitrogen (NH_4)	💧	💧
Dissolved reactive phosphorus (DRP)	💧	-
Potassium (K)	-	💧
Calcium (Ca)	-	💧
Bromide (Br)	-	💧
Fluoride (F)	-	💧
Iron (Fe)	💧	💧
Magnesium (Mg)	-	💧
Manganese (Mn)	💧	💧
Silica (SiO_2)	-	💧
Sulphate (SO_4)	💧	💧
Total no. tests conducted	17	22
💧 *Indicates test is undertaken*		

2.2. Approach to data analysis

This section outlines how data were selected and analysed for state and trend in groundwater quality. Further details summarise the methods used to present data analysis, and the relevant groundwater quality guidelines that are used for comparison.

2.2.1. Water quality guidelines and national reporting

A number of water quality guidelines and thresholds were used to understand and quantify state and trends detected in regional groundwater quality, and to make comparisons with national groundwater data.

Drinking Water Standards and Guidelines

Groundwater quality sample results were compared against the Ministry of Health (MoH) 2018 Drinking-water Standard for New Zealand (DWSNZ) or, where required, to the 2017 World Health Organisation (WHO). These standards or guidelines apply to water intended for human consumption. The DWSNZ (2018) sets a health-related maximum acceptable value (MAV) or an aesthetic (opposed to health risk) guideline value (GV) for a number of water quality variables. MAVs are the concentration at which a particular variable in water will pose a significant risk to the health of a person consuming two litres of water per day over their lifetime (assumed to be 70 years). The MAV for protection against microbes uses a faecal indicator bacteria, *Escherichia coli* (*E.coli*), to indicate the potential presence of other pathogenic bacteria in drinking water.

2020 National Policy Statement for Freshwater Management (NPS-FM)

The NPS-FM (2020) requires an integrated management approach to maintain and enhance freshwater ecosystems nationally, and acknowledges groundwater as a key pathway for freshwater. As there are recognised connections between groundwater and surface water systems in Taranaki, groundwater nitrate and ammonia concentrations have been compared against the NPS-FM (2020) annual median toxicity attribute states for nitrate (2.4 mg/l) and ammonia (0.24 mg/L) national bottom lines in surface water.

Application of the NPS-FM (2020) toxicity thresholds for rivers and lakes highlights where groundwater nutrient or other contaminant inputs may pose a potential risk to ecosystem health or the promotion of proliferation of nuisance plants and algae in receiving surface water bodies. In this report a comparison of the NPS-FM (2020) toxicity attribute states to groundwater quality has been provided to identify potential areas where groundwater nutrient levels may pose a risk to surface water ecosystems. In undertaking this assessment, it should be recognised that groundwater contributions to surface water are subject to sub-surface and instream attenuation processes and dilution (reducing the concentration of nutrients prior to and during discharge to surface water). However, further investigation is required to understand groundwater/surface water flow pathways, and their relationship to the fate and transport of nutrients in groundwater within the region.

2000 Australia and New Zealand Environment and Conservation Council (ANZECC) Water Quality Guidelines

Groundwater results were compared to ANZECC (2000) guideline's trigger values (TV) for aquatic toxicity or for stock drinking water quality for select variables. Comparisons were made to signal where groundwater may not be suitable for livestock to drink, and where groundwater discharges to surface water may have adverse ecological impacts on aquatic ecosystems. Note: these comparisons assume that flow in the surface water is comprised entirely of groundwater, not taking into account likely dilution.

Natural verses human induced concentrations of nitrate-nitrogen groundwater

Close et al. (2001) determined groundwater in New Zealand rarely has natural nitrate concentrations above 1 mg/L, while Daughney and Reeves (2005) concluded that nitrate concentrations above 1.6 mg/L are 'probably' due to human influence. Daughney and Reeves (2005) and Madison & Brunett (1985) further concluded, with high confidence, that groundwater concentrations of nitrate above 3 mg/L – 3.5 mg/L "are almost certainly indicative of human impact".

As the NPS-FM (2020) annual median nitrate toxicity attribute is <2.4 mg/L, this report will display where groundwater is not impacted (<1 mg/L) and is impacted by low levels of nitrate contamination (1 mg/L - <2.4 mg/L). However, where groundwater concentrations of nitrate are above 2.4 mg/L, the reader can infer these concentrations are most likely due to human influence.

2.2.2. Data used in this report

Data used to analyse the state and trends in groundwater quality across the Taranaki region has been collected over the period 1 July 2010 to 30 June 2020. During this period, some monitoring sites have been removed or replaced from the sampling network due to poor well or bore integrity or access issues. However, data from these sites may still be included in analysis where there is sufficient data.

Although the SWGM programme and NGMP test for 17 and 22 groundwater quality parameters respectively, descriptive statistics (state) and trend analysis have been calculated for 12 key indicators of human impact or natural groundwater chemistry, and/or where they are associated with a human/ecological health risk (Moreau et al 2016 and MfE 2019). Table 2 provides explanation for variable inclusion in groundwater state and trend data analysis.

In addition to the standard testing regime, a selection of shallow wells are sampled on a four yearly basis for the National Pesticides Survey. The survey is coordinated by the Institute of Environmental Science and Research (ESR). The Council has been participating in the survey since it began in 1990. The last survey took place in 2018 and results reported in Section 4.9. The next survey is scheduled to take place in 2022. In addition to the ESR National Pesticides Surveys, the Council independently tested groundwater samples from 30 wells for pesticides in 1995.

2.2.3. Data checks, processing and presentation

Groundwater quality samples are collected as per Council protocols[2] and to national groundwater sampling protocols (MfE 2006). This ensures that data collected from field measurements or returned from Hill or IGNS laboratories is entered correctly into the Council's LAB database.

For quality assurance purposes, duplicate samples from up to 10% of all groundwater sites sampled for this programme were submitted to an accredited external laboratory for comparative analysis. Results from this quality check show consistently good agreement between original and duplicates sample results. Further quality control checks of both laboratory and field data are carried out following each sampling round. These checks are intended to identify any results that differ significantly from the expected values at a sampling site. Any outliers are flagged and checked to ascertain if they are a representative result, or are a result due to sampling collection, analysis or data entry error. Box and whisker plots were generated in R and follow Turkey style as explained in Figure 3.

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[2] Council Procedure 44 internal document #31364121

Table 2 Key variables used to summarise the current state and trends of groundwater quality in the Taranaki region (Source: Moreau et al 2016 and MfE 2019)

Variable	Explanation for inclusion as a key variable	DWSNZ (2008) MAV (Health protection)	DWSNZ (2008) GV (Aesthetic protection)	ANZECC (2000) TV (Stock drinking water)	ANZECC (2000) TV (Aquatic toxicity)	NPS-FM (2020) (Aquatic toxicity)	Other
Electrical conductivity (EC)	EC values are useful in providing an indication of spatial and temporal variations in groundwater composition due to changes in natural processes, recharge sources, or human activities like over abstraction, saltwater intrusion or land use.	-	1,000 mg/L	2,000-2,500 mg/L	-	-	-
Bicarbonate (HCO_3)	Bicarbonate is a major anion species, present in groundwater due to several geochemical processes, including: interactions between the soil zone and atmospheric water and carbon dioxide, mineral dissolution and redox processes. Bicarbonate can also be a potential indicator of intensive land use impact where fertiliser is applied to land (Rosen, 2001).	-	-	-	-	-	-
Chloride (Cl)	Chloride is relatively unaffected by geochemical processes which makes it a good indicator of general groundwater quality. The primary source of chloride in groundwater is marine sourced rainfall recharge to an aquifer. However, saltwater intrusion and land use activities, such as wastewater and effluent discharges, can contribute chloride to groundwater.	-	250 mg/L	-	-	-	-
Sodium (Na)	Sources of sodium in groundwater include marine derived rainfall recharge, geochemical processes and weathering of sodium bearing rock within an aquifer. Sodium can also be indicative of groundwater contamination from industrial, agricultural and domestic sources.	-	200 mg/L	-	-	-	-
Iron (Fe)	Iron is only soluble in groundwater under oxygen depleted conditions. Its presence can aid the interpretation of ammonia and nitrate concentrations. Taranaki is dominated by volcanic geology so iron commonly occurs in regional groundwater.	-	0.2 mg/L	-	-	-	-
Fluoride (F)	Fluorine is a common component of many minerals in the Earth's crust. Therefore, fluoride can occur naturally in groundwater, sometimes at levels above those recommended for protection of human and stock health.	1.5 mg/L	-	2 mg/L	-	-	-
Bromide (Br)	Bromide is naturally abundant in sea water (≥65 mg/L) and as bromine the Earth's crust. Elevated concentrations of bromide in freshwater may be due to saltwater intrusion or contamination from fire retardants, pesticides and herbicides.	-	-	-	-	-	Adults: 6 mg/L Children ≤10 Kg: 2 mg/L (WHO, 2017)
Manganese (Mn)	Similar to iron, manganese is only soluble in oxygen depleted groundwater and can aid the interpretation of ammonia and nitrate concentrations. Manganese can naturally be found in Taranaki aquifers given the region's dominant volcanic geology.	0.4 mg/L,	0.04 mg/L	-	1.9 mg/L	-	-
Nitrite nitrogen (Nitrite)	Consumption of groundwater with excessive concentrations of nitrite can adversely affect human and stock health.	0.06 mg/L	-	30 mg/L	-	-	-
Nitrate nitrogen (Nitrate)	Nitrate contamination can indicate impact from anthropogenic activity such as intensive land use and is a national indicator of groundwater quality.	11.3 mg/L	-	-	-	Annual median: 2.4 mg/L 95th percentile: 3.5 mg/L	-
Ammoniacal nitrogen (Ammonia)	Ammonia usually exists in oxygen depleted groundwater as the reduced form of nitrogen (compared to the oxidised form nitrate). Conversely, ammonia can be transformed to nitrate in oxygen rich groundwater. Ammonia can indicate the occurrence of nitrogen contamination in groundwater where naturally reduced aquifer conditions may convert nitrate to ammonia. Contaminant sources can include fertiliser, effluent, landfill and industrial discharges to land and/or groundwater. The decomposition and reduction of naturally occurring organic matter within an aquifer can also contribute ammonia to groundwater.	-	1.5 mg/L	-	-	Annual median: 0.24 mg/L 95th percentile: 0.4 mg/L	-
Escherichia coli (*E. coli*)	*E. coli* is a species of bacteria lives in the lower intestine of warm-blooded organisms. Its presence in groundwater indicates faecal matter contamination within an aquifer and the potential presence of other pathogenic bacteria, protozoa and/or viruses.	<1 cfu/100mL	-	100 cfu/100mL (median)	-	-	-

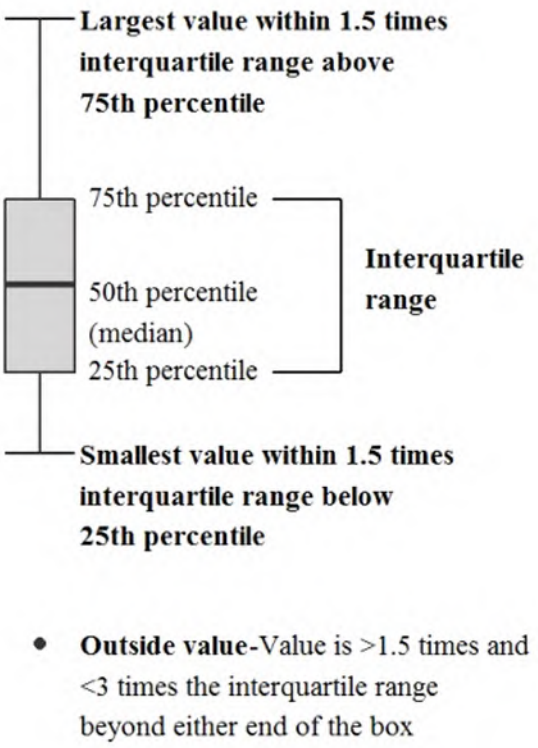

Figure 3 Summary statistics defined by Turkey boxplots used to report on the State of Groundwater Quality measurements

Note: *In order to present median and quartiles values graphically on boxplot, values that were below detection limits were set at the most common detection limit threshold (opposed to the most conservative value). Therefore, any values below these detection limits should not be directly interpreted.*

2.2.4. Summary statistics and current state analysis

Summary statistics have been calculated using the last five years of monitoring data (1 July 2015 to 30 June 2020) when there is at least 75% data coverage over the time period (i.e. data from at least 15 of the scheduled 20 samplings is available). Where this criteria has not been satisfied, summary statistics based on the last two years of monitoring are presented. These two-year summaries are indicative only and are denoted as such in the reported summary tables. Commentary on the state of groundwater quality is based on data for 12 key indicator variables as outlined in Section 2.2.2.

Wherever possible, censored data has been handled using the NADA package in R software (vers. 1.6-1.1; Lopaka Lee, 2020). Left censored data has been replaced with imputed values using regression on order statistics (ROS). This method fits a distribution to the non-censored values in the data record and uses the resulting model to impute replacement values for the censored data.

Summary statistics have been evaluated using the following methods:

- Where there is no censored data in the dataset, regular summary statistics have been calculated.
- Where the dataset consists of less than 70% censored data, ROS has been used to evaluate data below the censor limit. Depending on the proportion of censored data, this may affect percentile and median assessments. The minimum has been reported as equal to the lowest censor limit.
- Where the dataset consists of 70% or greater censored data, there is insufficient non-censored data to robustly perform a ROS evaluation. In these cases, regular summary statistics have been calculated to give an indication of results at the site. The minimum and median statistics have been reported as equal to the lowest censor limit.

2.2.5. Temporal trends analysis

Trend analysis has been undertaken for the 12 key variables sampled outlined in Section 2.2.2. Trend analysis has been carried out using the LWP-Trends library R package (version 1901), developed by Land Water People Ltd. (Snelder and Fraser, 2019). The methods employed have the primary purpose of establishing the direction and rate of any trend, along with a measure of the uncertainty in the result. Trend analysis is undertaken using the last 10 years of monitoring data (1 July 2010 to 30 June 2020) when the following criteria have been satisfied:

- There is at least 75% data coverage over the time period (data from at least 30 of the 40 scheduled samplings is available).
- The dataset consists of less than 70% censored data.

As a first step in the trend analysis, a visual inspection of the raw time-series data is undertaken, giving a view of the proportion and temporal distribution of censored data. A Kruskal-Wallis test (using a threshold of $\alpha=0.05$) is then employed to determine whether there is seasonality in the data.

Depending on the result of the seasonality test, a non-parametric Mann-Kendall or seasonal Kendall test is used to determine the direction of a monotonic trend through the time-series data. Trend rate, and the confidence in trend rate, are evaluated using Sen-slope regression of observations against time. This is a non-parametric regression procedure, where the Sen-slope estimate (SSE) is taken as the median of all possible inter-observation slopes (Hirsch et al. 1982). Where there is more than one observation within one season, the median of the observations is used in SSE assessments. In calculating the Kendall S statistic, censored data are dealt with as robustly as possible, following the methods of Helsel (2011), this allows inter-observation increases and decreases to be identified whenever possible (Snelder and Fraser, 2019). In calculating the SSE, censored data are replaced by a value 0.5x the highest common censor limit. While this biases inter-observation slopes associated with censored data, in most cases with a small proportion of censored data, the median slope will be unaffected.

Usually, when the SSE is affected by censored data this indicates that the trend rate is smaller than can be detected. Trends noted as being affected by censored data are critically analysed to assess if the resulting statistics are meaningful or not. In a small number of cases, trend assessment is not carried out due to there being insufficient unique data. This occurs when there are <5 non-censored data, or if there are <4 unique non-censored values.

In this report, the assessment of confidence in trend direction moves away from the traditional null hypothesis significance testing (NHST) approach used in previous reports, and instead follows the recommended credible interval assessment method of McBride (2019). Using this method, the reported trend direction (from the Kendall S statistic), is accompanied by the associated confidence in that trend direction being true. Confidence levels are categorised as in Table 3.

Table 3 Confidence categories for trend direction results

Trend Category	Confidence in direction
Very likely improving	90-100%
Likely improving	66–90%
Indeterminate	50-66%
Likely degrading	66–90%
Very likely degrading	90-100%

It is noted that the trend analysis methods implemented above are constrained to identifying a monotonic (single direction) trend through any time-series. In many cases, however, environmental data is not monotonic, with a change of conditions or individual events resulting in changes of behaviour at monitoring sites. To account for this, a Loess curve has been overlaid on trend-analysis plots to allow for a qualitative assessment of any non-monotonic trends, and further investigation into the possible cause of any change of behaviour.

Furthermore, it is important that while a trend direction is always reported this needs to be considered alongside the given confidence in that direction assessment, and the absolute and relative scale of the trend. Here, the SSE is used as a measure of absolute rate of change in a variable, while the percent annual change is calculated as ratio of the SSE to the median level of the variable at the site.

The term ‘environmentally meaningful’ used in this report defines where variable concentrations or levels over the ten year monitoring period have been shown to be changing, not only within a high degree of confidence, but at a rate that is significantly altering the quality of the groundwater at a particular location. Note, changes in groundwater quality can have both an overall positive or negative impact on a receiving environment or a resource, such as potable water supplies.

There are no groundwater quality guidelines which outline acceptable rates of change for individual variables. However, analysis of national groundwater quality data by Daughney and Reeves (2006), and Daughney and Randall (2009) suggests rates of change which are less than ±2% and ±5% per year, for major and minor elements respectively, are slow and may reflect natural processes. These suggested rates of change have been used in consideration of temporal trends in this report. However, all trends reported here were also evaluated for environmentally meaningfulness individually by collectively considering median values (from analysis of state), data range and distribution, and the rates of change. Daughney and Reeves (2006) further indicated that an absolute rate of change greater than ±0.1 mg/L nitrate in groundwater was most likely due to human influence and is included in this report as a measure of an environmentally meaningful trend.

3. Overview of groundwater in the Taranaki

This section provides an overview of factors influencing regional groundwater in Taranaki. Factors include both natural processes, such as geology and recharge mechanism, and pressures from human influence. Significant consented activities, with the potential to impact on groundwater quality, are also summarised.

3.1. Regional hydrogeology and groundwater systems

The majority of the unconfined aquifer systems in the region are located within the volcanic ring plain and the Marine Terrace deposits. Collectively, much of the region's groundwater abstraction occurs within these unconfined aquifers. Unconfined, semi confined and confined aquifers are located in the Eastern Hill Country, or at depth beneath the volcanic ring plain and marine terraces. Although groundwater abstraction occurs to a lesser extent in semi confined and confined aquifers, yields from regional confined aquifer systems can be considerable, particularly from the Whenuakura and Matemateaonga Formations. Figure 4 illustrates the distribution and complexity of the major geological units of Taranaki, which contain the region's predominant aquifer systems:

- Taranaki Volcanics formation aquifer
- Marine Terrace formation aquifer
- Whenuakura formation aquifer
- Matemateaonga formation aquifer

Generally, regional aquifers are recharged by rainfall infiltration. Limited investigations of aquifers in the Eastern Hill Country suggests surface water recharge to groundwater can occur in the region, see Section 3.2.1(a). However, this has not been explored extensively in the wider region. A number of spring-fed streams originate within the Te Papakura o Taranaki and at lower elevations across the ring plain. It is documented that many rivers on the ring plain derive up to 80% of their base-flow from within Te Papakura o Taranaki (TRC 1996). Regionally, groundwater flow paths generally radiate out from Taranaki Maunga (Mount Taranaki) or from the Eastern Hill Country towards the coast. However, the complex geology of the Taranaki region does create localised flow paths in some areas, Figure 4 details the cross-sections of regional geological conditions and intersections.

The Taranaki region receives regular and high volumes of rainfall throughout the year, due to the region's exposure to the prevailing westerly winds. Westerly winds push air, rich with water vapour from the Tasman Sea, over the dominant mountain topography. Rainfall volumes increase rapidly with elevation away from the coast and in the Eastern Hill Country, as the air is forced to drop moisture in order rise to greater elevations. The high rainfall volumes across Taranaki generally ensure rainfall surpluses are available to regularly recharge the region's aquifers, particularly where groundwater recharge zones are located in elevated areas of Taranaki Maunga or the Eastern Hill Country. For more information on rainfall and climate variability in the Taranaki region, refer to the latest SEM Groundwater Quantity report (TRC 2022).

3.1.1. Taranaki Volcanics Formation

Eruptions and lahars from Taranaki Maunga, during the Quaternary Period, have deposited volcanic material from the coastal boundary in the west, to the Taranaki Basin Tertiary deposits in the north and north-east. While a number of volcanic debris avalanche deposits, from the periodic collapse of Taranaki Maunga, dominate lithologies to the west and south of Taranaki (Roverato et al 2014). The area is bounded to the north and south by Quaternary Marine Terrace deposits, and is often described as the volcanic ring plain. Volcanic deposits comprise both coarse material (sands, breccia and agglomerates) and fine material (clay, tuff and ash), which create irregular rock sequences and hydrogeological conditions (Taylor and Evans, 1999). Subsequently, a complex system of unconfined, perched and semi confined aquifers exist within the volcanic deposits and are collectively known as the Taranaki Volcanics Formation aquifer.

The water table within the Taranaki Volcanics aquifer is typically encountered between 1 to 10 m below ground level, although there can be seasonal variations of up to 5 m. Groundwater flow generally reflects surface topography, and flows radially out from Taranaki Maunga. The Taranaki Volcanics aquifer is recharged mainly by rainfall infiltration, with possible contributions from stream and river bed leakage. Groundwater discharges at numerous puna wai (springs) and provides baseflow to the many rivers and streams that traverse the ring plain. Yield from the unconfined Taranaki Volcanics aquifer is generally low (0.5 L/s to <3 L/s), while confined volcanic aquifers beneath the Kaitake Ranges, New Plymouth, Okato and Kapuni may yield higher volumes (8 L/s to 20 L/s).

3.1.2. Marine Terrace Formations

Marine Terrace deposits occur in coastal areas south of Hawera (overlying the Whenuakura formation), and north of New Plymouth. Basal units comprise marine sands, often with conglomerate or shell layers, and progressively grade into terrestrial sediments (e.g. peat) with localised iron pans towards the surface. Formation of the Marine Terraces is attributed to sea level fluctuations and progressive uplift at the coastal areas. Lithological units within the Marine Terrace deposits range up to about 40 m in thickness, and can contain multiple unconfined aquifers.

The water table within the Marine Terrace aquifers generally lies between 1 to 15 m below ground level, while groundwater flow is generally a subtle reflection of surface topography towards the coast. Marine Terrace aquifers are unconfined and primarily recharged by rainfall infiltration. Groundwater composition and quality are highly variable, while yield can vary (0.3 L/s to <4 L/s) dependent on well or bore location and construction methods.

3.1.3. Tertiary Sedimentary Formations

There are nine Tertiary sedimentary formations recognised in the region, all of which dominate various areas throughout the Eastern Hill Country. The Otunui and Mount Messenger formations are fully exposed in the north of the region, while the remaining seven formations are exposed but continue beneath the Taranaki Volcanics and Marine Terrace formations. All formations tilt gently from the Eastern Hill Country towards the southwest of the region with groundwater flow generally following the same line out to sea.

Little is known about groundwater use in the Otunui and Mt. Messenger formations, while the Urenui Formation is regarded as an aquitard with no groundwater. In all other formations, shallow wells and bores draw from both the low yielding unconfined aquifers, and from the deeper more productive confined aquifers. High yields have been reported at bores drawing from confined aquifers in the Kiore Formation at Bell Block (35 L/s), Matemateaonga Formation at Kapuni and Eltham (7-20 L/s), and in the Whenuakura Formation at Pātea and Waverley (8-10 L/s).

Aquifers in the Whenuakura and Matemateaonga formations generally provide higher yields than the region’s shallow unconfined aquifers, and have the greatest volume of groundwater abstraction in the region. Recharge to these aquifers is not well understood. However, limited environmental isotope measurements suggest that recharge may occur through overlying unconfined volcanic and marine terrace deposits, and where the formations are exposed at the surface in the Eastern Hill Country (TRC 1996). Due to depth and confinement, aquifer systems within the Whenuakura and Matemateaonga formations are less susceptible to contamination from land use, and may exist under artesian conditions.

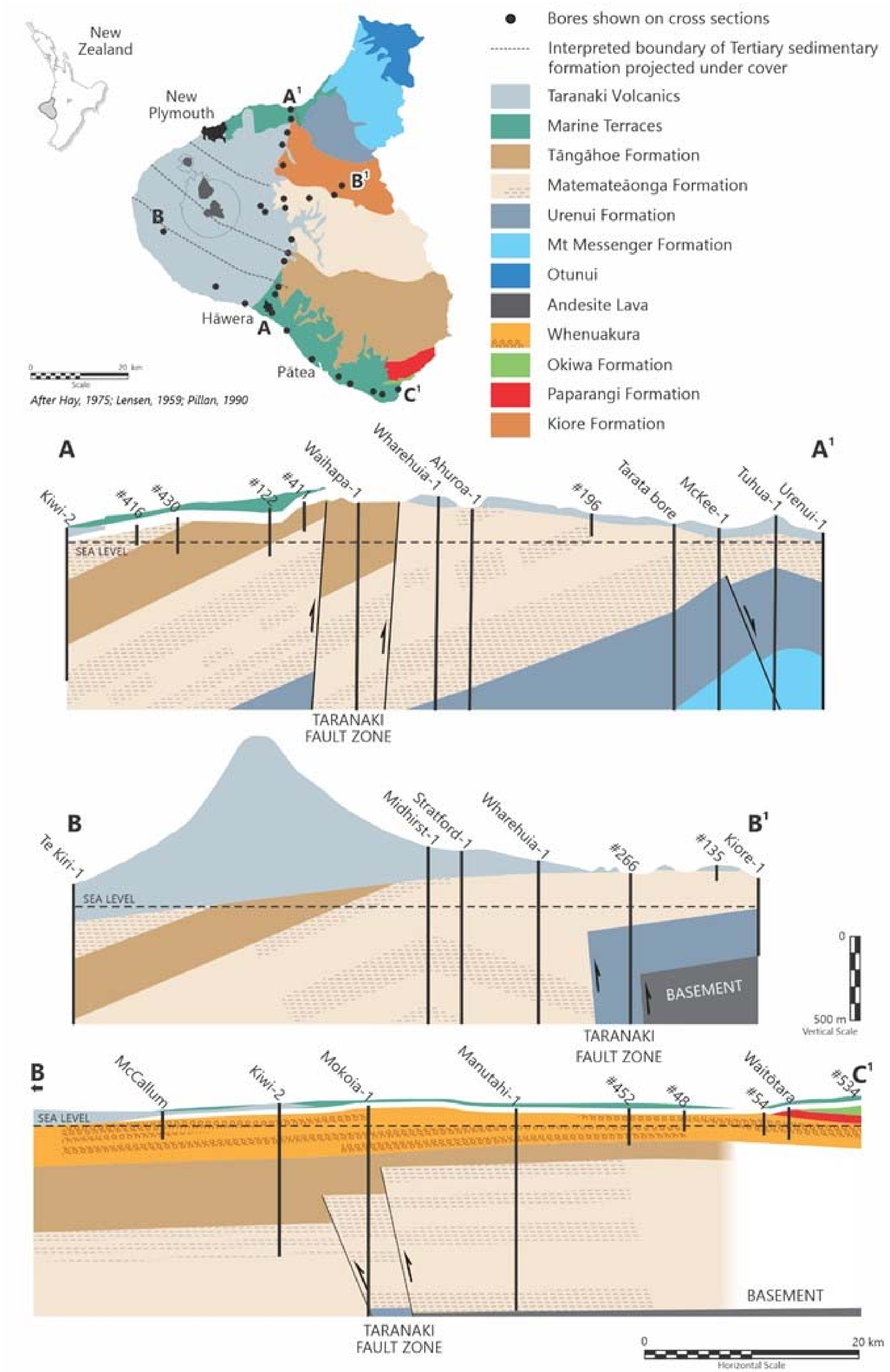

Figure 4 Distribution of the main geological units which form the major aquifer systems in the Taranaki region (Source: Brown 2013 and TRC 1996)

3.1.4. The influence of regional soil characteristics on hydrology

The properties of soil overlying aquifer recharge areas are an important consideration when ascertaining likely areas of rainfall infiltration and hydrochemical influences. Soils in the Taranaki region can broadly be categorised into four groups based on location (See Appendix III). The north and south-eastern slopes of Mount Taranaki are dominated by rapidly free-draining Typic Orthic Allophanic soils (e.g. Egmont Loam) derived from andesitic tephra eruptions. Debris avalanche deposits, from the periodic collapse of Taranaki Maunga on the western slopes, form stony and poorly drained Gley Allophanic soils on the western slopes. Shallow, erosion prone Orthic Brown soils, formed from uplifted tertiary marine sediments such as mud, silt and sand stones, dominate the Eastern Hill Country. Meanwhile, free draining Sandy Brown and Recent soils occupy patches of the region's coastal areas, especially south of Hawera through to Waitotara. However, localised iron pans impede drainage in some areas. (Manaaki Whenua 2020, Molloy 1998, TRC 1996). See Figure 5 for soil drainage classifications overlying regional aquifer recharge areas.

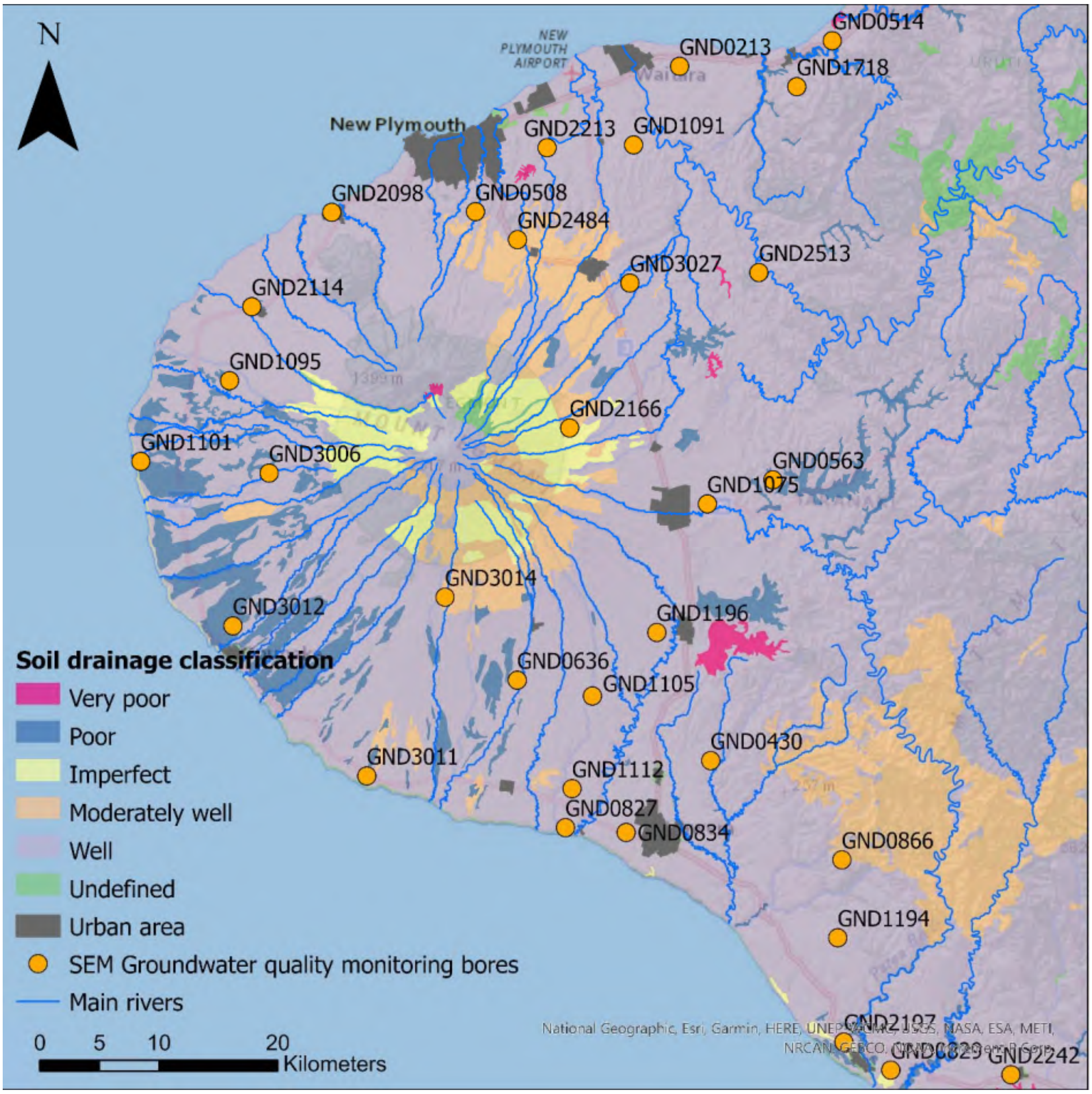

Figure 5 Soil drainage classification for the Taranaki region (Source: Landcare Research NZ 2000)

Soils in the ring plain area are highly productive for the growth of pasture or other crop types, while hill country soils support sheep and beef farming, and forestry (Molloy 1998). In general due to their marine or volcanic origins, regional soils have a great tendency to retain phosphorus within the soil profile where it is not available for plant growth. Further to this, soils in Taranaki are similar to most New Zealand soil in being slightly acidic (except on the coastal terraces about Hawera to Waverley and within debris avalanche deposits to the west of Taranaki Maunga), with low levels of potassium, sulphur, available phosphorus and nitrogen. To maintain or increase levels of soil productivity, lime and fertilisers have been applied to land to neutralise soil acidity and supplement soil nutrient and trace elements levels (Gillingham 2008, Manaaki Whenua 2020, Molloy 1998 and Fertiliser Association 2021).

3.2. Influences on groundwater quality

Given water is a very good solvent, minerals, salts and contaminants can easily be dissolved into, and transported by water. Aquifer geology, water residence time within an aquifer and land use activities in the recharge zone can all cause variation in the chemical composition of groundwater between aquifers or even spatially within the same aquifer.

3.2.1. Natural processes

Natural processes such as recharge mechanisms, interactions between water, rock and soil, and residence time directly influence the chemical composition of groundwater. Environmental conditions of the aquifer (like presence or absence of oxygen in groundwater) can encourage natural hydrochemical and microbial interactions, which further influence groundwater quality.

3.2.1.1. Aquifer recharge

Rainfall that seeps from the land’s surface, or river water that flows through the river bed to replenish an aquifer is known as recharge. While predominantly a naturally occurring process, recharge can also occur as a result of human activities such as irrigation or wastewater injection. The area where recharge occurs is called the recharge zone. Groundwater within a well or bore may have entered the aquifer via a recharge zone that is nearby, or many kilometres away, see Figure 6.

Unconfined aquifer systems in the region are predominantly recharged by infiltration of local rainfall. The volume of aquifer recharge can vary with changes in rainfall and evapotranspiration, and as a result of differing land use and vegetation cover, soils and geology. Most rainfall in Taranaki occurs during late autumn and winter through to early spring. Consequently, recharge rates peak over these periods. Lower rainfall volumes over summer, result in reduced recharge rates and lower groundwater levels.

Seepage, from rivers and streams, also contribute to aquifer recharge. Water in the Whenuakura River and groundwater samples from the Whenuakura aquifer at Waverley are chemically similar, suggesting that the Whenuakura River provides significant recharge to confined aquifers in South Taranaki (TRC, 1992). The Pātea River may also provide significant recharge to the Whenuakura aquifer, particularly where the formation is exposed at the surface in the Eastern Hill Country (Taylor and Evans, 1999). The contribution of surface water systems to aquifer recharge varies with changes in river flow and as a result of local geology.

3.2.1.2. Groundwater residence time

In general, the further along a flow path, or the slower the groundwater flow rate, the older and more reduced (oxygen depleted) the groundwater is likely to be, see Figure 6. Groundwater closer to the point of recharge or within an aquifer with greater transmissivity is typically younger and more oxidised (oxygen rich). Groundwater age/residence time and concentration of dissolved oxygen can also depend on where groundwater discharge or abstraction of an aquifer occurs.

Age dating of groundwater abstracted from the Taranaki Volcanics aquifer using tritium isotopes indicated that the water is generally less than 2 years old (TRC, 2008). This suggests the groundwater is either young or recently recharged. In contrast, age dating analysis by Taylor and Evans (1999) indicated that Whenuakura and Matemateaonga aquifer systems contain very old water, in some instances over tens of thousands of years old.

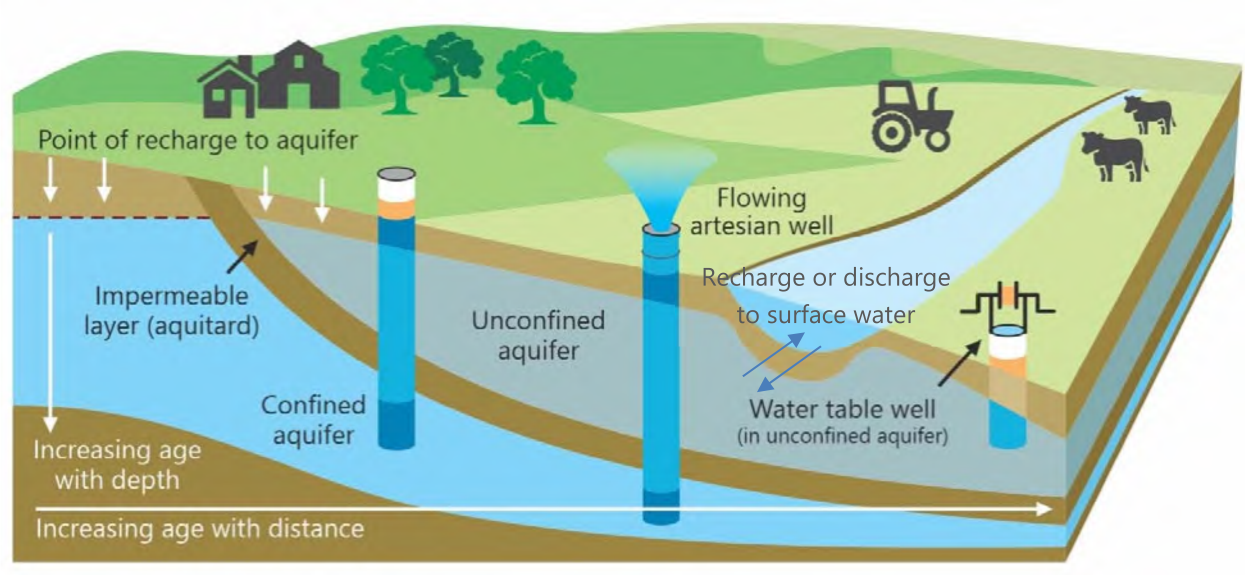

Figure 6 An overview of aquifer types, recharge mechanisms, groundwater flow paths and residence times (Source: modified from Environment Canada)

Note: *In the unconfined aquifer, groundwater is pumped to the Earth's surface. However, pressure in the confined aquifer can cause groundwater to flow to the surface without the use of a pump (flowing artesian well).*

3.2.1.3. Rock-water interaction

As water moves through aquifers, it interacts with soils and rock, dissolving ions (such as calcium, magnesium, bicarbonate or iron) from salts and minerals. Some soil and rock types dissolve into water more easily than others, which can give groundwater chemical characteristics that are unique to individual aquifers or specific types of aquifers.

The degree of rock-water interaction occurring within an aquifer is a function of groundwater recharge mechanisms, aquifer confinement and residence times. Concentrations of ions generally increase as contact time between aquifer lithologies and groundwater increases. Highly transmissive or recently recharged aquifers (usually unconfined) typically have lower concentrations of dissolved ions, reflecting less rock-water interaction. However, these aquifers may be more susceptible to surface contamination from land use activities, see Section 3.2.2.

Aquifers with low transmissivities, increasing confinement and groundwater residence times, tend to have greater concentrations of dissolved ions. Increases in depth, confinement and age can lead to groundwater becoming more saline in nature as it evolves to be more like seawater (Chebotarev 1955). Therefore, the hydrochemical signature of groundwater can provide an indication of groundwater age and aquifer characteristics.

The influence of water-rock interactions is apparent in groundwater quality data collected by the Council. Elevated concentrations of iron and manganese in the region's shallower volcanic aquifers is influenced by the weathering of volcanic rock. Both the Marine Terraces and Taranaki Volcanic formations typically reflect a water type that is sodium chloride/calcium chloride in nature. Variable concentrations of carbonate minerals (e.g. magnesium bicarbonate or sodium bicarbonate) are more typical of groundwater in the region’s deeper confined aquifers, within sedimentary rock sequences like the Matemateaonga and Whenuakura formations (TRC 1996).

3.2.1.4. Geochemical and biogeochemical processes

The chemical composition of groundwater can be significantly influenced by geochemical and biogeochemical processes. Geochemical processes include the formation of carbonic acid in the soil profile, due to interactions between organic matter in the soil and atmospheric water and carbon dioxide. The carbonic acid can then migrate into the underlying aquifer, lowering groundwater pH values in the water body. Biogeochemical processes include interactions between components that are non-living (soil, rock, air and water) and living (plants, animals, fungi and bacteria).

Redox reactions are the most common biogeochemical processes influencing the composition and concentration of ions within groundwater. Redox (reduction/oxidation) is the transfer of electrons between ions which are derived from groundwater interactions with surrounding aquifer lithology. An ion becomes ‘oxidised’ when it donates electrons (resulting in a loss of energy), and ‘reduced’ when it receives electrons (resulting in an energy gain). Bacteria in groundwater encourage redox reactions to harness the energy which is released. Bacteria prefer to use dissolved oxygen as an electron receiver as it provides the most energy gain. However, where dissolved oxygen is absent or becomes depleted, bacteria will utilise other electron receivers in successive order of preference, from dissolved oxygen, nitrate, manganese, iron, sulphate to carbon dioxide.

Reduced forms of some chemical species are more soluble in water than their oxidised forms and can result in the natural accumulation of manganese, iron, sulphide, methane and arsenic in oxygen poor groundwater (Daughney & Wall 2007). Denitrification refers to the biologically driven redox reaction where nitrate is reduced to nitrogen. Stages of the denitrification cycle can also include the reduction of nitrate to ammoniacal nitrogen within an aquifer. This can be important when considering the nitrate attenuation capacity of an aquifer underlying land use activities with the potential to leach nitrate.

A 2016 investigation by the Council and Lincoln Agritech, (Strenger and Clague 2016) into the redox state of groundwater in the GQMP sites, indicated that oxic groundwater was most prevalent in wells located in the shallow unconfined aquifers SGWM network. However, it should be noted that the SEM monitoring network is dominated by wells located within unconfined aquifers. There were six SGWM network wells that were drawing primarily anoxic groundwater, which suggests denitrification and attenuation is taking place in some areas of the region’s unconfined aquifers. Groundwater was generally classified as anoxic within the region’s confined aquifers. A small number of sites display variability in their redox state, some of which is seasonal.

3.2.2. Anthropogenic influences on groundwater quality

Contaminants arising as a result of anthropogenic (human) activities have the potential to adversely impact groundwater quality across both urban and rural settings. Contaminant sources with the potential to adversely affect groundwater quality can be divided into two broad groups; point and non-point source (diffuse).

Point sources pollution describes situations where a contaminant is directly discharged from a specific point or location. Point source pollutants in groundwater are usually found in a plume that has the highest concentrations of the pollutant nearest the contaminant source. Contaminant concentrations will generally decrease with distance from the point source. Point source discharges can include those from septic tanks, leaking effluent treatment ponds, underground storage tanks and pipelines.

Diffuse pollution is the accumulation of contaminants within the environment from an activity, or a range of activities, rather than being from a single specific point. Diffuse pollution is characterised by its occurrence across a large area, as opposed to the plume effect associated with point source discharges. It is often difficult to trace the exact origin or fate of contaminants generated through diffuse processes due to their cumulative nature, and the impact of soil, geology and groundwater flow on contaminant attenuation and distribution. Consequently, the management of diffuse pollution is challenging.

Diffuse pollution arises as a result of land use activities. Given its predominance across Taranaki, agricultural land use constitutes the region's greatest potential source of diffuse contaminants. These include the contaminants from animal excreta and land application of fertiliser and effluent. Specific contaminants associated with agricultural land use with the potential to adversely impact groundwater quality include nutrients, primarily in the form of nitrate, and faecal bacteria. Land use effects, and specifically those associated with agricultural land use, are discussed further below.

3.2.2.1. Land use effects

Around half of the Taranaki land area is used for agriculture and horticulture. Dairy farming remains the predominant land use, accounting for 207,086 ha, or 58% of land used for primary production in 2019. The area utilised for dairying across Taranaki has increased by 62,095 ha (43%) since 2002, primarily through conversion from dairy support or extensive sheep and beef pastoral farming. Much of this change occurred prior to 2012, and has slowed considerably in recent years. While there is some dairy farming in the lower hill country, most occurs on the ring plain of Taranaki Maunga and on the marine terraces in northern and southern coastal areas.

Sheep and beef farming occurs mainly on the steeper, less fertile slopes of the Taranaki eastern hill country. Land used for sheep and beef farming in Taranaki has reduced by 35,389 ha (-41%) and 28,901 ha (-29%) respectively since 2002. The decline in the area used for sheep farming has continued in recent years, reducing by 8,128 (-14%) since 2017, however the beef farming area has increased by 5,376 (8%) over the same period. These trends generally follow those seen elsewhere in New Zealand.

Horticulture and grain production accounts for just 7,146 ha (2%) of the total area used for agricultural and horticultural production in Taranaki, with less than 1% in horticultural land use. However, this is increasing. Between 2017 and 2019 the area in grain production grew by 2,540 ha (62%), and horticultural land use by 162ha (46%).

As of 2019, there were about 587,000 dairy cattle in Taranaki, up 4% (24,000 cows) from 1990. Nationally, the total dairy herd increased 82% over the same period. However, from 2014 to 2019, dairy cattle numbers remained steady in Taranaki, while nationally there was a 7% decline. As of 2020, the average stocking rate for dairy cattle in Taranaki was 2.78 cows/ha, in-line with the average stocking rate across North Island dairy farms. While cow numbers and associated stocking rates have been relatively stable in Taranaki over recent decades, the amount of milk solids being produced has increased by approximately 35% since 2000 (LIC, 2000, 2020) This increase in production is likely due to a range of factors, including improved herd management practice, breeding and genetics, but also supported by higher farm inputs in the form of fertilisers and supplementary feeds.

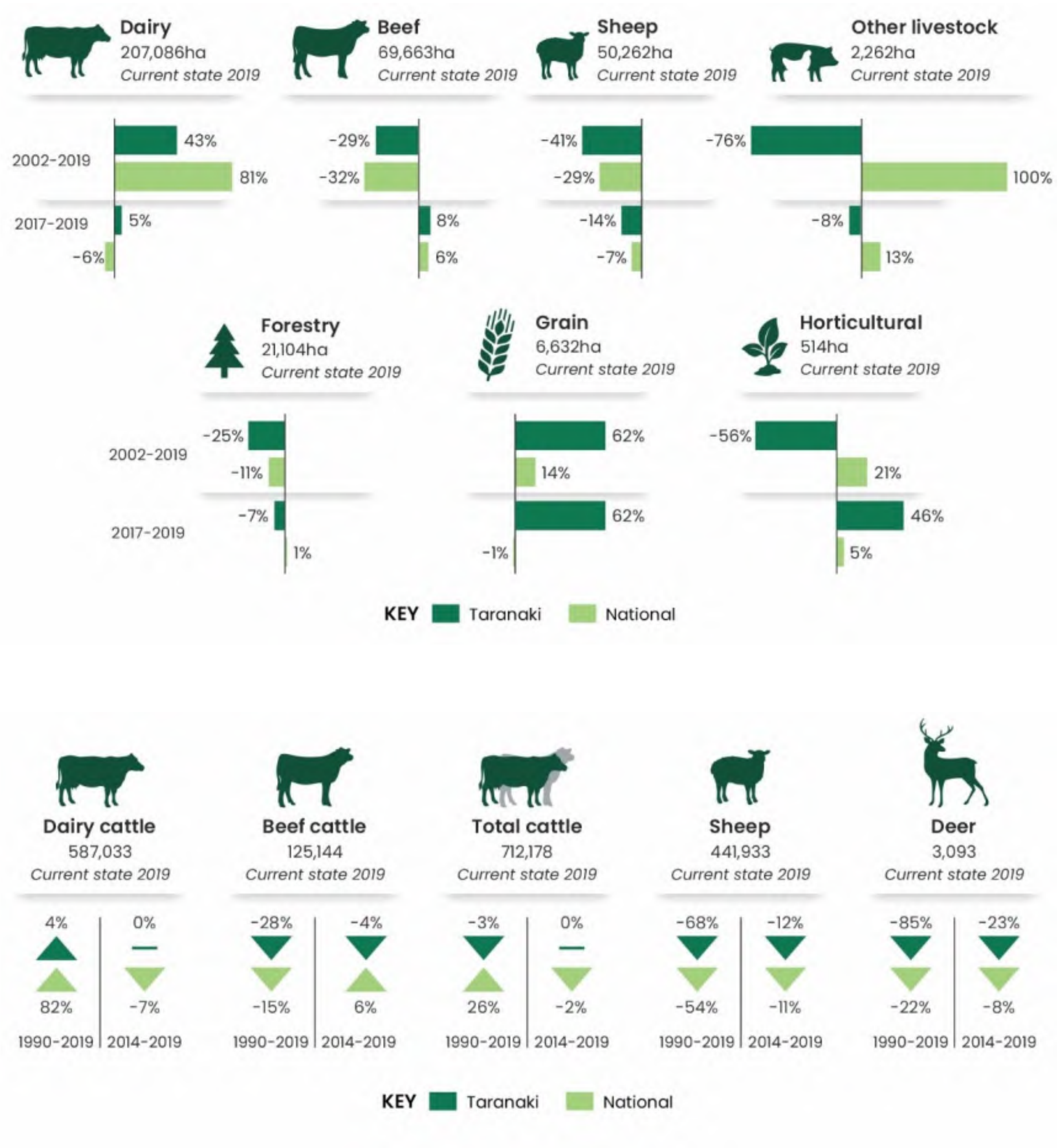

Figure 7 Changes in land use (top) and livestock numbers (bottom) in Taranaki over time

4. State of groundwater quality

Descriptive statistics were derived for the 12 key indicators to assess the state of groundwater quality in the region. Table 4 provides a summary of descriptive statistics for nine key indicators based on data collected over the last five or two years from GQMP sites. Note that the two year summary statistics are provided for indicative purposes only, and robust analytical conclusions should not be made based on this data.

Median concentrations for nitrite nitrogen, fluoride and bromide in groundwater were generally below their respective laboratory detection limits, or were well below DWSNZ (2018) or WHO (2017) MAVs. They have therefore not been included in Table 4 or reported on specifically in this section. These variables are still commented on in the following section on temporal trend analysis.

4.1. Electrical conductivity (EC)

Electrical conductivity is a general indicator of changes in groundwater composition. These changes could be the result of natural processes or human activities, including seawater intrusion or land use. Typical EC values in freshwater range from 300 µS/cm to 800 µS/cm (Hem 1985).

EC values can also be used to approximate concentrations of total dissolved solids (TDS) using the formula TDS (mg/L) = k x EC (µS/cm), k is the ratio of TDS/EC with a typical value of and k = 0.55 (HEM 1985). The DWSNZ (2018) GV taste threshold for TDS of 1,000 mg/L. While the ANZECC (2000) stock water TDS threshold is 2,000-2,500 mg/L to prevent decline in stock productivity.

Median electrical conductivity measurements across the region ranged from 66 µS/cm (GND2166) to 696 µS/cm (GND2513), (Table 4). No approximated median value exceeded the DWSNZ (2018) GV of 1,000 mg/L or ANZECC (2000) stock water threshold of 2,000-2,500 mg/L for TDS.

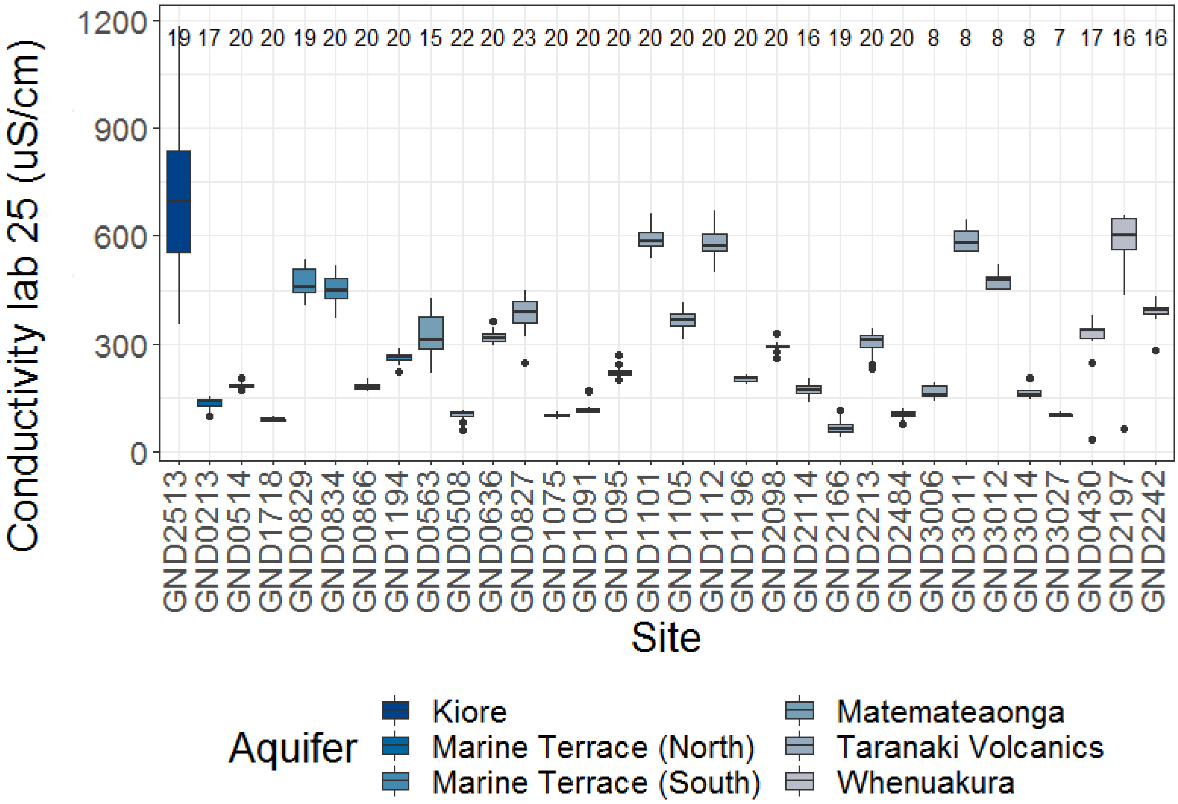

Figure 8 Electrical conductivity values recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020. Bores are grouped by aquifer.

Table 4 Summary statistics calculated based on data from nine key variables measured quarterly in 32 GQMP sites in the Taranaki region between 1 July 2015 and 30 June 2020

Note: *Statistical analysis methods outlined in Section 2.2.4. The range here is defined as the 5th and 95th percentile. Median values which are greater than DWSNZ (2018) MAVs are shown in bold font. Where % censored value is greater than 70%, the minimum and medium values stated are the detection limit.*

Site	Aquifer	Conductivity (µS/cm)				Nitrate nitrogen (mg/L)				Ammoniacal nitrogen (mg/L)				Dissolved iron (mg/L)				Dissolved manganese (mg/L)			
		Median	Range	n	% censored	Median	Range	N	% censored	Median	Range	n	% censored	Median	Range	n	% censored	Median	Range	n	% censored
Kiore																					
GND2513	Unconfined	696	441 - 995	19	0	0.003	0.001 - 0.017	19	37	2.10	0.901 - 2.56	19	0	2.62	0.16 - 10.39	19	0	**0.480**	0.090 - 0.705	19	5
Marine Terrance (North)																					
GND0213	Unconfined	143	107 - 152	17	0	0.740	0.637 - 1.05	19	0	0.006	0 - 0.044	19	37	<0.01	<0.01 - 0.04	19	74	0.001	0.00 - 0.011	19	42
GND0514	Unconfined	186	179 - 200	20	0	4.55	3.20 - 5.94	20	0	<0.004	<0.003 - 0.010	20	85	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - 0.01	20	95
GND1718	Unconfined	90	84 - 96	20	0	0.910	0.599 - 1.38	20	0	<0.003	<0.003 - 0.010	20	95	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - <0.01	20	100
Marine Terrance (South)																					
GND0829	Unconfined	456	418 - 530	19	0	9.70	7.34 - 11.22	19	0	<0.008	<0.003 - 0.010	19	84	<0.03	<0.02 - 0.03	19	95	<0.01	<0.01 - <0.01	19	100
GND0834	Unconfined	447	399 - 494	20	0	1.47	0.591 - 3.18	20	0	<0.007	<0.003 - 0.010	20	90	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - <0.01	20	100
GND0866	Unconfined	180	170 - 205	20	0	3.35	2.42 - 4.06	20	0	<0.004	<0.003 - 0.010	20	95	<0.03	<0.02 - 0.07	20	75	0.003	0.001 - 0.009	20	55
GND1194	Unconfined	265	223 - 277	20	0	2.29	1.15 - 3.28	20	0	<0.007	<0.003 - 0.011	20	85	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - <0.01	20	100
Matemateaonga																					
GND0563	Confined	312	252 - 404	15	0	0.010	0.010 - 0.010	3	67	5.02	4.72 - 5.76	3	0	7.10	5.66 - 8.72	3	0	0.23	0.203 - 0.257	3	0
Taranaki Volcanics																					
GND0508	Unconfined	106	84 - 115	22	0	0.505	0.276 - 1.06	24	0	<0.003	<0.002 - 0.006	24	71	<0.01	<0.01 - 0.03	24	75	0.003	0.001 - 0.009	24	25
GND0636	Unconfined	315	301 - 363	20	0	7.01	6.19 - 8.07	20	0	<0.007	<0.003 - 0.010	20	80	<0.03	<0.02 - 0.03	20	90	0.010	0.00 - 0.010	20	70
GND0827	Unconfined	387	322 - 441	23	0	3.30	2.31 - 5.46	23	0	<0.006	<0.003 - 0.022	23	74	0.03	0.01 - 0.17	23	9	0.002	0.001 - 0.008	23	13
GND1075	Unconfined	101	93 - 111	20	0	0.840	0.420 - 2.24	20	0	0.003	0.000 - 0.045	20	60	<0.03	<0.02 - 0.20	18	94	0.001	0.00 - 0.018	19	58
GND1091	Unconfined	117	110 - 167	20	0	2.13	1.96 - 2.69	20	0	<0.003	<0.003 - 0.010	20	95	<0.03	<0.02 - <0.03	20	100	0.001	0.001 – 0.001	20	55
GND1095	Unconfined	218	201 - 247	20	0	1.74	1.37 - 2.31	20	0	<0.005	<0.003 - 0.010	20	85	<0.03	<0.02 - <0.03	20	100	0.002	0.00 - 0.007	20	60
GND1101	Unconfined	583	544 - 653	20	0	8.11	6.94 - 12.11	20	0	<0.004	<0.003 - 0.011	20	85	<0.03	<0.02 - 0.07	20	85	0.004	0.001 - 0.014	20	45
GND1105	Unconfined	368	314 - 407	20	0	10.65	7.92 - 16.21	20	0	<0.007	<0.003 - 0.014	20	80	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - 0.01	20	85
GND1112	Unconfined	574	521 - 636	20	0	**24.00**	19.74 - 29.01	20	0	<0.007	<0.003 - 0.011	20	90	<0.03	<0.02 - <0.03	20	100	<0.01	<0.01 - 0.01	20	90
GND1196	Unconfined	204	192 - 213	20	0	3.20	2.79 - 3.63	20	0	<0.009	<0.003 - 0.011	20	75	<0.03	<0.02 - 0.10	20	90	<0.01	<0.01 - 0.01	20	90
GND2098	Unconfined	293	276 - 305	20	0	2.13	1.62 - 2.31	20	0	0.006	0.002 - 0.019	20	60	<0.03	<0.02 - 0.06	20	80	0.030	0.020 - 0.077	20	0
GND2166	Unconfined	66	44 - 111	19	0	1.41	0.386 - 3.32	18	0	<0.010	<0.003 - 0.011	18	83	<0.03	<0.02 - 0.03	18	94	0.012	0.006 - 0.037	18	11
GND2213	Unconfined	314	242 - 334	20	0	1.97	1.56 - 2.43	20	0	<0.010	<0.003 - 0.020	20	85	<0.03	<0.02 - 0.03	20	95	0.002	0.001 - 0.011	20	45
GND2484	Unconfined	106	86 - 113	20	0	0.260	0.164 - 0.362	20	0	<0.006	<0.003 - 0.010	20	90	<0.03	<0.02 - 0.04	20	80	0.001	0.001 – 0.001	20	55
GND3006	Unconfined	158	145 - 190	8	0	2.90	2.54 - 3.30	8	0	<0.010	<0.010 - <0.010	8	100	<0.02	<0.02 - 0.02	8	88	0.00	0.00 – 0.001	8	50
GND3011	Unconfined	580	557 - 635	8	0	0.003	0.000 - 0.117	8	50	0.029	0.016 - 0.046	8	0	4.55	0.77 - 9.12	8	0	0.092	0.075 - 0.280	8	0
GND3012	Unconfined	480	451 - 509	8	0	0.002	0.000 - 0.064	8	50	0.595	0.443 - 0.673	8	0	10.80	8.85 - 13.48	8	0	**0.595**	0.560 - 0.979	8	0
GND3014	Unconfined	161	148 - 193	8	0	2.05	1.77 - 2.43	8	0	<0.010	<0.010 - <0.010	8	100	<0.02	<0.02 - 0.02	8	88	0.008	0.002 - 0.218	8	0
GND3027	Unconfined	102	96 - 110	7	0	0.340	0.285 - 0.513	7	0	<0.010	<0.010 - 0.011	7	71	<0.02	<0.02 - <0.02	7	100	0.009	0.005 - 0.028	7	0
GND2114	Confined	173	140 - 199	16	0	0.004	0.000 - 0.436	18	56	0.481	0.273 - 0.522	18	0	1.15	0.02 - 2.26	18	6	**0.74**	0.009 - 2.200	18	0
Whenuakura																					
GND0430	Confined	337	205 - 360	17	0	0.010	0.001 - 0.279	19	37	0.444	0.146 - 0.503	19	0	0.04	0.02 - 0.06	19	0	0.009	0.007 - 0.098	19	0
GND2197	Confined	601	344 - 657	16	0	0.005	0.001 - 0.050	18	67	2.30	2.06 - 2.80	18	0	0.01	0.00 - 0.01	18	28	0.002	0.002 – 0.003	18	6
GND2242	Confined	394	345 - 420	16	0	<0.010	<0.003 - 0.027	18	78	0.740	0.706 - 0.822	18	0	0.01	0.00 - 0.02	18	44	0.002	0.001 - 0.010	18	6

Table 4 Summary statistics calculated based on data from nine key variables measured quarterly in 32 GQMP sites in the Taranaki region between 1 July 2015 and 30 June 2020

Note: *Statistical analysis methods outlined in Section2.2.4. The range here is defined as the 5th and 95th percentile. Median values which are greater than DWSNZ (2018) MAVs are shown in bold font. Where % censored value is greater than 70%, the minimum and medium values stated are the detection limit.*

Site	Aquifer	Bicarbonate (mg/L)				Chloride (mg/L)				Dissolved sodium (mg/L)				*E.coli* (MPN/100mL)			
		Median	Range	n	% censored	Median	Range	n	% censored	Median	Range	n	% censored	Median	Range	n	% censored
Kiore																	
GND2513	Unconfined	500	374 - 590	8	0	27.0	19.1 - 31.9	8	0	193.5	136.2 – 243.0	8	0	**9**	<1 - 112	16	44
Marine Terrace (North)																	
GND0213	Unconfined	42	37 - 46	19	0	18.2	17.3 - 18.6	19	0	13.6	13.0 - 14.4	19	0	Not tested			
GND0514	Unconfined	27	19 - 34	8	0	27.0	26.0 – 28.0	8	0	13.7	13.4 - 14.3	8	0	**1**	<1 - 29	20	50
GND1718	Unconfined	26	24 - 29	7	0	9.1	8.1 - 9.5	8	0	8.6	7.9 - 8.8	8	0	<1	<1 - 39	20	80
Marine Terrace (South)																	
GND0829	Unconfined	104	100 - 109	8	0	46.5	44.3 - 61.8	8	0	41.0	39 - 47.6	8	0	<1	<1 - 6	19	63
GND0834	Unconfined	83	72 - 89	8	0	58.0	48.9 - 68.5	8	0	50.0	45.7 - 53.3	8	0	<1	<1 - 14	20	75
GND0866	Unconfined	35	33 - 35	8	0	22.0	21.0 - 23.3	8	0	23.0	22.0 - 25.6	8	0	<1	<1 - 1	20	90
GND1194	Unconfined	94	84 - 97	8	0	16.8	15.4 - 18.9	8	0	16.9	16.6 - 17.8	8	0	<1	<1 - 1	20	85
Matemateaonga																	
GND0563	Confined	218	214 - 232	3	0	10.2	10.1 - 10.4	3	0	32.0	31.1 - 36.5	3	0	Not tested			
Taranaki Volcanics																	
GND0508	Unconfined	26	24 - 29	19	0	13.0	11.5 - 15.2	19	0	7.5	6.6 – 8.0	19	0	Not tested			
GND0636	Unconfined	50	44 - 52	8	0	34.0	31.0 - 42.8	8	0	24.0	22.4 - 26.3	8	0	<1	<1 - 2	20	80
GND0827	Unconfined	73	62 - 79	21	0	50.0	44.0 – 61.0	21	0	45.0	38.0 – 51.0	21	0	**3**	<1 - 80	19	26
GND1075	Unconfined	32	27 - 35	8	0	6.2	5.4 - 7.3	8	0	5.7	5.2 - 6.3	8	0	<1	<1 - 12	20	80
GND1091	Unconfined	22	20 - 25	8	0	16.4	15.5 - 16.6	8	0	9.4	8.6 - 9.6	8	0	<1	<1 - <1	20	100
GND1095	Unconfined	64	60 - 88	8	0	19.3	18.7 - 19.7	8	0	18.1	16.2 - 20.5	8	0	**1**	<1 - 20	20	45
GND1101	Unconfined	78	69 - 81	8	0	96.0	83.4 – 102.0	8	0	66.5	60.0 - 74.7	8	0	**1**	<1 – 2,543	20	70
GND1105	Unconfined	58	50 - 64	8	0	41.0	36.0 - 44.3	8	0	24.0	22.4 - 24.6	8	0	**2**	<1 - 62	20	50
GND1112	Unconfined	42	40 - 46	8	0	88.5	83.0 – 91.0	8	0	42.0	38.4 – 43.0	8	0	**1**	<1 - 7	20	70
GND1196	Unconfined	52	51 - 58	8	0	20.0	19.0 - 21.6	8	0	20.0	18.3 – 20.0	8	0	<1	<1 - 1	20	90
GND2098	Unconfined	84	83 - 85	8	0	35.0	34.0 - 36.6	8	0	33.0	30.4 - 33.6	8	0	<1	<1 - 261	20	65
GND2166	Unconfined	11	7 - 20	8	0	8.4	3.7 - 18.4	8	0	5.3	3.0 - 9.1	8	0	<1	<1 - 26	18	72
GND2213	Unconfined	116	97 - 126	8	0	28.0	27.0 – 29.0	8	0	29.0	27.4 – 31.0	8	0	<1	<1 - 5	20	80
GND2484	Unconfined	44	37 - 46	8	0	7.1	6.6 - 7.5	8	0	9.9	8.5 - 10.5	8	0	<1	<1 - 2	20	95
GND3006	Unconfined	38	33 - 41	8	0	16.4	15.6 - 19.6	8	0	11.8	11.1 - 13.8	8	0	<1	<1 - <1	8	100
GND3011	Unconfined	88	84 - 100	8	0	69.0	64.3 – 70.0	8	0	70.0	69.0 - 74.3	8	0	<1	<1 - 4	8	75
GND3012	Unconfined	172	168 - 186	8	0	42.5	39.7 - 44.6	8	0	58.0	55.3 - 66.6	8	0	<1	<1 - 14	8	88
GND3014	Unconfined	40	38 - 52	8	0	18.2	16.4 - 21.9	8	0	11.6	10.7 - 15.6	8	0	<1	<1 - <1	8	100
GND3027	Unconfined	39	38 - 43	7	0	5.8	5.4 - 6.4	7	0	6.3	6.2 – 8.0	7	0	<1	<1 - <1	7	100
GND2114	Confined	70	35 - 77	18	0	20.0	19.7 - 21.1	18	0	15.1	14.3 - 15.7	18	0	Not tested			
Whenuakura																	
GND0430	Unconfined	167	161 - 172	19	0	24.0	23.0 – 25.0	19	0	22	21.9 - 23.1	19	0	Not tested			
GND2197	Unconfined	326	299 - 351	18	0	34.0	33.0 – 35.0	18	0	130	117.7 - 140.3	18	0	Not tested			
GND2242	Unconfined	176	171 - 183	18	0	30.0	29.0 – 30.0	18	0	24	23.9 – 25.0	18	0	Not tested			

The lowest median EC values (<100 µS/cm) were detected in groundwater samples from GND2166 and GND1718 (Table 4). GND2166 is a 3.5 m deep well located just outside of Te Papakura o Taranaki where the unconfined Taranaki Volcanics aquifer is likely recharged by recent rainfall on Taranaki Maunga. GND1718 is an 11 m deep well screened in an unconfined Marine Terraces (North) aquifer, recharged by coastal rainfall and surrounded by a mix of high and low producing grassland.

The highest EC values, both median and 95th percentile, were detected in GND2513. This site also had the largest inter-percentile range of 554 µS/cm (Table 4). GND2513 is a 5 m deep well screened in the shallow unconfined Kiore aquifer. The well was installed in 2015, as part of a joint investigation by Lincoln Agritech and the Council (Stenger and Clague 2015), to study the anoxic conditions which had been identified at a nearby former GQMP site (GND1080). These conditions were considered unusual as anoxic environments are more typical of deeper confined aquifers where oxygen is limited. It is likely the anoxic aquifer environment at this location more readily promotes the dissolution of ions from the surrounding aquifer geology, and favours the denitrification and attenuation of nitrogen as ammonia. This is reflected in high EC values and concentrations of other key variables (such as ammonia, bicarbonate, iron, manganese and sodium) noted in groundwater samples from GND2513.

Box plot summaries of EC values recorded at each GQMP site are displayed In Figure 8 with sites grouped by aquifer. EC values recorded in bores screened in confined aquifers, like Whenuakura and Matemateaonga, were often not much greater than EC values recorded in wells screened in unconfined aquifers, such as Marine Terraces and Taranaki Volcanics. However, this may simply reflect that while the drivers of EC may differ between unconfined and confined, both natural processes and human activities may be equally as strong in influencing EC values. EC values in the groundwater of the Marine Terrace (North) unconfined aquifers appears to be comparatively lower than groundwater in most other aquifers (Figure 9).

Drivers of EC values detected in the remaining GQMP sites appear to vary with geographic location, recharge mechanisms, land use influence and aquifer confinement (Figure 9). Groundwater samples from GQMP sites situated in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki (including south of Kaponga) generally had greater median EC values (301 µS/cm - ≤650 µS/cm), than inland sites and sites located in northern and eastern parts of the region.

The greater EC values noted in coastal aquifers may reflect the fact that rainfall at the coast is richer in chloride and sodium ions, compared to rainfall that falls inland. However, aquifer lithology in this area is dominated by volcanic debris avalanche deposits and poorly drained soils (see Section 3.1.4), or marine derived formations and/or soils rich in marine derived salts. The less transmissive nature of these formations can promote extended rock/water interactions and ion enrichment of groundwater in both unconfined and confined aquifers. This is possibly the reason for high EC values noted in GND3011, GND3012 and GND2197, as discussed in Section 4.3. Land use contributions may also drive EC values in these areas as well, such as at GND1101 and GND1112, where elevated nitrate concentrations are also observed (Sections 4.3 and 4.6).

The fresh to moderately-freshwater EC values (0 µS/cm - ≤300 µS/cm) of inland GQMP sites (i.e. midway between Taranaki Maunga and boundary of the Volcanic Ring Plain), and sites located in the northern and eastern parts of the region, suggest that recharge to these aquifers is relatively recent. Analysis of groundwater Na:Cl ratios (Section 4.3) further suggests that groundwater is recharged by recent rainfall derived from marine origins. However, land use and/or natural rock-water interactions can still elevate EC values in these aquifers.

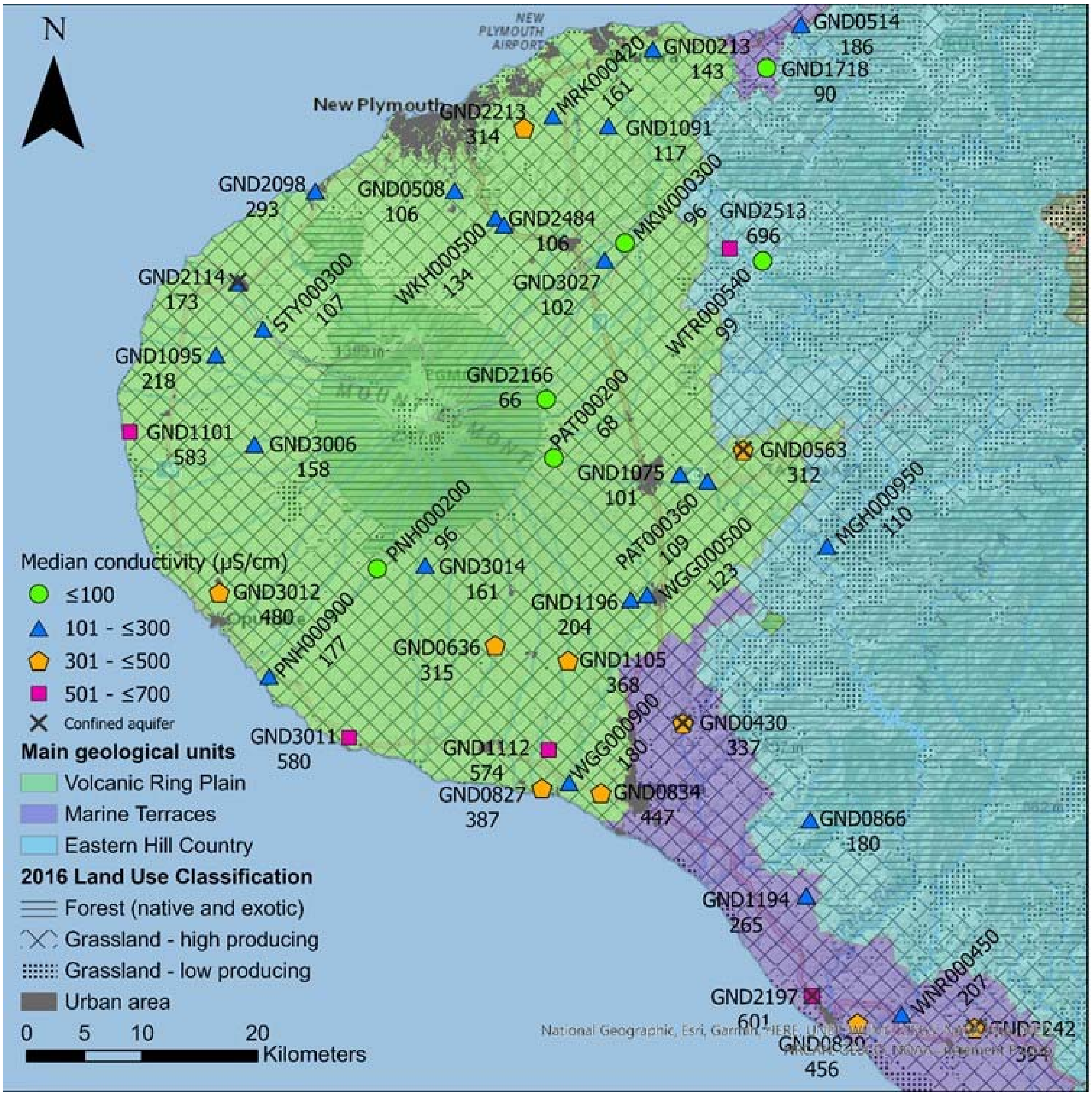

Figure 9 Median electrical conductivity (EC) values recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020

Note: *Groundwater sites are denoted by prefix GND. Median EC values, recorded at 15 surface water sites between 01 July 1995 and 30 June 2019, reported on in the 2019 SEM freshwater physicochemical report have been included for comparison. Calculated median values are recorded under their respective well or bore name.*

The strength of hydraulic connections between surface water and groundwater in the north and east of the region is unclear. Often groundwater from unconfined aquifers in these areas have median EC values within the range of median EC values of nearby rivers (TRC 2020) (Figure 9). This suggests some links between these aquifers and the region's larger river systems. However, it may be that the EC of these aquifers simply reflect where lower residence times and short flow paths provide less opportunity for ions from contamination or natural processes to build-up in groundwater. In contrast, aquifers closer to the coast, may have longer flow paths and groundwater residence times.

4.1.1. Summary

- EC values can be used to estimate TDS in groundwater samples. No approximated TDS median value exceeded the DWSNZ (2018) GV of 1,000 mg/L or ANZECC (2000) stock water threshold of 2,000-2,500 mg/L for TDS.

- Median groundwater EC measurements (State) ranged from 66 µS/cm to 696 µS/cm. The lowest median EC value was detected in an unconfined GQMP site very close to Te Papakura o Taranaki. While the highest median EC value was noted in a site in the Eastern Hill Country, which is sampled to monitor the unusual anoxic groundwater conditions of the local shallow unconfined aquifer.
- EC values in groundwater at GQMP sites can be influenced by one or more drivers such as, marine derived rainfall recharge, soil drainage conditions, aquifer confinement, sodium enrichment from aquifer geology and land use in the recharge zone.
- Groundwater EC values are generally greater in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki (including south of Kaponga) when compared to groundwater EC values from inland GQMP sites and sites located in northern and eastern parts of the region.

4.2. Bicarbonate (HCO_3)

Median concentrations of bicarbonate ranged from 11 mg/L (GND2166) to 500 mg/L (GND2513), (Table 4 and Figure 10).

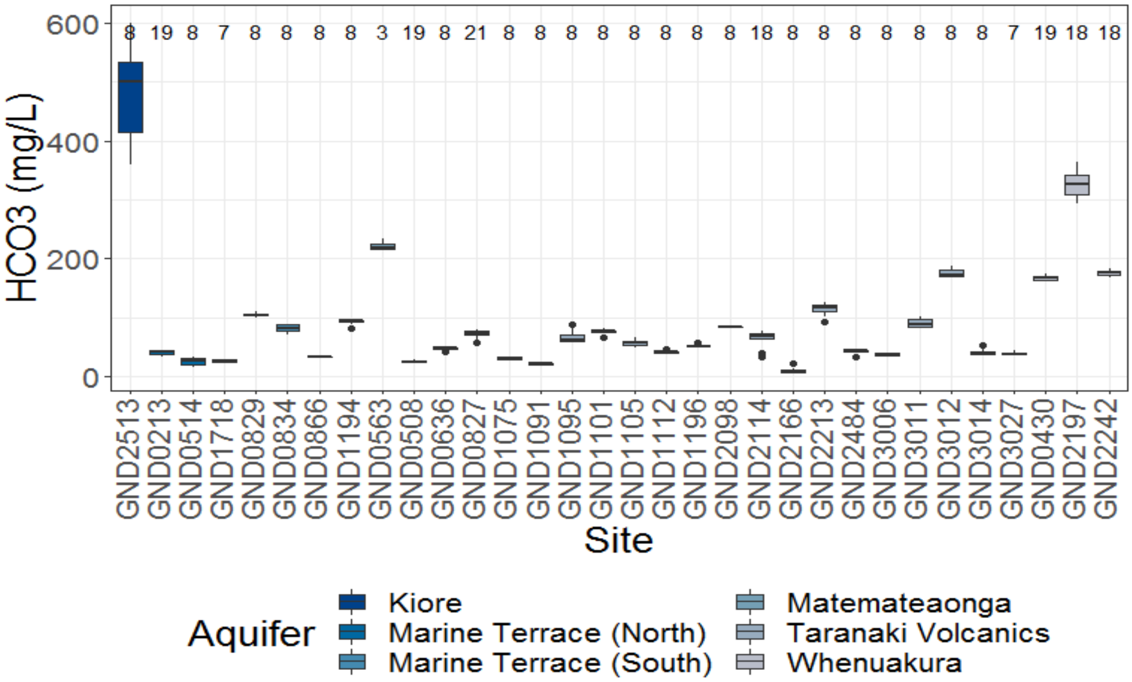

Figure 10 Comparison of bicarbonate concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020. Sites are grouped by aquifer

Bicarbonate concentrations were the highest in sites screened in unconfined and confined aquifers within the Kiore, Matemateaonga and Whenuakura aquifers. Here, bicarbonate concentrations most likely reflect oxygen poor conditions and longer residence times which promote carbonate enrichment of groundwater. GND3012 and GND2213, which are screened <11 m deep within unconfined aquifers of the Taranaki Volcanics Formation, also had notably high bicarbonate concentrations. It is likely that bicarbonate concentrations at GND2213 are driven by land use activities. While GND3012 may reflect where groundwater is influenced by localised reducing aquifer conditions arising from poor soil drainage (Figure 5) and a dominance of volcanic debris avalanche deposits. Sites screened in shallow and unconfined Marine Terrace (South) aquifers often had moderate concentrations of bicarbonate. This is most likely due to natural interactions between groundwater and the rich carbonate source rocks that comprise these aquifers.

Similar to EC, in GND2166 Bicarbonate concentrations reflect a transmissive unconfined aquifer which is rapidly recharged by fresh rainfall and has little rock/water interactions or influence from human activity. Bicarbonate concentrations in GND2513 are due to naturally oxygen poor conditions of the local unconfined aquifer that promote redox driven rock/water interactions.

Spatially, groundwater samples from GQMP sites situated in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki generally had greater bicarbonate concentrations (51 mg/L - ≤500 mg/L), than inland sites and sites located in northern and eastern parts of the region (≤50 mg/L). While often the coastal and southern sites appeared to be more impacted by land use (as discussed in Section 4.6), it is more likely that bicarbonate concentrations in these aquifers are driven by carbonate rich lithology and/or aquifers with potentially lower transmissivities and longer residence times.

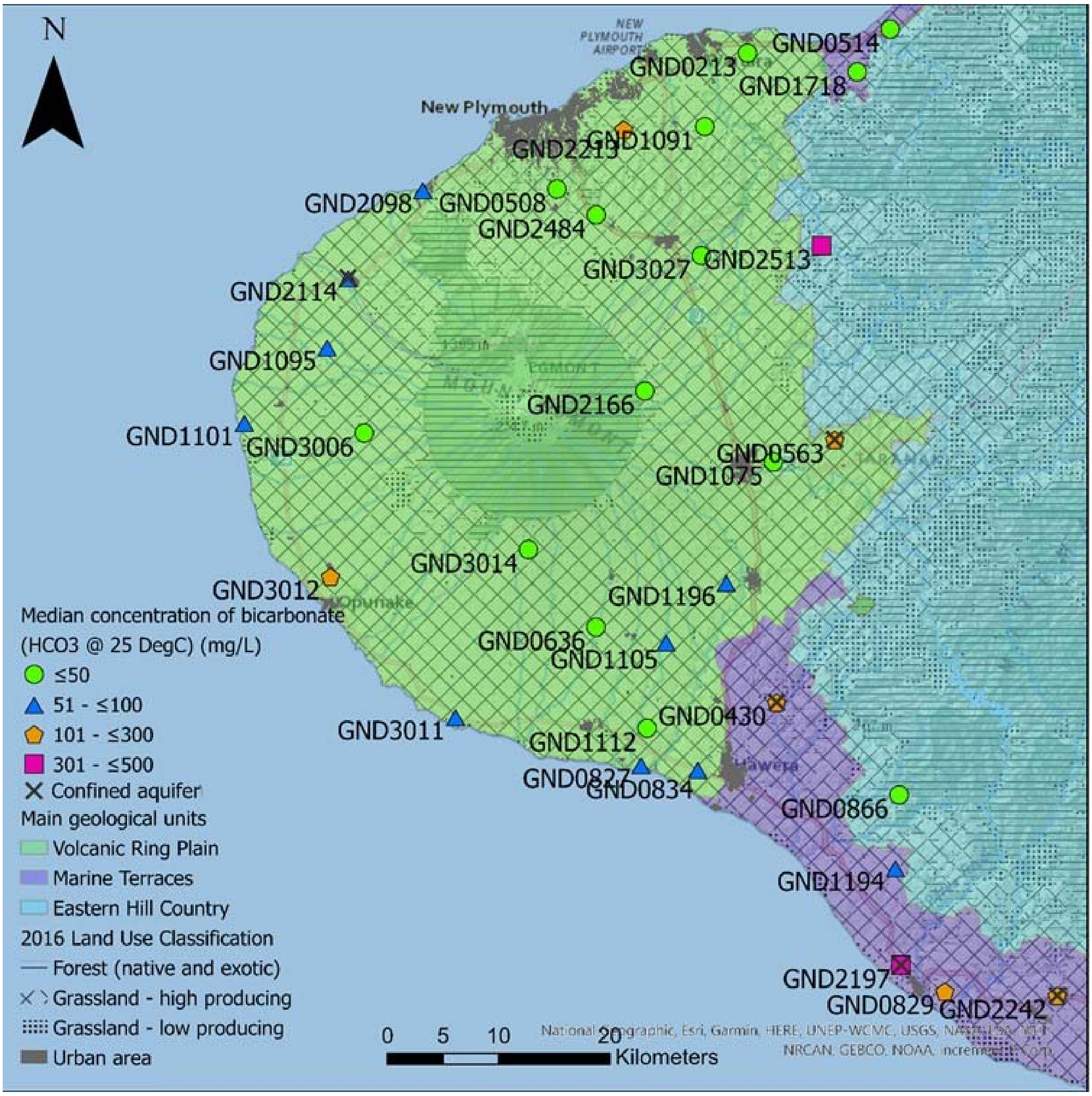

Figure 11 Median bicarbonate concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020

4.2.1. Summary

- Median concentrations of bicarbonate ranged from 11 mg/L to 500 mg/L.

- The lowest median bicarbonate concentration was detected in a sitevery close to Te Papakura o Taranaki and reflects an unconfined aquifer which is rapidly recharged by rainfall. The highest median bicarbonate concentrations was detected in a shallow well in the Eastern Hill Country, which is sampled to monitor the unusual anoxic groundwater conditions of the local unconfined aquifer.
- Bicarbonate concentrations appear to be greater in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki, and notably in the Marine Terrace (South), Kiore, Whenuakura and Matemateaonga Formations. Bicarbonate concentrations in these aquifers are driven by carbonate rich lithology and/or aquifers with potentially lower transmissivities and longer residence times.

4.3. Chloride (Cl) and sodium (Na)

Chloride and sodium are considered together in this section as the relative ratio of sodium to chloride in a sample can be used to differentiate the source of salinity in groundwater. Median concentrations of chloride ranged from 5.8 mg/L (GND3027) to 96 mg/L (GND1101), while median concentrations of sodium ranged from 5.3 mg/L (GND2166) to 193.5 mg/L (GND2513) (Table 4, Figure 12). Groundwater samples from GND2513 periodically exceeded the DWSNZ (2018) GV for sodium (200 mg/L).

There appear to be no patterns in chloride and sodium concentrations associated with particular aquifers. However, geographically, chloride and sodium concentrations appear to be greater in GQMP sites located in coastal areas west/south-west of Taranaki Maunga through to South Taranaki. Meanwhile, sites located inland close to Taranaki Maunga, and in the northern and eastern parts of the region, tended to have lower concentrations of chloride and sodium. This is similar to spatial patterns noted for EC and bicarbonate levels, and the combination of drivers such as; proximity to the marine environment and natural processes influenced by aquifer lithology and transmissivity, are most likely the same.

Seawater has an approximate ratio of sodium to chloride (in mg/L) of 0.55. When plotted, this linear ratio is referred to as the seawater dilution line (SWDL). This ratio can also be reflected in rainwater when the rainwater is derived from seawater evaporation. However, in such a case, the absolute concentration of each ion in the rainwater is orders of magnitude lower than that in seawater. If salinity in groundwater is derived from marine sourced rainfall recharge, the Na:Cl ratio will be similar to that found in seawater (0.55), and will plot along the SWDL. Deviations away from this ratio indicate additional inputs of either ion from geochemical processes within the groundwater system or from human activities.

The relative ratios of sodium to chloride at all 32 GQMP sites sampled over the last five years are plotted in Figure 13. Ratios are derived from median concentrations of sodium and chloride. Figure 13 indicates 11 GQMP sites have Na:Cl ratios that plot close to the SWDL, i.e. the Na:Cl ratios at these sites are +/-0.2 within the Na:Cl ratio of seawater (0.55). GND1101 and GND2166, which had the highest and lowest median concentrations of chloride and sodium respectively, fall within this group. Rainfall at the coast is more likely to have higher levels of chloride, and GND1101 is strongly influenced by its proximity to the coast near Rahotu. However, land use may also contribute to the chloride and sodium values noted at this site, as discussed in Section 4.6. Meanwhile, GND2166, located at the foot of Taranaki Maunga, represents a site where rainfall may still be of marine origin, but concentrations of chloride and sodium are diluted due to the site's distance inland.

It is likely that much of the rainfall recharge to regional aquifers is sourced from seawater given the coastal location of Taranaki. However, as nearly two thirds of GQMP sites plot below the SWDL (Figure 13), it appears much of the region's groundwater is enriched with sodium. This is most likely due to natural processes, like rock/water interaction with sodium rich source rocks, which actively occurs within both confined and unconfined aquifers. Sites GND3027 and GND2513, which had the lowest and highest median concentrations of both chloride and sodium respectively, fall within this group and show the extent of sodium enrichment within different aquifers. While groundwater at GND3027 is very fresh, with low concentrations of both chloride and sodium, levels of sodium are greater than chloride indicating sodium enrichment is occurring in this aquifer. As noted in the results of previous sections, groundwater at GND2513 represents an unconfined aquifer with unique reducing conditions.

GND1112 and GND0514 plot slightly above the SWDL, suggesting localised chloride enrichment of groundwater in Taranaki Volcanics aquifers. Na:Cl ratios at both sites fall within +/- 0.2 of the seawater Na:Cl ratio (0.55), indicating marine derived rainfall recharge is likely to be a strong source of chloride in groundwater. However, nitrate concentrations in both sites suggests land use is having an impact on groundwater quality (see Section 4.6) and may also be contributing to groundwater concentrations of chloride in these aquifers.

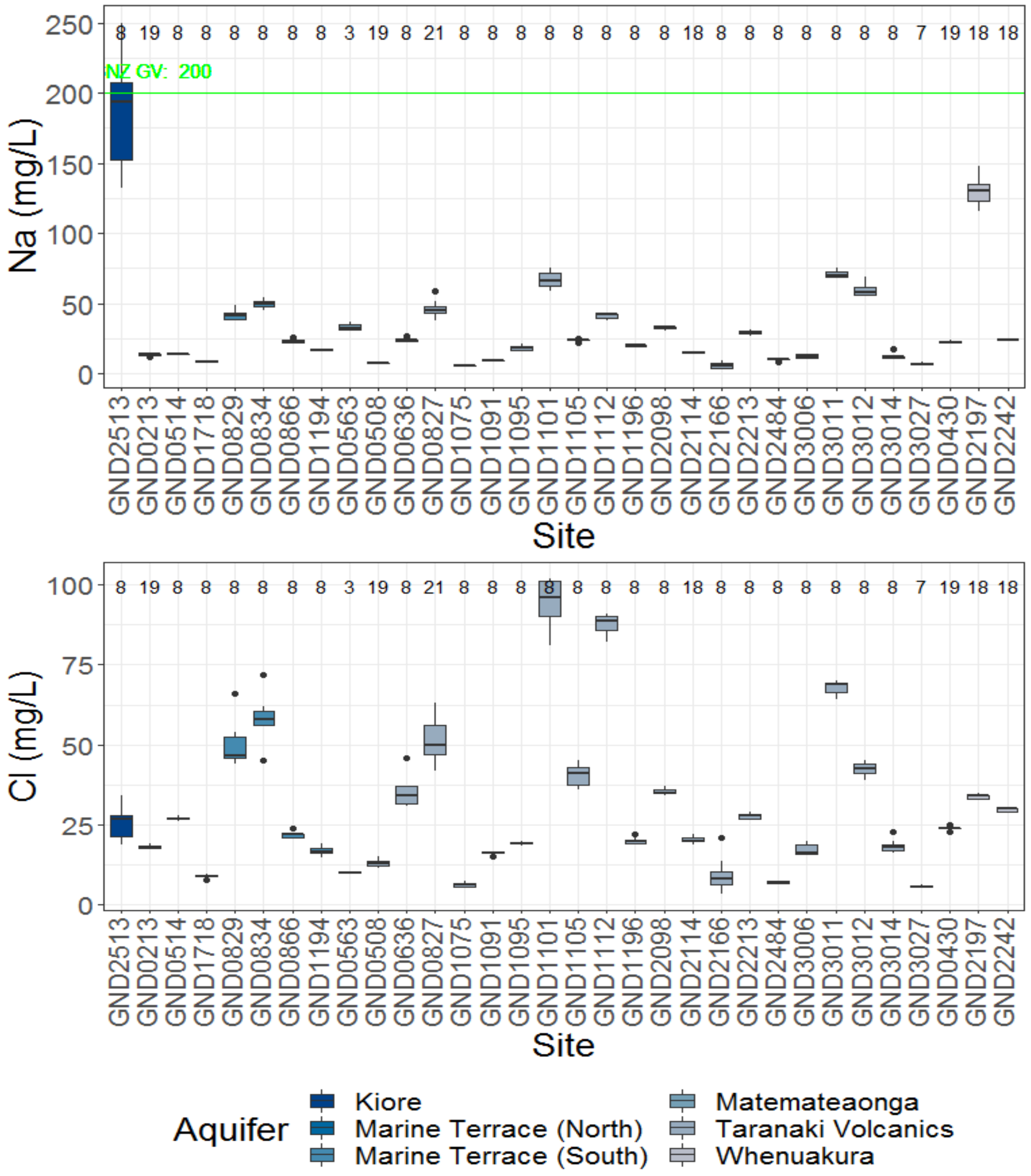

Figure 12 Comparison of sodium and chloride concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020 (Sites are grouped by aquifer)

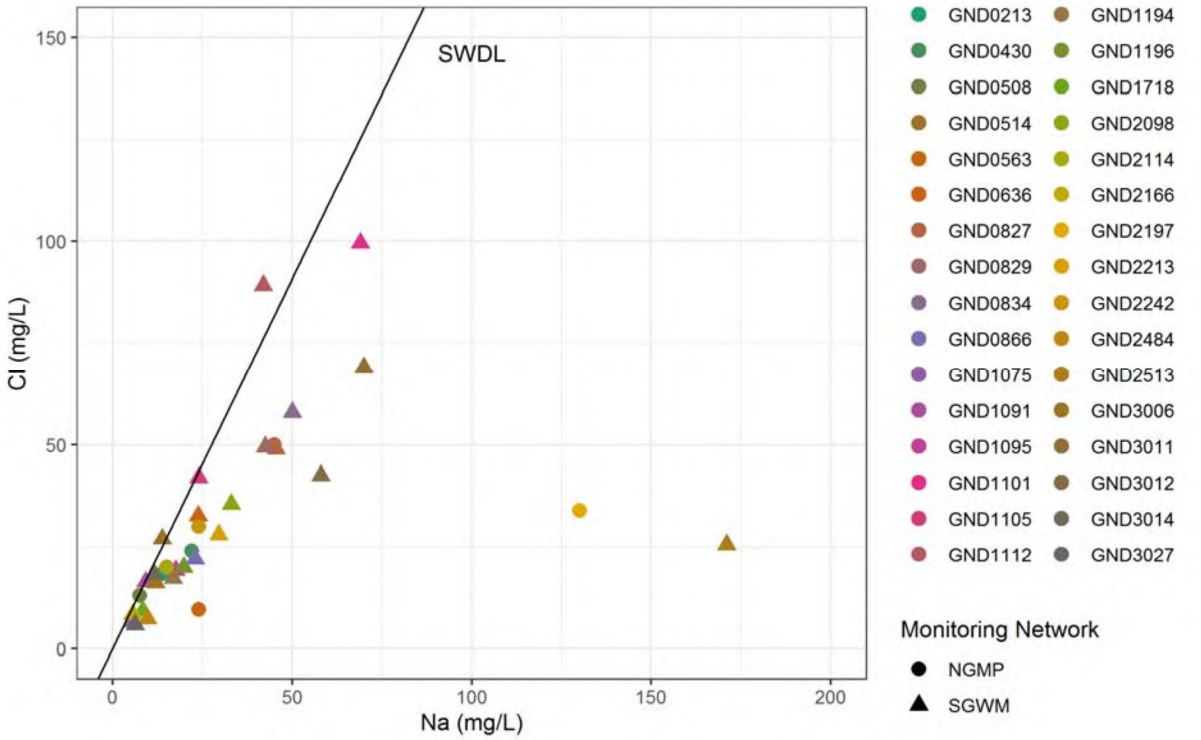

Figure 13 Sodium to chloride ratios of groundwater samples from 32 individual GQMP sites plotted against the seawater dilution line (SWDL)

Note: *Ratios are derived from median concentrations of sodium and chloride recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020. The SWDL represents the approximate ratio of sodium to chloride in seawater (0.55).*

4.3.1. Summary

- Median concentrations of chloride ranged from 5.8 mg/L to 96 mg/L, while median concentrations of sodium ranged from 5.3 mg/L to 193.5 mg/L.
- Chloride and sodium concentrations appear to be greater in GQMP sites located in coastal areas west/south-west of Taranaki Maunga through to South Taranaki. This could be due to a combination of factors like proximity to the marine environment, aquifer geology and natural processes.
- GQMP sites located inland close to Taranaki Maunga, and in the northern and eastern parts of the region tended to have lower concentrations of chloride and sodium. This reflects where fresh rainfall, derived from marine sources, recharges many of the region’s aquifers.
- Sodium concentrations at one site periodically exceeded the sodium DWSNZ (2018) GV value of 200 mg/L. This site is sampled to monitor the unusual anoxic groundwater conditions of the local unconfined aquifer.
- In general, rainfall recharge is sourced from seawater and accounts for much of the chloride and sodium measured in regional aquifers. However, as nearly two thirds of GQMP sites plot below the SWDL, it appears much of the region’s groundwater is enriched with sodium.
- Sodium enrichment of groundwater is likely due to natural processes, like rock/water interaction with sodium rich source rocks, which actively occurs within both confined and unconfined aquifers.

4.4. Iron (Fe) and manganese (Mn)

While there is no statistical correlation between iron and manganese, elevated concentrations of both variables tend to coincide in groundwater from oxygen poor aquifers. Manganese dissolves out first into groundwater under reducing conditions, despite iron being the more abundant ion in most rock types

(Rosen 2001). For these reasons, concentrations of iron and manganese are evaluated together in this section.

Median concentrations of iron ranged from detection limit (lab dependant: <0.01 mg/L to <0.03 mg/L) in multiple sites, to 10.8 mg/L (GND3012). Similarly, median concentrations of manganese from detection limit (<0.0005mg/L to <0.01 mg/L) in multiple sites, to 0.74 mg/L (GND2114) (Table 4).

Table 5 The 11 GQMP sites in which groundwater samples were above the DWSNZ (2018) GV and/or MAV for iron (Fe) and/or manganese (Mn) on one or more sampling occasions between 1 July 2015 and 30 June 2020

Note: *Table shows where iron and manganese were both above GV and/or MAV thresholds in six of the 11 sites.*

Site name	Sites above the DWSNZ (2018) Fe GV <0.2 mg/L (Staining of laundry & sanitary ware)	Sites above the DWSNZ (2018) Mn GV <0.04 mg/L (Staining of laundry & sanitary ware)	Sites above the DWSNZ (2018) Mn MAV <0.4 mg/L (Health significance)	Comment
GND0563	✓	✓		Groundwater quality affected by adjustments to bore depth and sedimentation issues as noted in previous results sections.
GND1075	✓	✓		Although well screened in an unconfined aquifer, localised conditions may favour low level natural dissolution of Fe and Mn from volcanic source rocks.
GND2513	✓		✓	Well screened in an unusually high reducing aquifer environment which promotes dissolution of Fe and Mn.
GND2114	✓		✓	Fe and Mn concentrations may reflect reducing conditions of a semi-confined/confined aquifer.
GND3011	✓	✓		Although well screened in an unconfined aquifer, localised conditions may favour natural dissolution of Fe and Mn from volcanic source rocks.
GND3012	✓		✓	Although well screened in an unconfined aquifer, localised anoxic conditions may favour natural dissolution of Fe and Mn from volcanic source rocks.
GND0827	✓			Individual sample shows a one off spike in iron.
GND430			✓	Mn concentrations may reflect the confined reducing aquifer conditions about this bore.
GND2098		✓		Although bores are screened in an unconfined aquifer, localised conditions may favour low level natural dissolution of Fe and Mn from volcanic source rocks.
GND2166		✓		
GND3014		✓		

The DWSNZ (2018) GVs iron and manganese, and the MAV for manganese was exceeded at 11 individual GQMP sites on one or more sampling occasions. Table 5 lists the 11 sites against the respective DWSNZ (2018) thresholds which they were above, and shows where both iron and manganese concentrations were elevated at the same six sites. Only GND0827 is used as a potable water supply, and in which case only GV for iron was exceeded. GND0563 historically was used as a potable water supply but levels of iron and manganese have made it unusable for this purpose. All other sites are either used for monitoring purposes only, or for stock or industrial use.

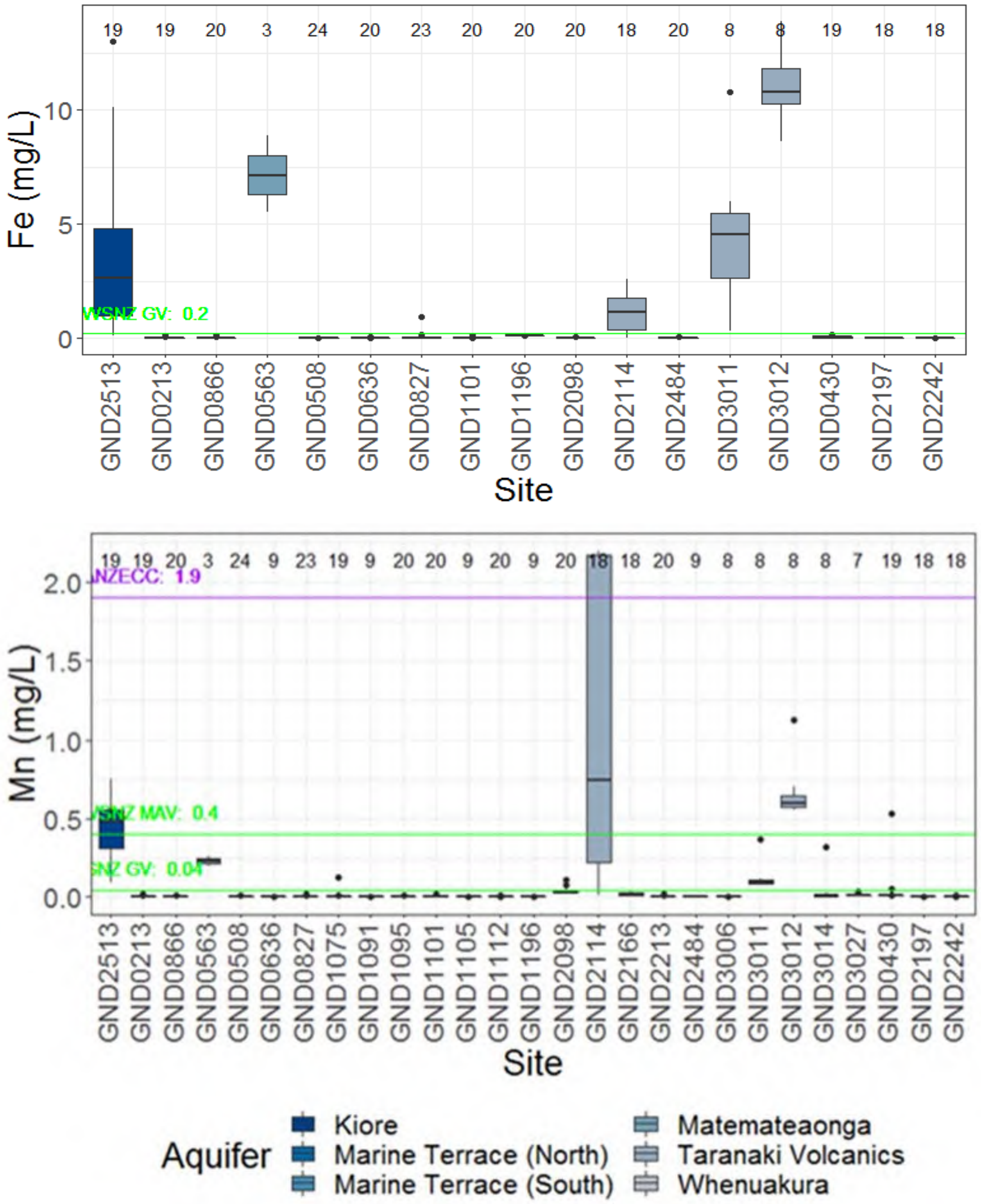

Figure 14 Comparison of iron and manganese concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020. Sites are grouped by aquifer

Note: *Boxplots are only shown where site datasets contained >1 non-censored measurement*

Concentrations of manganese in groundwater samples from GND2114 were also periodically above the ANZECC (2000) toxicity TV of 1.9 mg/L (see Figure 14). GND2114 is 41.9 m deep bore and is the only GQMP site screened within a confined Taranaki Volcanics aquifer. The bore, located <60 m from the Kaihihi Stream in Okato, has both fresh and evolving groundwater quality signatures. Low EC values and an Na:Cl ratio of 0.76, which is just outside the +/- 0.2 range of saltwater Na:Cl ratio (0.55), suggests recharge to this point of the aquifer is relatively recent. However, moderate concentrations of HCO_3, ammonia, iron and manganese indicate aquifer conditions favour some degree of dissolution of ions from surrounding source rock. It may be that GND2114 represents groundwater moving from an unconfined to a semi-confined aquifer, rather than groundwater typical of a purely confined aquifer.

Box plot summaries of iron and manganese concentrations recorded at each GQMP site are displayed in Figure 14, with sites grouped by aquifer. Iron and manganese are most likely to be present together in groundwater from aquifers within the Taranaki Volcanics Formation. It is likely iron and manganese are naturally present in groundwater from these aquifers due to the volcanic geology of Taranaki, which can be rich in both ions. Meanwhile, the anoxic conditions, encountered in the region’s confined aquifers and about GND2513, promote the natural dissolution of both ions. Poor soil drainage about wells GND3011 and GND3012 may also provide the oxygen poor conditions required to actively dissolve iron and manganese into local aquifers, see Figure 5.

4.4.1. Summary

- Median concentrations of iron and manganese ranged from detection limit, in many of the 32 GQMP sites, to 10.8 mg/L and 0.74 mg/L respectively.
- Groundwater samples exceeded the DWSNZ (2018) GVs for iron (<0.2 mg/L) and manganese (<0.04 mg/L) at seven and six sites respectively, on one or more sampling occasions. Only one site is used as a potable water supply, and in which case only GV for iron was exceeded.
- Groundwater samples exceeded the DWSNZ (2018) MAV for manganese (0.4 mg/L) at four sites on one or more sampling occasions. However, exceedances were not detected in GQMP sites used for potable supply.
- Concentrations of manganese in groundwater samples from one site were also periodically above the ANZECC (2000) toxicity TV of 1.9 mg/L.
- Elevated concentrations of iron and manganese generally occur in tandem.
- The volcanic geology of Taranaki Volcanics Formation can be rich in iron and manganese. Concentrations of both ions are commonly detected in groundwater from aquifers within this formation, usually at low levels.
- Redox processes in anoxic groundwater systems can naturally increase dissolved concentrations of both iron and manganese in groundwater. Elevated concentrations of both ions are typically seen in the region’s confined aquifers, and at a site well known for its unusual anoxic unconfined aquifer.

4.5. Ammoniacal nitrogen (NH_4-N)

Median concentrations of ammoniacal nitrogen (ammonia) ranged from below detection limit in multiple sites (lab dependant, ranges from <0.0003 mg/L to <0.01 mg/L) to 5.02 mg/L (GND0563), see Table 4. As noted in previous sections, the groundwater quality at GND0563 has been impacted by bore integrity issues, apparent since 2011 onwards, and adjustments made to bore depth. This is most likely the driver of the highly elevated ammonia concentrations at this bore.

Median concentrations of ammonia in three GQMP sites (GND0563, GND2197 and GND2513) exceeded the DWSNZ (2018) GV of 1.5 mg/L. Only one of these sites, GND2197, is currently used as a potable water supply. Median ammonia concentrations were above the NPS-FM (2020) annual median to protect against ammonia toxicity in freshwater ecosystems (0.24 mg/L) in a further four sites; GND0430, GND2114, GND2242 and GND3012, see Figure 15.

Box plot summaries of ammonia concentrations recorded at each GQMP site are displayed in Figure 15, with sites grouped by aquifer. While there are no spatial patterns for ammonia in the region, generally elevated concentrations of ammonia were detected in groundwater samples from bores screened in confined aquifers within the Taranaki Volcanics, Matemateaonga and Whenuakura Formations. The exception to this is wells GND2513 and GND3012, which have both been noted on in previous sections as being influenced by unusual localised anoxic conditions in an unconfined aquifer.

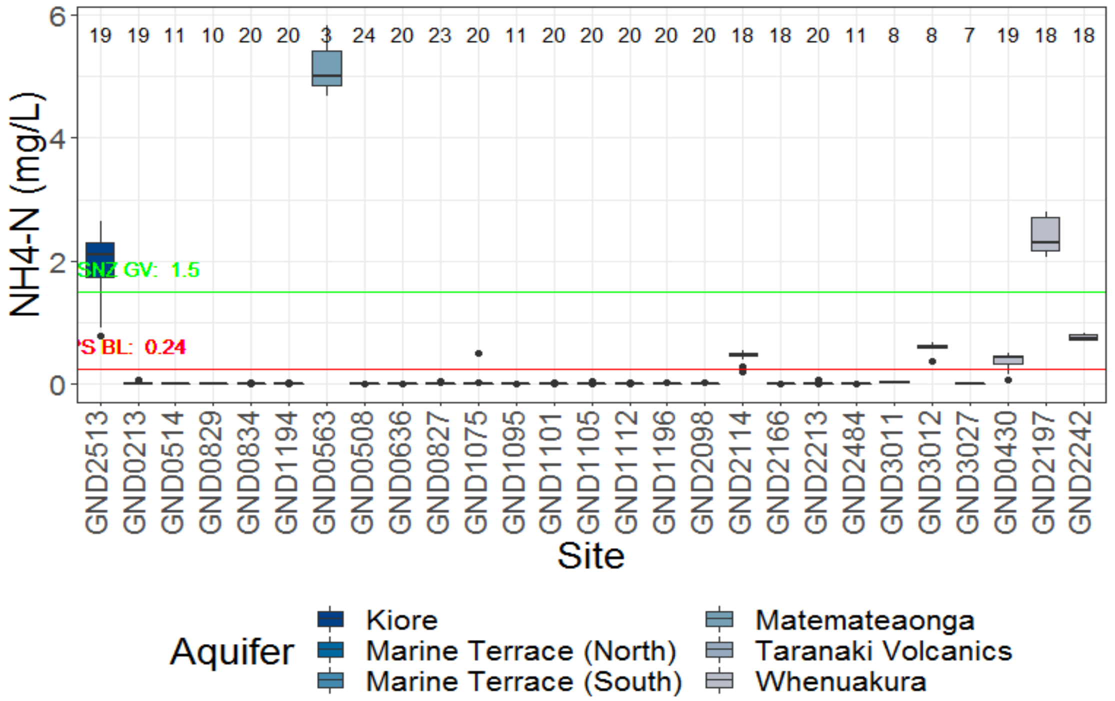

Figure 15 Comparison of ammoniacal nitrogen concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020 (Sites are grouped by aquifer)

Note: *Boxplots are only shown where site datasets contained >1 non-censored measurement*

A plot of individual ammonia concentrations against their respective nitrate concentrations for all 32 GQMP highlights where low levels ammonia and nitrate were present together in unconfined aquifers (Figure 15). While the plot generally supports the understanding that ammonia persists over nitrate in reduced environments typical of confined aquifers, some sites screened in unconfined aquifers also show signs of oxygen poor conditions. GND2098 and GND3011, alongside the seven aforementioned GQMP sites with elevated ammonia concentrations, have also been identified as displaying other redox sensitive parameters, as discussed in previous results sections (i.e. bicarbonate, sodium, iron and manganese). Meanwhile in other sites, such as GND0827 and GND1105, the presence of ammonia alongside elevated nitrate concentrations suggests ammonia may be present in the aquifer due to land use impacts, and/or occurs where aquifer conditions are occasionally oxygen poor.

A comparison of ammonia to nitrate concentrations also highlights where confined aquifer conditions may not always be oxygen poor. For example, the periodicity of nitrate concentrations >1 mg/L in GND2114 suggests groundwater, at times, may be sufficiently oxygenated to maintain nitrogen in the form of nitrate nitrogen over ammonia. It may also suggest that land use is the source of nitrogen to this aquifer and that GND2114 represents conditions of a semi-confined rather than confined aquifer.

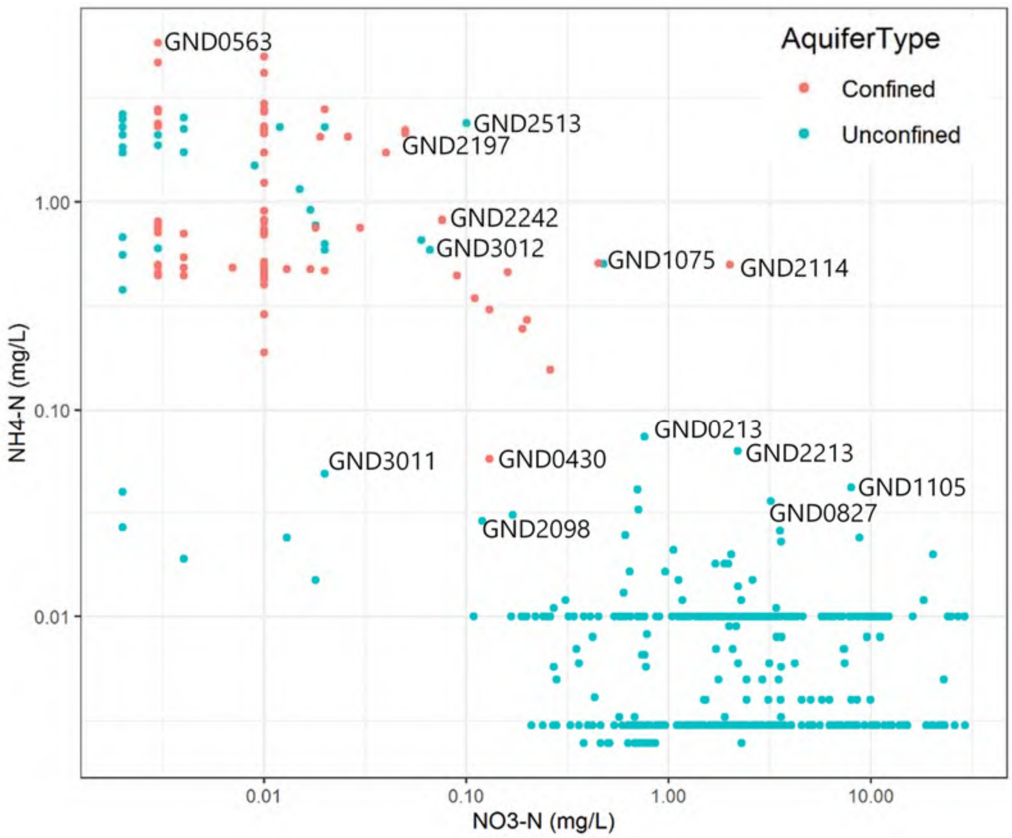

Figure 16 Ammoniacal nitrogen and nitrate nitrogen concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020

4.5.1. Summary

- Median concentrations of ammoniacal nitrogen (ammonia) ranged from below detection limit in multiple sites to 5.02 mg/L. The highest median concentration of ammonia was detected in a bore in which the hydrochemistry is most likely affected by adjustments to bore depth and on-going sedimentation issues.
- Concentrations of ammonia in three GQMP sites exceeded the DWSNZ (2018) GV of 1.5 mg/L, on one or more sampling occasions. Only one of these sites is currently used as a potable water supply.
- In seven sites median ammonia concentrations were above the annual median set in NPS-FM (2020), to protect against ammonia toxicity in freshwater ecosystems (0.24 mg/L).
- Observed concentrations of ammoniacal nitrogen are generally dictated by the oxidation state of the groundwater.
- Higher concentrations of ammoniacal nitrogen are generally found in deeper aquifers across Taranaki, or in areas of the region where shallow groundwater is highly reducing.
- Ammoniacal nitrogen can be present in groundwater as a result of land use inputs and/or naturally occurring processes.

4.6. Nitrate (NO_3-N)

Median concentrations of nitrate nitrogen (nitrate) ranged from below detection limit (lab dependant, <0.001 mg/L to <0.002 mg/L) in multiple sites, to 24 mg/L in GND1112 (Table 4, Figure 17). Box plot summaries of nitrate concentrations recorded at each GQMP site are displayed in Figure 17, with sites grouped by aquifer.

Only one site, GND1112, had a median nitrate concentration above the DWSNZ (2108) MAV of 11.3 mg/L. This site also recorded a maximum groundwater nitrate concentration of 29.2 mg/L, and was noted in the previous reporting period (TRC 2017) for exceeding the MAV, along with one other bore (GND1101). GND1112 is a 12.2 m deep large diameter unlined well, screened within an unconfined Taranaki Volcanics aquifer between Hawera and Manaia, and has been noted in previous sections for very high concentrations of chloride and sodium at ratios which tracked close to Na:Cl ratio in seawater, but with evidence of chloride enrichment.

In addition to GND1112, nitrate concentrations in four further GQMP sites were also above the DWSNZ (2108) MAV of 11.3 mg/L on one or more sampling occasions (GND0827, GND0829, GND1101 and GND1105, see Figure 17). All four of these sites are located within South Taranaki, with ND0829, GND1101 and GND1105 historically noted for highly elevated levels of nitrate in groundwater (TRC 2017). Of the four sites, the highest maximum concentration of nitrate was recorded in a groundwater sample from GND1105 (18.2 mg/L). GND0827, GND0829, GND1105 and GND1112 are all used for stock and/or domestic supplies. Well owners are advised of these results. Analysis of state also indicated that median nitrate concentrations in 27 of the 32 GQMP sites were ≤50% of the MAV.

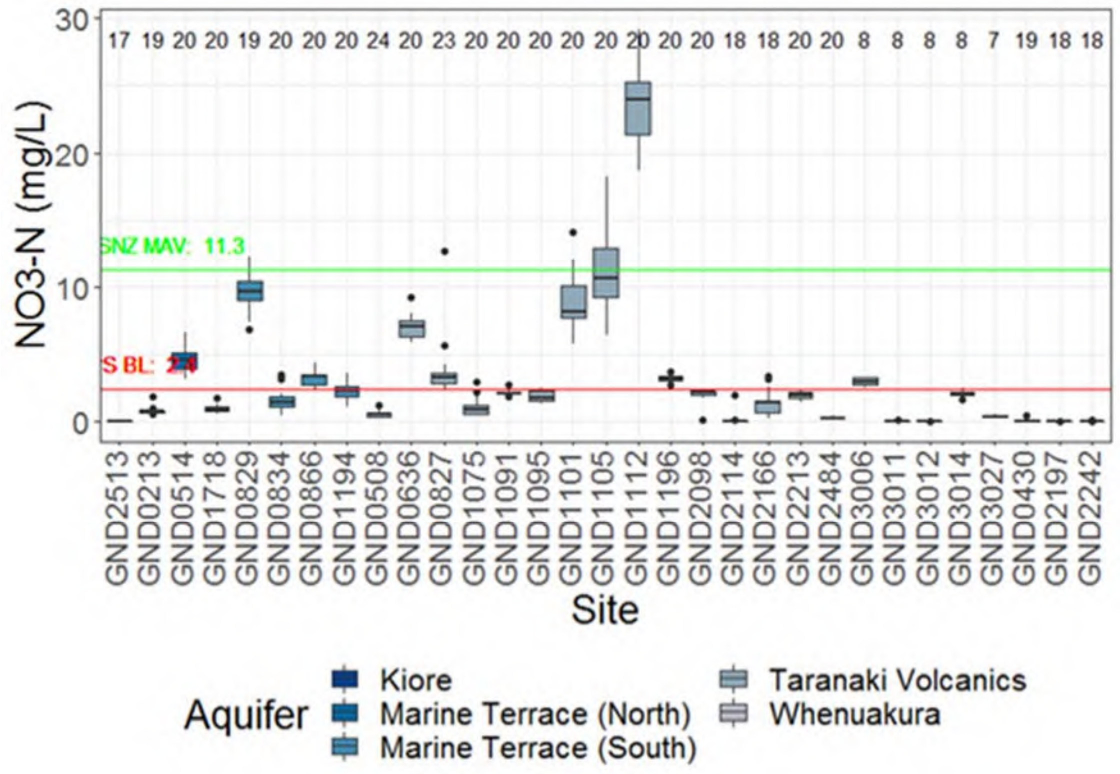

Figure 17 Comparison of nitrate nitrogen concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020. Sites are grouped by aquifer

Note: *Boxplots are only shown where site datasets contained >1 non-censored measurement*

In a total of 10 GQMP sites, median nitrate concentrations were above the annual median stipulated in the NPS-FM (2020) for protecting against nitrate toxicity in river aquatic ecosystems (2.4 mg/L). In addition, groundwater samples from nine sites were periodically above this toxicity threshold (Figure 17). While this highlights that nitrogen is elevated in groundwater in some areas, further work is required to identify the fate and transport of nitrogen-enriched groundwater to receiving waterbodies where these thresholds apply.

Based only on data collected from the 32 GQMP sites over the last five year, median concentrations of nitrate in groundwater were mapped to check for any spatial patterns in groundwater nitrate concentrations across the region (Figure 18). Figure 18 shows that nitrate concentrations are generally low in all of the Region's confined aquifers. However as demonstrated in Section 4.5, nitrogen generally persists in confined aquifers in the form of ammonia rather than nitrate, due to oxygen poor conditions. In contrast, groundwater concentrations of nitrate are most evident in GQMP sites screened in unconfined Taranaki Volcanics and Marine Terrace aquifers, which underlie high producing grassland.

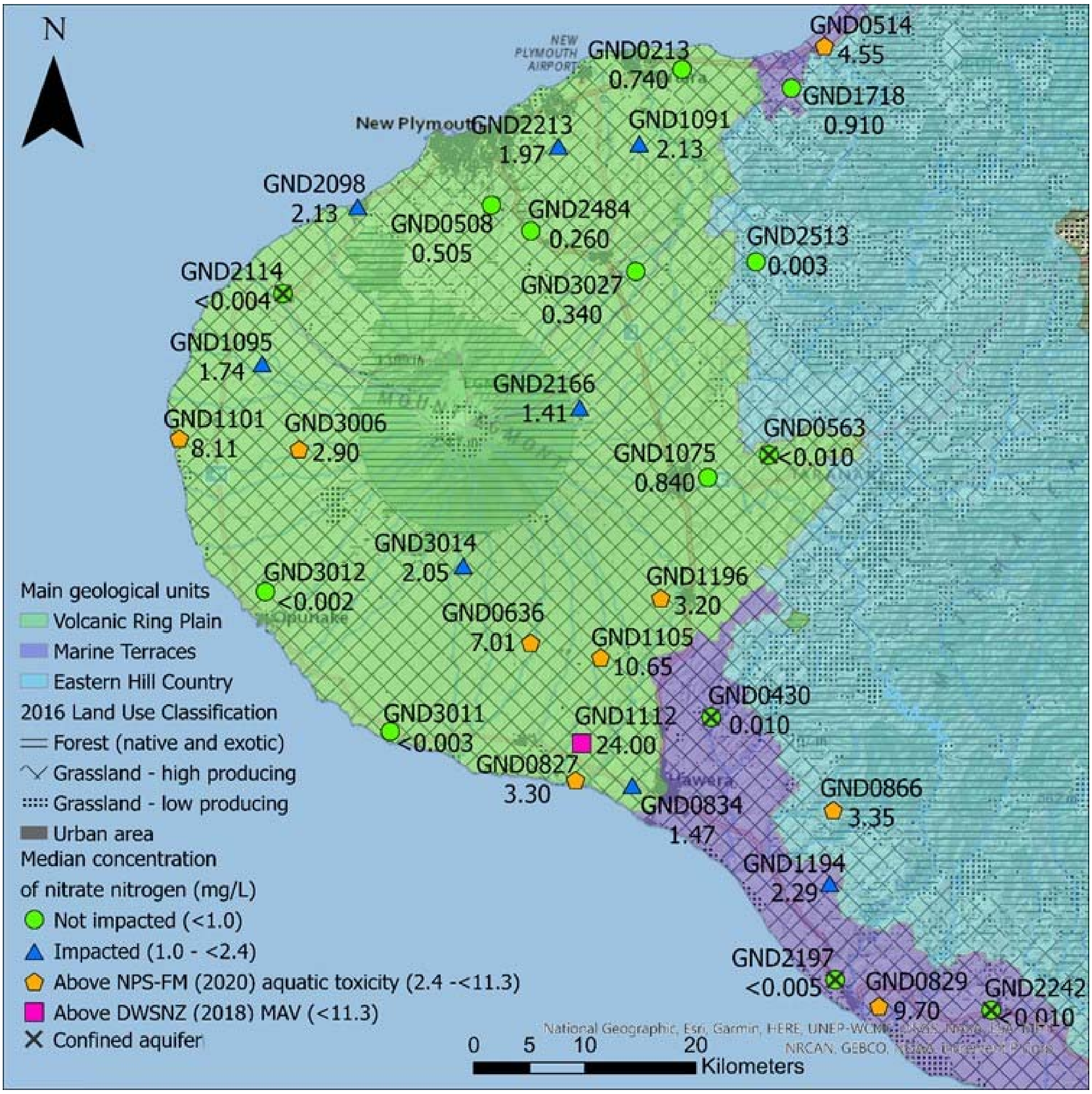

Figure 18 Median nitrate nitrogen concentrations recorded at 32 GQMP sites between 1 July 2015 and 30 June 2020

Elevated concentrations of nitrate are evident in an area of South Taranaki, which extends from Kaponga to Eltham and down towards the coast to Manaia and Hawera. This area includes GND0636, GND0827, GND1105, GND1196 and GND1112, which are noted for levels of nitrate routinely above the DWSNZ (2018) MAV for nitrate or the NPS-FM (2020) aquatic toxicity threshold. Intensive agriculture is the predominant land use in this area.

Elsewhere in Taranaki, spatial patterns suggest nitrate contamination is more prevalent in unconfined aquifers in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki (including south of Kaponga). Groundwater samples which detected concentrations of nitrate above the DWSNZ

(2018) MAV and the NPS-FM (2020) aquatic toxicity threshold for nitrate were all generally collected from GQMP sites within this area (Figure 18).

Although spatial patterns in groundwater nitrate contamination can be linked to intensive agricultural land use or particular industries near to recharge zones for GQMP sites, these patterns were also similar to the spatial patterns noted for EC values, bicarbonate, sodium and chloride concentrations in the region's unconfined aquifers. This suggests groundwater nitrate concentrations in west and south Taranaki may also be driven by poor soil draining conditions and volcanic avalanche deposits, which create irregular hydrogeological conditions. Subsequently, these aquifers may have lower transmissivities, which in turn accumulate and retain nitrate within groundwater for longer periods.

While much of the land in northern and eastern areas of Taranaki has also historically been used for agriculture and industry, the unconfined aquifers in these areas tend to have soil and geological conditions that may favour higher aquifer transmissivities and have hydraulic connection to nearby rivers or waterways. Therefore, groundwater recharge, either from rainfall or surface water, is more effective at diluting or flushing out nitrate concentrations within an aquifer. However, further research is required to understand the influence of localised aquifer geology on groundwater chemistry, and if hydraulic connections between groundwater and surface water exist in these areas.

4.6.1. Variation and seasonality in groundwater concentrations of nitrate

The nitrate results from all 32 GQMP sites were collated for the last ten monitoring years (1 July 2010 to 30 June 2020) to look at the variation in groundwater concentrations of nitrate annually. Groundwater concentrations of nitrate from individual sites were normalised against their respective median nitrate values in order to allow a full network analysis.

Figure 19 indicates that the annual distribution of nitrate concentrations in regional aquifers has not notably varied over the last six monitoring years. Nor does any particular monitoring year show a peak in groundwater concentrations of nitrate. This suggests that nitrate levels in regional aquifers may be relatively stable.

Temporal trend analysis of nitrate concentrations in groundwater did not indicate seasonality in any individual GQMP sites, see Section 5. However, when the last ten years of nitrate data from the entire GQMP network were normalised and analysed together, seasonality was weakly evident. A Kruskal Wallis test was used to compare the distributions of groundwater concentrations of nitrate between four seasons (spring, summer, autumn and winter), and showed some evidence (i.e. $p < 0.05$) of a difference between the seasons. A subsequent Dunn's test suggested that (at a network scale) groundwater concentrations of nitrate are higher in winter compared to autumn and summer (Appendix IV). It is noted that this analysis is based on limited data; further investigation would be necessary to understand seasonality in relation to the fate and transport of nitrogen in groundwater.

During summer months rainfall volumes are generally low, resulting in limited soil drainage and groundwater recharge. Plant uptake of nitrogen also decreases during this period. As a result, nitrate can accumulate in the soil profile and in the unsaturated zone overlying the seasonal water table. As rainfall volumes increase during late autumn and winter, the excess of water drains through the soil profile and recharges aquifers, transporting stored nitrate from the soil profile into the groundwater system. As a result, marginal peaks in groundwater concentrations of nitrate may be observed during winter.

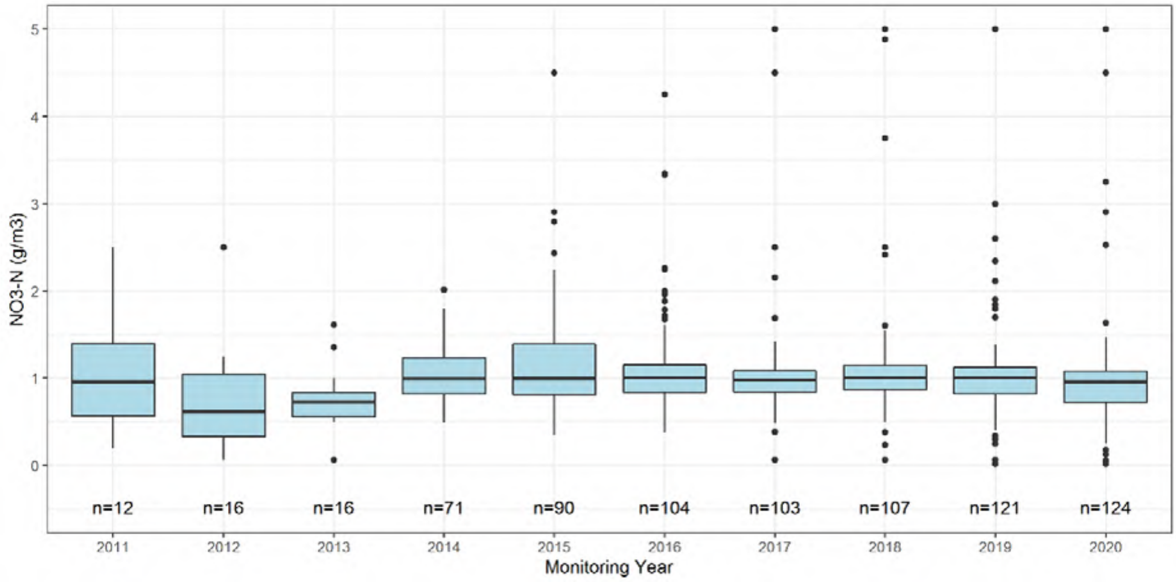

Figure 19 Boxplots showing the range of groundwater concentrations of nitrate nitrogen from 32 GQMP sites for individual monitoring years between 1 July 2010 and 30 June 2020

Note: *Data has been normalised against intra-site medians. The plot has been truncated at 5 mg/L* NO_3*-N for ease of interpretation. Omitted data generally reflects where the median absolute concentration of nitrate for a particular site is very low, thus accentuating slightly higher absolute concentrations at that site. In addition, given the limited data available for years 2011 to 2013 these years have not been considered or incorporated in discussion.*

4.6.2. Summary

- Median concentrations of nitrate nitrogen (nitrate) ranged from below detection limit, in multiple sites, to 24 mg/L.
- Median nitrate concentration in one GQMP site exceed the DWSNZ (2018) MAV of 11.3 mg/L. However, nitrate concentrations in groundwater samples from a further four sites were above the same MAV on one or more sampling occasions. Four of these sites are used for stock and/or domestic water supply. Owners are advised of any exceedances recorded.
- Median nitrate concentrations in 27 of the 32 GQMP sites were ≤50% of the MAV.
- Median nitrate concentrations were above the NPS-FM (2020) annual median (2.4 mg/L), to protect against nitrate toxicity in freshwater ecosystems in rivers, in a total of 10 GQMP sites. In addition, groundwater samples from a further 9 sites were periodically above this toxicity threshold. Further work is required to understand the fate and transport of nitrate in groundwater and the potential impacts on receiving waterbodies.
- Groundwater concentrations of nitrate are generally greater in the coastal areas west/south-west of Taranaki Maunga through to South Taranaki (including south of Kaponga and Eltham), when compared to nitrate levels in groundwater sampled from inland GQMP sites and sites located northern and eastern parts of the region.
- Elevated concentrations of nitrate are evident in an area of South Taranaki, which extends from Kaponga to Eltham and down towards the coast to Manaia and Hawera. This is most likely due to intensive agricultural land use within this area.
- In other areas of Taranaki, leaching of nitrogen from activities associated with intensive agricultural land use are most likely the main source of nitrate in regional aquifers.
- There is some evidence that nitrate concentrations are greater during winter compared to autumn and summer.

4.7. *Escherichia coli* (*E. coli*)

Groundwater samples from all SWGM sites are tested for *E. coli* bacterium to assess the bacteriological state of groundwater. Groundwater samples from NGMP sites are not sampled for *E. coli* as these sites are predominantly screened within confined aquifers, which are less likely to be infiltrated by surface water containing these types of indicator bacteria.

Median counts of *E. coli* ranged from below detection limit in multiple sites (<1 MPN/100 mL) to 9 MPN/L100 mL (GND2513). Median counts of *E. coli* were above the DWSNZ (2018) MAV of <1 MPN/100 mL in seven of the 25 SWGM sites sampled (Table 4). Groundwater from five of these seven sites is used for stock and/or domestic supply. Overall, *E. coli* was detected in groundwater samples on one or more sampling occasion, in 21 of the 25 routinely tested sites (Figure 20).

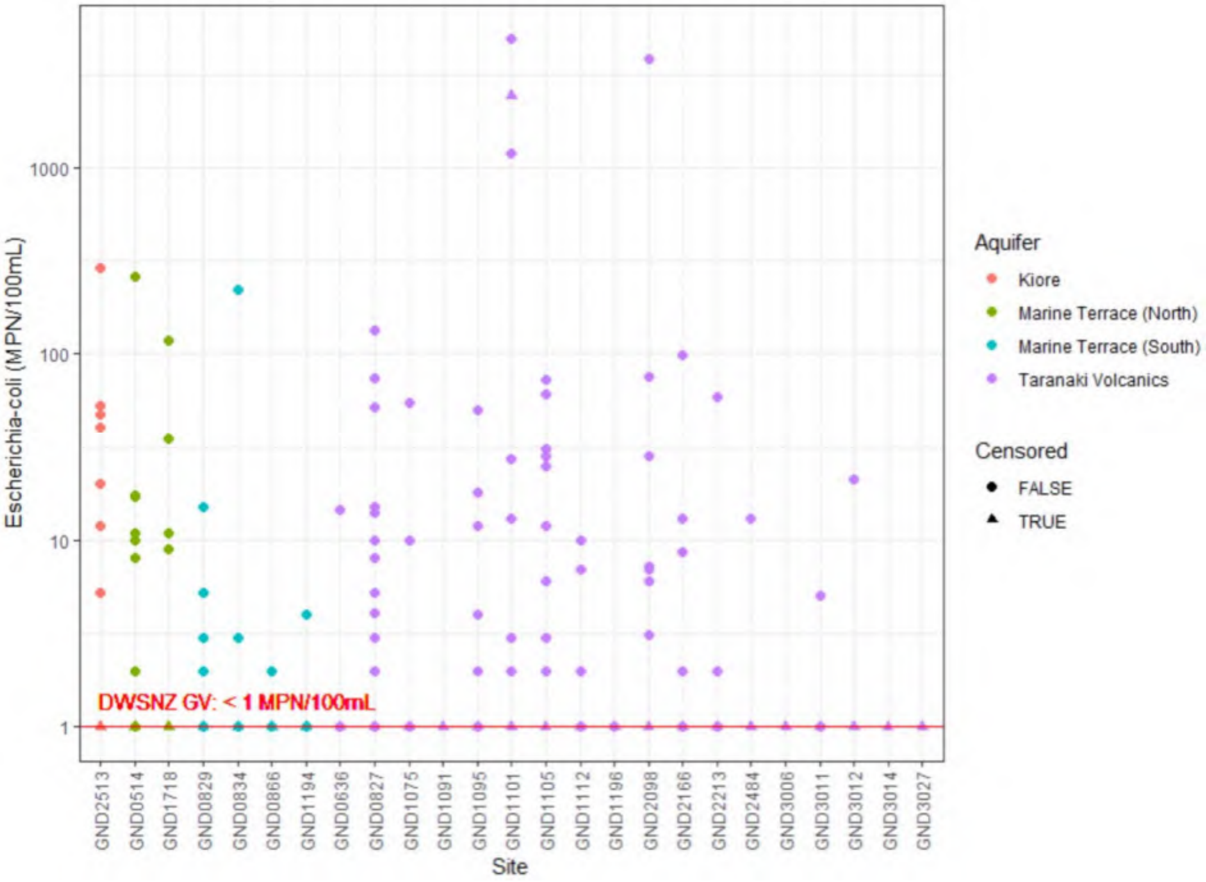

Figure 20 Counts of *Escherichia coli* (*E.coli*) detected in groundwater samples from 25 GQMP sites sampled between 1 July 2015 and 30 June 2020

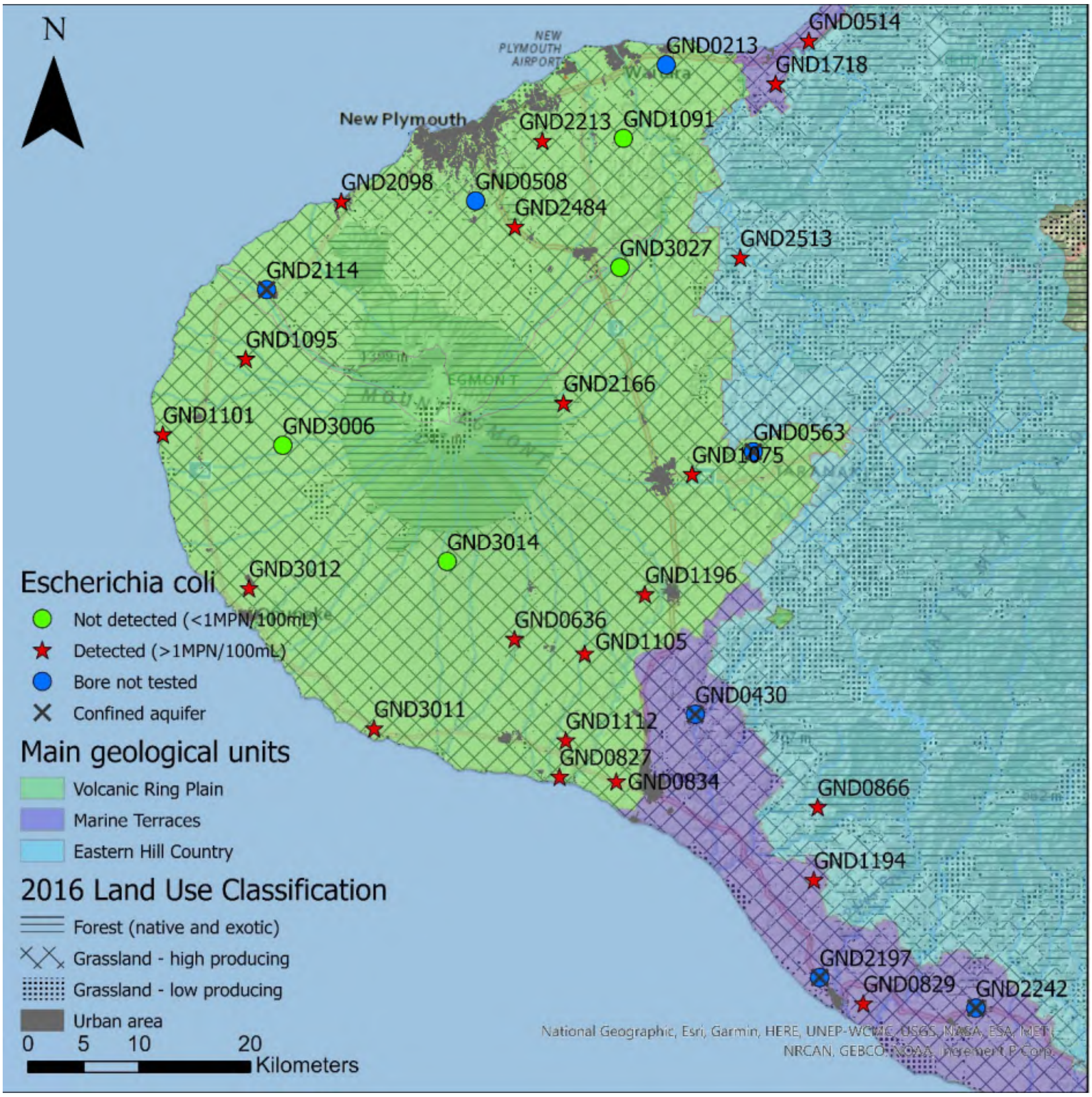

Figure 21 Location of positive counts of *Escherichia coli* (*E.coli*) detected in groundwater samples from 32 GQMP sites tested between 1 July 2015 and 30 June 2020

4.7.1. Relationship between bore or well construction type and counts of *E.coli* in groundwater

Further analysis was conducted to examine the relationship between bore or well construction types within the GQMP network and occurrence of *E.coli* contamination of groundwater using GQMP data collected over the last ten years.

Results show that *E.coli* contamination of groundwater occurs more often in monitoring sites that are dug and unlined (Table 6). Typically these sites have large diameters and are constructed to depths less than 15 m deep. A total of 52% of groundwater samples from dug and unlined wells had a positive count of *E.coli* (i.e. ≥1 MPN/100 mL). A higher proportion of groundwater samples from dug-unlined wells also detected counts of *E.coli* >1 MPN/100 mL compared to other bore or well types (Table 6). These findings were supported by the results of Dunn's tests which were carried out on all combinations of bore or well constructs and showed evidence (i.e. $p<0.05$) that wells which are dug and unlined were most at risk of *E.coli* contamination (see Appendix V for further details). These types of wells have no subsurface barriers (such as overlying aquitards or structural lining within the well itself) which prevent the potential infiltration of bacterial laden surface water into a bore or well via the soil profile and/or shallow water table.

Table 6 Percentage of samples with positive and elevated counts of *Escherichia coli* (*E.coli*) in groundwater by different construction type

Note: *Samples included were taken from 25 GQMP sites routinely for E.coli between 1 July 2010 and 30 June 2020. One construction type (drilled – open ended casing) is not represented within the subset of sites sampled for E.coli. % samples with elevated counts of E.coli are a subset of the % samples with positive counts of E.coli.*

Construction type	n of sites	n of samples tested for *E.coli*	% samples with positive counts of *E.coli* (i.e. ≥1 MPN/100 mL)	% samples with elevated counts of *E.coli* (i.e. >1 MPN/100 mL)
Bored or augured – lined	1	24	8	4
Bored or augured - unlined	4	122	26	18
Drilled - screened	12	214	20	14
Dug - lined	6	189	29	20
Dug - unlined	3	97	52	38

Bores and wells[3] that are dug and lined, or bored/augured and unlined may also be somewhat vulnerable to *E.coli* contamination (Table 6). While a total of 29% and 26% of all groundwater samples collected from dug–lined and bored/augured-unlined wells respectively had positive counts of *E.coli*. The results of Dunn's test did not find evidence that these two construction types were more at risk from bacteriological contamination than any other constructs (Appendix IV). *E.coli* contamination may be a slight risk in dug-lined, or bored/augured-unlined wells as these wells also have large diameters and are constructed to depths which are generally less than 15 m deep.

It should be noted that some *E.coli* contamination is apparent in all sites regardless of construction type (Table 6). Therefore, it cannot be ruled out that groundwater *E.coli* contamination may reflect the level of bore or wellhead security at individual sites, rather than being related to construction type (i.e. how successfully the bore or wellhead prevents surface water from directly entering the bore or well). A greater understanding of bore or wellhead security at individual sites in the GQMP is required to better correlate relationships between construction types and the level of *E.coli* contamination of groundwater. A greater number of sites may also need to be sampled to increase representation of certain construction types. It is clear the more recently installed wells, which were designed specifically for monitoring purposes and installed following good drilling practice have had significantly less detections of *E. coli* than at other sites (e.g. GND3006, GND3011, GND3012, GND3014 and GND3027).

4.7.2. Seasonality in groundwater counts of *E.coli*

Temporal trend analysis of *E.coli* counts in groundwater did not indicate seasonality in any individual GQMP site (Section 5). However, when the last ten years of *E.coli* data across the entire GQMP network were grouped by quarterly season, A Kruskal Wallis test showed weak evidence of seasonality (i.e. $p < 0.05$).

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[3] The Freshwater Plan 2001 defines all wells and bores of less than 20 m in depth as wells and all wells and bores of greater than 20 m in depth as bores.

Consequent Dunn’s tests between all paired combinations of seasons showed evidence that counts of *E.coli* in groundwater are greater in autumn and, to a lesser extent, in summer, compared to counts detected in winter and spring (Appendix IV).

4.7.3. Summary

- Median counts of *E. coli* ranged from below detection limit in multiple sites, to 9 MPN/100 mL,
- Over the last five years, median counts of *E. coli* were above the DWSNZ (2018) MAV (<1 MPN/100 mL) in seven of the 25 GQMP sites which are routinely tested for bacteria. However, in total, positive counts of *E. coli* were detected on one or more sampling occasion in groundwater samples from 21 sites. Of the 21 sites which detected positive counts of *E.coli*, 13 are used for stock and/or domestic supply.
- There is some evidence of a relationship between well construction type and frequency and magnitude of *E.coli* counts detected. It is likely that wells which are dug or bored/augured have more pathways for surface water intrusion, resulting in increased risk of bacteriological contamination.
- The adequacy of bore or wellhead protection of GQMP sites and the influence of regional meteorological characteristics needs to be further investigated.

4.8. Nitrite nitrate (NO_2-N), fluoride and bromide

Nitrite nitrogen (nitrite), fluoride and bromide were included in key variable analysis, as all three variables have associated DWSNZ (2018) or WHO (2017) MAVs. Analysis showed that median concentrations for all three of these variables are either below their respective laboratory detection limits, or the DWSNZ (2018) or WHO (2017) MAVs. They are most likely present in groundwater at low levels due to natural processes. It should be noted that nitrite is tested only in groundwater samples from SGWM wells, while fluoride and bromide are only tested for under the NGMP.

4.9. Pesticides and emerging organic contaminants

Regional groundwater bores/wells which were selected for inclusion in the ESR National Pesticide Survey were generally located within areas of horticulture (both commercial and private gardens) and intensive agriculture (dairy). On two separate sampling occasions, groundwater samples from a well within an area used for land farming, and from a well located at a waste water treatment plant (WWTP), were also included in the ESR survey. In 1995, the Council undertook an independent survey of pesticides in regional groundwater. Sites for this study were also located in areas where groundwater was considered vulnerable to pesticide contamination.

Results of regional testing for pesticides in groundwater show that pesticides were not often detected in the sites sampled. Over the length of the ESR pesticide surveys, pesticides have only been detected in groundwater on three sampling occasions, including twice from the same well. In these cases, however, concentrations of the pesticides detected have been below the DWSNZ (2018) pesticide MAVs (Table 7).

The Council’s independent survey of pesticides in 1995 detected the presence of pesticides in one groundwater sample from a single well. The pesticide levels in this groundwater sample, tested in 1995, were below MAVs, or were at levels considered not to be a risk to human health at the time.

In the 2018 survey of pesticides by ESR, samples were also tested for “emerging organic contaminants” (EOCs) which included chemicals associated with or derived from caffeine, artificial sweeteners, some medications, skin-care products and packaging. Of the eight wells tested, samples from five showed traces of EOC compounds which were similar to levels detected nationally (Close and Humphries 2019).

Table 7 Pesticides detected in select sites sampled between 1990 and 2018 by ESR for the national survey of pesticides in groundwater, and as part of targeted groundwater investigations conducted by TRC

Site	Depth (m)	Location	Land use	Year			
				1994	1995	1998	2018
GND0810	3.6	Lepperton	Garden nursery	Simazine 0.2 mg/L (MAV 2 ppb)		Simazine 0.03 ppb	
GND2515	6.9	New Plymouth	Dairy near golf course & WWTP				Terbuthylazine 0.029 ppb (MAV 0.08 ppb)
GND0508* **Presumed monitoring well*	8.6	Carrington Road near New Plymouth city outskirts	Dairy		Metalaxyl 2.4 ppb (p.MAV 100 ppb) Simazine 0.1 ppb		

5. Temporal trends in groundwater quality

Temporal trend analysis of groundwater quality across the Taranaki Region has been undertaken on data collected from the 32 GQMP sites between 1 July 2010 and 30 June 2020.

Each of the 12 key groundwater quality variables were checked for temporal trends, using the methods outlined in Section 2.2.5. In addition, total oxidised nitrogen (NNN) data was analysed for trends over the last ten years. This is because groundwater samples from SGWM sites were not routinely tested for nitrate before October 2013, whereas these samples were regularly tested for NNN. NNN is the total of nitrite nitrogen (nitrite) and nitrate nitrogen (nitrate), of which nitrate is the most chemically stable form. As nitrite is not often present in groundwater, unless under strong redox conditions or gross contamination, it can be assumed most of the nitrogen in NNN takes the form of nitrate.

5.1. Trend results

Following quality control, 52 site-variable time series were found to have sufficient data for trend analysis. The resulting trend analysis spans across ten GQMP sites, and 11 of the 12 key indicator variables measured. Table 8 summarises the results of these temporal trend analyses.

The results of the trend analysis carried out found improvements were very likely for 15 site-variable time series, with a further 17 found very likely to be degrading.

The results of the statistical temporal trend analysis were critically analysed in order to identify any misleading results, and determine those trends that are environmentally meaningful (as defined in Section 2.2.5). Given the nature of the trend methods used, statistical results need to be reviewed with respect to their context when:

- There has been a change laboratory detection limits over the monitoring period, or there are a large number of censored values within a dataset;
- The concentrations for a variable are very small. In these cases small deviations from these low levels over time can result in a high percent annual change, giving the appearance of a temporal and/or environmentally meaningful trend;
- The examined dataset consists of few unique values with a very small range. In these cases, changes recorded by temporal trends analysis are likely within the level of measurement uncertainty and are not truly indicative of groundwater quality changes; and
- There has been a change of behaviour/conditions at the site within the monitoring period, which biases the assessed monotonic trend.

Examination of trend results falling into the first three of the above cases showed that variable concentrations/levels were being maintained rather than changing over time. Overall, only eight of the trends detected over the network were considered to be environmentally meaningful. As the majority of temporal trends detected were mostly at four of the ten sites, temporal changes in groundwater quality have been considered by bore or well.

Table 8 Summary of statistical temporal trend analyses performed on data collected from GQMP sites between 1 July 2010 and 30 June 2020

Note: *State Median values are based on five years of data in Table 4. Analysis performed on 12 key indicator variables on groundwater quality. NNN refers to total oxidised nitrogen, ammonia = ammoniacal nitrogen and nitrate = nitrate nitrogen*

Site	Measure	n	Proportion censored values	State Median	Median Sen Slope (units/year)	% annual change	Trend Category	Confidence in reported direction (%)
GND0430	Iron	40	0.20	0.040	0.003	9.9	Very Likely Degrading	100
	Bromide	40	0.07	0.090	0.002	2.6	Likely Degrading	86
	Chloride	40	0.0	24.0	0	0	Likely Degrading	76
	Conductivity	34	0	337.2	2.6	0.8	Likely Degrading	88
	Fluoride	40	0.03	0.080	0	0	Likely Degrading	69
	Manganese	40	0.03	0.009	0	0	Indeterminate	56
	Ammonia	32	0	0.444	0	0	Indeterminate	56
	Nitrate	40	0.38	0.010	-0.002	-2.7	Likely Improving	77
	Bicarbonate	40	0	167.0	-0.432	-0.3	Very Likely Improving	97
	Sodium	40	0	22.0	0	0	Very Likely Improving	100
GND0508	Chloride	40	0	13.0	0.161	1.3	Very Likely Degrading	99
	Conductivity	36	0	106.0	0.029	0.0	Indeterminate	52
	Bromide	39	0.15	0.040	0	0	Likely Improving	76
	Sodium	40	0	7.5	-0.033	-0.4	Likely Improving	86
	Bicarbonate	39	0	26.0	-0.316	-1.2	Very Likely Improving	100
	Manganese	41	0.39	0.003	0	-11.5	Very Likely Improving	98
	Ammonia	39	0.51	0.003	-0.001	-19.2	Very Likely Improving	100
	Nitrate	40	0	0.505	-0.014	-2.7	Very Likely Improving	91
GND0563	Bromide	33	0.15	0.060	0.002	4.1	Very Likely Degrading	99
	Conductivity	32	0	312.1	8.2	2.7	Very Likely Degrading	98
	Fluoride	33	0	0.630	0.031	14.4	Very Likely Degrading	100
	Iron	33	0.03	7.1	0.275	53.3	Very Likely Degrading	100
	Bicarbonate	33	0	218.0	2.3	1.2	Very Likely Degrading	99
	Manganese	33	0.15	0.230	0.011	22.6	Very Likely Degrading	100
	Sodium	33	0	32.0	0.560	2.4	Very Likely Degrading	98
	Chloride	33	0	10.2	-0.006	-0.1	Likely Improving	67
GND0827	Iron	41	0.42	0.030	0.001	6.8	Very Likely Degrading	98
	Bicarbonate	40	0	73.00	2.0	2.9	Very Likely Degrading	100
	Nitrate	41	0	3.3	0.185	6.0	Very Likely Degrading	100
	Conductivity	39	0	387.1	0.484	0.1	Indeterminate	54
	Manganese	41	0.36	0.002	0	-3.3	Likely Improving	75

Site	Measure	n	Proportion censored values	State Median	Median Sen Slope (units/year)	% annual change	Trend Category	Confidence in reported direction (%)
	Bromide	40	0.03	0.180	-0.007	-3.2	Very Likely Improving	99
	Chloride	40	0	50.0	-1.1	-2.0	Very Likely Improving	100
	Fluoride	40	0	0.120	-0.004	-3.1	Very Likely Improving	97
	Sodium	40	0	45.0	-0.379	-0.8	Very Likely Improving	97
	Ammonia	38	0.60	0.006	0	-1.1	Very Likely Improving	99
GND0829	Conductivity	32	0	456.5	3.9	0.9	Very Likely Degrading	94
	NNN	32	0	9.7	0.570	6.4	Very Likely Degrading	100
	E.coli	32	0.62	0.228	0	0	Very Likely Improving	94
GND1075	Conductivity	33	0	100.8	0.412	0.4	Likely Degrading	87
	NNN	33	0	0.840	0.030	3.4	Likely Degrading	85
	Ammonia	33	0.52	0.003	0	0	Likely Improving	87
GND1091	Conductivity	33	0	116.5	1.8	1.6	Very Likely Degrading	100
	NNN	33	0	2.1	0.019	0.9	Likely Degrading	86
GND1095	Conductivity	33	0	218.5	2.5	1.2	Very Likely Degrading	100
	E.coli	33	0.48	1.0	0	0	Indeterminate	66
	NNN	33	0	1.7	-0.043	-2.1	Very Likely Improving	91
GND1101	*E.coli*	33	0.70	1.0	0	0	Indeterminate	58
	NNN	33	0	8.1	-0.164	-1.7	Likely Improving	87
	Conductivity	33	0	583.0	-8.5	-1.4	Very Likely Improving	92
GND2213	Conductivity	33	0	313.9	9.4	3.1	Very Likely Degrading	98
	NNN	33	0	2.0	-0.103	-5.2	Very Likely Improving	100

GND0430 is a 234.6 m deep bore located within a confined Whenuakura Formation aquifer. Temporal trend analysis detected trends in ten variables at this site, three of which were found with a high level of confidence (iron, bicarbonate and sodium). In general, the temporal trends detected in variables were indicative of natural processes (i.e. the rate of change for major and minor variables were less than ±2% or ±5% per year respectively). Examination of trend plots for GND0430 suggests the slight changes in the hydrochemical signatures observed at this bore are within cyclic fluctuations or are being maintained by natural processes.

Of the eight temporal trends detected in the key variables measured at GND0563, seven trends were found with high confidence. Trends for bicarbonate, fluoride, iron and manganese were considered environmentally meaningful. However, these trends have been induced by ongoing bore integrity issues and multiple depth modifications at the bore. Located with the confined Matemateaonga Formation, bore GND0563 was originally an open-ended (no bore screen) 77 m deep bore. Due to increasing sediment infiltration into the bore, apparent since 2011 (TRC 2107), the bore was backfilled to 26 m sometime during 2018. While this resolved sedimentation issues temporarily, increases in iron concentrations made the bore water unusable, both in the dairy shed and as a drinking water supply. Subsequently, the bore was deepened again to 50 m. However, this has not reinstated the former quality of groundwater abstracted from the bore, and sedimentation continues to be a problem.

Statistical analysis of data from GND0508 detected trends in eight key variables, with five trends being detected with high confidence. However, review of trend plots for GND0508 indicate temporal trend analysis was heavily influenced by the very low concentrations/levels of variables present in the groundwater. Long term monitoring suggests groundwater quality is being maintained, with the very small number of measured parameters falling below any threshold of concern. GND0508 is a 14 m deep well within an unconfined Taranaki Volcanics aquifer, with groundwater quality that is likely influence by localised rainfall patterns (TRC 2021). Changing rainfall patterns may be reflected in small changes noted in chloride levels at the well.

GND0827 is an 8 m deep unlined large diameter well, within an unconfined Taranaki Volcanics aquifer. Trends were detected in ten monitored groundwater quality variables at this site, with eight of the trends found with high confidence. Concentrations of nitrate and bicarbonate at GND0827 were found to be very likely degrading. These trends are considered environmentally meaningful and show some evidence of land use impact on the local aquifer (Table 8). This is expected given the well's location in an area of intensively farmed land. A review of the time series data for the remaining eight variables indicate that in most instances, variable concentrations are very low and much of the recorded change occurred early in the data record. This has led to the statistical trend analysis categorising variables as very likely improving or likely improving. In the case of iron, the dataset has been heavily influenced by changing detection limits. Despite these influences, the very likely improving trends for ammonia, bromide, chloride, fluoride and manganese, while albeit very small improvements, suggest either land use management around GND0827 have improved or there has been a gradual change in source of groundwater to the well.

A total of 14 improving or degrading trends suggest that groundwater levels of EC, *E.coli*, ammonia, and NNN are changing in the remaining six wells (GND0829, GND1075, GND1091, GND1095, GND1101 and GND2213). All six wells are large diameter dug - lined or bored/augured – unlined wells, are screened shallower than 11 m deep and are located in unconfined Taranaki Volcanics or Marine Terraces (South) aquifers. Trends detected in these wells generally reflect where changing groundwater quality is likely due to land use, as all wells are located in areas of intensively farmed land. Of the nine trends that were found with high confidence, only two, for groundwater concentrations of NNN in wells GND0829 and GND2213, were considered environmentally meaningful.

Temporal trend analysis indicated groundwater EC and NNN concentrations have increased over the last ten years at wells GND0829, GND1075 and GND1091. However, it should be noted that EC and NNN levels for GND0829 and GND1091 either peaked early in the monitoring period and now appear to be improving, or have stabilised later in the monitoring period, respectively. Further to this, counts of *E.coli* in GND0829 have decreased in recent years to below detection limits (<1 cfu/100 mL). This may be due to improvements to wellhead security at the site.

EC levels at wells GND1095 and GND2213 were found to be very likely degrading (increasing), while concentrations of NNN at both sites are very likely improving. A review of the time series data indicates a small but steady increase in EC levels over time in GND1095, while concentrations of NNN have gone through a low within the last ten years and appear to be increasing again. In GND2213 which is located less than 50m from a tributary of the Mangaoraka Stream, EC values appear to have increased and stabilised at a new level from 2014 onwards. Over the last 10 years NNN levels at the site have improved to levels more typical of un-impacted groundwater.

At well GND1101, EC levels and NNN concentrations were found to be very likely improving and likely improving respectively. Past reporting on groundwater quality trends (TRC 2017) had also noted an improving trend in nitrate (assumed to be NNN).

Trend analysis of *E.coli* levels at GND1095 and GND1101 suggest that generally counts of *E.coli* are being maintained below or at MAV. Meanwhile, the likely improving trend found in concentrations of ammonia at well GND1075 is very low in magnitude and is impacted by a large proportion of censored values in the time series, indicating that ammonia levels at the site are being maintained at low concentrations.

Trend plots are included in Appendix V.

6. Discussion

The state and trends of groundwater quality across Taranaki is influenced by both natural processes and human activities. Observed concentrations of 12 key indicator variables of groundwater quality highlight patterns that can be associated with a range of drivers, such as aquifer confinement, groundwater residence time, rock/water interaction with local geology and soil, regional recharge mechanisms, redox related processes, and human influences including land use management practices. The composition of groundwater has been shown to vary in response to the occurrence and magnitude of these influences across the region, and can also change over time.

6.1. State of regional groundwater quality

Analysis of GQMP data collected between 1 July 2015 and 30 June 2020 indicates variability in the composition and quality of groundwater across the region's aquifers. The region's shallow unconfined aquifers are generally more oxidised and their proximity to land surface means that they display greater impacts from land use activities. Deeper, older water contained in confined aquifers is generally more chemically evolved, and more influenced by natural processes than human induced factors.

The mineral content of the region's deep and confined aquifers is typically greater than that of groundwater in the region's shallow and unconfined aquifers. Aquifer depth, reducing groundwater conditions and longer groundwater residence times naturally promote greater concentrations of bicarbonate, sodium, iron, manganese and ammonia in confined aquifers. Additionally, elevated levels of EC, nitrate, chloride and *E.coli* in groundwater samples from some of the region's more oxidised, unconfined aquifers suggests groundwater in Taranaki can be impacted by land use.

Reducing conditions have been shown to exist in some soil profiles above unconfined aquifers, and within unconfined aquifers. Examples include the Kiore aquifer, and Taranaki Volcanics aquifer about GND3012. Here, the groundwater chemistry reflects the conditions of an oxygen-poor confined aquifer despite being unconfined. Reducing conditions may assist with the removal of nitrate from groundwater in unconfined aquifers by promoting denitrification. Conversely, the alternating presence of ammonia and nitrate in groundwater samples from bores screened in confined aquifers, as seen in GND2114, suggests land use may contribute to the presence of nitrogen, in the form of ammonia, in confined groundwater aquifers.

Analysis of Na:Cl ratios in groundwater indicates the main source of recharge to regional aquifers is rainfall derived from marine evaporation. Concentrations of chloride and sodium, along with EC values, were greater in samples from GQMP sites located in coastal areas west/south-west of Taranaki Maunga through to South Taranaki. This may reflect that rainfall at the coast is richer in chloride and sodium, compared to rainfall that falls inland. Nearly two thirds of GQMP sites plot below the SWDL, suggesting that much of the region's groundwater is enriched with sodium from rock/water interactions with sodium rich source rocks.

Spatially, levels of bicarbonate, EC, sodium, chloride and nitrate in groundwater tended to be greater in GQMP sites located west/south-west of Taranaki Maunga through to South Taranaki. Unconfined aquifers west/south-west of Taranaki Maunga within the volcanic ring plan appear to be geologically influenced by volcanic avalanche deposits, which create irregular hydrogeological conditions (Roverato et al 2014). In contrast the Marine Terraces (South) formations in South Taranaki are more likely to contain marine derived carbonate rich geological sequences. These geological units are more likely to display lower groundwater transmissivities, longer residence times and have fewer hydraulic connections to surface water. Subsequently, these characteristics promote natural processes such as the sodium and bicarbonate enrichment of groundwater, and may allow for the accumulation of nitrate in groundwater at levels above drinking water and ecological thresholds.

Recorded levels of bicarbonate, EC, sodium, chloride and nitrate are comparatively lower in aquifers in the east and north of the region. Here, unconfined aquifers are influenced by lahar deposits (Roverato et al

2014), which are thought to support higher transmissivities, shorter groundwater residence times and have more hydraulic connections to surface water. This would potentially enable regular flushing or dilution of variables like nitrate, and limit natural mineral enrichment of groundwater.

As natural concentrations of nitrate in New Zealand are rarely considered to be above 1 mg/L (Close et al. 2001), it is clear that many of the regional unconfined aquifers show some degree of human impact. Further to this, median groundwater concentrations of nitrate in 10 GQMP sites are above the NPS-FM (2020) bottom line for aquatic toxicity of an annual median of 2.4 mg/L. In addition to this, groundwater samples from a further nine sites were periodically above the NPS-FM (2020) bottom line on individual sampling occasions. Note that this is an indicative comparison only, as the NPS-FM attribute is defined as a one-year median of monthly data, while the median for groundwater quality in this report is based on five years of quarterly data. While seven GQMP sites had median groundwater concentrations of ammonia were above NPS-FM ammonia aquatic toxicity threshold for receiving surface waterbodies (0.24 mg/L), these sites were screened in confined aquifers or were influenced by unusual localised anoxic conditions in an unconfined aquifer and are unlikely to impact surface water.

An analysis of nitrate concentrations over the entire GQMP network suggests that there has been little change in groundwater nitrate levels over the last five years. There is weak evidence that levels of nitrate and *E.coli* in groundwater are higher in winter and autumn, respectively, which likely reflect early seasonal rainfall leaching nutrients and bacteria more readily into unconfined aquifers. Elevated nitrate in groundwater is largely associated with intensive agriculture land use.

6.1.1. Suitability of groundwater for potable water supply

Groundwater in Taranaki can be considered suitable for stock water supply in most wells/bores, with no or minimal treatment. However, groundwater will generally require treatment if it is to be used for potable supply.

Comparison of median concentrations of key indicator variables against their respective DWSNZ (2018) MAVs or GVs, show that iron, manganese, sodium and ammonia are above one or more of these thresholds in a total of 15 (47%) GQMP sites. The presence of these variables in groundwater, found both in confined aquifers and unconfined aquifers with oxygen poor conditions, are most likely due to natural processes influenced by reducing environments and longer groundwater residence times. Often, elevated concentrations of iron, manganese, sodium and ammonia were detected in the same seven GQMP sites. Of these, two are used for domestic or potable supply, and these only had groundwater concentrations of iron and ammonia above their respective GVs.

The median concentration of nitrate was above the DWSNZ (2018) MAV in only one GQMP wells, however, nitrate levels in this well were regularly more than double the MAV of 11.3 mg/L. In addition, groundwater samples from a further four sites had nitrate concentrations above the MAV on one or more sampling occasion. Groundwater from all five wells are used for stock and/or domestic supplies. Well owners are advised of these results. Overall, median nitrate concentrations in 27 of the 32 GQMP sites were ≤50% of the MAV.

There is some discussion in the science community presently around whether a more stringent maximum acceptable value (MAV) for nitrate should be set to protect human health, although there is not yet a strong consensus in New Zealand as to whether the science supports further limits on nitrate levels in groundwater.

Median counts of *E.coli* were above the DWSNZ (2018) MAV in seven of the 25 GQMP sites tested routinely for bacteria. However, positive counts of *E.coli* were detected on one or more sampling occasion in groundwater samples from almost all of the GQMP wells screened in unconfined aquifers. Site owners are informed when detections are made. It is likely that much of the *E.coli* contamination is due to local sources of bacteria, such as animal or human effluent, which is able to make its way into the well or bore when there is poor bore or wellhead protection or certain construction methods have been used. There is some evidence that dug and unlined wells (as well as possibly dug or bored/augured wells in general) are slightly more at risk of bacteriological contamination than other bore or well constructs. It is recommended that these well types, alongside poorly constructed monitoring sites in general, are replaced with drilled and screened GQMP monitoring wells in the same location. More work may also be required to understand and improve the level of bore or wellhead security at individual GQMP sites.

Groundwater concentrations of nitrite, fluoride and bromide were not above their respective DWSNZ (2018) MAV or WHO (2017) thresholds. While an evaluation of the pesticide surveys undertaken by the Council and ESR show that regionally there are limited low levels of pesticide or EOCs in groundwater, these are not at a level of concern to human health. This may reflect the relatively small extent of horticulture within the region, as well as the reliance of groundwater being more prevalent in rural areas than in urban areas. Heavy metals and metalloids are not routinely tested as part of the GQMP, although the limited results available do not indicate an issue.

6.2. Temporal trends in groundwater quality

Improving or degrading trends were found with high confidence in 32 site-variable time series (Section 2.2.5). There was a nearly even split between trends that showed groundwater quality was very likely improving (15 trends) and very likely degrading (17 trends) in regional aquifers. Only eight trends overall were considered environmentally meaningful.

In general, the results of the undertaken trend analyses suggest that natural processes (like rock/water interactions or rainfall patterns) have driven small scale hydrochemical changes across a number of key indicator variables in regional aquifers over the last 10 years. Such variables include bicarbonate, bromide, chloride, fluoride, iron and manganese. Meanwhile, anthropogenic influences appear to be a stronger driver of temporal trends for a select few regional groundwater quality variables (EC, *E.coli*, nitrate and NNN). In general, the reported trends are consistent with those from the previous reporting period (TRC 2017), although updated trend reporting methods and terminologies have been used in this report.

Bore integrity issues at GND0563 appear to have caused a number of changes to groundwater quality at this location, with trends in four groundwater quality variables at this bore considered to be environmentally meaningful. However, given that the groundwater quality trends at GND0563 reflect where an unscreened bore has led to a deterioration in down-hole conditions due to sedimentation, and does not represent groundwater quality of the Matemateaonga aquifer, it is recommended that GND0563 is removed from the GQMP and NGMP networks.

Analysis of the state of groundwater quality highlights that elevated nitrate concentrations are evident to varying degrees within the region’s shallow aquifers. This is highly likely due to human influence and the effects of intensive agricultural land use. Environmentally meaningful trends in concentrations of nitrate (or NNN) were found with high confidence at only three sites, including one improving trend and two deteriorating trends. It is also noted that previous analysis of groundwater quality over a 16 year period (TRC 2017) found statistically significant and environmentally meaningful trends in groundwater concentrations of nitrate in seven GQMP sites that are still currently monitored (four improving and three worsening trends). Only groundwater concentrations of nitrate in GND0827 and GND1095 continue to show degrading and improving trends with a high level of confidence between the two reporting periods. This may suggest groundwater nitrate concentrations in all other sites are being maintained over the last ten years, or that changes are not yet able to be measured with a high level of confidence.

6.3. National context

Median values for nitrate and *E.coli* in Taranaki groundwater are comparable to those found nationally and are similar to those in other regions of New Zealand dominated by agricultural land use. Levels of *E.coli* and nitrate in Taranaki groundwater are proportionately less likely to exceed MAVs than sites surveyed nationally.

Comparison of temporal trends suggests changes in groundwater quality are more influenced by anthropogenic activities than natural processes, both at a regional and national scale.

Monitoring results from the GQMP were compared against figures from two national groundwater quality reports. Both reports are based on groundwater quality data collected from regional councils for SEM reporting, and from the NGMP database (Moreau et al 2016, and MfE and StatsNZ 2019). It is noted that both national reports cover different analysis periods than used in this report, however, the analysis methods used between regional and national reporting are similar and results are considered comparable.

Moreau et al (2016) determined the overall median groundwater concentration of nitrate in Taranaki to be 2.3 mg/L, which was the third highest in New Zealand behind Canterbury (3.2 mg/L) and Southland (4.9 mg/L), and marginally ahead of Waikato (2.2 mg/L). These regions are all known for their large agricultural sectors.

Table 9 The number of sites surveyed nationally and regionally in which median values of *E.coli* and nitrate nitrogen exceed national drinking water standards, alongside overall median values calculated for the same variables

Note: *n= the total number of sites assessed for each variable*

DWSNZ (2018) MAV	No. of sites nationally where median exceeds MAV From: MfE & StatsNZ (2014-2018)	No. of sites regionally where median exceeds MAV (TRC 2015–2020)	Overall national median From: IGNS (2005–2014)	Overall regional median (TRC 2015–2020)
E.coli (<1 cfu/100 mL)	68% (n=364)	33.3% (n=24)	<1 cfu/100 mL	<1 cfu/100 mL
Nitrate-nitrogen (<11.3 mg/L)	19% (n=433)	3.1% (n=32)	1.5 mg/L	1.85 mg/L

6.4. Overall assessment of regional groundwater quality

Consideration of current median values of the 12 key indicator variables alongside temporal trends analysis can provide an indication of where the quality of regional groundwater is of concern environmentally or from a drinking water standard perspective. State and temporal trend analysis of groundwater chemistry in four sites (GND0563, GND0827, GND0829 and GND2213) indicate that concentrations of select variables are changing at rates that are considered environmentally meaningful. However, only changes in overall hydrochemistry at GND0563 indicated the state of groundwater in this bore is no longer suitable for potable supply. Given that groundwater quality at this bore is being impacted by the deteriorating state of the bore’s integrity, it is recommended that GND0563 be removed from the GQMP network.

Groundwater concentrations of nitrate and NNN in the remaining three bores are changing at rates that could either exceed the DWSNZ (2018) MAV for nitrate or have an impact on any receiving environments. For example, the current rate of change could see levels of NNN exceed the DWSNZ (2018) MAV for nitrate (11.3 mg/L) in just under three years at GND0829 (although, it should be noted that nitrate concentrations at this site have reduced since 2018). Meanwhile, nitrate concentrations at GND0827 have steadily degraded since the last reporting period, with the median nitrate concentration increasing from 2.41 (TRC 2017) to 3.3 mg/L.

Many of the data records for GQMP sites were not yet of suitable length to enable robust analysis for temporal trends. A more widespread analysis for trends will be possible as these datasets grow in coming years and this will enable a better insight into how groundwater quality is changing, and at what rate, across the region.

The risk that nutrient rich groundwater may pose to hydraulically connected surface water in the region, either in promoting aquatic ecosystem toxicity or the instream proliferation of nuisance plants and algae, is mostly unknown, as are the influence of localised aquifer characteristics (such as aquifer lithology, overlying soil conditions, groundwater residence times, redox in unconfined aquifers) on nutrient attenuation and reduction within the region’s unconfined aquifers.

Targeted investigations, such as the Waiokura Stream catchment study, have highlighted changeable redox conditions and hydrochemical links between groundwater and the Waiokura Stream. Sources of nutrients (like nitrate) in the stream were also found to be strongly associated with agricultural land use activities in the Waiokura catchment (van der Raaij and Martindale 2016). However, these are the preliminary findings of only one study exploring localised hydraulic connections. Regionally, it is expected that some attenuation and dilution of nutrients will occur along the groundwater flow path and within surface water.

Developing management policies and strategies that consider the potential contaminant contribution of groundwater to surface water may be difficult as nutrients are highly mobile in water. Many of the regional unconfined aquifers already show some degree of human impact above the NPS-FM (2020) nitrate aquatic toxicity threshold. Dry stock and dairy farming are typically attributed as sources of nutrient loading, however, in Taranaki, the intensity of these two activities has been relatively stable for some time. Moreover, the nutrient contribution from increased application of nitrogen-based fertilisers in recent times, and the impact of large scale industry in the region needs to be considered and managed appropriately. Analysis of groundwater age would help understand where and when to expect the cumulative impacts of land use to become apparent in regional aquifers and waterways.

Further research into aquifer characteristics and possible hydraulic links and the fate and transport of nutrients, bacteria and other contaminants in the Taranaki unconfined aquifers can help with developing regional policies and strategies for managing nitrate (and other contaminants) in groundwater. This is especially important, as in recent years there has been a move away from discharges to water in preference of discharge to land overlying regional aquifers. Such a move has been made in order to improve surface water quality, however the subsequent environmental impact on groundwater quality is as yet unknown. Such research will in turn assist with meeting national attribute objectives outlined in the NPS-FM (2020).

7. Conclusion

The results of monitoring by the Council over the last five years shows indicators like *Escherichia coli* bacteria (*E. coli*), nitrate nitrogen (nitrate), ammoniacal nitrogen (ammonia), iron and manganese are occasionally found at levels considered unsafe for humans or stock to drink, or at levels that can make the water look or taste unpleasant.

People using private groundwater supplies are most at risk of drinking groundwater with *E. coli* bacteria and elevated levels of nitrate. Overall, median nitrate and *E. coli* levels in Taranaki groundwater are comparable to other regions across Aotearoa where intensive agriculture is the predominant land use. Human activities and animal and industry wastewater discharged to land locally are both common sources of bacteria and nitrate. Poorly constructed wells and bores, or those that are not adequately isolated from direct sources of contamination, or surface runoff, are more likely to display elevated levels of *E.coli*.

At certain concentrations, nitrate can pose a health risk to babies and breastfeeding mothers. The DWSNZ sets a maximum acceptable value (MAV) for nitrate intended to protect against these risks. There is some discussion in the science community presently around whether a more stringent MAV should be set to protect our health, although there is not yet a strong consensus in New Zealand as to whether the science supports further limits on nitrate levels in groundwater. In Taranaki, there was only one site where median levels of nitrate were found to exceed the MAV for drinking water. Median nitrate concentrations were less than half of the MAV at 27 of 32 sites monitored (84%).

The presence of *E. coli* is used as an indicator of the potential presence of pathogens that can make us sick. Monitoring during 2015 to 2020 showed that *E. coli* were detected on at least one occasion at 21 of the 25 sites (84%) located in aquifers most at risk from *E. coli* contamination. At a number of sites the presence of *E. coli* is related to poor bore or well construction, which allows for the ingress of overland runoff into groundwater supplies. *E. coli* concentrations found in purpose designed monitoring wells installed following good drilling practices are consistently low. These results highlight the importance of the proper construction of wells/bores and treating groundwater prior to using it for household drinking water.

The presence of iron, manganese and ammonia in groundwater is mostly due to the local geology and natural processes that occur in aquifers with low levels of oxygen. The concentration of these contaminants in water at some locations can cause the staining of plumbing fixtures, clogging of pipes or result in the taste or look of groundwater being unpleasant, making the water unsuitable for certain uses. Iron concentrations are a particularly common challenge for those utilising groundwater supplies in Taranaki.

Between 2015 to 2020, 12 of 32 monitored sites (38%) were found to have concentrations of iron and/or manganese exceeding an aesthetic or heath related standard set out in the DWSNZ. A further three sites (9%) had exceedances of the aesthetic standard for ammonia.

Test results show that pesticides and heavy metals are generally not an issue in our groundwater, although there have been isolated instances where contamination by chemical substances and herbicides/fungicides has been detected.

Temporal trend analysis of GQMP data collected over a ten year period (2010 to 2020) was conducted on 52 data sets from 10 GQMP sites covering 11 of the 12 key indicator variables. A total of eight environmentally meaningful trends were identified through the analysis. Four of these were related to site GND0563 and are likely related to physical changes made to the bore and its rapidly declining structural integrity. It is recommended that this bore is removed from the GQMP. The remaining four meaningful trends detected in levels of nitrate/NNN and bicarbonate indicate groundwater quality is deteriorating at two sites and improving at one site. Overall, trend analysis found few environmentally meaningful trends at sites where sufficient monitoring data was available for analysis. This suggests groundwater quality across the region is generally stable. In some instances, however, this means that concentrations of contaminants, like nitrate, are being maintained at levels above national drinking water standards or aquatic ecosystem toxicity thresholds.

Comparisons between temporal trend analyses conducted on regional and national data sets indicated that changes in groundwater quality are more likely to be driven by land use or human influence, rather than natural processes at regional and national scales.

7.1. Recommendations

1. THAT the Ministry of Health, Taranaki District Health Board and private bore or well owners be informed of groundwater quality results from potable supply bores;
2. THAT the Council continues to monitor new research regarding the potential health risks associated with nitrate in drinking water and liaise with the Taranaki District Health Board in respect of any research outputs;
3. THAT changes to regional policy and plans are made that enable identification of all groundwater wells/bores installed in the region. Any bores or wells established historically should be registered with the Council.
4. THAT an analysis of groundwater data from both GQMP sites and wells/bores used in consent compliance monitoring is undertaken collectively to better understand the extent and magnitude of nutrient contamination (particularly nitrate) in regional aquifers;
5. THAT hydraulic connections between groundwater and surface water are investigated to aid in the attribute objective and target setting that is to be implemented in regional policy through the NPS-FM (2020); and
6. THAT the range of analyses currently carried out on samples from the SGWM network be extended in forthcoming sampling events to include calcium, magnesium and potassium. Routine periodic testing of heavy metals and metalloids should also be scheduled in to the GQMP.

Glossary of common terms and abbreviations

The following abbreviations and terms may be used within this report:

Anisotropic	Different physical properties in all directions.
Anoxic	Water that is depleted of dissolved oxygen.
Aerobic	Water containing oxygen or a related process requiring oxygen.
ANZECC	Australia and New Zealand Environment and Conservation Council Water Quality Guidelines (2000)
Aquifer	A permeable water-bearing geological formation through which water moves under natural conditions and which yields water to wells at a sufficient rate to be a practical source of water supply.
Bore	Bore means a hole drilled into the ground and completed for the abstraction of water or hydrocarbons to a depth of greater than 20 metres below the ground surface.
Censored data	Any data for which the precise value is partially unknown. For the purpose of this report censored data relates to a sampling result returned below the analysing laboratories limit of detection for that test (i.e. a nitrate result of <0.001 mg/L).
Confined aquifer	When an impermeable formation, such as clay, overlies an aquifer so that air and water are no longer in contact and the pressure is no longer equal to atmospheric pressure. Water in a well will stand at a different level to the water table.
Denitrification	A microbially facilitated process of nitrate reduction.
DO	Dissolved oxygen.
DWSNZ	Drinking Water Standards for New Zealand 2005 (Revised 2018).
E.coli	Escherichia coli, an indicator of the possible presence of faecal material and pathological micro-organisms. Usually expressed as colony forming units per 100 millilitre sample.
Effluent	Liquid waste including slurries.
Electrical conductivity	Conductivity, an indication of the level of dissolved salts in a sample, usually measured at 20°C and expressed in mS/m.
GQMP	Groundwater quality monitoring programme.
GV	Guideline Value (taken from DWSNZ).
Heterogeneity	The quality or state being diverse in physical character or content.
Heterogeneous	See Heterogeneity.
IANZ	International Accreditation New Zealand.
Infiltration	The seepage of water into soil or rock.
Intervention	Action/s taken by Council to instruct or direct actions be taken to avoid or reduce the likelihood of an incident occurring.
Leaching	The loss of mineral and/or organic solutes through percolation.
Lithology	The general physical characteristics of a rock or the rocks in a particular area.
MAV	Maximum Acceptable Value (taken from DWSNZ).
mS/m	Millisiemens per metre.
µS/cm	Microsiemens per centimetre

NGMP	National Groundwater Monitoring Programme.
NH_4	Ammonium, normally expressed in terms of the mass of nitrogen (N).
NO_3	Nitrate, normally expressed in terms of the mass of nitrogen (N).
Objective	A statement of a desired and specific environmental outcome.
Oxic	Water in which dissolved oxygen is present.
Oxidation state	See Redox.
pH	A numerical system for measuring acidity in solutions, with 7 as neutral. Numbers lower than 7 are increasingly acidic and higher than 7 are increasingly alkaline. The scale is logarithmic i.e. a change of 1 represents a ten-fold change in strength. For example, a pH of 4 is ten times more acidic than a pH of 5.
Policy	A specific statement that guides or directs decision making. A policy indicates a commitment to a general course of action in working towards the achievement of an objective.
Purging	The removal of groundwater from a well or bore prior to obtaining a sample.
Recharge	The addition of water from other sources to an aquifer, e.g., seepage from rivers, percolation of rainfall.
Redox	Redox (reduction-oxidation) reactions include all chemical reactions in which atoms have their oxidation state changed; in general, redox reactions involve the transfer of electrons between species. Oxidation is the loss of electrons or an increase in oxidation state by a molecule, atom, or ion. Reduction is the gain of electrons or a decrease in oxidation state by a molecule, atom, or ion.
Reduction processes	See Redox.
Residence time	The amount of time water is present within an aquifer between recharge and discharge.
Resource consent	Refer Section 87 of the RMA. Resource consents include land use consents (refer Sections 9 and 13 of the RMA), coastal permits (Sections 12, 14 and 15), water permits (Section 14) and discharge permits (Section 15).
RFWP	Regional Freshwater Plan for Taranaki (2001).
RMA	Resource Management Act 1991 and including all subsequent amendments.
SEM	State of the Environment
SGWM	Shallow groundwater monitoring.
Transmissivity	Transmissivity is a measurement of the rate at which groundwater can flow through an aquifer section of unit width under a unit hydraulic gradient.
Unconfined aquifer	Groundwater which is freely connected to the atmosphere and which is free to rise and fall in the saturated zone, or water of an unconfined aquifer, or water under water table conditions.
Water table	The upper level of an underground surface in which the soil or rocks are permanently saturated with water.
Well	A hole dug, augured or drilled, tapping the water-table or springs to a depth of 20 m or less below the ground surface.
Yield	The volume of water per unit of time able to be abstracted from a bore or well.

Bibliography and references

Ballantine, D.J., and Davies-Colley, R.J., (2009). Water quality trends at NRWQN sites for the period 1989-2007. NIWA client report (HAM2009-26). Prepared for Ministry for the Environment, March 2009.

Britannica, The Editors of Encyclopaedia. "Biogeochemical cycle". Encyclopedia Britannica., (2020). https://www.britannica.com/science/biogeochemical-cycle [Accessed July 2021].

Brown, K.B., (2013). Stocktake and assessment of Taranaki Groundwater Resources. Report prepared by Geosearch Limited for Taranaki Regional Council.

Burgess, A.C., and Davis, E.B., (1966). Soil fertility problems of Taranaki. New Zealand Grasslands Publication 1966.

Chebotarev II., (1995). Metaporphism of natural water in the crust of weathering Geochim. Cosmochim. Acta. 8 (pp. 22-28).

Close M., and Humphries, B., (2019). National Survey of Pesticides and Emerging Organic Contaminants (EOCs) in Groundwater 2018. Client report CSC19016. Institute of Environmental Science and Research.

Daughney, C.J., and Reeves, R.R., (2005). Definition of hydrochemical facies in the New Zealand National Groundwater Monitoring Programme. Journal of Hydrology (NZ) 44(2). pp 105-130.

Daughney, C.J., and Reeves, R.R., (2006). Analysis of long-term trends in New Zealand's groundwater quality based on data from the National Groundwater Monitoring Programme. Journal of Hydrology New Zealand 45: 41-62.

Daughney, C.J., and Wall, M., (2007). Groundwater quality in New Zealand: State and Trends 1995-2006. GNS Science Consultancy Report 2007/23 prepared for the Ministry for the Environment.

Environment Canada., (2021). Groundwater. https://www.canada.ca/en/environment-climate-change/services/water-overview/sources/groundwater.html [Accessed June 2019].

Fertiliser Association NZ., (2018). Fertiliser use in NZ: http://www.fertiliser.org.nz/Site/about/fertiliser_use_in_nz.aspx. [Accessed March 2021].

Gillingham, A., (2008). 'Soils and regional land use - Central and western North Island', Te Ara - the Encyclopaedia of New Zealand, http://www.TeAra.govt.nz/en/soils-and-regional-land-use/page-4 [Accessed March 2021].

Helsel, D.R., (2011). Statistics for censored environmental data using Minitab and R (Vol. 77). John Wiley & Sons.

Helsel D.R., and Hirsch R.M., (1992). Statistical methods in water resources. Studies in Environmental Science, Vol. 49. Elsevier, Amsterdam.

Hirsch, R.M., Slack, J.R., and Smith, R.A., (1982). Techniques of trend analysis for monthly water quality data. Water resources research, 18(1), pp.107-121.

Hem, D., (1985). Study and Interpretation the Chemical of Natural of Characteristics Natural Water. 3rd edition USGS Water Supply Paper 2254 66-69 US Govt Printing Office Washington DC.

Jowett, I., (2018). Review of minimum flows and water allocation in Taranaki. Jowett Consulting Ltd. chlorideient Report: IJ1702. July 2018.

Livestock Improvement Corporation Limited (LIC) and Dairy NZ Limited., (2000). New Zealand Dairy Statistics 1999-2000. LIC, Hamilton and Dairy NZ, Hamilton. https://www.lic.co.nz/about/dairy-statistics
[Accessed December 2020].

Livestock Improvement Corporation Limited (LIC) and Dairy NZ Limited., (2010). New Zealand Dairy Statistics 2009-10. LIC, Hamilton and Dairy NZ, Hamilton. https://www.lic.co.nz/about/dairy-statistics
[Accessed December 2020].

Livestock Improvement Corporation Limited (LIC) and Dairy NZ Limited., (2020). New Zealand Dairy Statistics 2019-20. LIC, Hamilton and Dairy NZ, Hamilton. https://www.lic.co.nz/about/dairy-statistics
[Accessed December 2020].

Manaaki Whenua Landcare Research., (2000). Land Resource Inventory of Taranaki 2000.

Manaaki Whenua Landcare Research., (2020). The New Zealand Soils Map Viewer https://doi.org/10.26060/9vfz-hw43 [Accessed December 2020].

McBride, G.B., (2019). Has water quality improved or been maintained? A quantitative assessment procedure. Journal of Environmental Quality, 48(2). https://doi.org/10.2134/jeq2018.03.0101

McMahon, P.B., and Chapelle, F.H., (2008). Redox Processes and Water Quality of Selected Principal Aquifer Systems. *Ground Water*. [online] 46 (2), 259-271. Available from: https://oh.water.usgs.gov/tanc/pubs/McMahon-ground-water-april_2008 [Accessed August 2017].

Ministry for the Environment., (2006). A national protocol for the state of the environment groundwater sampling in New Zealand. Ministry for the Environment. Wellington.

Ministry for the Environment. 2009. Water Quality in Selected Dairy Farming Catchments: A baseline to support future water-quality trend assessments. Wellington: Ministry for the Environment.

Ministry for the Environment., (2016): Land-use and Carbon Analysis System: Satellite imagery interpretation guide for land-use classes (2nd edition) 2016 Update. Ministry for the Environment. Wellington.

Ministry for the Environment., (2014). National policy statement for freshwater management 2014. Gazetted 4 July 2014. Ministry for the Environment, Wellington.

Ministry for the Environment & Statistics NZ., (2019). New Zealand's Environmental Reporting Series: Environment Aotearoa 2019 Summary. Publication number: ME 1417. Published in April 2019 by Ministry for the Environment and Stats NZ. Available from www.mfe.govt.nz and www.stats.govt.nz

Ministry of Health., (2018). Drinking-water Standards for New Zealand 2005 (Revised 2018). Ministry of Health, Wellington.

Molloy, L., (1998). Soils in the New Zealand Landscape – the living mantle, 2nd Edition. New Zealand Society of Soil Science c-/- Department of Soil Science, Lincoln University. New Zealand.

Moreau, M., Reidi, M.A., and Aurisch, K., (2016). Update of national Groundwater Quality Indicators: State and trends 2005-2014. GNS Science Consultancy Report 2015/107. 42p.

National Institute of Atmosphere and Water., (2021). https://niwa.co.nz/our-science/freshwater/tools/kaitiaki_tools/land-use/agriculture/dry-stock/activities [Accessed June 2021].

Neal, C., Neal, M., Hughes, S., Wickham, H., Hill, L., and Harman, S., (2007). Bromine and bromide in rainfall, cloud, stream and groundwater in the Plynlimon area of mid-Wales. Hydrology and Earth System Sciences Discussions, European Geosciences Union, 2007, 11 (1), pp.301-312.

Pattle Delamore Partners., (2011). Audit of Taranaki Regional Council State of the Environment Groundwater Programmes. Report prepared for Taranaki Regional Council.

Pattle Delamore Partners., (2011). New Zealand Guidelines for the Monitoring and Management of Sea Water Intrusion Risk on Groundwater. Report prepared for Envirolink Project 420-NRLC50

Rosen, M.R., (2001). Hydrochemistry of New Zealand's aquifers. In Rosen MR. and White PA. (EDs). Groundwaters of New Zealand (pp. 77-110). New Zealand Hydrological Society, Wellington.

Roverato, M., Cronin, S., Procter, J., and Capra, L., (2014). Textural features as indicators of debris avalanche transport and emplacement, Taranaki volcano. Geological Society of America Bulletin. 127. 3-18. 10.1130/B30946.1.

Rusydi, A.F., (2018). IOP Conf. Ser.: Earth Environ. Sci. 118 012019. https://iopscience.iop.org/article/10.1088/1755-1315/118/1/012019 [Accessed July 2021].

Schullehner, J., Hansen B., Thygesen, M., Pedersen, C.B., and Sigsgaard, T., (2018). Nitrate in drinking water and colorectal cancer risk: A nationwide population-based cohort study. International Journal of Cancer. 2018; 143(1):73-79. https://doi.org/10.1002/ijc.31306

Sherris, A.R., Baiocchi, M., Fendorf, S., Luby, S.P., Yang, W., Shaw, G.M., (2021). Nitrate in Drinking Water during Pregnancy and Spontaneous Preterm Birth: A Retrospective Within-Mother Analysis in California. Environmental Health Perspectives. 2021; 129(5):057001. https://doi.org/10.1289/EHP8205

Smedley, P.L., and Kinniburgh, D.G., (2002). A review of the source, behaviour and distribution of arsenic in natural waters. Applied Geochemistry, 17: 517-568.

Snelder, T., and Fraser, C., (2018). Aggregating trend data for environmental reporting. LWP Client Report 2018-01.

Snelder, T., and Fraser, C., (2019). LWP-Trends library Version 1901: LWPTrends_v2101.r. Tools for analysing water quality trends. Land Water People Ltd Report, p35. Christchurch New Zealand. Note – this tool is constantly updated.

Statistics New Zealand., (2020). Infoshare https://www.stats.govt.nz/tools/stats-infoshare [Accessed December 2020].

Stenger, R., and Clague, J., (2016). Investigations of redox gradients in shallow groundwater systems: Monitoring results July 2015 - April 2016. Report 1046-2-6. Report prepared by Lincoln Agritech Limited for Taranaki Regional Council.

South Taranaki District Council, (2018). Waste Assessment. https://www.southtaranaki.com/repository/libraries/id:27mlbegko1cxbyf94es5/hierarchy/Documents/Plans%2C%20strategies%20and%20reports/Waste%20Management%20and%20MInimisation%20Plan/2018%20South%20Taranaki%20District%20Council%20Waste%20Assessment.pdf

Taranaki Regional Council., (1992). South Taranaki Groundwater Survey and Management Policies. ISSN: 0114-8184, Taranaki Regional Council, Stratford, November 1992.

Taranaki Regional Council., (1996). Groundwater Resources of The Taranaki Region. Taranaki Regional Council, Stratford, August 1996.

Taranaki Regional Council., (2008). Groundwater Chemical Quality. State of the Environment Monitoring 1994-2007. Technical Report 2017-45. Taranaki Regional Council, Stratford, October 2017.

Taranaki Regional Council., (2015): Taranaki as one. State of the Environment Report 2015. Taranaki Regional Council, Stratford, June 2015.

Taranaki Regional Council., (2015): Procedure for Groundwater Sampling [Procedure 44]. Taranaki Regional Council, Stratford, October 2015.

Taranaki Regional Council., (2017): Taranaki Regional Council requirements for good farm management Available from: www.trc.govt.nz. Taranaki Regional Council, Stratford, March 2017.

Taranaki Regional Council., (2017). Groundwater Chemical Quality. State of the Environment Monitoring 2016-2017. Technical Report 2008-58. Taranaki Regional Council, Stratford, October 2008.

Taranaki Regional Council., (2020). Freshwater Physicochemical Programme State of the Environment Monitoring Annual Report 2018-2019. Technical Report 2019-98. Taranaki Regional Council, Stratford, October 2020.

Taranaki Regional Council., (2022): Groundwater Quantity State of the Environment Monitoring Triennial Report 2017-2020. Available from: www.trc.govt.nz. Taranaki Regional Council, Stratford, July 2022.

Taylor, C.B., and Evans, C.M., (1999). Isotopic indicators for groundwater hydrology in Taranaki, New Zealand. Journal of Hydrology (NZ) 38(2). pp 237-270.

van der Raaij R.W., and Martindale, H., (2016). Application of hydrochemical and isotopic methods to assess water source and contaminant pathways in the Waiokura Catchment, Taranaki, New Zealand, DRAFT GNS Science Report 2016/65. 39 p.

World Health Organisation., (2017). Guidelines for Drinking-water Quality: fourth edition incorporating the first Addendum. Geneva: World Health Organization; 2017. License: CC BY-NC-SA 3.0 IGO.

Younger, P.L., (2007). Groundwater in the environment: an introduction. Blackwell. London 2008. ISBN 1-4051-2143-2.

Appendix I

Monitoring site details

Site	Easting	Northing	Area	Date drilled	Depth (m)	Diameter (mm)	Screened depth (m BGL)	Construction method	Usage	Aquifer	Aquifer type	Date monitoring began	Programme
GND0213	1711187	5682097	Motunui	18/12/1982	21.7	76.2	17.6 - 20.6	Drilled - screened	Monitoring	Marine Terrace (North)	Unconfined	23/09/2015	NGMP
GND0430	1713802	5623656	Hawera	05/11/1992	234.6	150	54.0 - 234.0	Drilled - open ended casing	Stock	Whenuakura	Confined	13/12/1994	NGMP
GND0508	1694021	5669859	New Plymouth	29/05/2003	14	50	8.0 -14.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	13/12/1994	NGMP
GND0514	1724029	5684247	Urenui	14/07/1987	4.2	1200	0.5 - 4.2	Dug - lined	Stock & domestic	Marine Terrace (North)	Unconfined	22/10/2014	SGWM
GND0563	1719027	5647305	Toko	06/01/1995	77.7	100	72.7 - 77.7	Drilled - open ended casing	Domestic	Matemateaonga	Confined	26/09/1995	NGMP
GND0636	1697543	5630420	Kaponga	28/09/1994	6.5	50	-	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	21/10/2013	SGWM
GND0827	1701591	5618033	Hawera	Unknown	8	1500	-	Dug - unlined	Domestic	Taranaki Volcanics	Unconfined	13/12/1994 (NGMP) 09/01/2002 (SGWM)	NGMP & SGWM
GND0829	1728941	5597650	Patea	Unknown	5.2	1000	-	Bored or augered - unlined	Stock & domestic	Marine Terrace (South)	Unconfined	24/01/2002	SGWM
GND0834	1706701	5617616	Hawera	Unknown	7	1500	-	Bored or augered - unlined	Domestic	Marine Terrace (South)	Unconfined	09/01/2002	SGWM
GND0866	1724829	5615319	Manutahi	Unknown	7	1000	-	Bored or augered - lined	Stock & domestic	Marine Terrace (South)	Unconfined	29/04/2001	SGWM

Site	Easting	Northing	Area	Date drilled	Depth (m)	Diameter (mm)	Screened depth (m BGL)	Construction method	Usage	Aquifer	Aquifer type	Date monitoring began	Programme
GND1075	1713523	5645279	Stratford	Unknown	7	-	-	Dug - lined	Stock & domestic	Taranaki Volcanics	Unconfined	14/05/2001	SGWM
GND1091	1707330	5675479	Lepperton	Unknown	7.5	1500	-	Dug - lined	Stock & domestic	Taranaki Volcanics	Unconfined	17/05/2001	SGWM
GND1095	1673342	5655645	Okato	01/01/1945	7.5	1000	-	Dug - lined	Unused	Taranaki Volcanics	Unconfined	21/05/2001	SGWM
GND1101	1665886	5648848	Rahotu	Unknown	5.5	1000	-	Dug - lined	Stock	Taranaki Volcanics	Unconfined	22/05/2001	SGWM
GND1105	1703856	5629095	Hawera	Unknown	7.2	1200	-	Unknown	Domestic	Taranaki Volcanics	Unconfined	23/05/2001	SGWM
GND1112	1702153	5621304	Hawera	Unknown	12.2	1000	-	Dug - unlined	Stock & domestic	Taranaki Volcanics	Unconfined	24/05/2001	SGWM
GND1194	1724486	5608758	Manutahi	01/01/1930	7.02	1000	-	Dug - lined	Domestic	Marine Terrace (South)	Unconfined	23/01/2002	SGWM
GND1196	1709272	5634442	Eltham	10/01/2002	8.5	50	2.4 - 8.4	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	15/11/2013	SGWM
GND1718	1721048	5680386	Urenui	01/12/2004	11	1000	-	Bored or augered - unlined	Domestic	Marine Terrace (North)	Unconfined	27/01/2015	SGWM
GND2098	1681945	5669803	Oakura	03/09/2008	13.5	50	7.5 - 12.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	14/10/2014	SGWM
GND2114	1675221	5661873	Okato	09/08/2009	41.9	150	34.4 - 41.9	Drilled - screened	Industrial	Taranaki Volcanics	Confined	07/12/2015	NGMP
GND2166	1701952	5651677	Inglewood	23/12/2009	3.5	50	-	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	30/01/2015	SGWM
GND2197	1725006	5599997	Patea	01/04/2011	144.2	220	96.5 - 141.5	Drilled - screened	Public supply	Whenuakura	Confined	08/12/2015	NGMP
GND2213	1700043	5675241	Lepperton	Unknown	10.7	1200	-	Bored or augered - unlined	Domestic	Taranaki Volcanics	Unconfined	01/08/2011	SGWM

Site	Easting	Northing	Area	Date drilled	Depth (m)	Diameter (mm)	Screened depth (m BGL)	Construction method	Usage	Aquifer	Aquifer type	Date monitoring began	Programme
GND2242	1739058	5597248	Waverley	24/01/2012	171.3	276	129.2 - 168.2	Drilled - screened	Public supply	Whenuakura	Confined	08/12/2015	NGMP
GND2484	1697570	5667514	New Plymouth	01/01/2008	8.3	50	2.3 - 6.3	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	22/10/2014	SGWM
GND2513	1717861	5664741	Huinga (Toko)	18/05/2015	5	50	1.0 - 5.0	Drilled - screened	Monitoring	Kiore	Unconfined	31/07/2015	SGWM
GND3006	1676679	5647875	Rahotu	26/03/2018	8	50	2.0 - 8.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	26/06/2018	SGWM
GND3011	1684896	5622370	Otakeho/ Oeo	29/08/2018	13.5	50	10.0 - 13.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	21/09/2018	SGWM
GND3012	1673639	5634990	Opunake	27/08/2018	10.5	50	7.0 - 10.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	20/09/2018	SGWM
GND3014	1691470	5637406	Opunake/Makaka	10/09/2018	12.5	50	9.0 - 12.0	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	21/09/2018	SGWM
GND3027	1707018	5663862	Inglewood	26/11/2018	11.6	50	8.1 - 11.1	Drilled - screened	Monitoring	Taranaki Volcanics	Unconfined	11/12/2018	SGWM

Appendix II

Water quality variables and analytical methods

Appendix Two: Water quality variables and analytical methods

Groundwater samples are obtained from all SGWM and NGMP network bores on a quarterly basis, generally during the months of September, December, March and June. Sampling is undertaken in accordance with the Council's Groundwater Sampling Procedure (TRC, 2015).

If direct access to the well or bore is possible, groundwater is purged using a low-flow peristaltic or pneumatic bladder pump to remove any standing water within the bore. Groundwater is pumped from the bore and monitored continuously as it passes through a flow-cell housing a multi parameter field chemistry meter. Groundwater samples are taken when field parameters such as temperature, pH, electrical conductivity and dissolved oxygen stabilised within set criteria (See Figure 1A). These practises are employed to make sure that the groundwater sample collected is representative of the surrounding aquifer.

A number of bores in the SEM Groundwater Quality programme are regularly used by private bore owners for example: irrigation and domestic supply bores. This means 'fresh' groundwater is continuously drawn into the bore from the aquifer and stabilisation of field parameters can occur rapidly. When direct access to the bore is not available, samples are obtained from the nearest available tap or hose. If the bore is in regular use, water will be run for a short period of time and field chemistry measurements taken when obtaining the sample. If not in regular use, a purge will be attempted and field chemistry monitored for stabilisation. When stabilised, the sample is obtained.

Groundwater samples collected for the NGMP are collected in a range of unfiltered, filtered and acid preserved sample bottles provided by GNS Science. Groundwater samples collected for the SGWM programme are collected in unpreserved sample bottles. All samples are chilled to between $4^{o}C$ - $8^{o}C$ during storage and transport to the laboratory for analysis. Samples requiring microbial analysis are delivered to the laboratory within 12 hours of being taken.

Figure 1A Groundwater bore GND0508 is continuously monitored while purged of standing water using a peristaltic pump purging. Groundwater sample is collected when field parameters are stabilised

Rational for physico-chemcial and microbiological variables measured in the Council's SEM Groundwater Quality programme are outlined in in Table 4A below. Between 2002 and June 2018, groundwater samples collected for the SGWM programme were tested by the Council's IANZ accredited laboratory, Stratford, Taranaki. From June 2018, these samples were sent RJ Hill Laboratories in Hamilton for analysis. Groundwater samples collected for the NGMP were sent the IGNS Laboratory in Wairakei, Taupo for analysis. Analytical methods and detection limits for each laboratory are showing in Table 5A to Table 8A.

Table A4 Core physico-chemical and microbiological water quality variables in the SEM GQMP

Variable type	Variable	Explanation	Monitoring history
Bacteria	*Escherichia coli (E.coli)*	*E. coli* can indicate pollution due to faecal matter and the presence of potentially harmful pathogens in groundwater. The Ministry for the Environment uses E. coli as a national indicator of groundwater quality.	*E. coli* tested under SGWM programme since July 2006. Not currently tested un NGMP.
Major ions	Total & Dissolved sodium (Na) Dissolved potassium (K) Dissolved calcium (Ca) Dissolved magnesium (Mg) Chloride (Cl) Sulphate (SO4) Total alkalinity	Concentrations of major ions can give an indication of the chemical composition of the water, the origins of groundwater, water residence time in the aquifer and the extent of rock/water interaction. Concentrations of major ions can also be indicative of groundwater contamination from industrial, agricultural and domestic sources.	All major ions except total alkalinity tested under the NGMP since 1994. Cl tested under SGWM programme since March 2018. Total Na tested between March 2018 & Sept 2019, switched to Dissolved Na in Dec 2019. SO4 and Total Alkalinity tested since July 2017 and June 2018 respectively. K and Ca currently not tested for under SGWM.
Nutrients	Nitrite-nitrate nitrogen (NNN or TON) Nitrate nitrogen (NO_3-N) Nitrite nitrogen (NO_2-N) Ammoniacal nitrogen (NH_4-N) Dissolved reactive phosphorus (DRP)	Dissolved concentrations of nutrients can indicate impact from anthropogenic activity such as intensive land use or industrial discharges. Nitrate nitrogen (nitrate) represents the oxidised form of nitrogen. Elevated concentrations of nitrate can have an adverse effect on human health and can be harmful to aquatic life. Nitrate is a national indicator of groundwater quality. Ammoniacal nitrogen (ammonia) usually exists under oxygen-poor conditions and represents the reduced form of nitrogen. Therefore, ammonia can be used as an indicator of contamination in the absence of nitrate. Natural sources of DRP in groundwater can sometimes occur due to rock/water interactions within an aquifer. However, this typically occurs in anoxic environments. Human sources of DRP are derived from intensive land use practices, and from effluent and industrial discharges.	Nutrients tested under the NGMP since 1994 with the exception of DRP which is irregularly test for. NH_4-N and NNN inconsistently tested under the SGWM programme since 2002, regularly tested since 2013. NO_3-N and NO_2-N regularly tested for since Oct 2013. DRP testing began in March 2018.
Metals	Dissolved iron (Fe) Dissolved manganese (Mn)	Trace metals are usually present in groundwater at low concentrations - elevated concentrations can suggest contamination of groundwater. Elevated concentrations of dissolved lead and manganese can adversely affect human health.	Trace elements tested under NGMP since 1996. Not currently tested under SGWM.

Variable type	Variable	Explanation	Monitoring history
Trace elements	Bromide (Br) Fluoride (F)	Bromide naturally occurs in water but can suggest contamination from wastewater and agricultural run off. The DWSNZ (2005) MAV for fluoride is set to protect against potential dental fluorosis. Elevated concentrations of dissolved boron can have adversely affect human health.	Trace elements tested under NGMP since 1996. Not currently tested under SGWM.
Other	Temperature (Temp) pH Electrical conductivity (EC) Dissolved oxygen (DO) Redox potential Dissolved reactive Silica (SiO_2)	Temperature measured in the field to identify when the bore is purged and water samples can be collected for analysis. Water with a low pH can have a high plumbosolvency. It is measured in the field to identify when the bore is purged and water samples can be collected for analysis. Electrical conductivity can provide a measure of total dissolved solids. Measured in the field to identify when the bore is purged and water samples can be collected for analysis. Dissolved oxygen (DO) can indicate whether groundwater is under reduced or oxidised conditions. DO is measured in the field to identify when the bore is purged and water samples can be collected for analysis. Redox potential is a measure of how oxygen rich (oxic) or oxygen poor (anoxic) the environment within an aquifer is. Can be used to map contamination plumes and understand where natural aquifer conditions encourage denitrification in groundwater. Can help interpret the extent of rock/water interaction.	Field measurements of temp, pH, EC and DO may have been tested for under the NGMP since 1994. However, this hasn't been recorded by TRC or NGMP until 2002. Records are patchy until 2013. Lab measurements of Temp, pH, EC and DO have been tested since 1994, but not always recorded. SiO_2 tested under NGMP since 1994. Lab EC & pH, and Field Temp tested under SWGM programme since Jan 2001. Field pH, EC, DO tested SWGM Oct 2013. SiO_2 tested under SWGM between Oct 2013 to June 2016 and redox potential since Oct 2014.
Calculations	Total dissolved solids (TDS) Bicarbonate (as HCO3) Carbonate (as CaCO3	Can help interpret the extent of rock/water interaction.	HCO_3, TDS calculated for NGMP since 1994. $CaCO_3$ tested intermittently. HCO_3, added to SGWM March 2018.

Table 5A RJ Hill Laboratory analytical methods and detection limits used in the SEM GQMP (Shallow Groundwater Monitoring network from June 2018)

Variable	Method	Detection limit
Filtration, Unpreserved	Sample filtration through 0.45µm membrane filter.	-
Total Digestion	Nitric acid digestion. APHA 3030 E (modified) 23rd ed. 2017.	-
pH	pH meter. APHA 4500-H+ B 23rd ed. 2017. Note: It is not possible to achieve the APHA Maximum Storage Recommendation for this test (15 min) when samples are analysed upon receipt at the laboratory, and not in the field. Samples and Standards are analysed at an equivalent laboratory temperature (typically 18 to 22 °C). Temperature compensation is used.	0.1 pH Units
Total Alkalinity	Titration to pH 4.5 (M-alkalinity), autotitrator. APHA 2320 B (modified for Alkalinity <20) 23rd ed. 2017.	1.0 g/m^3 as $CaCO^3$
Bicarbonate	Calculation: from alkalinity and pH, valid where TDS is not >500 mg/L and alkalinity is almost entirely due to hydroxides, carbonates or bicarbonates. APHA 4500-CO2 D 23rd ed. 2017.	1.0 g/m^3 at 25°C
Electrical Conductivity (EC)	Conductivity meter, 25°C. APHA 2510 B 23rd ed. 2017.	0.1 mS/m
Filtration for dissolved metals analysis	Sample filtration through 0.45µm membrane filter and preservation with nitric acid. APHA 3030 B 23rd ed. 2017.	-
Dissolved Iron	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.02 g/m^3
Dissolved Manganese	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.0005 g/m^3
Dissolved Potassium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.05 g/m^3
Dissolved Sodium	Filtered sample, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.02 g/m^3
Total Sodium	Nitric acid digestion, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.021 g/m^3
Chloride	Filtered sample. Ion Chromatography. APHA 4110 B (modified) 23rd ed. 2017.	0.5 g/m^3
Total Ammoniacal-N	Phenol/hypochlorite colourimetry. Flow injection analyser. (NH4-N = NH4+-N + NH3-N). APHA 4500-NH3 H (modified) 23rd ed. 2017.	0.010 g/m^3
Nitrite-N	Automated Azo dye colorimetry, Flow injection analyser. APHA 4500-NO3- I (modified) 23rd ed. 2017.	0.002 g/m^3
Nitrate-N	Calculation: (Nitrate-N + Nitrite-N) - NO2N. In-House	0.0010 g/m^3
Nitrate-N + Nitrite-N	Total oxidised nitrogen. Automated cadmium reduction, flow injection analyser. APHA 4500-NO3- I (modified) 23rd ed. 2017.	0.002 g/m^3
Dissolved Reactive Phosphorus	Filtered sample. Molybdenum blue colourimetry. Flow injection analyser. APHA 4500-P G (modified) 23rd ed. 2017.	0.004 g/m^3
Reactive Silica	Filtered sample. Heteropoly blue colorimetry. Discrete analyser. APHA 4500-SiO2 F modified from flow injection analysis) 23rd ed. 2017.	0.10 g/m^3 as SiO_2
Sulphate	Filtered sample. Ion Chromatography. APHA 4110 B (modified) 23rd ed. 2017.	0.5 g/m^3
Escherichia coli	MPN count using Colilert , Incubated at 35°C for 24 hours. APHA 9223 B 23rd ed. 2017.	1 MPN / 100mL
Escherichia coli	Membrane filtration, Count on mFC agar, Incubated at 44.5°C for 22 hours, MUG Confirmation. APHA 9222 G 23rd ed. 2017.	1 cfu / 100mL

Table 6A Taranaki Regional Council analytical methods and detection limits used in SEM GQMP (Shallow Groundwater Monitoring network prior to June 2018)

Variable	TRC Lab method code	Method	Detection limit
Filtration	Sample processing	Sample filtration through 0.45µm membrane filter.	-
pH	Method 8.1.2: pH (PH-1)	(1) Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (Part 4500-H+B) (2) Physical and Chemical Methods for Water Quality Analysis, Water and Soil Miscel. Publication No. 38, 1982	0.1 pH Units
Total Alkalinity	Method 8.3.1: Alkalinity - Titrimetric, pH 4.5 (ALKT-1)	(1) Standards Methods, 22nd Edition 2012, APHA-AWWA-WEF (Part 2320B) (2) ASTM, Part 31, 1980 `Water'	1.0 g/m^3 as $CaCO_3$
Electrical Conductivity (EC)	Method 8.1.1: Conductivity (CONDY-1	(1) Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (Part 2510B) (2) Instrument Manual for Orion conductivity meter.	0.1 mS/m
Dissolved Iron	Method 8.5.1: Dissolved and Recoverable Metals (FED-1)	Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (3030F.3B, 3111B, 3111D)	0.03 g/m^3
Dissolved Manganese	Method 8.5.1: Dissolved and Recoverable Metals (MND-1)	Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (3030F.3B, 3111B, 3111D)	0.01 g/m^3
Dissolved Sodium	Method 8.5.2: Sodium and Potassium –AE (NA-4, K-4)	(1) Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (3500-NaB, 3500-K) (2) Water Research Vol 17, No 11	0.06 g/m^3
Total Sodium		Nitric acid digestion, ICP-MS, trace level. APHA 3125 B 23rd ed. 2017.	0.021 g/m^3
Chloride	Method 8.3.2 A: Chloride -Ferric Thiocyanate Colorimetry (CL-1)	Annual Book of ASTM Standards, Part 31 `Water', Standard D512, Method C (1980)	0.2 g/m^3
Total Ammoniacal-N	Method 8.4.1: Ammonia (NH4-1)	Physical and Chemical Methods for Water Quality Analysis - Water and Soil Miscel. Publication No. 38, 1982	0.003 g/m^3
Nitrite-N	Method 8.4.2 A: Nitrite (NO2-1)	Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (4500-NO2-B)	0.001 g/m^3
Nitrate-N	NO3-5	Calculation: (Nitrate-N + Nitrite-N) - NO2N. In-House	0.001 g/m^3
Nitrate-N + Nitrite-N	Method 8.4.2 C: Nitrate - Hydrazine Reduction (NNN-5)	Standard methods, 22nd Edition 2012 APHA-AWWA-WEF (part 4500-NO3 - H)	0.01 g/m^3
Dissolved Reactive Phosphorus	Method 8.4.5: Reactive Dissolved Phosphorus (DRP-1)	Physical and Chemical Methods for Water Quality Analysis, Water and Soil Miscellaneous Publication No. 38, 1982	0.003 g/m^3
Reactive Silica	Silica -Molybdosilicate Colorimetric SIDR-1, SITD-1)	Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (Part 4500-SiO2 C)	1.0 g/m^3 as SiO_2
Sulphate	Method 8.3.8: Sulphate – Turbidimetric (SO4-1)	(1) Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (4500-SO42-E) (2) Department of Transportation, California Test 417, 1999.	0.5 g/m^3
Escherichia coli	Method 7.4: E. coli MF procedure (ECOL-1)	(1) Test Methods for Escherichia coli and Enterococci in Water by the Membrane Filter Procedure, USEPA, 1985 (2) Standard Methods, 22nd Edition 2012, APHA-AWWA-WEF (Part 9213D)	1 cfu / 100mL

Table 7A Institute of Geological & Nuclear Sciences analytical methods and detection limits used in the National Groundwater Monitoring Programme

Variable	Method	Detection limit
Alkalinity (as HCO3)	Auto titration method APHA 2320 - B 22nd Edition 2012	5 mg/L
Ammonia (as filterable NH3)	Flow Injection Analyser APHA 4500 NH3-H 22nd Edition 2012	0.003 mg/L
Barium	ICP-OES APHA 3120-B 22nd Edition 2012	0.001 mg/L
Bicarbonate (total)	HCO3 Titration Method ASTM Standards D513-82 Vol.11.01 of 1988	20 mg/L
Boron	ICP-OES APHA 3120 22nd Edition 2012	0.1 mg/L
Bromide	Ion Chromatography APHA 4110-B 22nd Edition 2012	0.02 mg/L
Calcium	ICP-OES APHA 3120-B 22nd Edition 2012	0.01 mg/L
Chloride	Ion Chromatography APHA 4110-B 22nd Edition 2012	0.05 mg/L
Conductivity	Conductivity Meter APHA 2510 B 22nd Edition 2012	1.0 µS/cm
Fluoride	Ion Chromatography APHA 4110-B 22nd Edition 2012	0.02 mg/L
Iron	ICP-OES APHA 3120-B22nd Edition 2012	0.01 mg/L
Magnesium	ICP-OES APHA 3120-B 22nd Edition 2012	0.01 mg/L
Manganese	ICP-OES APHA 3120-B 22nd Edition 2012	0.005 mg/L
Nitrate Nitrogen	Flow Injection Analyser QuickChem 8500 Series 2 Method	0.002 mg/L
Nitrite Nitrogen	Flow Injection Analyser QuickChem 8500 Series 2 Method	0.002 mg/L
pH	Electrometric Method APHA 4500-H+ B 22nd Edition 2012	-
Dissolved reactive phosphorus	Flow Injection Analyser APHA 4500-P G (modified) 22nd Edition 2012	0.002 mg/l
Potassium	ICP-OES APHA 3120-B 22nd Edition 2012	0.11 mg/L
Silica (SiO2)	ICP-OES APHA 3120-B 22nd Edition 2012	0.05 mg/L
Sodium	ICP-OES APHA 3120-B 22nd Edition 2012	0.02 mg/L
Sulphate	Ion Chromatography APHA 4110-B 22nd Edition 2012	0.03 mg/L
Total dissolved solids	By calculation	

Table 8A Taranaki Regional Council field analytical methods and detection limits used in the SEM GQMP

(Source: https://www.ysi.com/proplus)

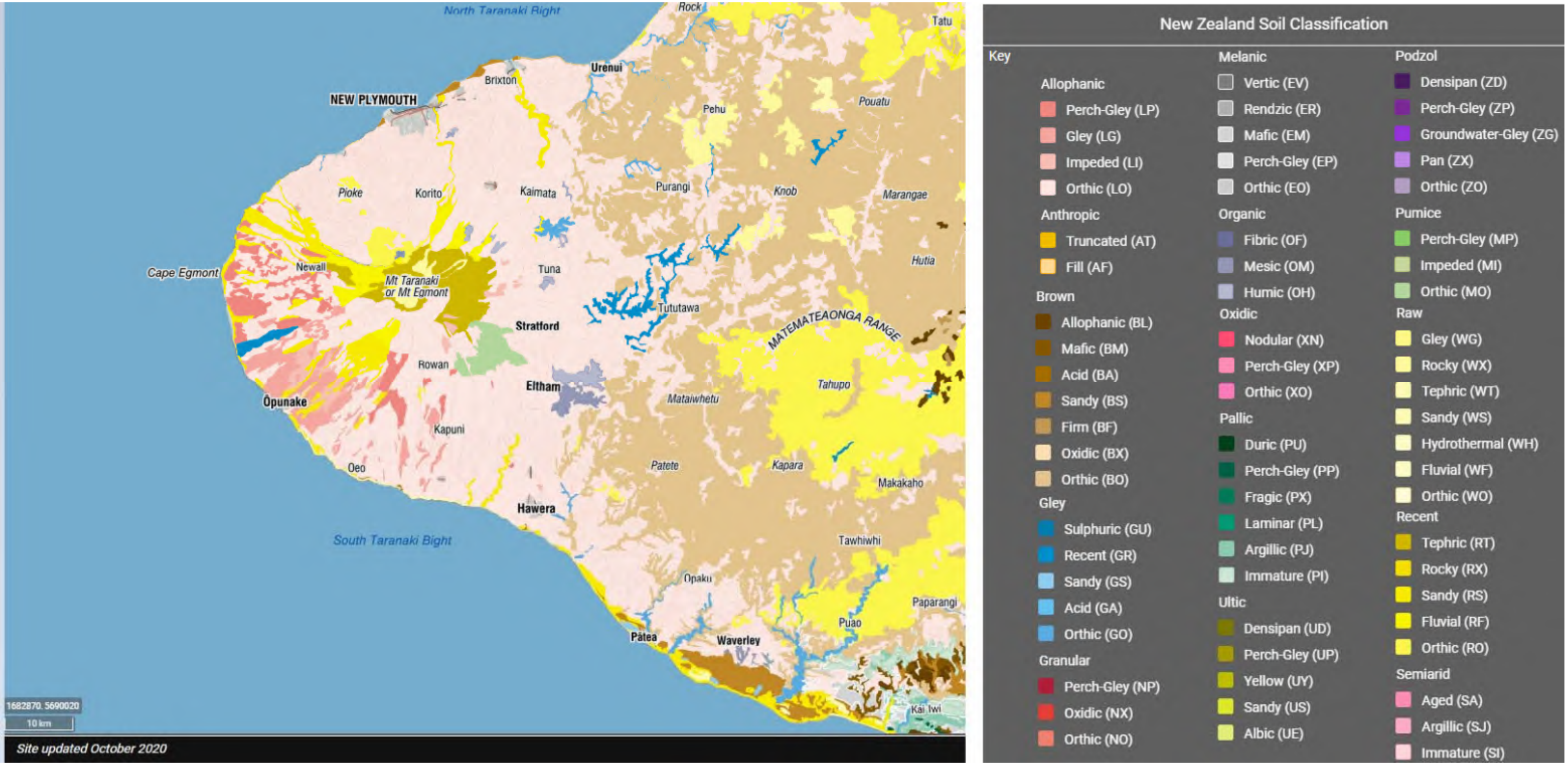
Variable	Method	Detection limit
Redox potential mV	YSI Pro Plus	0.1 mV
Acidity pH units	YSI Pro Plus	0.01 pH units
Temperature Deg. C	YSI Pro Plus	0.1 C
Oxygen mg/L	YSI Pro Plus	0.01 mg/L
Electrical conductivity uS/cm@25ºC (based on range 50.01 – 200mS/cm)	YSI Pro Plus	0.1 mS/cm

Appendix III

New Zealand Soil Classification Map

Appendix Three: New Zealand Soil Classification Map

Manaaki Whenua - Landcare Research 2020. The New Zealand Soils Map Viewer.
Soil Map View is built and operated by the Informatics and Soils and Landscapes teams at Manaaki Whenua (Landcare)
https://doi.org/10.26060/9vfz-hw43 https://soils-maps.landcareresearch.co.nz/#maps



Appendix IV

Additional analysis of select variables using Kruskal-Wallis and Dunn's tests

Appendix Five: Additional analysis of select variables using Kruskal-Wallis and Dunn's tests

Seasonality in groundwater concentrations of nitrate nitrogen

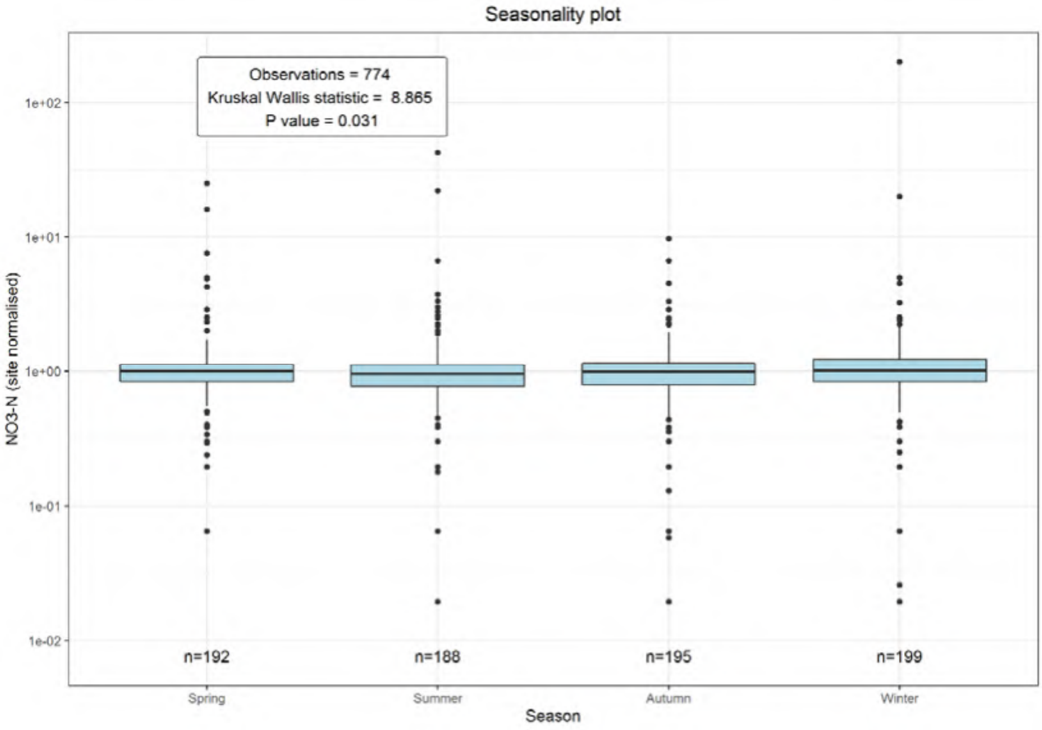


Figure 3A Boxplots showing seasonal differences in groundwater concentrations of nitrate nitrogen based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Table 12A The distribution (expressed as percentiles) of nitrate nitrogen concentrations in groundwater between four seasons. Based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Season	n	10th	25th	median	75th	90th
Spring	192	0.66	0.83	1	1.13	1.41
Summer	188	0.55	0.77	0.95	1.11	1.4
Autumn	195	0.51	0.79	0.98	1.14	1.5
Winter	199	0.53	0.83	1.01	1.23	1.79

Table 13A Results of Dunn's tests investigating seasonal differences in groundwater concentrations of nitrate nitrogen. Based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Comparison	Z	*p* unadjusted	*p* adjusted
Autumn - Spring	-0.691	0.49	0.49
Autumn - Summer	0.801	0.423	0.846
Spring - Summer	1.48	0.138	0.553
Autumn - Winter	-2.07	0.038	0.191
Spring - Winter	-1.37	0.17	0.511
Summer - Winter	-2.86	0.004	0.025

Relationship between bore construction type and counts of *Escherichia coli* (*E.coli*) in groundwater

Table 14A Results of Dunn's tests investigating possible relationships between types of bore constructs and the detection of positive counts of *Escherichia coli (E.coli)* in groundwater. Based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Comparison	Z	*p* unadjusted	*p* adjusted
Bored/augured-lined – Bored/augured-unlined	-1.59	0.113	0.563
Bored/augured-lined - Drilled-screened	-1.29	0.198	0.594
Bored/augured-unlined - Drilled-screened	0.680	0.496	0.993
Bored/augured-lined - Dug-lined	-1.96	0.050	0.298
Bored/augured-unlined - Dug-lined	-0.612	0.540	0.540
Drilled-screened - Dug-lined	-1.49	0.137	0.550
Bored/augured-lined - Dug-unlined	-3.68	0.000	0.002
Bored/augured-unlined - Dug-unlined	-3.56	0.000	0.003
Drilled-screened - Dug-unlined	-4.59	0.000	0.000
Dug-lined - Dug-unlined	-3.31	0.001	0.007

Seasonality in groundwater counts of *Escherichia coli (E.coli)*

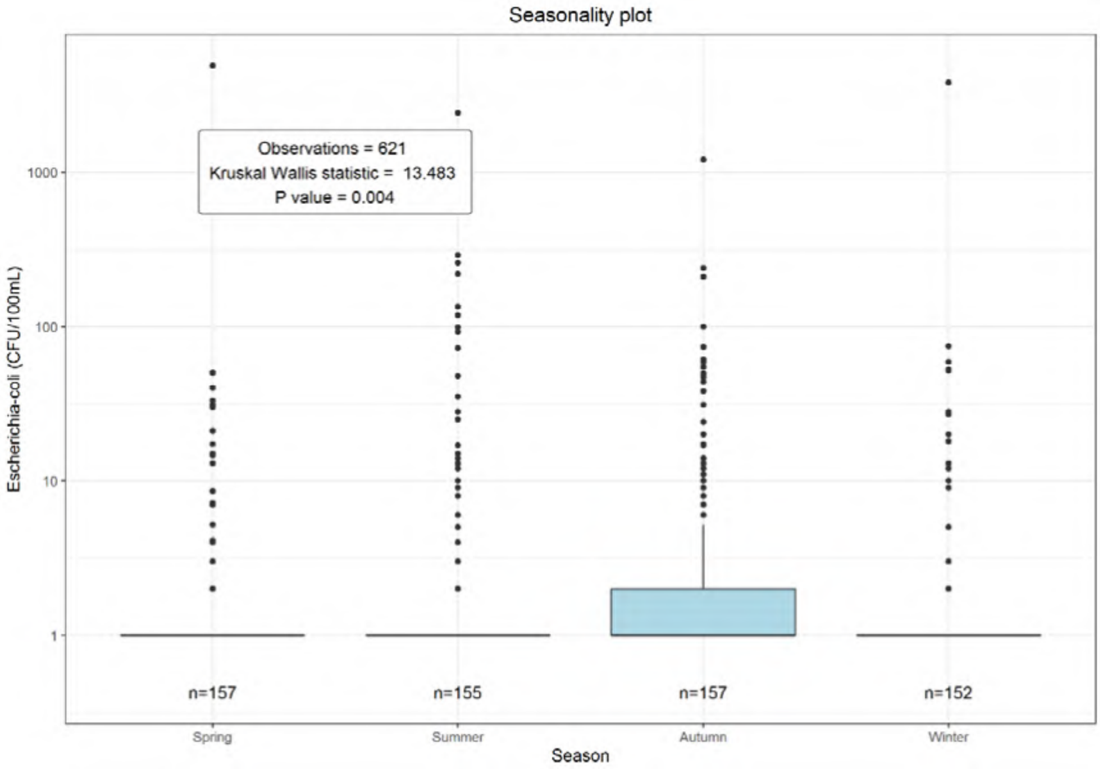


Figure 4A Boxplots showing seasonal differences in groundwater counts of *Escherichia coli* (*E.coli*) based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Table 15A The distribution (expressed as percentiles) of *Escherichia coli* (*E.coli*) counts in groundwater between four seasons. Based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Season	n	% samples with positive counts of *E.coli* (i.e. ≥1 MPN/100 mL)	% samples with elevated counts of *E.coli* (i.e. >1 MPN/100 mL)	10th	25th	median	75th	90th
Spring	157	21.66	14.65	1	1	1	1	4.54
Summer	155	33.55	23.87	1	1	1	1	13.60
Autumn	157	39.49	28.66	1	1	1	2	17.12
Winter	152	19.74	15.13	1	1	1	1	4.80

Table 16A Results of Dunn's tests investigating seasonal differences in groundwater counts of *Escherichia coli* (*E.coli*). Based on data from 32 SEM GQMP bores collected between 01 July 2010 and 30 June 2020

Comparison	Z	*p* unadjusted	*p* adjusted
Autumn - Spring	3.06	0.002	0.013
Autumn - Summer	0.976	0.329	0.658
Spring - Summer	-2.07	0.038	0.154
Autumn - Winter	2.92	0.003	0.017
Spring - Winter	-0.108	0.914	0.914
Summer - Winter	1.95	0.052	0.155

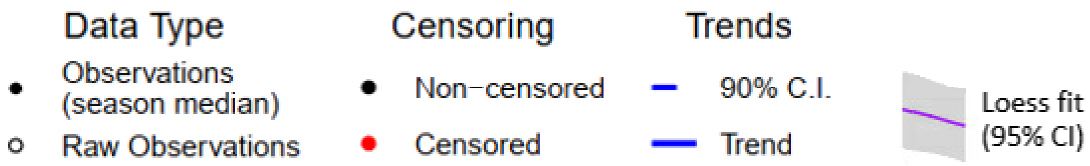
Appendix V

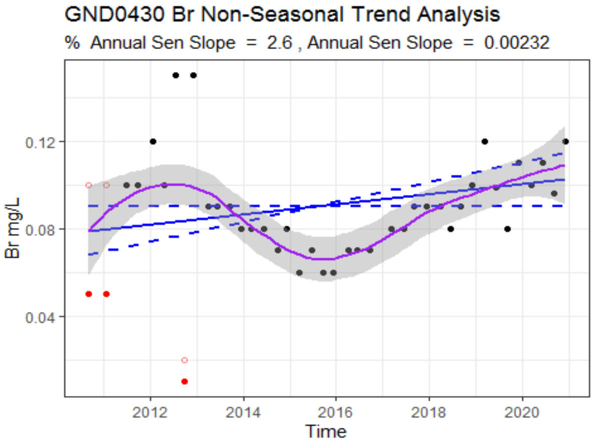
Temporal trend plots for GQMP data

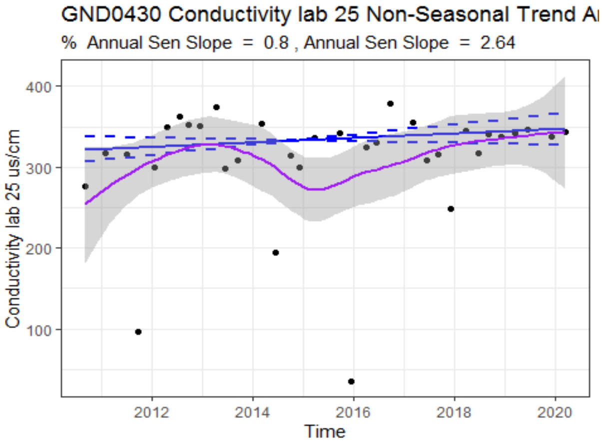
Appendix **Five** – Temporal trend plots for SEM GQMP data

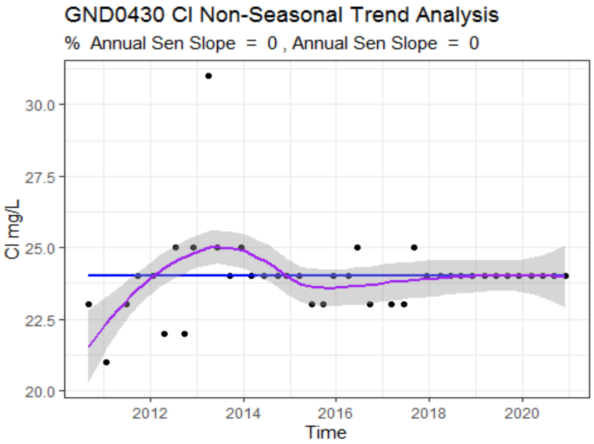
Ten year trend analysis is undertaken on groundwater data collected over the TRC SGWM and NGMP networks when there is 75% data coverage over the last ten years (minimum 30 of 40 samples taken), and when there is less than 70% raw censored data.

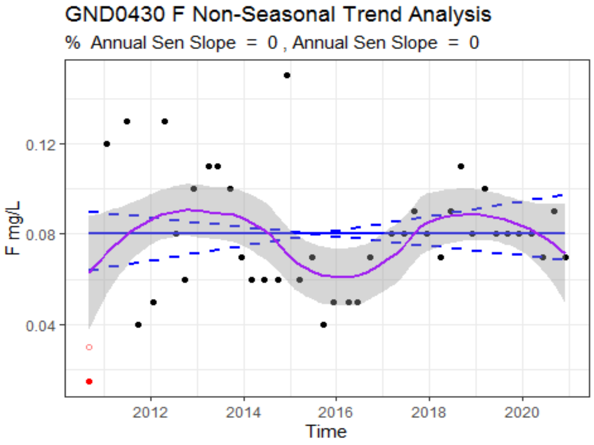
Legend for all plots:





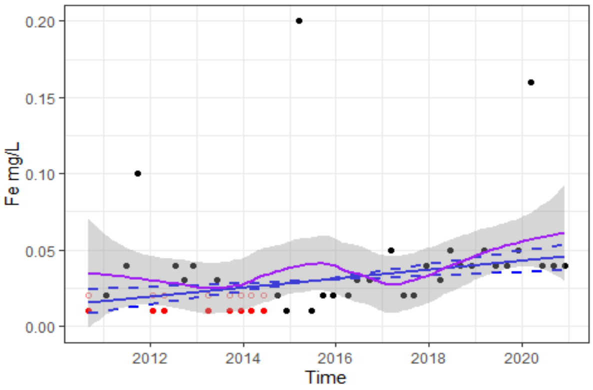






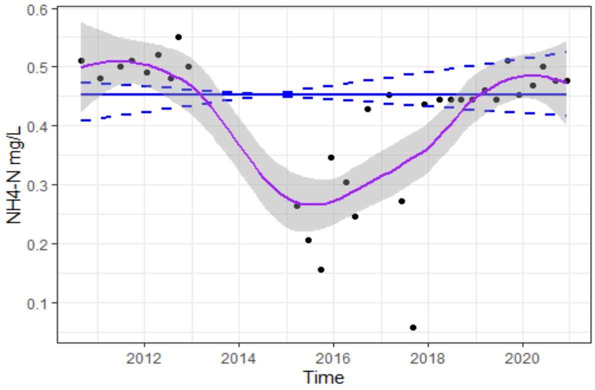
GND0430 Fe Non-Seasonal Trend Analysis

% Annual Sen Slope = 9.9 , Annual Sen Slope = 0.00296



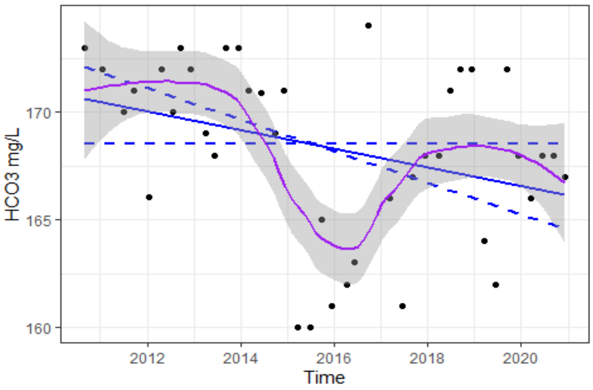
GND0430 NH4-N Non-Seasonal Trend Analysis

% Annual Sen Slope = 0 , Annual Sen Slope = 0



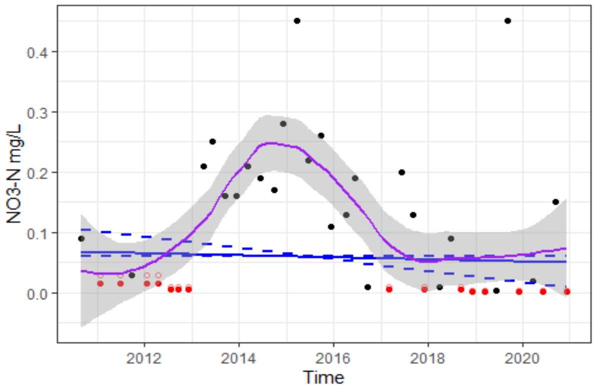
GND0430 HCO3 Seasonal Trend Analysis

% Annual Sen Slope = -0.3 , Annual Sen Slope = -0.432



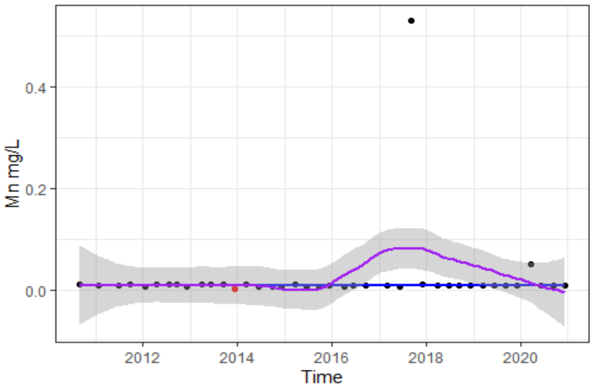
GND0430 NO3-N Non-Seasonal Trend Analysis

% Annual Sen Slope = -2.7 , Annual Sen Slope = -0.00162



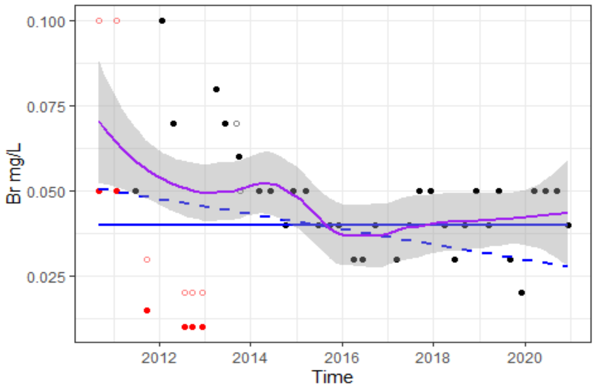
GND0430 Mn Non-Seasonal Trend Analysis

% Annual Sen Slope = 0 , Annual Sen Slope = 0



GND0508 Br Non-Seasonal Trend Analysis

% Annual Sen Slope = 0 , Annual Sen Slope = 0



GND0430 Na Non-Seasonal Trend Analysis

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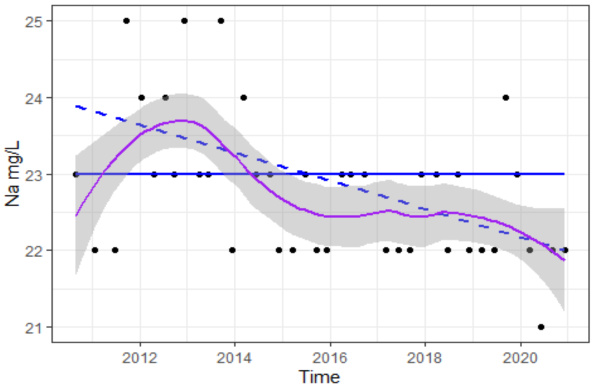
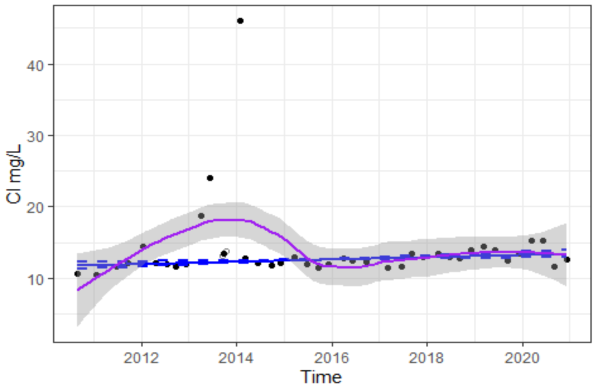


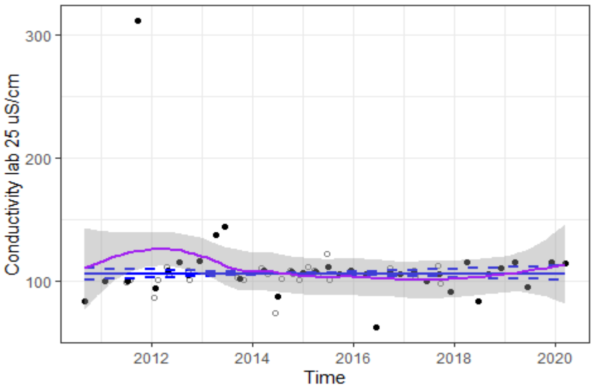
GND0508 Cl Non-Seasonal Trend Analysis

% Annual Sen Slope = 1.3 , Annual Sen Slope = 0.161



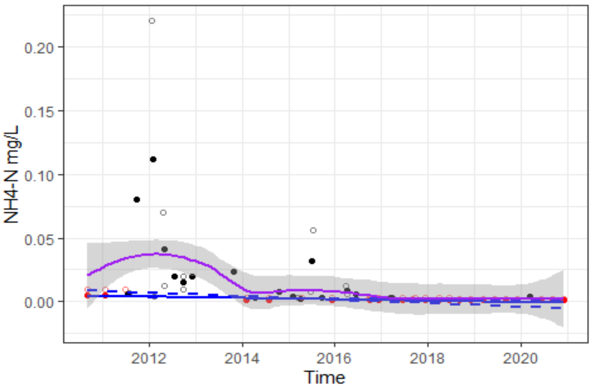
GND0508 Conductivity lab 25 Non-Seasonal Trend A

% Annual Sen Slope = 0 , Annual Sen Slope = 0.0293



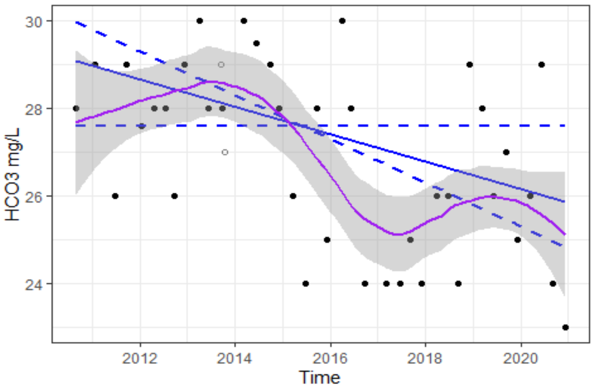
GND0508 NH4-N Non-Seasonal Trend Analysis

% Annual Sen Slope = -19.2 , Annual Sen Slope = -0.000576



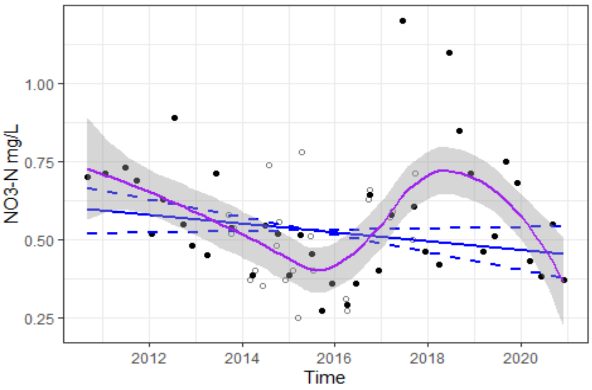
GND0508 HCO3 Non-Seasonal Trend Analysis

% Annual Sen Slope = -1.2 , Annual Sen Slope = -0.316



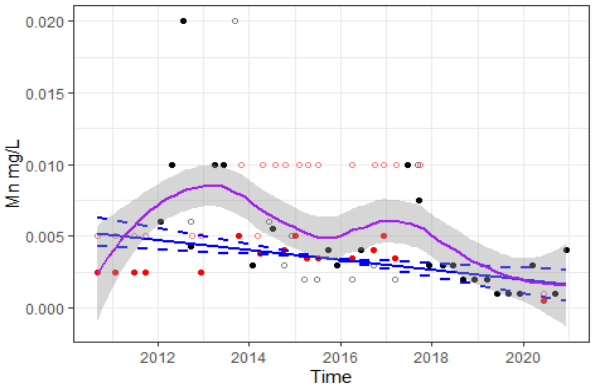
GND0508 NO3-N Non-Seasonal Trend Analysis

% Annual Sen Slope = -2.7 , Annual Sen Slope = -0.0138



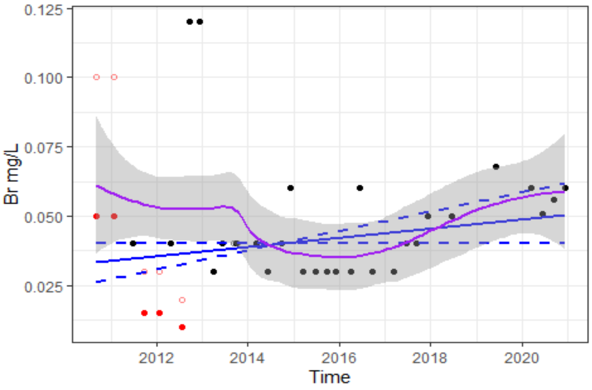
GND0508 Mn Non-Seasonal Trend Analysis

% Annual Sen Slope = -11.5 , Annual Sen Slope = -0.000345



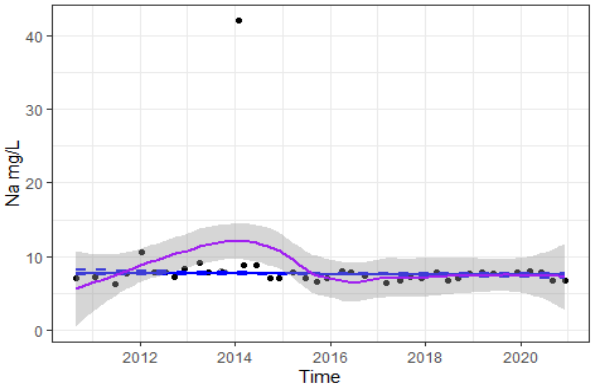
GND0563 Br Non-Seasonal Trend Analysis

% Annual Sen Slope = 4.1 , Annual Sen Slope = 0.00163



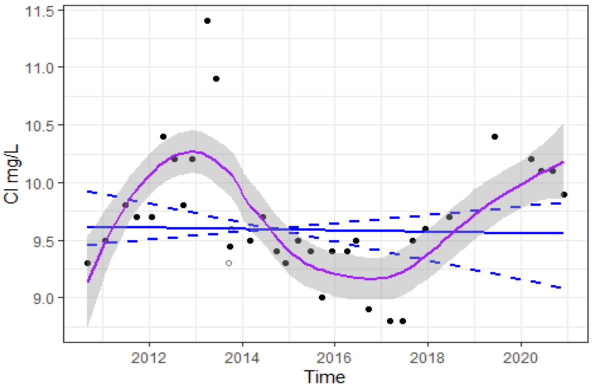
GND0508 Na Non-Seasonal Trend Analysis

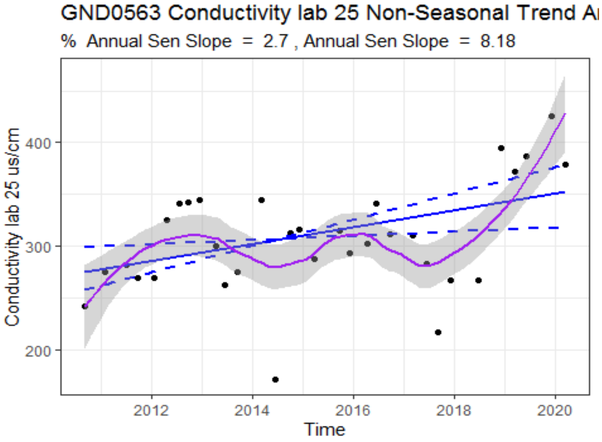
% Annual Sen Slope = -0.4 , Annual Sen Slope = -0.0333



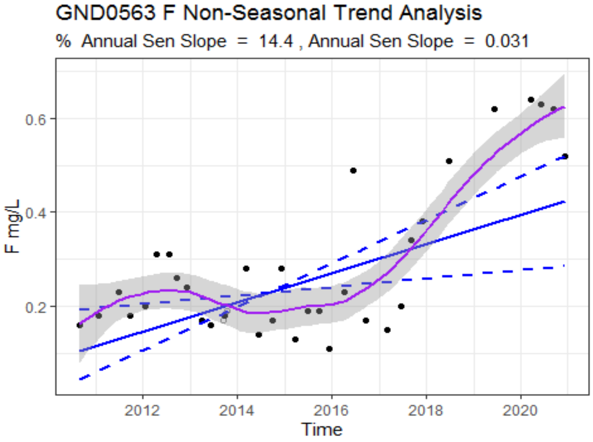
GND0563 Cl Non-Seasonal Trend Analysis

% Annual Sen Slope = -0.1 , Annual Sen Slope = -0.00614

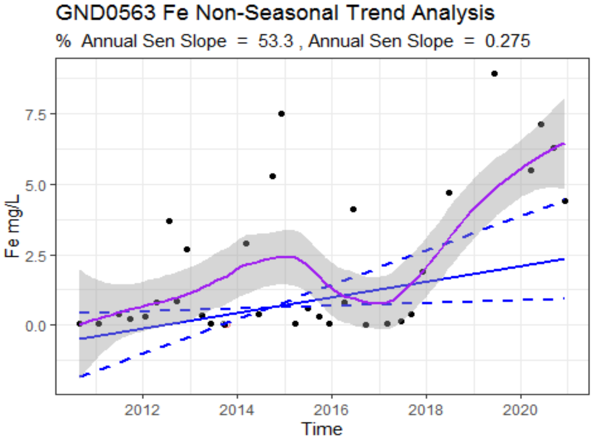



GND0563 Conductivity lab 25 Non-Seasonal Trend A

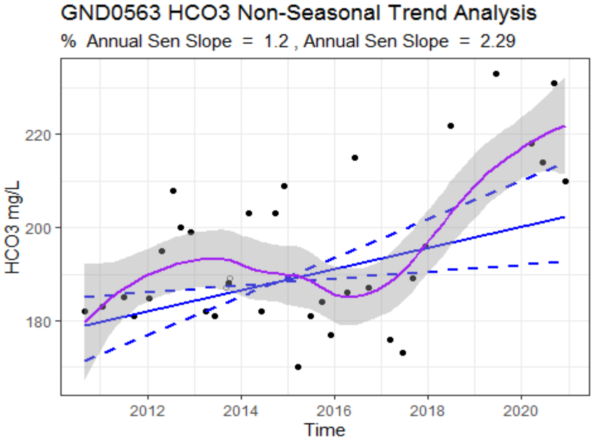
% Annual Sen Slope = 2.7 , Annual Sen Slope = 8.18


GND0563 F Non-Seasonal Trend Analysis

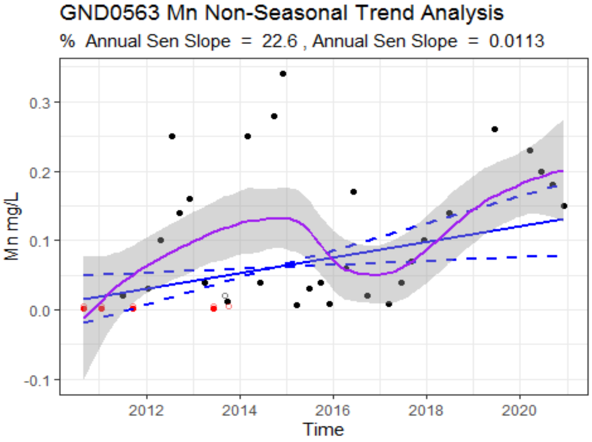
% Annual Sen Slope = 14.4 , Annual Sen Slope = 0.031


GND0563 Fe Non-Seasonal Trend Analysis

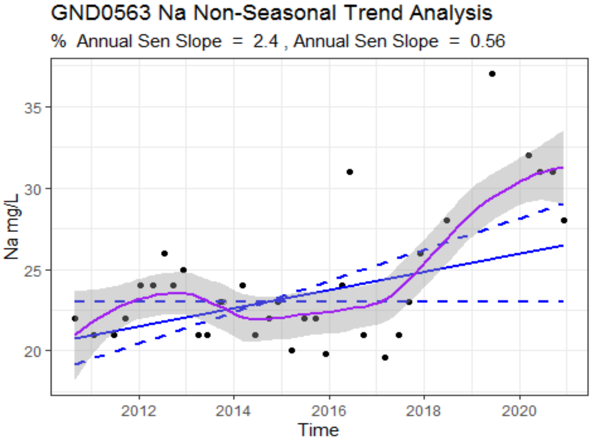
% Annual Sen Slope = 53.3 , Annual Sen Slope = 0.275


GND0563 HCO3 Non-Seasonal Trend Analysis

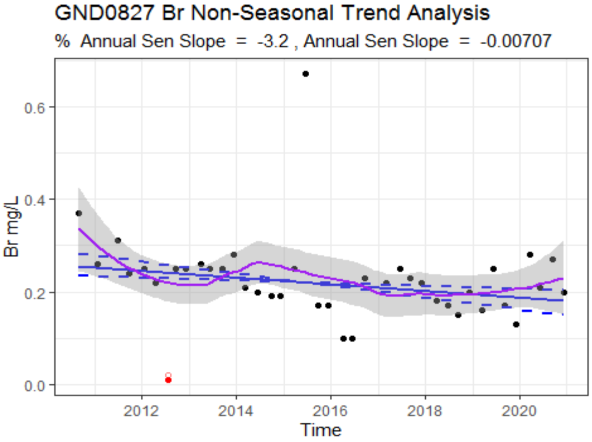
% Annual Sen Slope = 1.2 , Annual Sen Slope = 2.29


GND0563 Mn Non-Seasonal Trend Analysis

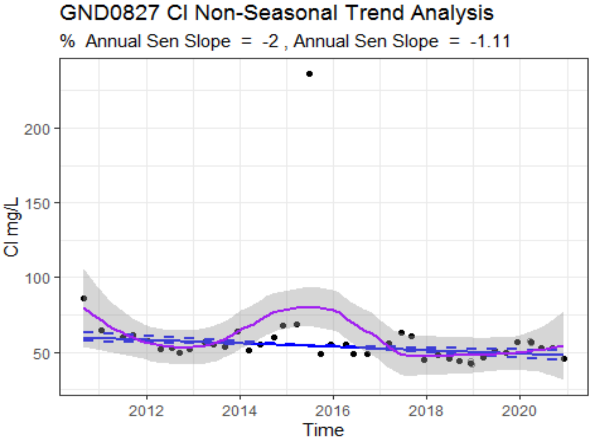
% Annual Sen Slope = 22.6 , Annual Sen Slope = 0.0113


GND0563 Na Non-Seasonal Trend Analysis

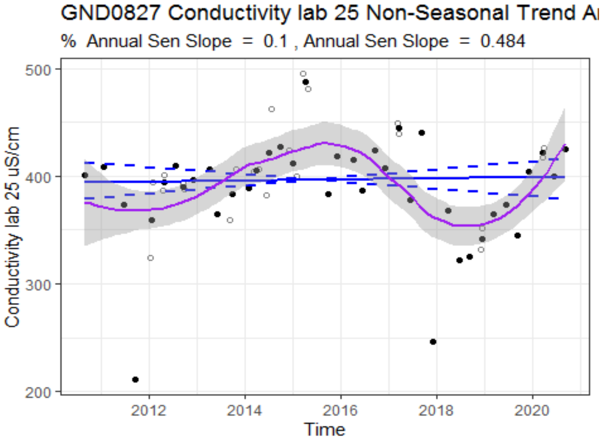
% Annual Sen Slope = 2.4 , Annual Sen Slope = 0.56


GND0827 Br Non-Seasonal Trend Analysis

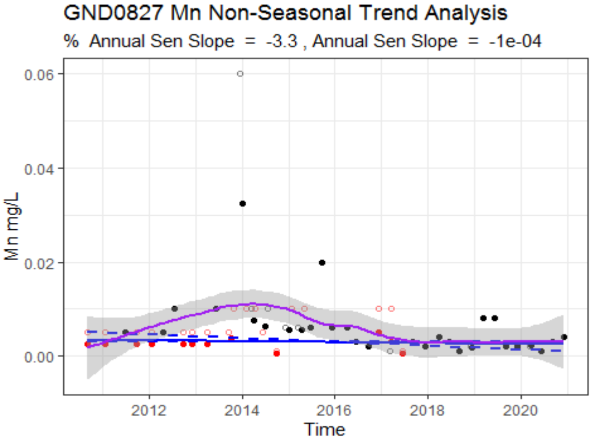
% Annual Sen Slope = -3.2 , Annual Sen Slope = -0.00707


GND0827 Cl Non-Seasonal Trend Analysis

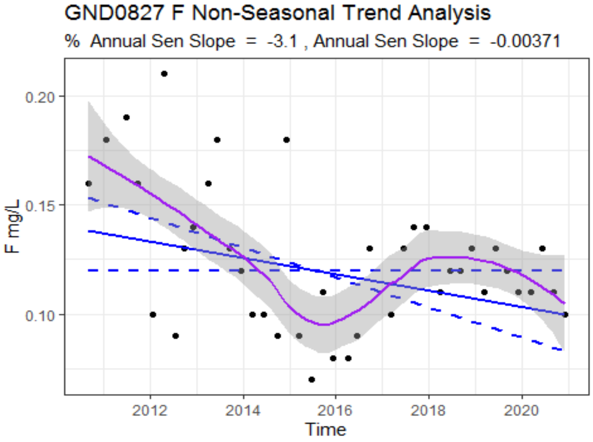
% Annual Sen Slope = -2 , Annual Sen Slope = -1.11


GND0827 Conductivity lab 25 Non-Seasonal Trend A

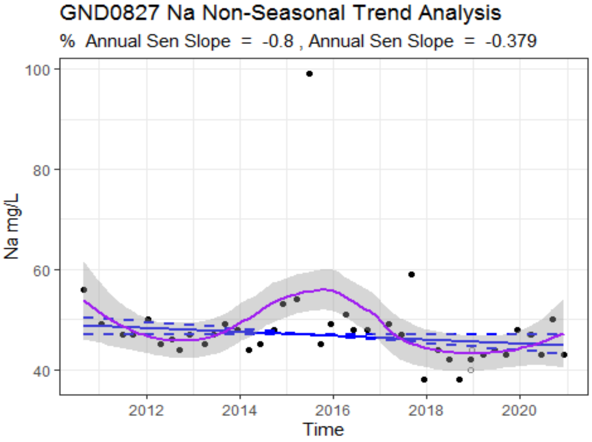
% Annual Sen Slope = 0.1 , Annual Sen Slope = 0.484


GND0827 Mn Non-Seasonal Trend Analysis

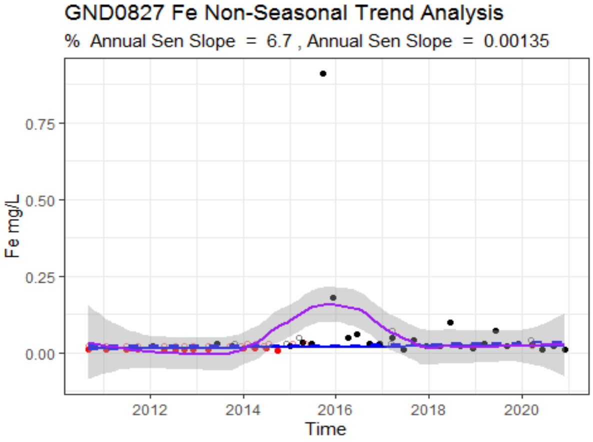
% Annual Sen Slope = -3.3 , Annual Sen Slope = -1e-04


GND0827 F Non-Seasonal Trend Analysis

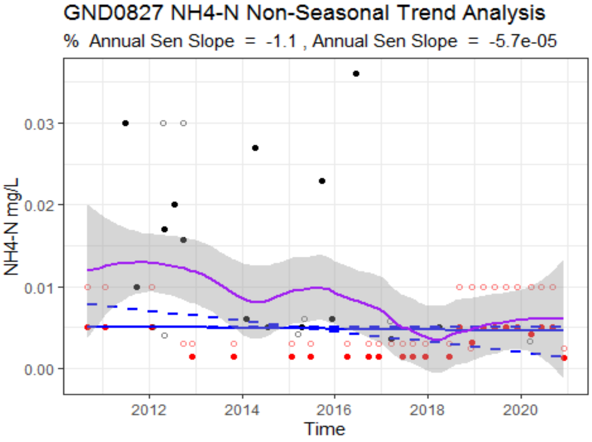
% Annual Sen Slope = -3.1 , Annual Sen Slope = -0.00371


GND0827 Na Non-Seasonal Trend Analysis

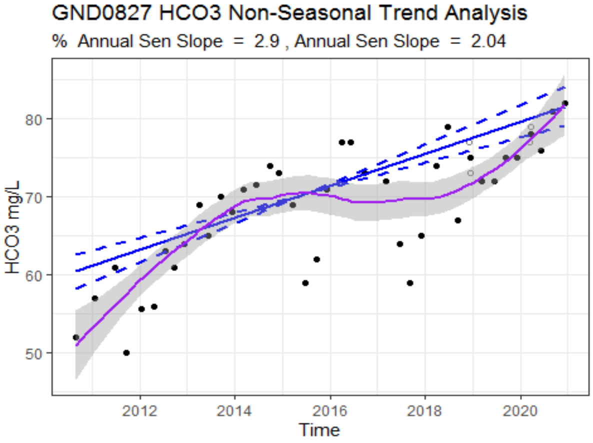
% Annual Sen Slope = -0.8 , Annual Sen Slope = -0.379


GND0827 Fe Non-Seasonal Trend Analysis

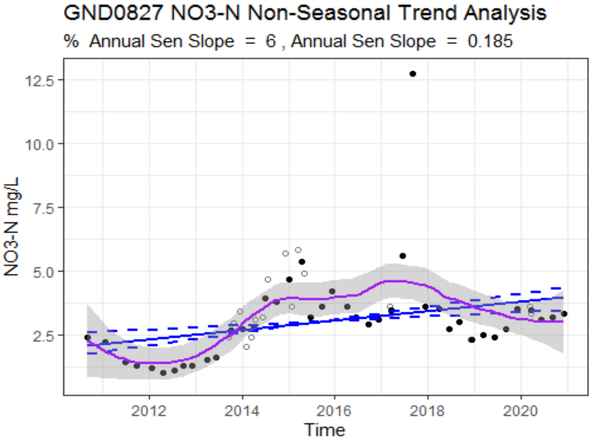
% Annual Sen Slope = 6.7 , Annual Sen Slope = 0.00135


GND0827 NH4-N Non-Seasonal Trend Analysis

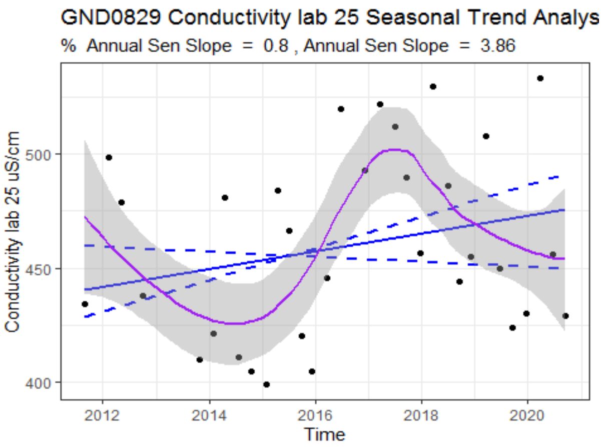
% Annual Sen Slope = -1.1 , Annual Sen Slope = -5.7e-05

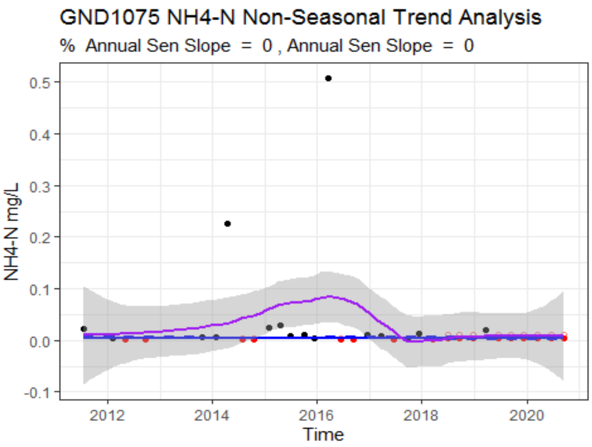

GND0827 HCO3 Non-Seasonal Trend Analysis

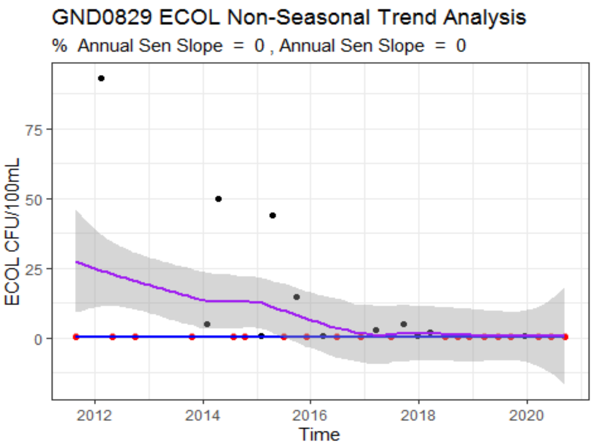
% Annual Sen Slope = 2.9 , Annual Sen Slope = 2.04

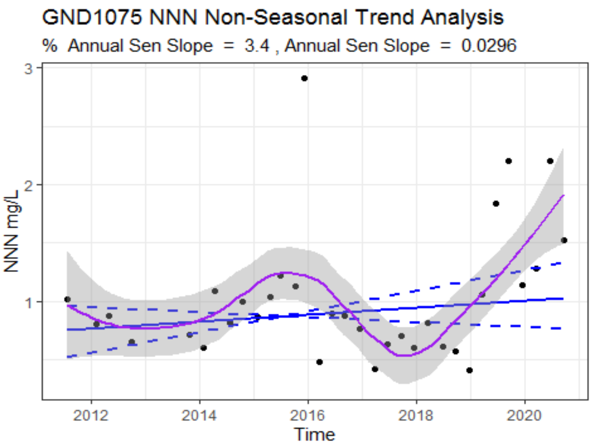

GND0827 NO3-N Non-Seasonal Trend Analysis

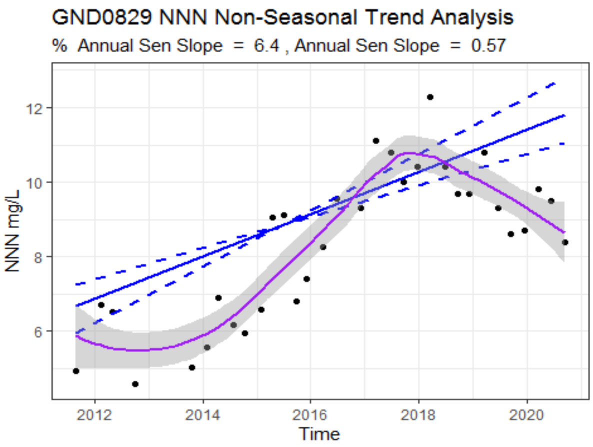
% Annual Sen Slope = 6 , Annual Sen Slope = 0.185

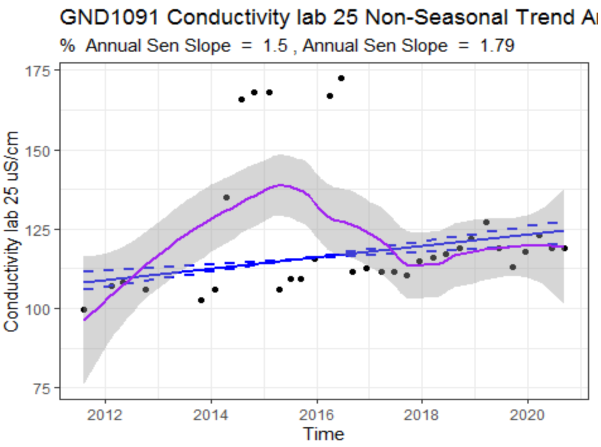

GND0829 Conductivity lab 25 Seasonal Trend Analys
% Annual Sen Slope = 0.8 , Annual Sen Slope = 3.86
Conductivity lab 25 uS/cm
500
450
400
2012
2014
2016
2018
2020
Time

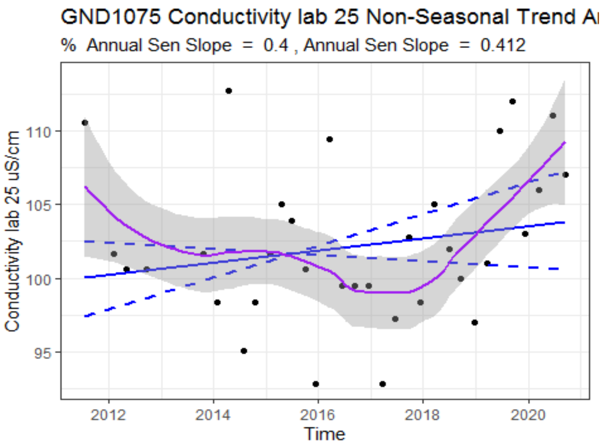

GND1075 NH4-N Non-Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
NH4-N mg/L
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
2012
2014
2016
2018
2020
Time

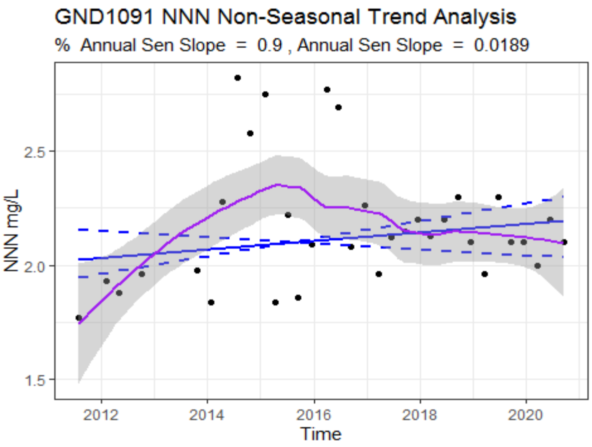

GND0829 ECOL Non-Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
ECOL CFU/100mL
75
50
25
0
2012
2014
2016
2018
2020
Time

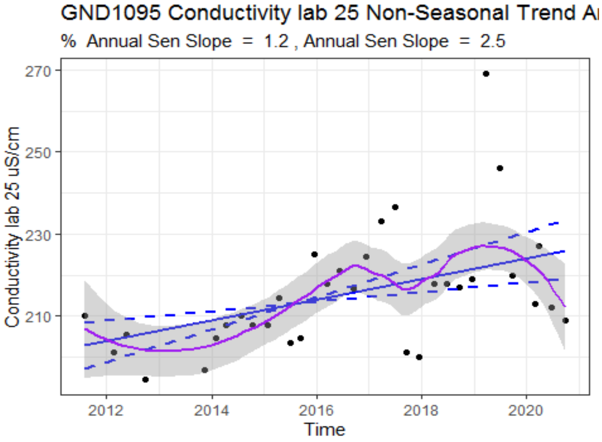

GND1075 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = 3.4 , Annual Sen Slope = 0.0296
NNN mg/L
3
2
1
2012
2014
2016
2018
2020
Time

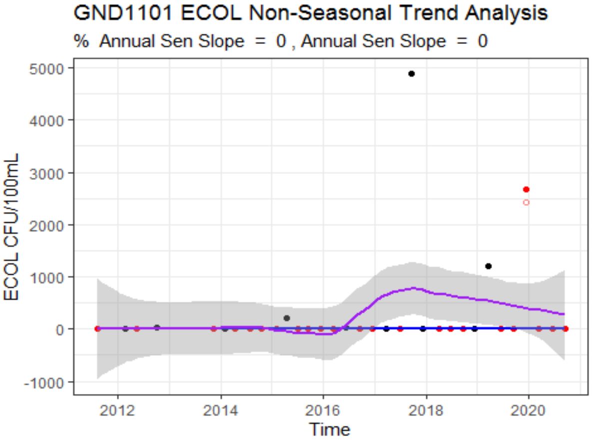

GND0829 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = 6.4 , Annual Sen Slope = 0.57
NNN mg/L
12
10
8
6
2012
2014
2016
2018
2020
Time

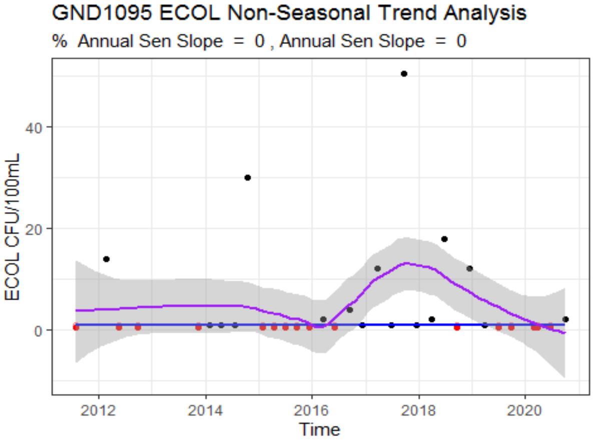

GND1091 Conductivity lab 25 Non-Seasonal Trend A
% Annual Sen Slope = 1.5 , Annual Sen Slope = 1.79
Conductivity lab 25 uS/cm
175
150
125
100
75
2012
2014
2016
2018
2020
Time

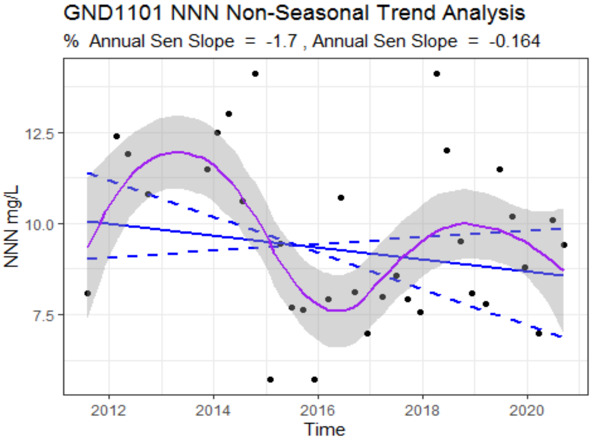

GND1075 Conductivity lab 25 Non-Seasonal Trend A
% Annual Sen Slope = 0.4 , Annual Sen Slope = 0.412
Conductivity lab 25 uS/cm
110
105
100
95
2012
2014
2016
2018
2020
Time

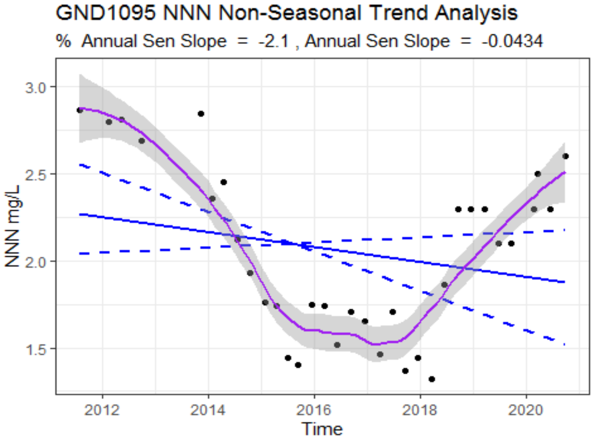

GND1091 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = 0.9 , Annual Sen Slope = 0.0189
NNN mg/L
2.5
2.0
1.5
2012
2014
2016
2018
2020
Time

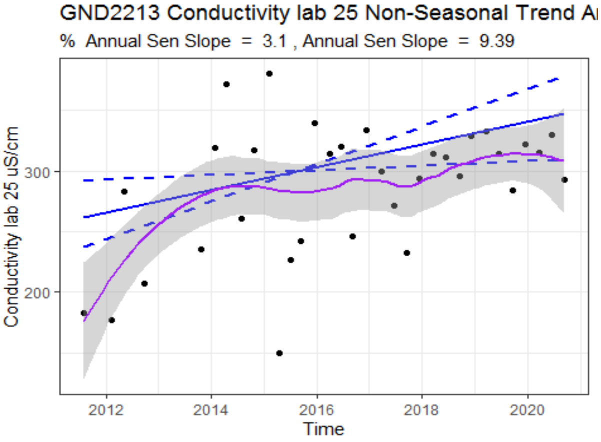

GND1095 Conductivity lab 25 Non-Seasonal Trend A
% Annual Sen Slope = 1.2 , Annual Sen Slope = 2.5
Conductivity lab 25 uS/cm
270
250
230
210
2012
2014
2016
2018
2020
Time

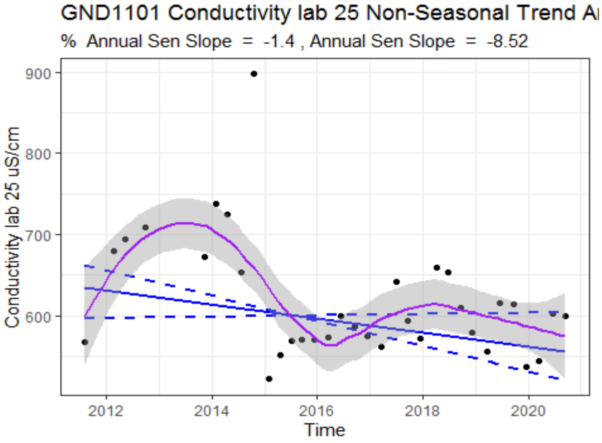

GND1101 ECOL Non-Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
ECOL CFU/100mL
5000
4000
3000
2000
1000
0
-1000
2012
2014
2016
2018
2020
Time

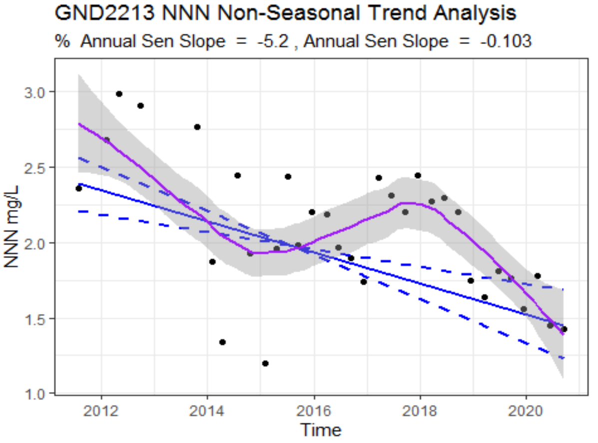

GND1095 ECOL Non-Seasonal Trend Analysis
% Annual Sen Slope = 0 , Annual Sen Slope = 0
ECOL CFU/100mL
40
20
0
2012
2014
2016
2018
2020
Time


GND1101 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = -1.7 , Annual Sen Slope = -0.164
NNN mg/L
12.5
10.0
7.5
2012
2014
2016
2018
2020
Time


GND1095 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = -2.1 , Annual Sen Slope = -0.0434
NNN mg/L
3.0
2.5
2.0
1.5
2012
2014
2016
2018
2020
Time


GND2213 Conductivity lab 25 Non-Seasonal Trend A
% Annual Sen Slope = 3.1 , Annual Sen Slope = 9.39
Conductivity lab 25 uS/cm
300
200
2012
2014
2016
2018
2020
Time


GND1101 Conductivity lab 25 Non-Seasonal Trend A
% Annual Sen Slope = -1.4 , Annual Sen Slope = -8.52
Conductivity lab 25 uS/cm
900
800
700
600
2012
2014
2016
2018
2020
Time


GND2213 NNN Non-Seasonal Trend Analysis
% Annual Sen Slope = -5.2 , Annual Sen Slope = -0.103
NNN mg/L
3.0
2.5
2.0
1.5
1.0
2012
2014
2016
2018
2020
Time