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Regional geothermal geochemistry monitoring programme (REGEMP) 11 Review: 2018 Interpretation of Geochemical Data

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REGEMP II REVIEW

2018 Interpretation of Geochemical Data

for: Waikato Regional Council

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EXECUTIVE SUMMARY

This report is the fourth review of the Regional Geothermal Geochemistry Monitoring Programme (REGEMP), which Waikato Regional Council (WRC) recommenced in 2006 (i.e., REGEMP II). The purpose of REGEMP II is to collate geochemical data from surface geothermal features in the Waikato Region, and assess trends in the data that might assist in best management of the features.

The current review considered four distinct components:

- Data integrity (the current state of the dataset)
- Statistical analysis (similarities and differences between features)
- Spatial analysis (how the chemistry changes by location)
- Temporal analysis (changes over time)

The REGEMP review showed REGEMP II continues to produce valuable data about the region's geothermal features. Based on the results of the review, the following has been recommended:

- Add a site at Soda Springs or Ketetahi (if access rights can be renegotiated) to the next REGEMP monitoring round, or consider searching for an alternative and accessible geothermal feature within the Tongariro area;
- Consider a formal arrangement with GNS Science to collect and share data from features south of Taupo (to reduce sampling costs and travel times);
- Continue to regularly collect regular physicochemical data (especially temperature) from features (at a more frequent rate than more comprehensive sampling occurs;
- Collect isotope data every eight to ten years;
- Investigate potential drivers for variation across parameters (e.g., what, including pH and temperature, are the most likely drivers of variation as represented PC1 and PC2 in the PCA analysis). Such a project may best be actioned as a sponsored research project with a university (e.g., as a Post-Graduate Diploma or MSc topic, or as a summer scholarship);
- Investigate possible reasons for change in the temperature of features at Orakei Korako and Waiotapu, beginning with a physical assessment (e.g., topographical changes, the state of the features etc.), and a review of any third-party monitoring (Contact Energy, iwi etc.); and
- Make data collation the focus of the next REGEMP II review, including making sure any missing data (present in REGEMP spreadsheets) are in the main database, assigning location keys for data that do not have them.

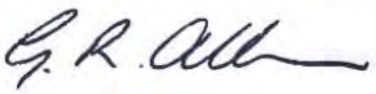
A Shiny app was developed to provide interactive presentation of the results of the REGEMP survey. In addition, a review of laboratory service providers was undertaken to ensure that WRC was receiving the best service available.

ACKNOWLEDGEMENT OF SUBMISSION

This report was prepared by Dr Nathaniel Wilson and reviewed in-house by Dr Grant Allen

Respectfully submitted

Babbage Consultants Ltd



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1 INTRODUCTION

1.1 Background

As part of its State of the Environment monitoring, Waikato Regional Council (WRC) runs a Regional Geothermal Geochemistry Monitoring Programme (REGEMP). The purpose of the REGEMP is to collect and review geochemical data from geothermal features across the Waikato Region. Waikato Regional Council can then use these data to sustainably manage the region's resources.

The programme (REGEMP I) began in 1993 (Huser & Jenkinson 1996), but formal management of the programme did not begin until 2005 (REGEMP II; Luketina 20017). REGEMP II has since had three reviews, with GEOKEM carrying out reviews in 2007 and 2012, and Golder providing a third review in 2013 (Webster-Brown & Brown 2007; 2012, Golder 2013). This 2018 report is the fourth review of REGEMP II.

1.2 Scope of Report

This review follows a similar structure to that used in Golder (2013). The report focuses on:

- A review of the REGEMP II databases
- General statistical analysis
- Spatial trends in the data
- Changes in the chemistry of features over time (temporal trends)
- Recommendations to enhance REGEMP II

As in Golder (2013), we conducted all statistical analyses and developed all the graphics for this report in R (version 3.5.1). The associated scripts are available from Babbage on request.

2 REGEMP DATA

2.1 Data Sources

This iteration of the REGEMP uses data from publicly available sources:

- Data supplied from WRC, and;
- Data from GNS Science

Figure 2-1 presents all the geothermal features in the REGEMP II that WRC has formally assigned location keys.

2.1.1 Waikato Regional Council data

Waikato Regional Council collates the data it collects into a centralised WRC database, but the REGEMP also considers data from other sources. Consequently, WRC currently hold data relevant to the programme in three datasets: the active database (9,819 records), data collated into the format that Webster & Brown (2012) and Golder (2013) used (1,235 records), and a dataset of results that are missing some geographical data (Council defined location keys etc.; 991 records).

Older data (older than 2009) come from a range of sources, including published journals. More recent data come from WRC's ongoing State of the Environment monitoring programme.

There were very few discrepancies between the second and third datasets (14 distinct results), but the current Waikato Regional Council data set was missing a lot of the collated other data (1,039 records). Much of these data were old (>75 years old), some had no monitoring site data (location keys etc.), and/or were for features that are not relevant to the REGEMP II programme, such as data from the Waikato River, or from the Emerald lakes system in Tongariro (refer Golder 2013).

This review used a compilation of all three datasets, along with data for isotopes that Waikato Regional Council that WRC was adding to its main database. The master data set had more than 10,000 records.

2.1.2 GNS Sciences data

GNS Science collects data from Waikato geothermal systems as part of its national volcano monitoring programme. These data are available from http://ggw.gns.cri.nz/ggwdata/. All these data are already included in the WRC data set (e.g., data for Soda Springs and Ketetahi).

2.2 Data Coverage

Golder (2013) used data from the WRC database up to mid-2013. Since then Waikato Regional Council has collected and analysed samples from 116 features in 22 systems (Table 2-1), all collected from 2014 onwards. Figure 2-1 shows the spread of recent and historical data for the REGEMP.

Systems sampled for the first time since 2009 include Kāwhia, Rotokawa, Te Kopia, and Whangairorohea. Systems sampled between 2010 and mid-2013, for which there are no new data include Ohinewai, Hamilton, Waikato River, Wairakei, and Soda Springs. There are no new WRC data for any systems in the Tongariro area. The owners of the springs at Ketetahi no longer allow WRC (or GNS Science) access to any of the system's features.

Table 2-1. Systems sampled for the REGEMP II between July 2013 – June 2018.

Area	System	Feature(s)	Year(s)
North Waikato	Coromandel	4	2018
	Kaiaua	4	2015
	Kāwhia	1	2017
	Matamata	5	2014-2018
	Miranda	1	2018
	Ngatea	2	2018
	Okauia	5	2014-2018
	Te Aroha	10	2014-2018
	Te Maire (Naike)	1	2014-2018
	Waingaro	1	2018
Taupo Volcanic Zone (TVZ)	Atiamuri	7	2015-2018
	Horohoro	1	2015
	Mokai	2	2018
	Ngatamariki	4	2014-2018
	Orakei-Korako	15	2014-2018
	Reporoa	11	2015-2018
	Rotokawa	2	2015-2018
	Taupō-Tauhara	10	2014-2018
	Te Kopia	5	2015-2017
	Waikite	7	2014-2018
	Wai-O-Tapu	17	2014-2018
	Whangairorohea	1	2014-2018

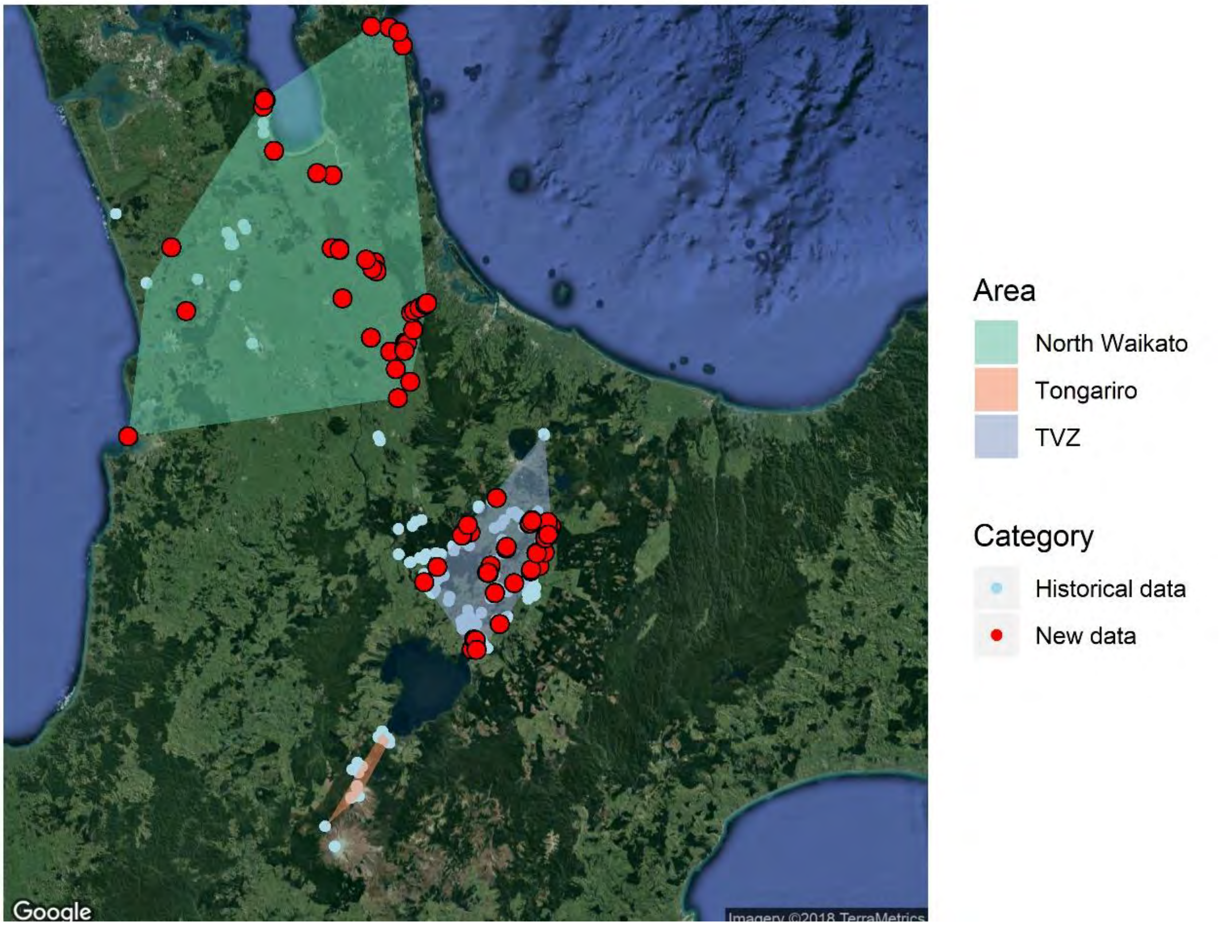

Figure 2-1 Recent (data since mid-2013) and historical REGEMP sites (no data since mid-2013)

2.3 Data Selection

The master dataset is large, but most of the individual records had relatively few data associated with them, such as temperature and/or pH data only. Furthermore, some data in the collated dataset came from non-geothermal features, or was marked to be excluded.

To prune the data, particularly for the purposes of statistical and spatial analysis, we only considered records that had data for the geothermally relevant parameters outlined in Table 2-2. When restricted to records with at least one of these parameters (excluding temperature and pH), the master dataset decreased to 3,958 records. When restricted to records that had all these parameters, the dataset decreased to 172 records, and was limited to data from July 2009 onwards.

Unless explicitly stated in the database, concentrations were assumed to be measured in the dissolved phase. Data marked as "totals" were excluded.

Table 2-2. Parameters used in this review

Parameter	Symbol
Physico-chemical parameters	
Temperature	-
pH	-
Major elements and ions	
Ammonium	NH_4^+
Bicarbonate	HCO_3^-
Boron	B
Calcium	Ca
Chloride	Cl
Fluoride	F
Magnesium	Mg
Potassium	K
Silica	SiO_2
Sodium	Na
Sulphate	SO_4^-
Sulphide	S^{2-}
Trace elements (metals and metalloids)	
Aluminium	Al
Antimony	Sb
Arsenic	As
Bromide	Br
Caesium	Cs
Iron	Fe
Lithium	Li
Mercury	Hg
Rubidium	Rb
Thallium	Tl

3 GENERAL STATISTICAL ANALYSIS

3.1 Approach

As discussed in Section 2, there were 172 records which had results for all the parameters considered in this review. In Golder (2013) there were 96 complete records, so there is twice as much data to work with in 2018.

As in Golder (2013), before any spatial or temporal trends were reviewed, we used more general statistical methods to analyse the data. We used hierarchal cluster analysis (HCA) to determine the relative "uniqueness" of the systems that Waikato Regional Council monitors, and principal component analysis (PCA) to assess what parameters cluster together.

3.2 Hierarchical Cluster Analysis

3.2.1 Introduction

Hierarchal cluster analysis collates data into groups based on their similarity. In this case, the model calculates "similarity" as the variance between observations measured for each sample.

To carry out HCA on the REGEMP II data, we scaled the data (to allow for differences in concentration ranges between parameters), grouped the 172 complete data records by system and calculated the means for each system. If we had not taken the means, the HCA would have been by record, with 172 "branches" to consider.

3.2.2 Results

Figure 3-1 presents the results of the hierarchical clustering in a dendrogram. Tokaanu, the only Tongariro system that had full records, is in orange, Taupo Volcanic Zone (TVZ) sites are in blue, and North Waikato sites are green.

The dendrogram shows how the data branch. Data on each branch are distinct from data on other branches, and sub-branches of data have more in common with each other than they do with data on other branches. The height of the branch indicates the degree of distinction (and is relative to overall variance).

In Golder (2013), Kāwhia was the most "unique" system, mostly likely because of seawater influences (the spring is only accessible at low tide). In this review, which considers three more parameters (aluminium, mercury and sulphide), Tokaanu, in the Tongariro area, is the most distinct, followed by Kāwhia and Te Aroha (both in the North Waikato area).

More generally, North Waikato systems are distinct from systems in the TVZ, but there is also evidence for as much variance between systems in these areas as there is between areas, as demonstrated by the Ngatea/Whangairorohea sub-branch and the Atiamuri/Te Maire sub-branch.

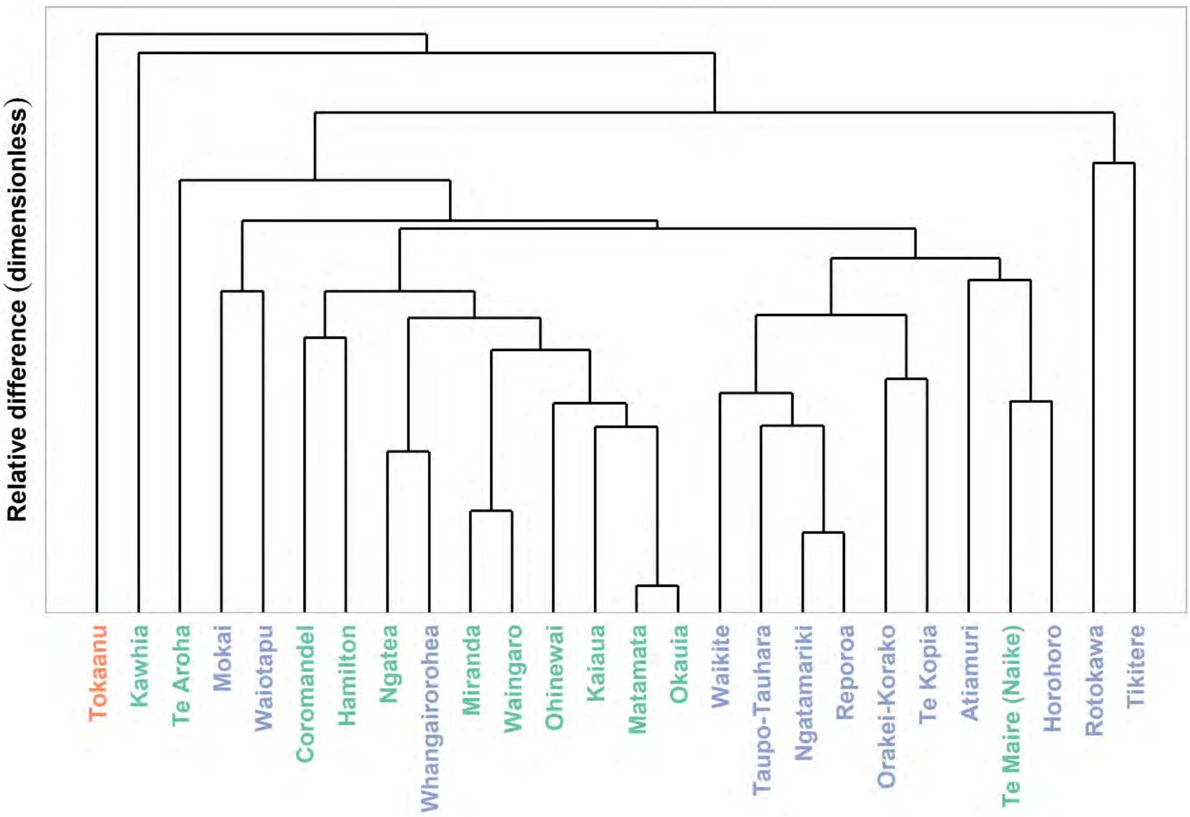

Figure 3-1 Dendrogram for the HCA of the REGEMP II data (coloured by area)

3.2.3 Importance

The relative distinctiveness of Tokaanu (Tongariro) and Kāwhia (marine influenced) illustrates how important it is for Waikato Regional Council to keep sampling these systems. In the absence of data from any other Tongariro system (e.g., Soda Springs or Waihi) continued data from Tokaanu is critical to Waikato Regional Council's management of its Tongariro features.

3.3 Principal Component Analysis

3.3.1 Introduction

PCA is a technique that clusters sets of potentially correlated data into sets of linearly uncorrelated variables. These new sets are called principal components (PCs), and are ordered by the amount of variance each component can explain (PC1 explains the most amount of variance, PC2 explains the next most amount of variance etc).

The use of PCA for the analysis of geochemical data is widespread (Loska & Wiechula, 2003). To account for differences in magnitude between parameters (major ions in mg/L compared to trace elements in µg/L), the results were scaled to standardise the variance.

PCA of the REGEMP II data omitted physicochemical data (temperature and pH). Temperature and pH control geochemical composition, and so it is not appropriate to include them.

3.3.2 Results

The PCA for the 172 records indicated that a single component (PC1) could explain 33 % of the variance, and 78 % of the variance could be explained by five components (PC1 through PC5) of a possible 22 (PC1 through PC22); Figure 3-2a). As Figure 3-2a shows, the steep decreases in the amount of variation each component explains increases suggests the method is appropriate for the data. PCA is not appropriate when the explanation-of-variance is similar across components.

The data across PC1 and PC2, shown in Figure 3-2b, shows there are clear distinctions between geographic areas, and that the parameters group into five clusters. Table 3-1 defines these clusters, and how the results compared to the results from Golder (2013).

Table 3-1. Clusters of elements, as defined using PCA (common parameters in bold)

Cluster	Association	Parameter(s)	Golder 2013 results
Cluster 1	Positive (PC1 dominant)	B, HCO_3, SO_4	NH_4, B, K
Cluster 2	Negative (PC1 dominant)	Fe	HCO_3
Cluster 3	Positive (PC2 dominant)	Mg, Ca	Mg, Ca, Fe, SO_4
Cluster 4	PC1 & PC2 positive	Na, Br, Cl, K	Na, Br, Cl
Cluster 5	PC1 positive and PC2 negative	As, Sb, Cs, Li, Rb, Tl, Al, F, Hg, NH_4, S_2, Si	As, Sb, Cs, Li, Rb, Tl
Cluster 6	Negative (PC2 dominant)	-	F, Si

The results of the PCA are different from those in Golder (2013). These differences are likely because:

a) This new analysis has more data; and
b) This new analysis can consider more parameters.

The new data set had 172 records, twice as many as Golder (2013) could use. With more data, outliers have less influence, and given the relatively small size of the current data set (172 records over 23 parameters), further changes may occur as Waikato Regional Council collects more data. The ability to include more parameters in this review (aluminium, mercury, sulphide) means the whole pattern of variance changes.

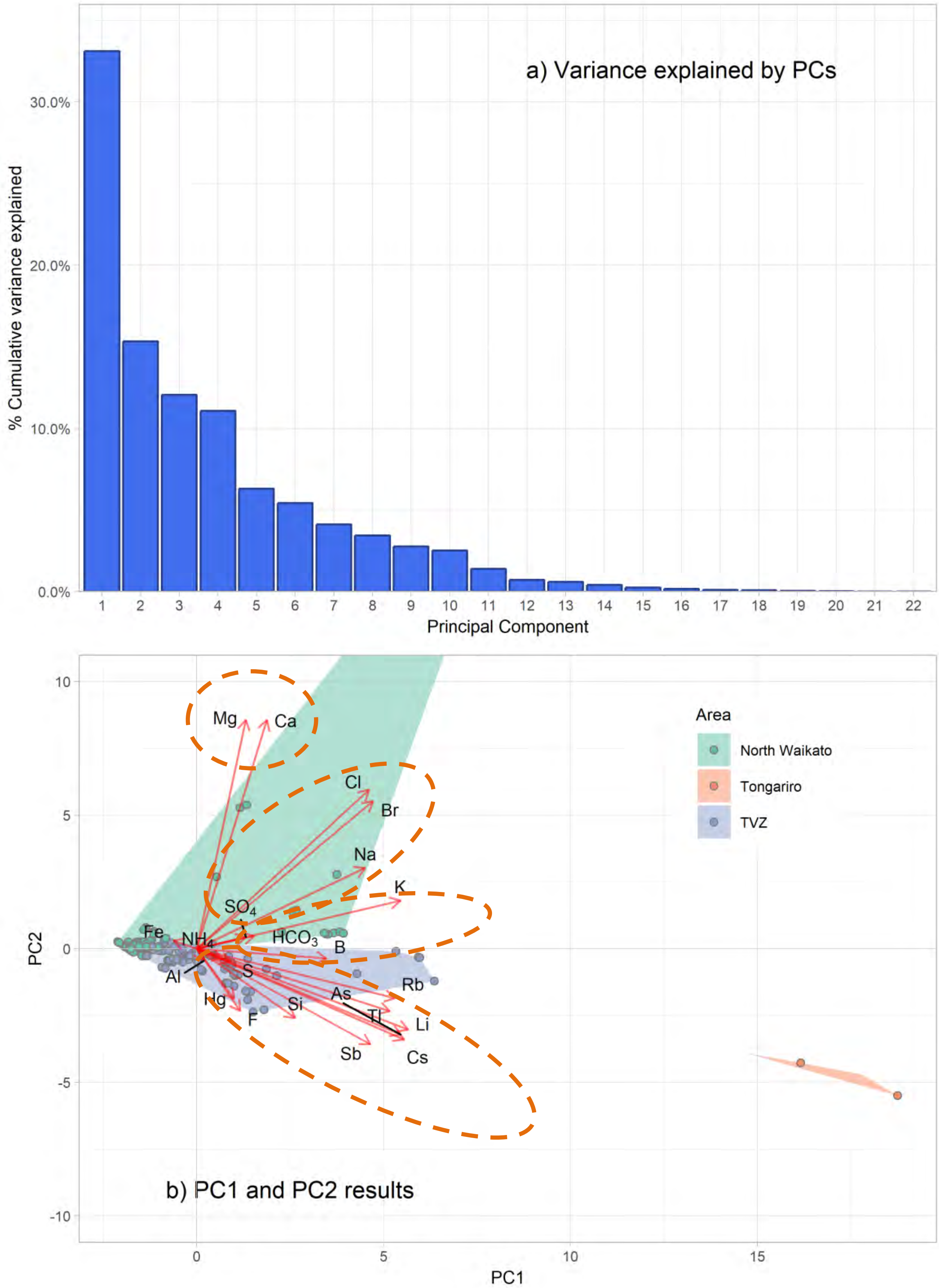

Figure 3-2 PCA results. a) Variance explained; b) Biplot of results for first two components

With more data and more parameters, the key changes from Golder (2013) are:

- Data are in five clusters (not six)
- The principal components that explain the variance differ to what was proposed in Golder (2013), with noticeable changes in clustering of iron, bicarbonate, ammoniacal nitrogen, fluoride, sulphate, and silica
- A much larger cluster of parameters (12 of 22) positively associate with the first principal component (PC1) and negatively associate with the second principal component (PC2); and
- No parameters that have a negative association with PC2 and no association with PC1

Potential explanatory values include temperature, pH, the types of feature in each system (e.g., shallow-source features tend to show different chemistry to deeper-sourced features) and other hydrogeological considerations. pH, for example, correlates negatively with iron, so pH could contribute to PC2. An investigation into the key influences requires in-depth study (refer Section 6), and is outside the scope of the review.

3.3.3 Importance

The results of the PCA indicate that there are two explanatory factors (PC1 and PC2) that can explain close to 50 % of the variance shown in the 172 records used in the analysis. For this report, the principal outcome is that it is reasonable to use "sentinel" parameters as proxies for each cluster. Therefore, for the consideration of spatial and temporal analyses, this review will focus on:

- Boron (Cluster 1)
- Iron (Cluster 2)
- Magnesium (Cluster 3)
- Chloride (Cluster 4)
- Arsenic (Cluster 5)

3.4 Key points

The key points from general statistical analysis are:

- Tokaanu and Kāwhia are the most distinct systems, Tokaanu being the only systems regularly sampled in the Tongariro area and Kāwhia likely most affected by seawater intrusion;
- Given no sites in Tongariro have been sampled since 2013, and the distinctiveness of Tokaanu, more features in this area should be added to the REGEMP
- If features need to be dropped to enable sampling in Tongariro, Okauia or Matamata are the best candidates
- With more data, parameters group into five clusters, with many parameters (12 of 22) positively correlating with PC1 and negatively with PC2

4 SPATIAL TRENDS

4.1 Approach

This review follows the approach used in Golder (2013), presenting the data on a map, but presents the data on a feature-level scale instead of a system-level scale. Commentary remains at a high-level, and focuses on general spatial distributions.

4.2 Results

4.2.1 Physiochemistry: Temperature

In general, the TVZ has hotter surface features than in North Waikato, with a spring at Te Aroha (Mokena), which has a deep source, being the exception (Figure 4-1). The feature at Tokaanu (in the Tongariro area) was also a relatively hot feature. These results reflect the much more active geothermal processes occurring within the TVZ and south to Tongariro than occur further north, and are consistent with the results presented in Golder (2013).

Spatial trend: Highest in the south and south-east. Coolest to the north and north-west.

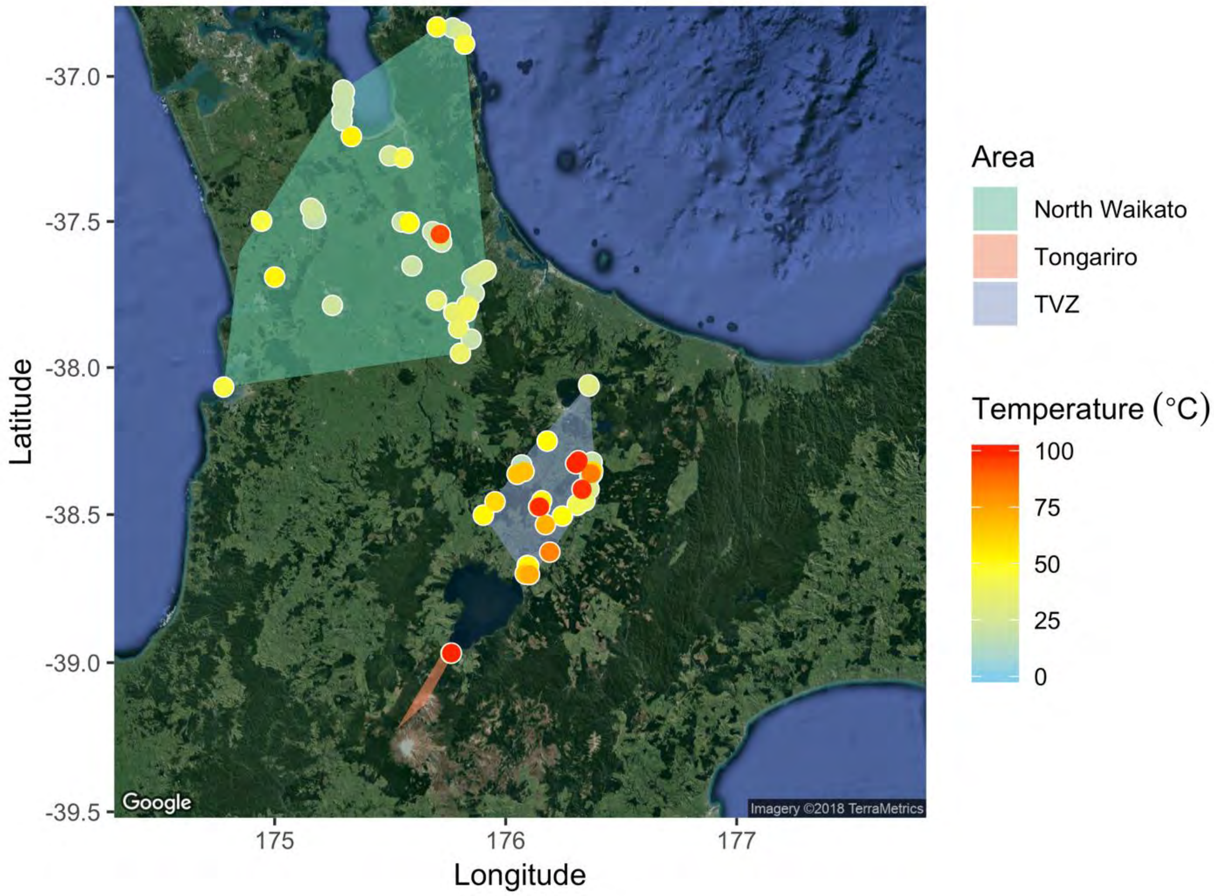

Figure 4-1 Temperature data for features currently monitored in REGEMP II

4.2.2 Physicochemistry: pH

The results for pH show that most alkaline features occur in the North Waikato area, and acidic systems are confined to the TVZ (Figure 4-2). As discussed in Golder (2013), non-geothermal influences (high pH greywacke-sourced groundwater) are the most likely driver of the alkaline features in the North Waikato. The more neutral pH values observed along the coastal fringes are likely an effect of seawater intrusion.

The acidic pH features are associated with shallow geothermal interactions, in which meteoric water (rain etc.) heats up and enhances oxidation of surface minerals, leading to acid formation and high sulphate concentrations. Features in the TVZ with neutral or alkaline pH have deeper sources of geothermal water, but surface pools or ponds can be acid (even with an alkaline source). At the surface, oxidation processes (such as the conversion of sulphide compounds (H_2S etc) to sulphate (SO_4), and degassing (loss of CO_2 etc.) cause acidification.

Spatial trend: Alkaline to the northwest, acidic features more common to the south-east.

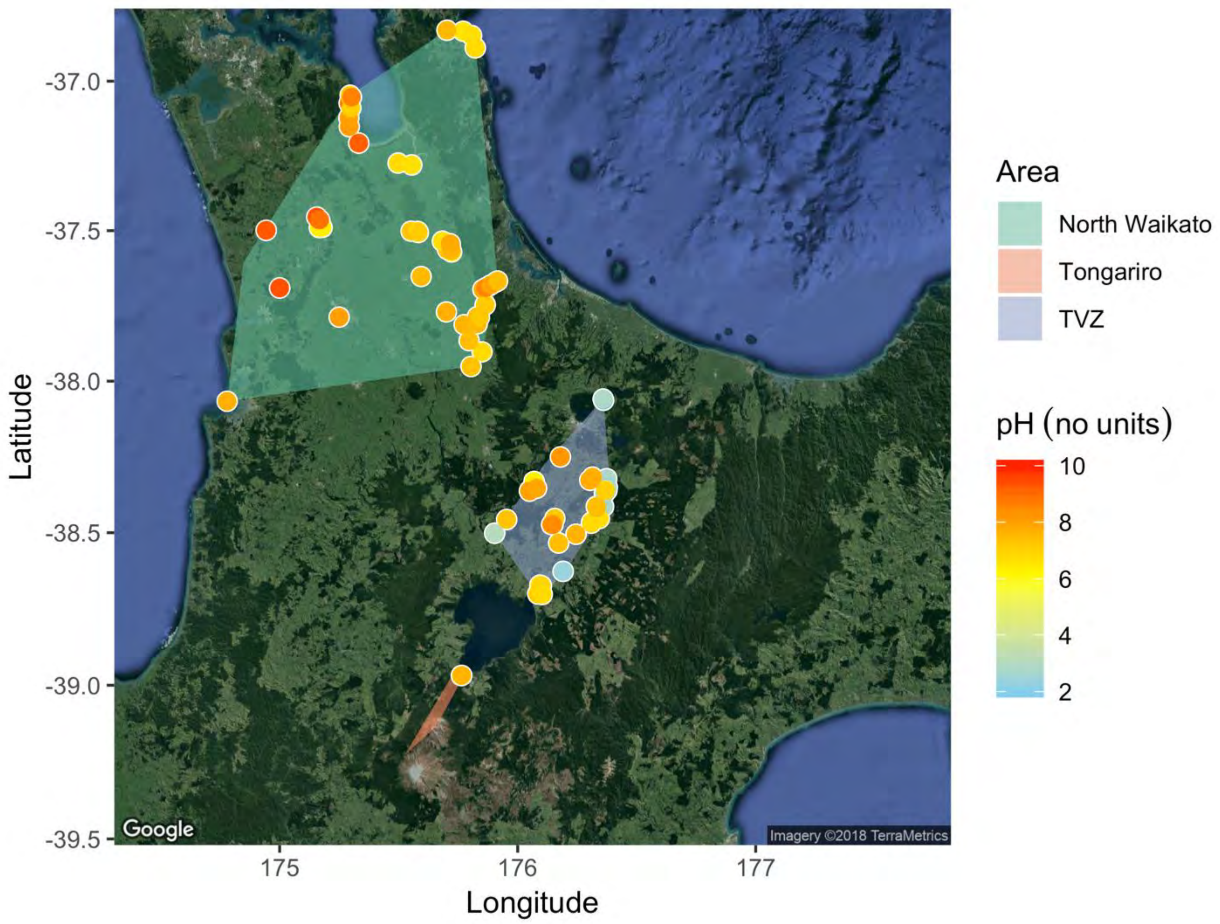

Figure 4-2 pH data for features currently monitored in REGEMP II

4.2.3 Cluster One: Boron

Boron's spatial distribution is less clear than observed for temperature or pH. As B was distinct in that PC2 did not influence its variance (only PC1), these results indicate that PC1 is unlikely to be temperature or pH alone. Non-geothermal influences, such as greywacke derived groundwater or seawater may be an influence, but geothermal source is likely also important, with Mokena at Te Aroha (with magmatic influences) being the feature with the highest B concentrations.

Boron was not considered in Golder (2013).

Spatial trend: Variable, with no clear spatial distinctions.

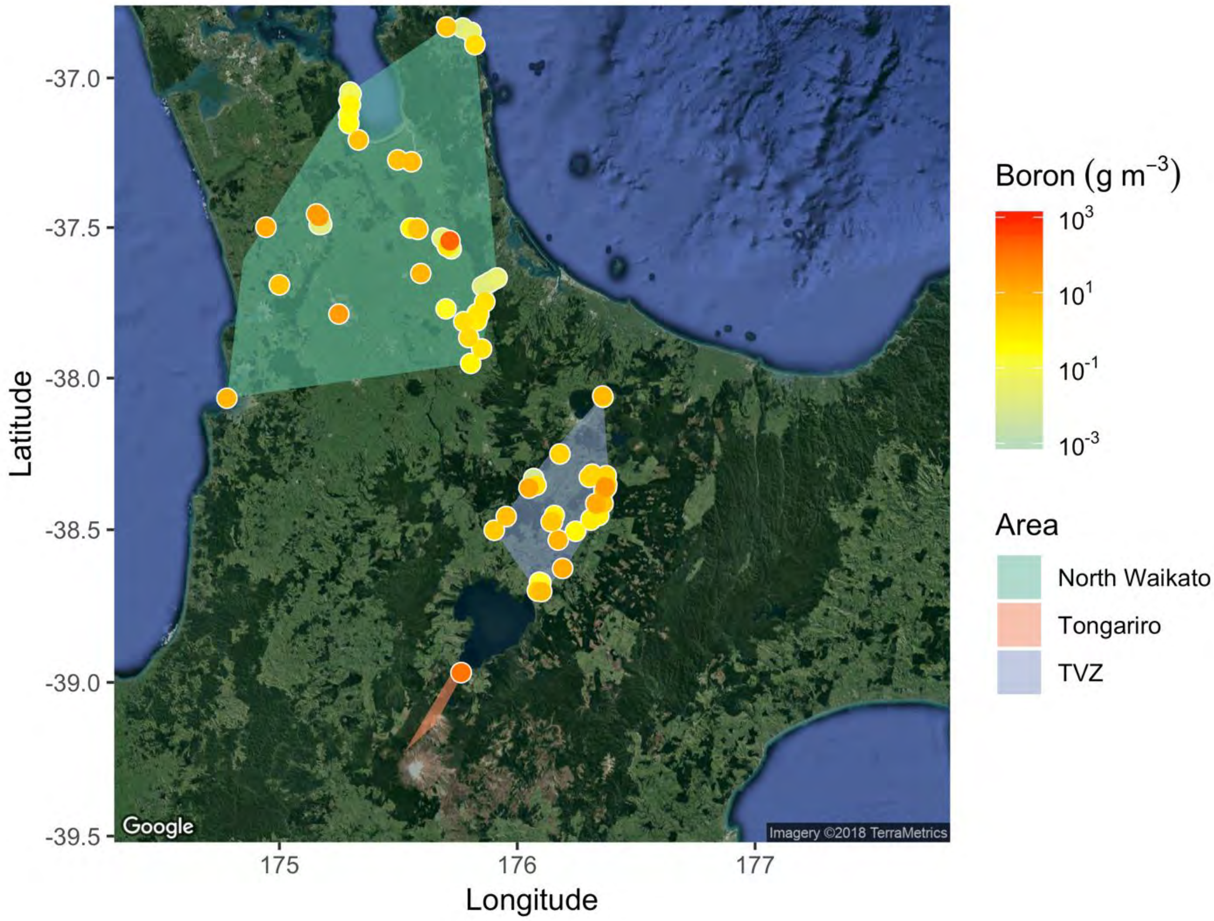

Figure 4-3 Boron data for features currently monitored in REGEMP II

4.2.4 Cluster Two: Iron

The broad trend for iron, as shown in Figure 4-4, is for an inverse relationship with pH, consistent with Golder (2013). At an individual level, there are exceptions, such as for some features around Te Aroha (a different feature from the deep magmatic sourced Mokena spring). Iron is only soluble at higher pH values in reducing conditions (no oxygen), and the highest concentrations were notable for individual features with the lowest pH in a given system.

These exceptions were not highlighted in Golder (2013), because the focus was on systems, not features. These results demonstrate the variable nature of geothermal features, even within localised geographic areas.

Spatial trend: Typically low across the region, with localised exceptions.

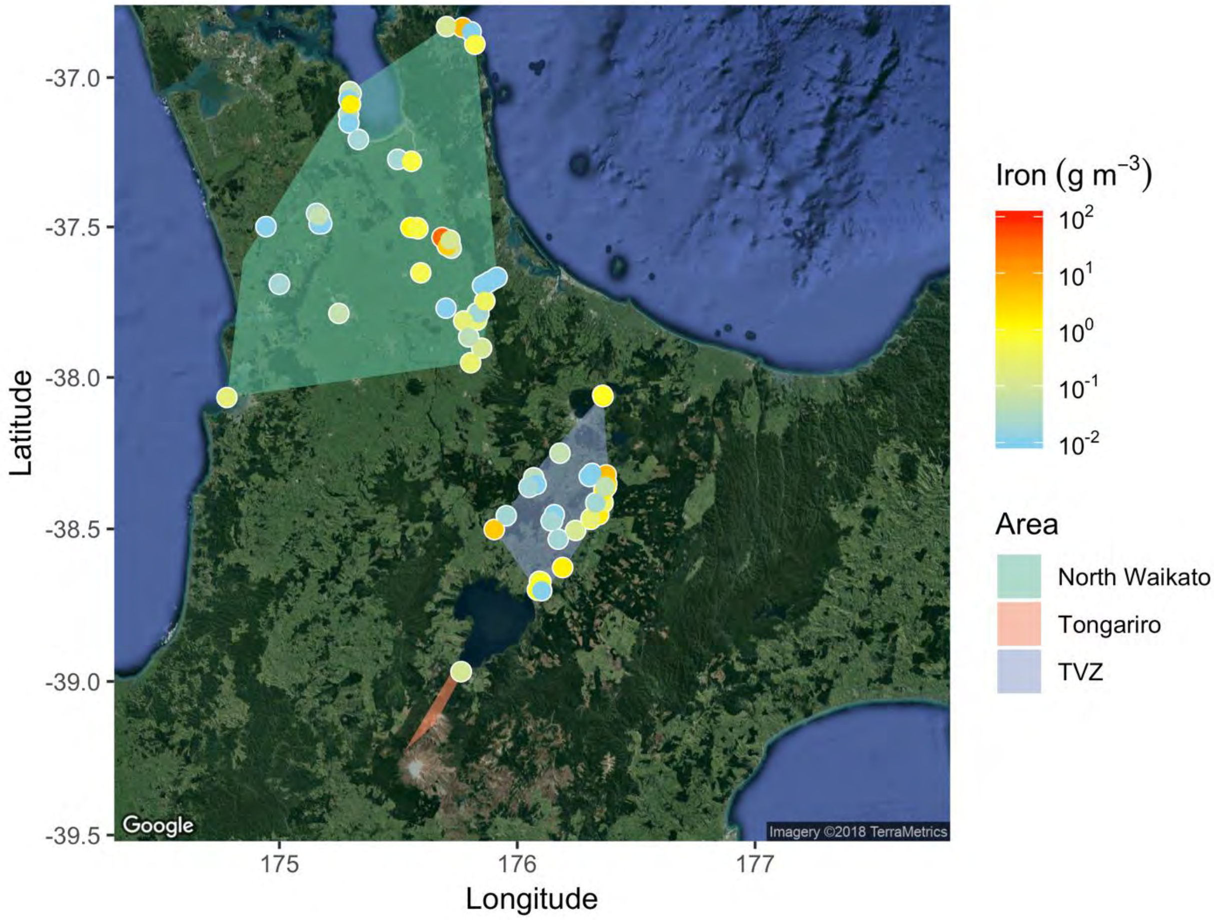

Figure 4-4 Iron data for features currently monitored in REGEMP II

4.2.5 Cluster Three: Magnesium

The results for magnesium (Figure 4-5) indicate that seawater intrusion is a significant influence on this parameter (and the pattern is similar for calcium, which resides in the same cluster). The highest results for magnesium are on the coastal fringes (Coromandel and Kāwhia).

Temperature is another contributing factor. Relatively high Mg concentrations are also found in hotter, deeper features (e.g., at Te Aroha, and features in the TVZ), but Tokaanu is an exception to this trend.

Spatial trend: Highest in coastal features, otherwise generally similar to temperature.

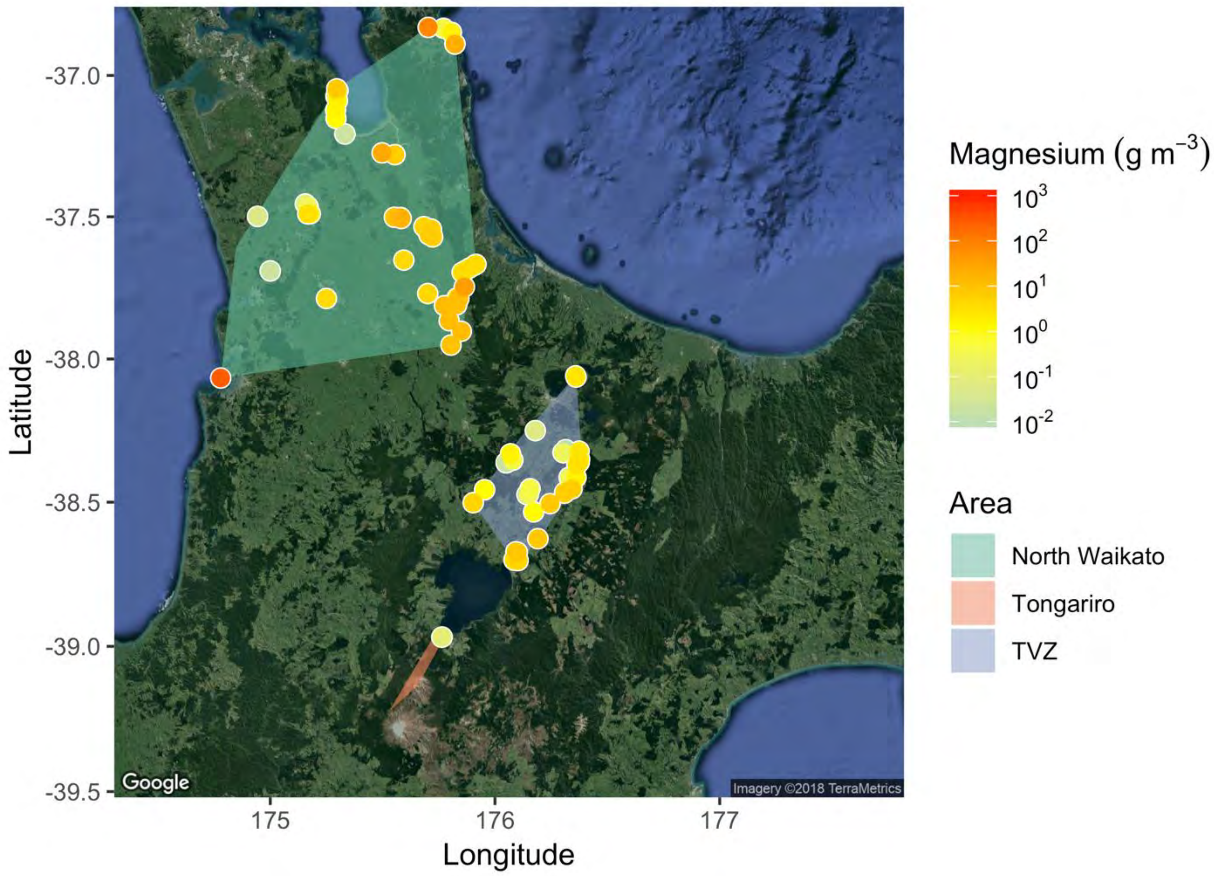

Figure 4-5 Magnesium data for features currently monitored in REGEMP II

4.2.6 Cluster Four: Chloride

Similar to magnesium, both seawater and temperature appear to be major influences on chloride concentrations (Figure 4-6). Depth to source is also important, as geothermal fluids with high chloride concentrations tend to come from deeper (hotter) sources. The results presented in this review are consistent with those presented in Golder (2013).

Spatial trend: Elevated at coastal margins and towards the south west.

4.2.7 Cluster Five: Arsenic

The distribution of results for arsenic (Figure 4-7), and its related cluster of parameters, resembles that for temperature (Figure 4-1). Unlike Golder (2013), where the results for individual Te Aroha features were averaged, arsenic is noticeably elevated in the high temperature feature there (Mokena), especially compared to results elsewhere in North Waikato.

Spatial trend: Highest in the south and south-east. Lowest to the north and north-west.

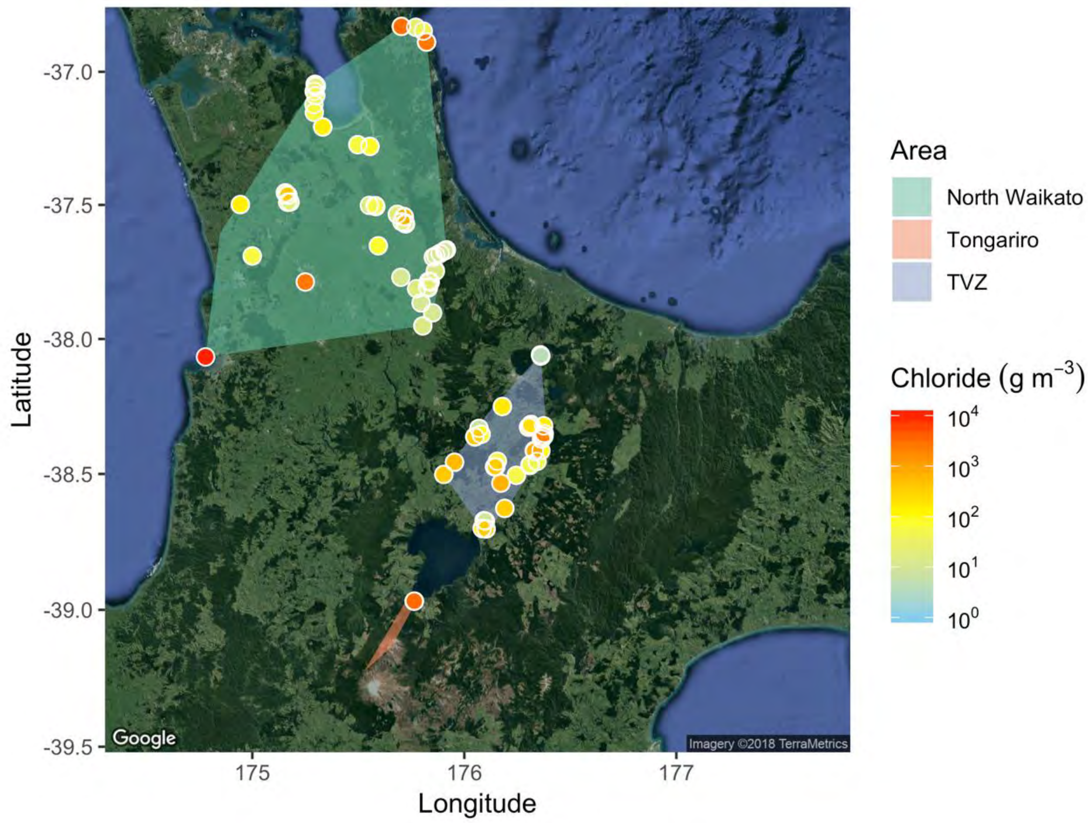

Figure 4-6 Chloride data for features currently monitored in REGEMP II

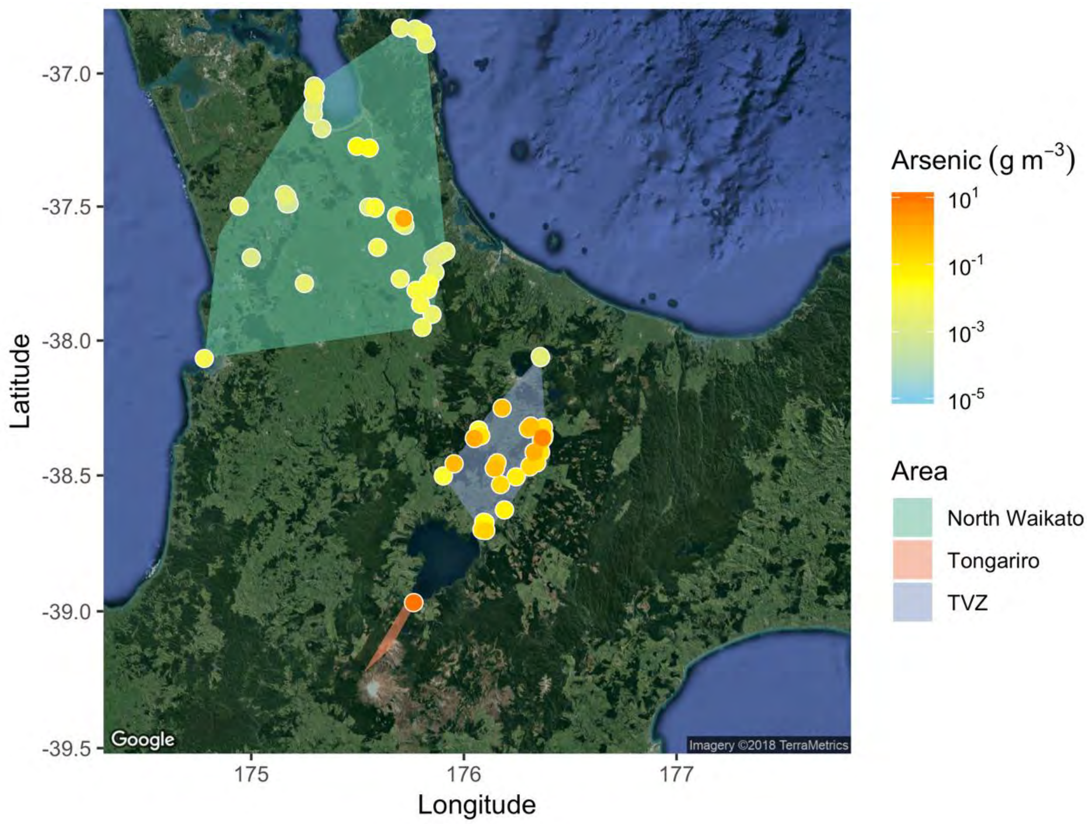

Figure 4-7 Arsenic data for features currently monitored in REGEMP II

4.2.8 Isotopic data

Isotopic measurements of dissolved gases using deuterium (^2H) and oxygen-18 (^{18}O) can also provide insight into geothermal systems. Deep geothermal waters tend to be enriched in ^{18}O (Stewart, 1981), due to interactions between hot water and host rocks, but there are no such effects on ^2H. Consequently, geothermal features with deep sources should be distinguishable from shallower features more affected by meteoric water (lit. water from the sky) and non-geothermal groundwater sources.

In 2018, Waikato Regional Council took samples from 55 features, of which 52 were from features listed in the REGEMP database at the time of survey. Figure 4-8 presents the results for these 52 features along with historical data (98 samples in total).

The results presented in Figure 4-8 highlight that the hotter, deeper systems of the TVZ are distinct from the generally cooler and shallower North Waikato features. The Mokena feature of Te Aroha, consistent with results for water chemistry, is the exception, and stands distinct from the rest of the results from the North Waikato, which are much more influenced by non-geothermal water types.

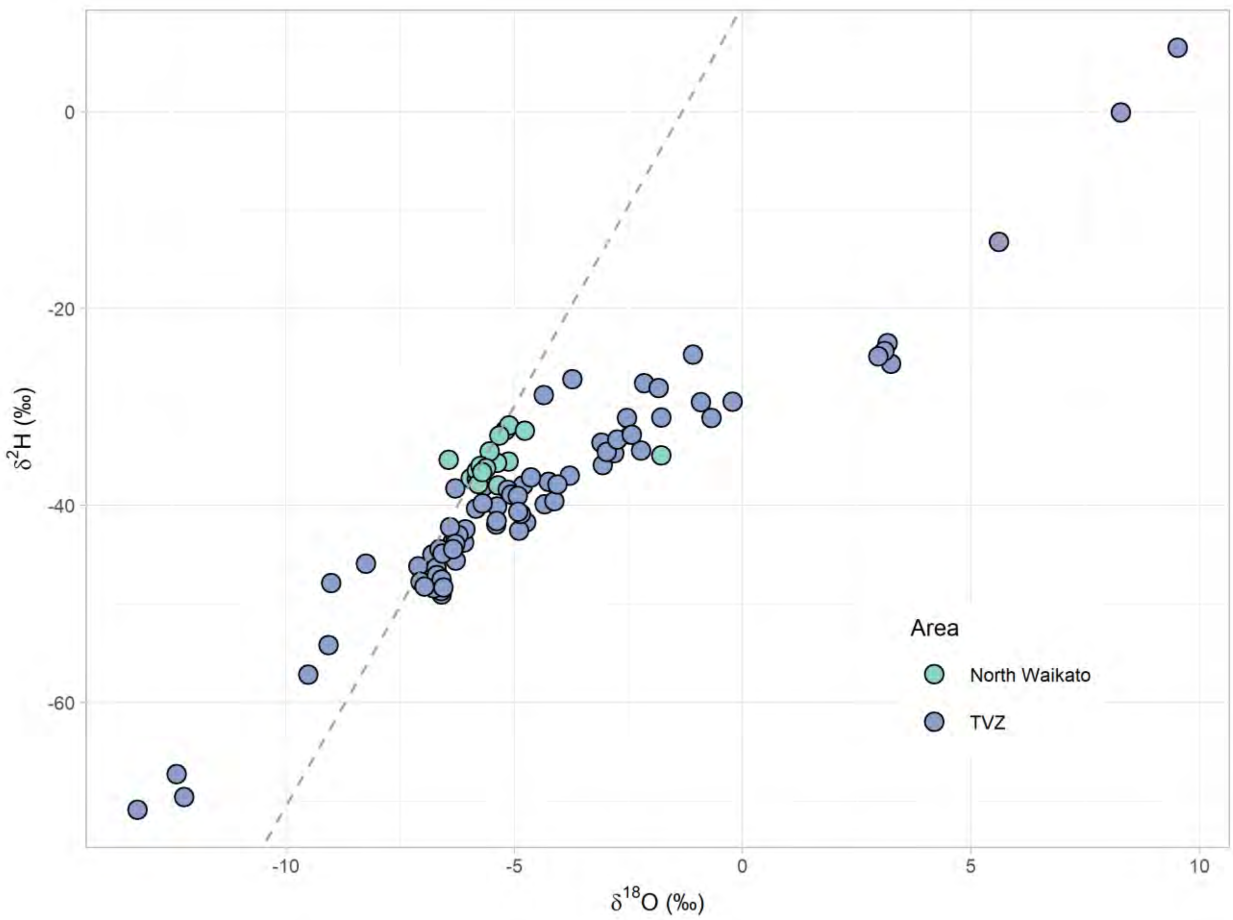

Figure 4-8 Isotope data for features currently monitored in REGEMP II. Dashed line is the global meteoric water line. (Craig, 1961).

4.3 Key Points

Analysis by feature provides a better degree of insight than offered at the system-by-system level used in Golder (2013). The review is also more robust because more data were available.

This review of spatial trends confirms the need for the REGEMP to sample from a wide range of features to account for the many drivers that can influence geothermal chemistry. The coverage is relatively comprehensive, but we strongly recommend at least one feature from the Tongariro area be routinely sampled.

Isotope data, which was not available for historical reviews, provides clear insights into the sources of water to the surface features. Routine isotopic analysis is not recommended, but collection of such data for every second review (i.e., every eight to ten years) could assist reviews of trends over time.

5 TEMPORAL TRENDS

5.1 Site Selection and Approach

This review was restricted to sites that had been sampled since 2009, and had at least ten data points on record. Only six of the seven proxy parameters considered for the spatial assessment (Sections 4.2.1 through 4.2.7) were used. There were no features for which there was enough data for iron.

No site has been sampled regularly enough to apply rigorous statistical analysis. In this review, analysis is restricted to visual assessments of results over time.

5.2 Trends Over Time

Graphs over time for each of the seven parameters are included in Appendix A. Excluding temperature, none of the parameters considered exhibited visual trends that could not be explained by:

- A sequence of atypical values (e.g., South Pool at Orakei Korako (location key 3065_178), which is generally near-neutral, had an early single measurement of pH ~2)
- Uncertainty based on significant variation over time

In contrast to the general results, temperature trends were detected in the following features:

- Map of Africa (3065_11), Orakei Korako (increasing);
- North Pool (3065_177), Orakei Korako (decreasing);
- South Pool (3065_178), Orakei Korako (decreasing);
- Ruatapu Cave (3065_185), Orakei Korako (increasing); and
- Waiotapu Geyser (3074_195), Waiotapu (decreasing)

Orakei Korako is one of the region's more dynamic systems, and Waiotapu geyser has a new outlet. To pinpoint why the changes are occurring, Waikato Regional Council will need to carry out site specific investigations to determine the potential causes (refer Section 6). Temperature data for other sites varied, with fluctuations as much as 20 °C over time, reinforce the need for more data before carrying out statistically robust trend analyses of the REGEMP data.

5.3 Implications

The analysis of changes over time indicates that temperature is the best measurement for change of those parameters considered in this review. While trends were less apparent on the basis of other parameters, temperature data indicates some features are cooling, while other some are getting hotter. In addition, the large swings observed at some features means that regular monitoring is important in separating what "normal" might look like for many of these complex features.

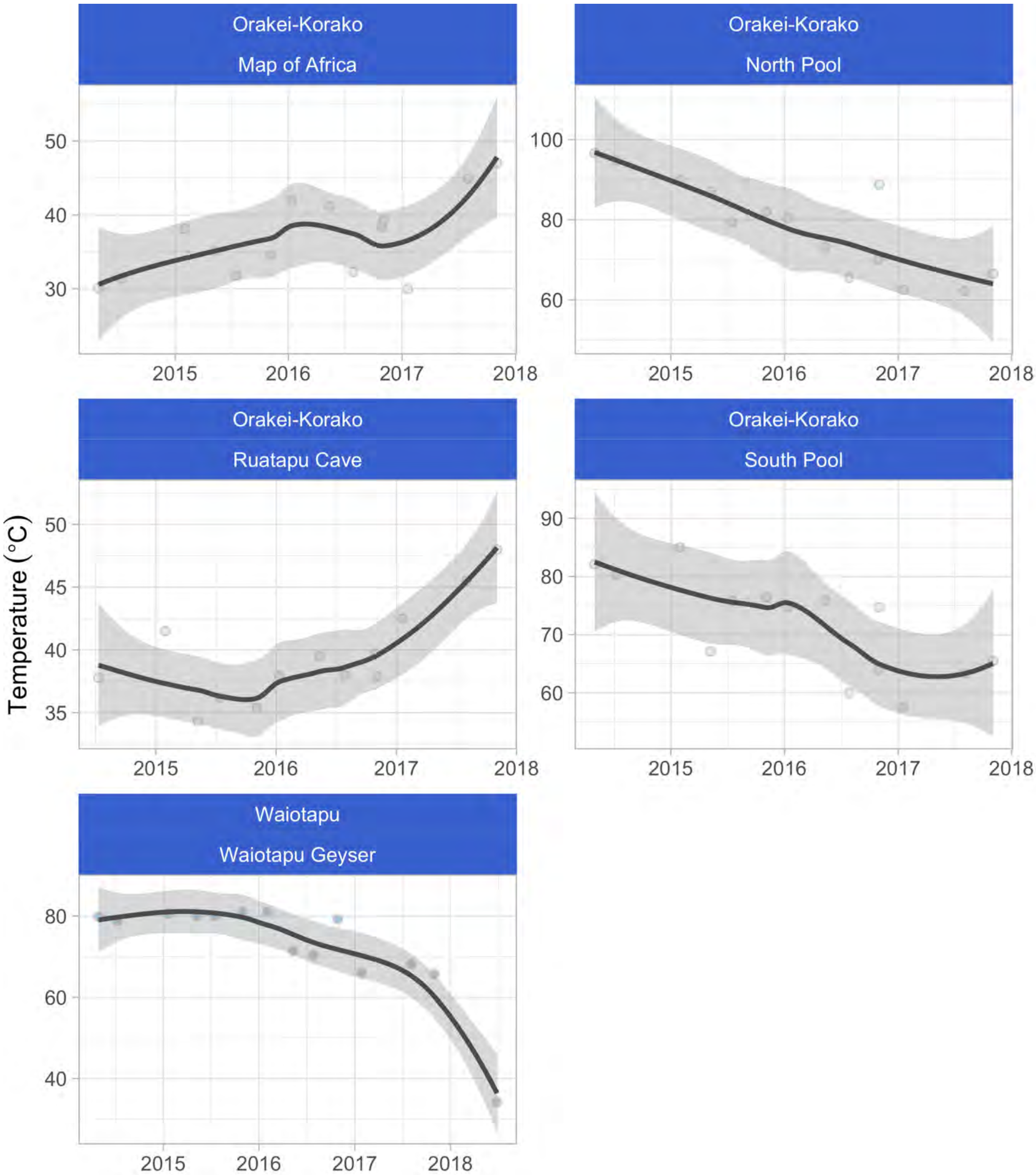

Figure 5-1 Features with apparent temporal trends in temperature. Trendlines use LOESS (moving average adjusted for near neighbours) with uncertainly marked as grey shading

6 RECOMMENDATIONS

With twice as much suitable data than available in Golder (2013), statistical analyses could be applied to a wider range of parameters. The data now group into five clusters, but the segregation may change in future as Waikato Regional Council generates and collates more data.

As in Golder (2013), this review has considered statistical similarities between sites and systems as well as spatial and temporal trends. In the next REGEMP, we recommend that resources be spent on collating on what, if any, other data are available, along with making all the relevant data from the current REGEMP spreadsheets have location keys and are added to WRC's main database.

Such an exercise has not been carried out since at least 2008, and should include both published and grey literature, including consent monitoring data (which may only be in monitoring reports to WRC), and iwi and citizen science monitoring, which will need to be audited for quality control. Other entities, such as GNS science or New Zealand's universities may also have as-yet unpublished data that could be added in as well.

Based on the review, the we recommend the following changes to REGEMP:

- Add a site at Soda Springs or Ketetahi (if access rights can be renegotiated) to the next REGEMP monitoring round (Tongariro geothermal features), or consider searching for an alternative and accessible geothermal feature within the Tongariro area;
- Consider a formal arrangement with GNS Science to collect and share data from features south of Taupo (to reduce sampling costs and travel times);
- Continue to regularly collect regular physicochemical data (especially temperature) from features (at a more frequent rate than more comprehensive sampling occurs;
- Collect isotope data every eight to ten years;
- Investigate potential drivers for variation across parameters (e.g., what, including pH and temperature, are the most likely drivers of variation as represented PC1 and PC2 in the PCA analysis). Such a project may best be actioned as a sponsored research project with a university (e.g., as a Post-Graduate Diploma or MSc topic, or as a summer scholarship);
- Investigate possible reasons for change in the temperature of features at Orakei Korako and Waiotapu, beginning with a physical assessment (e.g., topographical changes, the state of the features etc.), and a review of any third-party monitoring (Contact Energy, iwi etc.); and
- Make data collation the focus of the next REGEMP II review, including making sure any missing data (present in REGEMP spreadsheets) are in the main database, assigning location keys for data that do not have them.

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APPLICABILITY AND LIMITATIONS

Restrictions of Intended Purpose

This report has been prepared solely for the benefit of Waikato Regional Council as our client with respect to the brief. The reliance by other parties on the information or opinions contained in the report shall, without our prior review and agreement in writing, be at such party's sole risk.

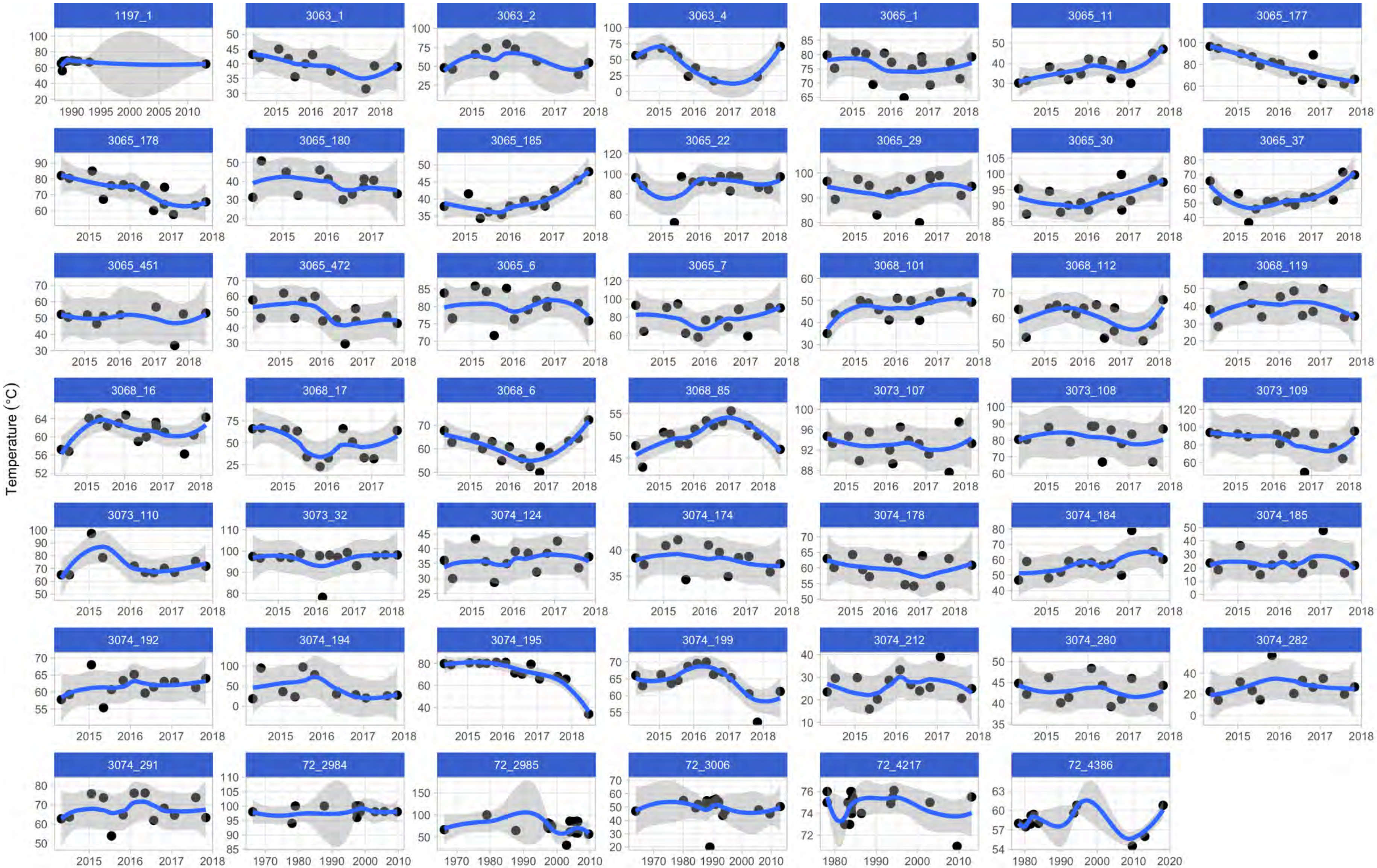
Legal Interpretation

Opinions and judgements expressed herein are based on our understanding and interpretation of current regulatory standards, and should not be construed as legal opinions. Where opinions or judgements are to be relied on they should be independently verified with appropriate legal advice.

Reliability of Investigation

Babbage has performed the services for this project in accordance with the standard agreement for consulting services and current professional standards for environmental site assessment. No guarantees are either expressed or implied.

Appendix A
Temporal Data


Temperature (°C)
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3063_1
3063_2
3063_4
3065_1
3065_11
3065_177
3065_178
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3065_185
3065_22
3065_29
3065_30
3065_37
3065_451
3065_472
3065_6
3065_7
3068_101
3068_112
3068_119
3068_16
3068_17
3068_6
3068_85
3073_107
3073_108
3073_109
3073_110
3073_32
3074_124
3074_174
3074_178
3074_184
3074_185
3074_192
3074_194
3074_195
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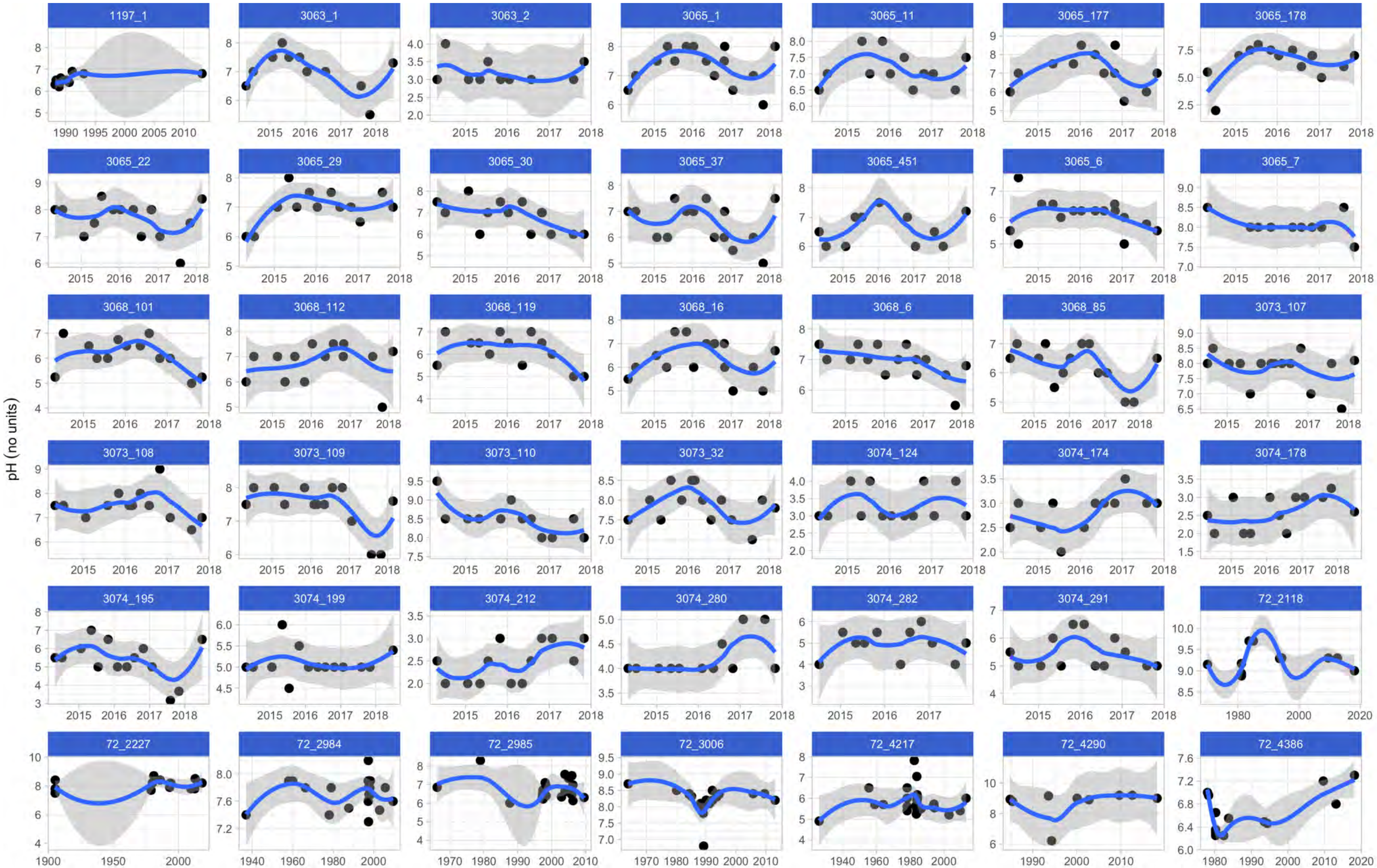
72_4217
72_4386


pH (no units)
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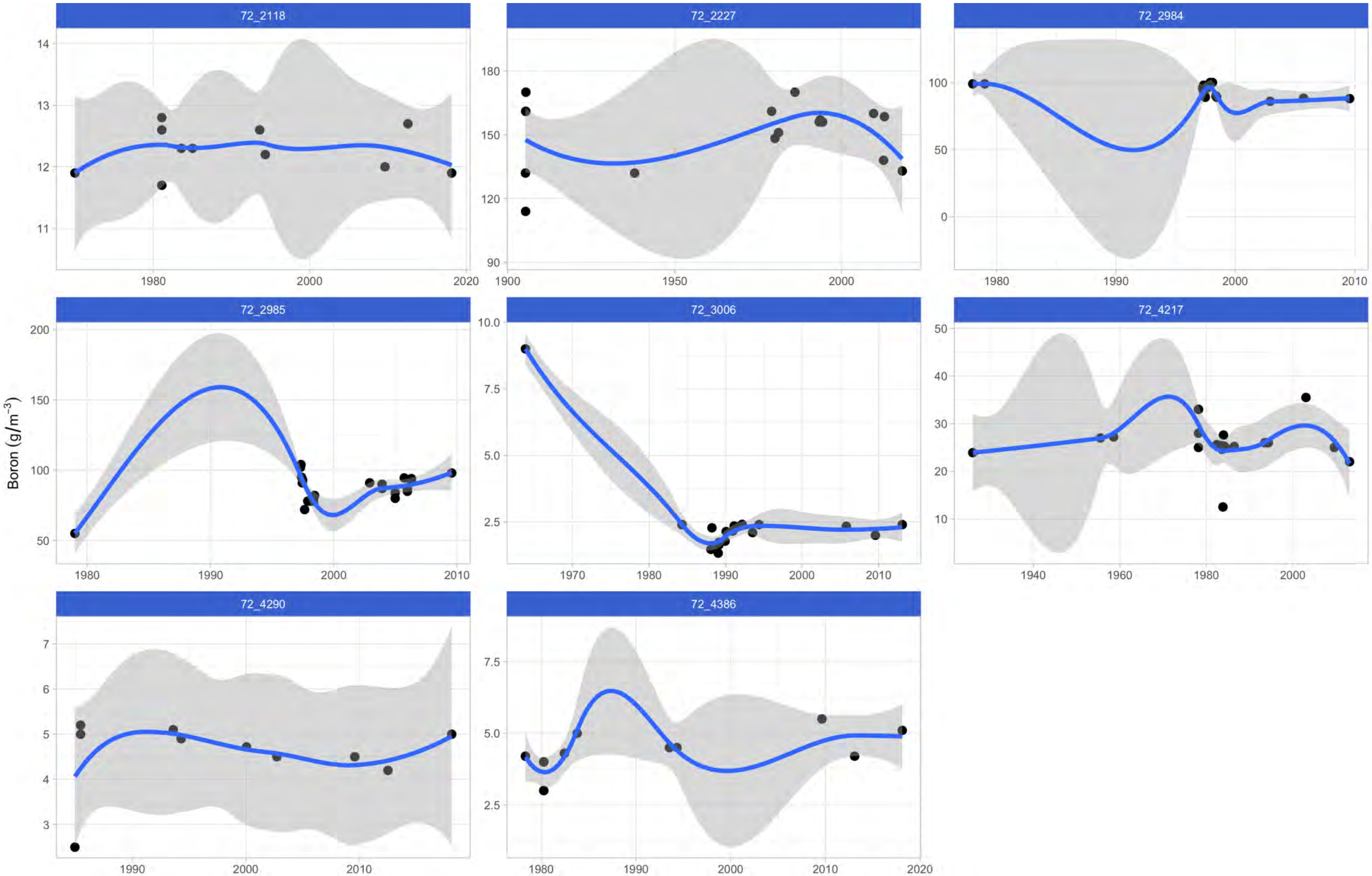
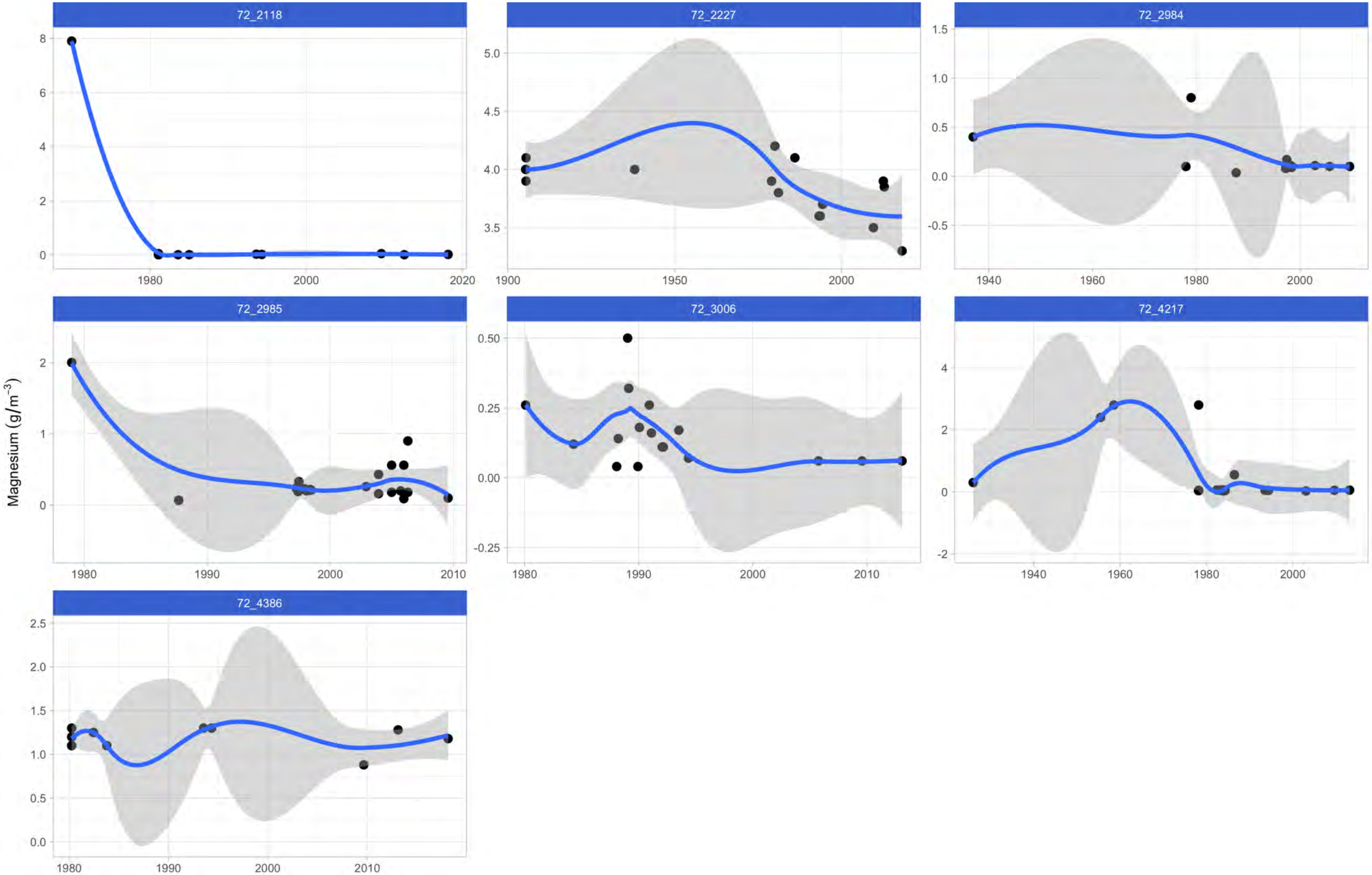
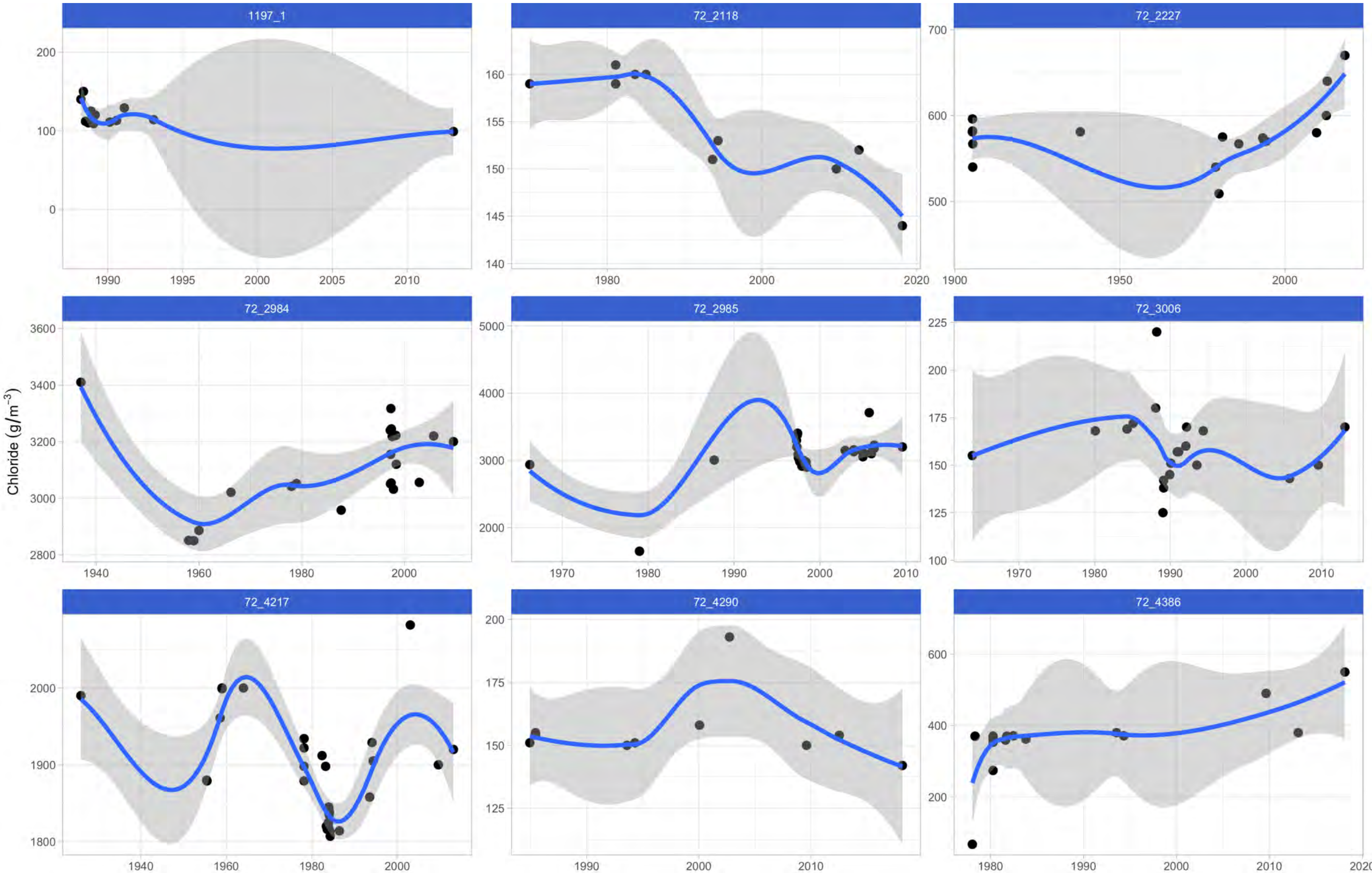
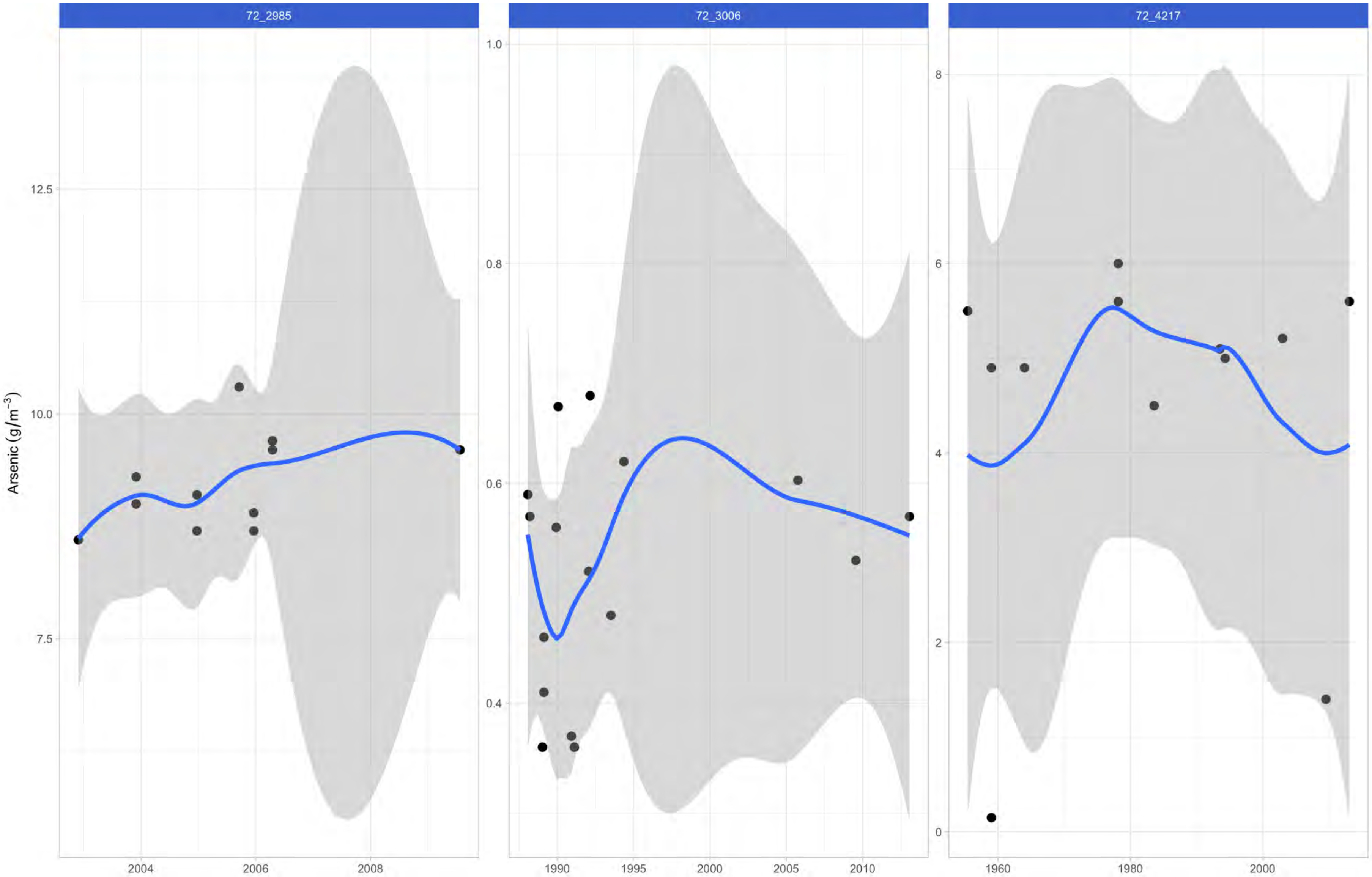
3063_1
3063_2
3065_1
3065_11
3065_177
3065_178
3065_22
3065_29
3065_30
3065_37
3065_451
3065_6
3065_7
3068_101
3068_112
3068_119
3068_16
3068_6
3068_85
3073_107
3073_108
3073_109
3073_110
3073_32
3074_124
3074_174
3074_178
3074_195
3074_199
3074_212
3074_280
3074_282
3074_291
72_2118
72_2227
72_2984
72_2985
72_3006
72_4217
72_4290
72_4386


72_2118
72_2227
72_2984
72_2985
72_3006
72_4217
72_4290
72_4386
Boron (g/m^{-3})


72_2118
72_2227
72_2984
72_2985
72_3006
72_4217
72_4386
Magnesium (g/m^{-3})


1197_1
72_2118
72_2227
72_2984
72_2985
72_3006
72_4217
72_4290
72_4386
Chloride (g/m^{-3})


72_2985
72_3006
72_4217
Arsenic (g/m^{-3})
12.5
10.0
7.5
2004
2006
2008
1.0
0.8
0.6
0.4
1990
1995
2000
2005
2010
8
6
4
2
0
1960
1980
2000

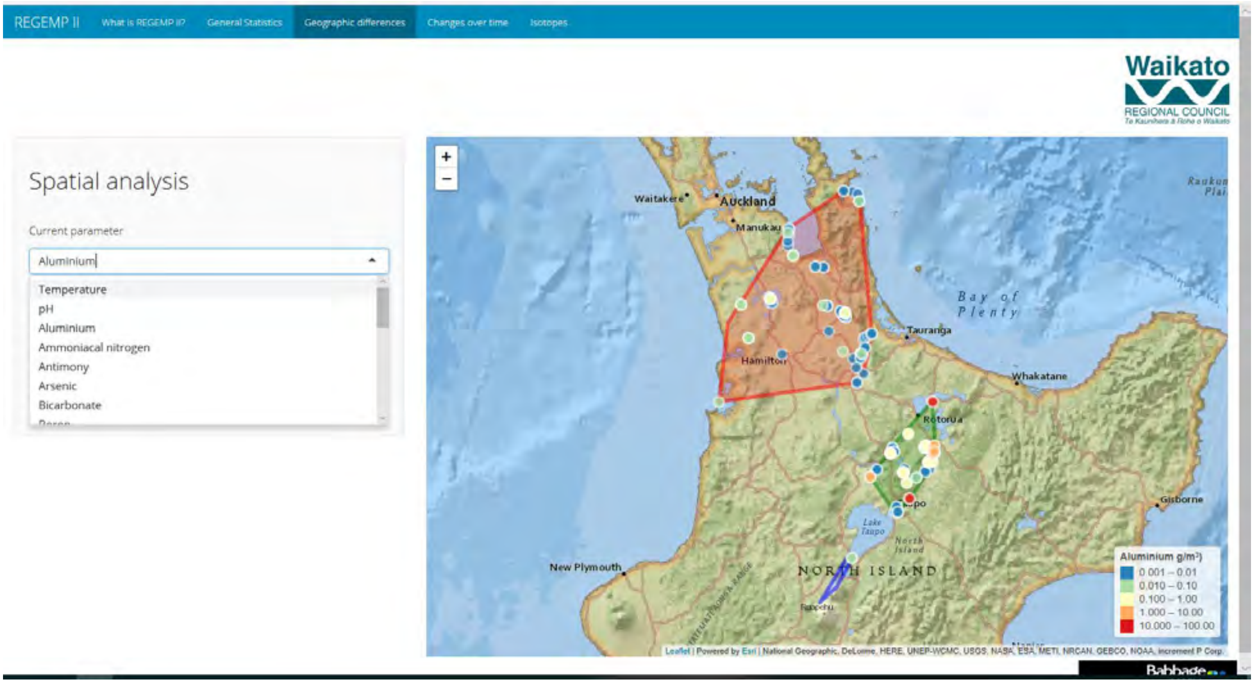
Appendix B

The REGEMP Shiny App description

THE REGEMP SHINY APP

For the purposes of presentation, the results of the REGEMP review were developed into a Shiny[1] app using R[2] that WRC could host on its website. Shiny is open source tool for developing interactive and web-based outputs from R analyses. The app is also available, upon request, from WRC to be run inside R Studio[3] (an open source Graphic User Interface for R). The app is functional as of R 3.5.3.

The app spreads the results of the REGEMP review across a series of tabs, with varying degrees of interaction, depending on the data considered. The geographic data tab is the most interactive (see screenshot below), the statistical data tab the least interactive.



Any user of the app will need the following packages installed:

- shiny - The package the performs the Shiny operations
- shinythemes - A supplementary package for themes in Shiny (cosmetic only)
- tidyverse - A package containing the "grammar" for these scripts
- readxl - Allows Excel files to be directly read

[1] https://shiny.rstudio.com/

[2] R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

[3] https://www.rstudio.com/

- ggdendro - A package for making dendrograms in ggplot (part of tidyverse)
- leaflet - For interactive maps
- leaflet.esri - For loading ESRI basemaps into leaflet

In addition, the following data (all subsets of the parent database) will be needed (inside a data folder in the parent app folder):

- Cleandata.csv – For the PCA analysis
- Fulldata.csv - For time series
- Geogdata.csv – The geographic data
- HCAdata.csv – Data for the HCA analysis
- Isodata.csv – Isotope data

The packaged app also includes WRC's and Babbage's logos (inside a "www" folder).

Appendix C

Laboratory Services Review

COMPARATIVE LABORATORY ASSESSMENT

Terms of Reference

Analytica Laboratories, Eurofins New Zealand, GNS Sciences, Hill Laboratories and SGS New Zealand were contacted by email to obtain quotes for the trace analysis in geothermal waters of the analytes listed in Table C1. The laboratories were asked for the analytical method and detection limit applicable to each test, and the standard turnaround time, assuming 12 samples were submitted for analysis. In addition, IANZ was consulted for the relevant certificates of accreditation

Exclusions

SGS New Zealand responded to our request within 24 hours, advising that it could not offer the full suite of analyses, and suggested we contact another laboratory. As such, SGS did not form part of our comparative laboratory assessment.

Analytical Methods and Detection Limits

The analytical methods proposed by each laboratory were largely the same (Table C2). There were some differences in detection limits between laboratories (Table C3). However, in almost all cases, the detection limit was consistent with trace analysis.

Standard Turnaround Time

The standard turnaround time ranged from three to five working days at Analytica Laboratories to ten working days at GNS Sciences. Hill Laboratories reported a turnaround time of eight days, which was comparable to that of Eurofins New Zealand of between seven and ten working days. All laboratories offered faster turnaround times, but at an additional cost.

Accreditation

All the analytical laboratories were accredited by IANZ for chemical testing and, as such, compliant with NZS ISO/IEC 17025 general requirements for the competence of testing and calibration laboratories. Except for salinity and dissolved bromine, tests are performed by all laboratories in accordance with the terms of accreditation.

Table C1 - Analyses required for geothermal samples.

Type	Parameter	Fraction
Physical tests	Bicarbonate alkalinity (also referred to as bicar-bonate)	Total
	Electrical conductivity (at 25 C)	Total
	pH	Total
	Reactive silica (Si as SiO2)	Dissolved
	Salinity	Total
	Temperature	Total
	Total alkalinity	Total
Nutrients	Ammoniacal nitrogen	Total
Cations	Calcium	Dissolved
	Magnesium	Dissolved
	Potassium	Dissolved
	Sodium	Dissolved
Anions	Chloride	Dissolved
	Fluoride	Total
	Sulphate	Dissolved
	Total sulphide	Total
	Unionised hydrogen sulphide	Total
Metals and metalloids	Aluminium	Dissolved
	Antimony	Dissolved
	Arsenic	Dissolved
	Boron	Dissolved
	Bromine	Dissolved
	Caesium	Dissolved
	Iron	Dissolved
	Lithium	Dissolved
	Mercury	Total
	Rubidium	Dissolved
	Thallium	Dissolved

Table C2 Analytical methods.

Parameter	Analytica Laboratories	Eurofins New Zealand	GNS Sciences	Hill Laboratories
Bicarbonate	APHA 2320 B. 23rd ed. 2017.	APHA 4500-CO2 D. 22nd ed. 2012 (calculated)	ASTM D513-82 Vol.11.01 of 1988	Subcontracted
Conductivity*	APHA 2510 B. 22nd ed. 2012	APHA 2510 B. 22nd ed. 2012	Subcontracted	APHA 2510 B. 22nd ed. 2012
pH	APHA 4500-H^+ B. 22nd ed. 2012	APHA 4500-H^+ B. 22nd ed. 2012	Subcontracted	APHA 4500-H^+ B. 22nd ed. 2012
Reactive silica	Subcontracted	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 4500-SiO2 F. 22nd ed. 2012.	APHA 4500-SiO2 F (mod.) 22nd ed. 2012.
Salinity	Conductivity meter in salinity mode	Based on APHA 2510. 22nd ed. 2012	Subcontracted	APHA 2520 B. 22nd ed. 2012
Temperature	Supplied by client, otherwise 20 °C	Supplied by client, otherwise 20 °C	Supplied by client, otherwise 20 °C	Supplied by client, otherwise 20 °C
Total alkalinity	APHA 2320 B (mod.) 22nd ed. 2012	APHA 2320 B (mod.) 22nd ed. 2012	APHA 2320 B (mod.) 23rd ed. 2017.	APHA 2320 B (mod.) 22nd ed. 2012.
NH4N	APHA 4500-NH3 F (mod.) 22nd ed. 2012.	APHA 4500-NH3 H. 22nd ed. 2012. FIA	APHA 4500-NH3 H. 23rd ed. 2017. FIA	APHA 4500-NH3 H. 22nd ed. 2012. FIA
Calcium	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3120 B. 23rd ed. 2017. ICP-OES	APHA 3125 B. 22nd ed. 2012. ICP-MS
Magnesium	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3120 B. 23rd ed. 2017. ICP-OES	APHA 3125 B. 22nd ed. 2012. ICP-MS
Potassium	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3120 B. 23rd ed. 2017. ICP-OES	APHA 3125 B. 22nd ed. 2012. ICP-MS
Sodium	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3120 B. 23rd ed. 2017. ICP-OES	APHA 3125 B. 22nd ed. 2012. ICP-MS
Chloride	APHA 4110 B. 22nd ed. 2012. IC	US EPA 300.0 (mod.) IC	APHA 4110 B. 22nd ed. 2012. IC	APHA 4110 B. (mod.) 22nd ed. 2012. IC
Fluoride	Subcontracted	US EPA 300.0 (mod.) IC	APHA 4500-F^- C 23rd ed. 2017. ISE	APHA 4500-F^- C. 22nd ed. 2012. ISE
Sulphate	APHA 4110 B. 22nd ed. 2012. IC	US EPA 300.0 (mod.) IC	APHA 4110 B. 23rd ed. 2017. IC	APHA 4110 B (mod.) 22nd ed. 2012. IC
Total sulphide	APHA 4500-S2 I. 22nd ed. 2012	APHA 4500-S2- B, C and F. 22nd ed. 2012	Subcontracted	APHA 4500-S2- E (mod.) 22nd ed. 2012
Unionised H_2S	Σ conductivity, temp., pH & total sulphide	Σ total dissolved solids, temp., pH, total sulphide	Subcontracted	Σ conductivity, temp., pH & total sulphide
Aluminium	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Antimony	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Arsenic	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Boron	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3120 B. 23rd ed. 2017. ICP-OES	APHA 3125 B. 22nd ed. 2012. ICP-MS
Bromine	US EPA 200.8. ICP-MS	Not available	APHA 4110 B. 23rd ed. 2017. IC	APHA 3125 B. 22nd ed. 2012. ICP-MS
Caesium	US EPA 200.8. ICP-MS	Not available	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Iron	US EPA 200.8. ICP-MS	APHA 3120 B (mod.) 22nd ed. 2012. ICP-OES	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Lithium	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Total mercury	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	Subcontracted	US EPA 245.7, Feb 2005 (CVAFS)
Rubidium	US EPA 200.8. ICP-MS	Not available	APHA 3125 B. 23rd ed. 2017. ICP-MS	APHA 3125 B. 22nd ed. 2012. ICP-MS
Thallium	US EPA 200.8. ICP-MS	APHA 3125 B (mod.) 22nd ed. 2012. ICP-MS	Subcontracted	APHA 3125 B. 22nd ed. 2012. ICP-MS

Notes: *at 25 °C; FIA = flow injection analysis; IC = ion chromatography; ICP-OES = inductively coupled plasma optical emission spectrometry; MS = mass spectrometry; AAS = atomic absorbance spectroscopy; CVAFS = cold vapour atomic fluorescence spectroscopy.

Table C3 Detection limits.

Parameter	Analytica	Eurofins	GNS Sciences	Hill Laboratories
Bicarbonate (as $CaCO_3$)	1.0	1.0	20	20
Conductivity (mS/m)	0.01	0.1	0.1	0.1
pH (unitless)	1.0	0.1	0.1	0.1
Reactive silica (as SiO_2)	0.1	0.02	0.01	0.1
Salinity	10	2	0.2	0.2
Total alkalinity (as $CaCO_3$)	1.0	1.0	5.0	1.0
Ammoniacal nitrogen	0.01	0.01	0.003	0.01
Calcium	0.05	0.01	0.01	0.05
Magnesium	0.01	0.01	0.005	0.02
Potassium	0.05	0.01	0.1	0.05
Sodium	0.01	0.02	0.02	0.02
Chloride	0.5	0.02	0.05	0.5
Fluoride	0.05	0.02	0.01	0.05
Sulphate	0.5	0.02	0.03	0.5
Total sulphide	0.005	0.2	0.05	0.05
Unionised H_2S	0.005	0.05	0.002	0.002
Aluminium	0.001	0.002	0.0005	0.003
Antimony	0.0001	0.001	0.0001	0.0002
Arsenic	0.0005	0.001	0.0005	0.001
Boron	0.005	0.005	0.05	0.005
Bromine	0.005	Not available	0.02	0.005
Caesium	0.00001	Not available	0.00005	0.0001
Iron	0.005	0.005	0.0005	0.02
Lithium	0.00001	0.001	0.0005	0.0002
Total mercury	0.00005	0.0005	0.00008	0.00008
Rubidium	0.00001	Not available	0.00005	0.0001
Thallium	0.00001	0.0005	0.00005	0.00005

Note: All units g/m^3 unless stated.