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REGEMP II

2013 interpretation of geochemical data

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REGEMP II

2013 Interpretation of Geochemical Data

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REPORT

Report Number: 1278205074_002_Rev0

Golder Associates

Executive Summary

This report represents the third review of the Regional Geothermal Geochemistry Monitoring Programme (REGEMP) since it was reinstated in 2006. The purpose of the REGEMP is to collate geochemical data from geothermal sites throughout the Waikato Region so that trends and patterns in these data can be determined and aid in their management.

The results of Principal Component Analysis (PCA) indicate that geothermal systems within the North Waikato have generally distinct chemical signatures from those in the central Taupo Volcanic Zone (TVZ) and Tongariro (southern TVZ). Elements monitored as part of the REGEMP programme can be grouped into six broad clusters, and representative elements from each cluster will be the focus of further analysis in this report.

The drivers of spatial trends were the depth of source waters, magmatic intrusion and saline influences. In general, systems within the central TVZ were typically hotter and elevated with respect to elements associated with geothermal processes, compared to sites in the North Waikato and Tongariro. Despite a difference in approach, the results of spatial analysis of REGEMP data in three dimensions were consistent with those reported in previous reports.

With the exception of a change in temperature measured at Spring #1 in the Te Maire system, no long-term trends were evident in data for sites for which it was considered there were sufficient data to analyse. However, the analysis of long-term trends is considerably constrained by the relatively small datasets for these ten sites.

The current dataset suitable for PCA is relatively small, and future insights are likely in later reviews (i.e. once more data are collected). Cluster analysis indicates that systems with chemistry that closely resembles Kawhia and Waihi are not currently being monitored.

The following alterations to the REGEMP design are recommended:

- Maintain the monitoring frequency (no greater than four years between samples, and more frequently where possible).
- Continue to analyse samples for a comprehensive range of parameters (e.g., consistent with data produced since 2009).
- Resume monitoring at Kawhia, Tokaanu and Waihi.
- Remove Emerald Lakes (and Tama Lakes) from the REGEMP database.

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List of Abbreviations

As	Arsenic
B	Boron
Br	Bromine
Ca	Calcium
Cl	Chlorine
Cs	Caesium
F	Fluorine
Fe	Iron
Golder	Golder Associates (NZ) Limited
HCO_3^-	Bicarbonate
Li	Lithium
Mg	Magnesium
Na	Sodium
NH_3	Ammonia
NH_4^+	Ammonium
PC	Principal Component
PCA	Principal Component Analysis
REGEMP	Regional Geothermal Geochemistry Monitoring Programme
Sb	Antimony
Si	Silicon
SiO_2	Silicon dioxide
SO_4^{2-}	Sulfate
Rb	Rubidium
Temp	Temperature
Tl	Thallium
WRC	Waikato Regional Council

1.0 INTRODUCTION

1.1 Background

Waikato Regional Council (WRC) operates a Regional Geothermal Geochemistry Monitoring Programme (REGEMP). The purpose of the REGEMP is to collate geochemical data from geothermal sites throughout the Waikato Region so that trends and patterns in these data can be determined and assist in the sustainable management of these resources.

The programme was first initiated in 1993/94 (Huser & Jenkinson 1996), but was not actively managed until 2005/06 (Luketina 2007). The programme is reviewed approximately every four to five years, and this 2013 report represents the third review. The first two reviews were undertaken by GEOKEM (Webster-Brown & Brown 2007; 2012).

1.2 Report Scope

The 2013 review follows a similar structure to the 2012 report. As such, this report contains:

- Analysis of geographic and temporal trends, and correlations between chemical species.
- An assessment of sampling results from the 2013 monitoring programme in the context of previous monitoring results.
- Commentary on any unusual results.
- Recommendations to enhance the programme.

The open-source software package R (version 3.0) was used to analyse and interpret the REGEMP data. Examples of scripts used to generate the statistical and graphical outputs presented in this report are provided in Appendix A.

2.0 2013 DATA AND CONTEXTUAL ANALYSIS

2.1 Data Sources

Since 2009, data from 22 geothermal locations (systems hereforth) in three broad areas (North Waikato, Taupo Volcanic Zone (TVZ) and Tongariro) have been collected (Figure 1). The systems are listed in Appendix B, along with a list of those systems for which historical data have been generated but were not sampled in the same period. All data used are provided in Appendix C. The inclusion of new data followed protocols outlined in Webster-Brown & Brown (2012). Specifically:

- The parent dataset was that developed by Webster-Brown & Brown (2012).
- Data for the Emerald Lakes and Tama Lakes in Tongariro National Park were available, but these data were not included for the purposes of temporal analyses. Neither set of lakes is considered to be significantly geothermally influenced (Webster-Brown & Brown 2012).
- Data for major ions (e.g., calcium and magnesium) were assumed to be in their dissolved form.
- Data for parameters considered unrelated to geothermal geochemistry (e.g., oxidised nitrogen species) were not included.

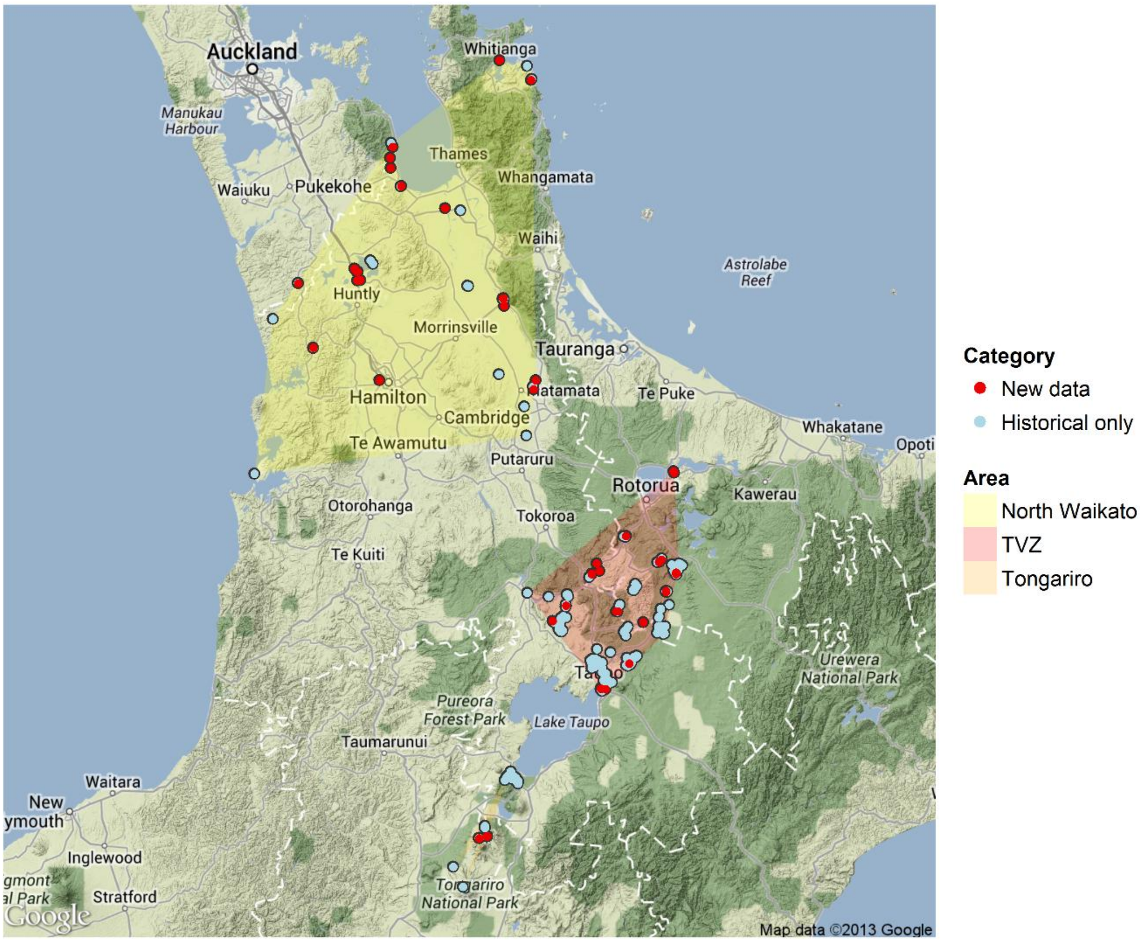


Figure 1: Sites currently included in the REGEMP, along with sites for which historical data are available.

2.2 Associations

2.2.1 Approach

In previous reports, the association between parameters was assessed by comparing linear goodness of fit (r^2) values for pairs of elements. The focus of the 2010 review was lithium. In the present review, a more holistic approach was undertaken and data were analysed using Principal Component Analysis (PCA).

PCA is a statistical technique in which observations that may be correlated are converted to sets of linearly uncorrelated variables. These uncorrelated sets are called Principal Components (PCs), and are ordered by the amount of variance explained (i.e., PC1 explains the most variance, PC2 explains most of the remaining unaccounted variance, etc.). The total number of PCs is equal to one less than the total number of sets of observed variables. For the purposes of the review, results were scaled (all variance was standardised in R before analysis) to account for the varying magnitudes of results (e.g., chloride concentrations were typically orders of magnitude greater than measured concentrations of arsenic). The PCA method is an increasingly widespread technique for geochemical data analysis (refer Cheng et al 2010 or Xue et al. 2011).

The REGEMP PCA was based on data for:

- Major ions
  - Ammoniacal nitrogen species (NH_4 and NH_3)
  - Bicarbonate (HCO_3)
  - Boron (B)
  - Bromine as bromide (Br)
  - Calcium (Ca)
  - Chlorine as chloride (Cl)
  - Fluorine as fluoride (F)
  - Magnesium (Mg)
  - Silicon (Si as SiO_2)
  - Sodium (Na)
  - Sulfate (SO_4^{2-})
- Trace elements
  - Antimony (Sb)
  - Arsenic (As)
  - Caesium (Cs)
  - Iron (Fe)
  - Lithium (Li)
  - Rubidium (Rb)
  - Thallium (Tl)

The PCA technique requires complete sets of data for all observations. For this reason, data for sulfide, mercury and aluminium were not included, as these datasets were incomplete. Even after excluding these incomplete data records, of the 1,667 records in the current REGEMP database, only 96 were complete enough to be included in the PCA. It is recommended that future monitoring of all features includes the three parameters mentioned above in order to enable a more complete analysis.

2.2.2 PCA Results

The results of the PCA indicate that 40 % of the variance observed for elemental concentrations across the sites measured could be explained by a single factor (i.e., PC1), and 56 % explained by two components (i.e., PC1 and PC2). As shown in Figure 2, the data for records from the North Waikato Area were distinct from those from the TVZ and the Tongariro area, even allowing for outliers.

When the distribution of elements is considered within the analysis, the results indicate that these elements approximately aggregate into six clusters as follows:

- Cluster 1: Bicarbonate

- Cluster 2: Iron, calcium, magnesium, and possibly sulfate
- Cluster 3: Chloride, bromide, and sodium
- Cluster 4: Ammoniacal nitrogen, boron, and potassium
- Cluster 5: Antimony, arsenic, caesium, lithium, and rubidium
- Cluster 6: Fluoride and silicon (as SiO_2)

Data from the North Waikato were particularly associated with Clusters 1 to 3; the TVZ and Tongariro area were associated with Clusters 4 to 6. These associations, as have been discussed in Webster-Brown & Brown (2007: 2012), are most likely driven by the deeper sources of geothermal fluids in the TVZ (and thus relatively high concentrations of most trace elements), and the presence of saline intrusion (e.g., Na, Cl and Br in some North Waikato systems).

2.1 Cluster Analysis

The PCA dataset were also examined using hierarchical cluster analysis. Hierarchal cluster analysis groups samples by their similarity, based on the underlying variance of observations measured for each sample.

The results of this cluster analysis are presented in Figure 3. Soda Springs was not included in the analysis because there were insufficient data at this site to meet the criteria for PCA analysis. The results further emphasise the uniqueness of the Kawhia system, and there are no systems monitored closely associated with Waihi, nor any (apart from Soda Springs) in the Tongariro region. Sampling at a site at Tokaanu could thus also be resumed. Otherwise it is considered that the current suite of sites actively being monitored provide sufficient coverage of the region as a whole (Table 1).

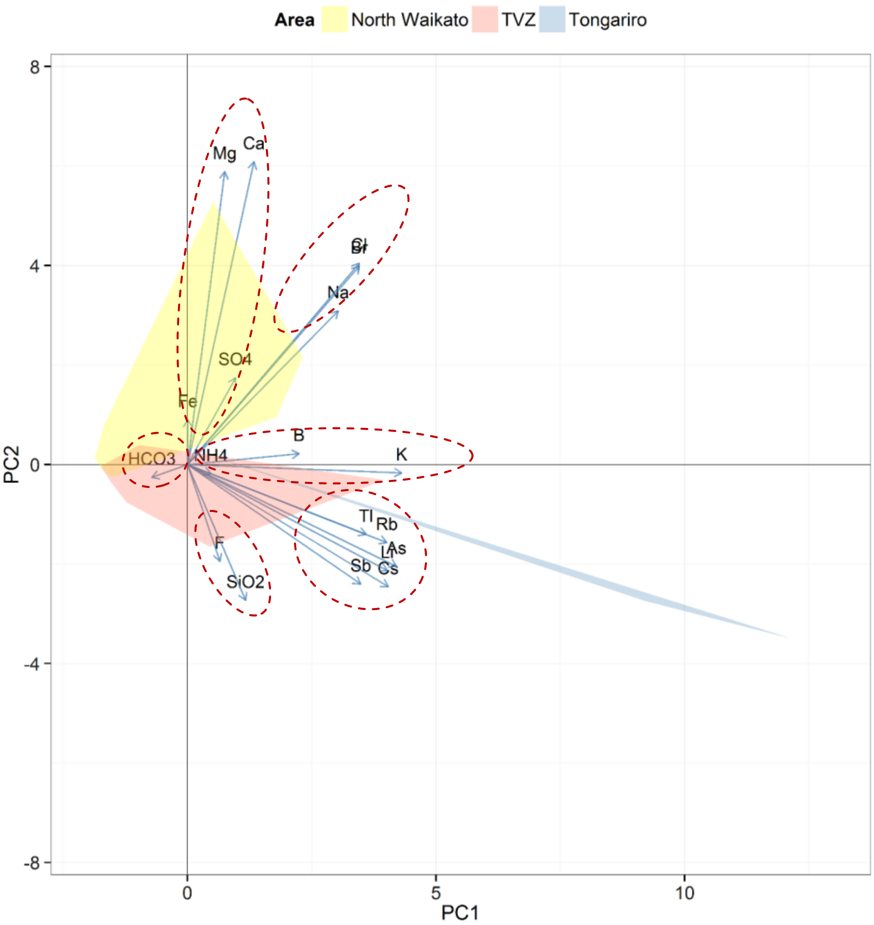


Figure 2: PCA of REGEMP sites with complete data records.

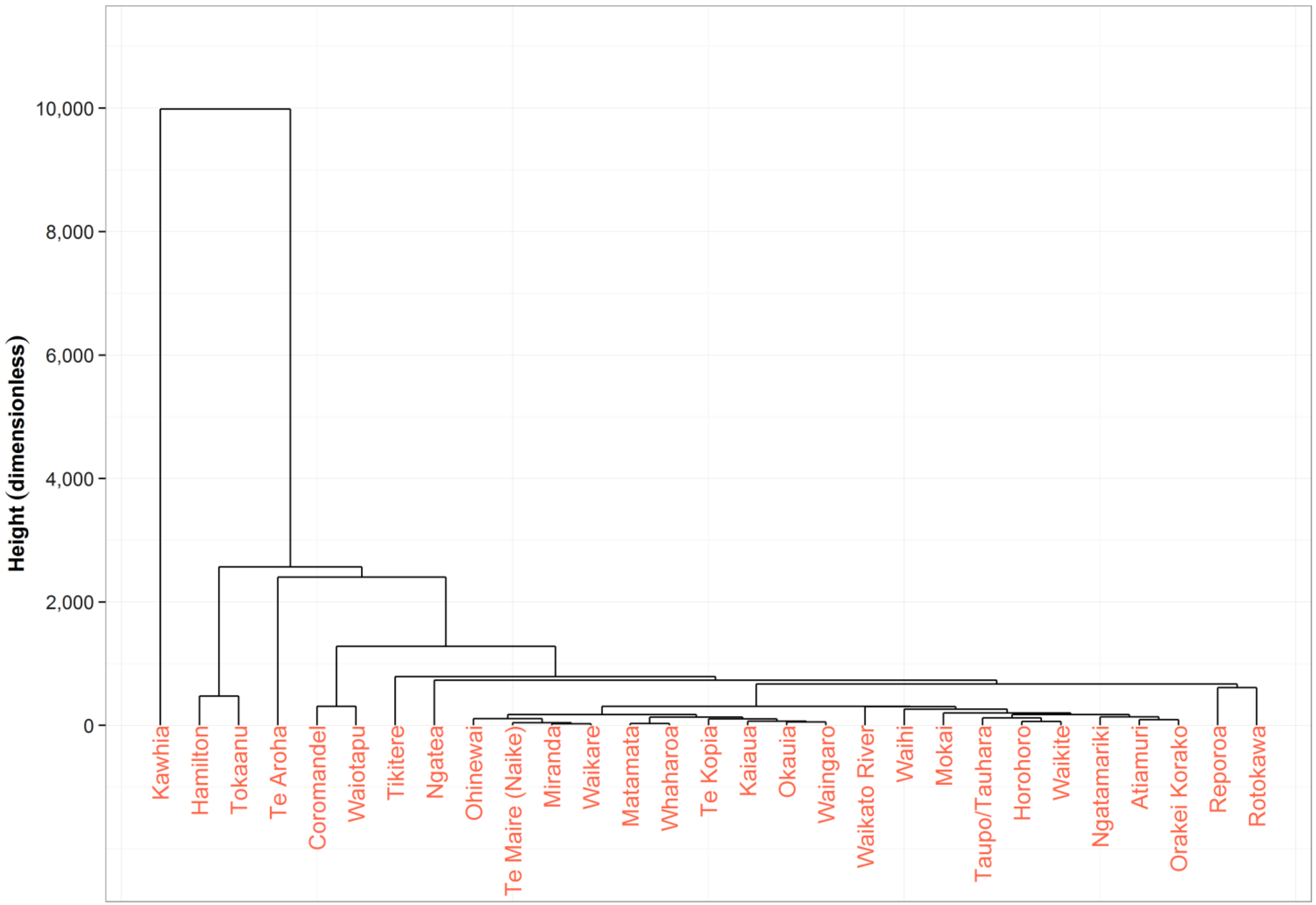


Figure 3: Hierarchal cluster analysis of systems for which data are included in the REGEMP.

Table 1: Hierarchal groups for all REGEMP data compared to systems currently monitored.

Group	Systems currently monitored
Kawhia	-
Hamilton, Tokaanu	Hamilton
Te Aroha	Te Aroha
Coromandel, Waiotapu	Coromandel
Tikitere	Tikitere
Ngatea	Ngatea
Ohinewai, Te Maire, Miranda, Waikare	Ohinewai, Te Maire, Miranda
Matamata, Waharoa	Matamata
Te Kopia , Kaiaua, Okauia, Waingaro	Kaiaua, Okauia, Waingaro
Waikato River	Waikato River
Waihi	-
Mokai	Mokai
Horohoro, Taupo/Tauhara, Waikite	Horohoro, Taupo/Tauhara
Ngatamariki, Atiamuri, Orakei Korako	Atiamuri, Orakei Korako
Reporoa, Rotokawa	Reporoa, Rotokawa

2.2 Implications for the REGEMP

All of the data used in the PCA were collected between 2005 and 2013. That only recent data were used reflects the difference between more comprehensive recent monitoring and historical monitoring, which has typically been focussed on individual parameters. The absence of comprehensive historical records should not be interpreted as a critique of the inclusion of these historical data in the REGEMP database, nor is the integrity of these data in question. Rather, the key finding of the PCA is that there are likely to be diminishing returns in examining every parameter monitored during reviews of the programme, as it is considered examination of a single element from each cluster should be sufficient to determine broad trends in the data. Thus, in this report, the focus will be on the following:

- Temperature and pH (general parameters)
- Bicarbonate, iron, sulfate, chloride, potassium, lithium and silicon (representing PCA clusters), plus arsenic, which is considered a contaminant of public concern.

It should be stressed that the results of the PCA should not be interpreted as justification for reducing the range of parameters currently analysed. Given the relative immaturity of the complete data set (i.e., 2005 onwards), examination of the data in later reviews may result in different clusters as the statistical power of the analyses increases, and it is also likely the introduction of sulfide data (once sufficient data are collected) will also significantly alter the results. It is thus recommended that the current range of analytes is retained.

The results of cluster analysis indicate that the current monitoring programme is generally comprehensive with regards to the types of systems monitored. However, it is considered that sites at Kawhia, Tokaanu and Waihi could be re-established.

2.3 Summary

The results of PCA indicate that geothermal systems within the North Waikato have generally distinct chemical signatures from those in the TVZ and Tongariro areas. Elements monitored as part of the REGEMP programme can be grouped into six broad clusters, and representative elements from each cluster will be the focus of further analysis in this report.

The dataset for the PCA is relatively small, and future insights are likely in later reviews (i.e., once more data are collected). In the interim, it is recommended that the broad selection of parameters measured during routine monitoring is maintained.

3.0 SPATIAL TRENDS

3.1 Approach

Several approaches have been used to assess differences across the Waikato Region. In Webster-Brown & Brown (2007), concentration contours were applied across the region. In Webster-Brown & Brown (2012), it was considered the use of contours led to biases because in some places (e.g., the TVZ) there are many systems within a relatively small area, whereas systems are relatively spread out across the North Waikato. Spatial analyses were instead considered along a single axis (North-South).

In the present review, a compromise between the two previous approaches has been made and data are again presented in three dimensions. Commentary in the present report, which is intended to be a broad overview, is at a system-by-system scale, so for comparisons across the region, the mean for each parameter measured at sites within each system were used. The amalgamation of data means data from exceptional sites (e.g., Champagne Pool in the Waiotapu system) are not highlighted, but their influence was considered sufficient that differences between systems with exceptional features were still apparent.

3.2 Results of Spatial Analyses

3.2.1 Approach

Spatial commentary is provided on a parameter by parameter basis. Results for the eight parameters (i.e., temperature, pH, chloride, potassium, sulfate, silicon, bicarbonate, lithium and iron) selected for this review are described in Sections 3.2.2 to 3.2.11 and presented in Figure 4 to Figure 8.

3.2.2 Temperature

The hottest systems are located in the TVZ area, and the coolest systems are located in the North Waikato (Figure 4a). These results are not at all novel, but do highlight one of the key differences between the warmer more active TVZ and Tongariro areas, and the “legacy” systems of the North Waikato.

Spatial trend: Low to the northwest, high to the southeast.

3.2.3 pH

The results for pH emphasise that there is no direct correlation between high temperatures and deep source waters. As shown in Figure 4b, low pH (less than pH 4) systems (which indicate the source of the thermal waters is relatively shallow) were more common in the hotter TVZ and the Tongariro areas than the relatively cooler North Waikato. The very alkaline pH values (e.g., pH >9) recorded in the northwest of the North Waikato region have not been commented on in previous reviews, and are most likely the product of the (non-geothermal) source of groundwater in these areas, which is derived from greywacke.

Spatial trend: Alkaline to the northwest, acidic to the south and southeast.

3.2.4 Chloride

As shown in Figure 5a, very high chloride concentrations were measured at the margins of the study area (Kawhia, Coromandel in the North Waikato area, Ruapehu in the Tongariro area). At Ruapehu, magmatic influences are the most likely cause of the elevated concentrations. The arc of elevated concentrations from Kawhia to Hamilton to Te Aroha and the Coromandel is likely the results of a mixture of both saline (coasts) and magmatic (Te Aroha) influences. Elevated chloride concentrations within the TVZ are attributed to deep sources of geothermal fluids.

Spatial trend: Elevated in the TVZ, on Ruapehu, and an arc from Kawhia to the Coromandel.

3.2.5 Potassium

Potassium concentrations are relatively low in most systems, but were elevated in some coastal systems (Kawhia and the Coromandel) and at Mokai and Ohaaki (Figure 5). The high results for the latter two systems were derived from deep well samples.

Spatial trend: Generally highest about the coast and about the TVZ.

3.2.6 Sulfate

As shown in Figure 6a, elevated concentrations of sulfate are associated with hot systems (e.g., systems in the TVZ), or where saline intrusions are evident (e.g., Kawhia and the Coromandel). Elevated sulfate concentrations are a particular feature of shallower geothermal systems, and thus elevated sulfate concentrations are also associated with low pH systems. High sulfate measured in the Te Aroha is likely the product of magmatic intrusion (refer Section 3.2.7).

Spatial trend: Elevated in some coastal features and central TVZ features.

3.2.7 Silicon

Silicon concentrations are particularly elevated at Mokai, Ohaaki and Waiotapu (Figure 6b). Results for silicon reflect the difference between hotter, typically deeper source waters of the TVZ compared to the cooler and shallower waters of the North Waikato and Tongariro.

Spatial trend: Elevated in the TVZ, relatively low elsewhere.

3.2.8 Bicarbonate

Bicarbonate concentrations are elevated along a corridor from Tokaanu (immediately south of Lake Taupo), through the TVZ and then north-northwest from Okoroire to Kerepehi at the base of the Firth of Thames (Figure 7a). This pattern (outside of the TVZ) broadly corresponds with the Hauraki rift zone, which runs perpendicular to the TVZ (Reyes 2008). The highest concentrations of bicarbonate were measured in sites within the Te Aroha system, and are attributed to inputs of carbon dioxide from a magma source approximately 150 m deep (Murithi 2012).

Spatial trend: Elevations in the TVZ and within Hauraki Rift Zone.

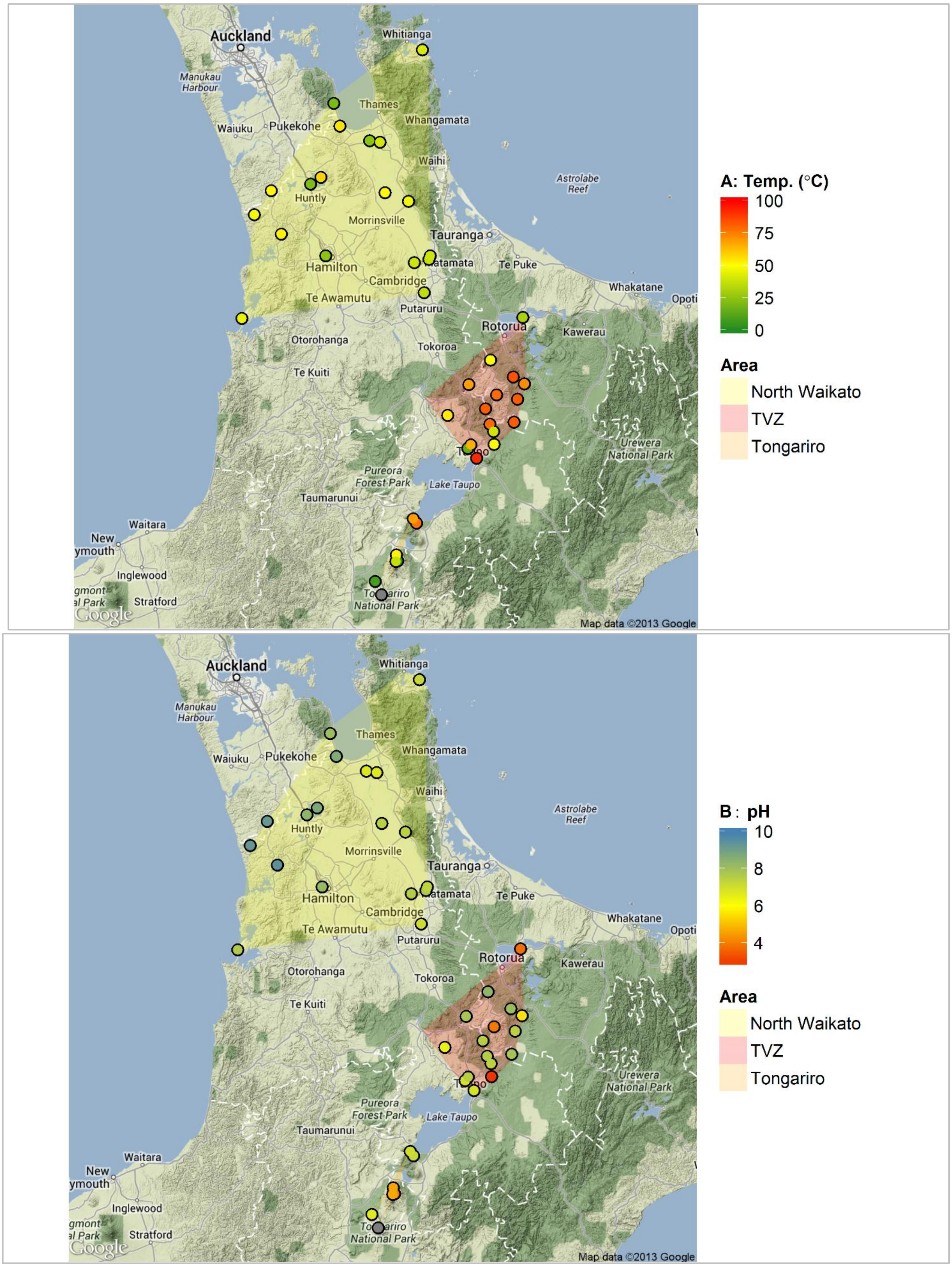
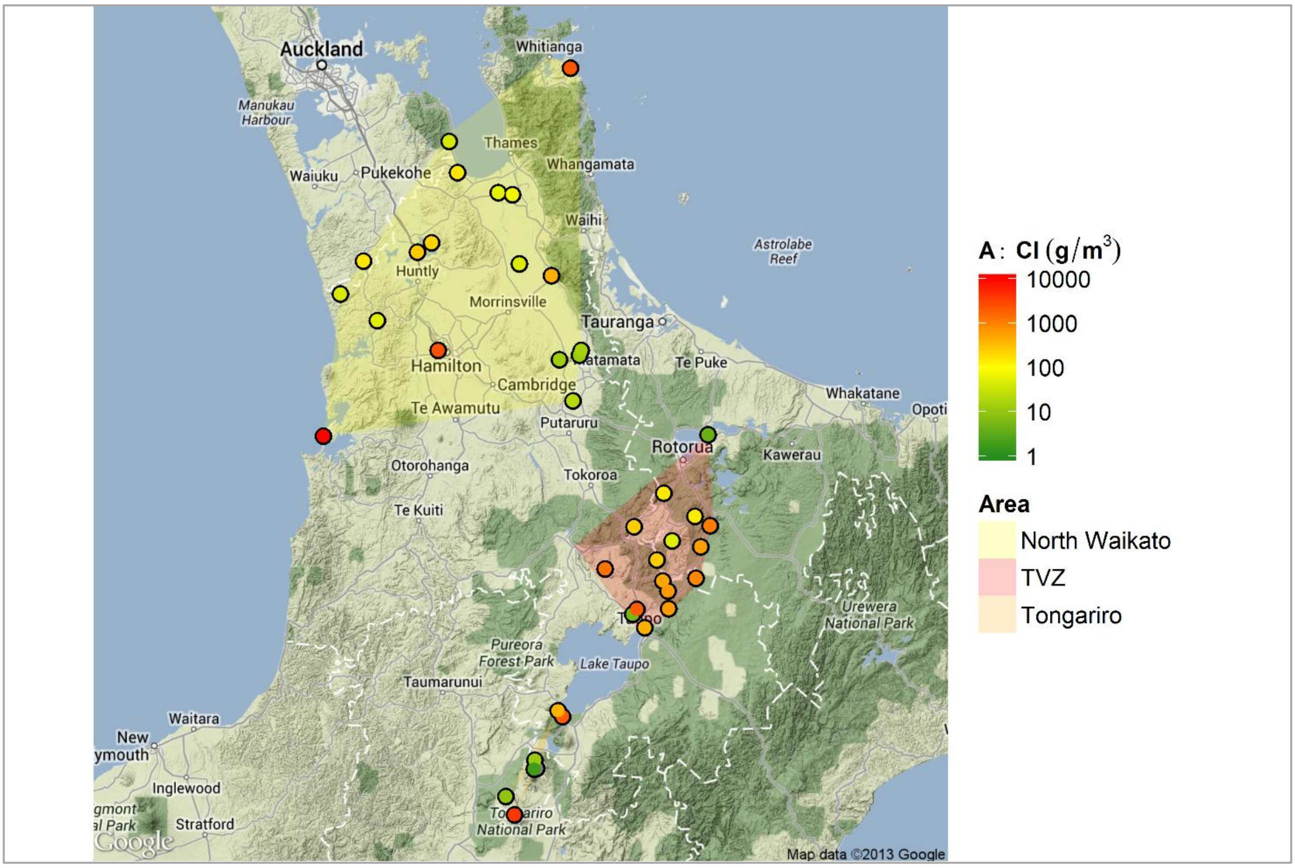


Figure 4: A) Temperature and B) pH in REGEMP geothermal systems (grey dot indicates no data).



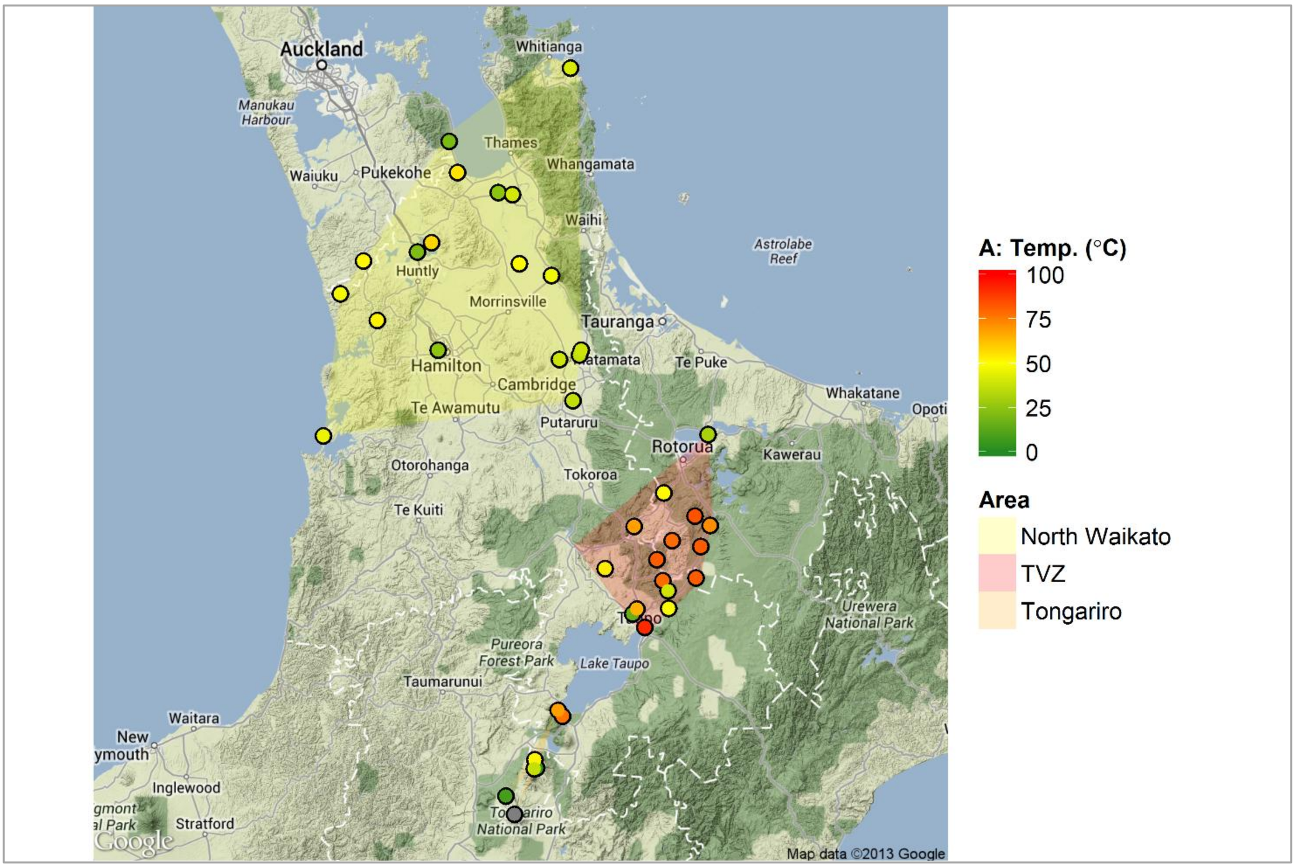


Figure 5: A) Chloride and B) potassium concentrations in REGEMP geothermal systems (grey dot indicates no data).

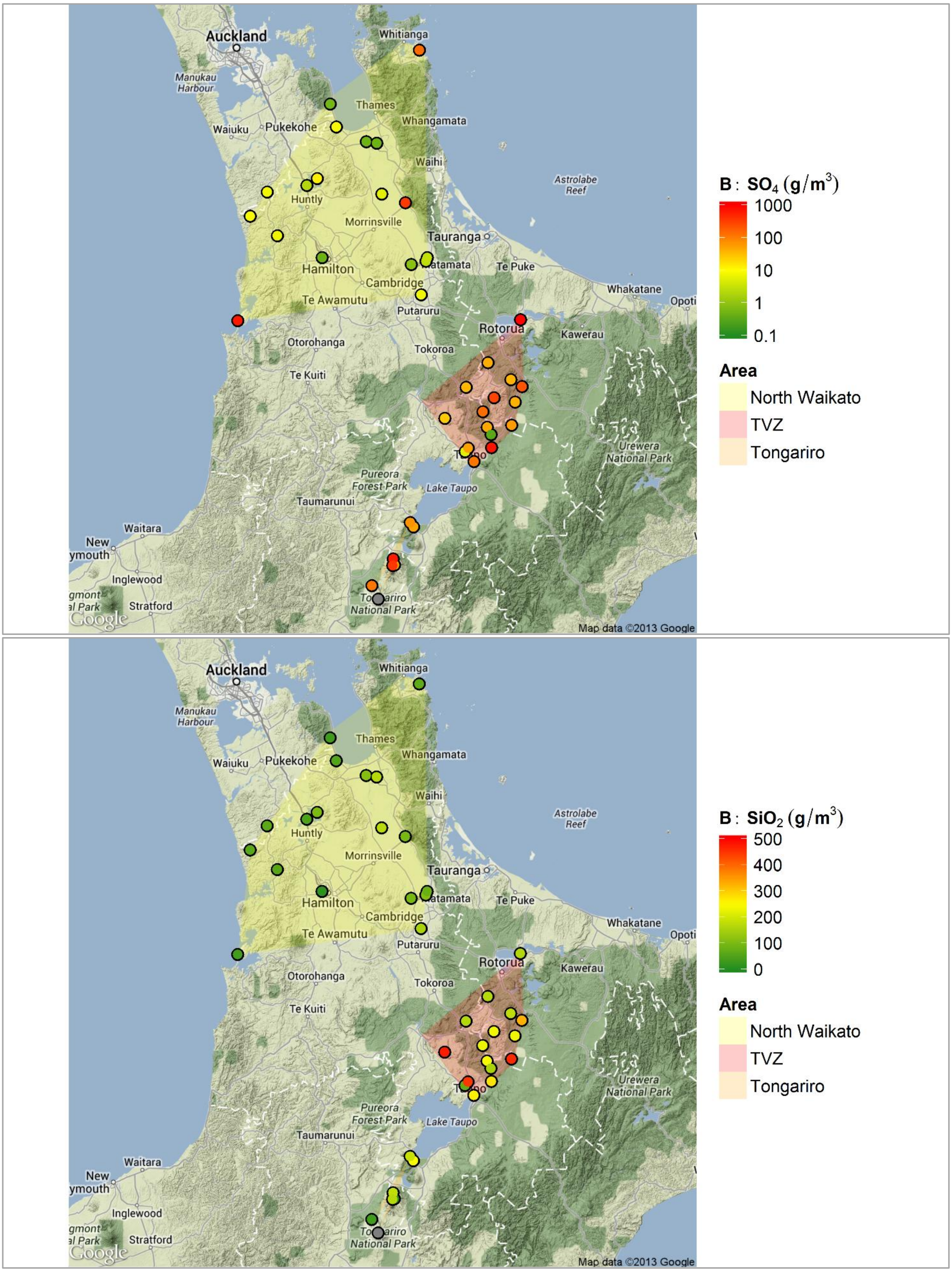


Figure 6: A) Sulfate and B) silicon (as SiO_2) concentrations in REGEMP geothermal systems (grey indicates no data).

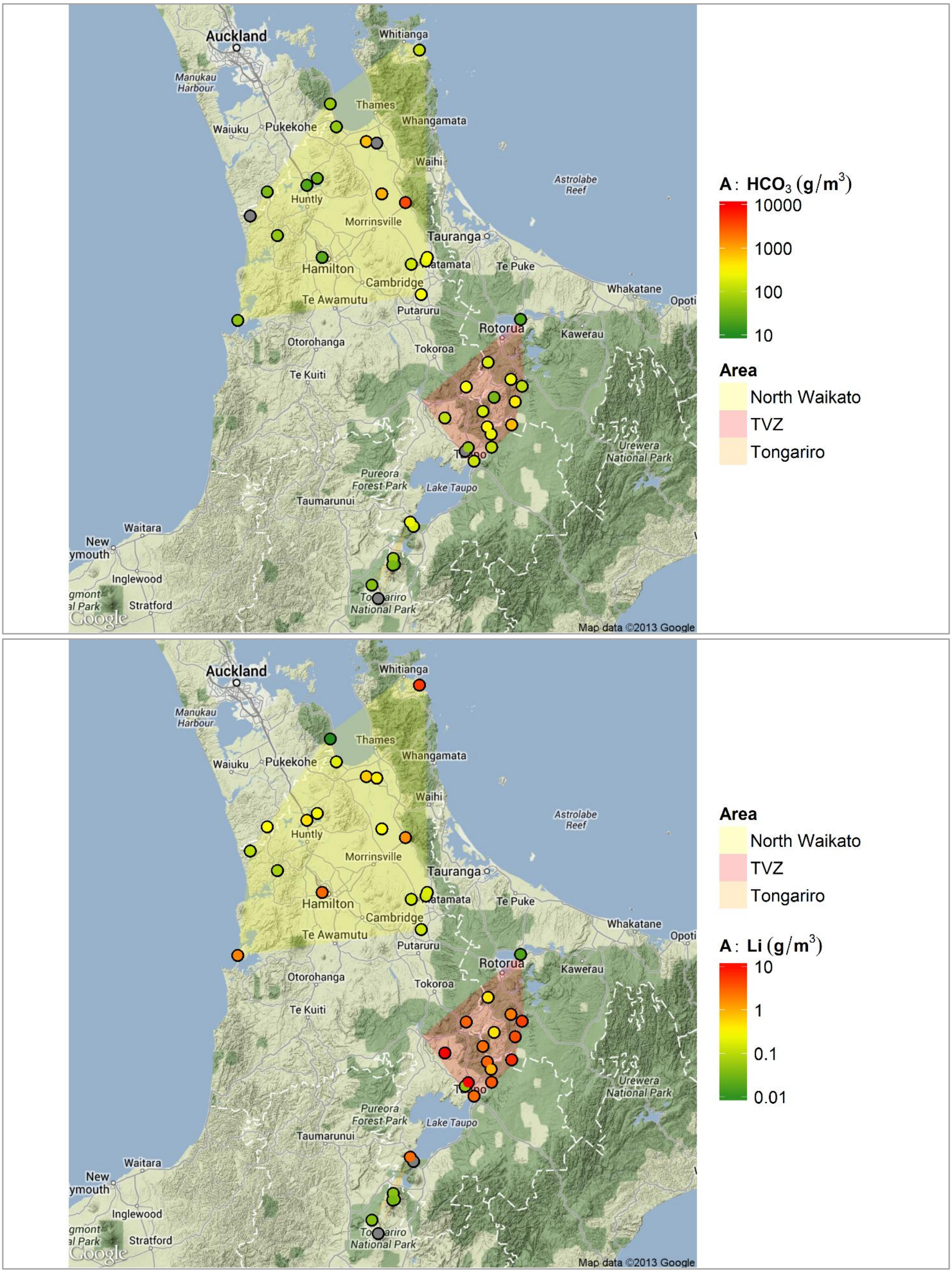


Figure 7: A) Bicarbonate and B) lithium concentrations in REGEMP geothermal systems (grey indicates no data).

3.2.9 Lithium

Elevated lithium concentrations are particularly associated with the TVZ, and were noticeably low in the shallow, magmatically influenced systems in the Tongariro area (Figure 7b). Elevated lithium concentrations were also measured in an arc from Kawhia and Hamilton through Te Aroha to the Coromandel, which coincided with elevated chloride concentrations (refer Section 3.2.3).

Spatial trend: Elevated in the TVZ, on Ruapehu, and an arc from Kawhia to the Coromandel.

3.2.10 Arsenic

With the exception of Te Aroha, arsenic, which was associated with lithium in the PCA, was not elevated in Northern Waikato geothermal systems. Instead, concentrations of arsenic were typically elevated about Lake Taupo, generally corresponding to deeper source waters. The difference in trends, compared to e.g., lithium most likely occurs because arsenic concentrations in seawater are relatively low. However, when saline intrusions can be discounted, arsenic and lithium correlate well (e.g., Webster-Brown and Brown 2012).

Spatial trend: Elevated about Lake Taupo, typically higher in southern systems compared to northern systems.

3.2.11 Iron

Spatial patterns for iron concentrations (Figure 8) strongly resembled that for pH. Elevated iron concentrations were associated with low pH systems. In alkaline systems (where iron is much less soluble), concentrations were very low. Elevated concentrations of iron were thus limited to selected sites within the TVZ and in the Tongariro area.

Spatial trend: Very low to the northwest, higher to the south and southeast.

3.3 Conclusions and Implications for the REGEMP

The drivers of spatial trends within the REGEMP data were the depth of source waters, magmatic intrusion and saline influences. In general, systems within the central TVZ were typically hotter and elevated with respect to elements associated with geothermal processes, compared to sites in the North Waikato and Tongariro area. Despite a difference in approach, the results of spatial analysis of REGEMP data in three dimensions were consistent with those reported in previous reports.

The results of spatial analyses indicate, although there is reasonable coverage of systems for most parameters, there may be grounds to reestablish a site at Kawhia (currently not monitored). Although monitoring the site presents some logistical challenges, the chemisty of the site is considered different enough from elsewhere that there would be value in continued monitoring.

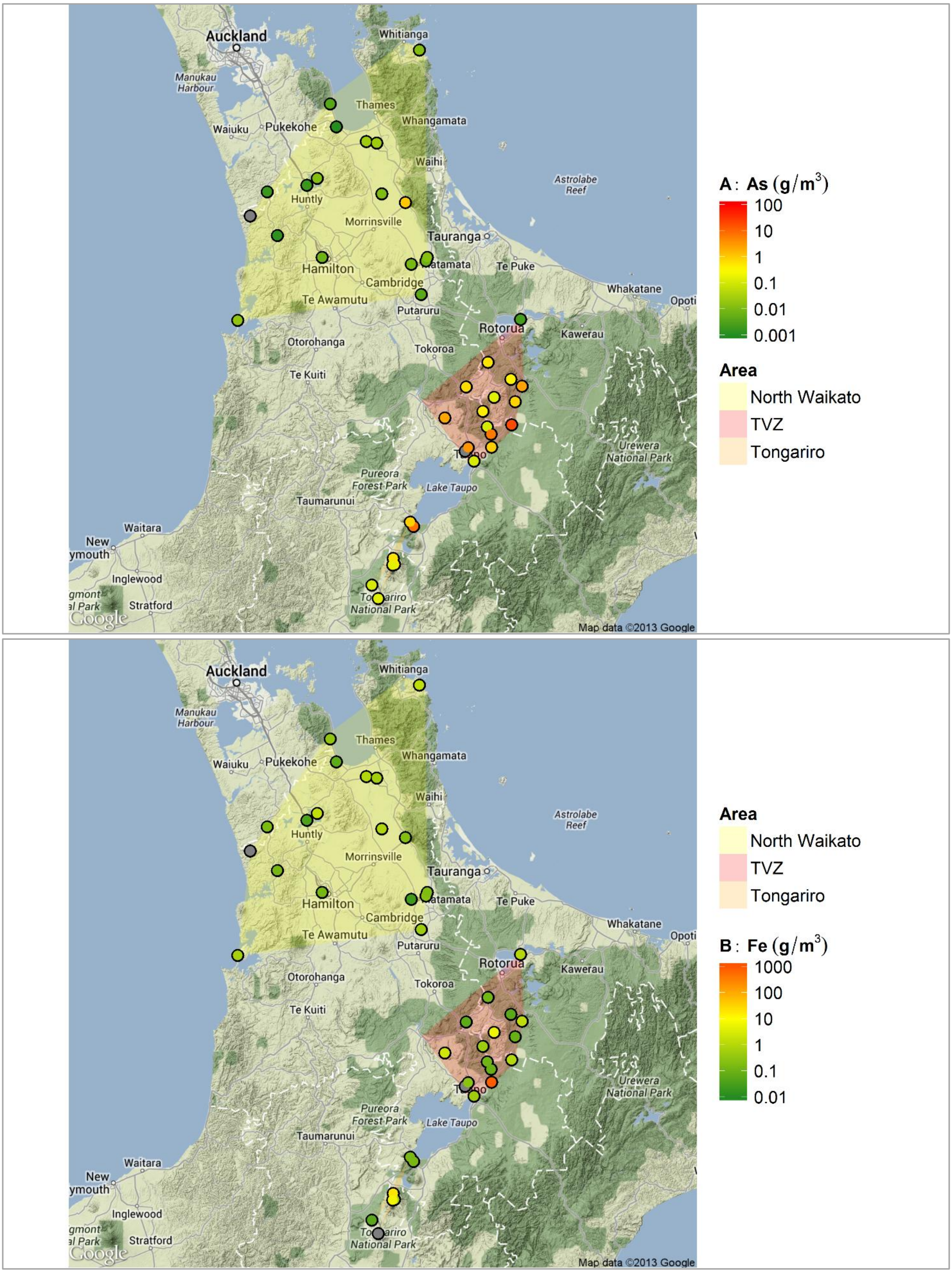


Figure 8: Iron concentrations in REGEMP geothermal systems (grey indicates no data).

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4.0 TEMPORAL TRENDS

4.1 Site Selection

Temporal trend analyses were undertaken on a location by location basis in previous reviews, but have been limited in most cases because of the relatively small number of data points collected at each site. Dataset sizes continue to present a significant limitation for any analysis of temporal trends - of the 62 sites sampled since 2009, only ten sites have data records with more than five sampling points.

In this review, it was considered that the analysis of data sets containing fewer than five data points was unlikely to provide any further insight not already offered in Webster-Brown & Brown (2007; 2012). In addition, where the frequency between samples was greater than 20 years, older data were omitted. The sites that met these criteria are listed in Table 2.

4.2 General Trends

4.2.1 Temperature and pH

Based on Shapiro-Wilkes analysis, the data for temperature and pH collected at each of the ten sites were not normal. As such, temperature and pH data from the sites selected for temporal analysis were assessed for differences using the Kruskal-Wallis Rank Sum test. The null-hypothesis for the Kruskal-Wallis Rank Sum test was that data are from an identical population (in this instance an unchanged source), but there was no assumption that these data follow the normal distribution.

Table 2: Sites with long (n>5) data records.

Area	System	Site	Earliest record	Length of record
North Waikato	Miranda	Hot pools	1984	9
	Te Aroha	Mokena	1905	16
	Te Maire	Spring #1	1969	10
	Waingaro	Waingaro Bore	1981	6
TVZ	Horohoro	Waipupumahana	1963	10
	Atiamuri	Whangapoa	1978	7
	Mokai	Waipapa Stream	1978	17
	Waiotapu	Champagne Pool #1	1905	33
		Oyster Pool	1905	6
Tongariro	Soda Springs	No Name Spring	2010	10

The results indicate there is no evidence that a statistically significant ($p<0.05$) change in either temperature or pH over time has occurred at any of the ten sites assessed. However, when the data are analysed further it is clear the limited length of the data records means the statistical analyses of results must be interpreted with caution. A noticeable decline in temperatures is apparent in the data for Spring #1 at Te Maire, Mokena at Te Aroha and Oyster Pool at Wai-O-Tapu (Figure 9). However, the results for Spring #1 at Te Maire have been relatively stable since the early 1990s, and elsewhere there are insufficient data to indicate whether the decreases are permanent or reflect the variability of the given spring. Te Maire aside, overall it is considered there is little evidence to indicate the presence of any detectable trends in temperatures of springs monitored across the Waikato region.

Similarly, the statistical analysis of pH data did not indicate a significant difference at Oyster Pool, but examination of the data (Figure 10) indicates there has been a shift from acidic to circumneutral pH values (pH about 7) between the early 1990s and the late 2000s. Again, the failure to detect this change is most likely a product of the small dataset.

4.2.2 Chemistry

The frequent presence of data less than detection limit values for iron and lithium meant it was considered the application of multivariate statistics was inappropriate, especially given the small datasets for most sites. The results for the representative elements for all North Waikato and TVZ sites analysed for temporal trends are instead presented graphically in Figure 11. Because monitoring at No Name Spring (Soda Springs; Tongariro) did not begin until 2009, chemistry data for this feature are presented separately (Figure 12).

Decreases in iron concentrations were noted for several systems. However, it is likely that historical values were for total rather than dissolved concentrations, and, in addition, the analytical detection limit for iron has decreased over time. For other changes, such as that observed for bicarbonate at Mokena, the length of time between sampling (~20 years) means there is no way to distinguish between whether the observations represent real changes or are the result of atypical one-off measurements and/or changes in analytical methods.

Overall, no overall temporal trends were evident in the data, which is consistent with the outcomes of statistical analyses for temperature and pH.

4.3 Summary and Implications for the REGEMP

With the exception of a change in temperature measured at Spring #1 in the Te Maire system, no long-term trends were evident in data for sites for which it was considered there were sufficient data to analyse. However, the analysis of long-term trends is considerably constrained by the relatively small datasets for these ten sites, of which the longest record (at Champagne Pool, Waiotapu), only extends to 33 samples across more than 100 years. It is therefore recommended that, if the assessment of long-term trends is to remain an aim of REGEMP, sampling continue at as many of the currently measured sites as is allowed by logistics and resources.

5.0 CONCLUSIONS AND FUTURE MONITORING

This review has considered spatial and temporal trends and statistical similarities between sites and systems for all applicable data from the REGEMP database. Based on these considerations, the following alterations to the REGEMP design are recommended:

- Maintain the monitoring frequency (i.e., no greater than four years between samples, and more frequently where possible).
- Continue to analyse samples for a comprehensive range of parameters (e.g., consistent with data produced since 2009).
- Resume monitoring at Kawhia, Tokaanu and Waihi.
- Remove Emerald Lakes (and Tama Lakes) from the REGEMP database (as they are not geothermal systems).

Figure 9: Temperature records for the ten currently monitored springs with long (n>5) records.

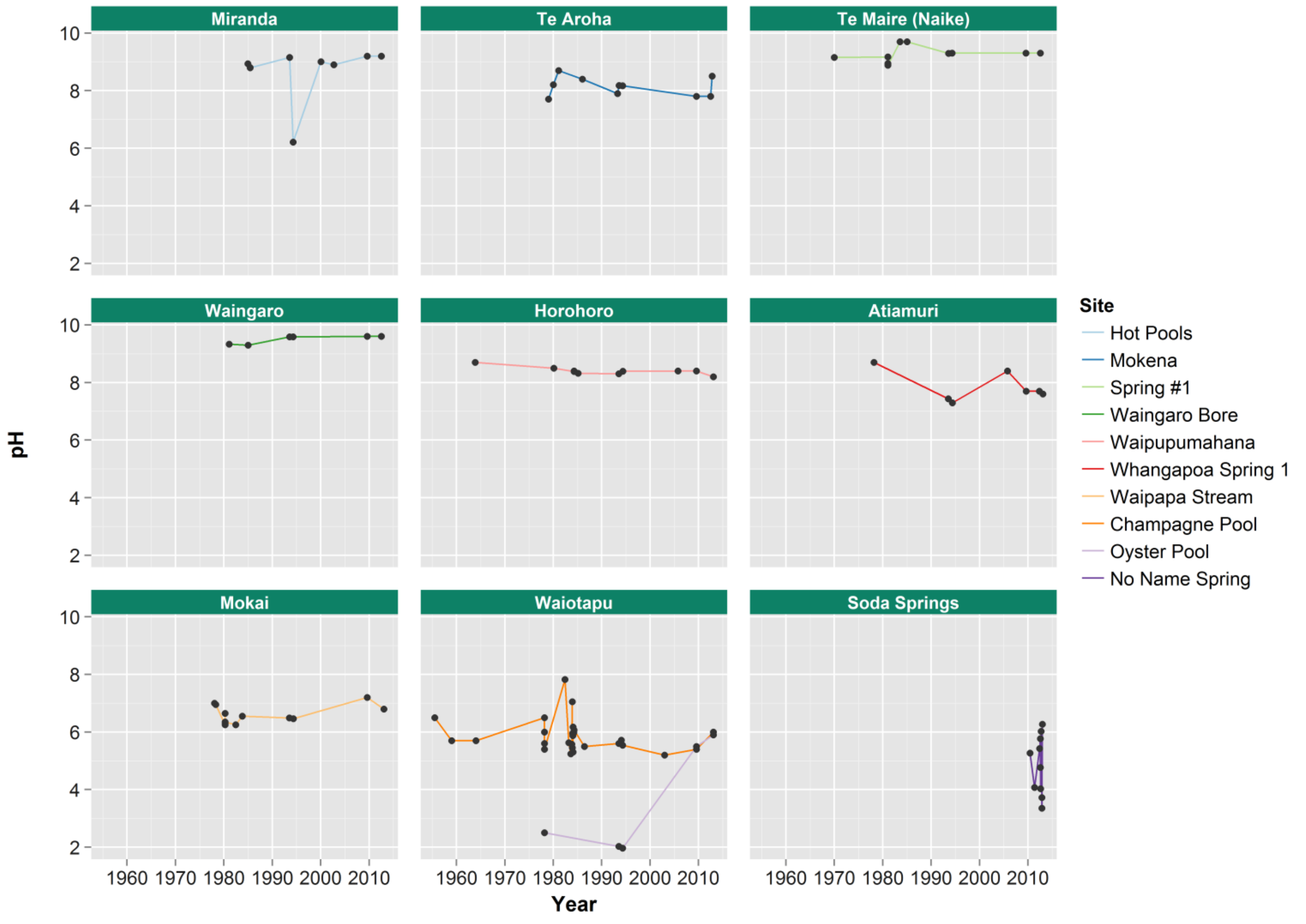

Figure 10: pH records for the ten currently monitored springs with long (n>5) records.

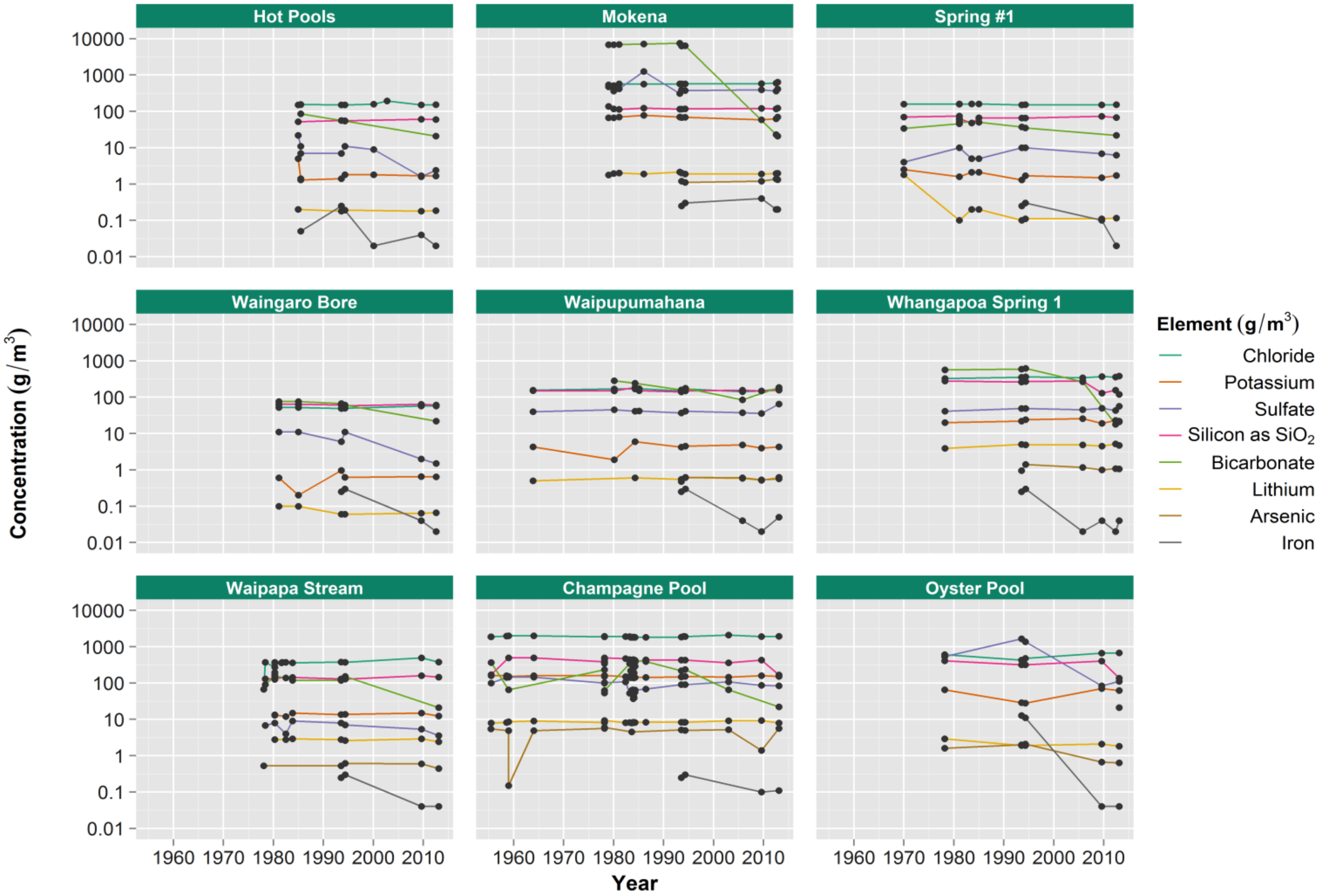

Figure 11: Elemental concentrations for currently monitored springs from North Waikato and the TVZ with long (n>5) records (HCO_3 not measured at Oyster Pool until 2011).

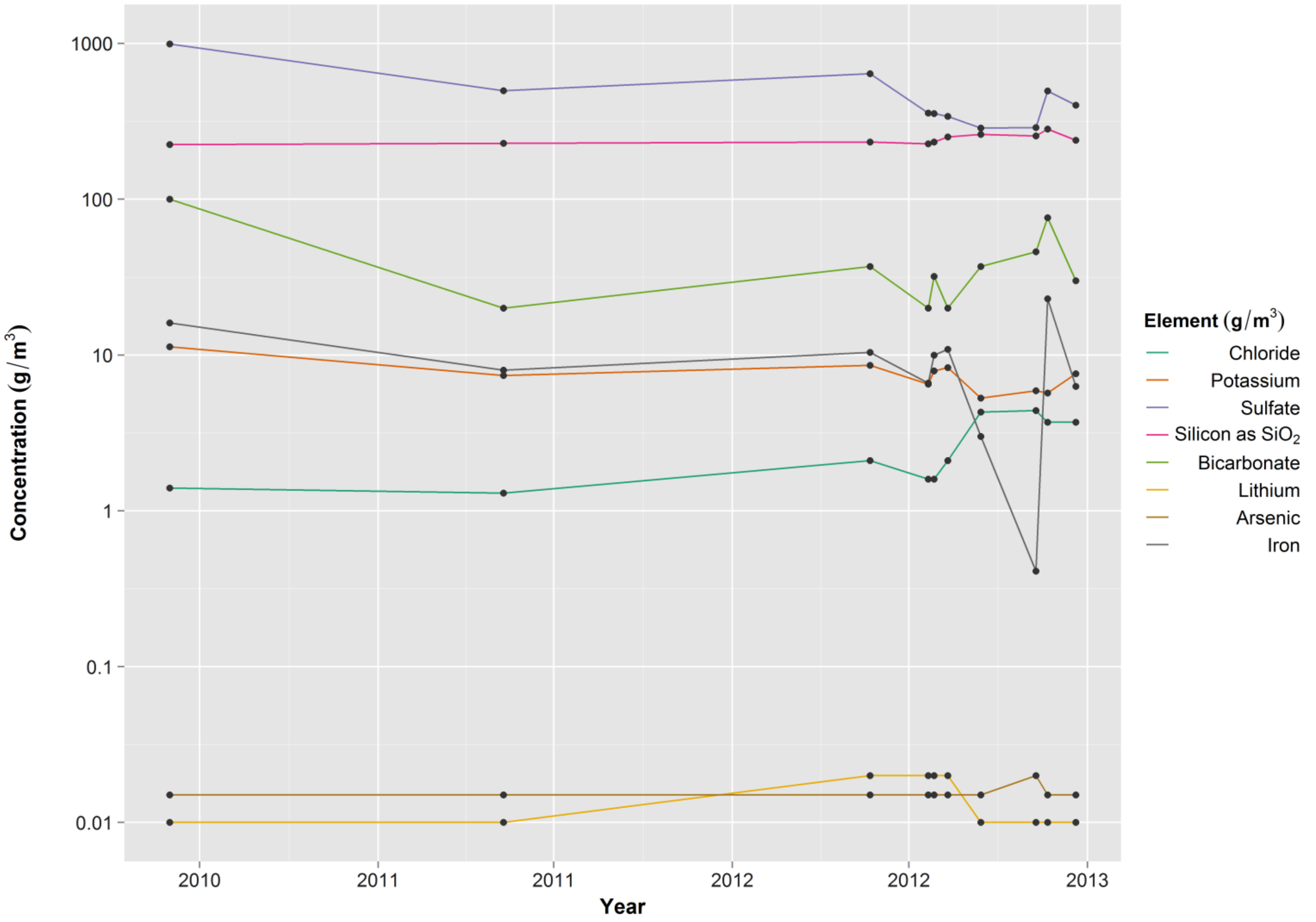

Figure 12: Elemental concentrations for No Name Spring in the Soda Springs geothermal system.

6.0 LIMITATIONS

Your attention is drawn to the document, “Report Limitations” (Appendix D). The statements presented in that document are intended to advise you of what your realistic expectations of this report should be, and to present you with recommendations on how to minimise the risks to which this report relates which are associated with this project. The document is not intended to exclude or otherwise limit the obligations necessarily imposed by law on Golder Associates (NZ) Limited, but rather to ensure that all parties who may rely on this report are aware of the responsibilities each assumes in so doing.

7.0 REFERENCES

Cheng Q, Bonham-Carter G, Wang W, Zhang S, Li W, Qinglin X 2010. A spatially weighted principal component analysis for multi-element geochemical data for mapping locations of felsic intrusions in the Gejiu mineral district of Yunnan, China. Computers & Geosciences 37(5): 662-669.

Huser B, Jenkinson D 1996. Regional Geothermal Features Monitoring Programme. Waikato Regional Council Technical Report 96/18.

Luketina K 2007. REGEMP II: Regional Geothermal Geochemistry Monitoring Programme Environment Waikato Technical Report 2007/36 http://www.waikatoregion.govt.nz/Services/Publications/Technical-Reports/Regional-Geothermal-Geochemistry-Monitoring-Programme-REGEMP-II/.

Murithi LM 2012. The chemistry of waters of Te Aroha geothermal system. Waikato Regional Council Technical Report 2013/07. http://www.waikatoregion.govt.nz/tr201307.

R Core Team 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL: http://R-project.org/.

Reyes AG 2008. Water-rock interactions in a low-enthalpy back-rift geothermal system, New Zealand. Proceedings of the 30th Anniversary Workshop of the United Nations University Geothermal Training Programme. August 2008.

Webster-Brown JG, Brown KL 2008. Interpretation of geochemical data (REGEMP II) and recommendations for further monitoring. Waikato Regional Council Technical Report 2008/01. http://www.waikatoregion.govt.nz/Services/Publications/Technical-Reports/Interpretation-of-Geochemical-Data-REGEMP-II-and-Recommendations-for-Further-Monitoring/.

Webster-Brown JG, Brown KL 2012. 2010 interpretation of geochemical data (REGEMP II) and recommendations for further monitoring. Waikato Regional Council Technical Report 2012/07 http://waikatoregion.govt.nz/tr201207.

Xue J, Lee C, Wakeham S, Armstrong RA 2011. Using principal components analysis (PCA) with cluster analysis to study the organic geochemistry of sinking particles in the ocean. Organic Geochemistry 42(4): 356-367.

APPENDIX A

REGEMP II Monitored Systems

Table 3: Systems sampled since 2009 and data included in the 2013 review.

System	Code	Zone
Coromandel	1	North Waikato
Kaiaua	2	North Waikato
Miranda	3	North Waikato
Ngatea	4	North Waikato
Ohinewai	5	North Waikato
Te Maire	6	North Waikato
Te Aroha	7	North Waikato
Hamilton*	8	North Waikato
Waingaro	9	North Waikato
Okauia	10	North Waikato
Matamata	11	North Waikato
Horohoro	12	Taupo Volcanic Zone
Waikite	13	Taupo Volcanic Zone
Atiamuri	14	Taupo Volcanic Zone
Waiotapu	15	Taupo Volcanic Zone
Reporoa	16	Taupo Volcanic Zone
Mokai	17	Taupo Volcanic Zone
Orakei Korako	18	Taupo Volcanic Zone
Waikato River	19	Taupo Volcanic Zone
Wairakei	20	Taupo Volcanic Zone
Taupo/Tokaanu	21	Taupo Volcanic Zone
Soda Springs	22	Tongariro

*Formerly referred to as Aberfoyle Street.

Table 4: Systems not sampled between 2010-2013.

System	Comments
Arapuni	No longer sampled
Aratiatia	No longer sampled
Emerald Lakes	Not geothermal (refer Webster-Brown & Brown 2012)
Kawhia	Not sampled recently (refer Webster-Brown & Brown 2012)
Kerepehi	Not sampled recently
Ketetahi	Not sampled recently
Ngatamariki	Not sampled recently
Ohaaki	Not sampled recently (refer Webster-Brown & Brown 2012)
Okoroire	Not sampled recently
Poihipi	Not sampled recently
Rotokawa	Not sampled since 2009*
Rotorua	Not in Waikato
Ruapehu	No longer sampled
Silica Rapids	No longer sampled
Te Kopia	Not sampled recently (refer Webster-Brown & Brown 2012)
Te Mihi	Not sampled recently
Tikitere	Not in Waikato
Tokaanu	Not sampled since 2009*
Waihi	Not sampled recently
Waikare	Not sampled recently
Waitoa	Not sampled since 2009*
Waharoa	Not sampled recently

*Sampling recommended in Webster-Brown & Brown (2012).

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APPENDIX B

R Scripts

```
#Examples of scripts used for REGEMP review

#Required libraries
library(ggmap)
library(ggplot2)
library(scales)
library(doBy)
library(grid)
library(plyr)
library(reshape2)
library(ggdendro)

#######Functions used
#Graph exporter - function to export graphs to file
Export<-function(gplot,filename,height=11.69,width=8.27,dpi=450){
  ggsave(file = paste(filename,'.png', sep=""),gplot,width=width,height=height,dpi=dpi,units="in")#  print(gplot)
#Creates graph
  #  dev.off() #Finishes print
}
#Formatting function for y axes
fmt <- function(){
  f <- function(x) as.character(round(x,3))
  f
}

#Function used for PCA analysis plot
PCbiplot <- function(PC, x="PC1", y="PC2") {
  # PC being a prcomp object
  data <- data.frame(obsnames=row.names(PC$x), PC$x)
  plot <- ggplot(data, aes_string(x=x, y=y)) + geom_point(size=0,aes(color=Area))
  plot <- plot + geom_hline(aes(0), size=.2) + geom_vline(aes(0), size=.2)
  datapc <- data.frame(varnames=rownames(PC$rotation), PC$rotation)
  mult <- min(
```

```
    (max(data[,y]) - min(data[,y])/(max(datapc[,y])-min(datapc[,y]))),
    (max(data[,x]) - min(data[,x])/(max(datapc[,x])-min(datapc[,x])))
  )
  datapc <- transform(datapc,
                      v1 = .7 * mult * (get(x)),
                      v2 = .7 * mult * (get(y))
  )
  plot <- plot + coord_equal() + geom_text(data=datapc, aes(x=v1, y=v2, label=varnames), size = 4, vjust=-1, color="black")
  plot <- plot + geom_segment(data=datapc, aes(x=0, y=0, xend=v1, yend=v2), arrow=arrow(length=unit(0.2,"cm")), alpha=0.75, color="steelblue")
  plot
}

#Function to calculate area about points
find_pcs <- function(df) df[chull(df$PC1, df$PC2), ]  #For areas about PCA clusters
find_loc <- function(df) df[chull(df$Lon, df$Lat), ]  #For areas about geothermal areas



######Examples of graphs
###Dendrogram
full<-reg[c(2,3,26:33,36,37,39:45,47,48)]  #Parameters used in PCA
full_p<-na.omit(full)  #Removes NA values
full_h<-summaryBy(data=full_p,.~System,keep.names=TRUE)  #Summary of data by system
rownames(full_h)<-full_a$System  #Names rows
full_ac<-full_h[2:20]  #Concentrations only
full_hc<-hclust(dist(full_ac),"ave") #Create clusteranalysis

#Graph dendrogram
dendro<-ggdendrogram(full_hc, rotate=F, size=5, theme_dendro=F, color="tomato")+scale_y_continuous(name=expression(bold(paste(Height~(dimensionless)))),limits=c(-2200,11000),breaks=c(0,2000,4000,6000,8000,10000),labels=comma)+

theme_bw()+nice+theme(axis.ticks.x=element_blank(),axis.title.x=element_blank(),axis.text.x=element_blank())
#view graph
```

```
print(dendro)
#Save graph
Export(dendro,"dendro",width=11.69,height=8.27)

###Spatial graph
#Specialised theme
nicem<-theme(legend.position="right",legend.key=element_blank(),
             #legend.background=element_rect(fill=NULL,colour="black",size=.5),
             legend.title=element_text(size=rel(0.9)),legend.text=element_text(size=rel(0.9)))

#Make graph
boxall<-make_bbox(Lon,Lat,reg,f=0.5)  #Define area
Allsite<-get_map(boxall,zoom=8,source="google",maptype="terrain")  #Get Google Map
Map_all<-ggmap(Allsite,extent="device") #Create map

#Create generic graph
all_poly<-Map_all+
  geom_polygon(data=sites_hull,alpha=0.2,aes(x=Lon,y=Lat,fill=Area))+  #Creates polygons
  scale_fill_manual(values=c("yellow1","red1","orange")) #Colour polygons
#Create temperature graph (spatial)
Fig4a<-all_poly+
  geom_point(size=4,data=reg_sum,color="black",aes(x=Lon,y=Lat))+ #Place black points for outlines
  geom_point(size=3,data=reg_sum,aes(x=Lon,y=Lat,color=Sample.Temp))+ #Add data

scale_color_gradient2(low="forestgreen",high="red",mid="yellow",midpoint=50,limits=c(0,100),name=expres
sion(bold(paste("A: Temp. (",degree,"C)"))))+ #Aesthetics
  nicem #Add pre-defined additional aesthetics
Export(Fig4a,"Fig4a",height=5.5)  #Export file

### Temporal plot
#Specialised theme
nice<-theme(legend.position="right",legend.key=element_blank(),
            axis.text=element_text(color="gray10",size=rel(1)),
            axis.title=element_text(size=rel(1.1)),
            #legend.background=element_rect(fill=NULL,colour="black",size=.5),
```

```
legend.title=element_text(size=rel(1)),legend.text=element_text(size=rel(1)),
panel.margin=unit(1,"lines"),
axis.title.x=element_text(vjust=-0.01),
axis.title.y=element_text(vjust=-0.01),
plot.margin=(unit(c(0.3,0.3,0.5,0.7),"cm")),
strip.text.x=element_text(color="white",face="bold",size=11),
strip.background=element_rect(fill="#0D8166"))

#Graph
Temp_fig<-ggplot(records_t,aes(Date,value,colour=Site.description))+  #Define basic graph
  #geom_point(color="black",size=3)+
  geom_line()+ #Add lines (will be coloured) by Site
  geom_point(color="grey20",size=2)+ #Add points
  scale_x_date(name=expression(bold(paste("Year"))))+  #Format x axis
  scale_y_continuous(limits=c(40,100),name=expression(bold(paste("Temperature
(",degree,"C)"))),labels=fmt())+  #Format y axis
  scale_colour_brewer(palette="Paired",name="Site")+nice+ #Define colours
  facet_wrap(~System,ncol=3)#+facets  #"Facet graphs - make one graph per System and aline into three
columns
print(Temp_fig)  #Show graph
Export(Temp_fig,"Fig9",height=8.27,width=11.69)  #Export graph to file
```

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APPENDIX C

REGEMP II Data

The appendix for this report is an Excel spreadsheet, Waikato Regional Council document number 2782285. This may be obtained upon request from the Waikato Regional Council

APPENDIX D

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Report Limitations

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