Waikato Regional Council Technical Report 2021/16

# Tauhara domestic bores - Updating of geographical and hydrogeological information

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Prepared by:
**Jesse Lebe**

For:
Waikato Regional Council
Private Bag 3038
Waikato Mail Centre
HAMILTON 3240

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Peer reviewed by:
Robert Reeves, GNS Science

Date June 2021

Peer reviewed by:
Mariana Zuquim, Bay Of Plenty Regional Council

Date June 2021

Approved for release by:
Michelle Begbie

Date November 2022

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# Table of Contents



# Figures

# Tables

# Abstract

Shallow domestic geothermal wells have been installed for houses in Taupō for private hot water access and space heating since the 1960s, within the resistivity boundary of the Wairakei-Tauhara geothermal system. In 2020, 524 domestic bores are known to exist, however minimal information updates have been done since 1988. For this study, the geographical information on bore locations required correcting as it was not measured with GPS or satellite technology. 125 bores required no changes, 291 required coordinate revisions, and 90 required coordinate revision and addition on *Ourmaps* (WRC's internal mapping software), and 18 are not on the WRC database. Water take and heat exchanger bores are identified as the most common bore types.

Geochemistry data shows that the allocated aquifer from which the bores extract their fluids has a predominant steam-heated water chemistry. Due to minimal data existing on the lithological conditions of the bores, lithostratigraphic data from well THM-18 is used as a reference for interpreting the subsurface stratigraphy of the allocated aquifer area. Elevation and bore depth measurements suggest that the Oruanui Formation is the most common lithological unit from which hot fluids are extracted. The Upper Huka Falls Formation is intersected by fewer bores and records lower temperatures than the overlying Oruanui Formation. Fluids exceeding 160 °C were encountered in the Middle Huka Falls Formation, however, the formation is a less practical drilling target than the Oruanui Formation aquifer for future domestic bore drilling due to its situation at significantly greater depths. The Oruanui Formation is the most productive and most ideal target zone for future fluid extractions due to having a reliable high temperature resource at a relatively shallow depth.

Future monitoring of the bores could create a better understanding of the relationship between the domestic bores and surface geothermal features and streams, which have seen a general decline in discharge in recent years. Reintroducing regular bore inspections, implementing tracer flow tests, and improving on 3D geological modelling would improve on the existing understanding of the geothermal bores and the shallow geothermal hydrogeology of Tauhara.

# 1 Introduction

## 1.1 Scope of Report

The initial purpose of this report was to update and review geographical and hydrogeological information of the Tauhara domestic bores in Taupō township. Bores in this study are located in the Taupō suburbs of Tauhara, Hilltop, and Waipahihi, which all lie within the boundary of Tauhara geothermal field (Figure 1-1), a part of the Wairakei-Tauhara geothermal system. As of April 2020, a total of 524 bores are known to Waikato Regional Council (WRC), however minimal update and monitoring were recorded since Curtis (1988) investigated the bores in 1986 – 1987. After working with the available data, the scope of the report was broadened to include the relationship between the lithostratigraphy of the shallow aquifers with the bore distribution. Another factor that drove the widening of the scope is an issue encountered in mid-2020, in which WRC was questioned about the organisation's knowledge about the drying of the Otumuheke Stream in Tauhara.

The used term "domestic bore" refers to a round drilled well of a limited diameter that has a liner and well head, and is a subset of a well. For simplicity purpose of this paper, the term "well" refers to "domestic bores", unless specific well purposes are mentioned (e.g. injection well, production well).


**Figure 1-1 A map showing the geographical divisions of areas with domestic bores in Taupō and Maunganamu. Areas correlate with the actual administrative boundaries of the township, but the extent of Taupō, Tauhara and Maunganamu have been limited to a smaller area for this study based on bore distribution. Maunganamu is the only area not situated within the boundary of Taupō township.**

## 1.2 Historical Monitoring Responsibilities

With the establishment of the Coal Mines Act in 1979, the responsibility for inspecting and monitoring the Tauhara domestic bores was the responsibility of the Mining Inspection Group (MIG), which was set up by the Ministry of Energy (Figure 1-2). The responsibility was again passed on in 1989 to the Ministry of Commerce under its Energy and Resources Division, due to the dissolution of the Ministry of Energy. After the establishment of the Resource Management Act 1991, regional authorities absorbed MIG's resource management function, before the inspectorate was formally assimilated into the Department of Labour (DOL). During this time, inspections were regulated and done by the DOL subdivision of Occupational Safety and Health (OSH). Before the second half of the 2000s, the DOL stopped inspecting and monitoring the Tauhara domestic bores, with the latest inspection report available to WRC being from late 2004. As of 2021, no regulatory or inspectorate body hold the responsibility for inspecting the domestic bores because the central government agency Worksafe is responsible for Health and Safety at worksites only, and a private dwelling is not a worksite unless work is being undertaken there. WRC is responsible only for environmental matters and not for monitoring health and safety issues relating to domestic bores. WRC undertakes a rudimentary monitoring programme of 6-weekly water level and temperature in several of the Taupo bores.

WRC requires a bore permit to be obtained for any new bores. Permit conditions stipulate that details of bores must be provided to Waikato Regional Council and that the bore construction must comply with geothermal bore construction official standards and guidelines The bore details are entered into the WRC database when they are received, however, there is a low level of compliance with the requirements for obtaining a permit and supplying the information.

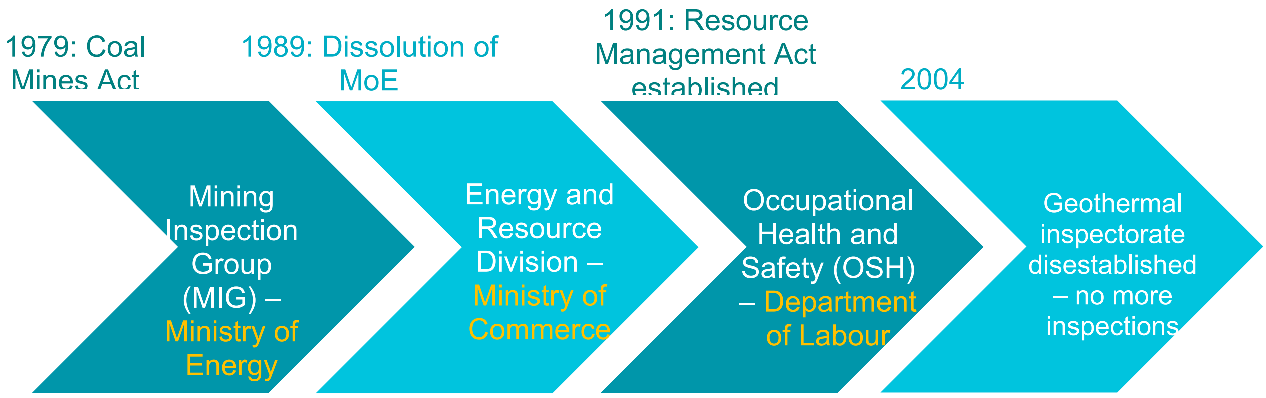


**Figure 1-2 Timeline of the domestic bore inspections, and the organisations responsible for undertaking the task.**

## 1.3 Regional Setting

Taupō township is situated in the central Taupo Volcanic Zone (TVZ), a volcanically active rifting-arc margin associated with the northwest subduction of the Pacific Plate underneath the Australian Plate, offshore the eastern margin of the North Island (Cole, 1990; Wilson et al., 1995; Wilson and Rowland, 2016). Due to its regional geological setting, the TVZ has a relatively high thermal gradient of ~50 °C/km (Reyes, 2007) and hosts geothermal systems with natural heat discharges exceeding 30 $MW_{th}$ (Bibby et al., 1995; Hochstein, 1995). The township lies on the northern and eastern side of Tapuaeharuru Bay at Lake Taupo, which marks the boundary of the Taupo Caldera Complex (Spinks et al., 2005), and lies within the axial rift zone of the TVZ, making Taupo an intra-rift caldera (Spinks et al., 2005). Lake Taupo also marks the southernmost part of the rhyolite segment of the TVZ.

All bores including those at Maunganamu are situated within the resistivity boundary of the Wairakei-Tauhara geothermal system (Daysh et al., 2015), directly to the south of the Tauhara geothermal field (Figure 1-3). Since 2010, the Te Huka power station has been extracting geothermal fluid from the Tauhara geothermal field, with the power station having an installed generation capacity of 24 MWe.

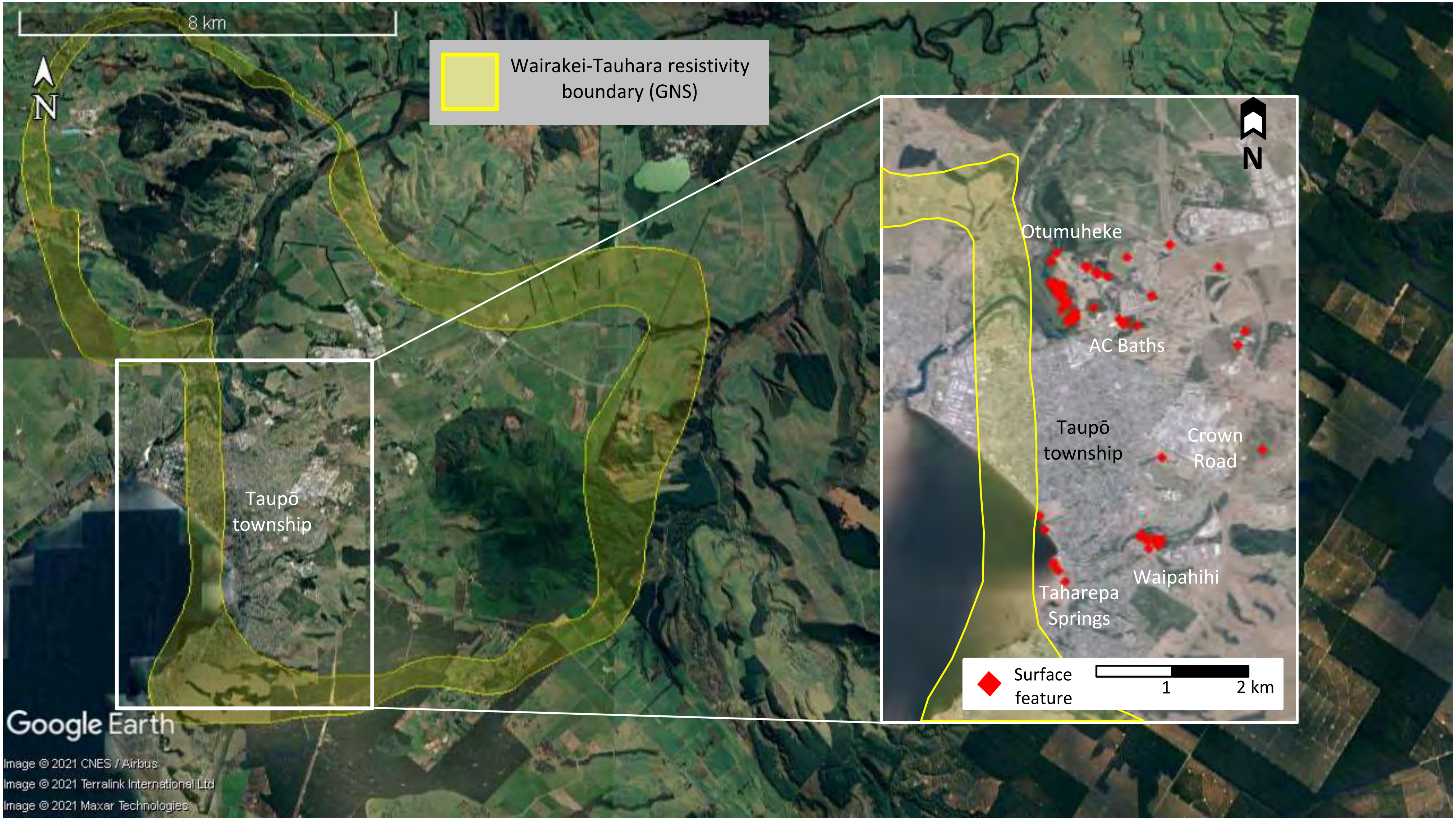


**Figure 1-3 Map showing Taupō township and the resistivity boundary of the Wairakei-Tauhara geothermal system surrounding it. The blowout map shows the locations of existing surface features, including historical features that are currently inactive.**

# 2 Updating of Geographical Information

## 2.1 Issues with Geographical Coordinates and Database

Many Tauhara domestic bores were recorded during the Ministry of Energy and then the Ministry of Commerce inspection periods, with most records dating no later than 1998. The use of Global Positioning System (GPS) devices was not readily available in New Zealand at the time of recording, and if it was used, its margin of error would be relatively large compared to today. The absence of GPS measurements during the recording and inspection of the bores resulted in the initial X-Y coordinates being less accurate.

An investigation was undertaken to create more accurate corrections to the geographical locations of the Tauhara domestic bores. Information on the bores were gathered from multiple sources including from OSH reports and images, a datasheet created by GNS Science (presumably using data from OSH), two WRC database systems in *Located* and *Wiski*, and *Ourmaps*. *Google Earth* was also used as a secondary tool for checking accuracy of coordinates provided by OSH.

### 2.1.1 Methodology for Investigation

The Microsoft Excel Open XML (XLSX) file produced by GNS Science records 506 individual domestic bores in the Taupō-Tauhara area (although a total of 524 bores are known to exist), along with New Zealand Map Grid (NZMG) X-Y coordinates, the maximum temperature and depth measurements of each bore if available, providing a good framework to start the investigation. Hence, a modified version of this file was used as the main document in recording changes and additional data throughout the investigation.

The initial step for checking each domestic well location is by inputting the available coordinates and address from the XLSX file into both *Ourmaps* and *Google Earth*, to observe whether the coordinates and address correspond to one another. The OSH documents and images are then inspected to find detailed information on the specific location in the property. If a more detailed location is available, or if the provided coordinates are incorrect, more accurate coordinate values are obtained from *Ourmaps*. The margin of error for the obtained coordinates are anywhere between ± 10 – 50 m and are recorded in NZMG for consistency.

An important step is to check if the bore is recorded on *Ourmaps* as a location; if it is present the *Located* key (LOC_KEY) should be recorded to create a more complete data record, and if absent should be recorded for the bore to be added into the system in the future. The result of this investigation was that from 506 bores, 125 bores have the right coordinates, while the remaining 381 bores needed varying degrees of corrections, of which 90 just need revised coordinates and 291 bores also need to be added to *Ourmaps, Located,* and *Wiski*.

### 2.1.2 Results of Updating Process

From the 506 bores recorded within the OSH inspection documents, only 125 bores had the right coordinates and did not require further changes within WRC databases (Figure 2-1). There were 291 bores requiring coordinate revisions, due to having incorrect X-Y coordinate records. Some of the inaccuracies are relatively acceptable (<10 m) considering many sites having margins of errors of ±10 – 15 m, however, in cases where the exact location of the bore in a property is located through evidence in the reports, the site would be marked as requiring a coordinate revision to create a more accurate location on the databases. Updates for these coordinates have been recorded in the Excel spreadsheet, and have been passed to the Environmental Monitoring data team to be included in the online databases. Furthermore, there are 90 bores that are not listed on the WRC databases, lack coordinates, and/or do not have a proper address recorded. Data points for these bores need to be created and uploaded into the WRC databases, and coordinates need to be searched if required. As a total of 524 bores are known to exist by WRC, information for 18 more bores needs to be recorded and added into the Excel spreadsheet which systematically records all the bores.

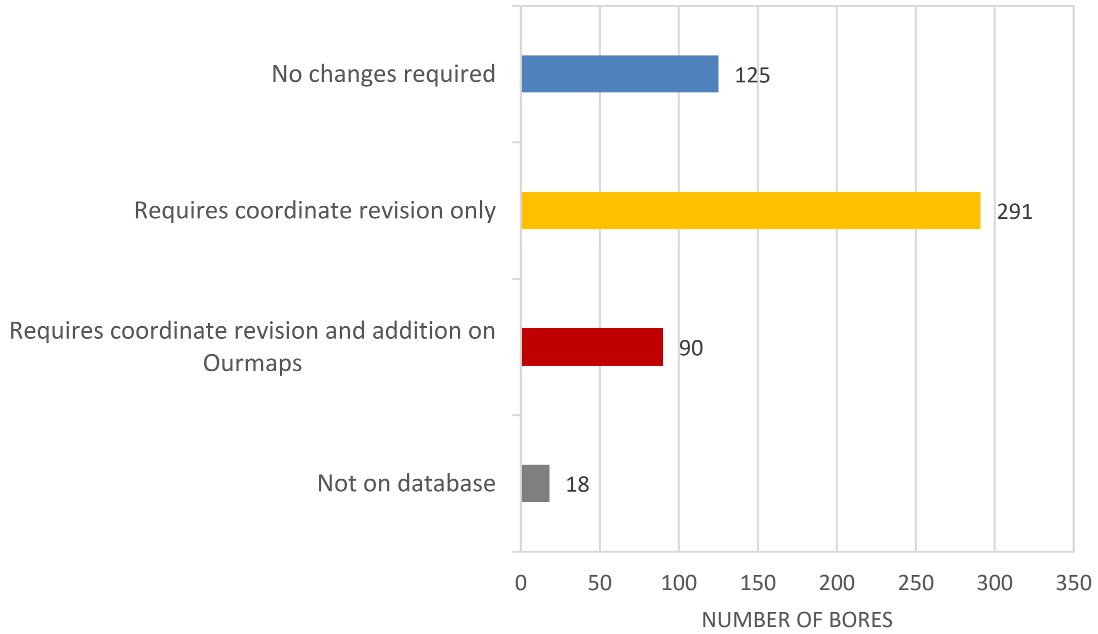


**Figure 2-1 Graph showing the different categories of data updating that needs to be conducted.**

# 3 Review of Bores and Hydrogeology

## 3.1 Bore Information

### 3.1.1 Bore Types

As WRC is not responsible for monitoring or inspecting the Tauhara domestic bores, most of the information possessed by WRC is secondary in nature. As mentioned in previous sections, work done by R.J. Curtis and the OSH documentation provide the majority of the data available to WRC.

During his study between 1986-87 for the Waikato Catchment Board, Curtis was only able to retrieve information for 381 bores, as many bores existing today had not yet existed during that time. Despite the relatively lower number of bores, the data collected by Curtis is very valuable, as it is one of the only two data sources available to WRC, and the data have quantitative elements to them.

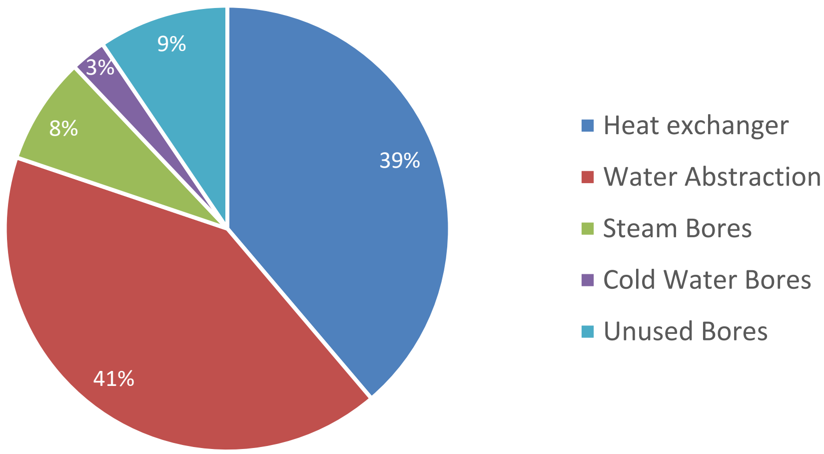


**Figure 3-1 Percentage of different bore types recorded by Curtis (1988) from a survey taken between 1986-87 from 381 locations.**

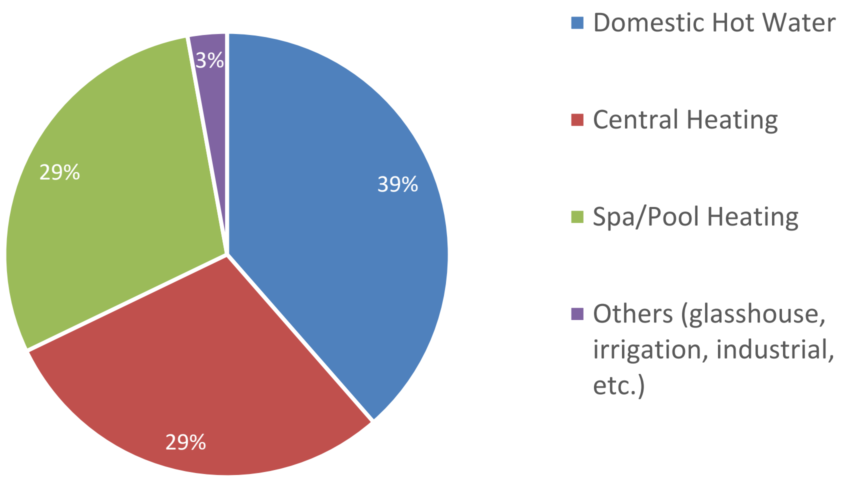


**Figure 3-2 Percentage of bore usages as recorded by Curtis (1988) from a survey taken between 1986-87 from 381 locations.**

From the questionnaire made by Curtis to domestic bore owners, we are able observe that most bores in the Taupō-Tauhara area are water abstraction (41%) and heat exchanger (39%) bores. Some of the bores have become unused (9%) due to the absence of sufficiently high-temperature resources, or due to a lack of maintenance or use (Figure 3-1). From the same set of bores, it is observable that domestic hot water use (39%) is the primary purpose for constructing a domestic well in the study area. Wells used for spa or pool heating, and for central heating are the next most abundant, both covering 29% of the bore population (Figure 3-2). These three uses add up to 97% of total recorded use in 1987, leaving just 3% to other uses including for industrial purposes. However, documentation done by OSH show that since Curtis' study, bores have been constructed in industrial sites (e.g. Matai St, Miro St, Crown Rd, Manuka St, etc.), which would significantly increase the percentage of bores used for other purposes.

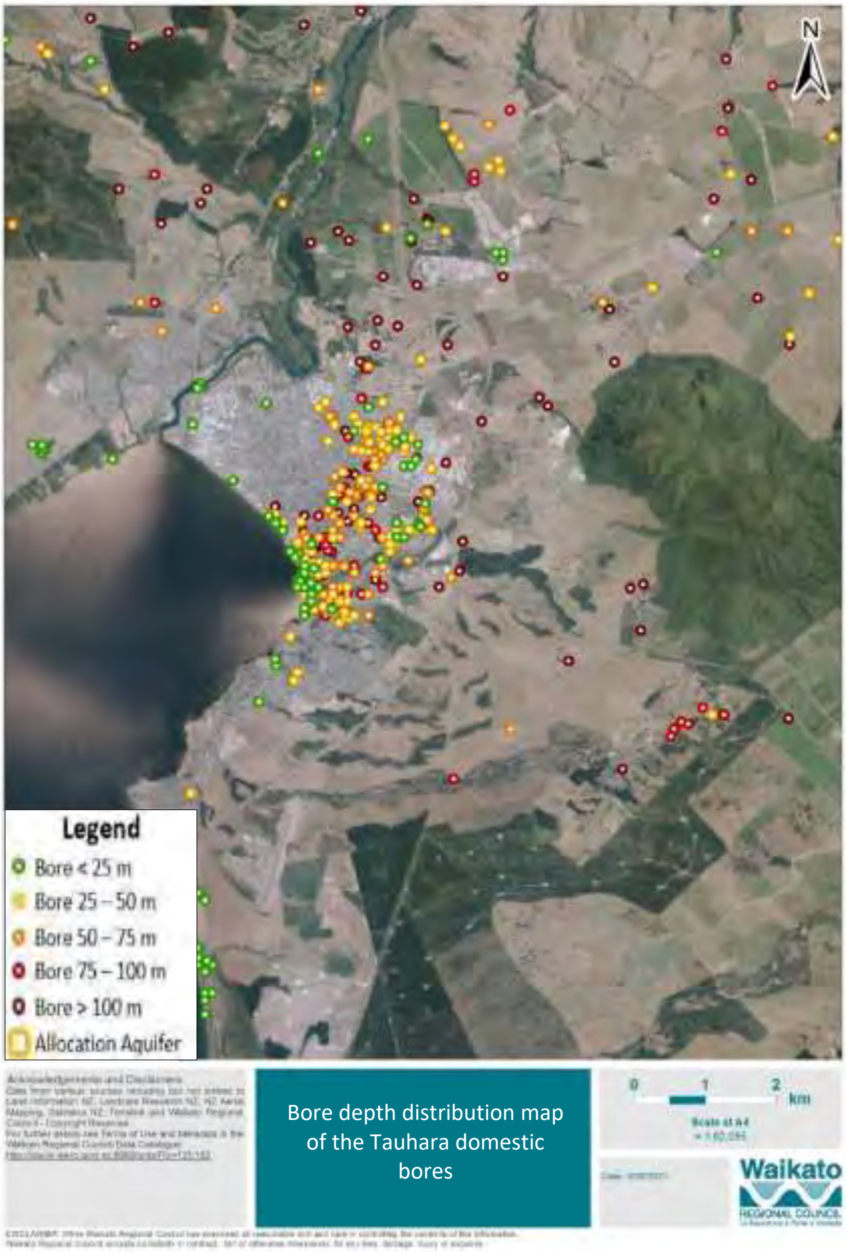


**Figure 3-3 A map showing the distribution bore depths and their location in Taupō township.**

### 3.1.2 Bore Measurements

The Tauhara domestic bores were constructed to a variety of depths (Figure 3-3), the shallowest measuring only 1.5 m deep, and up to a maximum recorded depth of 250 m. Many bores reach depths of 20 – 69 m, with few having to exceed 100 m (Figure 3-4).

There is an observed concentration of bores >25 m deep on properties located proximal to the Lake Taupō shore in southwest Hilltop and north Waipahihi, around the Waipahihi Stream. There are known alkali-chloride springs in this area (Figure 3-6); the Taharepa Springs (TH16) and Rocky Point Spring (TH17) in Hilltop, and Waipahihi Stream, Waipahihi Source Spring (THF6), and Otumuheke Stream (THF99). A smaller population of bores >25 m deep is also observed close to the industrial area of Tauhara. Bores between 25 – 75 m are well distributed, representing their greater population compared to bores with other depths. Bores exceeding 75 m in depth are also scattered across the area, with no clusters observed. Overall, there is no observed correlation between bore depth and location, except around the Waipahihi Stream area, where surface geothermal manifestations are recorded.

The maximum temperatures encountered after drilling vary from bore to bore, with a minimum recorded temperature of 9 °C, and a maximum record of 195 °C (Figure 3-5). Measurements below 50 °C are likely to correspond to groundwater or steam-heated water feeds, instead of a chloride-rich fluid originating from a deep reservoir. From the data, these relatively cold bores make up 5.3% of measured bores with data, similar to the 3% recorded by Curtis as the percentage of cold-water bores (Figure 3-1), which may suggest a minor increase in numbers constructed over time. A significant number of bores encounter maximum temperatures between 60 to 89 °C, with the greatest number of measurements ranging between 70 and 79 °C. As 40 °C is generally the minimum temperature required for effectively generating heat from a domestic bore, the data show that there is a relatively high success percentage of encountering sufficient temperatures.

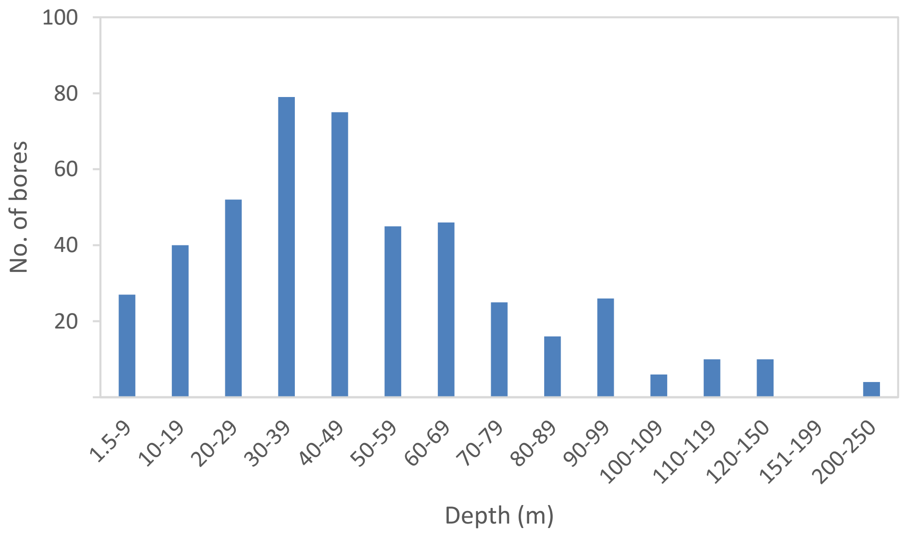


**Figure 3-4 Histogram of bore depths from 506 locations observed on Located and OSH Reports.**

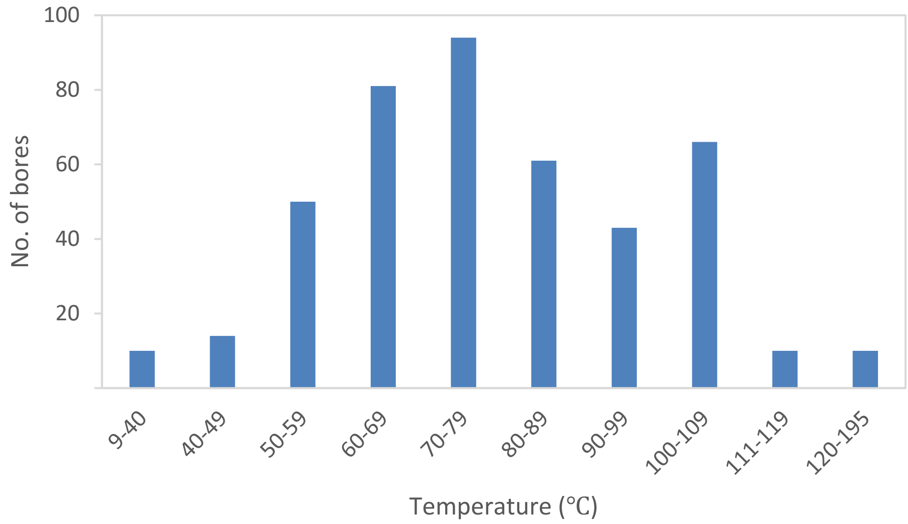


**Figure 3-5 Histogram of maximum measured bore temperature from 506 locations observed from Located and OSH Reports.**

### 3.1.3 Bore Water Chemistry

A few of the domestic bores have been utilised for water geochemistry sampling locations. Unfortunately, not many sampling locations have multiple samples, and some do not have data on important parameters. Due to the data availability, geochemistry analysis is restricted to a water type analysis, using chloride ($Cl^-$), sulphate ($SO^{2-}_4$) and bicarbonate ($HCO^-_3$). For this geochemistry analysis, data from eight domestic bores are used (Figure 3-6), and another eight other bores (deep bores and heating bores) and one geothermal surface feature (Waipahihi Source Spring) as comparisons.

Almost all water samples taken from domestic bores show steam-heated water type (Figure 3-7), which are inferred to be waters of meteoric origin which are heated by rising steam bodies and the geothermal gradient of the local area. This result is consistent with previous studies (Allis et al., 1989; Curtis, 1988; Morris, 1995), suggesting that the shallow aquifers feeding the domestic bores are heated by rising steam. The exceptions from the data population are wells T11 and T14, with T11 (Figure 3-6) showing almost equal components of each anion, and T14 showing a chloride-rich chemistry close to the mature water trend. The sample from T14 is more closely related to the samples from Waipahihi Source Spring, which show transitional peripheral chemistry. The two samples from Lakefront Reserve (LR1 and LR2) show volcanic water and steam heated water chemistry, different from T11 despite their proximity to the bore. The higher Cl concentration observed in T11 may be inferred to show a greater deep reservoir input in a confined environment. The chloride water chemistry at T14, which is located further to the south, may be caused by the bore tapping into an upflow zone or a different intermediate aquifer. More details on bore depth and lithology of T14 are needed to accurately understand the water chemistry. The deep bores THM01 and THM02, located in the eastern industrial district of Taupō have transitional steam-heated to peripheral chemistry, showing that they are more influenced by dilution than the fluids feeding the domestic bores.

The production fluids from Wairakei and Tauhara (Figure 3-8) are of mature composition, with significantly higher chloride constituents than the domestic bore waters. This further confirms the suggestion that the domestic bores tap into a different aquifer than the production fields (Section 2.2.5), which would progressively show more chloride closer to the upflow and reservoir.

Out of the samples taken from the domestic bores, TP111 and TP129 are the only locations with samples from different years. Both TP111 and TP129 were sampled in 1962 and 1978. TP111 is observed to not show any significant water type change between the sampling years, with only a very minor increase in chloride percentage observed. TP129 showed a greater change than TP111, initially showing a very sulphate-rich steam heated water chemistry in 1962 but showing a transitional sulphate-bicarbonate chemistry in 1978. It is likely that the change in water chemistry in 1978 was influenced by interactions with meteoric water, increasing the bicarbonate constituents of the aquifer proximal to TP129. However, this change brings the water sample from TP129 closer to the trend shown from other domestic bores, which might suggest that the 1962 sample was more unusual than the 1978 sample.


**Figure 3-6 Map showing the locations of domestic bores, and other bores and features used for the water geochemistry analysis. Bores TH02 and WK4 are located further north.**

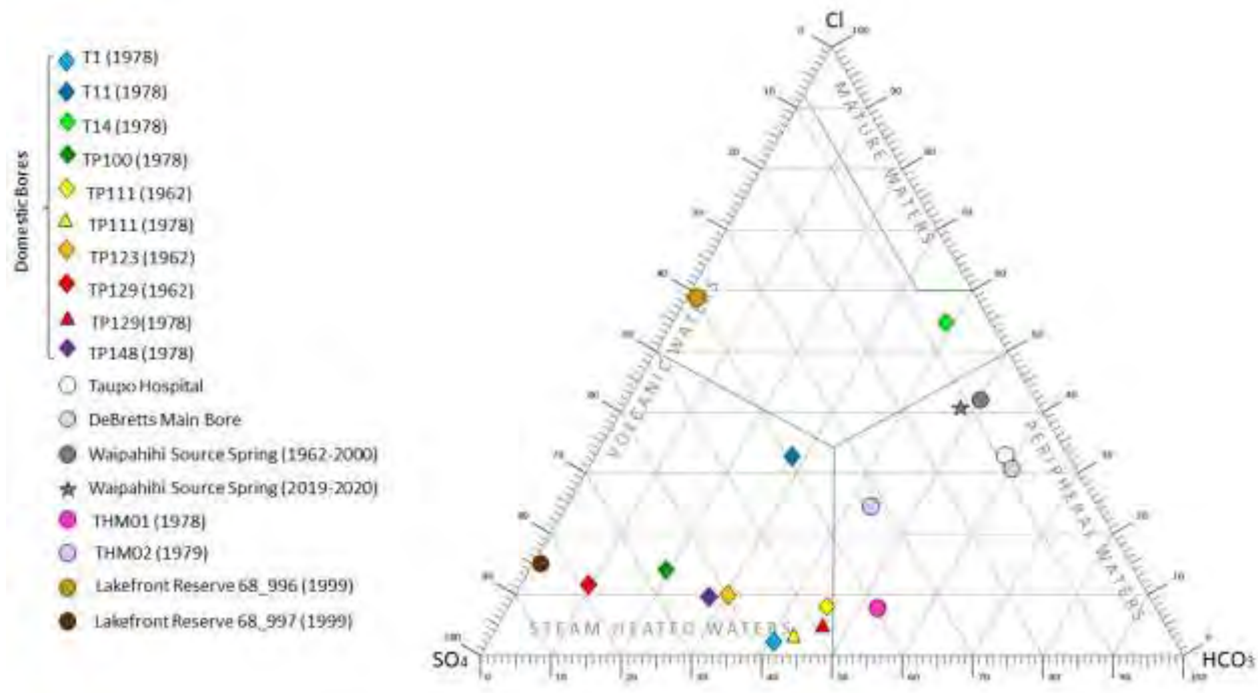


**Figure 3-7 Water type (Cl-SO4-HCO3) ternary diagram showing water samples from domestic bores, other commercial bores, two deep bores (THM01 and THM02), and the Waipahihi Source Spring.**

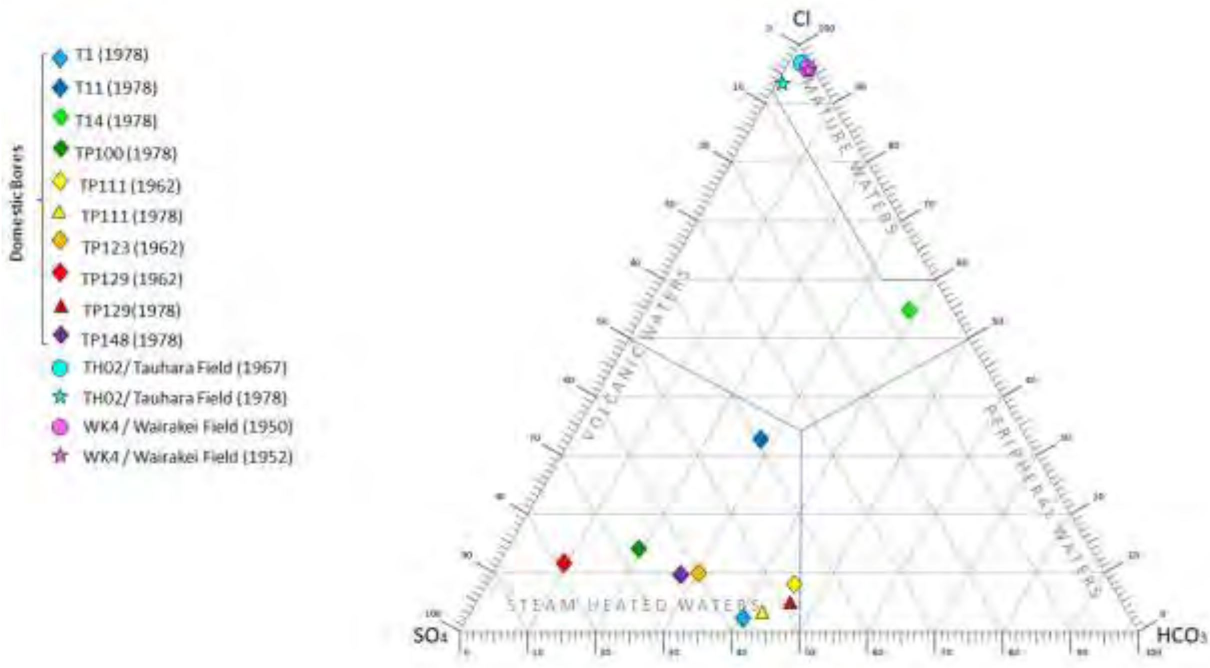


**Figure 3-8 Water type (Cl-SO4-HCO3) ternary diagram showing water samples from domestic bores and production bores from Wairakei and Tauhara.**

## 3.2 Geological and Hydrogeology

### 3.2.1 Significant Aquifers

Three rock units have been identified by Rosenberg et al. (2010) acting as shallow groundwater aquifers in the Tauhara geothermal field. Recent pumiceous tephra deposits (Figure 3-9, Table 1) previously assigned as the Taupo Formation (Figure 3-13) are the shallowest known aquifer unit, and an unconfined aquifer is found at surface levels at the Crown Bowl, THM9, throughout the Waipahihi Stream, and around the margins of Lake Taupō. Due to pumice's very high permeability, meteoric waters preferentially percolate through pumiceous lithology and enter the underlying Oruanui Formation, with which a hydraulic link is shared (Rosenberg et al., 2010). However, as recent pumice is found at the surface, it is inferred to mainly interact with colder waters of meteoric origin and could not provide enough heat for domestic use.

The Oruanui Formation (Figure 3-9) is composed of multiple sequences of pyroclastic materials (Table 1), some of which are permeable. The main recharge for this aquifer comes from meteoric waters, but the unit also receives relatively deep-sourced hot geothermal fluids. It is suggested by Rosenberg et al. (2010) that the Oruanui Formation may exist as a confined aquifer in locations where the recent sediments and less permeable sequences within Oruanui Formation overlie the aquifer. The third shallow aquifer is associated with the Tauhara Dacite. This aquifer has been encountered in bores relatively proximal to Mt. Tauhara, and its thickness decreases distally from the mountain. Due to its local extent at Mt. Tauhara, this aquifer is outside the scope of this investigation. The productivity of the domestic bores does not seem to be influenced by fluid extraction for power generation at the Wairakei and Te Mihi power stations, which lie within the Wairakei-Tauhara geothermal system. It has been suggested by previous studies (Allis et al., 1989; Curtis, 1988) that the southern part of the Tauhara geothermal field, which includes the bore-populated area, possesses higher aquifer permeability associated with more porous lithology and a higher degree of fracturing. The two shallowest aquifers are also stratigraphically situated above the cap rock (Figure 3-9), which is the Huka Falls Formation, and which may act as a boundary to minimise the influence on deep reservoir take further to the north. Hence, the upflow and outflow in the southern part of the geothermal field may be contemporary to the known zones to the north, where fluid extraction for power generation is taking place, and is separated by the less permeable geology as discussed by Curtis (1988). The domestic bores tap into the aquifer where permeability is inferred to be higher than in the north.

The Huka Falls Formation, although generally accepted as a common geothermal system cap throughout the Taupo Volcanic Zone is not a homogeneous lithological formation. This formation is divided into three sequences based on their lithology and depositional environment (Table 1). The Upper Huka Falls Formation (UHFF) and Lower Huka Falls Formation (LHFF) are primarily composed of relatively impermeable lacustrine siliciclastic deposits with some volcaniclastic constituents, with UHFF acting as a primary cap for the geothermal system. Despite being an intermediate unit lying between two relatively impermeable zones (Figure 3-10), the Middle Huka Falls Formation (MHFF) is hydrologically significant. Although it is composed of rhyolitic lavas, volcaniclastics, and breccias, secondary fracturing has created lateral permeability within this formation, making MHFF act as a confined shallow geothermal aquifer (Rosenberg et al., 2010). At locations where MHFF directly overlies the deeper Waiora Formation aquifer such as at TH4 and TH16, there is a possibility that a direct link between the two formations exist.

**Table 1 Lithological descriptions of the different lithostratigraphic observed within the investigation. Information from Cattell et al., 2016, Rosenberg et al., 2009, and Rosenberg et al., 2020. Included abbreviations are from Figure 3-8 and Rosenberg et al., 2009.**

| Group | Formation | Lithological Description |
| --- | --- | --- |
| RECENT<br>Recent sediments and volcaniclastics<br>- previously divided into alluvium, Taupo Fm. (T), and post-Oruanui Fm. (pO) | | Pumiceous pyroclastic fall and flow deposits and sediments, 20 – 40 m thick. Partial preservation of organic matter observed in Wairakei. Hydrothermally altered around Crown Road (Tauhara), with quartz cementation. Top pumiceous sequence act as an unconfined aquifer. |
| | | Sequence of ale brown lacustrine siltstones with pennate diatoms, rhyolitic tephra, and palaeosol layers. |
| TAUPO GROUP | Oruanui Formation<br>(O) | Unaltered to highly altered, highly weathered, and weak pyroclastic fall and flow deposits composed of mainly pumiceous non-welded ignimbrites and accretionary lapilli-rich fine ash tuffs, 25 – 135 m thick. |
| HUKA GROUP | Huka Falls Formation<br>(U, M, L) | <u>Upper Huka Falls Formation (UHFF):</u><br>The extensive and primary cap unit for the Wairakei-Tauhara geothermal system. Thinly-bedded sandstone-mudstones interbedded with coarse pumiceous tuffs and breccia, 5 – 300 m thick. Deposited in a lacustrine environment.<br><br><u>Middle Huka Falls Formation (MHFF):</u><br>Rhyolitic magmas, pumiceous tuffs, and coarse basal breccia with sandstone, sandstone, and rhyolitic pumice clasts. Inferred to have explosively erupted into a lake basin environment. A known confined shallow geothermal aquifer.<br><br><u>Lower Huka Falls Formation (LHFF):</u><br>Brown, green, or grey laminated and bedded, subhorizontal to slightly inclined deformed siltstones and sandstones. |
| | Waiora Formation<br>(W) | Interlayered lavas, rhyolitic tuffs, and ignimbrites. Localised and discontinuous variations observed including planar-bedding, lithic clasts, fine lapilli tuff layers, and massive pumice-lithic tuff breccia layers. An intermediate geothermal aquifer. |
| Crown Breccia<br>(CXB) | | Polymictic hydrothermal eruption breccia with illite-smectite and illite-chlorite-wairakaite-epidote (propylitic) alteration of Oruanui Formation, Huka Falls Formation, and Waiora Formation Rocks clasts up to 4 m in diameter. May be related to polymictic hydrothermal explosion breccias reported by Risworth (1967). In locations have undergone intense acidic alteration into kaolinite-rich minerals. |

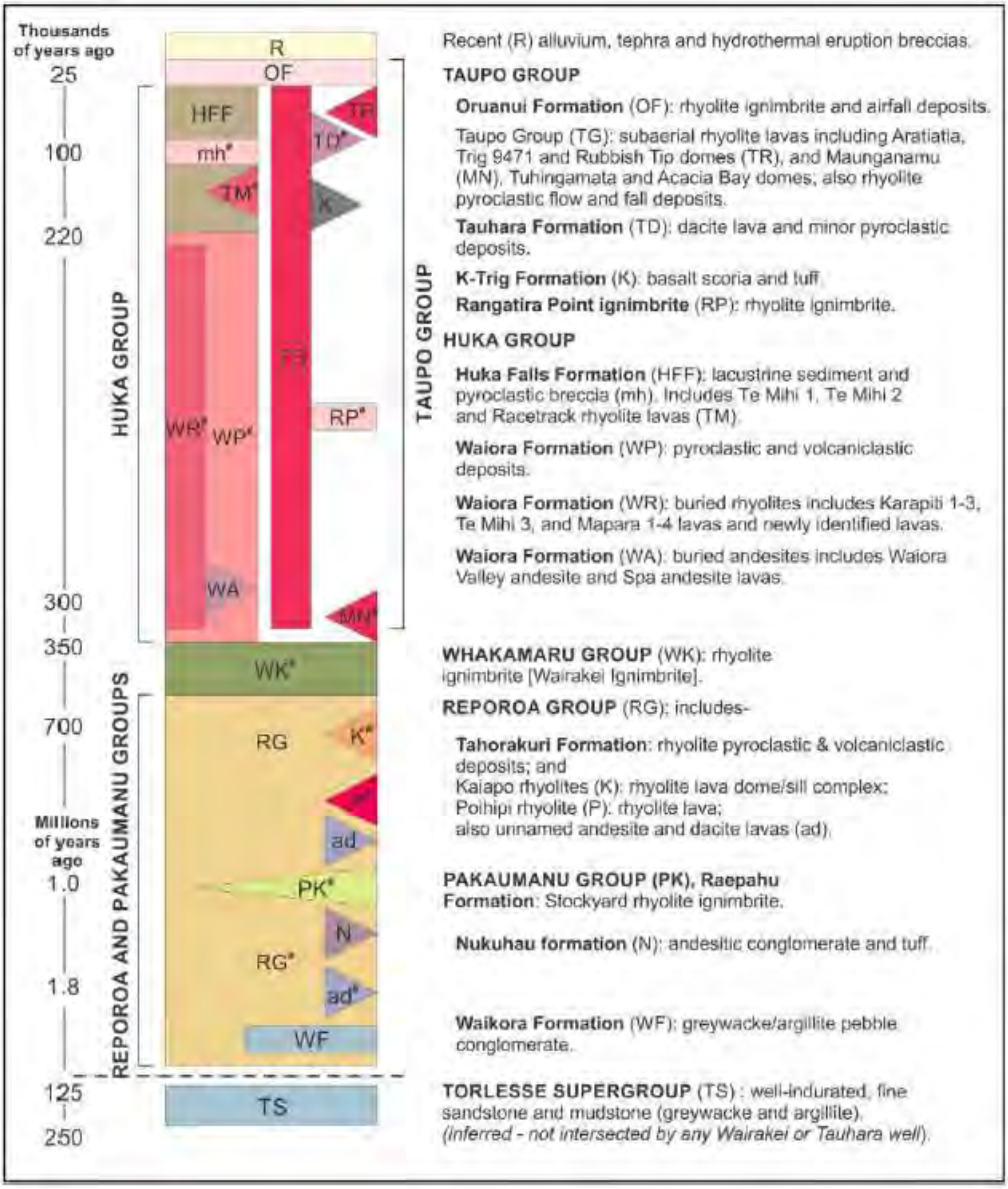


**Figure 3-9 Generalised stratigraphic sequence for the Wairakei-Tauhara geothermal system from Rosenberg et al. (2020). The stratigraphy presented here is the most recent but does not include the Crown Breccia as its geographical extent is locally limited.**

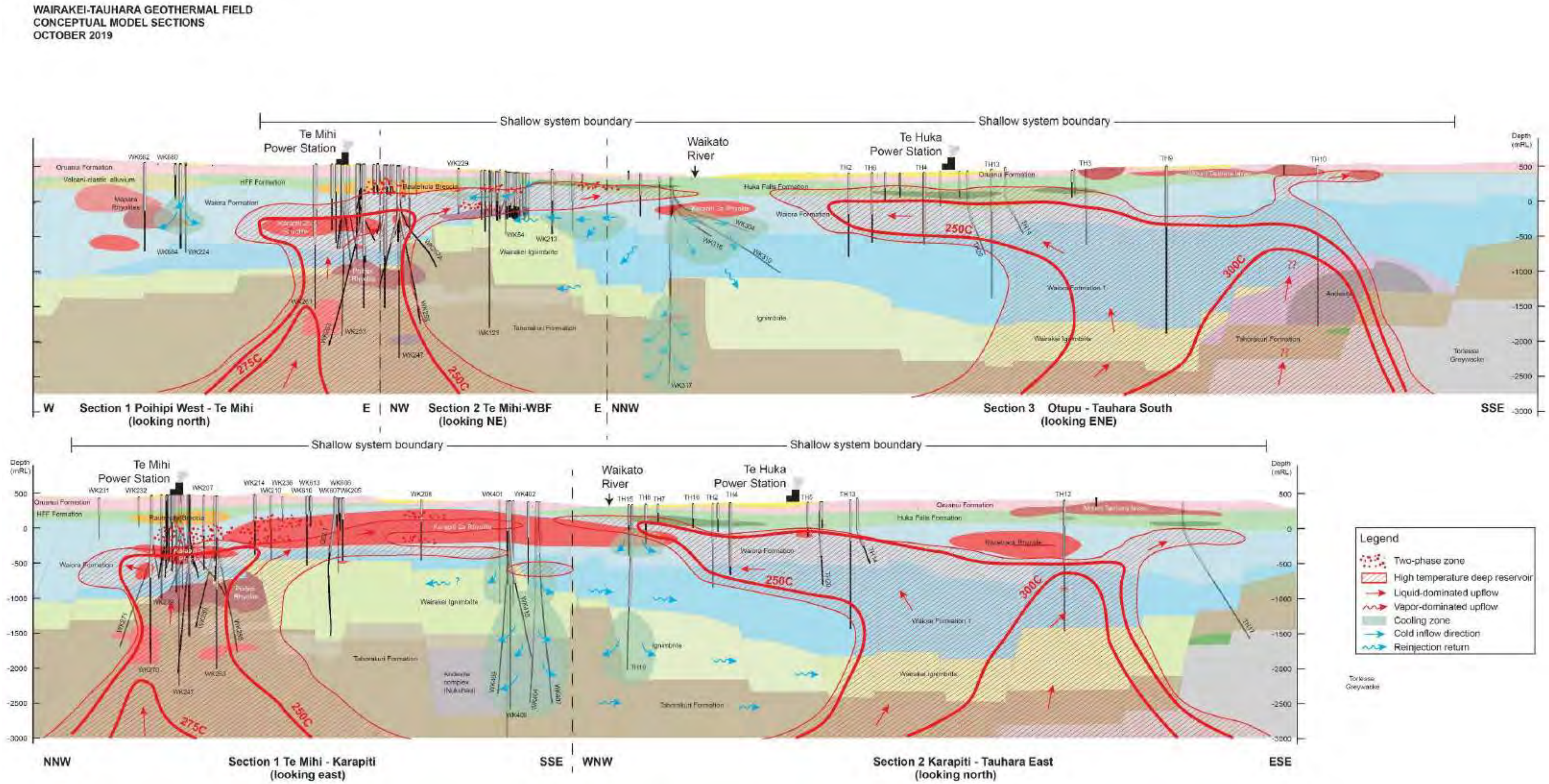


**Figure 3-10 Two-dimensional conceptual model sections of the Wairakei-Tauhara geothermal system created by Contact Energy (2019). The Middle Huka Falls Formation (MHFF) are shown as darker green zones within the Huka Falls Formation.**

### 3.2.2 Elevation Conversion and Bore Selection

The local topography of Taupō is heterogeneous due to the existence of hills and streams. Bore depth is a unidimensional measurement taken from the bore opening at ground level and does not correspond to elevation set relative to the mean sea level or another datum. As a result, bore depth information (Figure 3-11) is not very helpful when not analysed relative to the surface elevation.

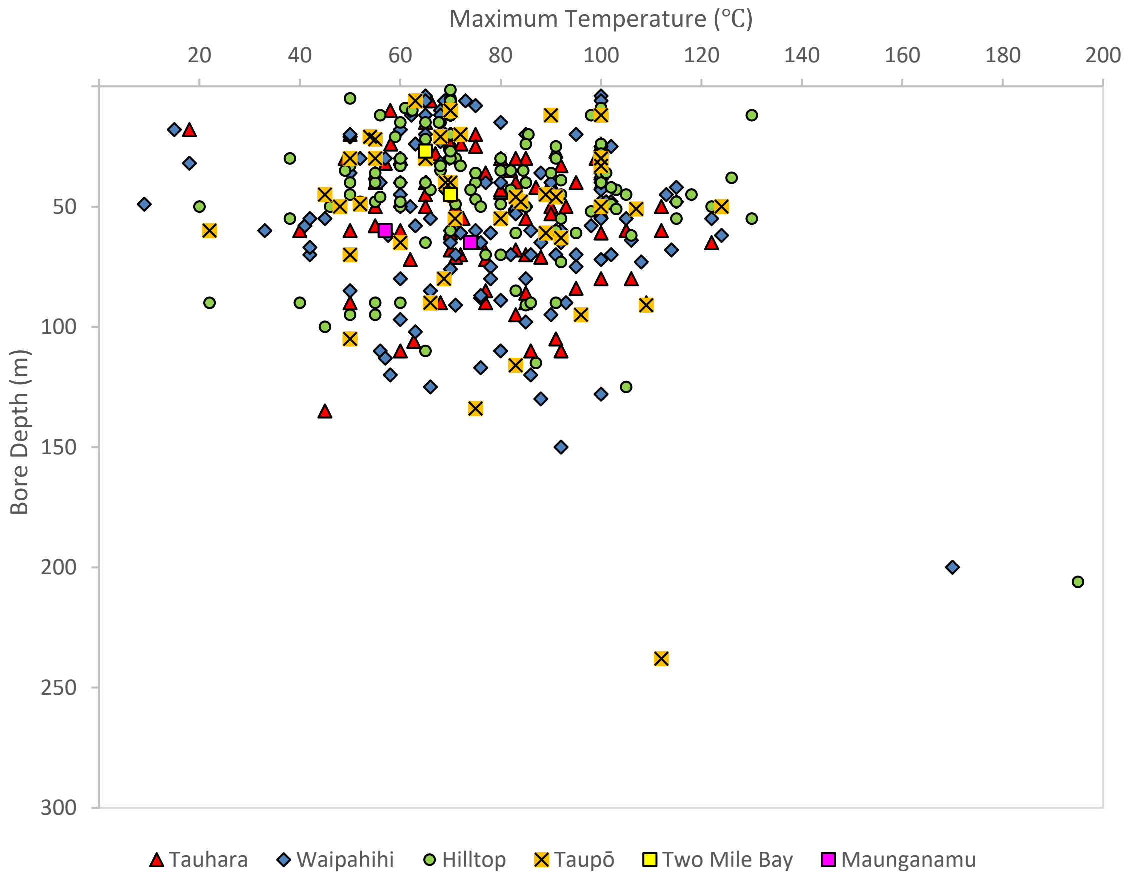


**Figure 3-11 Graph showing the relationship between temperature and depth measurements of 506 bores from all suburban areas as recorded on Located and OSH Reports. Bore depth is relative and does not reflect elevation, which varies in different locations.**

For this study, the wellhead elevation is converted to the preferred datum, *New Zealand Vertical Datum 2016* (NZVD2016), and the converted value is deducted by the maximum bore depth:

$$Elevation\ at\ max.bore\ depth = \\ Wellhead\ elevation\ in\ NZVD2016\ (m) - Max.bore\ depth\ (m)$$

A limitation was encountered when using elevation in NZVD2016 instead of bore depth. Of the 506 bores available to analyse, only 189 bores have a recorded bore-head elevation known to WRC, which are derived *from 20m Digital Elevation Model* with an accuracy of 6 m. Elevation for another 284 bores were successfully estimated from satellite data, bringing the total number of bores with elevation data to 473/506. Despite the numerical reduction and increased error margins for the elevation of analysed bores, the use of elevation in NZVD2016 was still preferred, as it allowed for the relative comparison between maximum bore depth, with the lithology and fluid conditions at the maximum depth horizon.

Bores proximal to the allocated aquifer were reviewed, to check the availability of geological bore logs or any lithostratigraphy data (Figure 3-7, 3-8). Two relatively deep bores (>500 m) proximal to the allocated aquifer with relevant geological data are identified (Cattell et al., 2015) and provide the most extensive lithostratigraphic information for the area proximal to the allocated aquifer (Table 1).

**Table 2 Table showing details of two relatively deep bores, THM16 and THM18, which are proximal to the allocated aquifer area. The lithostratigraphy at THM18 better represents the local subsurface geology.**

| | THM16 | THM18 |
|---|---|---|
| Located ID | 72_3606 | 72_5680 |
| Coordinates (x,y)(NZMG) | 2780366, 6274253 | 2779633, 6276647 |
| Depth | 800.5 m | 717 m |
| Elevation at maximum depth (NZVD2016) | 443.642 m | 398.61 |

THM16 is at Crown Rd in east Tauhara, and is situated within the Crown Bowl, a subsidence bowl at the site of a paleo-hydrothermal eruption vent. This subsidence bowl is characterised by the occurrence of the Crown Breccia (CXB), which consists of tuffaceous clasts from the Oruanui Formation (O) and Waiora Formation (W). Clastic clasts from the Huka Falls Formation (age of 258 ± 10 ka) in previous studies including Bignall et al. (2010) and Rosenberg et al. (2009) are alternatively abbreviated as "CB", which could have been confused as Crown Breccia. Core samples from the Crown Road subsidence bowl bores suggest that Crown Breccia is younger than the Oruanui Fm., as samples include clasts identified to be from the Oruanui Fm.

The stratigraphic sequence at THM16 and the other Crown Bowl bores (THM10, 11, 21) not only differs from THM18 due to the presence of the Crown Breccia, but also from the absence of Huka Falls Fm. deposits, which are well developed at THM18 and bores to the north of THM14. The top of the Waiora Formation is also encountered at a deeper elevation of -186 m at THM18 compared to 235 m at THM16 and is underlying Spa Andesite which is absent elsewhere. THM18 is preferred to THM16 as a reference bore for interpreting the hydrological relationship between subsurface lithology and the domestic bores. Despite THM16 being more proximal to many domestic bores, its lithology is greatly influenced by local hydrothermal alteration. The unique lithology at Crown Bowl is not observed outside of the subsidence bowl, and hence is interpreted as not being representative of the geology underlying the properties with domestic bores, or the general shallow aquifer in the area. Despite having Spa Andesites, which are not encountered in other bores, the elevation and thickness of the formations in THM18 are still used as a reference for this investigation, as no bores penetrate through formations deeper than the Middle Huka Falls Fm.

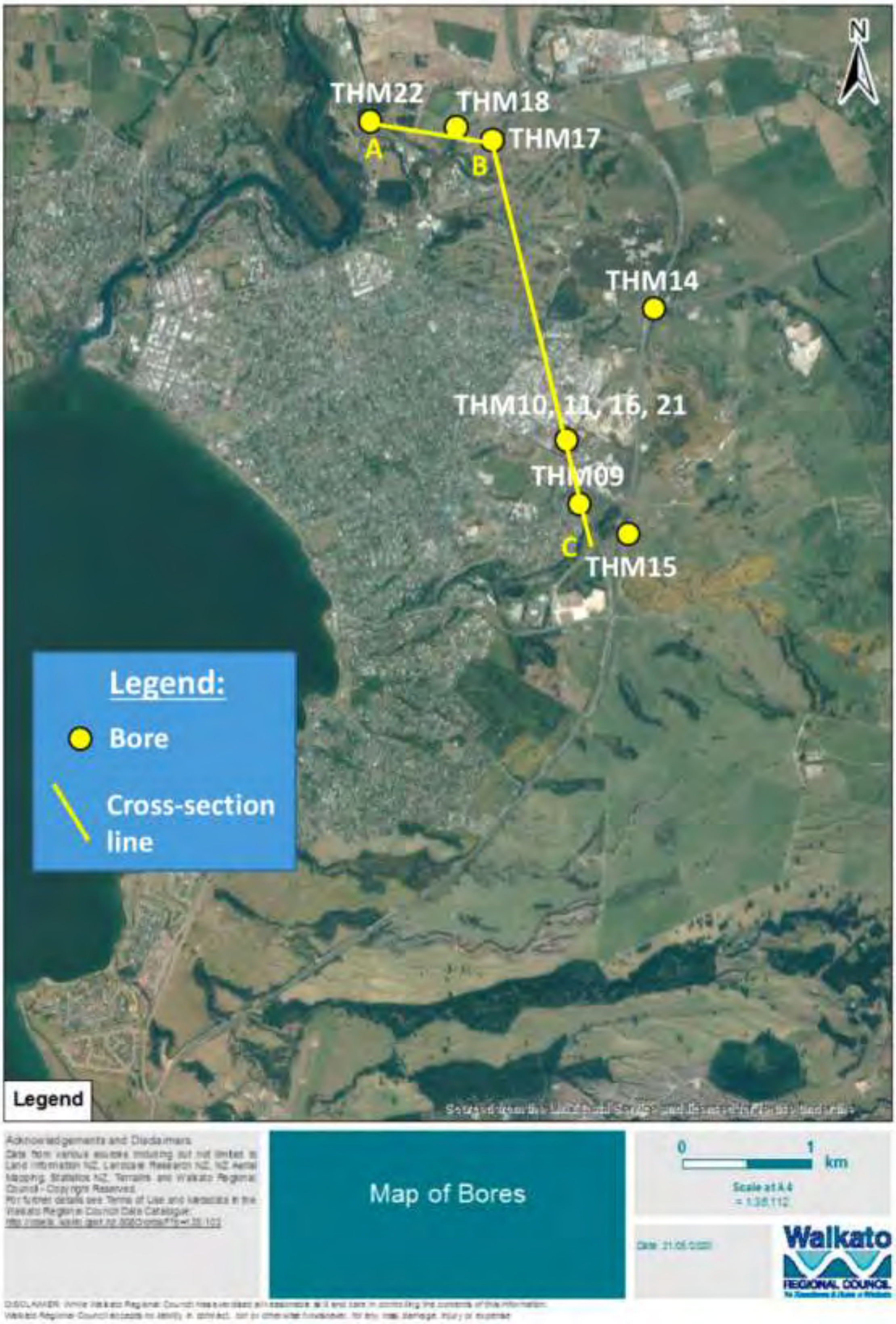


**Figure 3-12 A map showing the extent locations of bores used for the cross-section of east Taupō. Modified from Rosenberg et al., 2009.**

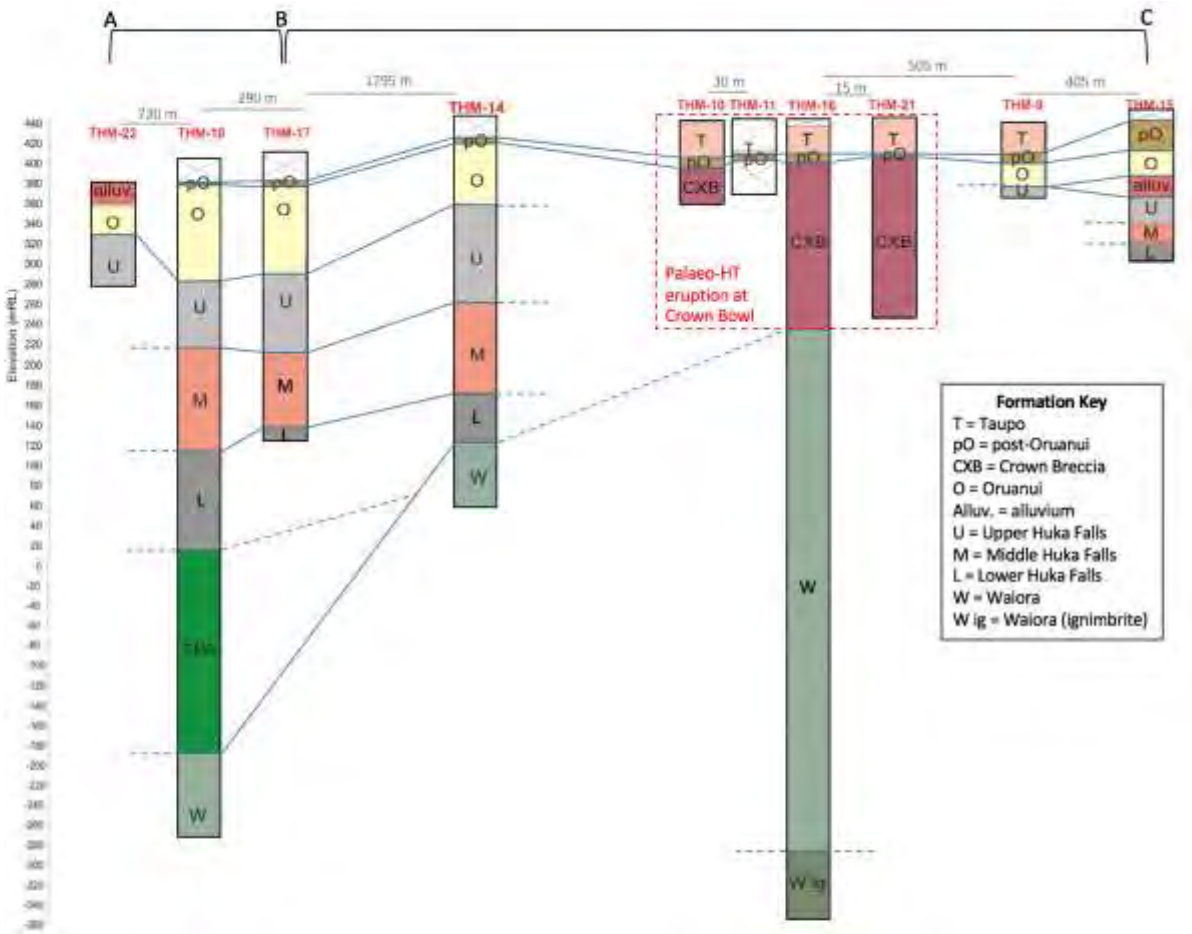


**Figure 3-13 A geological cross-section showing data from bores shown on Figure 2-8, from points A-B and B-C. Modified from Rosenberg et al., 2009. The stratigraphy of the area has been updated most recently by Rosenberg et al. (2020). This can be observed on Figure 3-9 and Table 2, where the post-Oruanui Formation, Taupo Formation and alluvium are collectively categorised as "Recent" (Table 2).**

### 3.2.3 Assumptions on Lateral Extent of Subsurface Lithostratigraphy and Hydrology

As THM18 is chosen as the bore with the most representative lithology (Figure 3-11, 3-12), an assumption is made for this investigation that the stratigraphy and formation thickness of the Huka Falls Formation and the overlying younger formations are consistent and extend into the area of allocated aquifer underlying the domestic bores. This assumption also ignores the possibility that the Crown Breccia, as well as occurrences of intrusive bodies and structural displacements, could take place and influence the lithology in any of the domestic bores. The hydrological properties of the observed formations are also assumed to be homogeneous throughout the area to simplify interpretations. The surface bore-head elevations are uninfluenced by the assumptions made. Based on stratigraphic log data, the undefined uppermost sections of the stratigraphy when not stated, or when referred to as alluvium on (Figure 3-8) are assumed belong to the "Recent" stratigraphic group (soil, pumice, gravels, clay, or sand) as listed on Table 1.

### 3.2.4 Elevation-based Lithostratigraphic Bore Analysis

The conversion of maximum bore depths into elevation, and the assumption that the lithology and stratigraphic succession from THM18 is laterally homogeneous in the allocated aquifer allows for the lithology of bores to be interpreted. It is obvious (Figure 3-14 to 3-19) that the most common geological unit encountered at the maximum depth of bores, and therefore tapped for hot fluids is the Oruanui Formation. Bores intersecting these formations have recorded fluids at temperatures between 9 and 130 °C. Lower temperature measurements are possibly caused by the bores tapping into lower temperature water bodies, the bore being a groundwater bore, or waters cooled by near-surface interactions. The undistinguished recent sediments are also observed to be encountered at the bores, although it is unlikely for these pumiceous sequences to retain its waters due to very high porosity conditions. There are two linear trends at temperature measurements of 70 °C and 100 °C intersecting recent sediments and Oruanui Formation (Figure 3-14). This may be due to aquifers being confined reducing external influences and allowing for the fluid temperature to remain stable at the two temperature points.

Significantly lesser number of bores intersect into the Upper Huka Falls Formation, most of which occur at Waipahihi, consistent with the role of this formation as an impermeable cap (Rosenberg et al., 2009). Bores in the inferred Upper Huka Falls Formation zone record a maximum temperature of 100 °C, lower than the Oruanui Formation, which has many bores exceeding 100 °C. Four bores intersect into the inferred Middle Huka Falls Formation zone, with two bores showing temperatures between 80 °C and 120 °C, and two bores exceeding 160 °C. The upper third of the Upper Huka Falls Formation is comprised of predominantly volcaniclastic sandstones with pumice pebbles, with thinly bedded intercalated siltstones the dominant lithology below the sandstones. Pumice pebbles in the sandstones could provide porosity and permeability in an otherwise impermeable aquitard zone if intergranular connectivity between the pebbles exist. Other possible permeable zones within this aquiclude include bedding contacts on sandstones and siltstones, and on fractures.

The two hottest bores are situated in Waipahihi and Hilltop which show that exceptionally high temperatures could be encountered at depth. However, there are four observed bores drilled below the inferred lower boundary of the Lower Huka Falls Formation but only encountering temperatures of 100 °C or lower, showing that drilling deeper is not always more productive. Two Mile Bay and Maunganamu only have two bore data available each, which show different results to the other geographical areas. Bores in Two Mile Bay show temperatures of 65 °C and 70 °C, at elevations of 331 m and 312 m respectively. The two bores show temperatures slightly below the area mean of 76.6 °C, but there is not enough data from Two Mile Bay to conclude it has below average fluid temperatures. Despite Maunganamu only having a low number of data, those measurements offer valuable information. The area has a bore with the highest recorded elevation at maximum depth at 480.6 m (NZVD2016), and while the temperature of 57 °C and 74 °C are just below the area mean, the bores have sufficient temperature for domestic use. The temperatures observed at these bores could possibly be related to the heat source under Mount Tauhara.

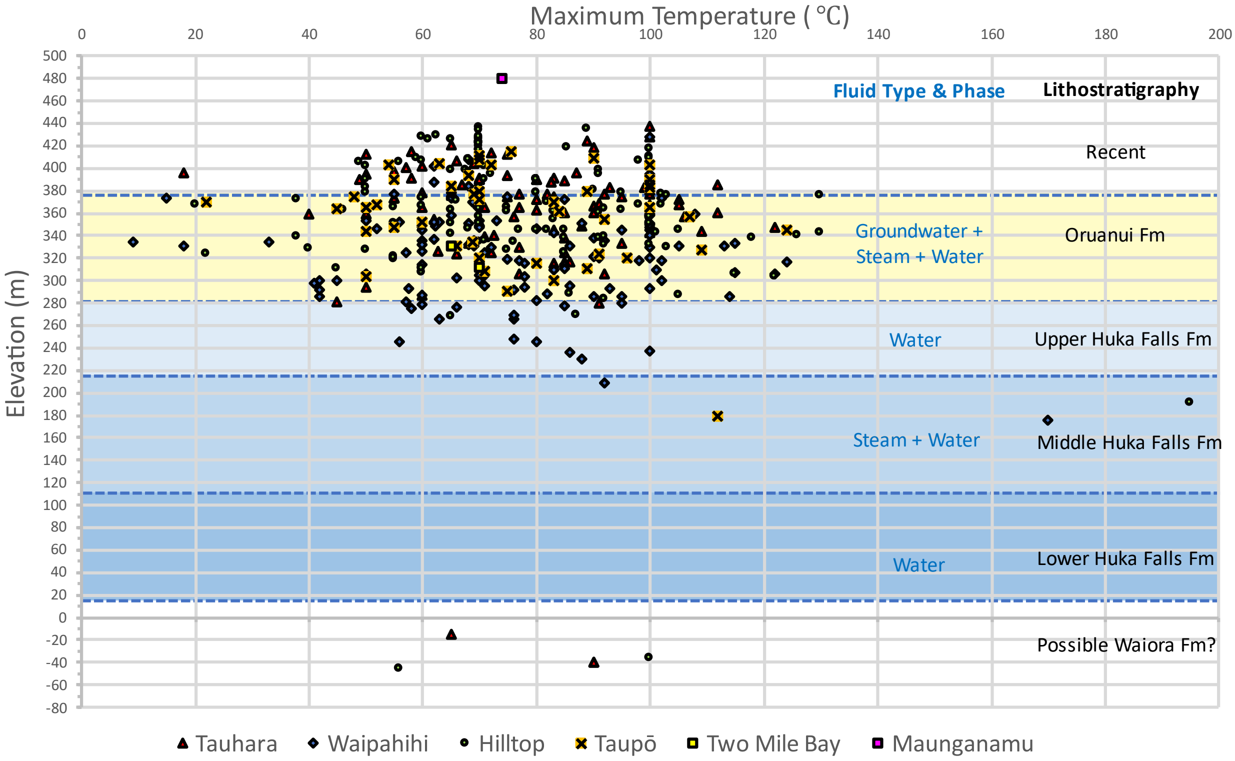


**Figure 3-14 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase in 473 bores. Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

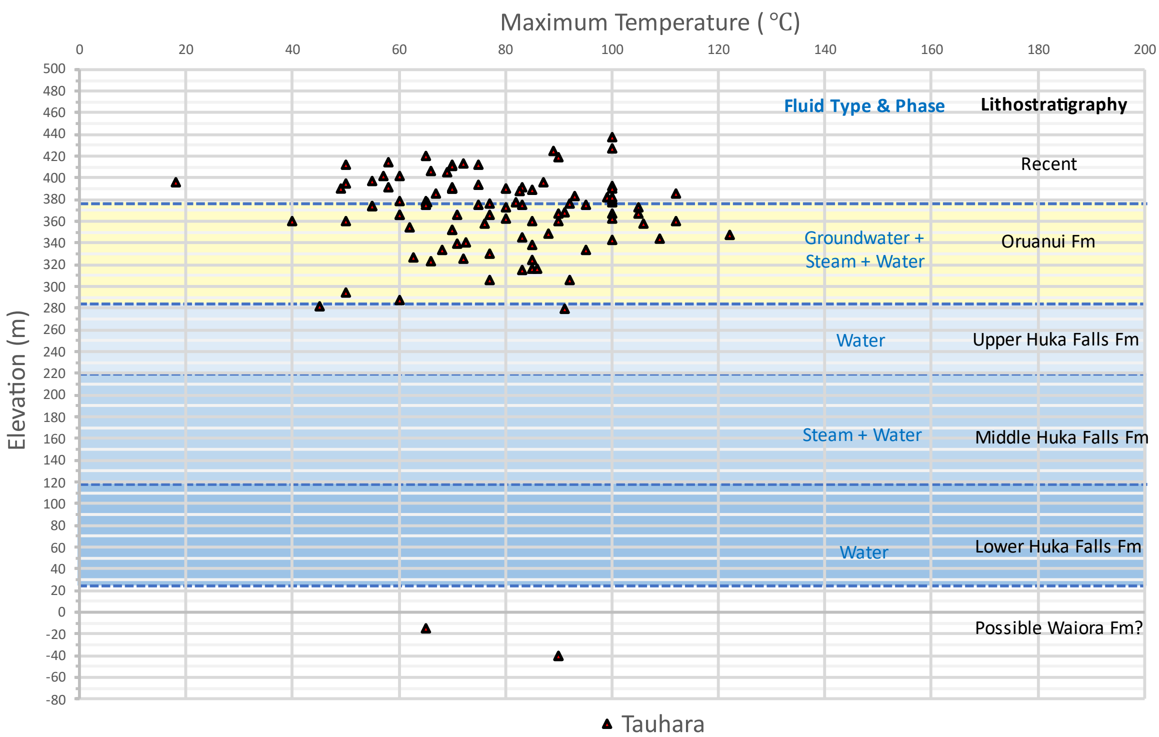


**Figure 3-15 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase of bores in Tauhara (geographical area). Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

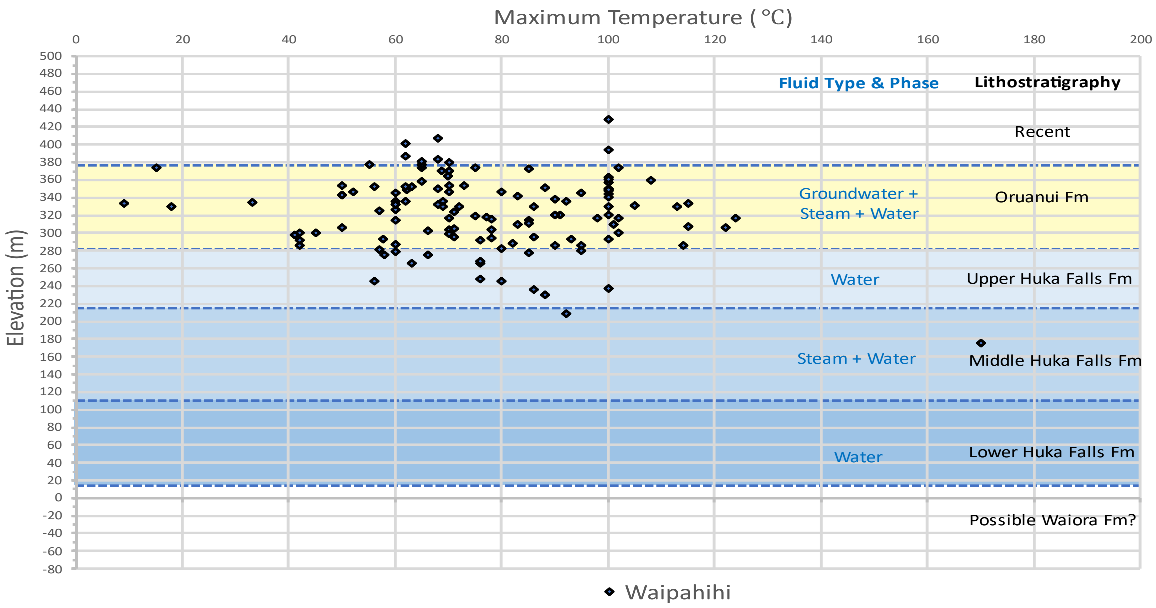


**Figure 3-16 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase of bores in Waipahihi. Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

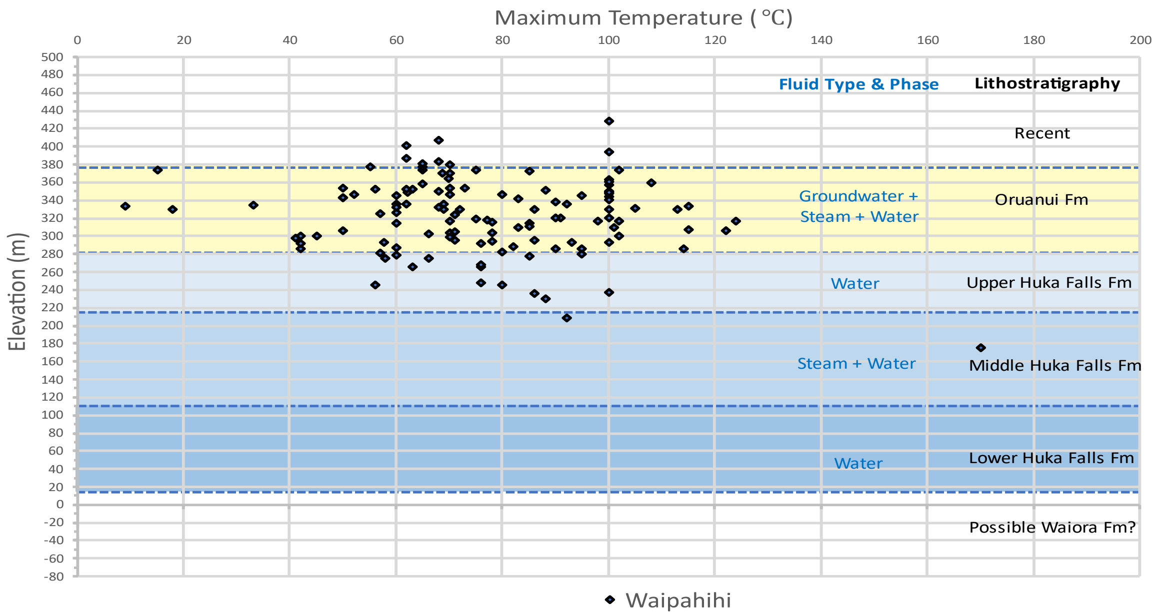


**Figure 3-17 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase of bores in Hilltop. Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

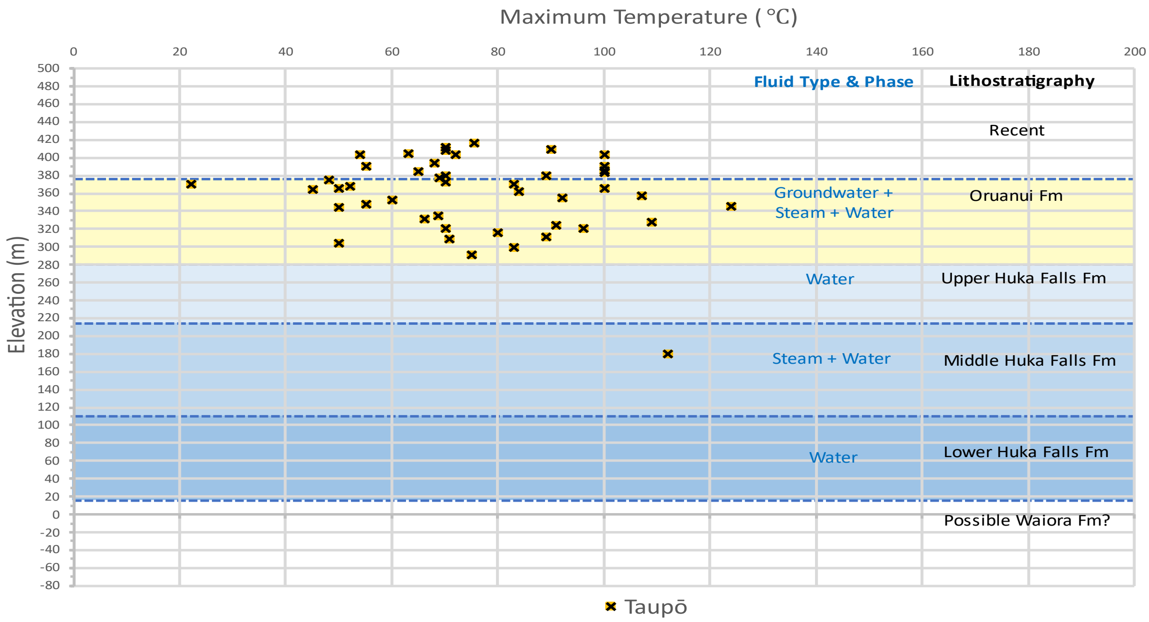


**Figure 3-18 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase of bores in Taupo (geographical area). Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

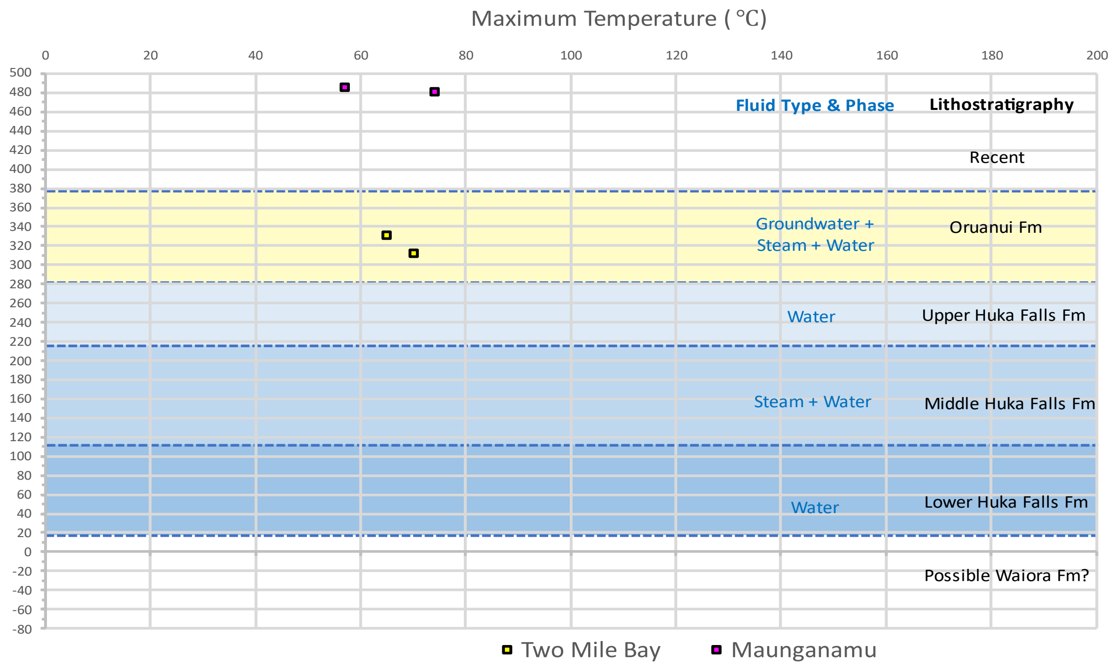


**Figure 3-19 Diagram showing the relationship between elevation at maximum bore depth in NZVD2016, maximum temperature, stratigraphy, and fluid phase of bores in Two Mile Bay and Maunganamu. Stratigraphy and water phase zones adapted from Hunt and Graham (2009).**

Temperature and elevation diagrams show that the Oruanui Formation aquifer is sufficiently hot for domestic utilisation, with some bores recording temperatures exceeding 100 °C in Tauhara, Waipahihi, Hilltop, and Taupō (Figure 3-14, 3-15, 3-16, 3-17). This zone has both steam and water resources, with known steam zones feeding into bores in Tauhara. One minor issue with this aquifer is the recorded low temperatures of less than 40 °C, but there are only 11 bores with such low temperatures so that this is a minor issue. Most bores tapping into the recent sediments are also sufficiently hot for the required use, with the most productive zone being approximately between elevations of 380 – 440 m NZVD2016. However, only one bore in Tauhara encounters fluid hotter than 100 °C, so Oruanui Formation is more ideal when targeting greater temperature ranges. Due to its shallower stratigraphy, the recent sediments Formation is also more influenced by shallow groundwaters and meteoric waters (Cattell et al., 2015), which makes them less reliable in generating consistent heat in the long run.

## 3.3 Energy Use

In 1987, water abstracted from domestic bores made up 9% of annual energy use in Taupo while domestic heat exchangers contributed another 6%. The two uses are small compared to their commercial counterparts (Figure 3-20). White (2006) estimated in 2006 that there is about 8 TJ/year of domestic heating in New Zealand, for houses in the order of 1000s, although no exact number was provided. 13 TJ/year was recorded for space heating in the Waikato, followed by 3 TJ/year for water heating. In a more recent study by Daysh et al. (2020), while exact numbers were also absent, it was suggested that in 2012 approximately 20% of installed geothermal operations are for space heating, but only contribute to less than 5% of energy use, excluding domestic use. There is not enough information on recent energy use distribution related to the domestic bores to make further conclusions.

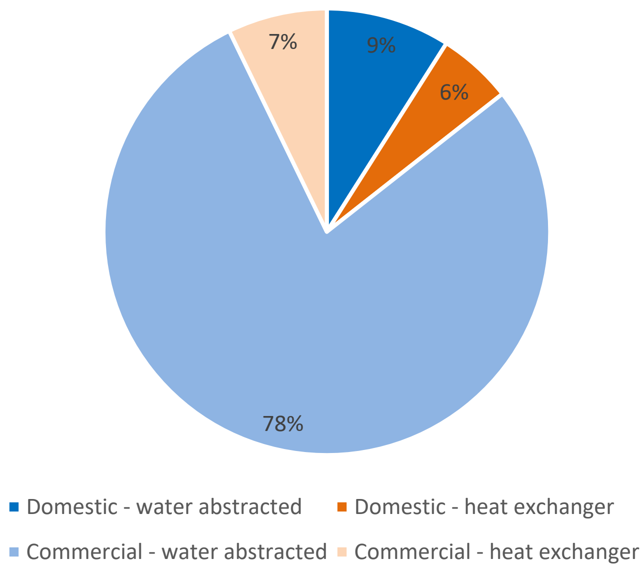


**Figure 3-20 Chart showing the proportions of estimated annual energy use from data taken in 1987 of 381 bores. Data from Curtis 1988.**

# 4 Current Issues with Surface Features

As discussed in Section 1.3 (Figure 1-3), most of Taupō township including the areas with the domestic geothermal bores lie within the resistivity boundary of the Wairakei-Tauhara geothermal system (Daysh et al., 2015). The areas of Otumuheke, AC Baths, Crown Road, Waipahihi (including Onekeneke), and Taharepa are known to have presently and historically active surface geothermal manifestations. Continuous monitoring of the physical and chemical properties of active surface features at Waipahihi, Otumuheke, and Taharepa is crucial for understanding the conditions and changes in the reservoir and feed zone.

Of the currently active features, Otumuheke stream and the surrounding geothermal wetland have been observed to show significant changes in the past years. The discharge has been observed to have dramatically weakened, while the wetland has dried up. Changes have been visible and the hapu and local community noticed the changes and inquired Waikato Regional Council about them, leading to a media response (Luketina, personal communication, 2020). A false colour TIR imagery of the stream area conducted by GNS between 2014 – 2020 (Macdonald et al., 2020) on water bodies show progressively cooler signals on several survey points, indicating cooling and drying throughout the survey period. The study recorded flow measurements at the gauging site similar to flows measured in a 2009 study (Reeves and Graham, 2009), contrary to the decreasing flow trends observed from WRC's flow recorded (Appendix 1). Water chemistry analysis show significantly greater sulphate concentration at 233 mg/l compared to bicarbonate 106 mg/l and chloride at 18.6 mg/l, indicating steam-heated water composition. Mannington (2020) included water drawdown associated with extraction from domestic bores as a potential cause of water level decline events, but evidence from pressure logs measured at domestic bores at Lake Taupo Holiday Report remain inconclusive and require further investigations.

Otumuheke stream is not the only feature to have experienced substantial changes, with some sinter-depositing springs observed to have stopped discharging earlier. Iron Bath Spring or THF1 [NZMS-260 U18: 2779839 E, 6273199 N] was a sinter-depositing spring but has stopped discharging since the late 1980s. Its drying has been associated with water over-extraction to satisfy water demands for the De Bretts Hotel (Allis et al., 1989), which took place during the period when domestic bores were already established. However, previous models (Allis, 1983) have suggested that the source of water used for the shallow bores originated in the east near Mount Tauhara and travelled west towards the township area. Using this model, it becomes less likely for water extraction from the domestic bores to have significantly affected Iron Bath Spring, which lies at the east of the township area. Another depleted feature is the Kathleen Spring or THF91 at [NZMS-260 U18: 2779566 E, 6276024 N] the northwest of the allocated aquifer area, which has stopped flowing since 1997, with both rainfall variations and extraction from aquifers noted as the possible causes.

# 5 Conclusions and Recommendations

## 5.1 Conclusions

There is no clear justification for trying to drill as deep as possible into the Huka Falls Formation and the Waiora Formation, despite high temperatures encountered at depth. The Oruanui Formation can provide enough reliable heat distribution for domestic use at shallower depths or higher elevations, helping minimise drilling risks, economic costs, and uncertainties. Despite the recent sediments also recording high enough temperatures, the formation is more easily influenced by cooling processes, and so provides a greater long-run risk for heat sustainability. The Oruanui Formation is the most low-risk and economically viable target zone for drilling a domestic bore in the Taupō township area.

Further studies and the continuous monitoring of the bores could help create a better understanding of the relationship between fluid takes, the aquifers, and hydrology of the system, while also helping future management and planning of the intermediate aquifer. Despite possibly minimal communication with the deep reservoir, geothermal surface features such as hot springs and streams are present within the Taupō township area, and their hydrological relationships with the domestic bores are not well understood.

## 5.2 Future Recommendations

Further research and having continuous monitoring of the domestic bores could help plan and understand the relationship between bore extraction with the nearby features. This is an especially interesting issue as many features, including geothermal streams, have shown a decrease in discharge over the years, with the role of bore extraction still uncertain in the depletion events. A better understanding of the bores and aquifer is required to make sure that domestic bores with water takes use the aquifer sustainably, and to plan accordingly to better manage locations for future heat exchanger, discharge, and injection wells.

### 5.2.1 Re-establishing Inspections

As of 2021, no institution holds the responsibility for monitoring and inspecting the domestic bores in Taupō. WRC currently undertakes Taupō bore runs every 6 weeks when water level and temperature are measured from the bores (Discover document #1417377), and correlates to the hydrological work done in the area. However, the bore run does not include all or a majority of the domestic bores; it is difficult to inspect all the bores as they lie in properties with different landowners, and approval should be sought from each property owner prior to inspection. Nonetheless the revival of an inspection programme would be beneficial for observing the conditions of most of the bores.

The ideal situation would be for WRC's bore run in Taupo to be extended to all or key domestic bores, regardless of the potential difficulties with landowner permissions. This would allow for recent changes to be observed and compared to the conditions before and during the early years of fluid extraction at Tauhara. Some bores could also be used as water geochemistry sampling sites and may be ideal locations for observing tracer flow tests.

### 5.2.2 Tracer Flow Testing

Previous studies (Allis et al., 1989; Rosenberg et al., 2010) suggest that the shallow aquifer fluids in south Tauhara migrated from an upflow zone around the southern slope of Mt Tauhara, which is separate to the deep upflow associated with the Tauhara geothermal field production. This water body is interpreted to migrate west towards the urban area while chemically evolving into a more bicarbonate water chemistry typical of outflow zones, feeding the shallow aquifers as well as the Waipahihi features (Bromley, 2020). One possible investigation method to undertake in the future is to observe domestic bore connectivity using the tracer flow test (TFT) method.

TFTs are commonly utilised in development geothermal fields of the Waikato Region for observing well connectivity, mass flow rates, and discharge enthalpy (McCabe et al., 1980; Quinao and Sirad-Azwar, 2012; Winick et al., 2015). This method involves injecting chemical tracers into a well at a constant rate and observing the time and occurrence of the injectate in other wells. Most of the approved tracers used for TFTs have relatively short half-life (λ), and some of the substances used in New Zealand include but are not limited to:

- Iodine isotopes: I-125 (λ: 60 days) and I-131 (λ: 8 days)
- Naphthalenetrisulphonic, Sodium Salt isomers: 1-, 2-
- Naphthalenetrisulphonic Acid, Disodium Salt (NDS) isomers (Winick et al., 2015): 1,5-, 1,6-, 2,6-, and 2,7 NDS
- Naphthalenetrisulphonic Acid, Trisodium Salt isomers: 1, 3, 6-
- Fluorescein
- Rhodamine B
- Rhodamine WT
- Sulphur Hexafluoride

The Waikato Regional Plan allows tracer discharges under **Rule 3.5.9.1:** ***Permitted Activity Rule – Discharge of Dye and Salt Tracers***.

Historical and ongoing tracer discharge processes are recorded within Resource Consent Application data.

Although most tracer tests for New Zealand were conducted for deep wells to understand the deep hydrology and permeability zones, the same test and principles could be conducted at shallower depths associated with the shallow Tauhara aquifers.

Recommended actions would be to inject a tracer dye from a bore near to the southern side of Mt Tauhara, and to monitor for the tracer occurrence at select domestic bores within the township area. The occurrence or absence of the dyes at a bore could help understand the subsurface hydrological connectivity, mass flow, and flow directions. A study conducted in 2009 (Rosenberg et al., 2010) indicate that the potentiometric surface of shallow aquifers was highest directly south of Mt Tauhara, and declining westward towards the township area). The two bores TH10 and THM 20 are ideal candidates as injection points due to their location [2782316, 5710271] close to the area with the maximum potentiometric surface. Although the Huka Falls Formation is only observed to be 2 m thick at TH10, Oruanui Formation at 36 m depth and Crowbar Rhyolites at 84 m depth could provide the permeability to allow for waters to migrate westward. Another candidate location is TH09 [2782091, 6274183], which sits approximately 2.3 km NE of TH10, and has a relatively high potentiometric surface that declines directly westward, with the Tauhara suburb and Crown Rd area about 2 km to its west. Due to the potentiometric surface contours of both areas, it is expected that tracer dyes would flow west and enter the area populated by domestic bores. Injecting further east in the shallower zone would also help avoid directly cooling the upflow zone at Waipahihi.

Undertaking a tracer flow testing does not only benefit geothermal knowledge but may add to WRC's knowledge of the local fresh groundwater flow. This is locally important as the groundwater at Taupō is influenced by both steam-heating and the very porous pumiceous lithology of the uppermost aquifer. Environmental and social risks associated with chemical contamination from tracer injection activities are considered to be very low as the effects of chemical tracers are considered under *de minimis* levels (or negligible due to minimal effects), and does not require public notification to the local communities.

### 5.2.3 3D Geological Modelling

The bore depth-lithology models provided in Section 3 are very simple 2-dimensional models. that do not consider lithological variations. It is recommended for 3-dimensional (3D) geological modelling to be undertaken in the future, using geological modelling tools such as Leapfrog Geo. A 3D geological modelling is more robust and provides a closer interpretation of actual geological conditions, allowing for the hydrogeology to be better understood. 3D modelling using Leapfrog Geo was considered for this report, but ultimately omitted due to not being part of the original report scope and time constraints.

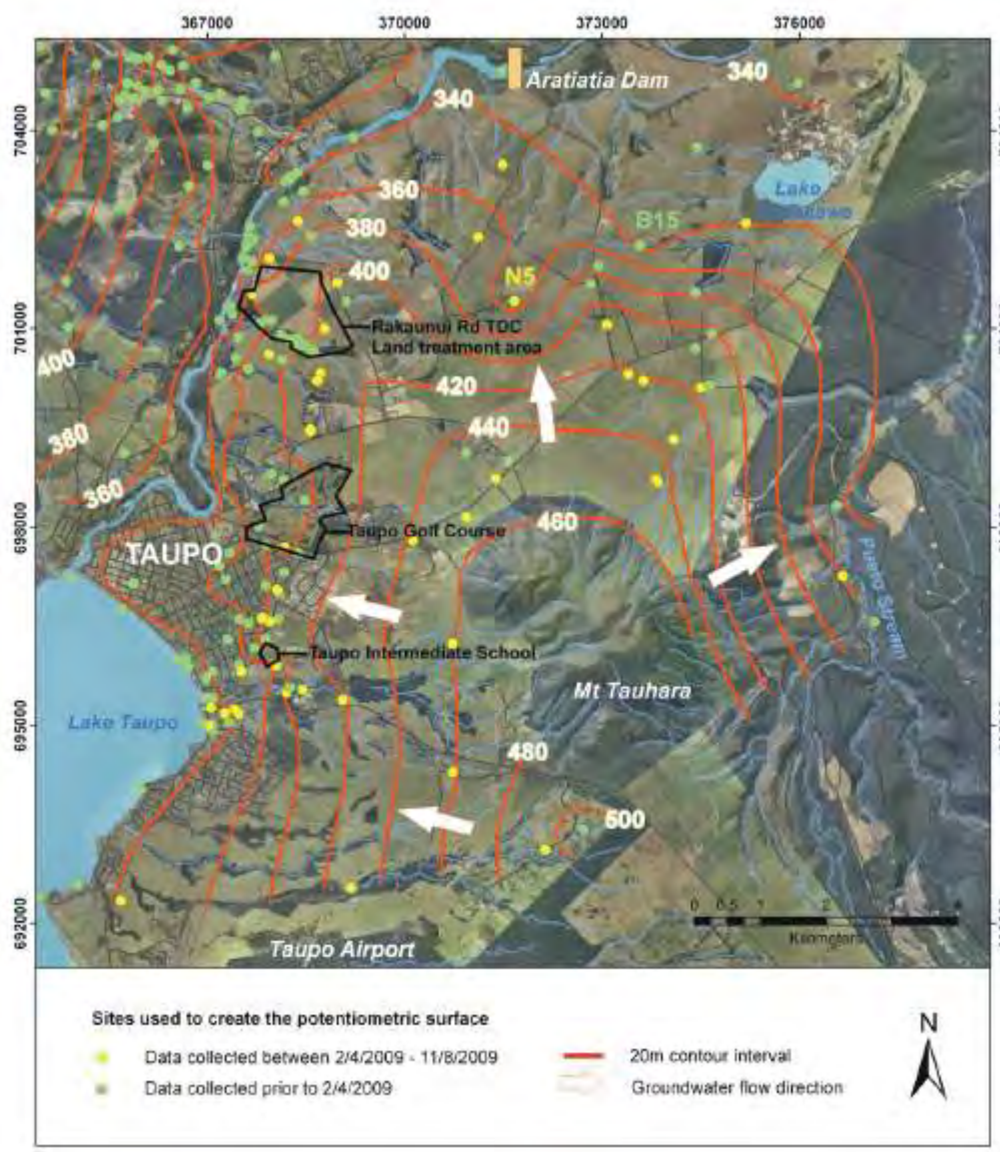


**Figure 5-1 Map of the area of Taupo-Tauhara geothermal system's potentiometric surface contours. It could be observed that the potentiometric surface is declining away from Mt Tauhara. From Rosenberg et al. (2010).**

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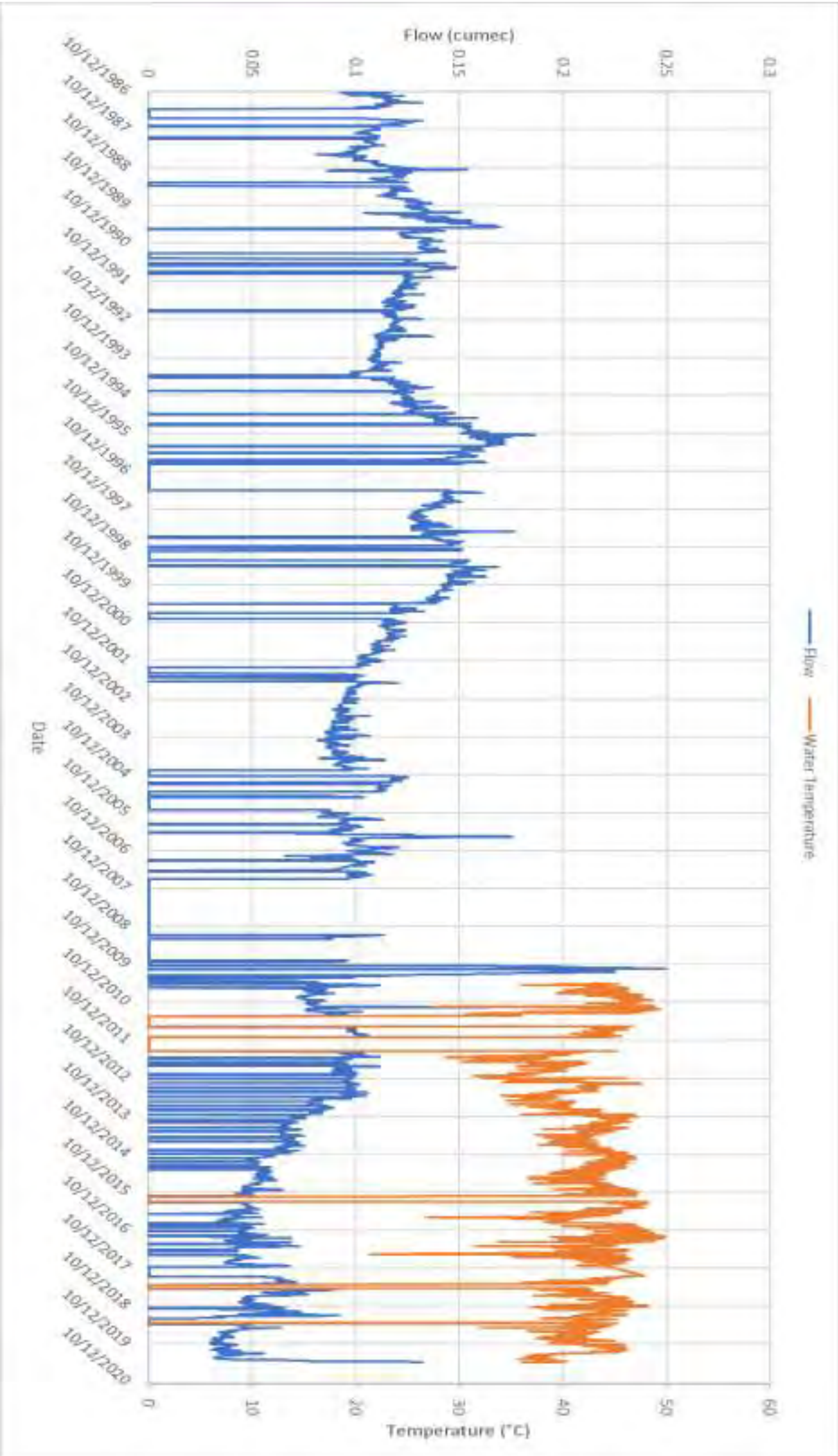
# Appendix 1

Flow and water temperature data measured by WRC at Otumuheke Stream. Water temperature data has only been recorded since 2010, while flow data has been recorded since 1986. There is a general decrease in flow observed at the site. Below is the long term time-series data for flow and water temperature.



Below is a graph showing discharge and water temperature data between 2009 to 2019.