The role of groundwater monitoring in the sustainable management and operation of the Ngā Tamariki Geothermal Field

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ABSTRACT

The extensive network of monitoring wells at the Ngā Tamariki Geothermal Field provides valuable information guiding the sustainable management and operation of the resource. In total, 34 shallow and intermediate wells are monitored for chemistry, pressure, water level, temperature, which give a detailed overview of a complex groundwater system above the deep geothermal reservoir.

The reservoir is overlain by three distinct hydrogeological units, including: a confined intermediate aquifer hosted within rhyolite lavas and breccias, an aquitard complex predominantly hosted within the Huka Falls Formation, and a shallow unconfined aquifer hosted in the Oruanui Formation and Taupō Pumice Alluvium. Chemistry and temperature monitoring indicate an upwelling of reservoir fluid into the northern part of the intermediate aquifer through a leak in the underlying clay-cap. Monitoring wells in the south contain cold sodium-bicarbonate waters, commonly encountered in Taupō and Middle Waikato catchments.

The objective of this paper is to provide a brief overview of the information obtained from the Ngā Tamariki groundwater monitoring program starting with the baseline sampling in 2009-2011, followed by the startup of the Ngā Tamariki binary plant in 2013, and continuous operation through to the present. We provide description of sampling and downhole monitoring techniques and share lessons learned associated with the ongoing maintenance of the network. Ultimately, the groundwater monitoring program provides comprehensive understanding of the regional groundwater system and supports the safe and sustainable operation of the field, with capability for early detection of responses to development.

1. INTRODUCTION

The Ngā Tamariki Geothermal System is situated within the Taupo Volcanic Zone, New Zealand, approximately 20 km NE of Taupo (Figure 1). In 2013, Might River Power (now Mercury NZ Ltd) and development partner Rotokawa Joint Venture Ltd (RJVL) commissioned an 85 MWe binary station. The station is currently connected to three production wells located in the center of the field, and five reinjection wells situated at the northern and southern ends of the field (Figure 2).

In the predevelopment natural state, the complex connectivity between the deep reservoir and shallow-intermediate aquifers was unknown.. A groundwater monitoring program was designed to address key development risks including: (1) major reservoir pressure drawdown causing coldwater inflow into the deep geothermal reservoir leading to quenching of the resource; (2) adverse changes to Significant Geothermal Features; (3) contamination of overlying freshwater aquifers used to supply water for domestic, stock, and irrigation uses.

To comply to resource consent conditions and ensure best practise management of the Ngā Tamariki field, an extensive groundwater monitoring network consisting of 34 shallow, intermediate, and deep wells was established. This network enables detailed understanding of groundwater conditions.

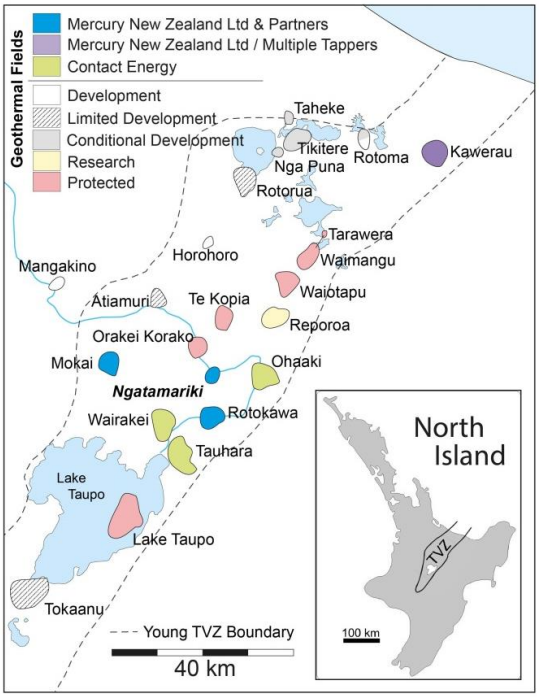


Figure 1: Location of the Ngā Tamariki geothermal field within the Taupo Volcanic Zone, New Zealand. Note that the fields operated by Mercury, Contact, and multitapper (Kawerau) are considered development fields.

Implementing robust groundwater monitoring prior to startup of geothermal operation enabled understanding of the hydrological flow, the vertical and horizontal location of aquifers, characteristics (chemistry, temperature) of groundwater across the field, and connections to the deeper geothermal reservoir. The knowledge gained from predevelopment surveys, and the subsequent monitoring program, provides the capability to detect potential adverse effects from the geothermal operation, and minimise, mitigate, or eliminate any significant impacts.

The following sections provide description of the hydrogeologic setting of the field, monitoring objectives,

monitoring methodology and equipment, and summary of monitoring results.

2.1 HYDROGEOLOGIC SETTING

The Ngā Tamariki geothermal reservoir is overlain by a complex groundwater system. From bottom to top, the principal hydrogeologic units listed in the table below.

The positions of these units (Figure 2) are further characterised below and have been described in prior publications (e.g. Bosely et al., 2010; Chambefort et al., 2016).

Unit	Elevation (mRL)	Thickness (m)
The geothermal reservoir	from -350 (prod. area)	base not defined
Whakamaru Ignimbrite Aquifer	-100 to -600	300-400m
Intermediate Aquifer	200 to -200	A few metres to 300m
Shallow Aquifer	350 to 250	~200m

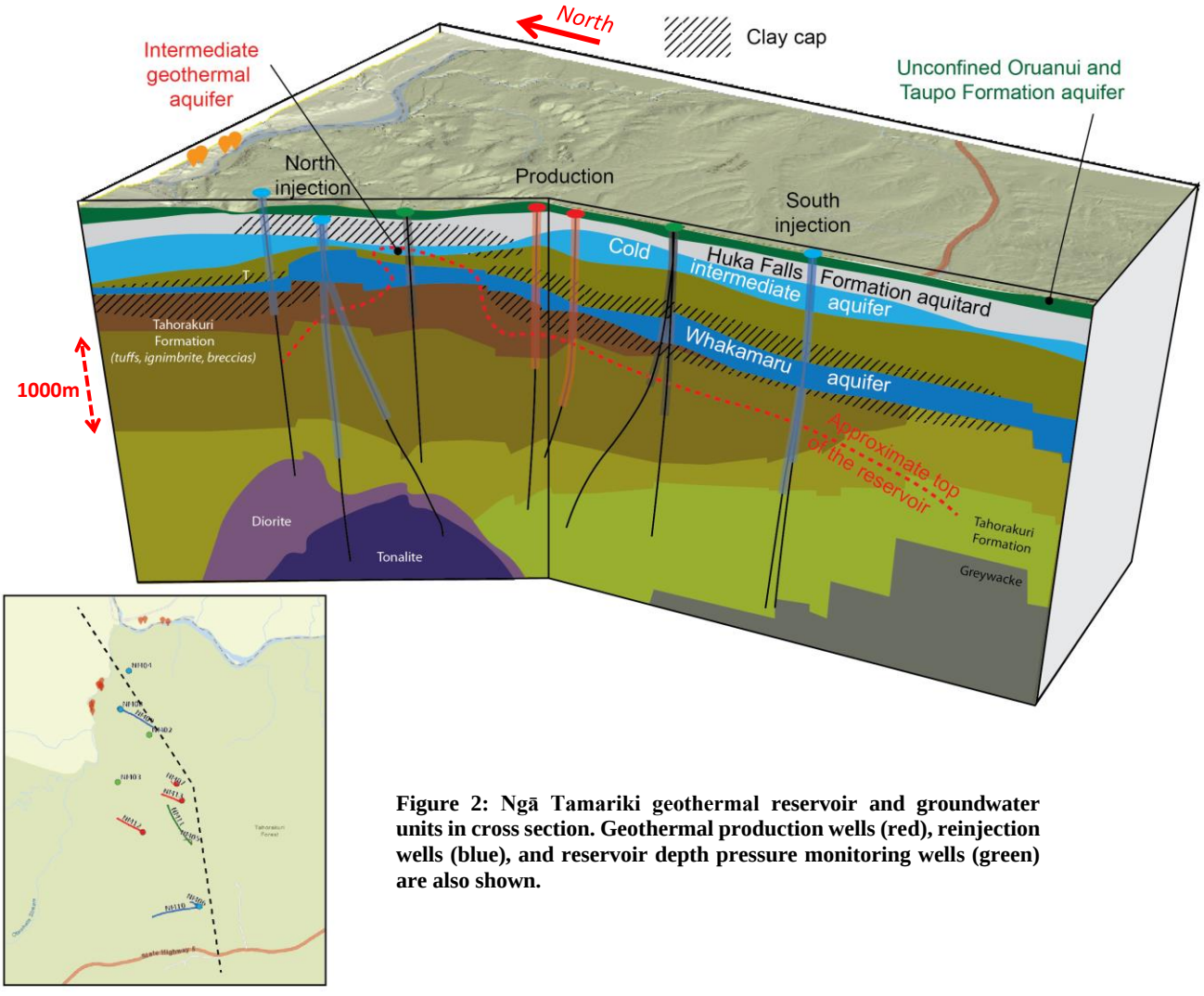


Figure 2: Ngā Tamariki geothermal reservoir and groundwater units in cross section. Geothermal production wells (red), reinjection wells (blue), and reservoir depth pressure monitoring wells (green) are also shown.

Table 1: Nga Tamariki hydrogeologic units

The geothermal system hosts a hot deep clay capped liquid **reservoir**. Fluid conditions are ~285°C near-neutral pH, and

chloride-dominated. The reservoir extends in a roughly north-south trend from SH5 to the Waikato River (Boseley et al., 2010; Chambefort et al., 2016). The deep reservoir is hosted in the Reporoa Group which consists of the Tahorakuri Formation, a volcanic succession of variably welded tuffs and ignimbrites, the Rotokawa Andesite, and a succession of andesitic lavas and breccias. The deep geothermal system is overlain conformably by an impermeable clay cap within the Whakamaru Ignimbrite.

In the northern part of the field, a leak in the clay cap allows geothermal fluid outflows into the intermediate aquifer. This geothermally influenced part of the intermediate aquifer has some connection to the surface, with thermal features, consisting of hydrothermal eruption craters (e.g. Simpson et al., 2014) and seeps, present along the Orakonui Stream and Waikato River at the northern and northwesters areas of the field (orange inverted symbols).

The Whakamaru Ignimbrite aquifer is a confined unit hosted in the welded unit of the Whakamaru Group Ignimbrite. This is bounded at the top by the Waiora Formation, an aquitard acting as the cap, and underlain by the relatively impermeable sedimentary succession of the Tahorakuri Formation. The Whakamaru Ignimbrite aquifer is largely isolated from the underlying geothermal reservoir by the clay-rich sedimentary units of the Tahorakuri Formation.

The intermediate aquifer occurs within a series of rhyolite domes, which converge near the centre of the field. These rhyolites are capped by the impermeable Huka Falls Formation and underlain by the Waiora Aquitard. The northern part of the aquifer mixes with upflowing geothermal fluid and is referred to as the **geothermal intermediate aquifer**. The southern part of the aquifer shows no geothermal influence and is referred to as the **cold intermediate aquifer**.

The Shallow Aquifer: the Oruanui Formation and the Taupo Pumice Alluvium host the shallow unconfined aquifer. This is separated from the deeper intermediate aquifers by the more impermeable Huka Falls Formation, a silty lake deposit expressed as mudstone-sandstone successions. The bottom of the aquifer corresponds to the top of the Huka Falls Formation, however the aquitard properties of the latter appear to be gradational with some of the upper Huka Falls Formation containing groundwater.

Recharge to the Shallow Aquifer comes mostly from rainfall (around 500 mm/year). Outflow is into the surrounding streams, including the Orakonui, Waiwhakarewaumu, and Mangamingi streams and the Waikato River. Groundwater flow patterns indicate a northward flow direction.

3. ORIGIN AND RATIONALE OF GROUNDWATER MONITORING

3.1 Water resources and geothermal development

The requirements for monitoring and protection of water resources in the vicinity of developed geothermal fields vary considerably around the world and have evolved over time. Early developments in New Zealand and elsewhere did not fully consider, or monitor for, the impacts of geothermal fluid take upon groundwater and surface water. In New Zealand, the philosophy and governance of groundwater monitoring in geothermal areas is derived from the resource consent process, which is managed by regional councils (Burnell et al., 2016; Doorman and McLeod, 2018; Jackson et al., 2010).

It is incumbent upon the operator to develop the scope of the monitoring program during the resource consent application process. Subsequently, as part of the geothermal development, the operator then executes the monitoring program, often with the support of third party scientific and technical consultation, sampling and maintenance contractors, and designated analytical laboratories. This process is exemplified by the work carried out by Mercury NZ Ltd. around the drilling and testing of groundwater monitoring wells to support commissioning of the Ngā Tamariki binary power plant.

3.2 Key objectives of groundwater monitoring at Ngā Tamariki

The origins of the groundwater monitoring program can be traced to a body of work undertaken in 2009, as part of an Assessment of Environmental Effects for the proposed development of Ngā Tamariki, to better define the geothermal reservoir, hydrogeology and how development might affect groundwater resources.

The culmination of this process was the development of a detailed Conceptual Hydrogeological Model and the identification of potential development risks. These are broadly encompassed by the following:

- Pressure drawdown in the reservoir that causes, or is likely to cause, quenching of the resource by cold water inflow.
- Flow of geothermal fluid freshwater aquifers.

The groundwater monitoring program was developed to provide early detection of changes related to these risk areas. Subsequently, in 2010, the monitoring program was incorporated into a suite of resource consents issued to Mighty River Power (now Mercury Energy Ltd) by the Waikato Regional Council to fulfil its requirements under the Resource Management Act.

The key elements of the groundwater program ensuring success are:

- **Extensive spatial coverage,** extending from production and injection areas to the field periphery
- **Various depth coverage** to provide data on all hydrological units (reservoir and the overlying aquifers)
- **Comprehensive coverage of parameters**: temperature, pressure, water levels, chemistry
- **Sufficient frequency of monitoring** to enable prompt detection of changes and issues. This can be revised as the understanding of groundwater evolves.
- **Baseline** monitoring and sampling prior to startup of generation.
- **Reliability** and redundancy of wells and monitoring systems.

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4. MONITORING PROGRAM AND METHODOLOGY

4.1 Well construction and equipment installation

The Ngā Tamariki groundwater monitoring network consists of 34 shallow (<100m deep) and intermediate wells (<350m deep), providing a comprehensive view of groundwater characteristics above and adjacent to the deep geothermal reservoir.

Development of the monitoring network involved drilling dedicated monitoring wells and also includes existing bores operated by partners and stakeholders.

- 16 static monitoring wells were drilled in 2008-2009.
- 2 additional shallow wells were drilled in June 2014, and a third additional shallow well was drilled in 2017.
- 5 wells NW of the developed field are situated to monitor for outflow or inflow into the field.
- Access to the remainder of the wells in the network is provided by stakeholders and private landowners.

Periodic monitoring occurred prior to commissioning, and the continuous monitoring systems were fully implemented by mid-2014. The intermediate aquifer monitoring wells were tested between October 2009 and mid-2010. In January 2011, permanent monitoring equipment was installed.

Baseline chemistry results from the Ngā Tamariki shallow aquifer monitoring wells were obtained as part of the groundwater studies carried out in 2009. Regular monthly monitoring of these wells commenced in August 2011 following the installation of submersible pumps.

Figure 3 shows an as-built diagram of a typical monitoring well at Ngā Tamariki with monitoring equipment installed.

4.2 Monitoring methodology

Parameters and frequency

Monitoring parameters include chemistry, pressure or water level, and temperature measurements. The majority of the intermediate aquifer monitor wells have continuous downhole pressure equipment. Manual water level measurements are also conducted on a regular basis in shallow wells.

Intermediate aquifer and reservoir pressure

The water level / downhole pressure of monitoring wells is continuously recorded. Downhole pressure equipment consists of 1/8” tubing connected to a chamber installed to a specific depth. An inert gas (nitrogen) is injected through 1/8” tubing. The nitrogen pressure should be equal to the aquifer pressure at the installed depth. The pressure is measured, monitored and recorded by a surface pressure transducer / transmitter. The gas tubing is periodically purged to avoid the ingress of aquifer water into the tubing, which adversely impacts data quality.

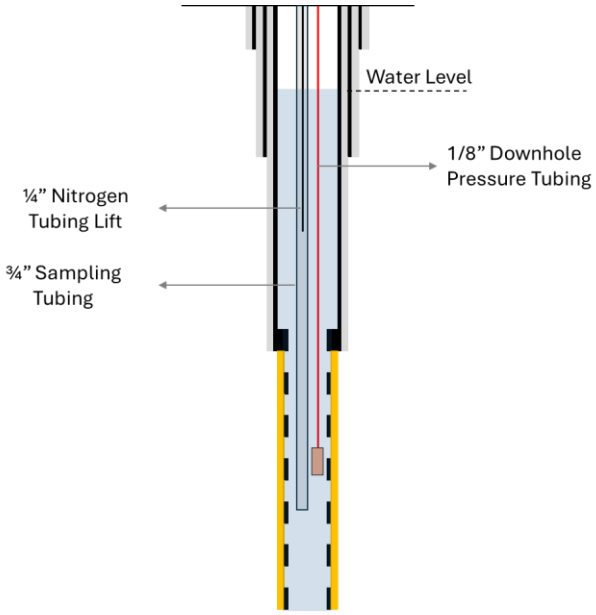


Figure 3: Downhole Installation Schematic of Ngā Tamariki Monitoring Wells

Water levels in the shallow aquifer

Water levels in the shallow aquifer are measured directly using a water level sounder, a device resembling a tape measure with a sensor at its tip. The sensor emits a beep upon contact with the water, indicating the water level.

Water chemistry sampling schedule

Waters from the shallow and intermediate aquifer wells are sampled at routine intervals to monitor chemistry and temperature. The chemistry monitoring frequency has undergone several revisions over development history in the following sequence:

- **2009-2013**: pre-startup baselining
- **2013**: geothermal station startup
- **2013–2021**: high frequency (monthly) monitoring following startup
- **2021–present**: reduced frequency. Sampling 6 monthly for the entire network and on a monthly or quarterly basis for select high priority wells.

Chemistry sampling procedure

The water is lifted to collect the samples. A ¼” tubing is inserted into ¾” tubing and placed below the water level (see Figure 4). Typical static water levels are encountered at between 35 – 70m depth. Nitrogen is injected through the ¼” tubing enabling the groundwater sample to flow through the ¾” tubing to the surface. In several wells, the sampling tubing has been replaced with downhole electric pumps to deliver the water to the surface.

Chemistry samples are analysed at the New Zealand Geothermal Analytical Laboratory (NZGAL), operated by GNS at Wairakei. Chemistry parameters measured include: pH, conductivity, total inorganic carbon (H_2CO_3, HCO_3^- and CO_3^{2-}), ammonia, arsenic, boron, calcium, chloride, fluoride, iron, magnesium, manganese, mercury, nitrate, potassium,

rubidium, silica, sodium, sulphate, and TDS (total dissolved solids).

4.3 Operational challenges and maintenance

Throughout the operational history of the field, consistent maintenance has been a key element to avoid data gaps.

Pressure and water level challenges

- In one deep pressure monitor (NM02), wellbore accessibility was impeded by anhydrite mineral buildup as a result of injection returns from the north. As a consequence, deep reservoir pressure monitoring had to be transferred to another deep well (NM11).
- In the intermediate aquifer monitoring wells, nitrogen pressure monitoring systems have experienced leaks causing erroneous declining readings. This is mitigated by routine nitrogen recharge done every 6 weeks.
- In shallow wells, the majority of pressure-based water level monitoring has displayed data drift over time. As such, manual water level checks taken at the same time as chemistry sampling are now used.

Access to remote locations

- Remote sites with continuous monitoring have periodically experienced outages. These have occurred due to degradation of solar charged batteries over time, as well as lightning strikes on occasion. At one site, monitoring was disrupted by a rodent chewing through a cable.
- Maintaining continuous access to bores has been challenging in some cases due to the large area covered by monitoring. Vegetative screening and deterioration of tracks made a shallow bore inaccessible from 2018-2022.

The timely detection and correction of these issues has been a result of consistent coordination by Mercury staff (site-based, environmental, geoscience), and contractors (sampling and site maintenance). Mercury is investigating the development of monitoring data dashboards with live feeds to enable prompt detection and response to any data recording issues.

4.4 Other monitoring programs

Surface hydrology and weather monitoring datasets provide additional understanding of groundwater recharge processes. Key surface data include flow, temperature, and chemistry measurement at the Mangamingi Stream and geothermal surface features along the Orakonui Stream and Waikato River in the NW part of the field. Hydrologic interpretations are further aided by onsite weather monitoring.

5. PRESSURE AND WATER LEVEL MONITORING RESULTS

5.1 Reservoir pressure

Two dedicated reservoir-depth monitoring wells located in the North and Central parts of the field provide real-time assessment of reservoir pressure conditions. The pressure drawdown trend of both monitoring wells is nearly identical, indicating good connectivity across the field. Figure 4 shows the pressure drawdown trend of NM03 since early development.

Minor reservoir pressure drawdown (~2 bar) has been observed in Ngā Tamariki since station commissioning in 2013. The reservoir pressure decreased in the early production years but has since stabilized as shown below. The reservoir pressure drawdown aligns with what has been predicted in reservoir model simulations.

Relatively stable pressures are maintained as a result of the station type and injection strategy at Ngā Tamariki. The binary plant reinjects nearly all (~98%) of produced fluids in a roughly equal split between the northern-southern ends of the field. Reinjection provides pressure support and ensures that reservoir pressure changes can be managed and are less likely to impact conditions in the overlying intermediate aquifers.

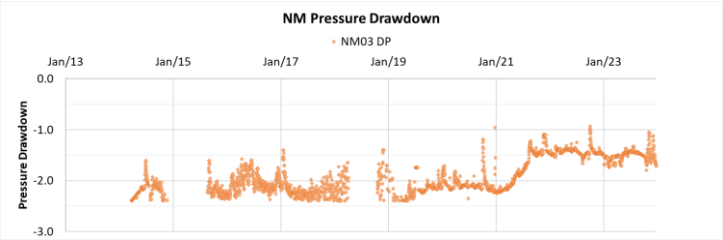


Figure 4: Ngā Tamariki reservoir pressure drawdown trend in bar. Negative values indicate slight pressure drawdown.

5.2 Intermediate aquifer pressure response

Continuous downhole pressure monitoring has been a critical component of the geothermal resource management strategy with focus on understanding impacts upon the intermediate aquifer systems. This enables early detection of any adverse effects on the intermediate aquifer related to extraction of geothermal fluids for power generation.

Intermediate aquifer pressure results have been largely stable (**Error! Reference source not found.**) over the timeframe of monitoring and lower in magnitude than the 2 bar drawdown change in the reservoir (Figure 4). An example of downhole pressure data from the geothermally-influenced and cold intermediate aquifers, compared with the changes observed in deep reservoir pressure, are shown in **Error! Reference source not found.**.

5.3 Shallow wells

Water level monitoring in the shallow groundwater aquifer indicates that fluctuations are primarily influenced by rainfall (see

Figure). The response time of these changes varies, with a lag time that depends on the depth of the water level. Notably, wet years in 2017-2018 and 2022-2023 preceded increases in water level in shallow wells by 3-6 months.

Monitoring to date has shown no temporal correlation between shallow groundwater levels and geothermal fluid abstraction at Ngā Tamariki.

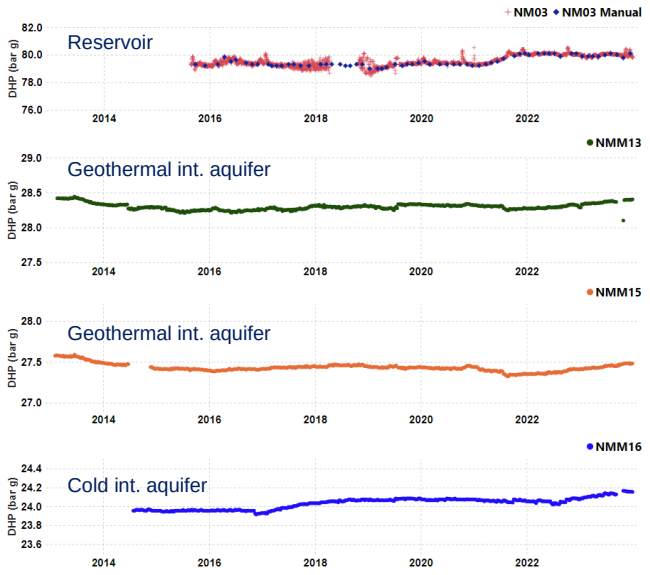


Figure 5: Downhole pressure monitoring for intermediate aquifer monitor wells. NMM13 and NMM15 monitor pressure within the hot geotherm intermediate aquifer while NMM16 is one of the cold intermediate aquifer monitor wells.

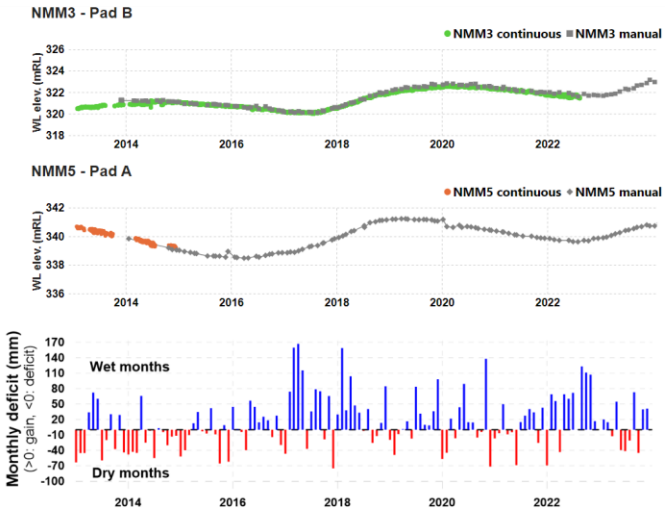


Figure 6: Water level monitoring for shallow groundwater aquifer plotted relative to monthly precipitation anomalies for the South Waikato – Taupo area.

6. WATER TEMPERATURE RESULTS

Water temperatures are recorded at the time of chemistry sample collection. Since station startup, water sample temperatures in both the shallow and intermediate aquifers have remained consistent.

In the geothermally influenced intermediate aquifer, water temperatures are lower than geothermometer temperatures (i.e. Quartz equilibrium temperature) due to cooling during the airlift sampling process (Figure 7). Notably, stable temperatures over time for samples collected from the geothermal intermediate aquifer suggests that the sampling program has been carried out under consistent conditions. During the airlift sampling, approximately 3 wellbore volumes are purged prior to collection.

7. WATER CHEMISTRY RESULTS

7.1 Intermediate aquifer results

Intermediate aquifer chemistry ranges from cold and dilute in the southern part of the field to hot and geothermally influenced in the northern part of the field.

Water chemistry in the intermediate aquifer can be classified into three distinct types:

- Local groundwater derived from meteoric water flowing through rhyolitic materials
- Diluted geothermal fluid mixed with groundwater
- Steam-heated groundwater

Chloride vs. enthalpy mixing relationship

The northern intermediate monitoring wells show significant geothermal influence as indicated by elevated chloride concentrations (up to ~600 mg/kg) and quartz geothermometer temperatures (Fournier and Potter, 1982) in excess of 200°C (1000 kJ/kg). The southern rhyolite domes host the cold intermediate aquifer characterized by sodium-bicarbonate chemistry (with chloride at less than 10 mg/kg), similar to most of the Taupo and Middle Waikato catchments (Chambefort et al, 2016). This fluid chemistry and thermal differentiation of the aquifer units is highlighted in a chloride vs. enthalpy diagram below in Figure 8.

Major ion water chemistry from baseline to present

The variation in major ion water chemistry in the intermediate aquifer is shown in Figure 9 in Piper diagram format for 2011 (baseline) and 2023 values. The divide between the geothermally influenced northern and cold dilute southern intermediate aquifers remains largely unchanged from baseline to present. The wells in the cold intermediate aquifer group are magnesium-bicarbonate or mixed type waters, while those in the geothermal aquifer are grouped as sodium-chloride type.

Two wells at the junction of the cold and geothermally influenced intermediate aquifers (NMM10 and NMM16 on Pad A) can be grouped as sodium-bicarbonate type. These mixed wells also show stable chemistry from baseline to present.

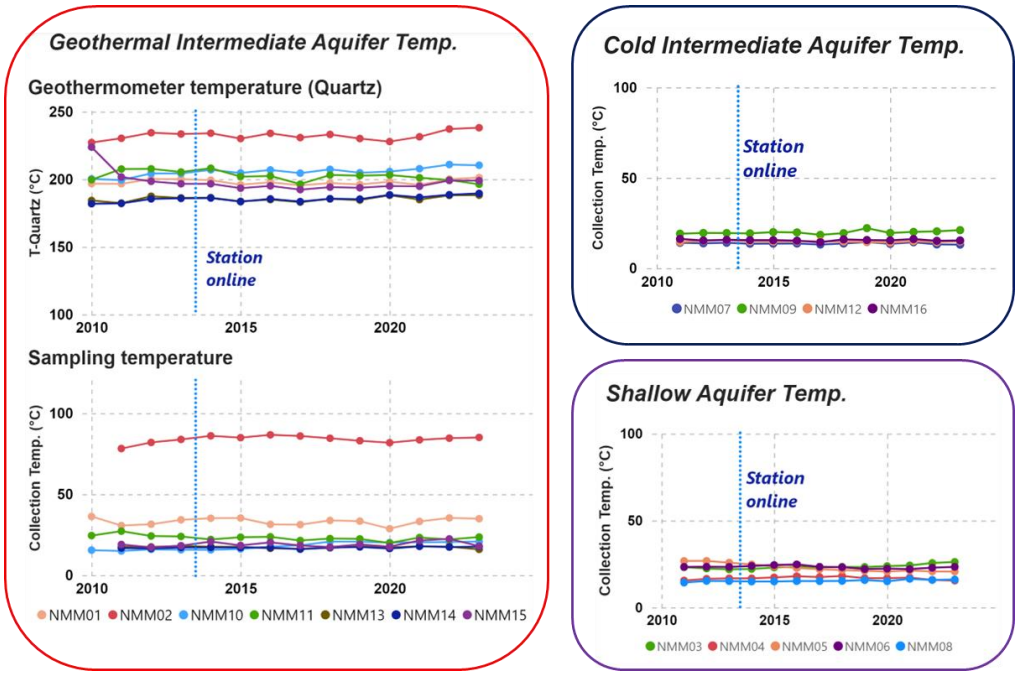


Figure 7: Example temperature monitoring timeseries for intermediate and shallow groundwater monitors.

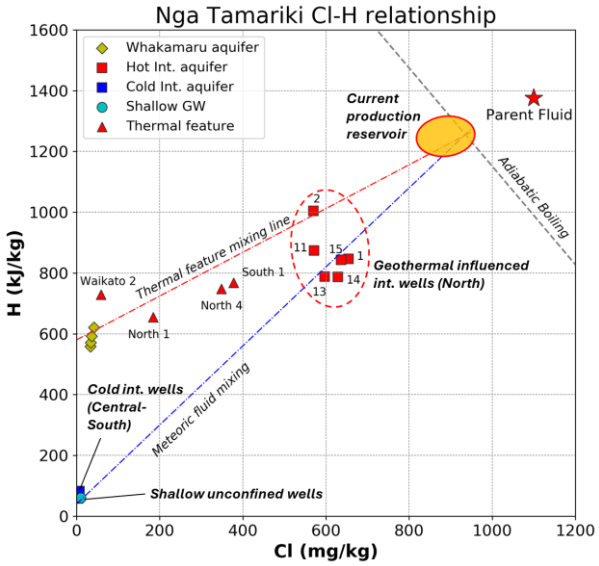


Figure 8: Chloride vs enthalpy diagram differentiation in fluid chemistry and enthalpy between the geothermal reservoir, intermediate aquifer, and cold shallow groundwater. Results from thermal features sampled at the northern end of the field are also shown for reference.

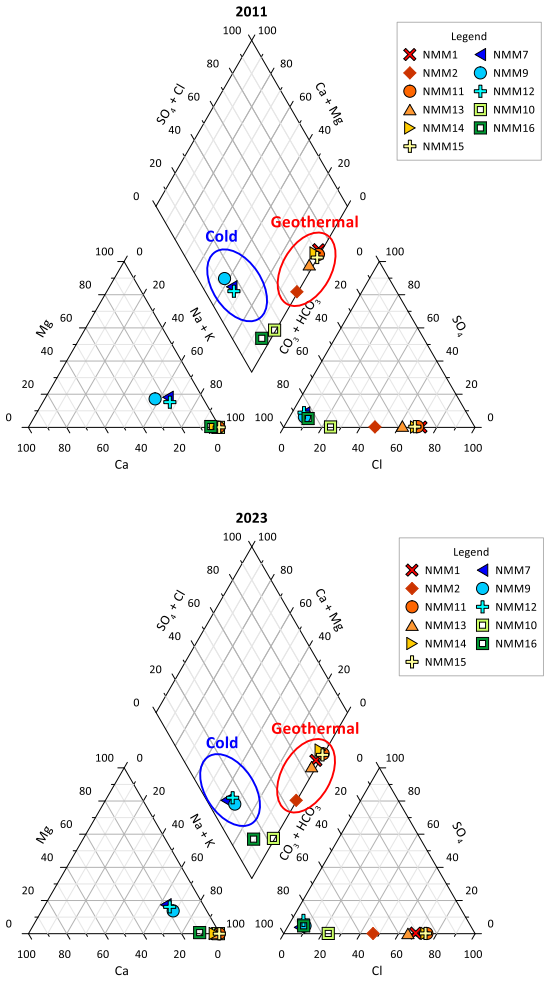


Figure 9: Piper diagram showing differentiation between geothermal and cold intermediate aquifers. No major changes in the intermediate aquifer chemistry have been detected after a decade of geothermal production.

7.2 Shallow aquifer chemistry monitoring

The shallow aquifer chemistry is sodium-bicarbonate type, commonly encountered throughout the Taupo and Middle-Waikato catchments, with few geothermal influences apart from limited interaction where surface thermal manifestations occur (e.g. Orakonui Stream). The majority of shallow aquifer chemistry monitoring has shown no response to geothermal development.

Sampling of shallow monitoring bores in the vicinity of wellpads have detected short-term chemical evidence of geothermal fluid, exhibited as elevated chloride concentrations. This was a consequence of consented surface brine soakage following well flow testing during the development period (prior to September 2013). The chemistry effect of the consented soakage is exemplified in the Figure (monitoring well NMM08 on Pad 3), where chloride increased to ~600 mg/kg in 2013 but has since declined to near baseline levels. This implies that the effects of consented soakage during development and pre-startup stage of the Ngā Tamariki binary plant were localized and short-term.

In order to protect shallow groundwater from recurrent exposure to geothermal fluids the brine ponds at well pads and the station are lined and have water level detection systems. This enables management of separated geothermal water during station shuts, maintenance, and well operations.

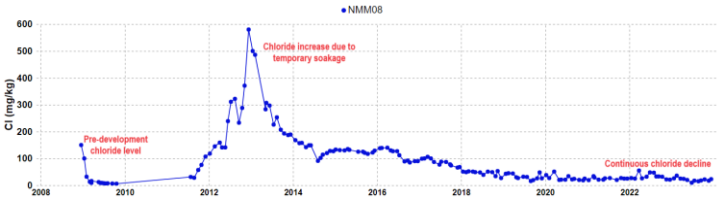


Figure 10: Example chloride trend showing short-term localized influence of brine soakage the shallow aquifer during geothermal development.

8. CONCLUSIONS

The network of monitor wells at Ngā Tamariki, and the extensive groundwater monitoring program put in place, provides an early warning capability to manage any adverse effect on the shallow and intermediate aquifers related to geothermal field operations. After more than a decade of monitoring there have been no significant changes in the overall distribution and characteristics of fluids in the aquifers as seen from the stable pressure, water level, and chemistry trends.

Monitoring of groundwater aquifers will continue in the foreseeable future, with a focus on regular maintenance of the monitoring network and equipment as well as optimising the monitoring program as required. This will ensure that the shallow/intermediate aquifers, and the geothermal resource in general, continue to be sustainably managed.

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