MODELLING THE TAURANGA LOW TEMPERATURE GEOTHERMAL SYSTEM

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ABSTRACT

A low temperature geothermal system underlies the Tauranga Harbour to Maketu area of the Bay of Plenty Region. The temperature of the system ranges from cool (18 °C) to warm groundwater (less than 70 °C). The resource is not mineralised, but freshwater. There are no active hot geothermal surface features and the resource is confined but not free-flowing artesian. The resource is tapped by direct use bores, and the variance of temperature across the field means a range of usage including: municipal supply, irrigation, commercial pools and domestic space and water heating /pool water.

The 1991 Resource Management Act stipulates that water 30°C and above is geothermal. For allocation purposes this has caused difficulties in the Tauranga area as the aquifer is both groundwater (<30°C) and geothermal (>30°C). They are one-in-the-same resource, but allocation from one can impact on the other.

To understand and simulate heat and mass flows through this low-temperature geothermal field a TOUGH2 numerical model has been created. This model covers a significantly larger area than typical Taupo Volcanic Zone field models. As regular monitoring of production rates is not widespread in the Tauranga System, finding suitable data to calibrate the model proved to be a challenge. In the end the calibration dataset included downhole temperature profiles, and water level changes due to seasonal production changes. Seasonal changes in production data required for this calibration were estimated from the metered data of a selected set of production wells.

In this paper, we present the details of the model and the data used for calibration. Simulation of the allocated and estimated actual use patterns of the resource were undertaken to understand the likely impact of continued abstraction of geothermal groundwater on pressure and temperature in the Tauranga Geothermal System.

1. INTRODUCTION

The Tauranga low-temperature geothermal system is located on the Bay of Plenty coast of the North Island of New Zealand (Figure 1). The system hosts a number of warm springs and has been used domestically and commercially for bathing, horticulture, heating, and cooling on an increasing scale over the last 30 years (White 2009). As use of the system increases, so too does the importance of resource management. To assist with this management, the Bay of Plenty Regional Council (BOPRC) commissioned GNS Science (GNS) to develop a numerical reservoir model of the system suitable for forecasting the response to scenarios of future use.

Monitoring of the Tauranga Geothermal System has been carried out sporadically (Hodges, 1994). Originally, the system was treated as a groundwater system because temperatures are predominantly lower than 70°C. However, the 1991 Resource Management Act (RMA) defined groundwater bores with temperatures >30°C as geothermal and so Tauranga has since been reclassified. In a resource report on Western Bay of Plenty, Hodges (1994) focused on groundwater levels and showed that they have declined in some parts of the Tauranga area after extraction started. It is not known if the extraction and decline are directly related, or if the area's climatic regime has changed. Since the study of Hodges, monitoring has continued as part of a regional groundwater monitoring network (Barber March 2012).

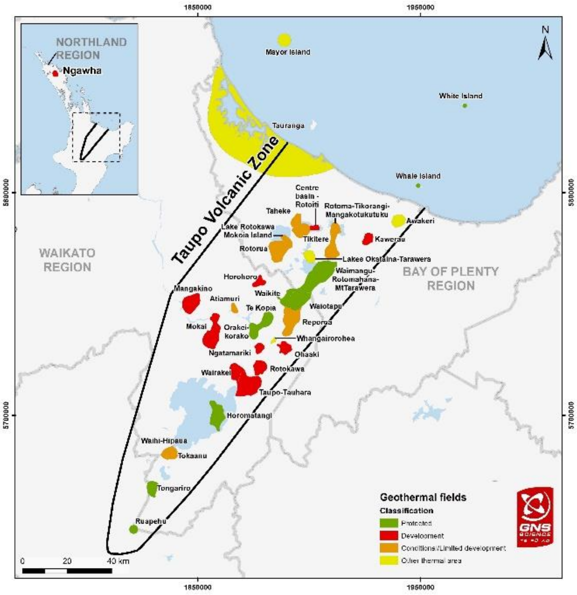

Figure 1: Location of the Tauranga Geothermal System marked in yellow.

1.1 Planning Context

1.1.1 Regional Policy Documents

BOPRC manages the geothermal resource under the RMA. It allocates geothermal heat, energy and water and is also responsible for the management and allocation of freshwater.

A hierarchy of planning documents provides the framework for managing geothermal resources, including the Regional Policy Statement (RPS) and the Natural Resources Regional Plan (NRP).

The RPS sets the overall direction for management through high level objectives and policies, and:

- provides for the sustainable management of geothermal resources;
- categorises geothermal systems according to their values and uses;
- requires the development of a set of management plans for certain systems; and
- provides for the relationship of Maori and their culture and traditions related to geothermal resources.

Under the RPS, the Tauranga System is categorised as a Low Temperature System and provides for extractive use where the adverse effects of the activity can be avoided, remedied or mitigated and where discharges must be managed to avoid signifncant adverse effects on surface water and stormwater. It also requires that a system management plan is developed for the Tauranga System. This plan must address matters such as a system objective, reservoir model predictions, allocation limits, and discharge and production strategies.

The NRP must give effect to the RPS and includes policies and specific rules requiring resource consents for drilling, for the taking of heat and energy, and for take and discharge of geothermal fluid. Resource consent applications require an assessment of effects of use on the sustainable management of the resource, and localized effects (for example on other users).

The geothermal provisions of the NRP are currently under review. Key phases of the review will include:

1. Technical inputs: building an understanding of the resource available for allocation through modelling and monitoring;
2. A system management plan: to provide a system-wide perspective and inform policy development;
3. Policy development: determine the efficiency and effectiveness of various policy options;
4. Community engagement: considering community values and aspiration and competing demands on the resource, including providing for cultural use and the values of tangata whenua.

1.1.2 Modelling in the Regional Plan Review

The development of the Tauranga Reservoir Model will inform future allocation frameworks to ensure overall sustainable management of the geothermal resource. For this reason, it is fundamental to the development of the system management plan and the plan review. Of particular interest is the effect of abstraction on ground water levels, risks of localized or more widespread cooling, and the effects of discharges (i.e. to develop a preferred discharge strategy).

2. THE TAURANGA GEOTHERMAL SYSTEM

2.1 Geological Setting

Tauranga City sits in the Tauranga Basin, a tensional graben that formed about 2-3 Ma (Davis and Healy, 1993). To the northeast is the Pacific Ocean, and to the west and northwest lie the mountains of the Kaimai and Coromandel Ranges respectively (Figure 2). The area forms part of the Coromandel Volcanic Zone (CVZ), a northwest-southeast trending feature close to the subduction zone between the Pacific and Australian plates. The CVZ was active between ~18 and 1.5 Ma (Adams *et al*., 1994; Briggs *et al*., 2005). During this time, three ignimbrite eruptions occurred and at least 21 dacite-rhyolite domes or dome complexes were emplaced (Briggs *et al*., 2005). Rhyolite domes like Mt Maunganui remain dominant landforms around Tauranga City.

In a large part of the Tauranga area, relatively young, eastward-dipping sediments known as the Tauranga Group Sediments have been deposited on top of the volcanic rocks. Sediments dated at ~6.5 ka (Davis and Healy, 1993) overlie some of the rhyolite domes. Tidal sediments are younger, between 3.4 and 0.7 ka (Davis and Healy, 1993). Sediments thicken seawards (Simpson and Stewart, 1987), reaching a thickness of approximately 300 m off the coast, but thinning to the west of the study area (Figure 2; White *et al*., 2009). There are active faults to the south and west of the study area, but none identified within it (Briggs *et al*., 2005; Edbrooke, 2001; Leonard *et al*., 2010).

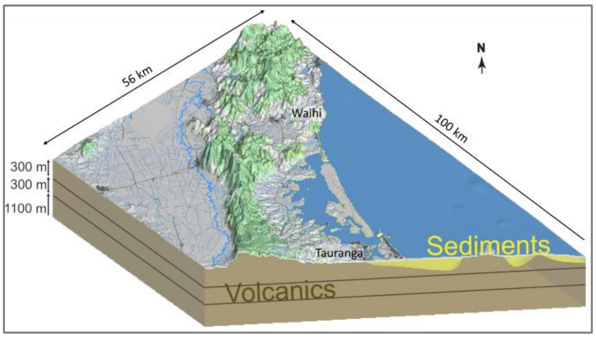

Figure 2: Geological setting of the Tauranga Geothermal System.

Permeability in the study area is thought to be primarily in volcanic rocks and dominated by small-scale fractures (Simpson, 1987). In contrast, the Tauranga Group Sediments appear to be relatively impermeable and form a confining cap (Simpson, 1987). Lithological variability in the sediments results in zones of higher permeability, rather than one single continuous aquifer (Schofield, 1972). In general, the shallow groundwater system is fed by recharge in sediments, while the deeper system contains considerably older fluids and is only recharged slowly by vertical seepage (Petch and Marshall, 1988). This suggests that permeability is low in the deep sediments and volcaniclastics, and that horizontal permeability is higher than vertical permeability in the shallow sediments.

2.2 Heat Flux and Temperature Data

Heat flow around Tauranga is elevated compared to the national average, with an estimated average of 88 mW/m^2 (Simpson 1987) which can be quite variable spatially. For example, at one site a heat flux of 55 mW/m^2 was measured, but 8 km away a value of 200 mW/m^2 was obtained (Studt and Thompson 1969). In several distinct areas (Maketu, Mt Maunganui and around Tauranga Harbour edge) the heat flux reaches as high as 336 mW/m^2 (Simpson 1987).

The Tauranga area has been drilled extensively for groundwater purposes, providing temperature information to several hundred metres below the surface (White et al. 2009). More than 600 wells have been drilled, providing 1623 temperature measurements (Figure 3). The bottom of the deepest well is at 904 metres below sea level, and the hottest temperature measured was 67°C. In general, measured temperatures are hotter under Tauranga City than in other parts. But note that wells are only drilled to the depth where the required fluid conditions are found.

For this study, 40 wells were used that had temperature profiles with depth. These were considered to be more useful for calibrating the reservoir model.

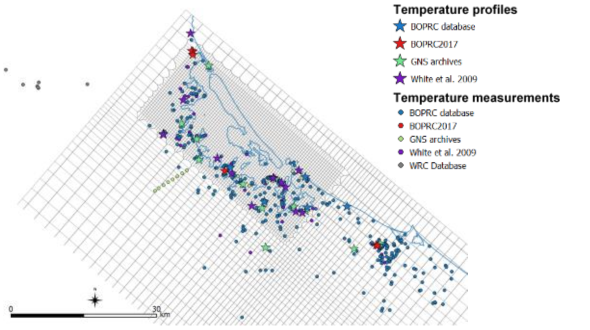

Figure 3: Locations of wells with measured temperature. Colours correspond to the sources of data

2.3 Water Level Data

There are 49 monitor wells in the Tauranga area where water levels are measured by BOPRC (Figure 4), many of which have operated for decades. They show seasonal variations of between 0.4 and 28 m (e.g. Figure 5). In all but one well, the water level decreases in the high-extraction months. There is no apparent correlation between well depth and amount of drawdown.

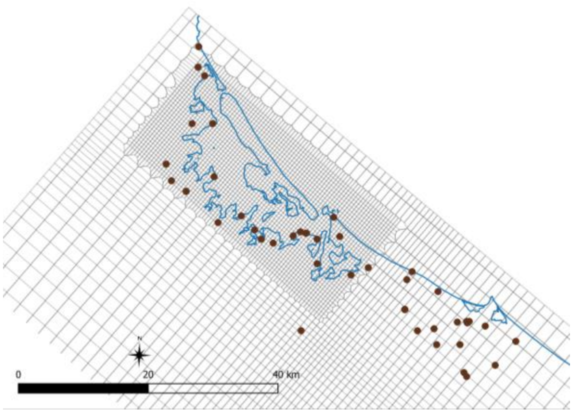

Figure 4: Locations of water level monitor wells.

2.4 Extraction Data

Water is extracted from 631 wells in the Tauranga Geothermal System (Figure 6). Of these, 23 have a nearby reinjection well. For each well, the location and consented extraction rate are known. The depths of the wells range from 1.5 m to 917 m, although the drilled depth is unknown for 66 wells.

The consented rates are a maximum that should not be exceeded, with actual extraction rates likely to be lower than the consented rate. However, the actual rates are not known in most of the wells in the Tauranga area. For modelling purposes, actual rates are required.

Some measurements of actual extraction rates have been done at Tauranga, with meters installed on 149 wells. The measurements were recorded for varying lengths of time between 2011 and 2017. The metered extraction dataset contained 231,563 data points making a manual analysis difficult.

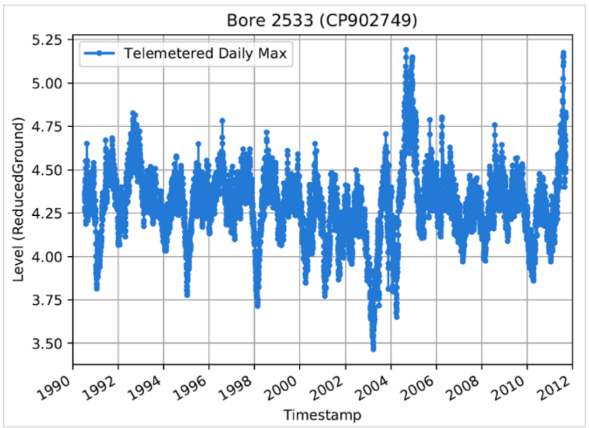

Figure 5: Example of monitored water level data, showing seasonal variations.

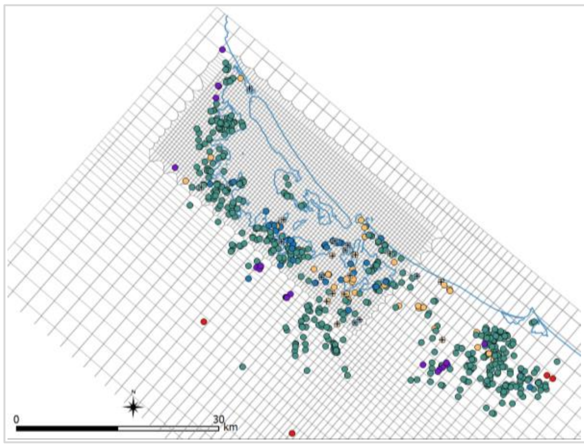

Figure 6: Locations of extraction wells (circles) and reinjection wells (black crosses) in the Tauranga Geothermal System.

BOPRC have noted that extraction in many wells varies with the seasons. For example, wells that are used for irrigation have more extraction in the spring and summer periods. Such seasonal variations could account for the seasonal changes seen in the water level data.

2.4.1 Estimating Actual Use

The reservoir model requires actual extraction rates rather than consented rates. But these have not been measured in most wells, so the rates were estimated from the metered data. For this estimation process, the wells were categorised into five different use classes: municipal, irrigation, commercial, domestic and unknown.

For each metered well, the consented rate was extracted from the consent database. Then the average annual use was calculated from the metered data. To ensure that seasonal effects did not skew the data, only wells with records longer than 1 year were used.

This approach provides two annual rates for each metred well – one from the consented data and one from the metered data. These individual rates were then summed for each of the use classes and the ratios of metered to consented rates were formed. Table 1 summarises the totals and ratios for each class.

Table 1: Summary of the metered data and associated consented extraction for the Tauranga area.

	Total Metered Annual Use (m^3)	Total Consented Annual Use (m^3)	Ratio of Actual to Consented
Municipal	2,103,501	9,413,468	0.2
Irrigation	3,488,582	12,655,481	0.3
Commercial	863,729	21,292	0.25*
Domestic	N/A	N/A	0.25*
Unknown	399,604	1,312,453	0.3

* No domestic wells were metered, and the single metered commercial well had extraction rates higher than those consented. For these classes, the average of the ratios for the other three usage classes was used.

Applying these class ratios across all the wells in the Tauranga area gives an estimated total annual take of 16,259,469 m^3/year compared to consented annual take of 63,720,784 m^3/year. That is, the estimated actual use is only one quarter of the consented rate.

Estimates of the seasonal extraction rates were made using a similar approach. The metered data for each use class was binned into calendar quarters and the proportion of used in each quarter was calculated. For the commercial and domestic wells where there were no usable metered data, the seasonal factors were based on a subjective assessment done in conjunction with BOPRC.

Using these two sets of estimates, values for actual annual use and annual variations were calculated for each extraction well in the Tauranga area. This information was used to model the historical changes in the reservoir together with the seasonal response.

3. RESERVOIR MODEL

A numerical reservoir model of the Tauranga area was developed using the TOUGH2 simulation software (Pruess et al, 1999). The model domain encompasses a 56 km by 100 km area extending to 2 km depth below sea level (Figure 7). It is oriented to the northwest-southeast to follow the geographical extension of the Tauranga Geothermal System (Figure 2). The grid comprises 72,845 elements, resolving to 500 m by 500 m in the central area covering the highest density of warm-water wells. The model extends beyond this area with a coarser grid spacing to ensure that model calculations in the central area of interest are not influenced by model boundaries. The top boundary of the model is taken from a digital terrain map of New Zealand. The model extends from the surface to -2000 masl, with varying heights used in the top layers to represent topographical changes. The bottom of the model is set to be significantly deeper than the deepest well.

The model represents the two main lithological units (Section 2.1) and follows the geological model of Tschritter et al. (2016), comprising a layer of sediments (Tauranga Group Sediments) and an underlying amalgamation of volcanic units. The latter ignimbrites, tuffs, breccias and lavas (White et al. 2009) were subdivided at -300 and -600 masl to allow vertical variations in permeability. It is known that permeability generally decreases with depth (Ingebritsen and Manning 2010).

Rock properties were assigned to the four units within the model, based initially on measured or assumed values. Density, porosity and specific heat capacity were based on literature values. Experimentation showed that the model was relatively insensitive to the values of these parameters. The model was sensitive to permeability and thermal conductivity and therefore a range of values were tested during calibration, to determine the values that gave the best match to the measured data. Horizontal permeability was set to ten times vertical to account for more permeable horizontal layering (Petch and Marshall 1988).

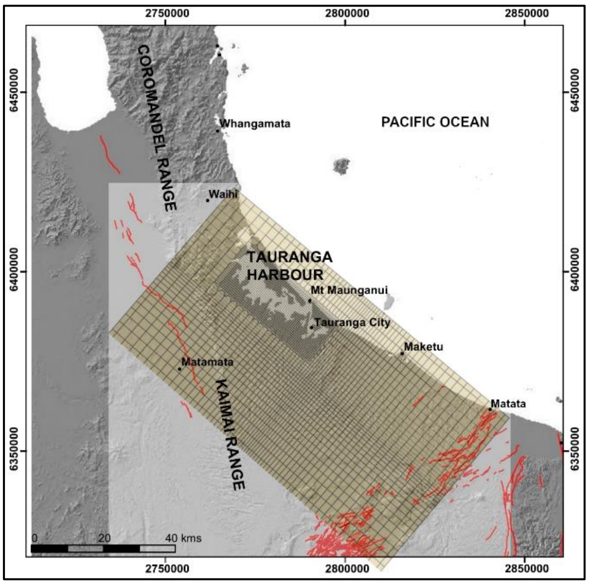

Figure 7: Map of the Tauranga study area. Red lines represent active faults (GNS Science 2012). The TOUGH2 model (brown grid) extends 100 by 56 km.

3.1 Boundary Conditions

All vertical boundaries in the model were prescribed as no-flow boundaries as they are far from the area of interest. The cells at the top boundary were fixed at atmospheric conditions: a temperature of 15°C, a pressure of 1 bara and totally unsaturated (100% air).

Recharge into the system due to rainfall was added into surface cells based on an average annual rainfall of 1200 mm/yr. Infiltration rates between 5% and 10% were tested during model calibration, with a final value of 10% of annual rainfall being used.

For the bottom boundary condition, only a heat source was placed along the base of the model because geochemistry suggests that there is negligible flow of geothermal fluids from depth (Hodges 1994; Reyes 2008). To prevent the model from becoming complicated beyond the level supported by the number of observations, a simple pattern of heat flow was applied to the base of the model. Across the portion of the field where an elevated heat flow is observed, the model used a heat flux of 200 mW/m², outside of that area a heat flux of 55 mW/m² was applied.

The model was run with the EOS3 module (Pruess et al, 1999) that included air as a gas as well as water. The interior of the model was initially fully saturated with water. The model was run for two million years to represent the age of the Tauranga Basin (Davis and Healy 1993), although the model had stabilised to a natural state before this time.

3.1 Match to Well Temperatures

The measured well temperature profiles indicate that the Tauranga system is dominated by conductive heat flows. During calibration of the natural state model it was found that there was a threshold permeability, above which convection became the dominant heat flow mechanism. Below that threshold, the model temperature profiles were sensitive to the thermal conductivity.

Figure 8 shows the locations of the 40 wells with temperature profiles used to calibrate the model and Figures 9 and 10 show examples of matches of the model to measured temperature profiles.

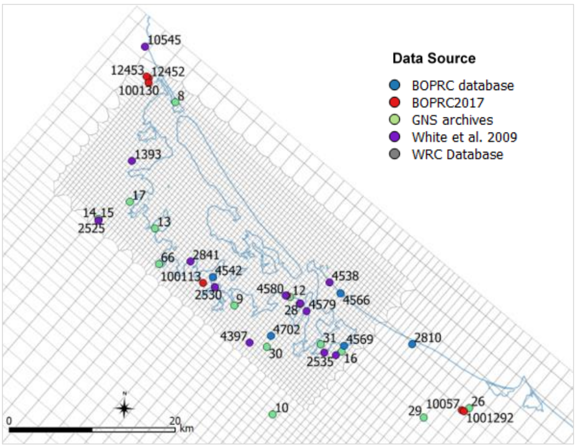

Figure 8: Locations of wells with measured temperature profiles with depth. Labels correspond to well numbers.

In 24 of the 40 wells, the modelled temperature profiles show an excellent fit with the measured data. Wells where the temperature fit is poor are often within a few metres of other sites with quite different temperature profiles. Matching these patterns is beyond the resolution of the current model. In areas where the fit could be improved, there is a mixture of temperatures being under- and over-estimated, suggesting that there is not a systematic problem with the model. The model temperatures generally show the same conductive temperature profile that is observed in the measured data.

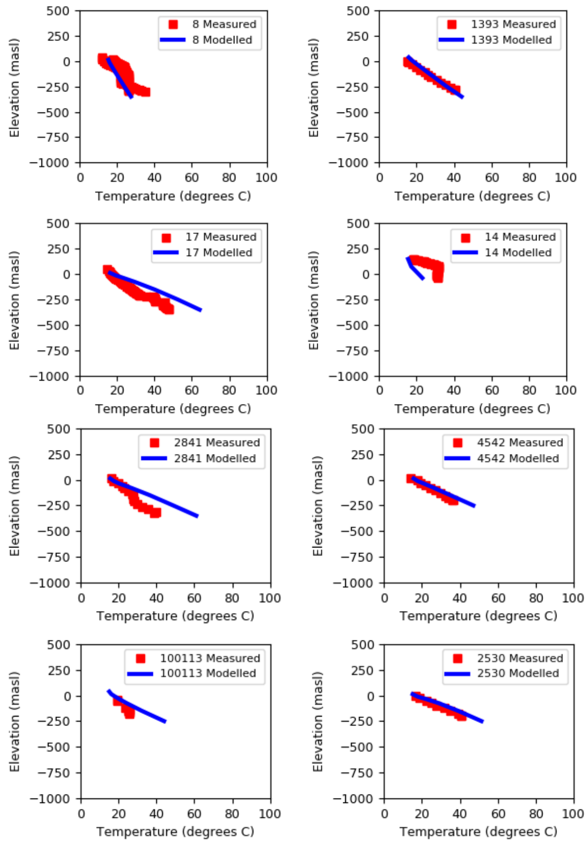

Figure 9: Profiles with depth for measured (red square) and modelled (blue line) temperatures to the north (upper four plots) and west (lower four plots) of the study area.

3.1 Match to Seasonal Water Level Changes

The model permeabilities are not well constrained by the temperature profiles. Often, the pressure response to changes in extraction are used for this purpose but this data was not directly available. Long-term water level records have been collected at Tauranga (Section 2.3) and can be used as a proxy for reservoir pressures since system temperatures are less than 70 °C.

These records do show long-term trends (for example see Figure 11), but as discussed in Section 2.4 there is little measured data on changes in extraction over those times. Without information on changes in extraction rates, the model cannot be used to match these trends.

However, the water level records do show a relatively consistent seasonal change. A comparison with rainfall patterns did not show a correlation with the seasonal water level changes, suggesting that rainfall is not the dominant control, although it may contribute. We used the metered extraction data to estimate seasonal changes in extraction rates. The metered data visually correlated with changes in water level.

Consequently, we calibrated the model response to estimated seasonal changes in extraction rates against estimated seasonal changes in water level in each monitor well to constrain model permeabilities. The estimated water level changes were done in a subjective assessment with BOPRC.

For example, from the water level record in Bore 2328 shown in Figure 11, the estimated seasonal change was 12m.

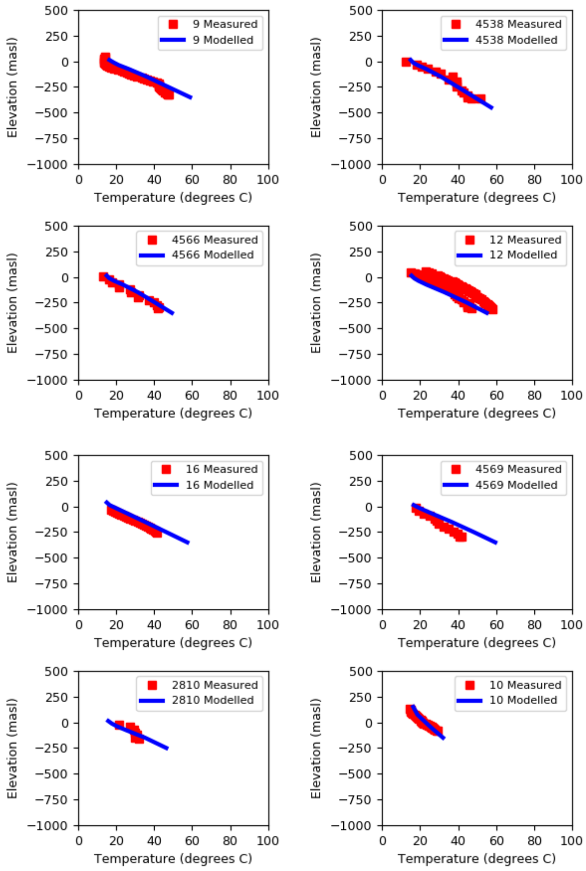

Figure 10: Profiles with depth for measured (red square) and modelled (blue line) temperatures to the centre (upper four plots) and south (lower four plots) of the study area.

Seasonal extraction was modelled for a period of eight years using the estimated seasonal extraction rates. This timespan allowed the system to stabilise after the initial drawdown when wells starting production. The simulated changes in water level were compared with the estimated magnitude of observed water level changes for each monitored well. Model permeabilities were adjusted until a suitable match to the estimated water level changes was achieved.

During this calibration, it was found that the threshold permeability for convection was too low to recharge the production areas and water levels fell to unrealistic levels. In order to match both the conductive temperature profiles and the measured water level changes, a vertical distribution of permeability was applied. Below -600 masl, a lower permeability volcanic unit was used with a vertical permeability of 10 micro-darcies.

The effects of other parameters such as rainfall recharge, localised zones of different permeability, and the vertical distribution of permeability were also explored. They were not found to improve the match of the model to the data.

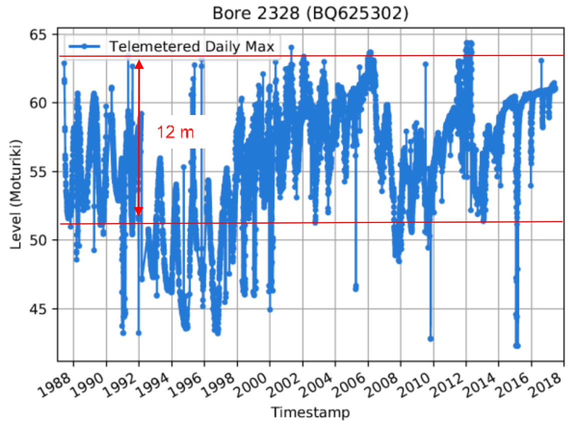

Figure 11: An example of water level data from a monitor well in the Tauranga area with the estimated seasonal variations in water level (red lines).

In general, the modelled seasonal changes replicated the estimated changes from the monitor well data (Figures 12 and 13). Given the uncertainty in the estimates of individual extraction rates and the magnitude of water level changes, it was considered that further refinement of the model parameters was not warranted.

Where modelled drawdown levels did not match measured ranges, there was a mixture of over- and under-estimation. Overall, there were more wells where the model underestimated the changes in water level compared to measured data, which means that the model is slightly conservative.

The model provided an acceptable match to both measured temperatures and estimated seasonal water level changes.

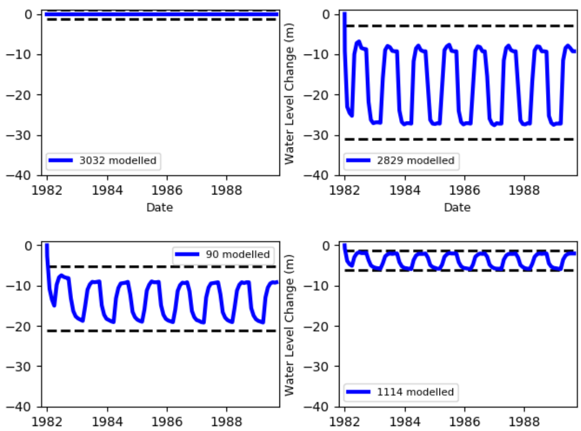

Figure 12: Comparison of modelled seasonal water level changes (blue line) with estimated changes from monitor bores (dashed black line) to the north of the study area.

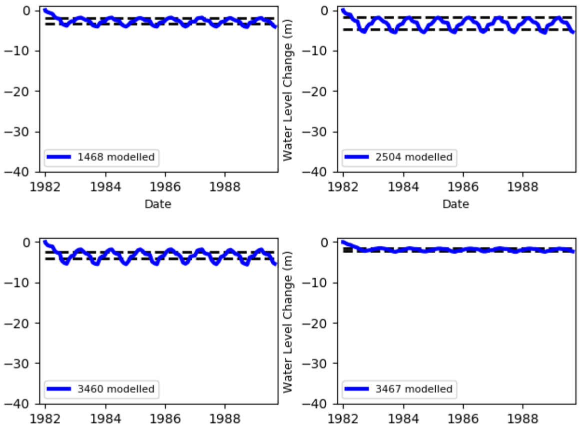

Figure 13: Comparison of modelled seasonal changes in water level (blue line) with estimated changes in monitor bores (dashed black line) in the centre of the study area.

4. USAGE SCENARIOS

The calibrated model was used to assess the possible effects of future extraction from the Tauranga Geothermal System. There are 631 extraction wells consented within the area, 23 of which also have associated reinjection wells. For these forecasts, we first simulated the current state of the reservoir by applying the estimated annual extraction rates for the last 30 years.

Then two different future scenarios were considered:

- Estimated use case, where extraction continues at current estimated rates.
- Consented use case, where extraction is assumed to increase to consented rates.

These scenarios were simulated for a further 30 years. Changes in water level and temperature at monitor wells and extraction wells were taken from the simulations. If the pressure in a well dropped to less than 1 bar then the well was assumed to have failed and was turned off.

4.1 Estimated Use Case

For this case, water levels in monitor wells were stable after 2018 (e.g. Figure 14). A cluster of four municipal extraction wells all within 200 m of each other to the west of Tauranga City and with relatively large extraction rates, showed continued drawdown for the next 30 years – with approximately 10m of drawdown over that time (Figure 15).

Water temperature changes in monitor and extraction wells for this case were less than 2°C.

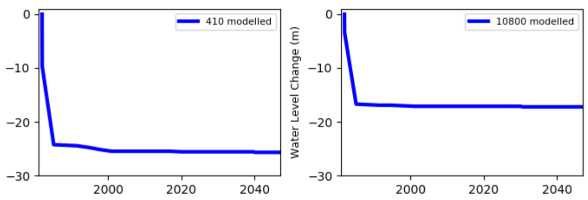

Figure 14: Simulated water level decline in two monitor wells for the Estimated Use Case.

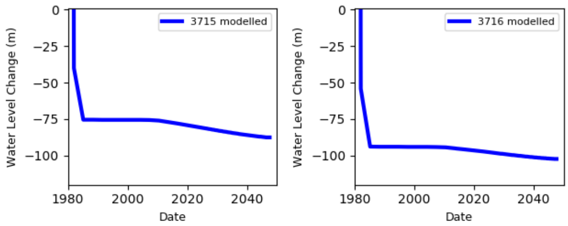

Figure 15: Water level decline in the two extraction wells that showed continued drawdown for the Estimated Use Case

4.2 Consented Use Case

For this case, estimated extraction rates were applied up to 2018 and from that time, the consented rates were used for each well. On average the consented rates are 4 times more than the estimated.

All wells showed a decline in water level when extraction increased in 2018 (e.g. Figure 16). Since wells are being shut-in when the pressure becomes too low, water levels recover in some locations. This level of simulated extraction was not sustainable for 41 wells, where pressures dropped below 1 bar. Wells failed across the model area, although over half were found to be in the southeast, possibly due to the high density of extraction wells in the area.

Temperature changes were also small for this case, less than 2°C for most wells. The largest changes were 5°C in two wells (Figure 17).

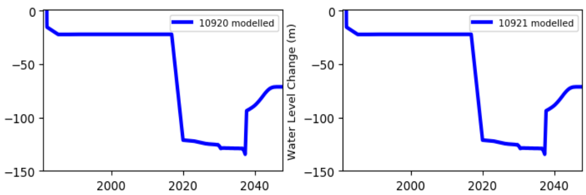

Figure 16: Simulated water level decline in two monitor wells for the Consented Use Case.

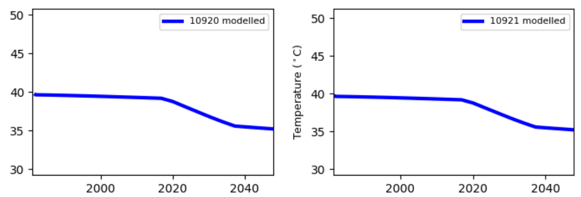

Figure 17: The largest simulated temperature changes for the Consented Use Case.

5. CONCLUSION

A model of heat and fluid flow through the Tauranga Geothermal System has been developed. It was calibrated against well temperature profiles and seasonal water level changes measured in monitor wells. The current extraction rates were estimated from an analysis of metered well flow rates and applied to all extraction wells. Using estimated extraction rates, the model matched well temperature profiles and seasonal water level variations.

Running this model into the future showed that the estimated current extraction rates are sustainable for the next 30 years. If extraction rates were to increase to consented values, wells will start to fail due to lack of recharge.

The results of this modelling can be used to inform and support the development of a system management plan for the Tauranga Geothermal System.

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