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# Modelling Direct Use from the Tauranga Low Temperature Geothermal System in New Zealand

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## ABSTRACT

An extensive low temperature geothermal system underlies the Tauranga Harbour in the Bay of Plenty, New Zealand. Temperatures in wells range from cool to warm, between 18 and 67 °C. The resource is freshwater, with minimal saltwater intrusion and no mineralisation. There are no active geothermal surface features. The resource is tapped by direct use bores that cover a range of applications including: municipal supply, irrigation, commercial pools, and domestic space and water heating. Management of the groundwater-geothermal resource is complex, with several hundred individual users. In addition, New Zealand legislation stipulates that water 30°C and above is classed as geothermal. This means that parts of the aquifer are managed as a groundwater system, while other parts are managed as geothermal water even though they can impact on each other. Monitoring of production is not widespread, with data collected from only a small fraction of wells.

In this paper, we describe the Tauranga system and present details of a numerical model used to simulate heat and mass flow through the system. A TOUGH2 model was created, using downhole temperature profiles and water level changes due to seasonal production changes for calibration. Seasonal changes in production data were estimated from a selection of metered production wells. Simulations of possible future use patterns of the resource were performed to understand the likely impact of continued abstraction of geothermal groundwater on pressure and temperature in the Tauranga low-temperature 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 local authority, the Bay of Plenty Regional Council (BOPRC), commissioned GNS Science 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, regulation changes in 1991 defined groundwater bores with temperatures >30°C as geothermal and so Tauranga has since been reclassified. In a resource assessment, 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, some monitoring has continued as part of a regional groundwater monitoring network (Barber March 2012).

BOPRC manages the geothermal resource allocating geothermal heat, energy and water and is also responsible for the management and allocation of freshwater. A planning framework sets the overall direction for management of the system 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 Māori and their culture and traditions related to geothermal resources.

Throughout the system, about 150 bores are used to take geothermal water from the groundwater system. The heat energy in this warm water is then used for a range of purposes such as heating commercial and municipal hot pools, frost protection on orchards, and heating of private buildings and pools. Many of these bores have been in continuous use for more than 30 years.

To assist with the management of the Tauranga System, a numerical reservoir model was developed to inform future allocation frameworks to ensure overall sustainable management of the resource. The model is a fundamental component of the system management plan. Of particular interest is the effect of production on groundwater levels, risks of localized or more widespread cooling, and the effects of discharges (i.e. to develop a preferred discharge strategy).

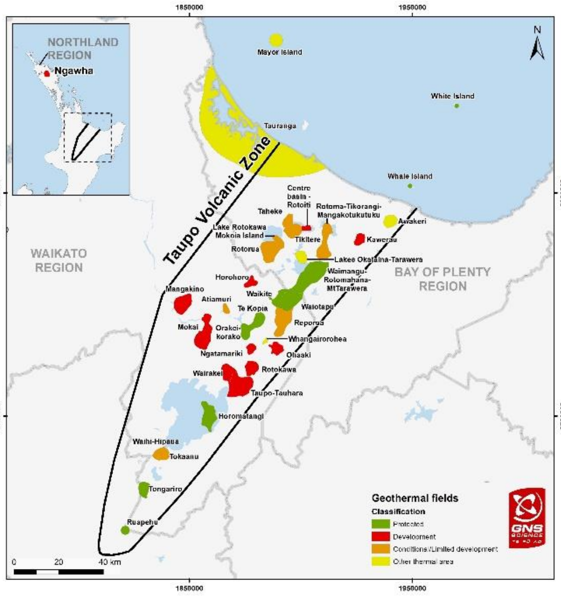


**Figure 1: Location of the Tauranga Geothermal System marked in yellow.**

## 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).

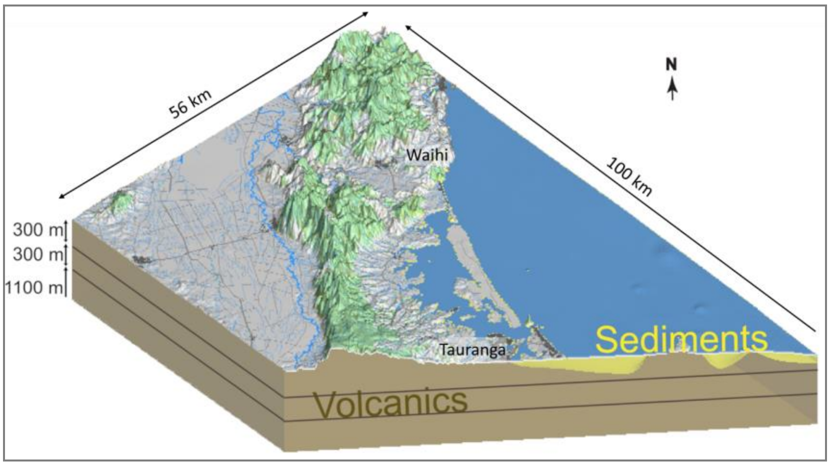


**Figure 2: Geological setting of the Tauranga Geothermal System.**

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 Thermal Environment

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. Measurements of heat flux have ranged from 55 mW/m$^2$ through to 200 mW/m$^2$ (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. Note that the wells were not drilled for exploration purposes, so the measured temperatures may not provide the full picture of the thermal environment.

Many of the temperature measurements were taken under unknown conditions. So, while they provide information about the temperature distribution in the Tauranga area, they are not all suitable for calibrating the reservoir model. For this study we have only used data from downhole profiles, as these were considered to provide more reliable calibration data. There are 40 temperature profiles in the area, the locations are the starred points in Figure 3.

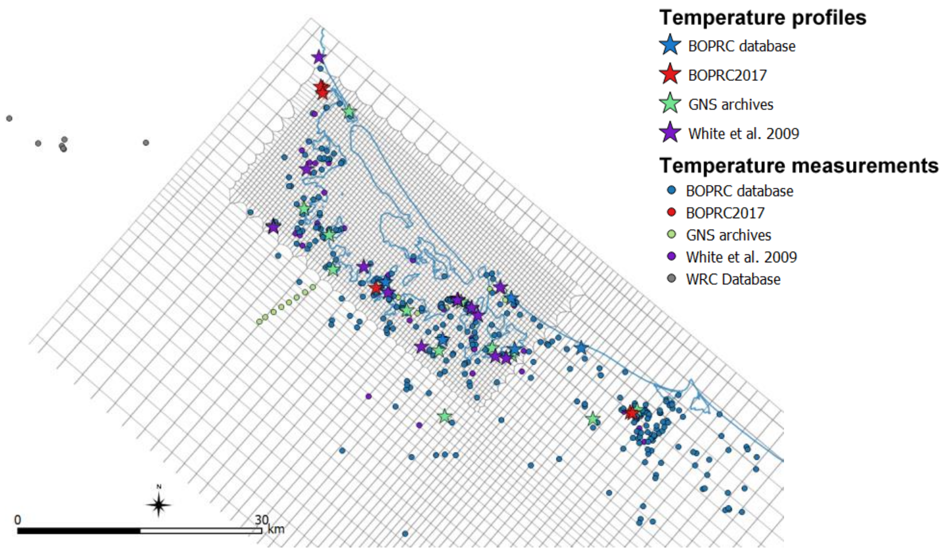


**Figure 3: Locations of wells with measured temperature. Colours and symbols correspond to the sources of data**

### 2.3 Pressure Data

As temperatures across the drilled region are less than 67°C the changes in fluid density are small. As a consequence, water level can be used as a measurement of reservoir pressures – with differences due to temperature being less than 1%. There are 49 monitor wells in the Tauranga area where water levels are measured (Figure 4), many of which have operated for decades. This data was used as part of the reservoir model calibration. Unfortunately, there is limited data on extraction rates over the period of production from the system. So there is insufficient information to simulate the historical extraction from the system that can be compared with the water level data. However, the water level data does show seasonal variations of between 0.4 and 28 m (e.g. Figure 5), and we have used that for model calibration.

### 2.4 Extraction Data

Water is extracted from 631 wells in the Tauranga Geothermal System (Figure 6). These include wells producing groundwater and warmer geothermal fluids. For each well, the location and consented extraction rate are known. The depths of the wells are mostly recorded and range from 1.5 m to 917 m, with the drilled depth being unknown for 66 wells.

The consented extraction rate specifies a maximum of some type. These are usually a maximum rate (l/s), a maximum daily use (m$^3$/day), a maximum yearly use (m$^3$/year) or some combination of these. However, the actual rates extracted from most of the wells are not known as they are not recorded, let alone any changes in extraction that may have occurred over time.

Some recording of actual extraction rates has been done at Tauranga, with meters installed on 149 wells. The measurements were recorded for varying lengths of time between 2011 and 2017.

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

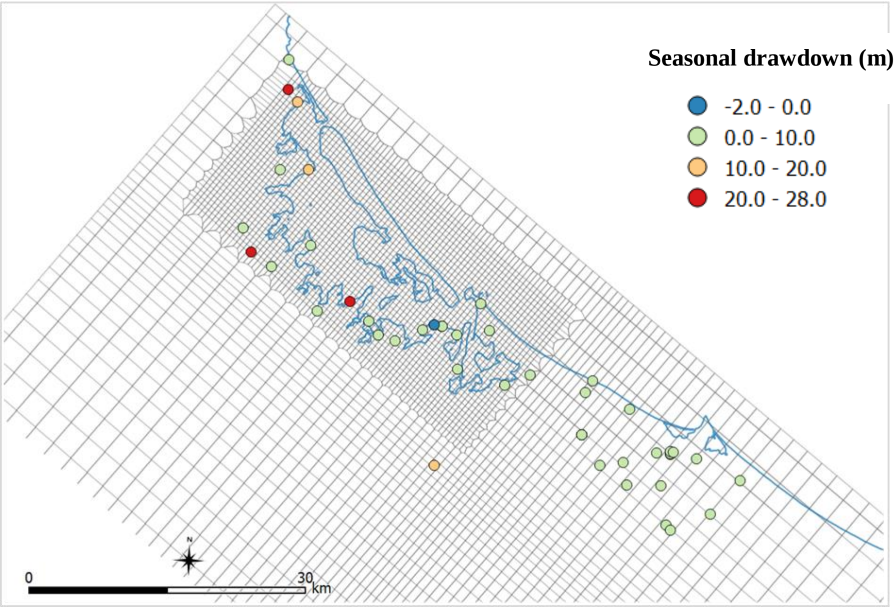


**Figure 4: Locations of water level monitor wells. Colours correspond to the changes in water level observed between summer and winter.**

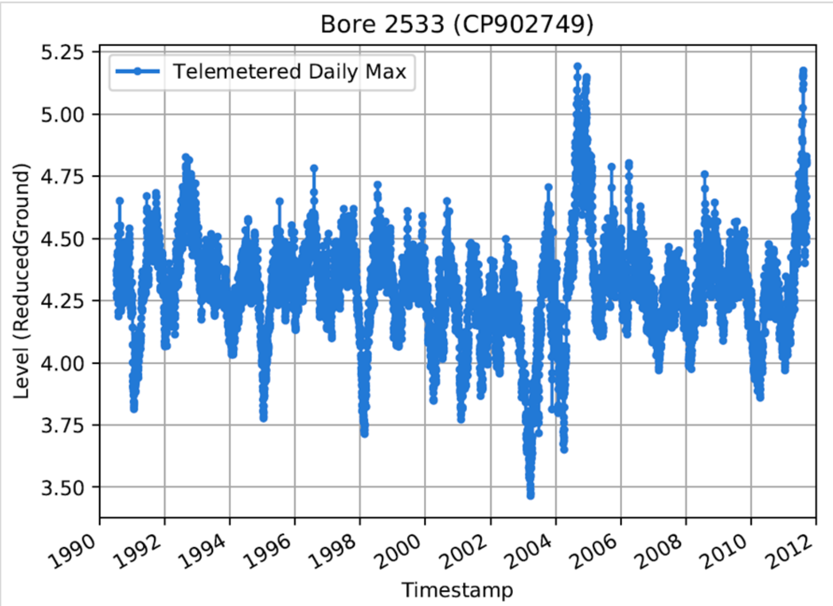


**Figure 5: Example of monitored water level data, showing seasonal variations.**

For each metered well, the consented rate was assessed from the consent database. This was done on an annual basis. For example, if water from a well is used for irrigation then higher rates will apply for spring and summer months. Even though this well may have both a maximum rate and a maximum annual rate, it is the annual rate that was averaged throughout one year. For each metered well, an average annual use was calculated. 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. For each use class, the annual rates summed and the ratios of metered to consented rates were formed. Table 1 summarises the totals and ratios for each class.

Note that 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.

**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 |

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 use. It should be noted that these estimates are strictly only valid over the years 2011 to 2017 where the metered data was collected. But with no other data that can be used to estimate the actual use from the system, these ratios of actual to consented have been applied across the whole period of production from the system.

Estimates of the seasonal extraction rates (Figure 5) were made using a similar approach. The metered data for each use class was binned into calendar quarters and the proportion 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. These estimates of seasonal variation were used in the reservoir model calibration.

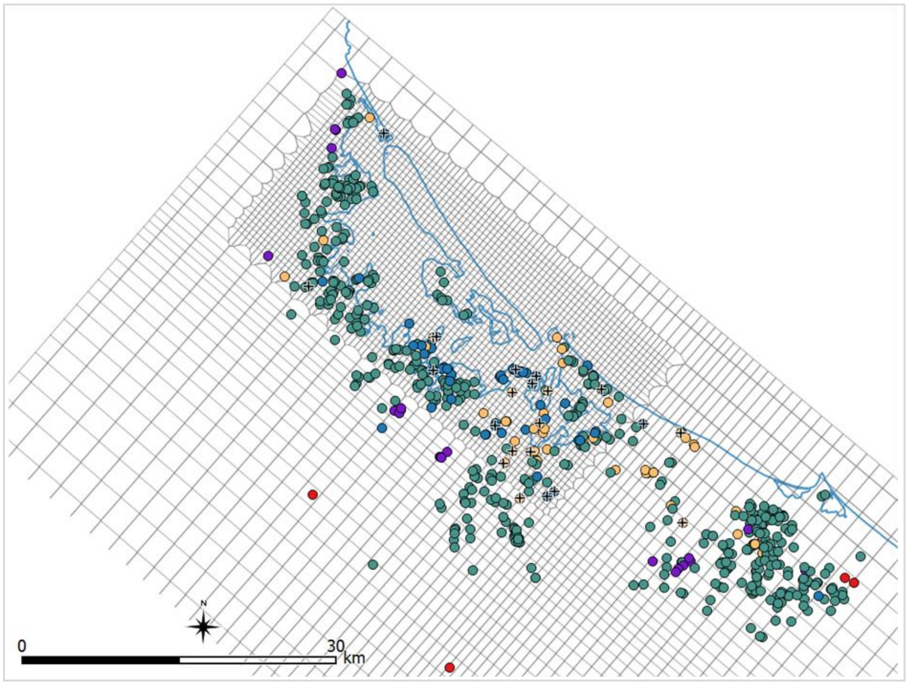


**Figure 6: Locations of extraction wells (circles) and reinjection wells (black crosses) in the Tauranga Geothermal System.**

## 3. RESERVOIR MODEL

A numerical reservoir model of the Tauranga area was developed using the TOUGH2 simulation software (Pruess et al. 1999). This is a spatially large model, with the model domain encompassing 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 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 was run with the EOS3 module (Pruess et al. 1999) that includes 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 steady state before this time.

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 variations in permeability. In this model we have applied a decreasing permeability with depth (Ingebritsen and Manning 2010).

Rock properties were assigned to the four units within the model, based initially on estimated 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. The horizontal permeability in the model was set to ten times vertical to account for more permeable horizontal layering (Petch and Marshall 1988).

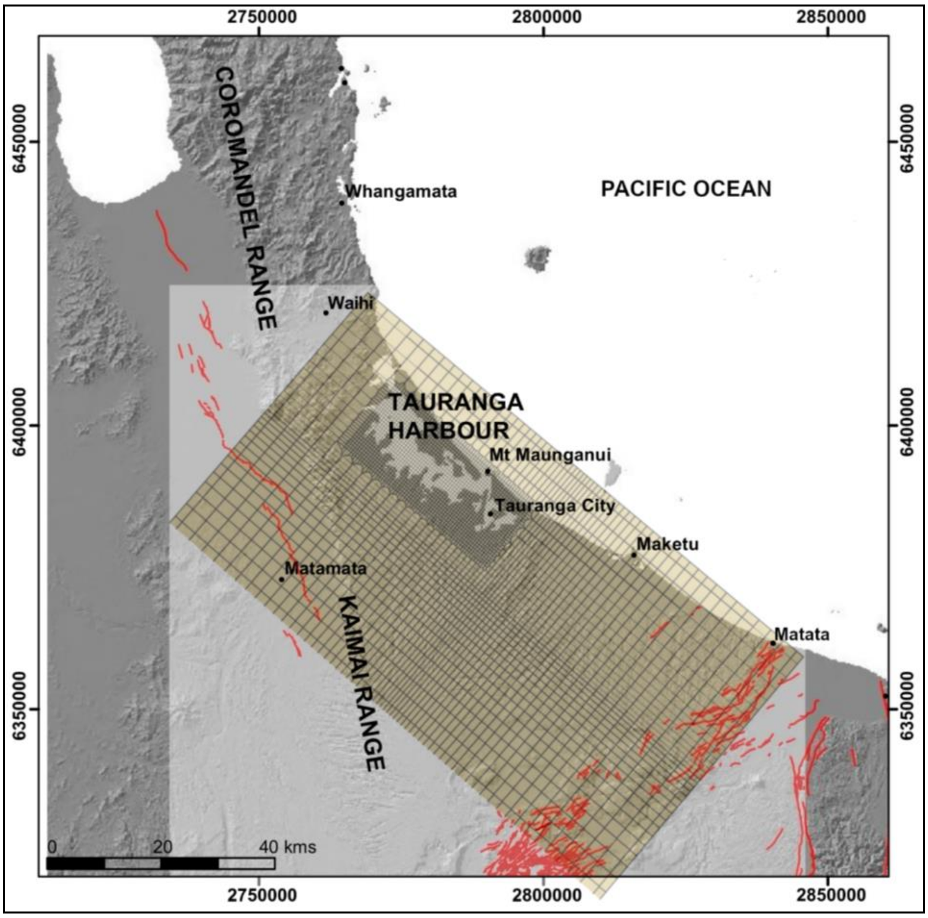


**Figure 7: Map of the Tauranga study area. Red lines represent active faults (GNS Science 2012). The TOUGH2 model (brown grid) extends 100 by 56 km.**

### 3.1 Boundary Conditions

All vertical boundaries in the model were set as no-flow boundaries as they are considered far enough from the area of interest to not influence the results. The top boundary of the model was set to fixed atmospheric conditions: with a gas (100% air) at a temperature of 15°C and a pressure of 1 bara.

Recharge into the system due to rainfall was added at the model surface 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.

At the bottom boundary, only a heat source was used because geochemistry data from surface fluids 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. 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 elevated heat flux was based on some of the higher measured values and was adjusted during the model calibration to improve match to the measured temperature.

### 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 if a single permeability was used for all units then 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. Allowing different permeabilities in the lithological units, provided sufficiently flexibility to allow conductive flows at depth while supporting the observed production rates that have taken place in the Tauranga System (Section 3.2).

Overall the model gives an acceptable match to the temperature data from the system, generally showing the same conductive temperature profile that is observed in the measured data. Figures 8 and 9 show examples of matches of the model to measured temperature profiles. 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 this spatial variability 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.

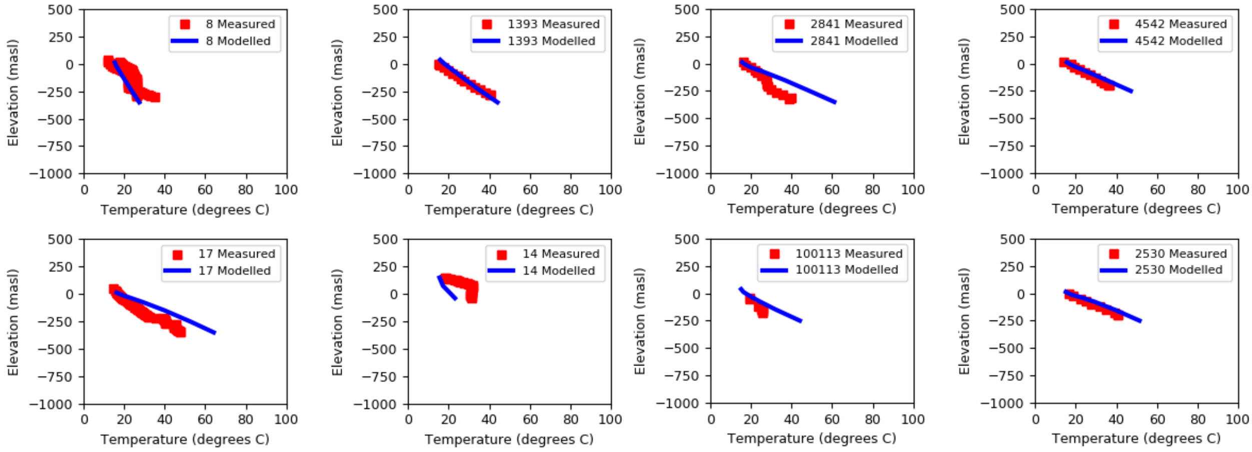


**Figure 8: Profiles with depth for measured (red square) and modelled (blue line) temperatures to the north (upper four plots) and west (lower four plots) of the study area.**

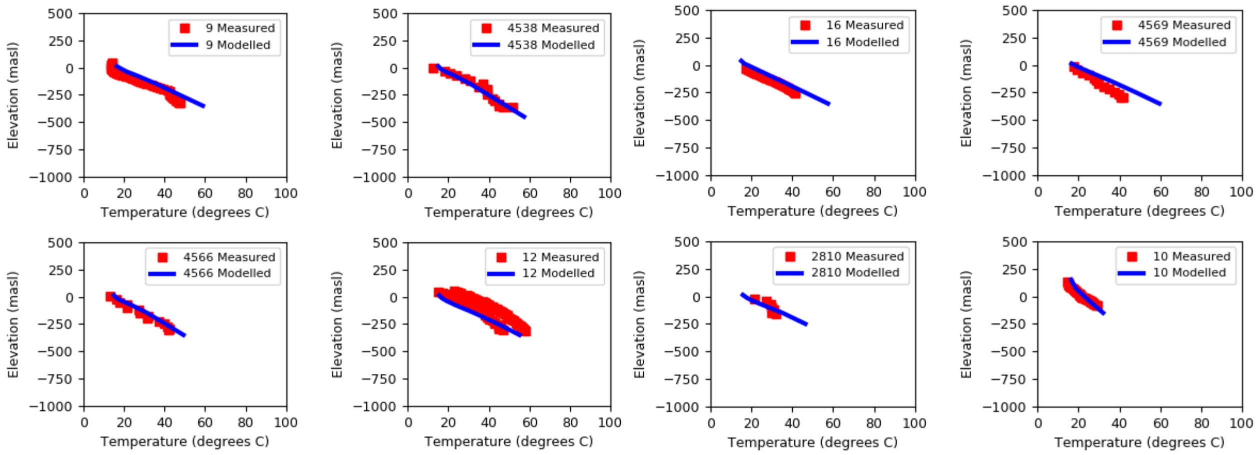


**Figure 9: Profiles with depth for measured (red square) and modelled (blue line) temperatures to the centre (upper four plots) and south (lower four plots) of the study area.**

### 3.2 Match to Historical Pressure Changes

The model permeabilities are not well constrained by the temperature profiles. Usually, the pressure response to changes in extraction provide sufficient constraints on the permeability. However at Tauranga, data on historical changes in extraction rates is not available, so this approach cannot be used to calibrate the model permeabilities. But long-term water level records have been collected (Section 2.3) providing information about changes in reservoir pressures.

The water level records show a relatively consistent seasonal change (for example see Figures 5 and 10). The metered extraction data visually correlates with changes in water level. But a comparison with rainfall data did not show a correlation with these changes, suggesting that rainfall is not the dominant control, although it may contribute. We therefore believe that these seasonal changes can be used to constrain the model permeabilities.

In Section 2.4 we discuss how we estimated seasonal extraction rate changes. These seasonal rate changes were applied to the model over a period of eight years, to allow the system to stabilise after the initial drawdown when wells starting production.

The simulated changes in water level were compared to the estimated magnitude in the water level records. These estimated water level changes were obtained in a subjective assessment with BOPRC. An example of this assessment from the water level record in Bore 2328 is shown in Figure 10, where the assessed seasonal change was taken to be 12m.

During the process of matching seasonal water level changes, it was found that applying a uniform permeability across the model that was below the threshold permeability for convection resulted in insufficient recharge to the production areas and water levels fell to unrealistic levels. In order to match both the conductive temperature profiles and the seasonal 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.

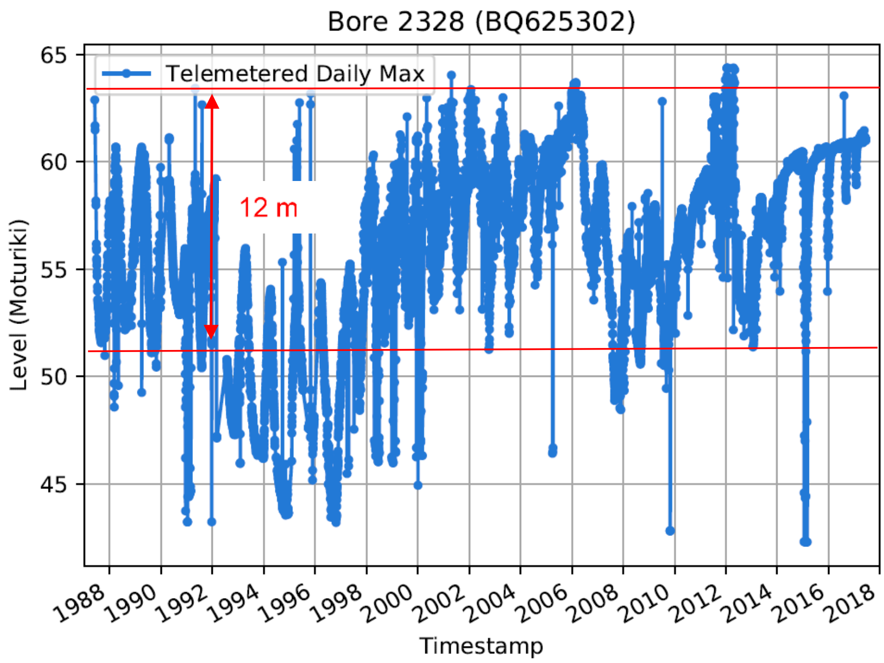


**Figure 10: An example of water level data from a monitor well in the Tauranga area with the estimated seasonal variations in water level (red lines).**

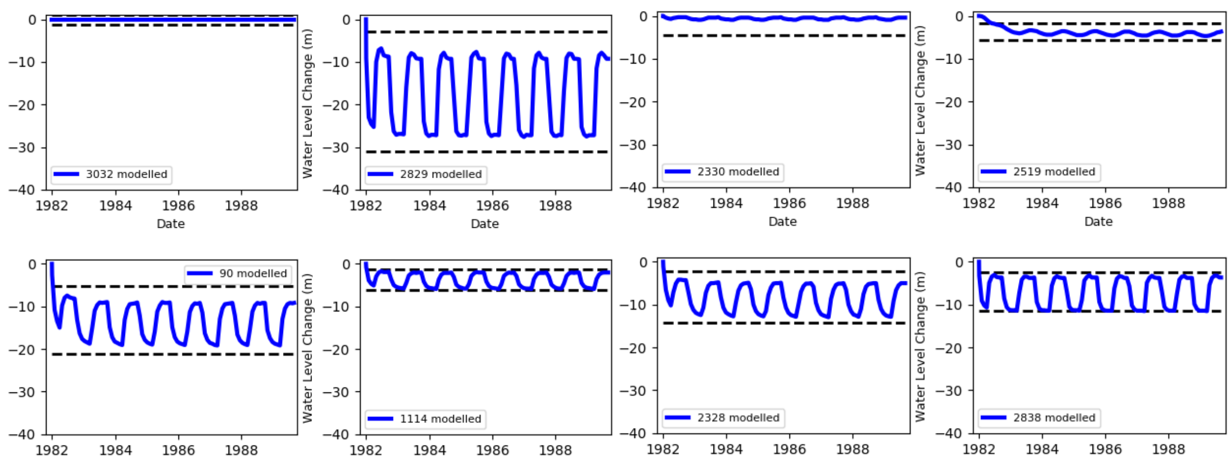


**Figure 11: Comparison of modelled seasonal water level changes (blue line) with estimated changes from monitor bores (dashed black line) to the north of the study area.**

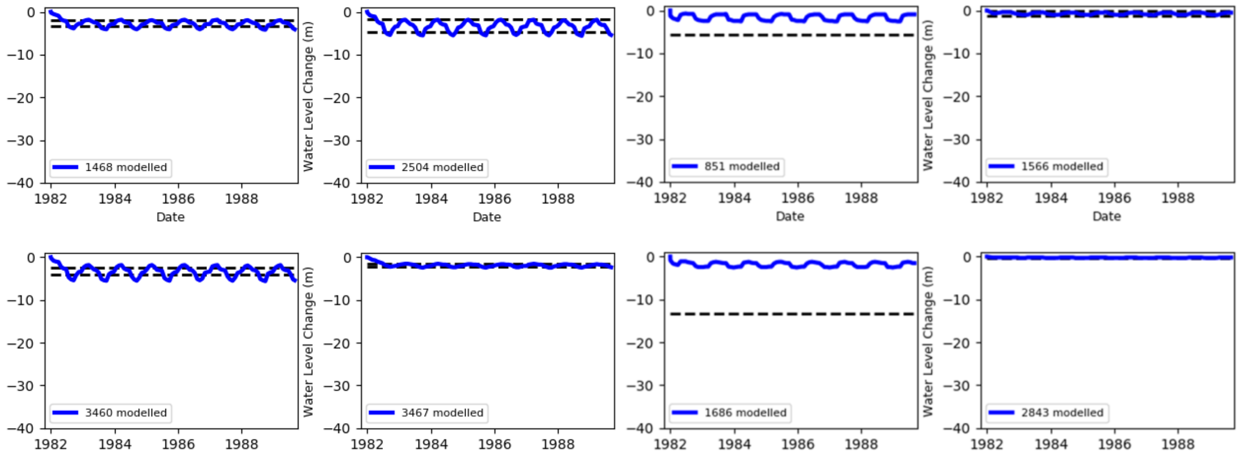


**Figure 12: Comparison of modelled seasonal changes in water level (blue line) with estimated changes in monitor bores (dashed black line) in the centre of the study area.**

In general, the modelled seasonal water level changes replicated the estimated changes from the monitor well data (Figures 10 and 11). 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 will be slightly conservative in predicting future changes.

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

## 4. EFFECTS OF FUTURE EXTRACTION

The calibrated model was used to assess the possible effects of future extraction from the Tauranga Geothermal System. Of the 631 extraction wells consented within the area 23 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 a historical period of 30 years.

Then two different future scenarios were considered:

- An estimated use case, where extraction continues at current estimated rates.
- A 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 obtained from the simulations. During the simulation, 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 13). 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 14). Temperature changes in monitor and extraction wells for this case were less than 2°C.

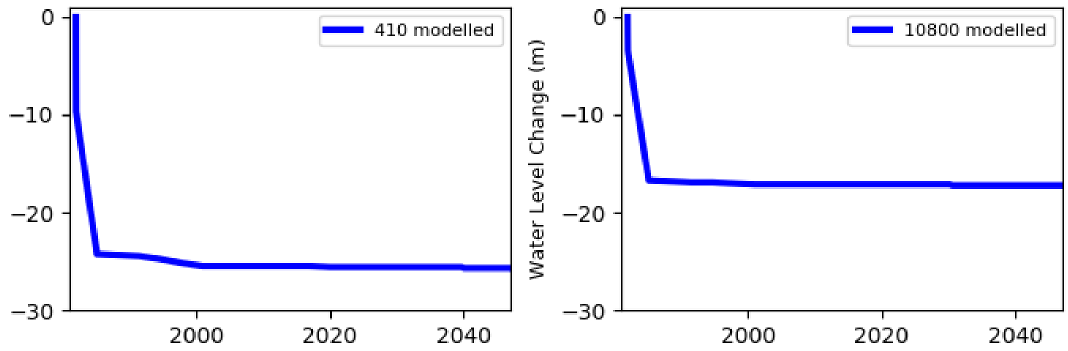


**Figure 13: Simulated water level decline in two monitor wells for the Estimated Use Case.**

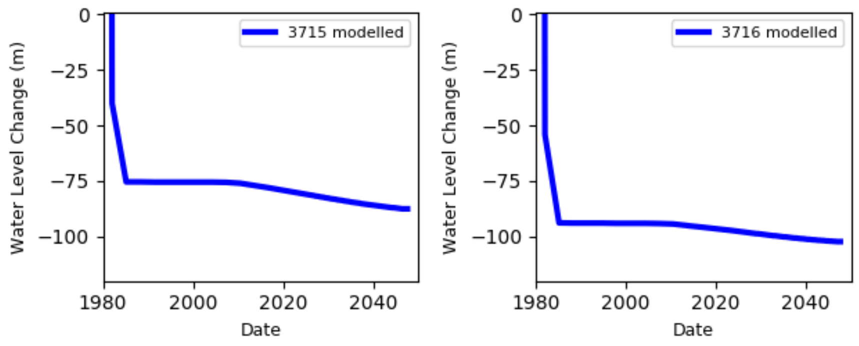


**Figure 14: Water level decline in the two extraction wells that showed continued drawdown for the Estimated Use Case**

### 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 case of Section 4.1.

In this case, all wells showed a decline in water level when extraction increased in 2018 (e.g. Figure 15). Since wells are being shut-in when the pressure becomes too low, water levels recover in some locations. This level of simulated extraction was found to be 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 simulated changes were a decline of 5°C in two wells (Figure 16).

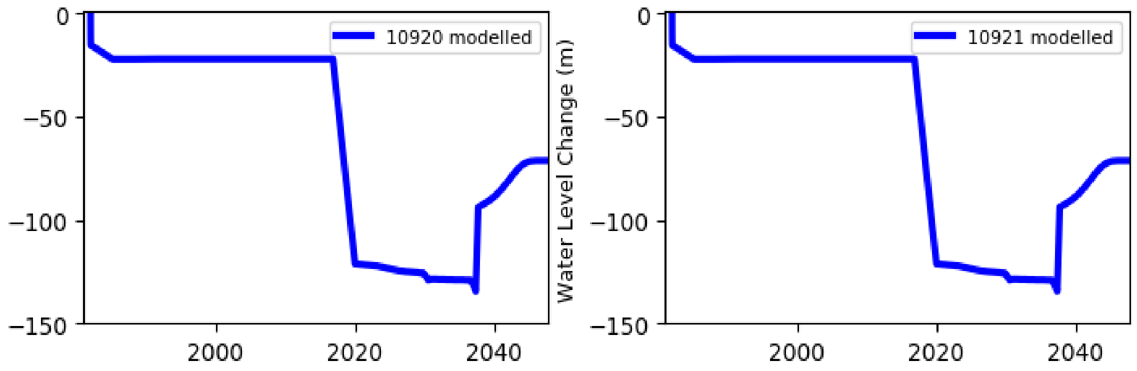


**Figure 15: Simulated water level decline in two monitor wells for the Consented Use Case.**

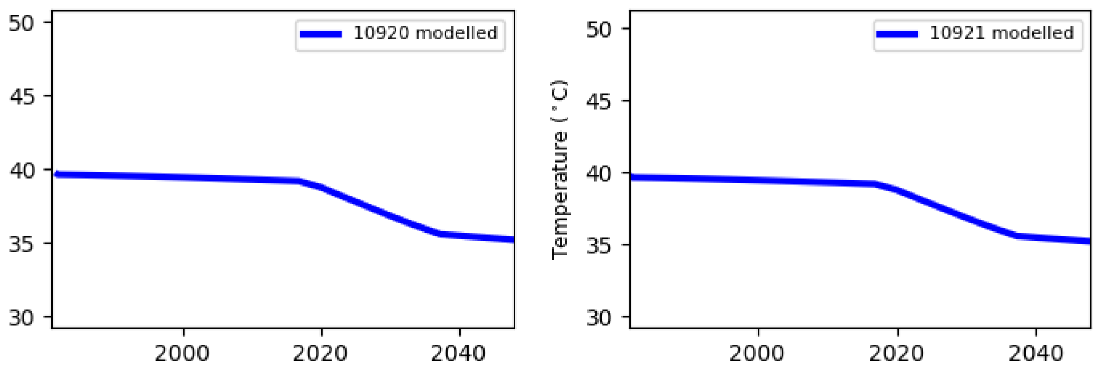


**Figure 16: The largest simulated temperature changes for the Consented Use Case.**

### 5. CONCLUSION

A model of heat and fluid flow through the Tauranga Geothermal System has been developed. The model covered geothermal and groundwater areas in the system. It was calibrated against well temperature profiles and estimated 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.

## 6. ACKNOWLEDGEMENTS

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