Update of the Tauranga Basin geothermal reservoir model

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DISCLAIMER

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EXECUTIVE SUMMARY

This report presents an update to a numerical reservoir model of the Tauranga Geothermal Field completed in 2013. The purpose of the update was to improve the simulation of extraction of fluid from the geothermal field. Measured data used for model calibration was expanded from the well temperature data used in 2013 to also include seasonal water level data from monitor wells.

The numerical model covers an area of 100 km by 56 km, which encompasses the warm-water wells found within the Tauranga Geothermal Field and some distance beyond them. The numerical model was constructed using data from 40 wells with measured temperature profiles, 149 wells with metered extraction rate data, and 49 wells monitored for water level, which were used for calibration. Current extraction rates for most of the production bores in the area are not known, with only a consented rate recorded. The extraction rates were estimated for this work from an analysis of metered extraction well data. To match both temperature and water level data, the model contained four rock units: one sedimentary unit and three volcanic units. The bulk permeabilities that gave the best match to the calibration data had good to moderate permeability in the sedimentary and shallow volcanic units, and low permeability in the deepest volcanic rocks. Estimated bulk permeabilities are similar to those used in the model in 2013 and comparable to values estimated for rocks elsewhere in New Zealand.

The geothermal system provides energy that has been used for over 30 years, and continues to be used for commercial, municipal, irrigation and domestic uses. As at 30 May 2017 there were 631 wells that were consented to extract water long-term from the Tauranga Geothermal Field, with 23 wells reinjecting water. All of these wells were classified into extraction types based on likely usage patterns. From the analysis of the metered data, it is estimated that current extraction rates are approximately 25% of consented rates. This level of extraction was used to simulate conditions as at May 2017.

Two simulations of future extraction from the Tauranga Geothermal Field were evaluated. In the first simulation, current levels of extraction were continued until 2047. The results show that this level of use is, and will continue to be, sustainable within that timeframe. For the second simulation, the extraction rates were increased to consented level. In this scenario, 41 wells are predicted to fail due to decline in water levels. Of these, 12 were for municipal use, one was for commercial use, and the other 28 were irrigators. Wells failed across the entire model area, although over half were found to the southeast, toward Maketu. In both simulations temperatures appear to be minimally affected, with modelled decreases of <5°C.

1.0 INTRODUCTION

The Tauranga low-temperature geothermal system is located on the Bay of Plenty coast of the North Island of New Zealand. The system has had about 10 historical warm springs, and has been used privately and commercially for bathing, greenhouses, aquaculture, 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. GNS Science (GNS) has been commissioned by the Bay of Plenty Regional Council (BOPRC) to update an earlier numerical reservoir model of the Tauranga Geothermal Field (Pearson and Alcaraz 2013, hereafter referred to as PA2013) to a state suitable for forecasting the response to scenarios of future usage.

Monitoring of 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, Tauranga has since been reclassified because the Resource Management Act (1991) defines groundwater bores with temperatures >30°C as Geothermal (Ministry for the Environment 2013). 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 of hot water. 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 (1994), monitoring has continued as part of a groundwater monitoring network (Barber March 2012).

1.1 Background

This report provides an update to the PA2013 numerical reservoir model of the Tauranga Geothermal Field. The PA2013 model was initially developed to provide a better understanding of heat flow through low-temperature geothermal fields (Pearson et al. 2014), as part of GNS’s Geothermal Resources of New Zealand Research Programme. It was calibrated using well temperatures provided by BOPRC. The consented extraction and reinjection rates as known at the time (Pearson and Alcaraz 2013) were modelled to investigate the possible effects of fluid extraction on the geothermal reservoir.

A review was undertaken in 2016 to identify aspects of the PA2013 model where it could be improved. The major issue identified in the review was that the simulated water levels declined much more than had been observed (Pearson-Grant and Burnell 2016). The review described new and existing permeability data from well tests and groundwater studies that could be used in the numerical model as a recommended approach toward better matching the water levels. Additional extraction rate and temperature data were also identified, allowing improved calibration and a better estimation of current extraction rates.

This report describes a new reservoir model (PB2018) based on the PA2013 model that incorporates improvements suggested in the 2016 review, as well as new data provided by BOPRC. As well as calibrating against temperature data, seasonal changes in water level in response to changing water extraction are used to calibrate the modelled water level response to extraction. The model is then used to forecast the effects of extraction at current estimated rates, and at consented rates which are considerably higher.

Section 2.0 of this report describes the geologic setting of the study area, rock properties and surface heat flux in the Tauranga area. Details of the reservoir model, including methodology and model setup are discussed in Section 3.0. Section 4.0 describes the data used in this study. Section 5.0 describes how the data was interpreted for use in model calibration, while Section 6.0 details the calibration. In Section 7.0, future scenarios of fluid extraction from the Tauranga Geothermal Field are simulated. Section 8.0 discusses assumptions and uncertainties.

2.0 STUDY AREA

The study area is an approximately 100 km by 56 km rectangle that covers Tauranga City and extends to the northwest to Waihi and to the southeast to Matata (Figure 2.1). There are a few historical springs with water temperatures up to 39°C, and temperatures of up to 70°C have been measured in wells drilled to 800 m depth (White et al. 2009).

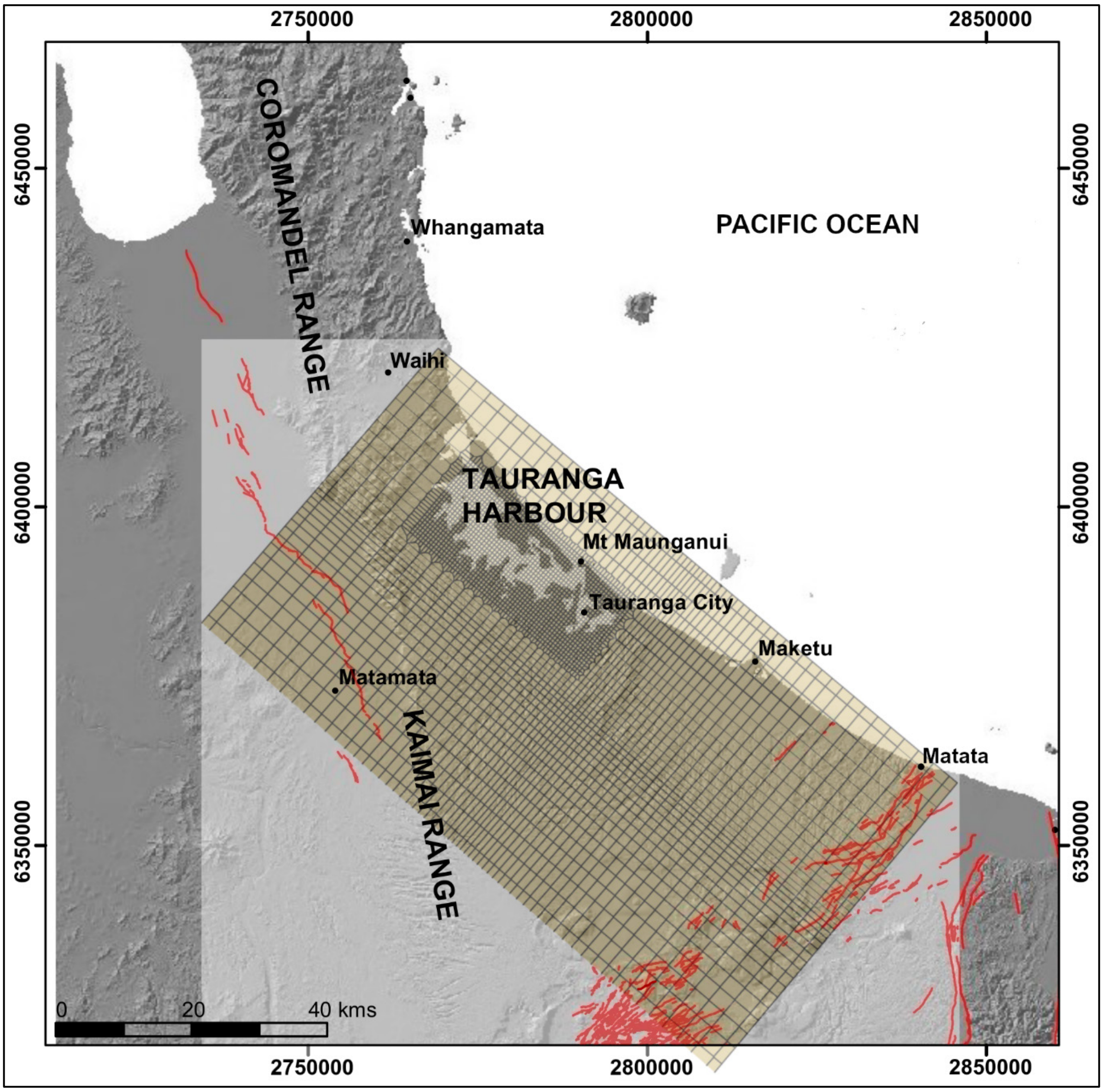

Figure 2.1 Map of the Tauranga study area. Red lines represent active faults (GNS Science 2012). The TOUGH2 model (brown grid) extends 100 by 56 km. Between Waihi and Maketu warm-water wells are found.

2.1 Geologic Setting

Tauranga Geothermal Field 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 2.1). The area forms part of the Coromandel Volcanic Zone (CVZ), a northwest-southeast trending volcanic chain 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 (252 m elevation) remain dominant landforms around Tauranga City.

In a large part of the Tauranga area, relatively young, eastward-dipping sediments (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 pinching out to the west of the study area (Figure 2.2; White et al. 2009). There are active faults to the south and west of the study area, but none in the area between Waihi and Maketu where warm water has been drilled (Figure 2.1; Briggs et al. 2005; Edbrooke 2001; Leonard et al. 2010).

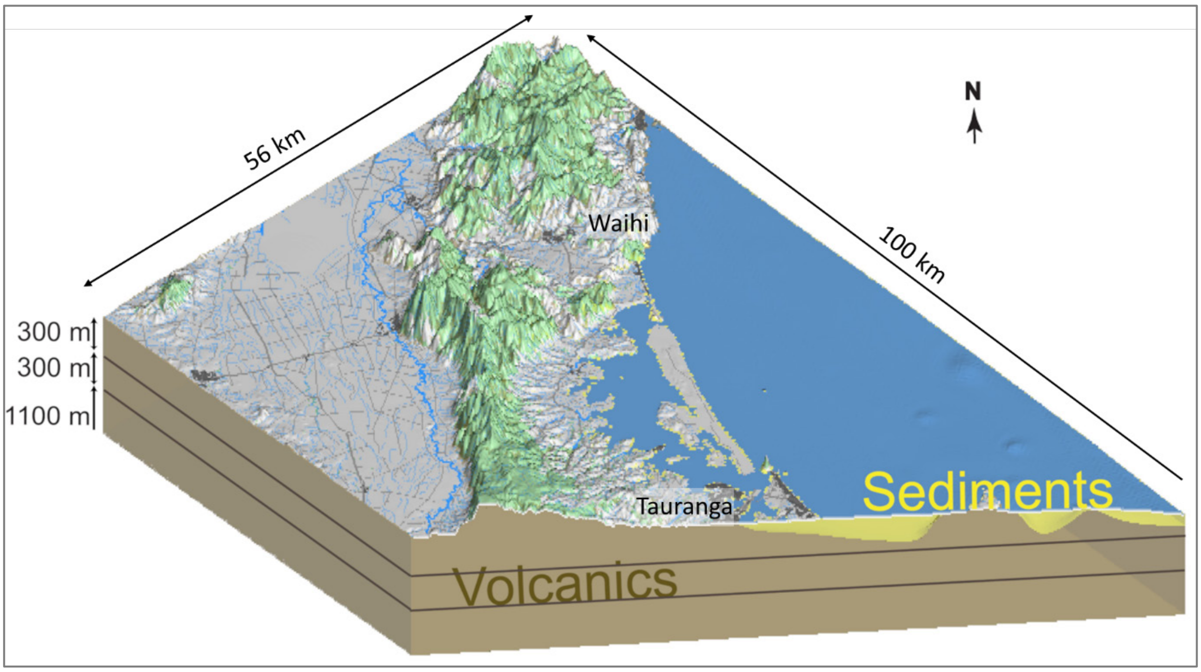

Figure 2.2 Cross-section of the geological model of the Tauranga area. The sedimentary (yellow) and volcanic (brown) rock types were represented in the model, but the volcanic unit was subdivided into three layers at -300 and -600 masl.

2.2 Rock Properties

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

Permeability is important because it controls:

- whether heat transfer occurs primarily by conduction or by fluid convection;
- the change in reservoir pressure (or equivalently water level) in response to extraction.

It is very difficult to measure permeability on a reservoir scale. Estimates can be made from calculations of hydraulic conductivity from pump tests. These estimates generally only relate to a small volume around a well (generally, several tens of metres radius). Data collated from pump tests, inferences from the conceptual hydrological model, and a groundwater flow model in the Tauranga area suggest permeability values of between ~1×10^{-10} m^2 and 1×10^{-18} m^2 (Pearson-Grant and Burnell 2016). The most common estimates of local permeability were between 1×10^{-12} m^2 and 1×10^{-13} m^2. The PA2013 model suggested slightly lower bulk permeabilities of 2.5×10^{-14} m^2 in the Tauranga sediments, and 1×10^{-16} m^2 in the deeper volcanic rocks (Pearson and Alcaraz 2013).

Thermal conductivity, density and porosity have also been estimated within the study area. Thermal conductivity has been measured in Tauranga Group Sediments to be 1.05 W/m°C (Simpson 1987). A number of measurements have been carried out in the volcanic units, resulting in average estimates of density at 1890 kg/m^3, porosity at 0.42 and thermal conductivity of 1.26 ± 0.05 W/m°C (Simpson 1987).

2.3 Heat Flux

Heat flow around Tauranga is elevated compared to the national average, with an estimated average of 88 ± 16 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, Figure 2.1) heat flux reaches as high as 336 mW/m^2 (Simpson 1987).

3.0 RESERVOIR MODEL

A numerical model of the Tauranga Geothermal Field was created using the TOUGH2 simulation software. This is a standard tool for simulating geothermal reservoirs. A description of TOUGH2 can be found in Pruess et al. (1999) with a summary in Pearson and Alcaraz (2013). For the PB2018 Tauranga model, python scripts were used in conjunction with spatial data in GIS format to create and analyse the TOUGH2 inputs and outputs.

3.1 Numerical Modelling Process

A numerical reservoir model of a geothermal system provides a tool to make quantitative predictions of the future behaviour of the system. In particular, a reservoir model can be used to estimate the system state (pressure and temperature) and how it changes as a result of future extraction from the reservoir. This is achieved by simulating fluid and energy flows using a computer program called a geothermal reservoir simulator.

The stages involved in developing a reliable and predictive numerical model are:

a) Construct an initial model. This involves building a model grid, and assigning parameters to all facets of the model (rock properties, heat sources, and any fluid sources).

b) Run the model using a reservoir simulator to calculate pressures, temperatures and flows.

c) Compare model results with measured data.

d) Refine model parameters to improve the comparison in Stage (c).

e) Repeat Stages (b)-(d) until a satisfactory match is reached in Stage (c).

This process is illustrated in Figure 3.1.

Geothermal reservoirs commonly have complex structure. Our understanding of these reservoirs is based on the interpretation of data that can only be observed at certain points – for example, in the wells and at surface features. On the other hand, a model requires input parameters prescribed at all parts of the reservoir. Since the parameters cannot be measured directly, an important part of the modelling process is deciding which parameters to include in the model and what values to assign to them.

Parameter values are determined by varying them within reasonable limits until an acceptable match is found between simulated and measured data. Acceptable ranges of the parameter values are determined from the conceptual model, measured data, and from measured and modelled values from analogous geothermal systems.

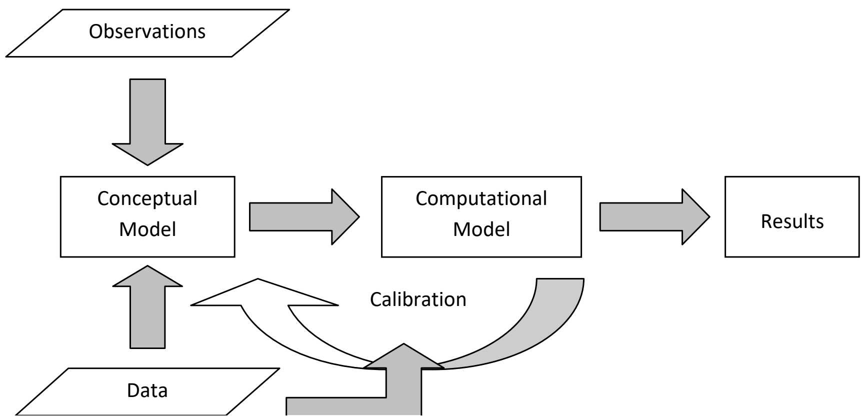

Figure 3.1 Schematic of numerical modelling process.

3.1.1 Model Calibration

A key stage in the development of a model is its validation by comparing the simulated data with field measurements. The data we use for this model are:

- Temperature profiles from wells in the natural state (pre-extraction).
- Seasonal changes in reservoir pressures/water levels due to seasonal variations in extraction rates.

While long-term water level records exist for some Tauranga wells (for example Figure 3.2), it is not clear how the long-term changes in water level relate to water extraction from the area. This is because no extraction rate data was collected before 2011 from wells in the Tauranga area, and what has been collected is only for a small number of wells. For example, there is no extraction rate data that can be used to help explain the increase in water level seen in Figure 3.2 from 2009.

Even though the long-term water level changes cannot be used for model calibration, the water level data can still be used. Since many of the water level records show a seasonal variation, it was possible to use the metered extraction rates to determine the seasonal changes in extraction, and to use those to calibrate against recent seasonal water level changes.

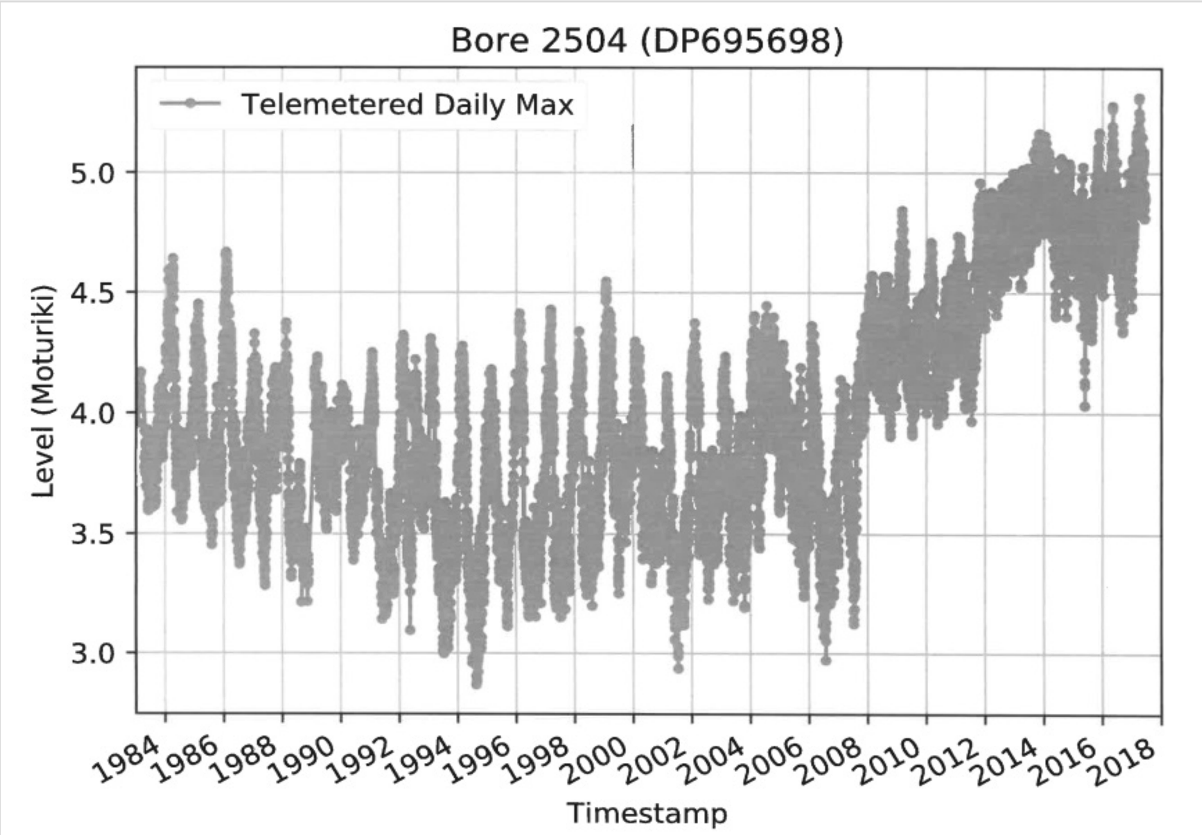

Figure 3.2 Water levels (m) recorded in a monitor bore in the Tauranga area.

3.2 Model Grid

The TOUGH2 model domain encompasses a 56 km by 100 km area extending to 2 km depth below sea level (Figure 2.2). It is orientated to the northwest-southeast to follow the geographical extension of the Tauranga Geothermal Field (Figure 2.1). The grid comprises 72,845 elements, resolving to 0.5 km by 0.5 km in the central 40 x 18 km area covering the highest density of warm-water wells. The model extends beyond this area with a coarser grid spacing of 3 km by 3 km to ensure that model calculations in the central area of interest are not influenced by model boundary conditions. The top boundary of the model is taken from the GNS digital terrain map of New Zealand built from Land Information New Zealand 20 m contour and spot height data using ArcInfo Topogrid. 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 two lithological units (described in 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 regarded as a single layer in the model because there is no detailed information available for individual units. However, the temperature profiles (which are generally shallow, i.e. <500 m) and the water levels, which are influenced by deeper rock properties, could not both be matched with a single volcanic unit in model PA2013. Therefore, the combined volcanic sequence was subdivided at -300 and -600 masl (Figure 2.2). It is also known that permeability generally decreases with depth (Ingebritsen and Manning 2010). The resulting rock type assignments in the model are shown in Table 3.1, with example depth slices in Figures 3.3 to 3.5. Final rock properties of the calibrated model can be found in Section 6.3.

Table 3.1 Rock types assigned to model layers.

Depth of Base of Layer	Default Rock	Model Rocks
-2000	Volcanics	Volcanics
-1750	Volcanics	Volcanics
-1500	Volcanics	Volcanics
-1250	Volcanics	Volcanics
-1000	Volcanics	Volcanics
-750	Volcanics	Volcanics
-600	Volcanics intermediate	Volcanics intermediate
-500	Volcanics intermediate	Volcanics intermediate
-400	Volcanics intermediate	Volcanics intermediate
-300	Volcanics shallow	Volcanics shallow
-200	Volcanics shallow	Volcanics shallow and Sediments
-100	Volcanics shallow	Volcanics shallow and Sediments
-50	Volcanics shallow	Volcanics shallow and Sediments
-25	Volcanics shallow	Volcanics shallow and Sediments
0	Volcanics shallow	Volcanics shallow and Sediments
25	Volcanics shallow	Volcanics shallow and Sediments
50	Volcanics shallow	Volcanics shallow and Sediments
100	Volcanics shallow	Volcanics shallow and Sediments

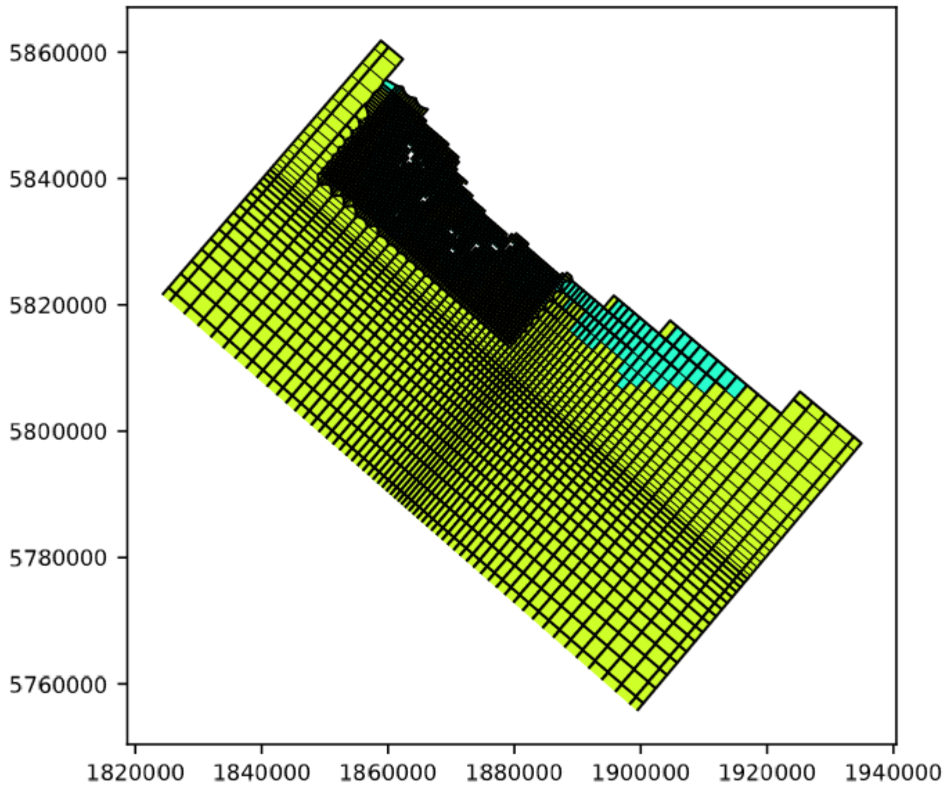

Figure 3.3 Model layer between 0 and 25 m above sea level. Green corresponds to sedimentary rock properties, yellow to volcanic. The cut away area occurs because this model layer is above the top of the topography in this area.

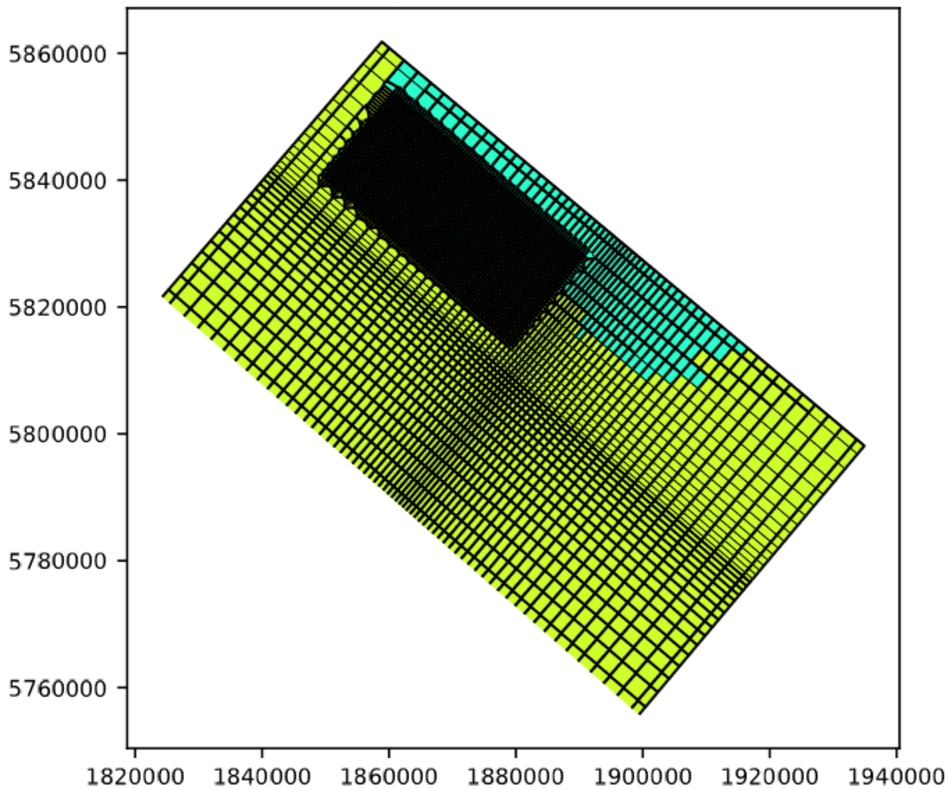

Figure 3.4 Model layer showing the distribution of sedimentary rock (green) compared to volcanic rock (yellow). Three model layers (-100 to -50, -50 to -25, and -25 to 0 masl) have this distribution.

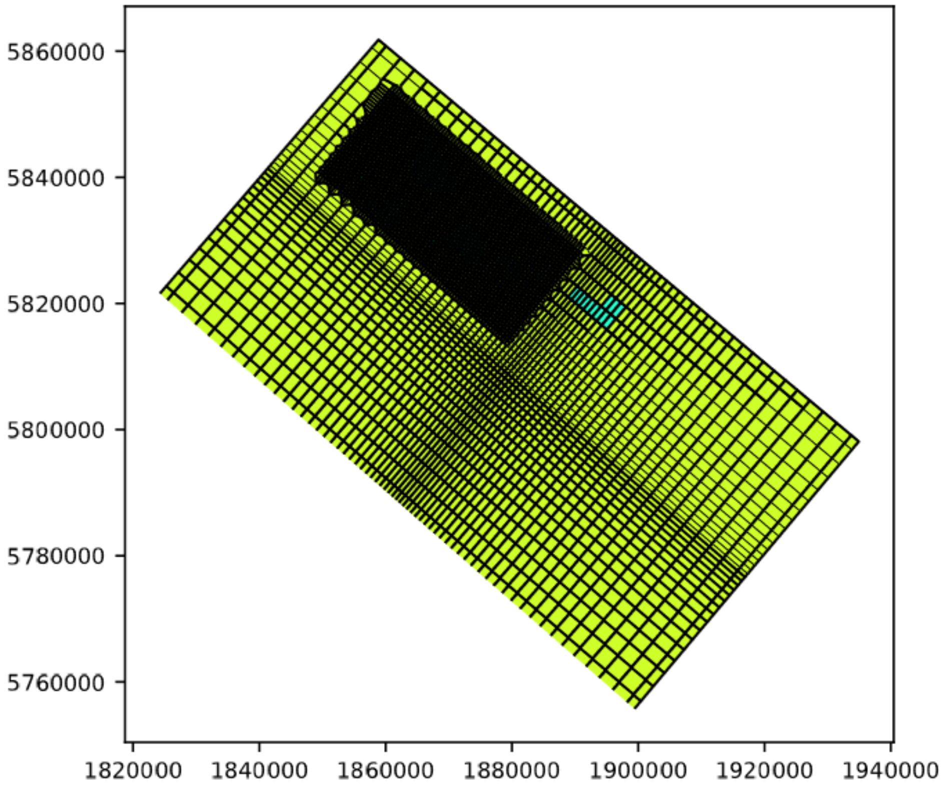

Figure 3.5 Model layer between -200 and -100 masl, where the geology is dominated by volcanic rocks (yellow) and the sedimentary rocks (green) have almost disappeared. Below this each layer only has the volcanic rock type.

Rock properties were assigned to the four units within the model, based initially on measured or assumed values. Density, porosity and specific heat capacity are given in Table 3.2. Experimentation showed that the model was relatively insensitive to the values of these properties. The model was sensitive to permeability and thermal conductivity and therefore a range of values (Table 3.2) 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; O'Sullivan 2012).

Table 3.2 Rock properties assumed in modelling of the Tauranga Basin.

Property	Rock Type	Value	Source
Density (kg/m^3)	Sediments	2500	Bear (1972)
	Volcanic units	1890	Simpson (1987)
Porosity	Sediments	0.1	Default
	Volcanic units	0.42	Simpson (1987)
Specific heat capacity (J/kg°C)	Sediments	1000	Default
	Volcanic units	1000	Default
Permeability (m^2)	Sediments	10^{-10} to 10^{-16}	Petch and Marshall (1988); Pearson-Grant and Burnell (2016)
	Volcanic units	10^{-10} to 10^{-17}	Harding et al. (2010); Bear (1972); Pearson-Grant and Burnell (2016)
Thermal conductivity (W/m°C)	Sediments	1 to 2.5	Simpson (1987); Bear (1972)
	Volcanic units	1 to 2.5	Simpson (1987); Bear (1972)

3.3 Boundary and Initial 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 (NIWA 2011), a pressure of 0.1 MPa and totally unsaturated (100% air).

Recharge into the system due to rainfall was added into surface cells based on average annual rainfall of 1200 mm/yr for the period between 1951 and 2000 (NIWA 2011). Infiltration in volcanic units in the study area has been inferred at approximately 50% of rainfall (White et al. 2007), with most of that remaining in the shallow groundwater system (White et al. 2009). Only a very small amount of rainfall recharge is thought to reach the deep reservoir (~5%, White 2012). Therefore between 5% and 10% of the mean annual rainfall was injected into the top of the model, equal to between 60 mm/yr and 120 mm/yr.

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 constant average heat flux of 55 mW/m² was used across the base of the whole model initially, but varied to refine the fit of the model temperatures to measured data. The best-fit model contained an additional rectangular area of higher heat flux of 200 mW/m² in its centre (Figure 3.6). Heat flow in PB2018 was kept relatively simple compared to the PA2013 model because that showed that pressure and temperature changes during extraction are relatively insensitive to heat flow at depth.

The interior of the model was fully saturated with fresh water, as geochemical analysis shows that geothermal fluids in the Tauranga Geothermal Field comprise mainly heated groundwater with minor seawater in the north and minor magmatic volatiles in the south (Hodges 1994; Reyes 2008). 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 by this time.

3.4 Differences between the 2013 and 2018 Models

The PB2018 model differs from PA2013 in several ways. In the 2018 model, we have used a simpler pattern of heat flow at depth as it was found to provide an acceptable match to the temperature data. The volcanic layer was divided into three (at 300 m and 600 m below sea level) allowing different permeabilities in each new layer. This was done to allow improved model calibration, because temperatures suggested conductive heat transfer overall (that is, very small flows of fluid) but the impact of extraction is smaller than would be expected in a low-permeability, conductive system. Three layers allowed a more permeable shallow portion and decreasing permeability with depth, which provided a better fit with the data. The offshore boundary condition was simplified to atmospheric pressure as pump tests, geochemistry and previous modelling show fluid flow is localised and there is minimal saltwater intrusion into the onshore Tauranga basin (Pearson-Grant and Burnell 2016; Hodges 1994; Reyes 2008).

More data was available and used in this model than was used to develop PA2013. For example, there were more temperature profiles with depth for model calibration. There were also more extraction wells to be incorporated. The grid was refined in areas with a high density of extraction wells. The largest change was that seasonal water level data was collated and used in the model calibration, resulting in improved permeability estimates.

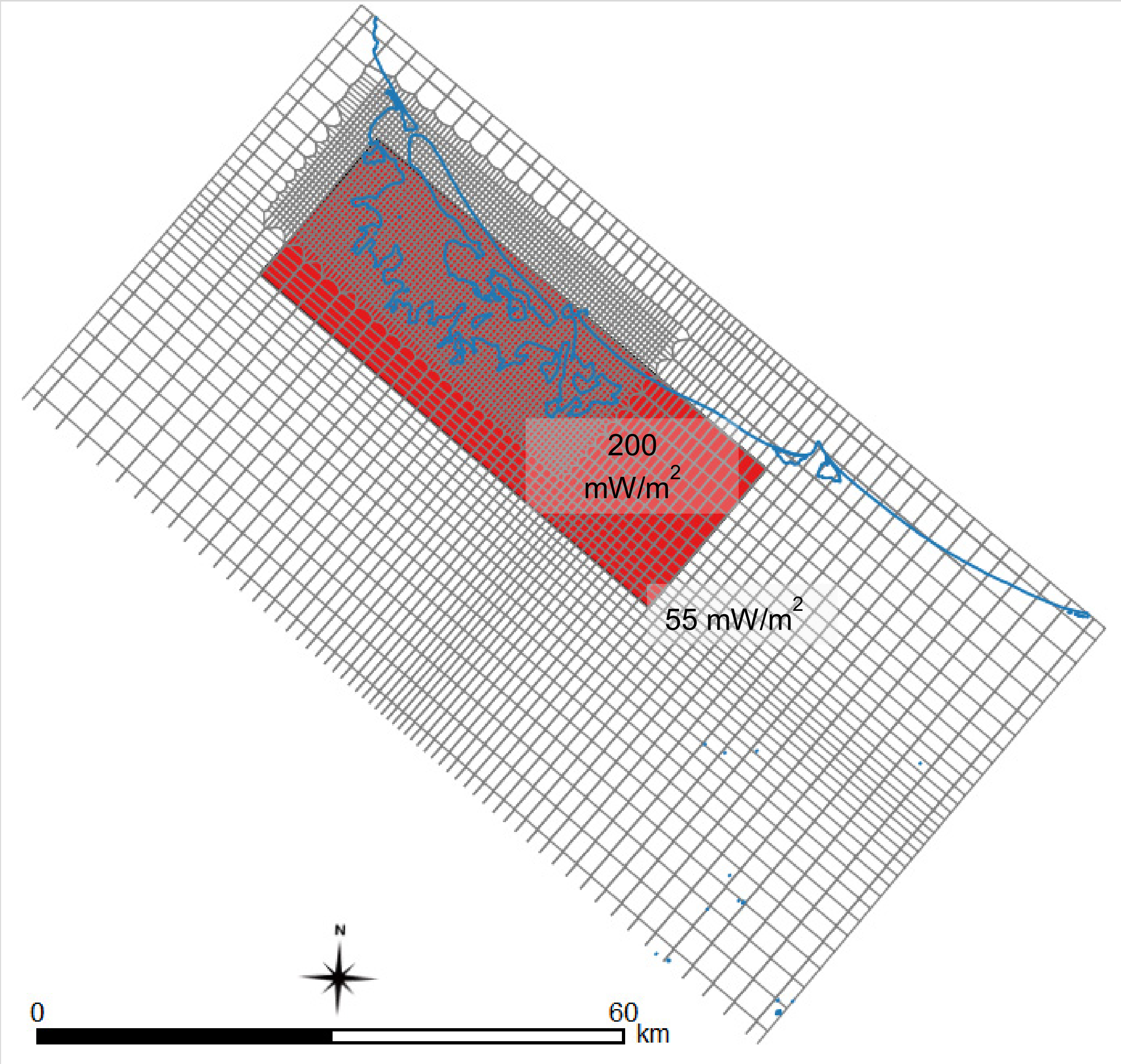

Figure 3.6 Heat flow into the base of the model. The red rectangle is a zone of higher heat flow, at 200 mW/m². Elsewhere is 55 mW/m². The blue outline is the coastline.

4.0 DATA

Data is collected in wells in the Tauranga area by BOPRC during the consenting process and at the time of drilling. This includes the location of each well, its depth, consent number, bore number and maximum extraction rate. In some cases, a temperature or a down-hole temperature profile were collected at the time of drilling. Some of these wells have also had extraction rates metered in the last few years. There are some monitor bores, which are generally not used for extraction, but have had water levels recorded over decades.

Wells that are discussed in this report are identified by a well number that is assigned when a consent is granted.

4.1 Data Provided by BOPRC

This section describes the data that was provided by BOPRC for this study (Table 4.1), and used in the creation and calibration of the model.

Table 4.1 Data provided by BOPRC for use in the modelling process.

Date	Sent By	Description
30/3/2017	Janine Barber	Temperature measurements collected in 7 wells, with location, depth, time and temperature measured down the well.
30/3/2017	Janine Barber	Metered groundwater use, including raw data and daily, monthly and yearly cumulative extraction. Well number, time and take volume were included, no location information.
30/3/2017	Janine Barber	Consented geothermal and groundwater takes for 282 wells including use, location and consented rates. Updated to 650 'active' wells on 30/5/2017. Some information corrected on 3/10/2017.
26/6/2017	Janine Barber	Selected monitor bore graphs of water level, descriptions of monitor data collected, and maps of locations for Tauranga and Kaituna regions. Graphs updated 5/12/2017.
20/10/2017	Anya Lambert	Consented geothermal and groundwater takes updated. Further updated with additional depths, locations and some corrected labels on 2/11/2017. Further update on 19/1/2017 for consents associated with multiple wells.
18/12/2017	Janine Barber	Consented reinjection discharges for 43 wells, and whether the discharge is shallow soakage or to depth, with rates and volumes.
18/12/2017	Janine Barber	Time series graphs of water level for 75 monitor bores, and a spreadsheet of estimated recovery and drawdown range for the 49 relevant bores, taken from the time series graph.

4.2 Temperature Data

The Tauranga area has been drilled extensively for groundwater purposes, providing temperature information to several hundred metres below the surface (White et al. 2009). 442 wells have been drilled, providing 1623 temperature measurements (Figure 4.1). The measurements were compiled from five sources – BOPRC database, new data collected by BOPRC (referred to as BOPRC2017, see Table 4.1), the groundwater report by White et al. (2009), Waikato Regional Council database, and measured temperature data from GNS archives, much of which can be found in Simpson (1987). The bottom of the deepest well, 2301, was at 904 metres below sea level with a temperature of 47°C. The hottest temperature measured was 67°C at 750 m depth in well 11568. Both of these wells are in the centre of the model area under Tauranga City.

Wells with temperature profiles are optimal for temperature calibration as they provide information about the geothermal gradient, whether the heat flow is conductive or convective, and whether there are anomalous measurements.

For this study, 40 wells were used that had temperature profiles with depth (Figure 4.1). In addition to the 17 wells used in the PA2013 model (Pearson and Alcaraz 2013), new BOPRC data and older data from GNS archives were incorporated from an additional 23 wells. The bottom of the deepest of these wells, 10545, was at 738 meters below sea level. This is a relatively cool well of 34°C to the north of the model area. The hottest temperature measurement was 64°C in well 66, a well of 580 m depth to the west of the model area. The temperature profiles and their modelled matches can be seen in Section 6.1.

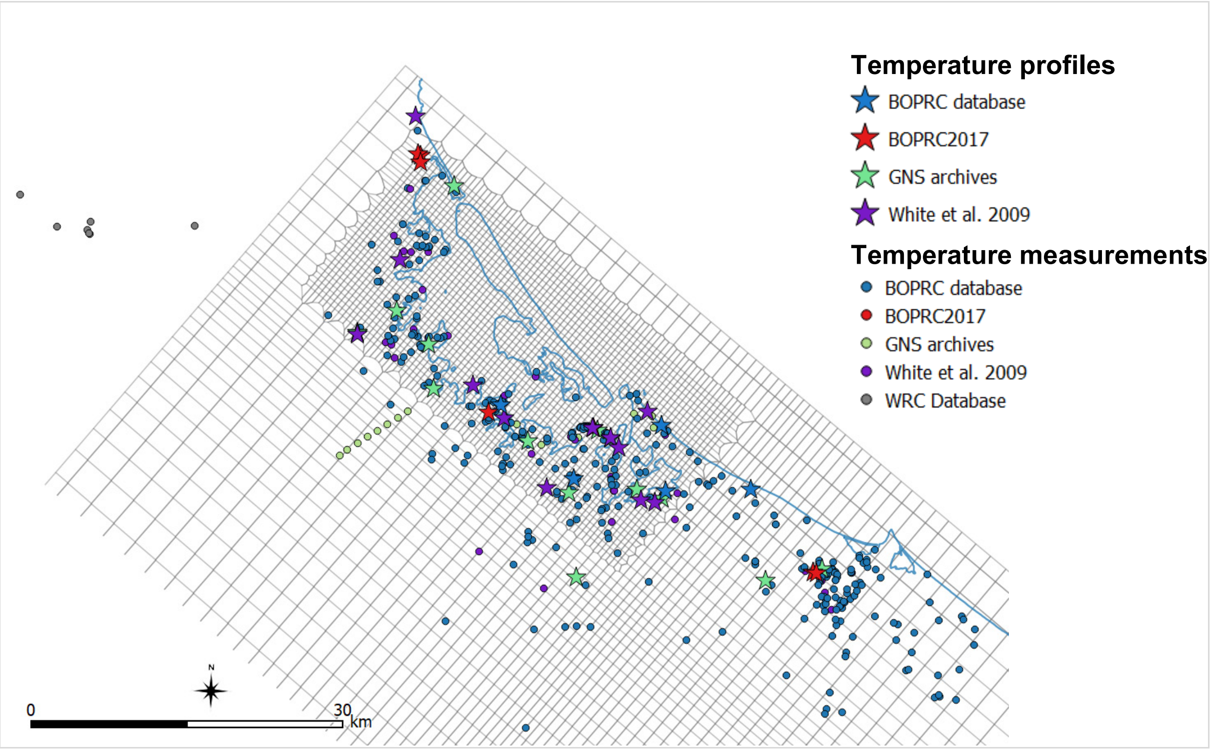

Figure 4.1 Locations of wells where temperatures have been measured. Stars represent temperature profiles with depth, circles represent wells where just one measurement was collected down-hole. Colours correspond to the sources of the data.

4.3 Water Level Data

There are 49 monitor wells in the Tauranga area where water levels are measured by BOPRC (Figure 4.2), many of which have operated for decades. They show seasonal drawdown of between 0.4 and 28 m, although one shows an increase in water level in the high-extraction months. There is no apparent correlation between well depth and amount of drawdown.

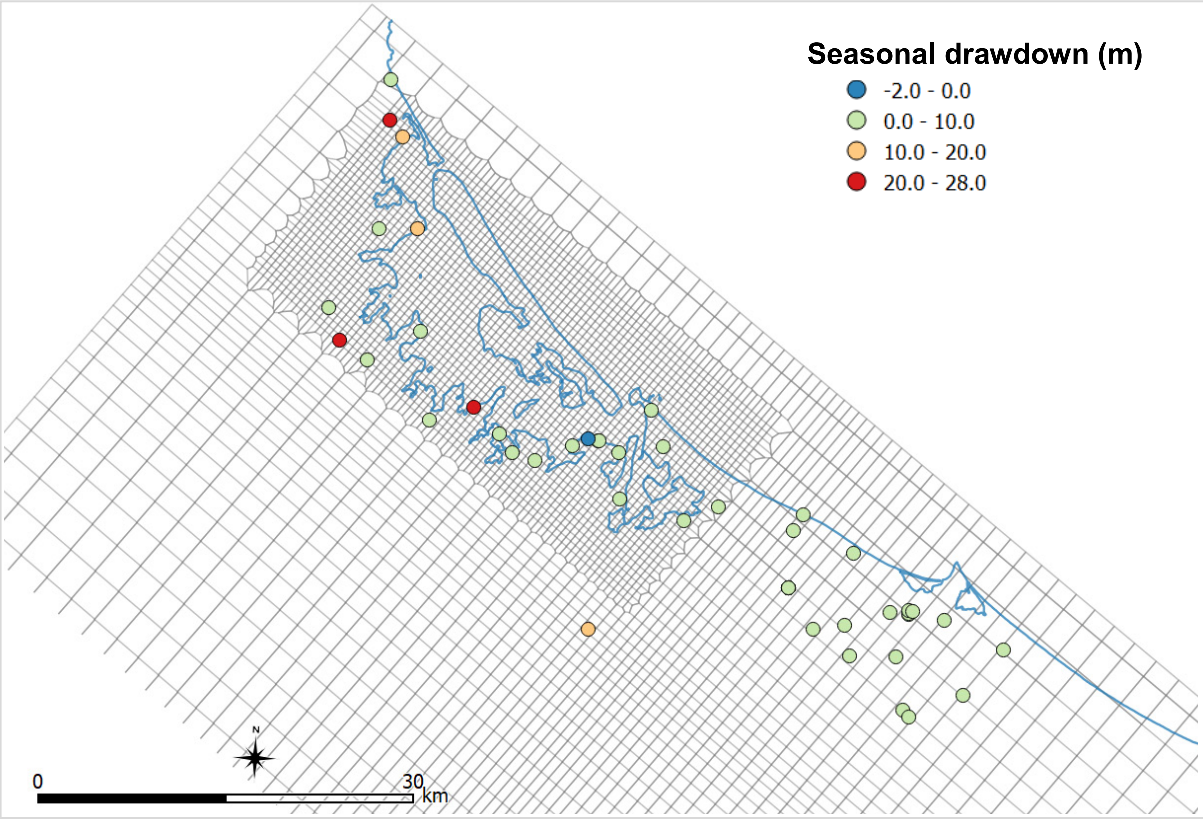

Figure 4.2 Locations of monitor wells. Colours correspond to the changes in water level observed between summer and winter, with more drawdown (positive values) expected in summer.

4.4 Extraction Data

Water is extracted from 631 wells in the Tauranga area. Of these, 23 have a nearby reinjection well (Figure 4.3). For each well, the location and consented extraction rate are known. The consented rate is given as one of the following:

- A maximum flow rate (in l/s).
- Daily, weekly or annual total flow (in m^3).

The depth of the wells ranges from 1.5 m to 917 m, although the drilled depth is unknown for 66 wells. Because modelling fluid extraction requires a well depth, for those 66 we assumed the average of the 565 wells with known depths, which was 193 m.

To work with the data, well use was classified into five different classes according to likely usage patterns: municipal, irrigation, commercial, domestic and unknown (Table 4.2).

The consented rates are the maximum and should not be exceeded, with current extraction rates likely to be lower than the consented rate. However, the current rates are not known in most of the wells in the Tauranga area.

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. But these seasonal fluctuations are not known for most wells.

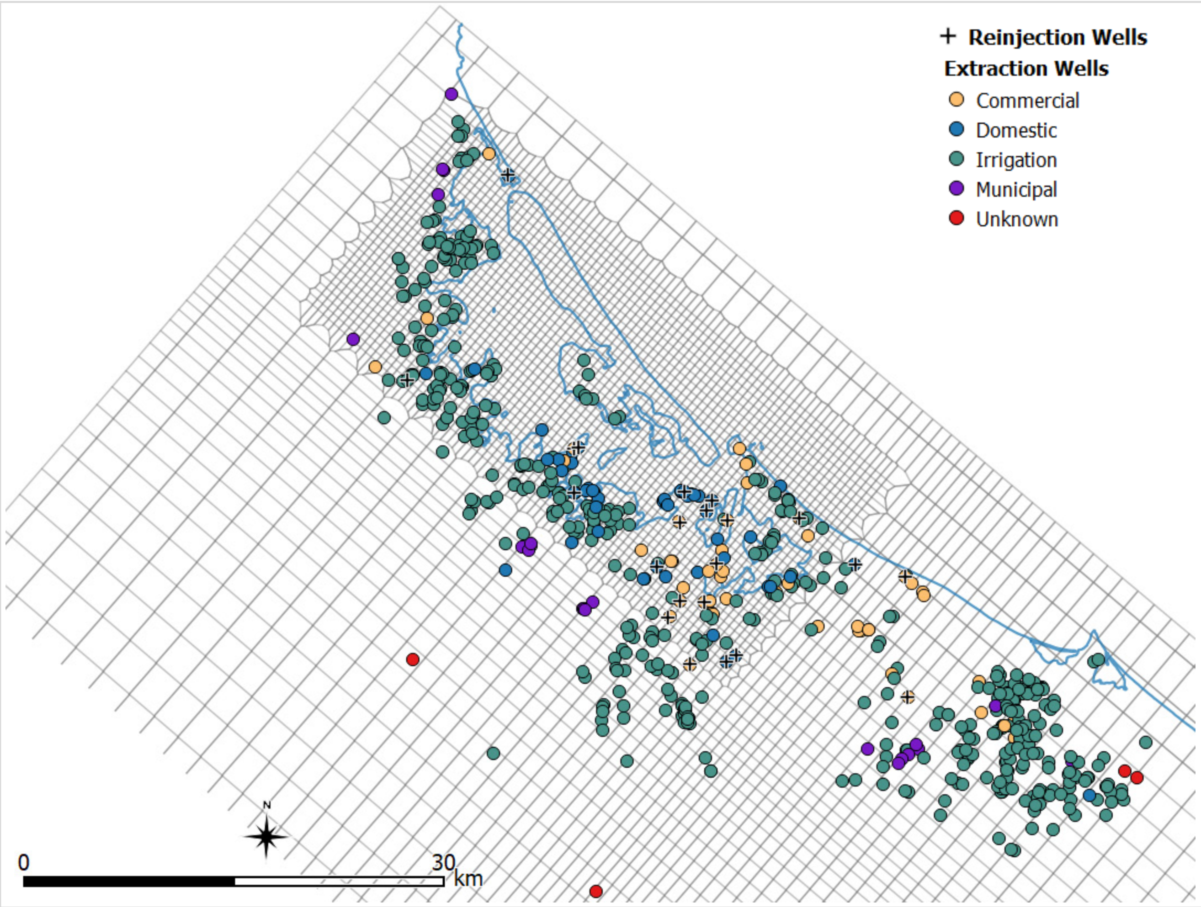

Figure 4.3 Extraction wells (circles) and reinjection wells (black crosses) in the Tauranga Geothermal Field.

Table 4.2 Summary of use for water extracted from the Tauranga Geothermal Field.

	Number of Wells	Number of Metered Wells	Total Consented Use (m^3/day)
Municipal	21	9	77,101
Irrigation	506	136	73,276
Commercial	42	1	15,313
Domestic	58	0	4,980
Unknown	4	3	3,789
Total	631	149	174,458

4.5 Metered Data

There are 183 metered wells where fluid extraction rates have been measured (Figure 4.4). The measurements were recorded for varying lengths of time between 2011 and 2017.

Wells were removed from the dataset if they were not included in the consent database and therefore their location and consented extraction rates were unknown, if they were not for geothermal or groundwater extraction, or if less than one year of fluid extraction data had been recorded. In addition, individual extraction rate measurements were removed if a data point was significantly outside the normal range of extraction for the well, or if the data point was duplicated (for example if metered and manual readings were collected at the same time). All the removed data was either for irrigation wells, or wells that had no consent data.

The final dataset contained 149 wells (Table 4.2) with 231,563 data points. This data was used to estimate current extraction rates for different classes of well use, and over different seasons. The use of this data will be discussed in Section 5.0.

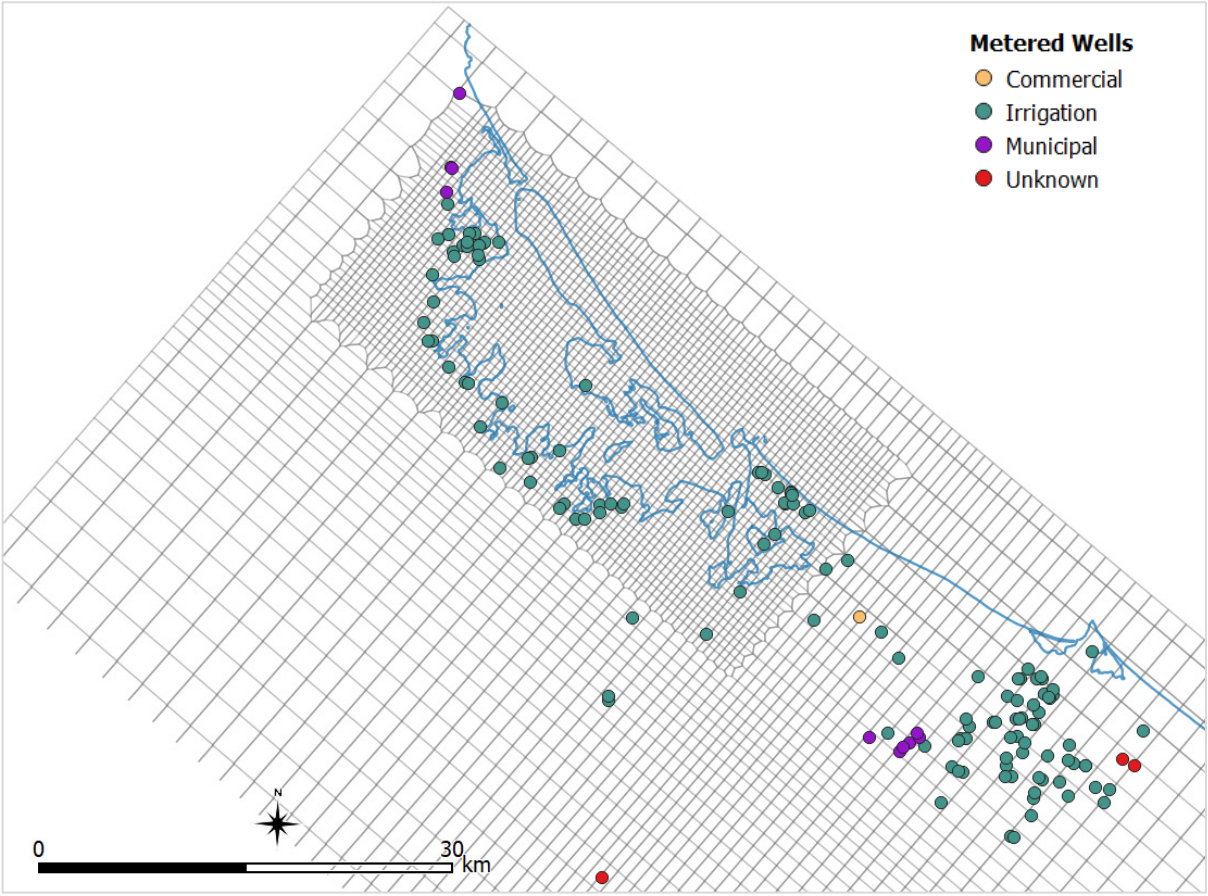

Figure 4.4 Locations of wells with metered extraction rates.

5.0 DATA INTERPRETATION

While consented extraction rates are known for all wells in the Tauranga area, there is little data on current extraction rates or their seasonal variations. We need to estimate current seasonal extraction rates in this model because comparing them to seasonal changes in water level gives the best indication of permeability. Seasonal extraction rates are calculated by using the metered data described in Section 4.4 to estimate current extraction rates for the different classes of well use, and for four three-month seasons each year that data is available for. For each well, we calculated:

- The average total flow per year.
- The average total flow for each quarter of a year.

These values were used to estimate a ratio of metered to consented extraction for each usage class, and its seasonal fluctuations. The ratios were then applied to all consented wells to provide estimates of current extraction rates (e.g. Figure 5.1).

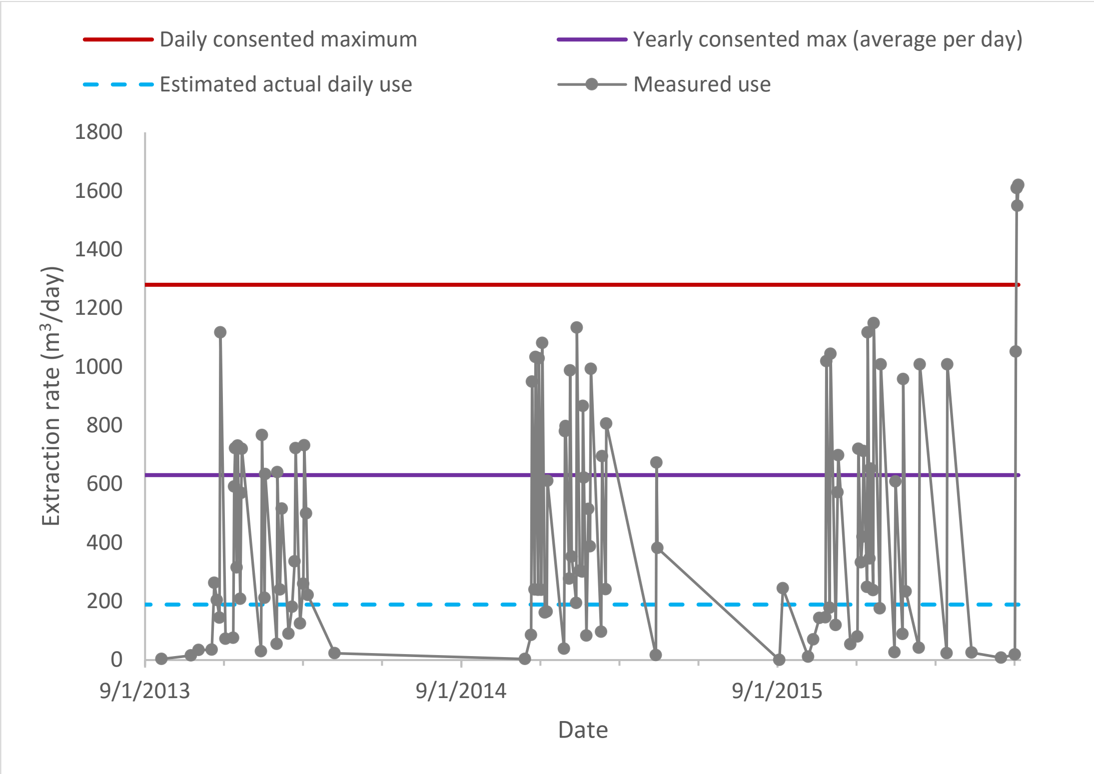

Figure 5.1 Current extraction rates (grey markers) plotted against consented and estimated extraction rates at well 10791. Consented rates per year were used in calculations (purple line), but for some consents a daily or hourly maximum rate (red line) was also specified. The estimated average extraction rate (blue dashed line) was calculated from the metered data as described in the text.

5.1 Seasonal Rainfall Effects

To determine how the water levels respond to seasonal variations in extraction, we first tried to look at any effects from rainfall. Rainfall data from station Tauranga Aero Aws (NIWA 2017), which ran from 1990 until 2017 was used to assess the effect of rainfall on groundwater levels. A timeseries of total rainfall per month shows that there are some months that are significantly wetter, although heavy rainfall is generally not sustained for subsequent months (Figure 5.2). Averaging the rainfall by month over the entire monitoring period (Figure 5.3) shows that more rainfall occurs in April to August, or autumn-winter. The wettest quarter, April to June, typically has 1.5 times the rainfall of the driest quarter of October to December. Measured changes in water level, and the fact that they do not occur at the same time as seasonal changes in rainfall, suggest rainfall is not the dominant control on water level changes, although it may contribute. Because of this, and practical difficulties associated with incorporating varying rainfall into the model, it was assumed to be negligible for the purposes of this study.

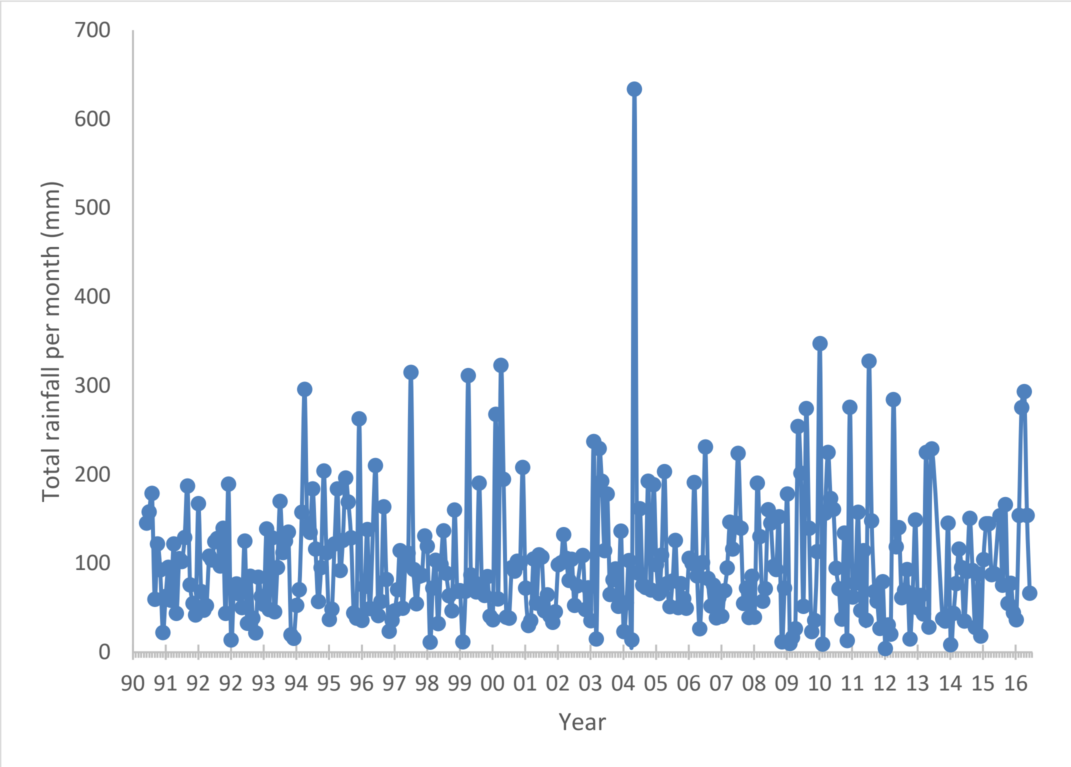

Figure 5.2 Monthly rainfall in the Tauranga area (NIWA 2017).

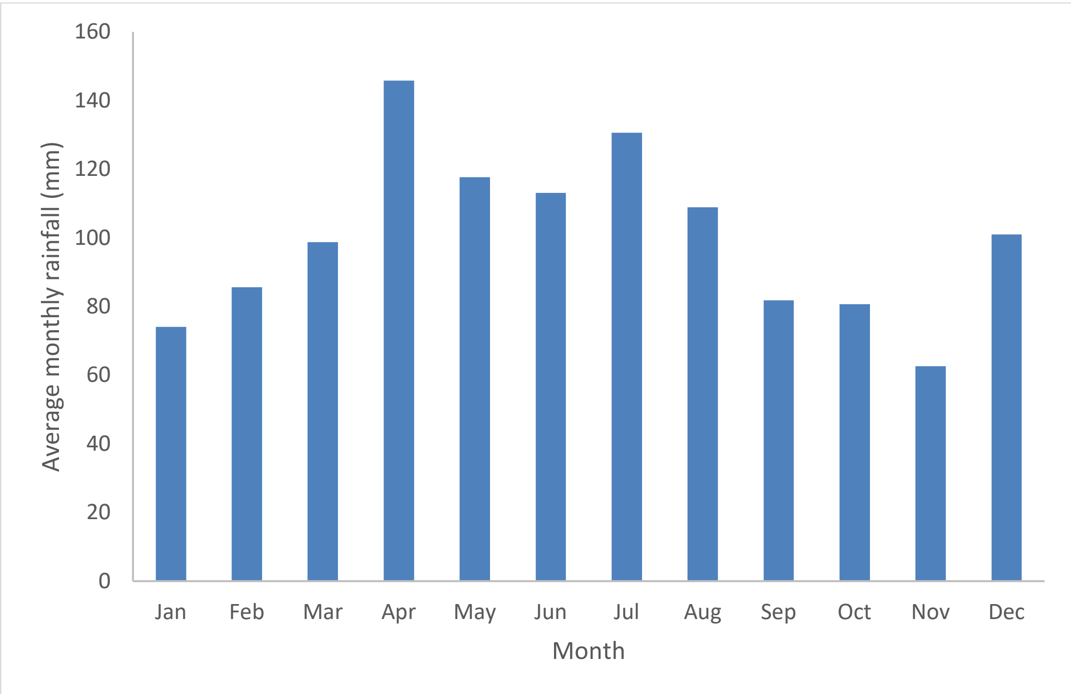

Figure 5.3 Average rainfall per month between June 1990 and May 2017.

5.2 Estimating Current Extraction Rates

Data from 149 metered wells (Section 4.5, Figure 4.4) was used to estimate how much fluid is being extracted compared to consented rates. In total, there were 231,563 individual data points. The wells were categorised into the five different classes as described in Section 4.3. Any wells classed as unknown were explored to determine use where possible, e.g. looking up the address in google maps to see if it was at an orchard for example. No domestic wells were metered, and the one commercial well had extraction rates higher than those consented, therefore the average of the ratios for the other three usage classes was used for both of those.

For each metered well, the consented rate was determined from the total annual extraction rate in the consent database. If this was not available, the maximum daily consented rate was used (consents may have a maximum rate in l/s, or a daily rate, a weekly rate and/or an annual rate in m^3 per time period). If there were multiple wells under the same consent, the total rate attached to the consent was divided by the number of wells to estimate the consented rate at each well.

The ratio of consented use to metered use was calculated for each usage class by summing the metered use and dividing it by the total consented use over the same period (Table 5.1). The overall average was used rather than averaging the ratios for each well because averaging individual ratios was found to be skewed toward the more numerous small extractors who use a higher proportion of their consents. Using the resulting ratios, the total estimated current take in the Tauranga area is 16,259,469 m^3/year compared to consented take of 63,720,784 m^3/year.

Table 5.1 Summary of the metered data and its associated consented extraction for the Tauranga area.

	Total Used Over Metered Period (m^3)	**Total Consented Over Metered Period (m^3)**	**Ratio Current Use 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

* Assumed average because there was insufficient metered data.

5.3 Estimating Variations in Seasonal Extraction

Consented rates apply annually, and do not specify likely changes over a year such as irrigators who primarily extract in the hotter summer months, and sometimes in winter months.

Metered data was available to estimate seasonal variability for municipal and irrigation extractors. It was recorded as cumulative take, and a python script was used to convert this into m^3/day by calculating the change in take since the previous measurement. The total use per season for each well was calculated using pivot tables in Excel. The total seasonal use for each class was averaged over all the relevant wells, and normalised relative to the largest season. The results can be seen in Table 5.2.

There was no metered data for domestic users. Data from commercial and unknown users did not span a full year, and therefore seasonal trends could not be identified. Domestic, commercial, and unknown usage rates were therefore assigned assumed values (Table 5.2) based on discussion with BOPRC.

Table 5.2 Seasonal changes in extraction normalised to the largest quarter for each class of use.

Usage Class	January to March	April to June	July to September	August to December
Municipal	0.44	0.53	1.0	0.63
Irrigation	0.97	0.21	0.29	1.0
Commercial	1.0	1.0	1.0	1.0
Domestic	0.2	0.5	1.0	0.5
Unknown	1.0	1.0	1.0	1.0

5.4 Estimating Current Seasonal Use

Extraction rates over a year were calculated from the annual estimated to consented ratio for each use class (Table 5.1), together with the seasonal factors in Table 5.2. This was done so that the average over a year was equal to the annual estimated extraction rate. The resulting seasonal extraction rates were used to simulate seasonal variations in water level as described in Section 6.2.

6.0 MODEL CALIBRATION

The model was iteratively calibrated against available data to determine key model parameters, including the heat flux through the base of the model and permeability of the various geological units. The natural state model was initially calibrated for temperature, and then seasonal extraction rates were added to calibrate for seasonal water level changes. If the natural state model no longer represented the temperature measurements after the water level calibration, model parameters were varied and the model was recalibrated until it matched both sets of data. Once the temperature and water level data were adequately represented by the model, it could be used to model future scenarios.

The PA2013 model was calibrated entirely against temperatures, and suggested, on the basis of predominantly conductive temperature profiles, that the Tauranga Geothermal Field has low permeability. However, this conclusion implied that any fluid extraction would result in large declines in water level, which have not been observed. In this work we have therefore used water level data in addition to temperature profiles to refine estimates for the permeability during the model calibration process.

6.1 Calibration with Well Temperatures

Well temperature measurements help to determine heat flow through the system, thermal conductivity (in a predominantly conductive system such as Tauranga), and maximum permeability. Calibrating for heat flow and thermal conductivity were discussed extensively in Pearson and Alcaraz (2013) and values derived in that report were used as a starting point in this model. The heat flow was modified within the calibration process to ensure that the data was matched, without introducing a level of complexity that is unnecessary for modelling future scenarios.

Temperature measurements help to determine the permeability of the system up to a certain threshold. In the Tauranga area, temperature generally increases linearly with depth (e.g. wells 13, 4542 and 2530, Figure 6.3), suggesting mostly conductive heat transfer (see Pearson and Alcaraz (2013)). If the permeability is too great then the heat flow is dominated by convective flow of hot fluid, and temperature profiles will not be linear with depth. Conversely, if permeability is poor the conductive temperature profiles will not be affected, but modelled water level changes due to extraction will increase. The aim of the model calibration is to determine a permeability which provides the best fit to both the temperature profiles and seasonal water level changes.

Figure 6.1 shows the locations of the 40 wells with temperature profiles used to calibrate the model as described in Section 4.2. Figures 6.2 to 6.6 show the measured temperature profiles with depth against the final modelled temperatures.

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, and therefore the location or temperature of a measurement may be questionable, or there may be site-specific characteristics that required a level of detail that the model does not represent. In areas where the fit is not as good, 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.

The data has significant uncertainty associated with its collection. Some of it is from more than 30 years ago and the geographical location of the well is now poorly known. Others show inconsistent temperature measurements down the well, e.g. well 4702 (Figure 6.5). In many wells the temperatures follow a linear profile, suggesting that heat flow is primarily conductive in the top ~500 m, e.g. 4542 and 2530 (Figure 6.3), 4566 (Figure 6.4), 3467 and 4570 (Figure 6.5), but in some wells this is not the case. This could be due to measurement error, local heat flow variations, localised permeability resulting in convective flow, or complex flow within the well bore. These effects are beyond the resolution that this model can resolve.

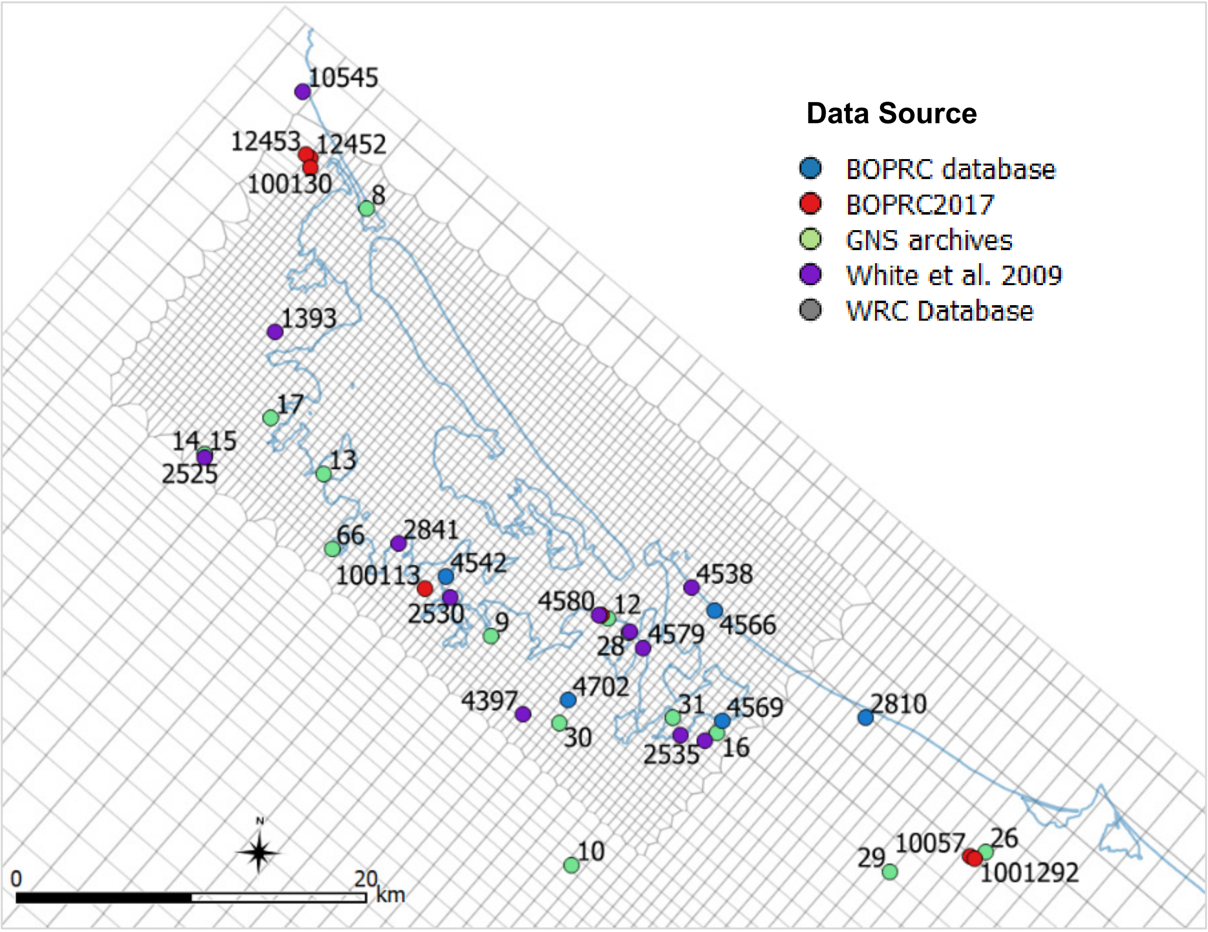

Figure 6.1 Locations of wells with measured temperature profiles with depth. Labels correspond to well numbers as in Figures 6.2 to 6.6.

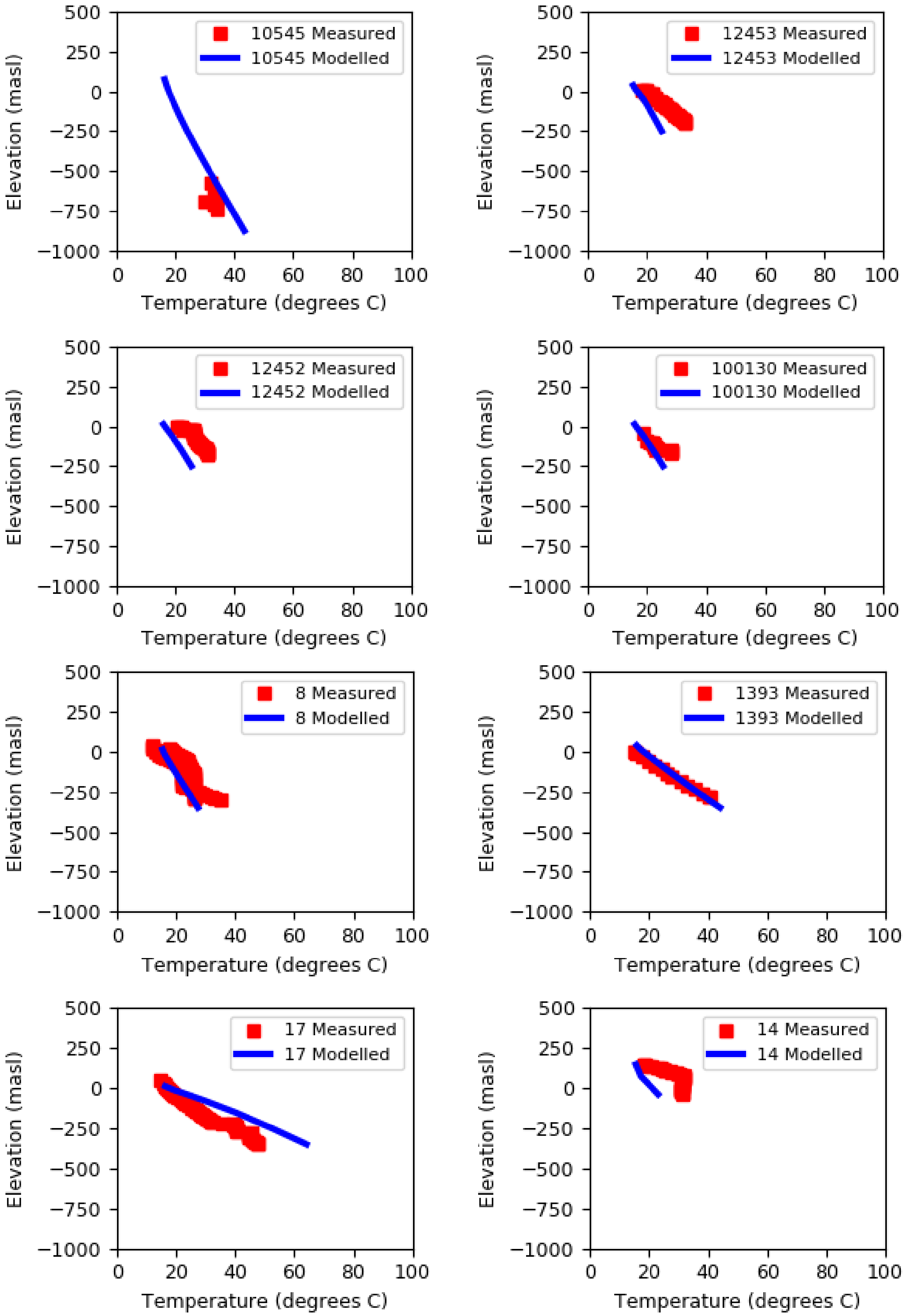

Figure 6.2 Profiles with depth for measured (red square) and modelled (blue line) temperatures to the north of the study area, in wells 10545, 12453, 12452, 100130, 8, 1393, 17 and 14.

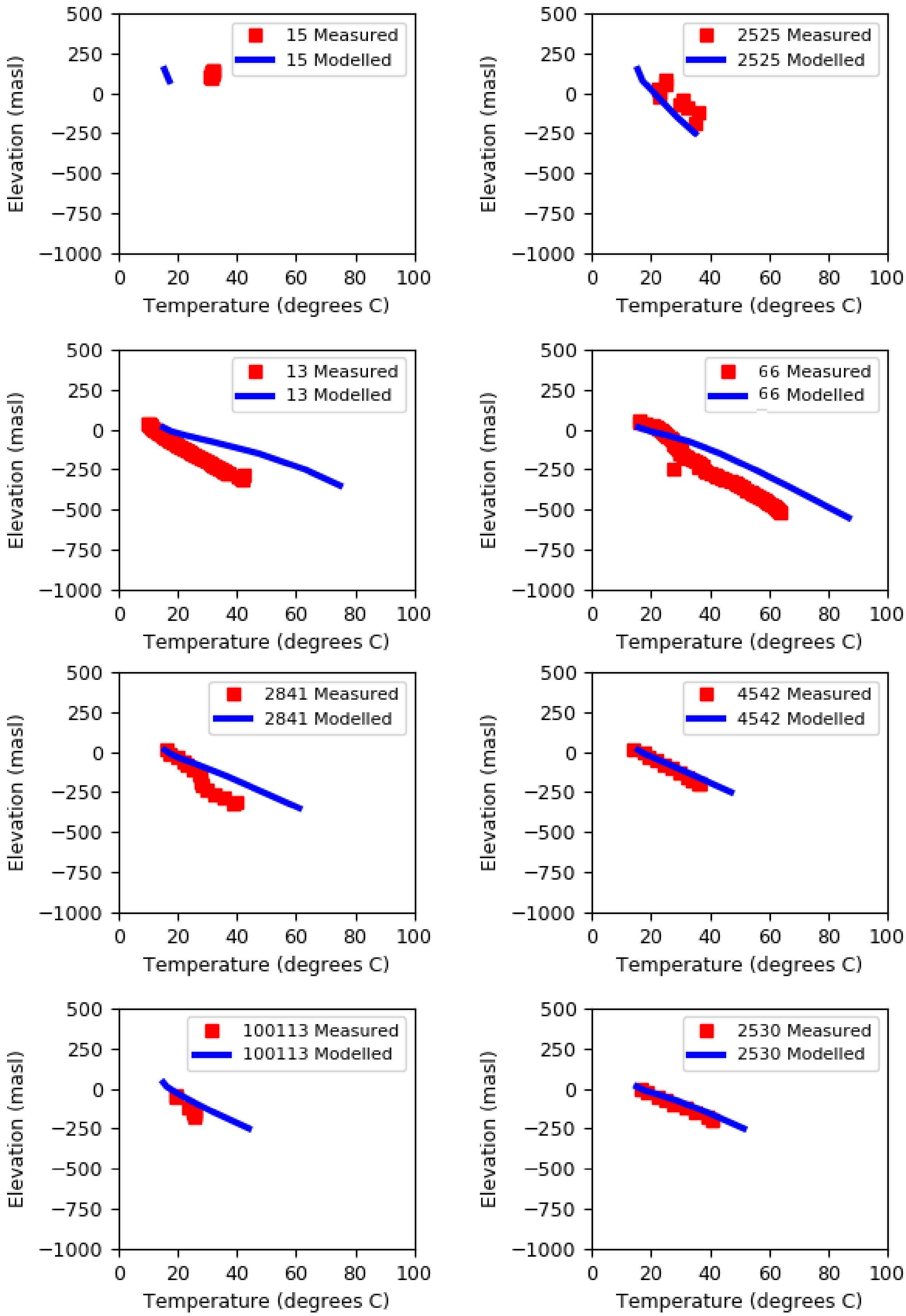

Figure 6.3 Profiles with depth for measured (red square) and modelled (blue line) temperatures to the west of the study area, in wells 15, 2525, 13, 66, 2841, 4542, 100113 and 2530.

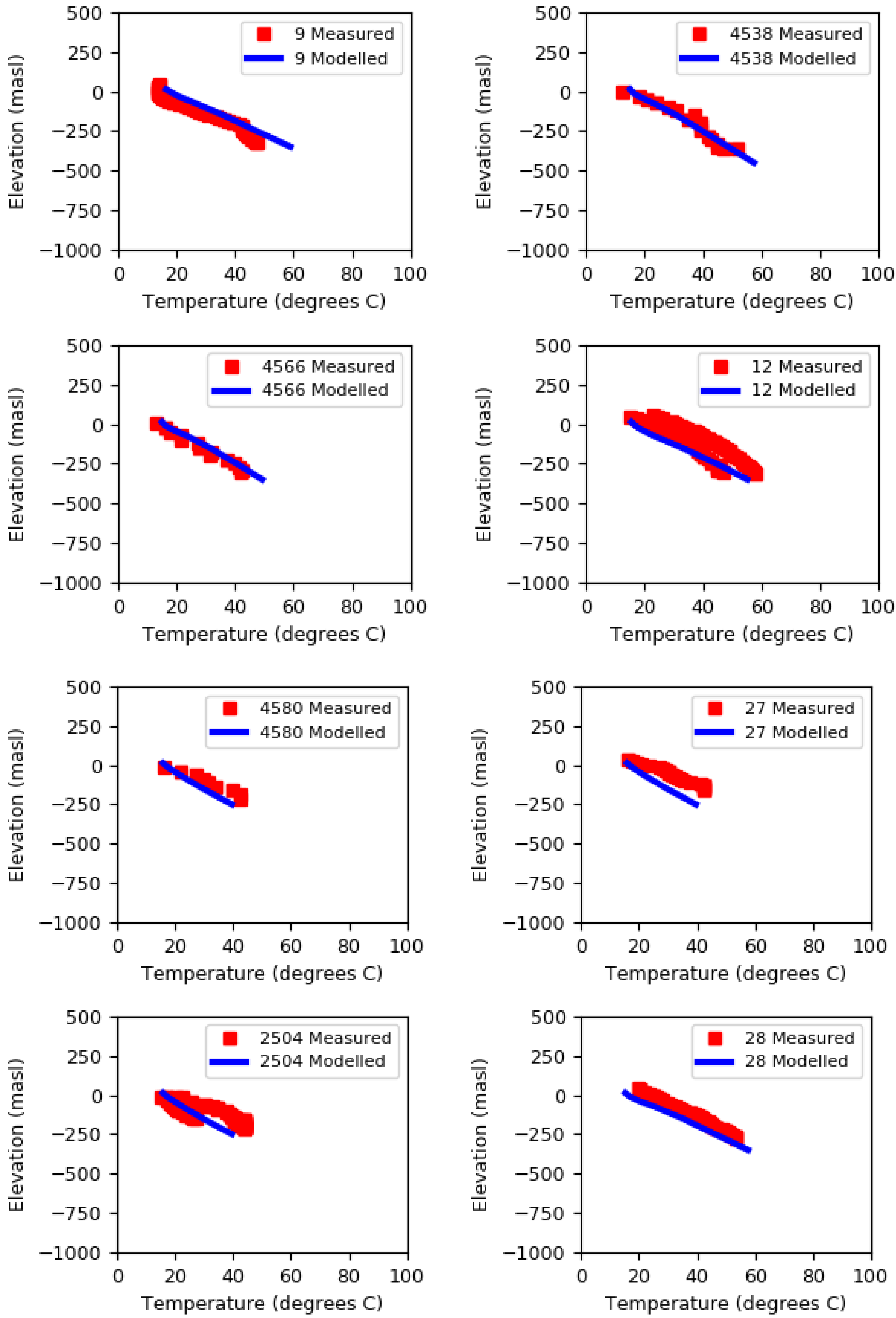

Figure 6.4 Profiles with depth for measured (red square) and modelled (blue line) temperatures in the centre of the study area, in wells 9, 4538, 4566, 12, 4580, 27, 2504 and 28.

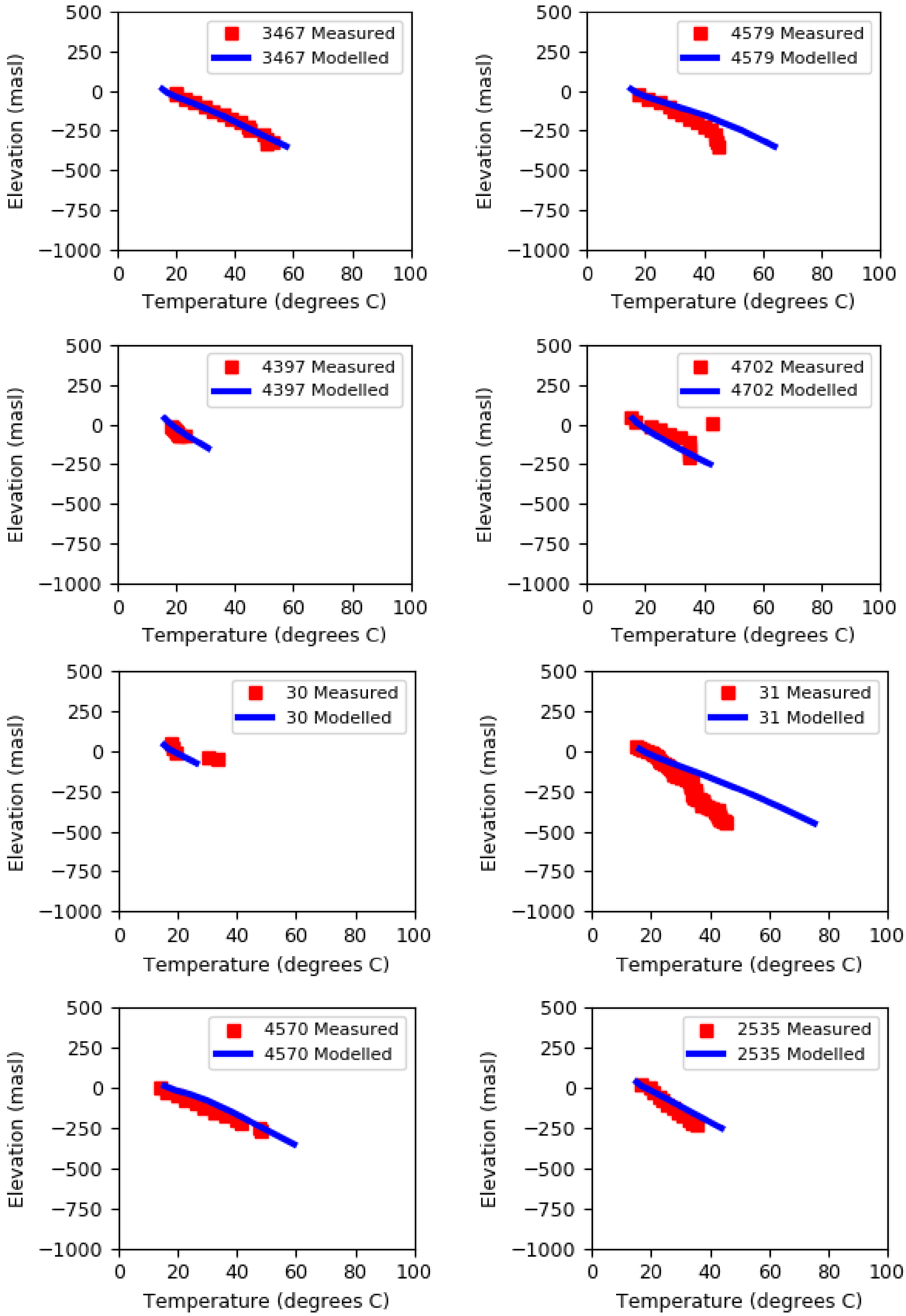

Figure 6.5 Profiles with depth for measured (red square) and modelled (blue line) temperatures in the south-central part of the study area, in wells 3467, 4579, 4397, 4702, 30, 31, 4570 and 2535.

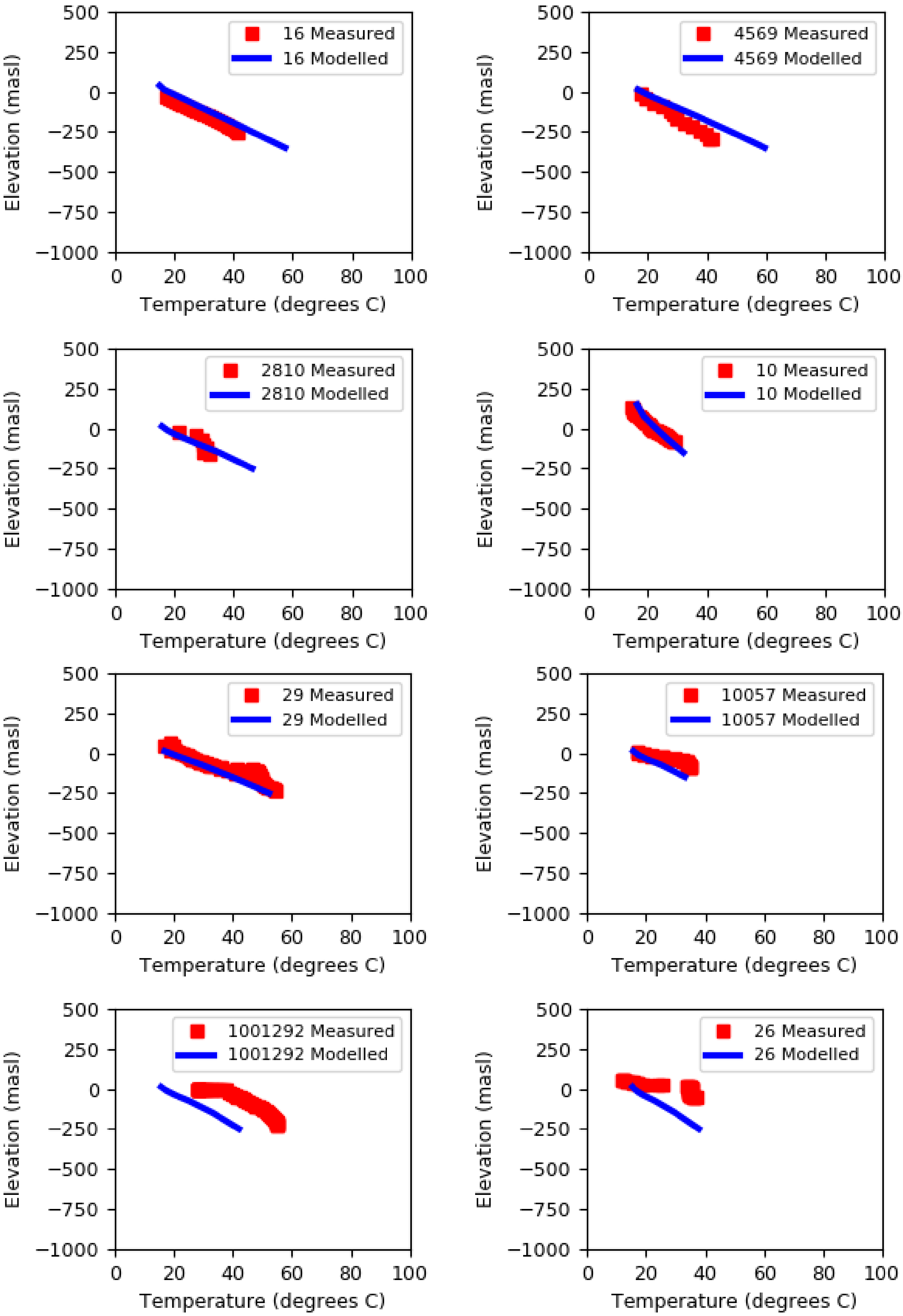

Figure 6.6 Profiles with depth for measured (red square) and modelled (blue line) temperatures to the south of the study area, in wells 16, 4569, 2810, 10, 29, 10057, 1001292 and 26.

6.2 Calibration with Seasonal Water Levels

Determining permeability is very difficult, but crucial to infer with a high degree of confidence how the water level/pressure drawdown responds to extraction. The most direct way to estimate model permeability is to use detailed water level and corresponding fluid extraction data, but this has not been collected in Tauranga.

Seasonal changes in water level (e.g. Figure 6.7) due to seasonal changes in fluid extraction (e.g. Figure 6.8) can also be used to calibrate the permeability in the model. During the summer, when extraction is typically greater due to increased irrigation, water levels drop. If the permeability is high, the change in water level is small as extracted water is quickly replaced from the surrounding area; if the permeability is very low, the water level decreases because extracted water is not replenished. Although seasonal changes in water level are measured in very few extraction wells in Tauranga, monitor wells do record seasonal water level changes thought to be due primarily to variations in regional extraction (Figure 6.9).

To calibrate with seasonal water level data, we estimated the magnitude of the seasonal change in each monitor well (e.g. Figure 6.10). This was a subjective assessment done in discussion with BOPRC. Because there are large uncertainties in the estimated extraction rates (Section 5.0) related to water level changes, and monitor wells were often not operational when regional extraction began, we matched the magnitude of the overall seasonal drawdown (Figure 6.11) rather than trying to match water level changes over time in detail.

Seasonal extraction was modelled for eight years after the end of the natural state model, using the extraction rates described in Section 5.0. This timespan allowed us to determine the magnitude of seasonal trends without needing long computational times. Reinjection was also included in the model, at the same rates as extraction. The changes in water level simulated by the model were compared with the magnitude of changes estimated from monitored well data. Permeability values were reassessed and the model was rerun multiple times, until the modelled seasonal changes in water level were within the same range as seasonal changes measured in the monitor wells (Figures 6.12 to 6.18).

The effects of other parameters such as rainfall recharge, localised zones of different permeability, and different layering of the rock properties were also explored. They were not found to improve the fit of the model to the data and so were neglected.

In general, the modelled seasonal changes replicated the range indicated from examination of the monitor well data. This is particularly true given the uncertainty in the regional extraction data. In a few cases (unmetered wells 2829, 4219, 4822, 4157, 90, 4593, 4441, 11147, 2009, 2015, 2310), the consented extraction rate had to be used rather than the estimated rate in order for the model to match drawdown in wells 3032, 2829 and 90 to the north of the model area (Figure 6.12). Changing the permeability could not improve the match to the north; a greater permeability, as suggested by well tests and groundwater modelling (Pearson-Grant and Burnell 2016) resulted in decreased modelled drawdown and so a worse fit to the data.

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 (Figure 6.19). However, it suggested large drawdown in neighbouring wells 410 and 10800 (Figure 6.18) which have not been observed. This may be due to overestimated extraction rates, or a local zone of high permeability.

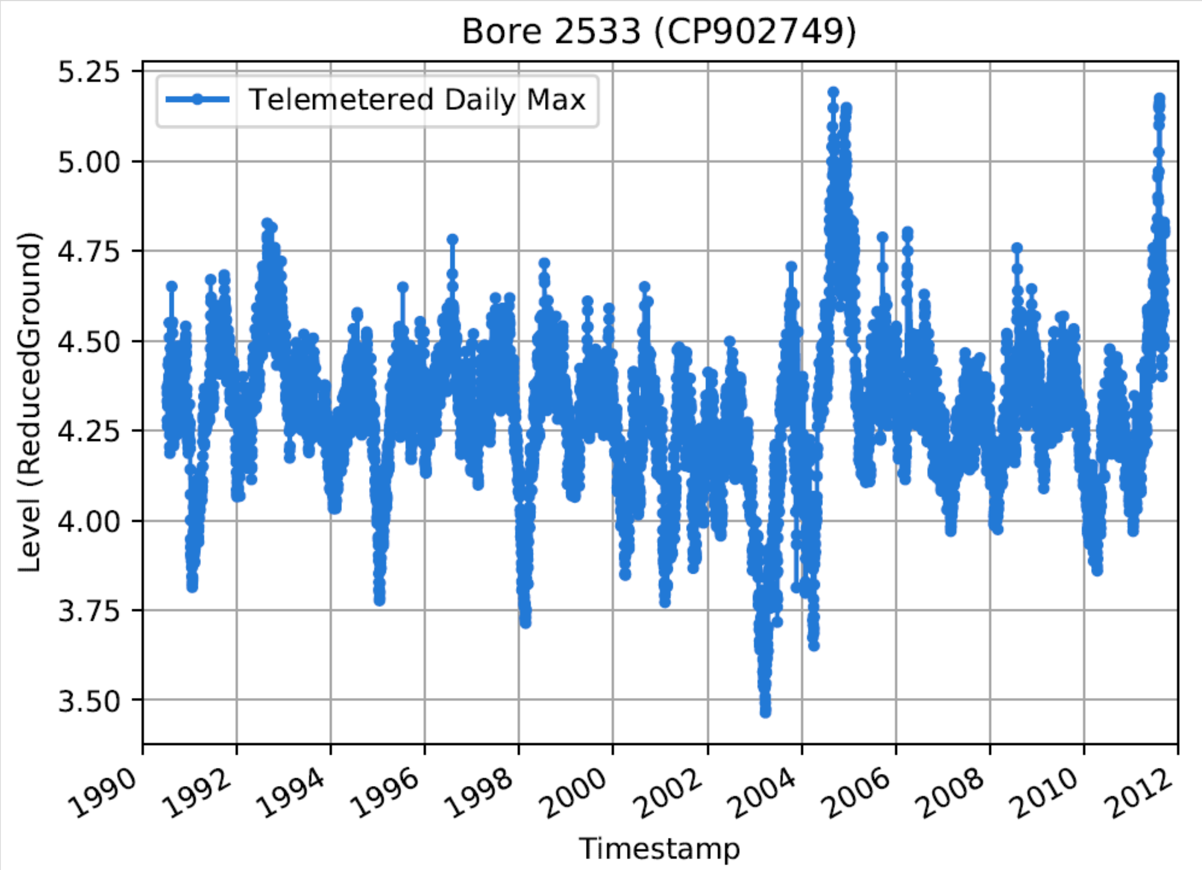

Figure 6.7 Seasonal variations in water level at a monitored well.

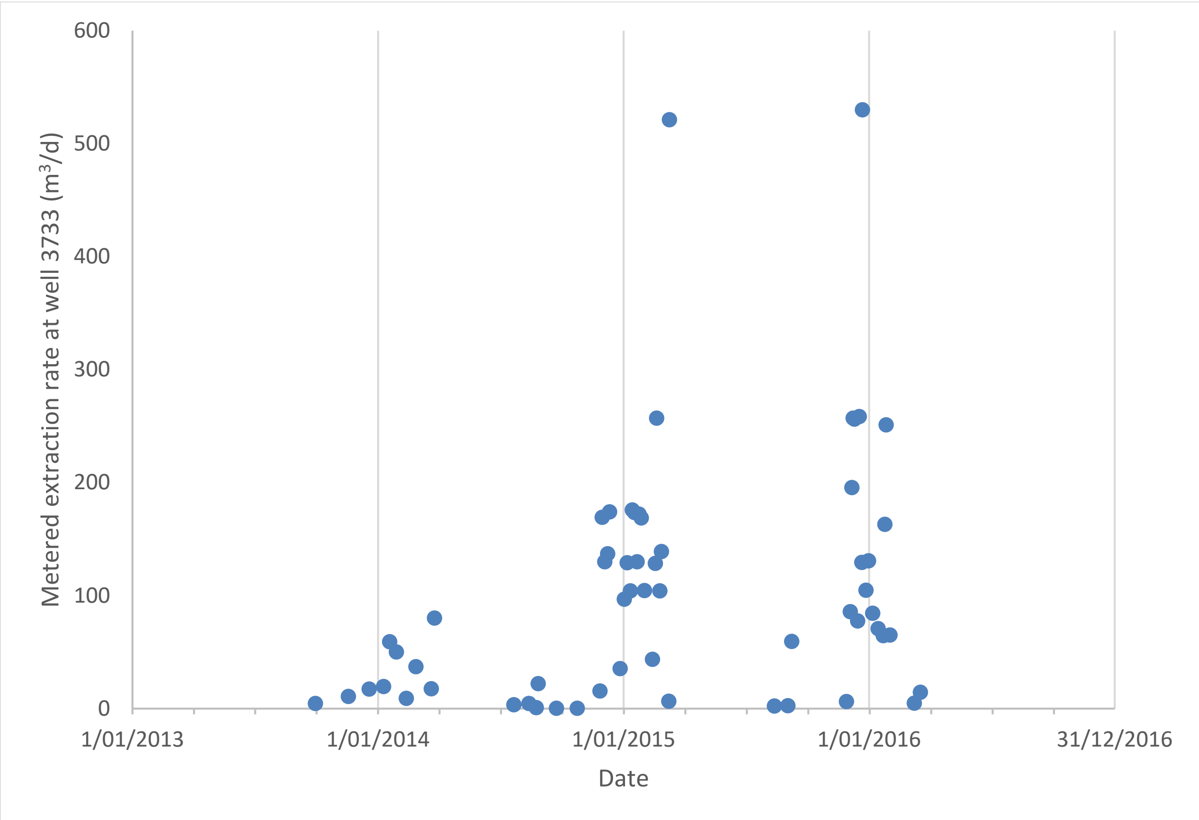

Figure 6.8 Seasonal variations in extraction rate at a metered well.

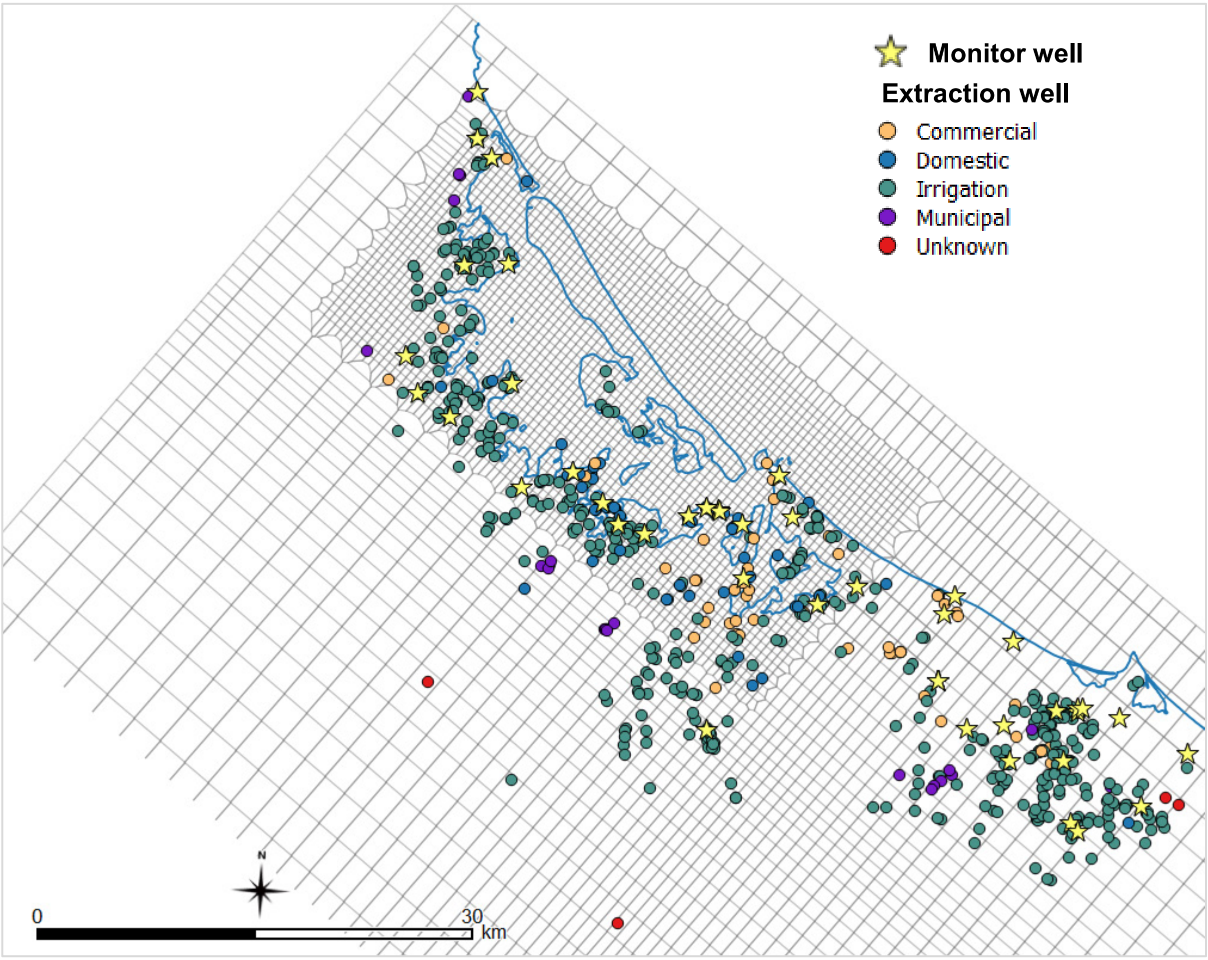

Figure 6.9 Monitor wells where seasonal changes in water level are recorded (yellow stars). Circles show extraction wells for commercial (orange), domestic (blue), irrigation (green), municipal (purple) and unknown (red) use.

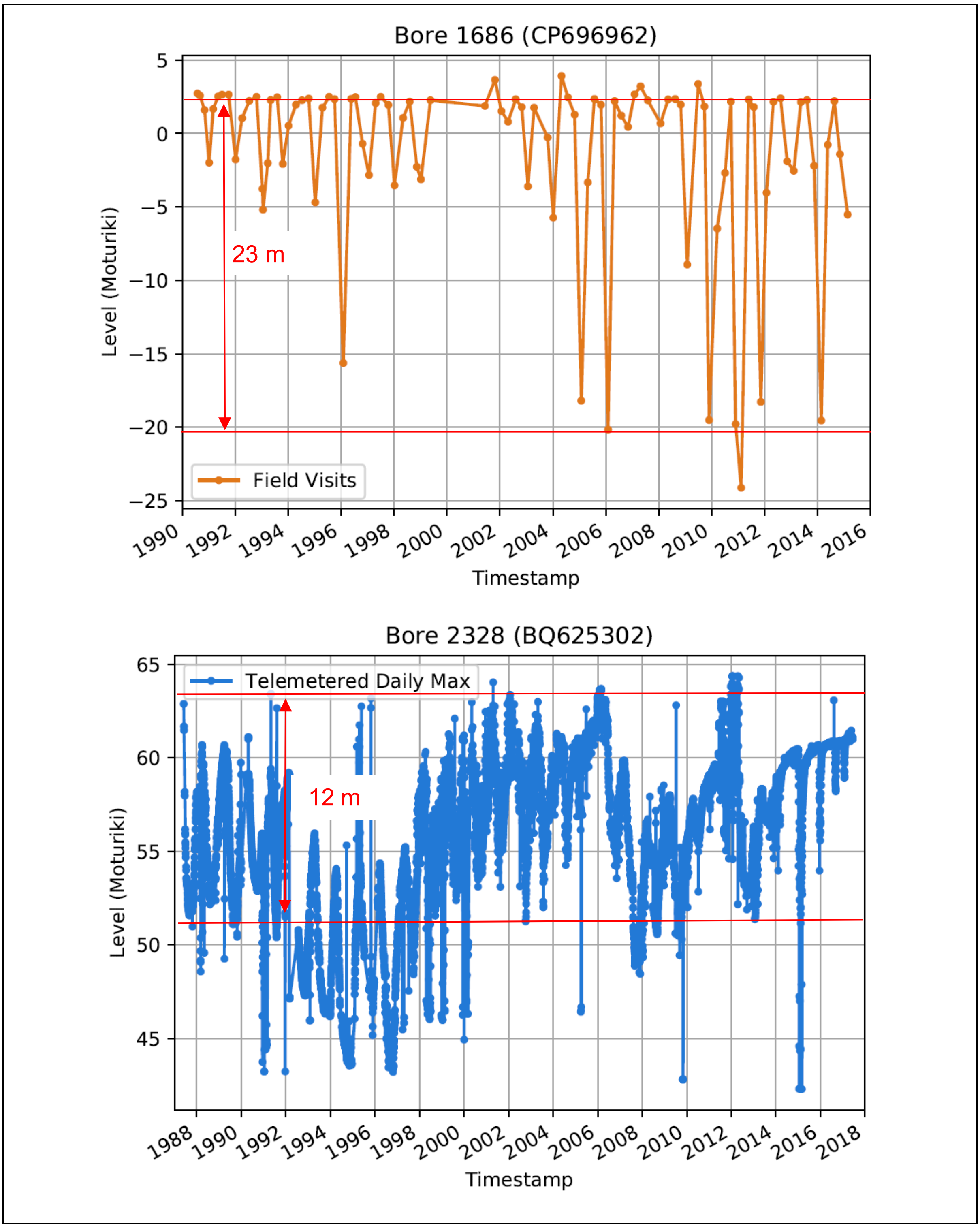

Figure 6.10 Example records from monitor wells in the Tauranga area that were used to estimate the seasonal variations in water level. Red lines correspond to the estimated seasonal change for that well.

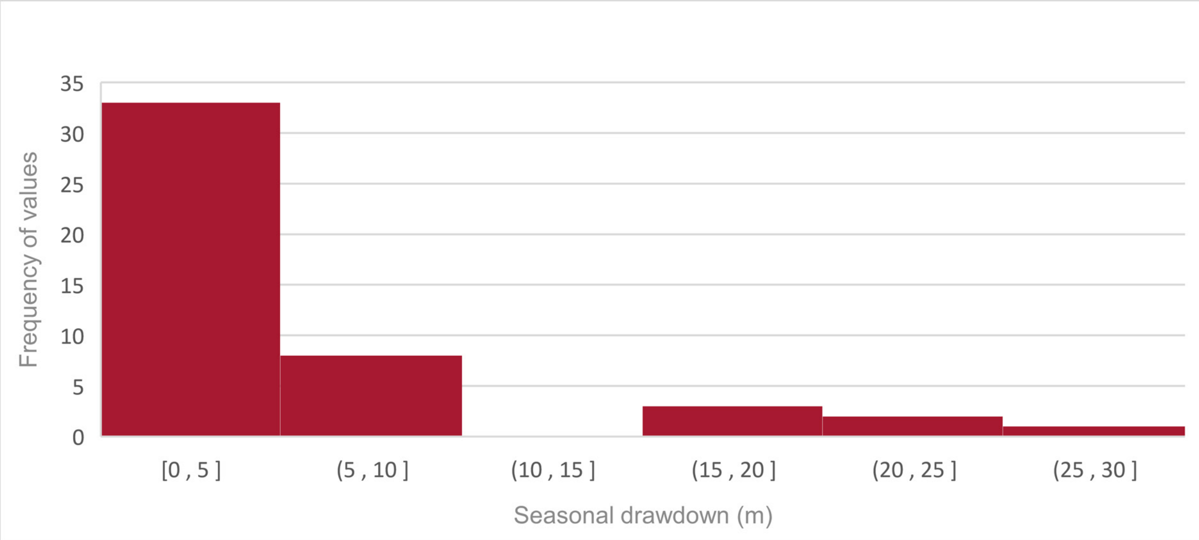

Figure 6.11 Histogram showing the number of wells with seasonal drawdown within a particular range.

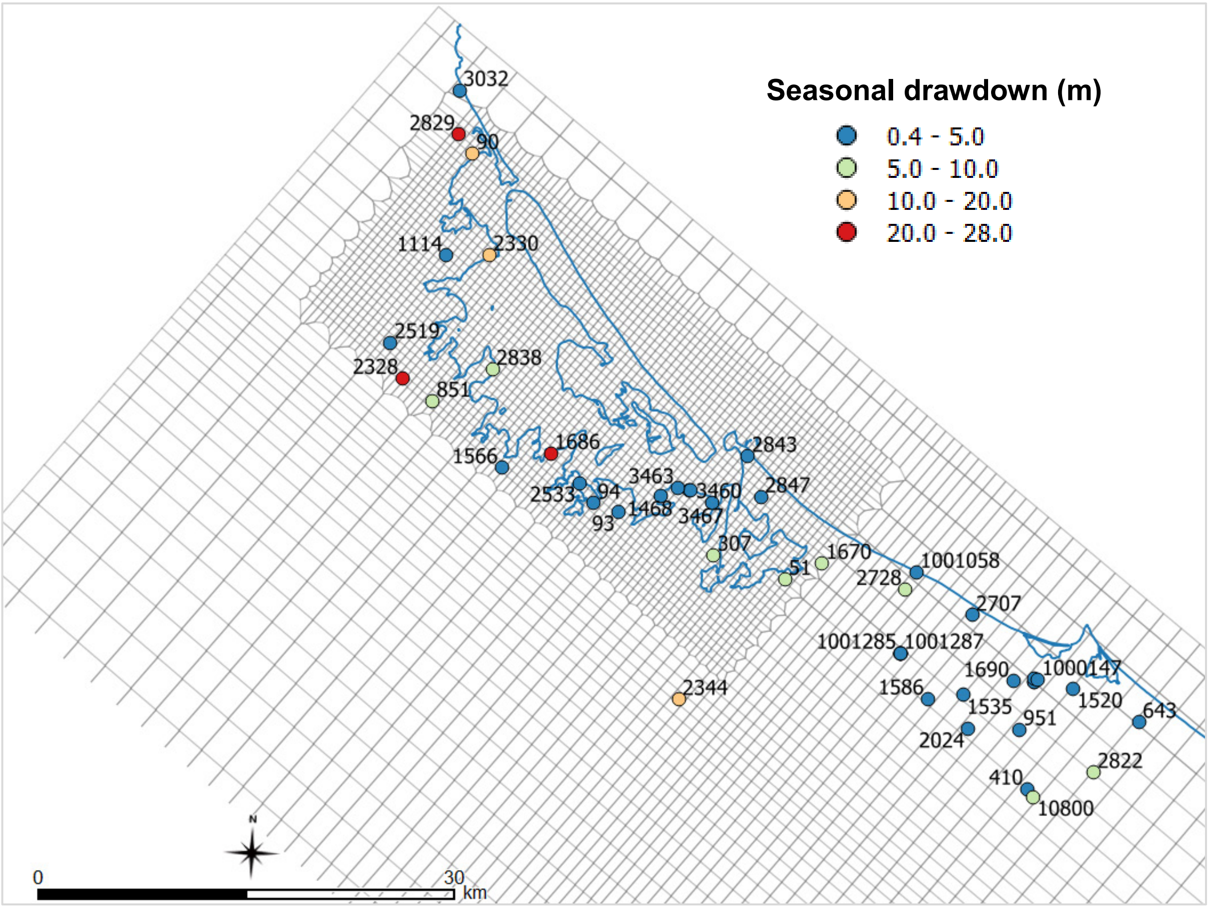

Figure 6.12 Monitor wells where seasonal water level changes are recorded.

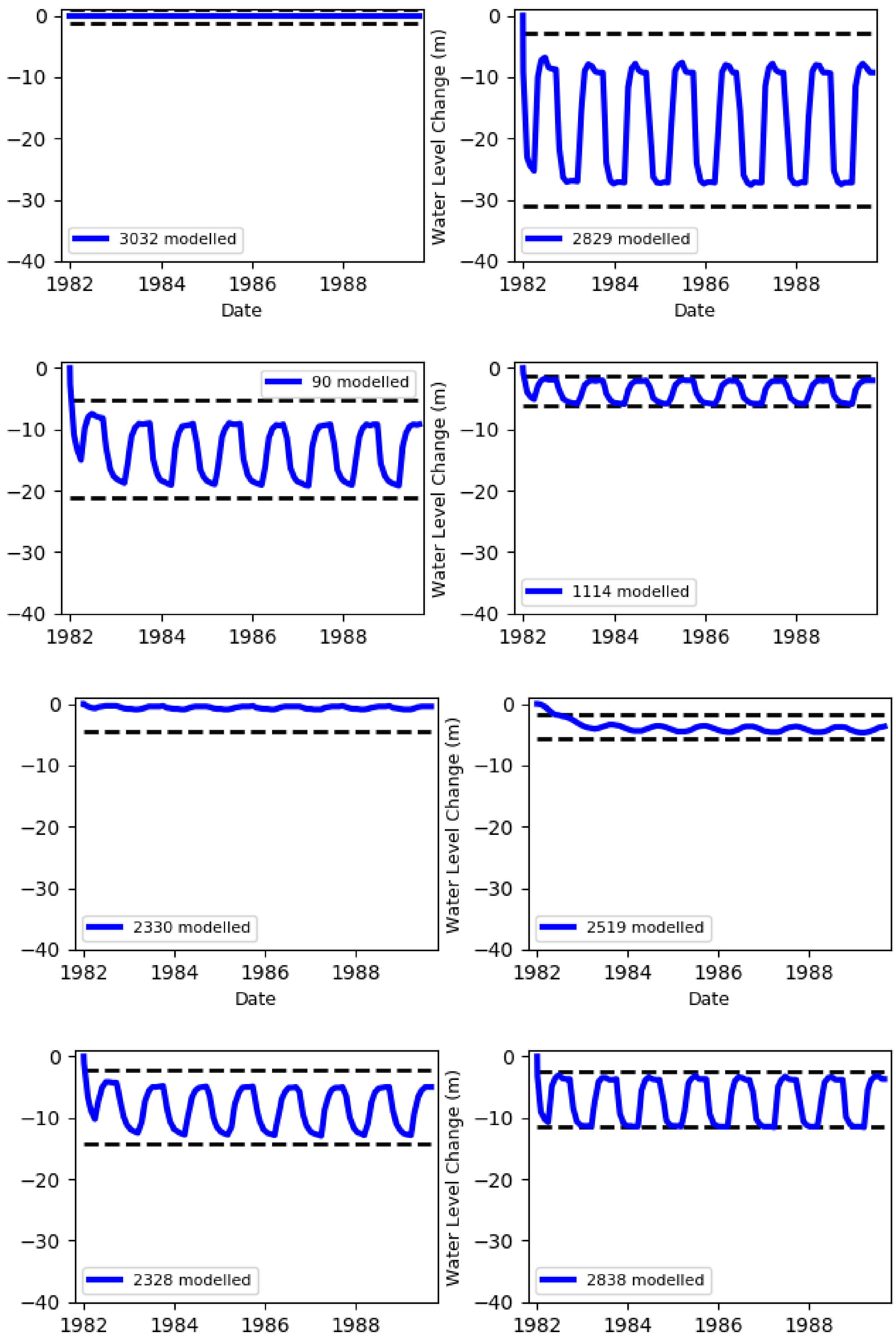

Figure 6.13 Seasonal changes in water level due to estimated seasonal changes in extraction measured in monitor bores (dashed black line) and modelled (blue line) to the north of the study area, in wells 3032, 2829, 90, 1114, 2330, 2519, 2328, and 2838.

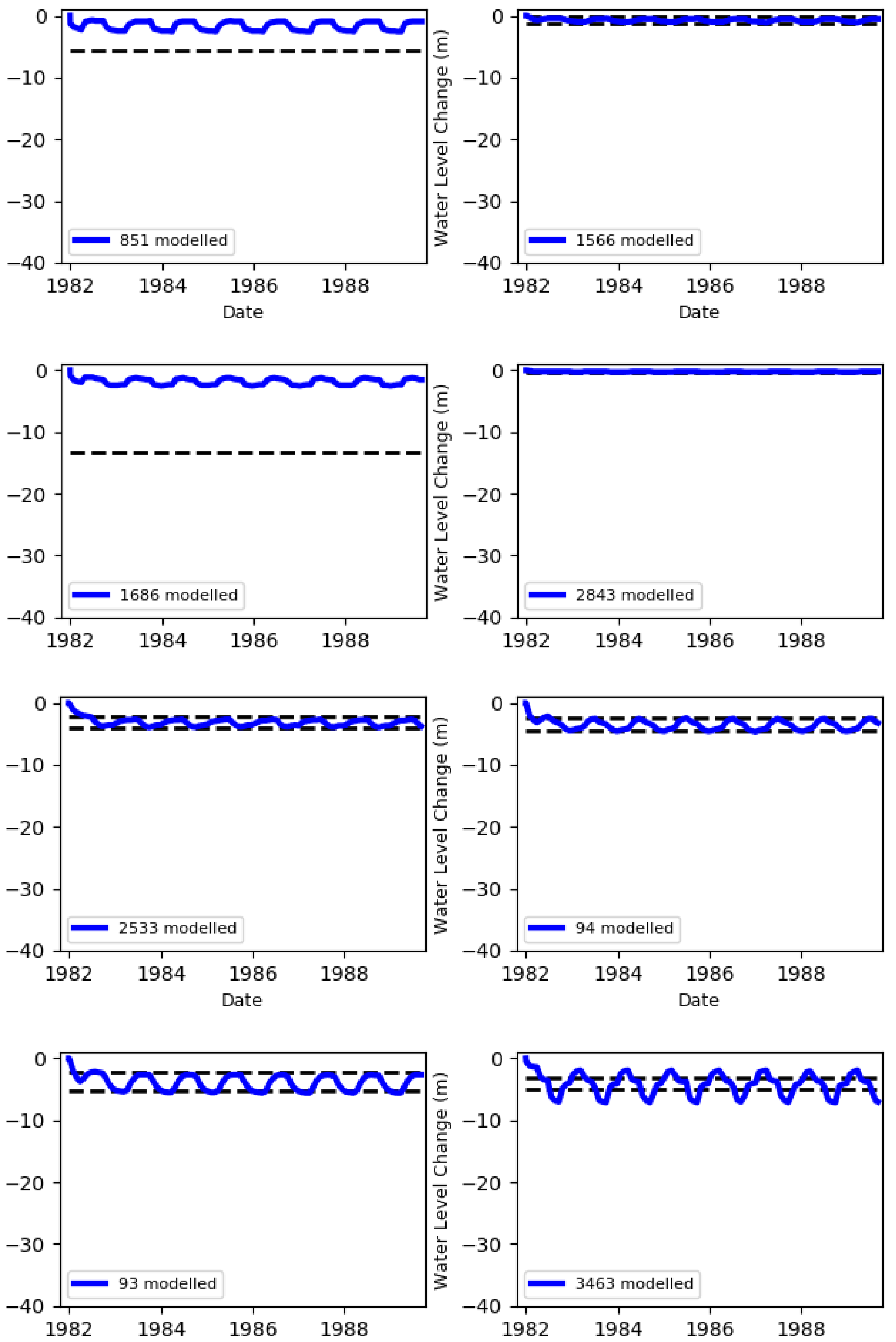

Figure 6.14 Seasonal changes in water level due to estimated seasonal changes in extraction measured in monitor bores (dashed black line) and modelled (blue line) in the west-centre of the study area, in wells 851, 1566, 1686, 2843, 2533, 94, 93, and 3463.

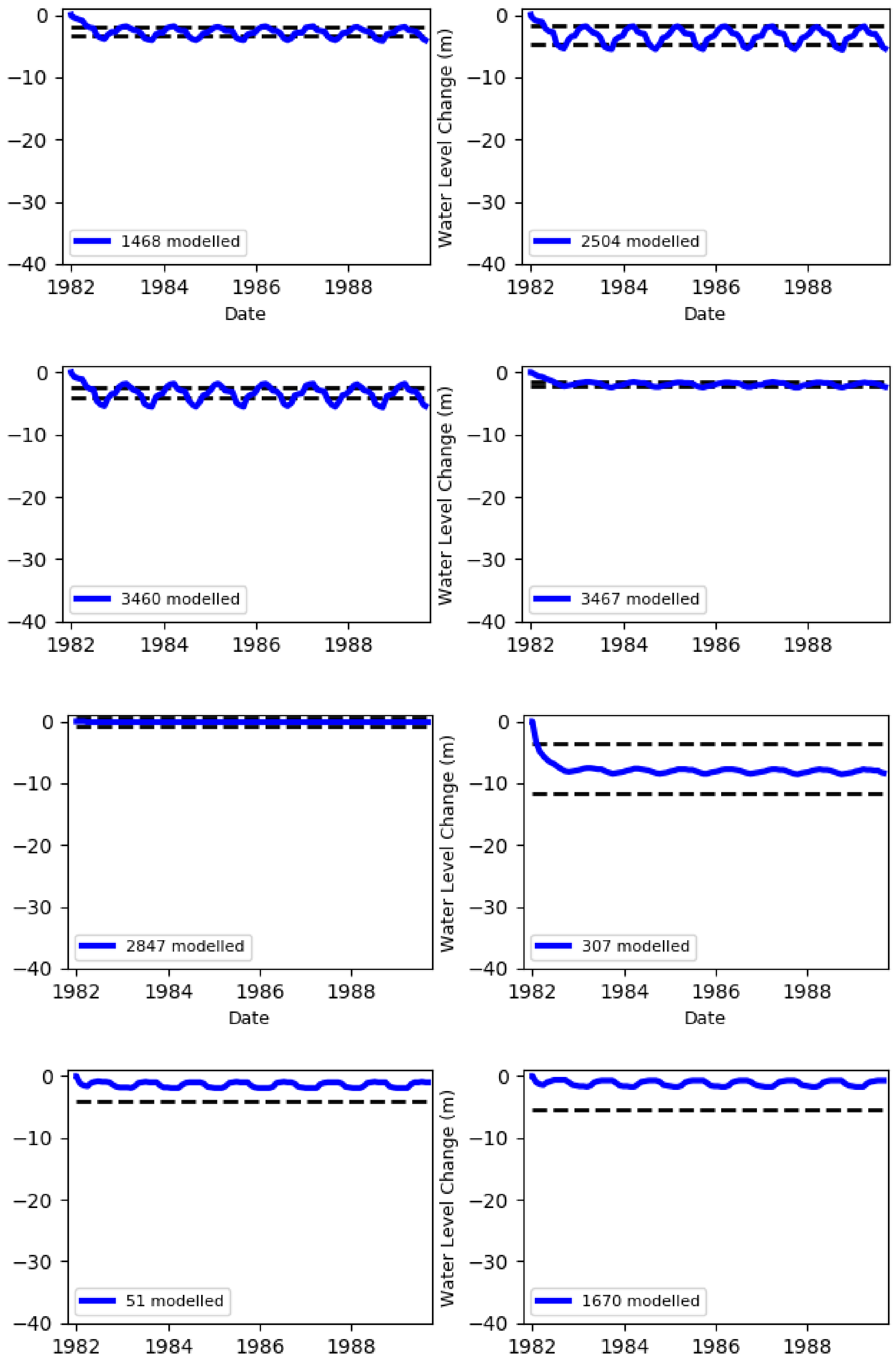

Figure 6.15 Seasonal changes in water level due to estimated seasonal changes in extraction estimated from monitor bores (dashed black line) and modelled (blue line) in the centre of the study area, in wells 1468, 2504, 3460, 3467, 2847, 307, 51, and 1670.

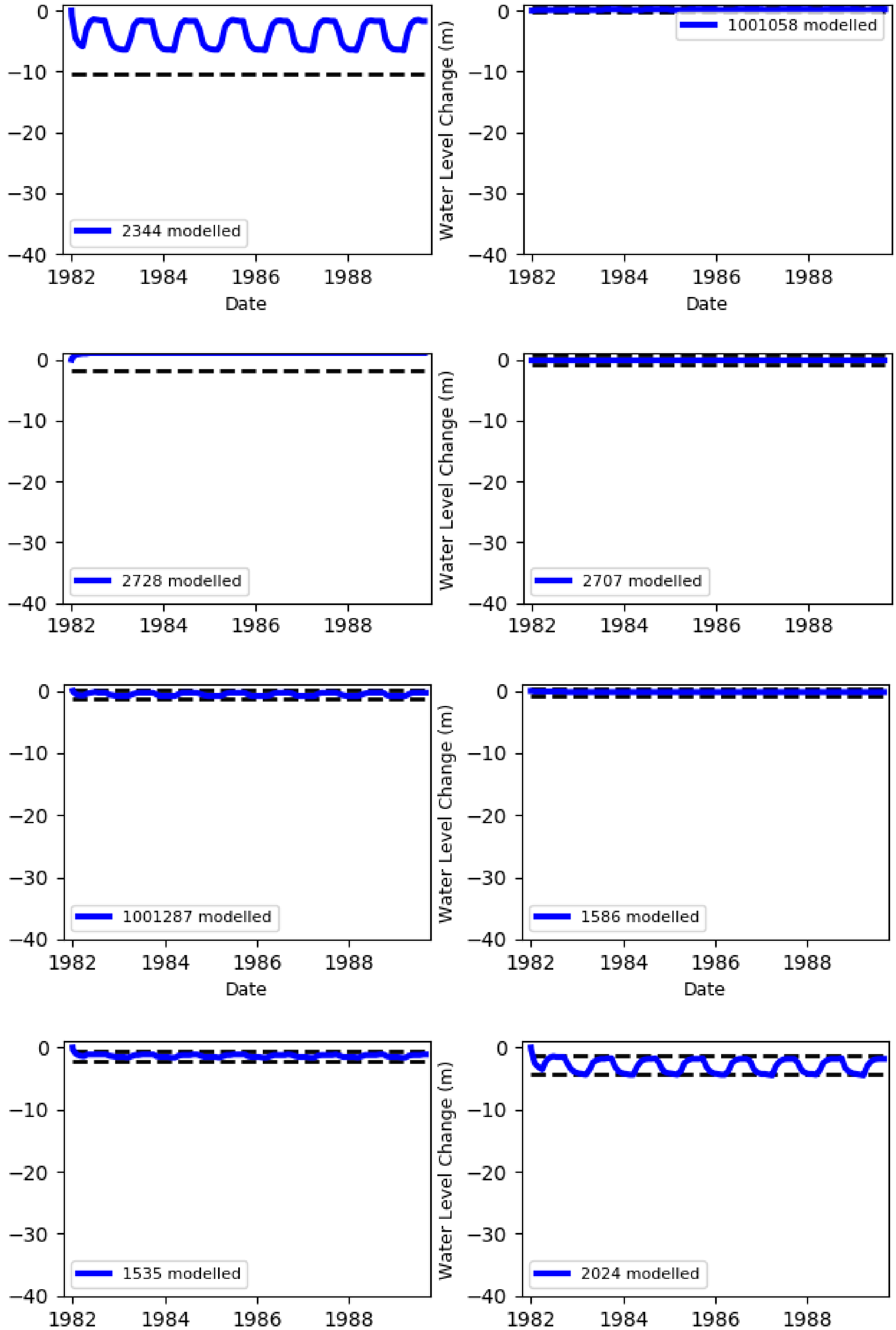

Figure 6.16 Seasonal changes in water level due to estimated seasonal changes in extraction, assessed from monitor bores (dashed black line), and modelled (blue line) in the south of the study area, in wells 2344, 1001058, 2728, 2707, 1001287, 1586, 1535, and 2024.

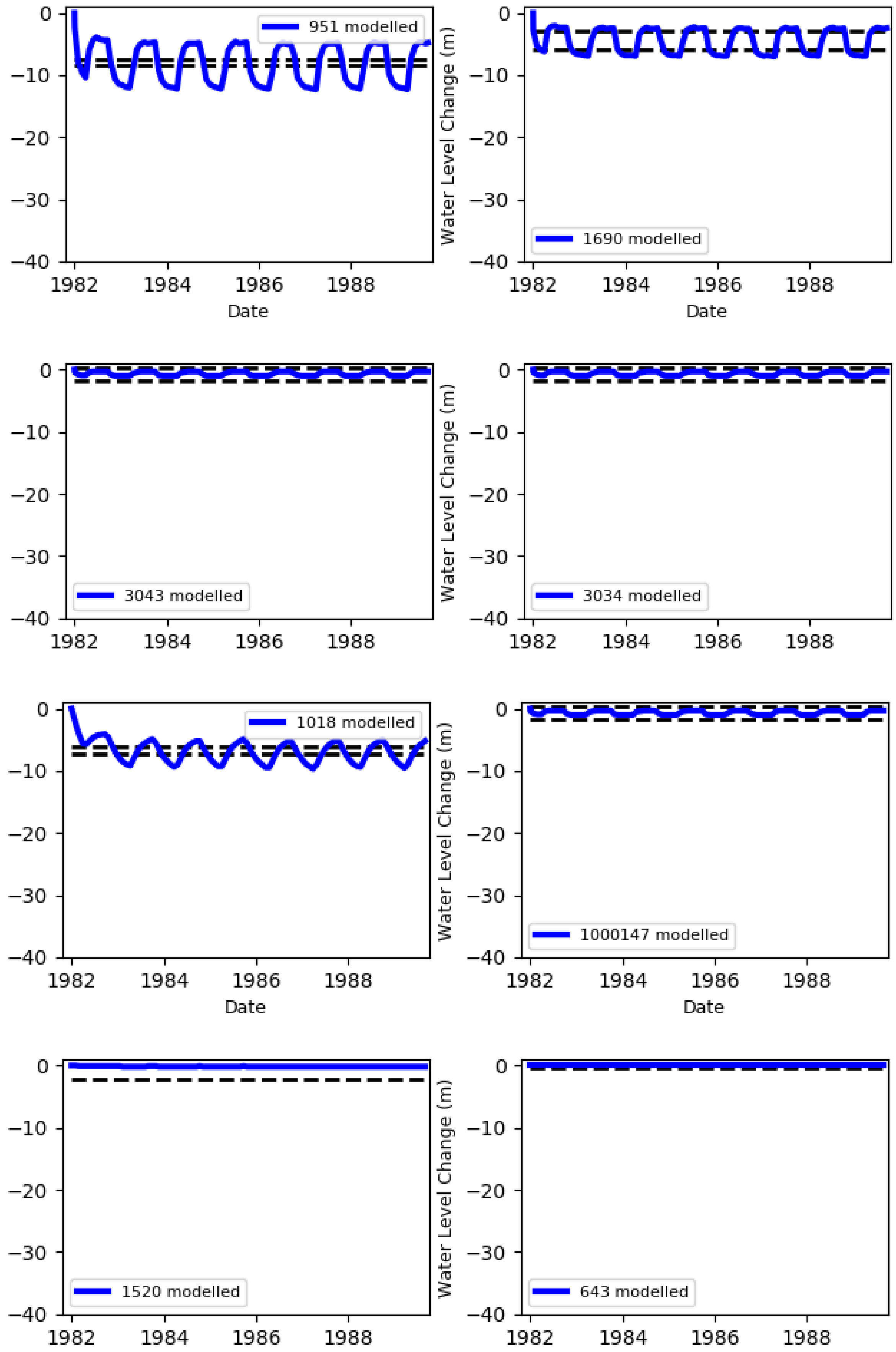

Figure 6.17 Seasonal changes in water level due to estimated seasonal changes in extraction, assessed from monitor bores (dashed black line), and modelled (blue line) in the southeast of the study area, in wells 951, 1690, 3043, 3034, 1018, 1000147, 1520, and 643.

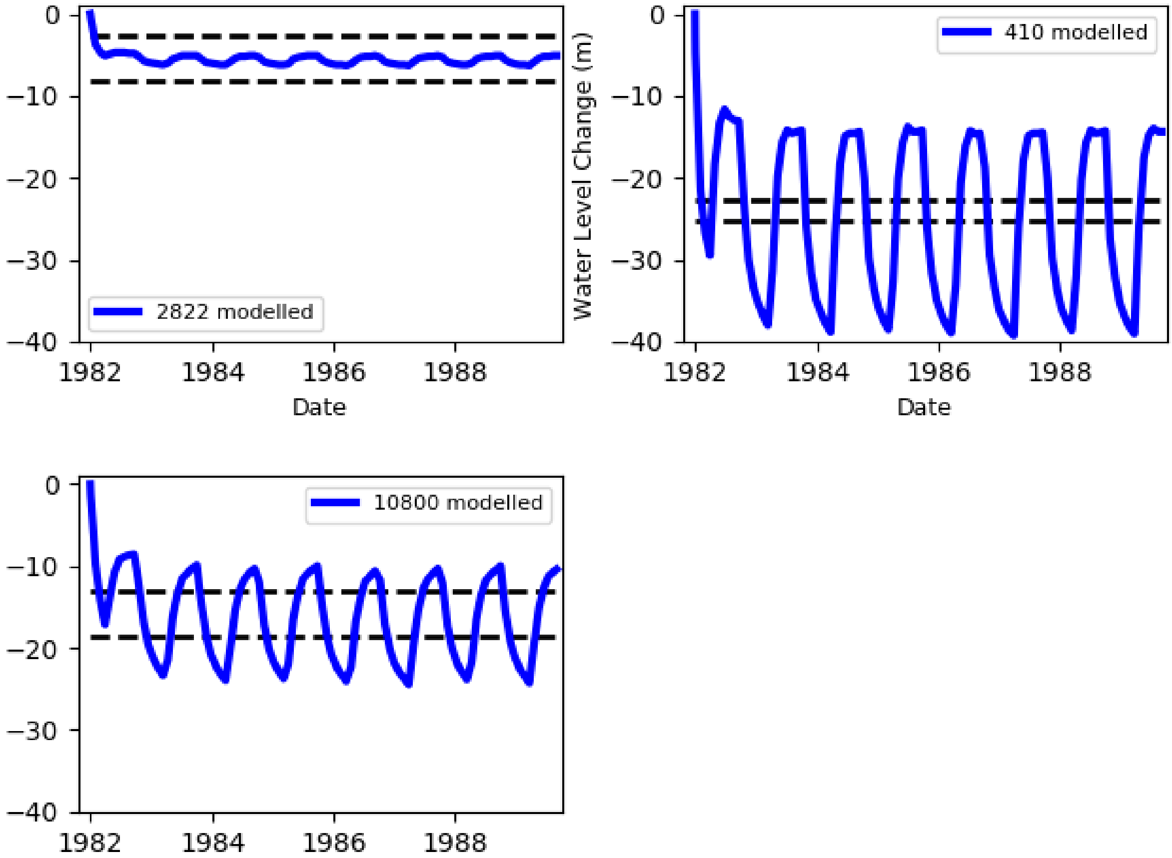

Figure 6.18 Seasonal changes in water level due to estimated seasonal changes in extraction, assessed from monitor bores (dashed black line), and modelled (blue line) in the furthest south of the study area, in wells 2822, 410, and 10800.

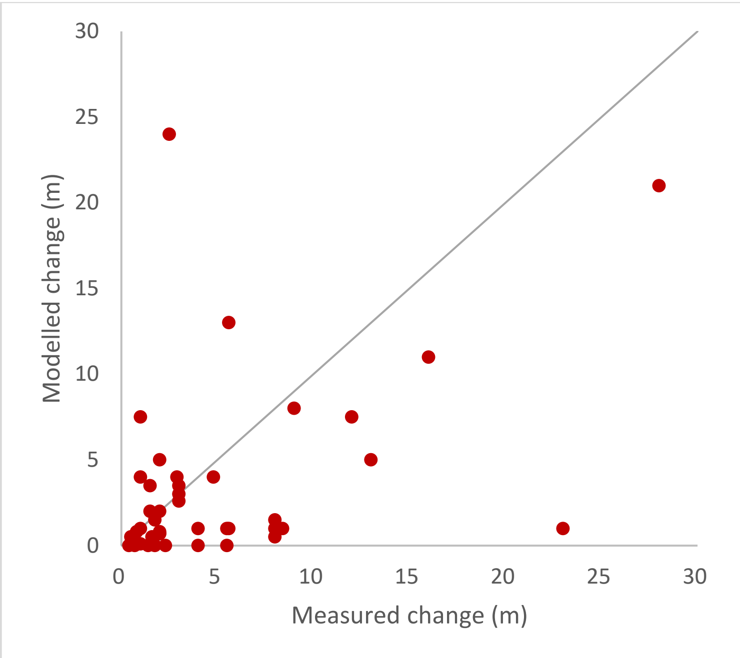

Figure 6.19 Measured and modelled change in water level for each well in response to seasonal variations in extraction rates. Each symbol corresponds to a monitor well.

6.3 Calibrated Rock Properties

The final rock properties, once the model was calibrated for well temperatures and seasonal changes in water level, are in Table 6.1. The 2018 model reproduced both the temperatures and seasonal changes in water level, and did not show the large drawdown levels that model PA2013 suggested.

Table 6.1 Rock properties as determined from model calibration.

Unit	Base Elevation (masl)	Lateral Permeability (m^2)	Vertical Permeability (m^2)	Porosity	Conductivity (W/mK)	Density (kg/m^3)
Tauranga Sediments	-200	2.50E-14	2.50E-15	0.1	1.25	2500
Shallow Volcanics	-300	2.50E-14	2.50E-15	0.4	1.8	1890
Intermediate Volcanics	-600	1.00E-14	1.00E-15	0.4	1.8	1890
Deep Volcanics	-2000	1.00E-16	1.00E-17	0.4	1.8	1890

7.0 MODELLING EFFECTS OF EXTRACTION

The calibrated model was used to assess the possible effects of future extraction from the Tauranga Geothermal Field. There are 631 extraction wells consented within the area, 23 of which also have associated reinjection wells (Figure 4.3). The consent rates are known, but not the current rates that fluid is being extracted.

7.1 Method

To simulate the effects of future extraction, the model was run for 30 years before the present day to reach stable conditions under extraction, and then for 30 years into the future. For the first 30 years, the model simulated extraction at estimated current rates (see Section 5.2). Reinjection was assumed to be at the same rate as extraction, with an enthalpy of 150 KJ/kg. This is equivalent to a water temperature of 35°C, 10°C less than the average of the corresponding extraction wells where temperature has been measured. Average extraction rate over a year was used to prevent computational time from becoming unfeasible.

Two different future scenarios were modelled:

- Estimated use case, where extraction continued at current estimated rates.
- Consented use case, where extraction was simulated at consented rates, which would be the maximum that could be taken from the field (excepting new consents).

Changes in water level and temperature at monitor wells and at extraction wells were taken from the simulation.

7.2 Estimated Use Case

Monitor and extraction wells showed similar responses to fluid extraction at current estimated rates. Four monitor wells showed simulated water level drawdown of more than 10 m (Figure 7.1). Water levels declined for up to five years, but then stabilised. Water temperatures were affected by less than 2°C in all monitor wells (Figure 7.2). Extraction wells typically showed larger modelled decline in water level, of between 0.1 and 25 m. A cluster of four municipal extraction wells (3709, 3715, 3716 and 1000017), all within 200 m of each other to the west of Tauranga City and with relatively large extraction rates, had the largest modelled drawdown of between 85 and 110 m (Figure 7.3). In most wells, the water level stabilised within 10 years, but in the four municipal wells and other large extractors the water level continued to decline slowly for the entire period until 2047 (Figure 7.3). Temperatures in all extraction wells were affected by less than 2°C (Figure 7.4), as they were in the monitor wells.

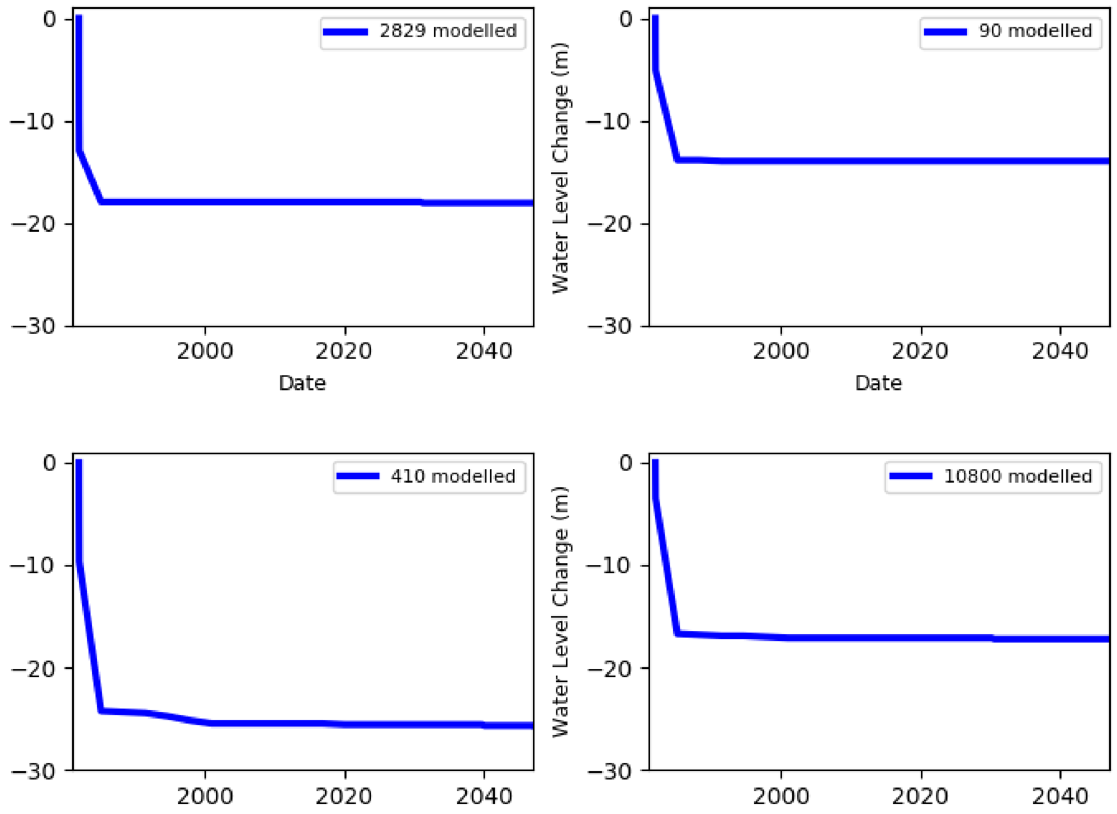

Figure 7.1 Changes in water level due to extraction at the four monitor wells that showed the largest model response. Extraction is at rates that are estimated to be representative of current use in the Tauranga area.

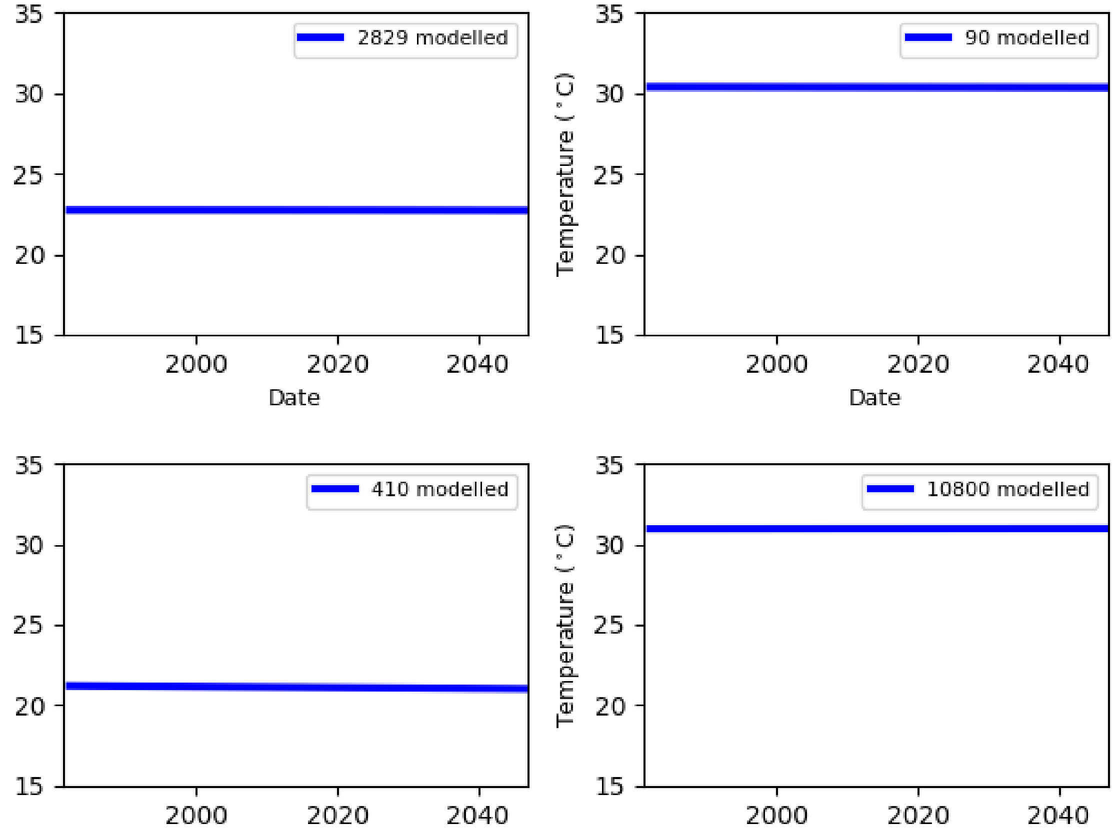

Figure 7.2 Modelled changes in temperature due to extraction at current estimated rates at the four monitor wells that showed the largest model response.

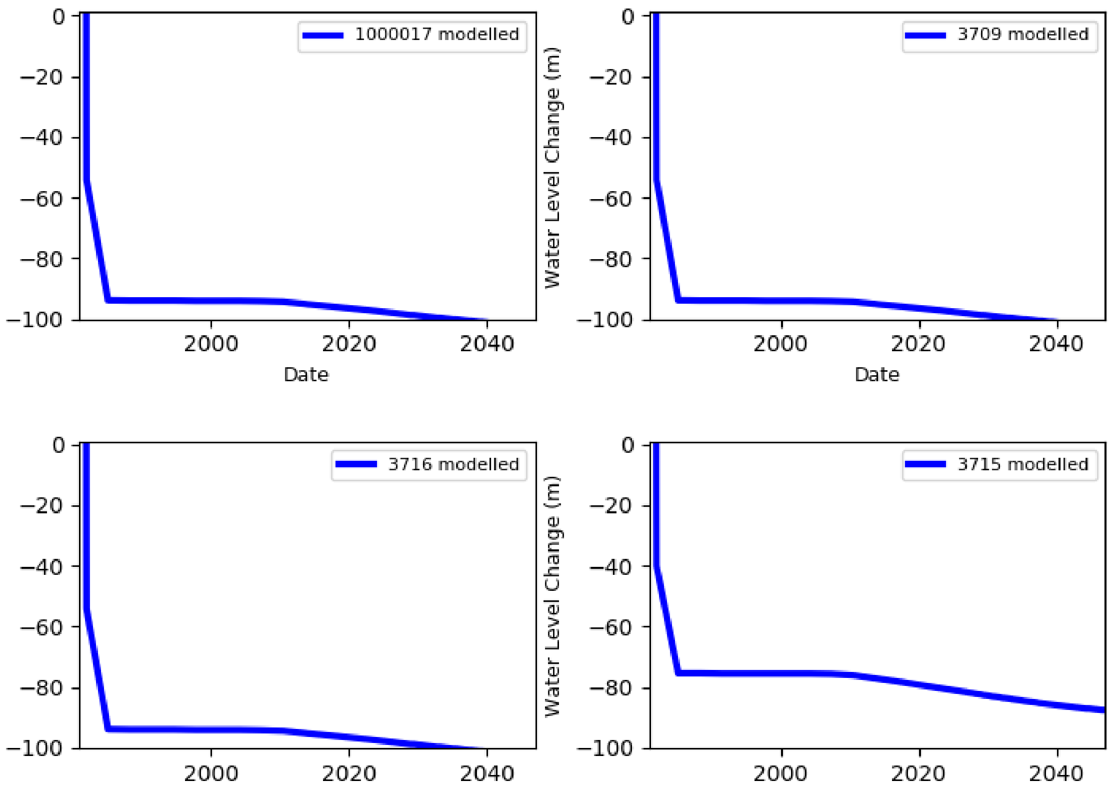

Figure 7.3 Water level decline in the four wells that showed the largest responses to continued extraction at current estimated rates.

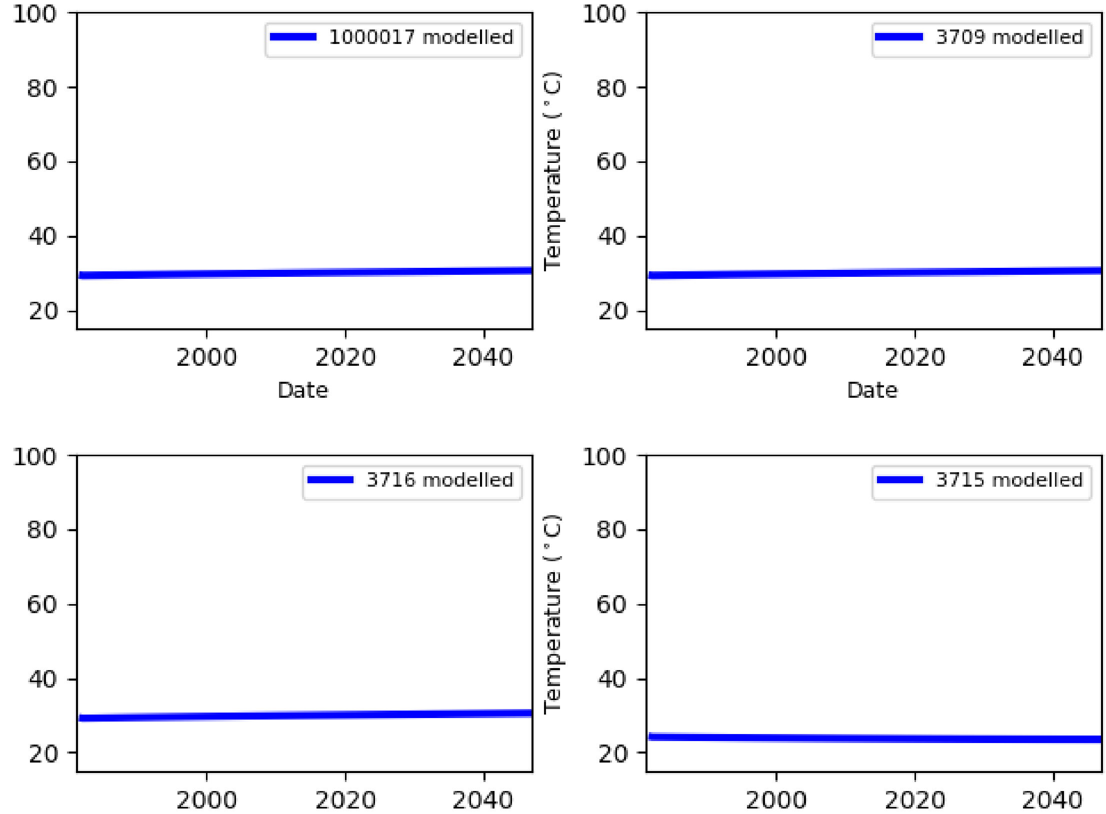

Figure 7.4 Water temperature in the four wells that showed the largest responses to continued extraction at current estimated rates.

7.3 Consented Use Case

Although current estimated extraction rates are less than consented rates, extraction may increase to consented rates in the future. Therefore, the model was run with extraction at consented rates for 30 years into the future to look at the effects of such potential extraction.

During the simulation, if the pressure in a well dropped to less than 0.1 MPa (equivalent to a water level drop to 10 m), that well was assumed to have failed and was turned off. After 20 years wells were still failing due to a lack of water.

In total, extraction at consented rates was not sustainable at 41 wells. Of these, 12 were for municipal use, one was for commercial use, and the other 28 were irrigators. Wells failed across the model area, although over half were found to the southeast, possibly due to the high density of extraction wells in the area (Figure 7.5).

Although water levels dropped to the point that extraction was unsustainable in 41 wells, temperature changes were generally less than 2°C. The largest changes were in municipal wells 10920 and 10921, where the modelled temperatures decreased by 5°C (Figure 7.6). The corresponding changes in water level at these two wells were complex as nearby wells failed; both wells are predicted to fail in 2036.

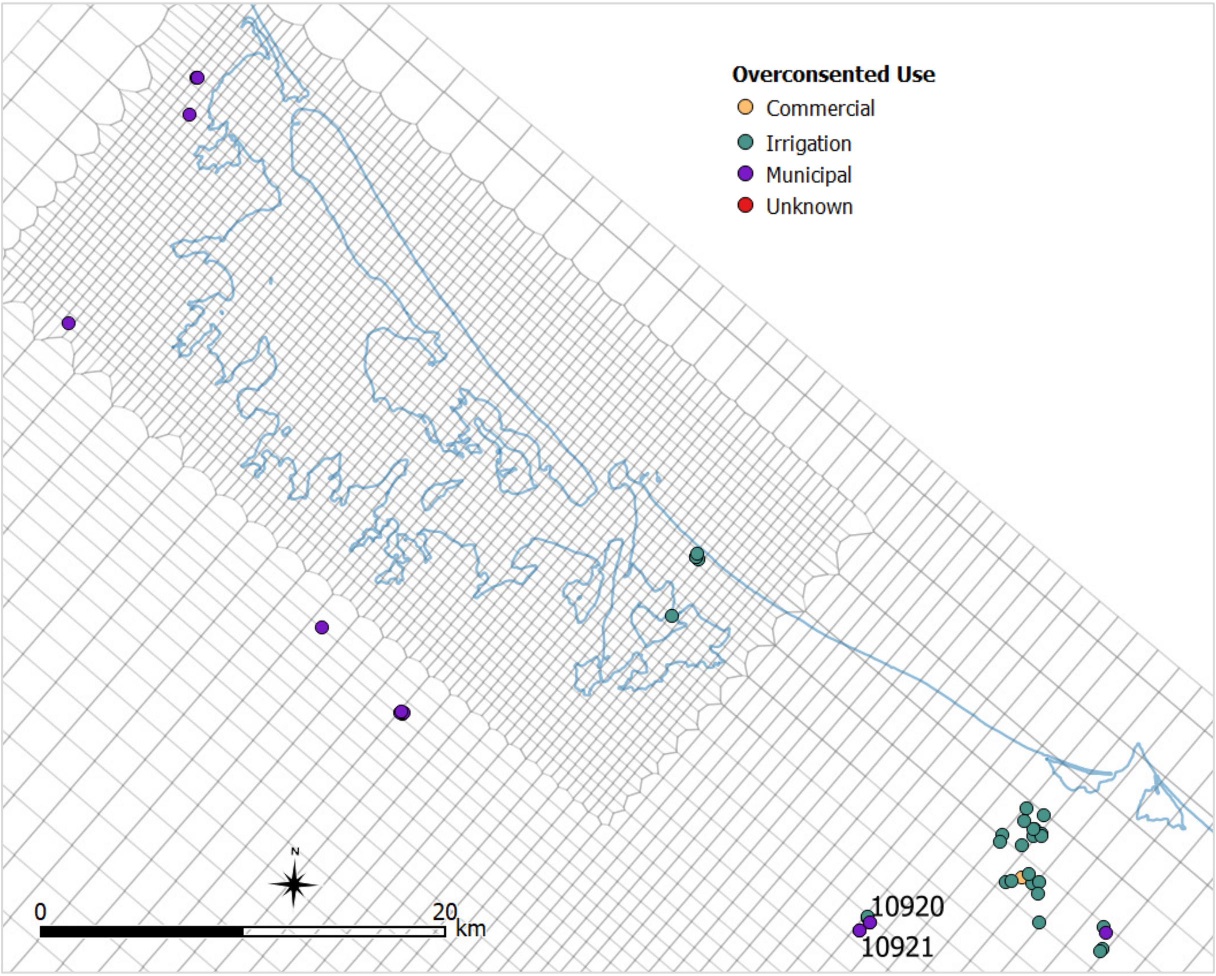

Figure 7.5 Wells where extraction at consented rates caused them to fail. 10920 and 10921 showed the largest decrease in temperature (Figure 7.6).

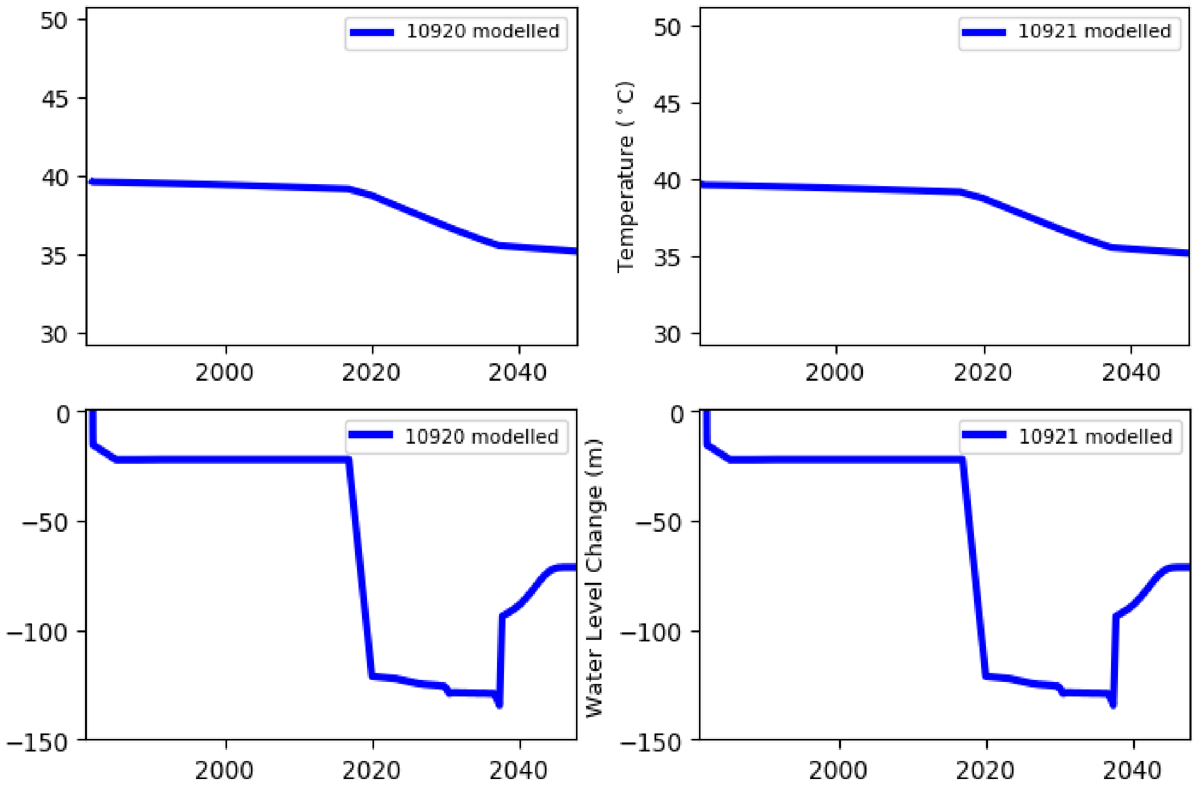

Figure 7.6 Extraction wells that showed the largest decrease in temperature (top), and the corresponding changes in water level (bottom).

8.0 ASSUMPTIONS AND UNCERTAINTIES

As a model is a numerical representation of a complex, real-world system, it requires several assumptions and has some uncertainties associated with it. Additionally, the data available for the Tauranga Geothermal Field could not in general be used directly, and required some assumptions before it could be used in the model.

8.1 Data

It was assumed that the temperature data was accurate, and was representative of reservoir temperatures in the Tauranga area. There were some uncertainties associated with the depth or location of the temperature measurements, but by using the 40 wells that had temperature profiles with depth available, and comparing with spot temperature measurements, any potential errors were minimised. The wells where temperature was measured are distributed across most of the study area (Figure 6.1), with more in areas where there is more extraction, and therefore are assumed to be representative of temperatures in the Tauranga Geothermal Field. Temperature measurements were not all collected at the same time, but as field observations and the modelling suggest that temperatures are fairly stable, it is assumed that this is not a source of uncertainty in the model.

There were some uncertainties associated with the consented fluid extraction data. If there were multiple wells on a consent, it was assumed that the extraction was divided equally between them, which may not be the case or may vary over time. Temporary earthworks were not included in the consent data as it was assumed that over 30 years their effects would be negligible. The bore depth was not known in 66 wells and so was assumed to be the average of the other 565 wells, at 193 m. For future work this would be useful to address as it could affect a well's response to extraction depending on the rock permeability and local recharge.

Reinjection was assumed to be at the same rates as extraction, but the rates may be less. Since reinjection tends to be at shallower depths than extraction, this may have an effect on shallow monitor wells, or the nearby extraction wells. The assumed reinjection enthalpy of 150 kJ/kg is equivalent to a water temperature of 35°C, which may not be realistic and could affect the modelled temperature in the well. As the number of reinjection wells is small, it is considered that these assumptions will have minor overall effect on the viability of the model.

For the metered wells, 31 wells were removed from the dataset because the data was duplicated in eight wells, or covered less than one year. It was assumed that the other metered wells were spatially and temporally representative of seasonal trends and consent-to-extraction ratios. This is obviously a major assumption, but given the data available was the only way to incorporate all of the unmetered extraction wells into the model. Municipal wells are not monitored to the west of Tauranga city (Figure 8.1), but modelling suggests that this is where the largest drawdown occurs.

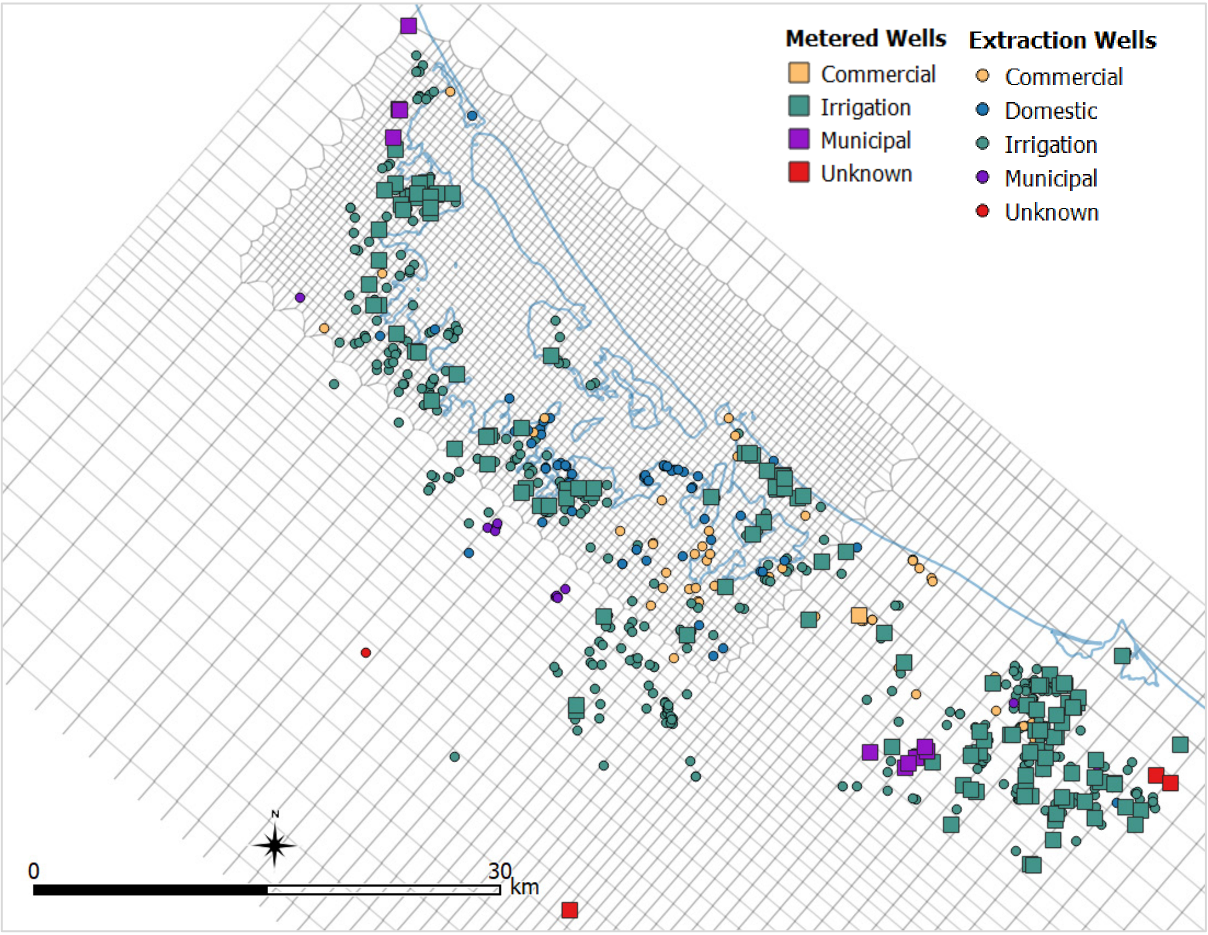

Figure 8.1 Metered wells where extraction rates are recorded (squares) compared to all extraction wells (circles).

8.2 Data Interpretation

The amount of warm water extracted from wells in the Tauranga area is not known, which is a major source of uncertainty. Therefore, it had to be estimated from metered extraction well data for both model calibration and for future scenario modelling. Dividing the extraction types according to likely use patterns (irrigation, municipal, commercial, domestic and unknown) was a way to reduce this uncertainty. However, some potentially quite varied usage patterns fell into the same groupings, for example golf courses and orchards are both counted as irrigation but may have significantly different extraction patterns over the course of a year.

To calibrate the model for permeability, water level data is the most useful to match. However, this data is sparse and is not collected in extraction wells. Monitor wells record changes in water level over time, and we assumed that these changes were primarily due to changes in extraction. We looked at the effects of rainfall but concluded that they would not be enough to cause the repetitive seasonal changes observed in monitor water levels (Section 5.1). However, rainfall or other unidentified factors may have contributed. This means that the seasonal variations in water level due to changes in extraction may have been overestimated. Additionally, there are long-term variations in water levels over years to decades for which our modelling did not account.

The metered data was used to estimate seasonal changes in extraction rate for each of the five usage classes. To do this, the metered data was used in two ways: 1) by comparing metered extraction rates over a year with consented rates to get an annual consent-to-extraction ratio; and 2) to estimate how much extraction rates changed seasonally. It was assumed that the metered data represented all wells of a usage class, which may not be the case. Additionally, some usage classes were not metered and therefore local knowledge was used to assume both seasonal trends and consent-to-extraction ratios. Further, seasonal variations in use will change from year to year but it is unknown by how much. Moving forward these are important gaps in knowledge to address to ensure that the model is as realistic as possible.

To estimate the current use, we took the total metered data and divided by the corresponding consented extraction. Averaging after totalling means that smaller extractors carry lesser weight than larger extractors. This is likely to be more of an issue for some classes of users than others, for example for irrigation use where consented rates varied widely.

Changes in monitor well water levels are a culmination of changes in extraction in all the wells in the surrounding area. They are therefore highly subject to uncertainties in the seasonal estimated extraction rates, particularly if large extractors or a large number of extractors are nearby.

Seasonal monitor well data had significant noise associated with it, and for some wells was intermittent. In some cases, it was monitored manually once every few months, in others it was automatically recorded every second. Therefore, we did not try and match it directly. BOPRC estimated the seasonal variation for each well, and we matched that with the model. In some wells the match was not perfect, which could have been due to issues with the data or model simplifications.

8.3 Model Uncertainties

All models are simplified due to incomplete information and computing limitations. This introduces uncertainties. The calibration process is designed to try and determine the most important parameters that are otherwise unknown. There can be a trade-off calibrating different parameters, for example very similar model results can be found with higher heat flow or higher thermal conductivity. In this model a relatively simple heat flow at depth was simulated, because model PA2013 showed water levels are relatively insensitive. Permeability was the focus of this model calibration although the effects of other parameters were explored.

Assuming four homogeneous rock units, one sedimentary and three volcanic, is a major simplification. The hypothesised buried faulting under Tauranga City (Booden et al. 2012; White et al. 2009) would result in greater permeability that could allow convection. This is supported by slightly non-linear thermal profiles under Tauranga City and Mt Maunganui (e.g. 4538, Figure 6.4; 31, Figure 6.5) and the elevated modelled heat flux in that area (Figure 3.6). The modelled water levels near well 4538 (2843, Figure 6.15) show a good fit to the monitored data suggesting that the permeability is well represented under Mt Maunganui. However, the model overestimates the observed changes in water level near well 2843 (3460, 3467, Figure 6.15) supporting the suggestion that permeability may be slightly greater under Tauranga City.

The model is a refinement over the two rock types in model PA2013. The effects of localised zones of different permeability to the north were explored but they did not improve the fit to the data. Modelling a more complex rock property distribution is not justified with the current dataset, but future work could include collecting more water level and temperature profile data to address this.

Grid resolution can also cause uncertainty. The grid was refined compared to the PA2013 model, particularly in areas with many extraction wells. In addition, further grid refinement was experimented with during the modelling process to see if it changed the fit to the available data. Model grid resolution cannot be made infinitely fine because of both a lack of data and the resulting long computational times.

To address assumptions and uncertainties, we have attempted to build robust simulations by using all information available to estimate extraction rates as realistically as possible, and checked that the resultant model was consistent with all known information (e.g. long-term drawdown, seasonal changes, groundwater models from pump test data, and thermal conductivity and heat flow measurements).

9.0 SUMMARY

We created a model of heat and fluid flow through the Tauranga Geothermal Field. It was calibrated against well temperature profiles and seasonal water level changes measured in monitor wells. The current extraction rates were estimated from metered wells, categorising the wells into extraction types that were thought to have similar characteristics (irrigation, commercial, domestic, municipal and unknown). The ratio of consented extraction to current extraction, and the seasonal variations in current extraction rate, were estimated for each type and then applied to all extraction wells of that type. Using the estimated current extraction rates, the model matched well temperature profiles and seasonal water level variations across most of the geothermal field.

Running this model into the future showed that with estimated current extraction rates, fluid extraction from the Tauranga Geothermal Fields is sustainable for the next 30 years. If extraction rates increase to consented values, 41 wells will fail due to lack of water.

9.1 Recommendations for Future Work

We believe that the model described in this report provides a reasonable representation of the Tauranga Geothermal Field and can therefore be used simulate the effects of future extraction. However, more detailed data would improve the robustness of the simulation. In particular, we would recommend that the following data be collected:

- Depth information for the 66 wells whose depths are currently unknown.
- Use of extracted fluid at the four wells that are currently classified as unknown.
- Measurements of temperature profiles with depth at every opportunity (for example during testing after a well is drilled).
- More regional heat flow data if possible.
- Longer records of extraction rates in metered wells.
- Metering in more wells, particularly those with large consented extraction rates, and those where there is minimal current metered data such as commercial and domestic users.
- Better estimates of how take is divided across multiple wells assigned to the same consent, for example the large municipal extractors.
- Ideally, the last three points could all be addressed by recording extraction rates in all wells in the Tauranga Geothermal Field, including when, where, how much, and for what purpose.

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