# CATCHMENTS OF GROUNDWATER AND GEOTHERMAL SYSTEMS IN THE UPPER WAIKATO AREA, TAUPO VOLCANIC ZONE, NEW ZEALAND

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## ABSTRACT

Groundwater systems are important to the economy and ecology of the approximately 4400 km$^2$ Upper Waikato River (UWR) catchment in the Taupo Volcanic Zone (TVZ), New Zealand. Cold groundwater is an important source of water for irrigation and industry and provides baseflow to rivers. Therefore, the groundwater systems are relevant to recreation and to the generation of a significant portion of New Zealand's hydroelectric power generation. Geothermal reservoirs also provide a significant portion of New Zealand's electrical power and also feed many unique geothermal features in the area.

This paper describes a method to represent and characterise groundwater catchments in the Upper Waikato area, including geothermal systems. This representation was derived using: a 3D geological model of the area including basement, faults, aquifers and aquicludes; prolate spheroids to represent the location and volume of geothermal systems; water budgets (including groundwater flows with estimates of natural outflow from geothermal systems); a piezometric map of the UWR; and catchment boundaries defined by Waikato Regional Council (WRC).

Groundwater catchments included:

- the "shallow" cold groundwater systems that flow to surface water;
- the "deep" geothermal fields, i.e., hot systems that are associated with geothermal fields; and
- the "deep" cold groundwater systems that flow to geothermal fields.

The location and volume of 14 geothermal fields in the UWR catchment were represented with prolate spheroids that intersect the ground surface. Each spheroid intersects the ground surface as an ellipse which represents the outer boundary of geothermal activity associated with each field. Geothermal fields in the UWR catchment are strongly associated with topographic lows suggesting that the piezometric elevation of cold groundwater systems is a factor in the distribution of the fields. For example, one major cluster of five fields (i.e., Reporoa, Waiotapu, Waikiti, Te Kopia and Orakeikorako) is located on the flanks of the Paeroa Range.

The method was demonstrated for the Wairakei geothermal field. The "shallow" cold groundwater catchment of the Wairakei geothermal field extends to the west and includes WRC catchment 3039804. The western area provides an estimated 1.2 m$^3$/s of recharge to the Wairakei geothermal field. This recharge contributes some, possibly all, of the estimated pre-development surface water discharge from the field of 1.2 m$^3$/s, including geothermal fluid, and is consistent with near-isothermal conditions in some deep wells outside the field. Cold groundwater also flows into the Wairakei geothermal field from rainfall recharge within the geographic area of the field as demonstrated by cold water inflows to geysers and springs after development (White and Hunt, 2005). The field is probably bounded to the east by the Waikato River.

Potential applications of the method include groundwater allocation. For example, groundwater allocation by WRC in the western area would be zero if they choose to protect all pre-development surface flows (i.e. cold and hot) from the geothermal field.

## 1. INTRODUCTION

Groundwater recharge in the Taupo Volcanic Zone (TVZ) is important to cold groundwater and to geothermal systems (White et al., 2012). Groundwater is a water source for agriculture, industry and municipal supply in the Upper Waikato River (UWR) catchment. The UWR is an important source of hydroelectric energy for New Zealand with installed capacity of 1084 MW (or approximately 20% of the country's installed hydroelectric power capacity) in eight power stations. Groundwater recharge to geothermal systems provides the key heat input to geothermal fields (Kissling and Weir, 2005). These fields provide significant electrical energy from nine geothermal-electric power stations, with installed capacity of 853 MW, or approximately 97% of the New Zealand's installed geothermal power capacity, located in the UWR. Groundwater recharge also supplies geothermal systems including springs and geysers (White and Hunt, 2005).

Therefore, an understanding of the groundwater circulation system that provides recharge to the fields, and groundwater circulation within the fields themselves, is crucial to the characterisation and modelling of geothermal systems in the Taupo Volcanic Zone. The importance of water flows in heat transport has led to the development of 3D geological models and water budgets of TVZ circulation systems including 'shallow' groundwater, i.e., flow that supports cold springs and seeps, and 'deep' groundwater, i.e., flow that potentially travels to the geothermal systems (White et al., 2012). These models and budgets demonstrated that most water flow is in the shallow system. For example, groundwater recharge is approximately 43% of rainfall in the UWR catchment. Most of this flow travels in the shallow groundwater system, i.e., recharge to the deep system is in the range of 2% to 8% of rainfall in the catchment.

Application of the results in this paper include management of water allocation, e.g., Waikato Regional Council (WRC) aims to maintain inflows (i.e., cold groundwater) to geothermal systems (Waikato Regional Council, 2012). A second application is the estimation of cold groundwater inflows to geothermal systems, which is relevant to models of geothermal system hydraulics.

## 2. METHOD

### 2.1 GEOLOGICAL MODEL OF THE UPPER WAIKATO

The geology of the Upper Waikato area is dominated by Pleistocene TVZ volcanic units, with associated volcanoclastic sediments overlying basement greywacke. Extensive volcanism in the TVZ is divided into three periods (Wilson et al., 1995): old TVZ where the commencement of volcanic activity in the TVZ is indicated by eruptions that formed the Mangakino Caldera, with at least nine eruptions in the interval 1.6 Ma to 0.95 Ma (Wilson et al., 2009); young TVZ in the period between the onset of eruptions from the Whakamaru Caldera (approximately 300 ka) and deposition of Rotoiti Pyroclastics at approximately 61 ka (Wilson et al., 2007, 2009) including formation of calderas including Maroa, Reporoa, Rotorua, and Taupo; and modern TVZ, from 61 ka to the present day, including volcanic activity associated with the Taupo Caldera and the formation of Lake Taupo.

Seventeen hydrogeological units were represented with a 3D geological model including: basement greywacke, ignimbrites (Pakaumanu Group, Whakamaru Group, Kaingaroa Formation and Maroa Group) volcanic cones, volcanic domes, lake sediments, Oruanui Formation, lake sediments and Tauranga Group sediments. In addition, the model represents calderas and includes faults and fault blocks.

### 2.2 GROUNDWATER BUDGETS

A general water budget equation is used to describe the relationships between steady-state water inflow, water outflow and water storage within a defined area of a catchment (Scanlon *et al.,* 2002; Scanlon, 2012):

water inflow = water outflow

i.e., $P + Q_{IN} = ET + Q_{OUT}$

Water inflows include:

P precipitation,

$Q_{IN} = Q^{SW}_{IN} + Q^{GW}_{IN}$

$Q^{SW}_{IN}$ quick flow and base flow

$Q^{GW}_{IN}$ groundwater inflow

Water outflows include:

AET evapotranspiration

$Q_{OUT}$ water flow out from the area including surface flow ($Q^{SW}_{OUT}$) and groundwater ($Q^{GW}_{OUT}$).

Mean annual rainfall (P) was estimated in each catchment (Figure 2) from the nationwide National Institute of Water and Atmospheric Research (NIWA) dataset based on the rainfall measurements at individual climate stations, interpolated throughout New Zealand by NIWA and averaged for the period 1960–2006 (Tait *et al.,* 2006). Mean annual AET was estimated using GIS with a national-scale map developed by NIWA for the period 1960–2006 without specific consideration of land use, land cover, soil type or groundwater recharge (Woods *et al.,* 2006). Areas for water budget calculation include surface catchments relative to the locations of surface flow monitoring sites defined by WRC and parts of these catchments, e.g., the areas of surface geothermal activity (Section 2.5).

The water budgets have used surface water flows and groundwater flows have been assessed with the groundwater budget including gauging measurements, i.e., in the WRC historic gauging data set; White et al., 2015). In addition, flows in geothermal systems were collated from various sources (e.g., Greg, 1958). Groundwater inflows and outflows were calculated by assuming that water budgets balance in each area.

### 2.3 PIEZOMETRIC MAP

Piezometric maps aim to represent static groundwater elevation using multiple information, including measurements of groundwater depth in wells, the relation between groundwater elevation and ground elevation and the elevation of fixed-head cells included lakes and permanently-flowing rivers and streams (White et al., 2015). Piezometric elevations were calculated on a 100 m by 100 m grid and compared with published groundwater level maps (e.g., at Wairakei; Bromley, *et al*. 2000).

### 2.4 GROUNDWATER SYSTEM

Catchments of the shallow systems were primarily defined with surface catchment boundaries, groundwater budgets and a piezometric map of the Upper Waikato with principal aquifers defined by the 3D geological model.

### 2.5 LOCATION AND VOLUME OF GEOTHERMAL SYSTEMS

The extents of 14 geothermal fields in the Upper Waikato area were estimated by geometric volumes, i.e., prolate spheroids truncated by the ground surface. These fields include: Wairakei, Tauhara, Rotokawa, Ohaaki, Ngatamariki, Reporoa, Waiotapu, Waikiti, Te Kopia, Orakeikorako, Mokai, Horohoro, Atiamuri and Mangakino.

Each spheroid intersects the ground surface as an ellipse. The shape and area of these ellipses represent the outer boundary of geothermal activity associated with each field at the ground surface; the base of the spheroid is truncated by the basement.

## 3. RESULTS

### 3.1 GEOLOGICAL MODEL

The elevation of the top surface of the basement model unit (Figure 1) varies considerably in the Upper Waikato model area. Large basement offsets have occurred as the TVZ developed. The basement top surface has been separated into distinct fault blocks. Faults and calderas are key structural elements of the TVZ (Wilson *et al*., 1995; Spinks *et al*., 2005) that are represented in the model. For example, the basement under the central TVZ is as much as 7 km below sea level, approximately 3 km below sea level under the Reporoa Basin and approximately 1 km below sea level at Lake Ohakuri (Leonard *et al*., 2010). Lakes often form in calderas; for example, Lake Huka occupied the Reporoa Caldera, and part of the present Lake Taupo area, before the Oruanui eruption (Manville and Wilson, 2004).

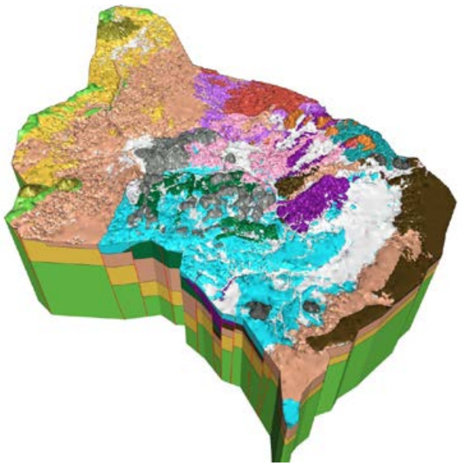

**Figure 1: Three-dimensional geological model of the Upper Waikato area viewed to the north (White et al., 2015).**

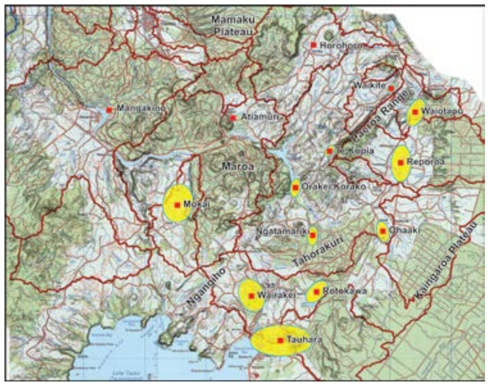


**Figure 2: Location of 14 geothermal fields (red squares), surface extents of thermal features in these fields (yellow elipses) and surface catchments in the Upper Waikato area (red lines; White et al., 2015).**

### 3.1 DISTRIBUTION OF GEOTHERMAL FIELDS

Geothermal fields are strongly associated with topographic lows (Figure 2). Two major clusters of fields are on the flanks of the Paeroa Range (i.e., fields including: Reporoa, Waiotapu, Waikiti, Te Kopia and Orakeikorako and around the topographic high in the Ngangiho-Tahorakuri area (i.e., the Wairakei, Rotokawa, Ohaaki and Ngatamariki fields). Other fields are also associated with topographic lows (Horohoro, Atiamuri and Mangakino). The topographic "setting" of Mokai is similar to Wairakei as both these fields occur on local topographic lows. The Tauhara field extent includes Mt Tauhara as geothermal features occur to the west and east of the mountain.

The orientation of ellipses (i.e., the direction of the long axes) that include surface geothermal features typically show clear preferences. The orientation of the elipses around Paeroa Range is parallel to the strike of the range. Similarly, ellipses for the Rotokawa and Ohaaki fields are orientated orthogonally to the Tahorakuri topographic high. In contrast, the elipses of Wairakei, Orakeikorako and Mokai are orientated orthogonal to the strike of the high ground. However, the orientation of the ellipses somewhat subjective as often few surface features are identified in the fields.

Geothermal fields are strongly associated with grabens, calderas and faults (Figure 3). Most fields are associated with the Reporoa Basin and the Whakamaru Caldera. Fields immediately to the north of the Paeroa Range are associated with the Paeroa Fault.

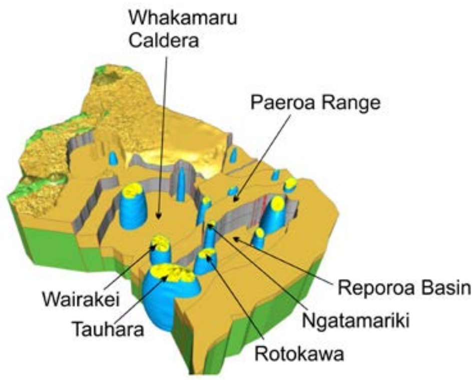


**Figure 3: The vertical distribution of geothermal fields rendered as prolate spheroids (blue) and surface expression (yellow; Figure 2). The spheroids are shown above basement (green) and pre-Whakamaru volcanics (ochre).**

### 3.3 SHALLOW AND DEEP CATCHMENTS – EXAMPLE OF WAIRAKEI

The possible groundwater catchment of the Wairakei geothermal field is within WRC surface catchment 3039804 (Figure 4). This surface catchment also includes two other geothermal fields (i.e., Tauhara and Rotokawa) that are not considered here.

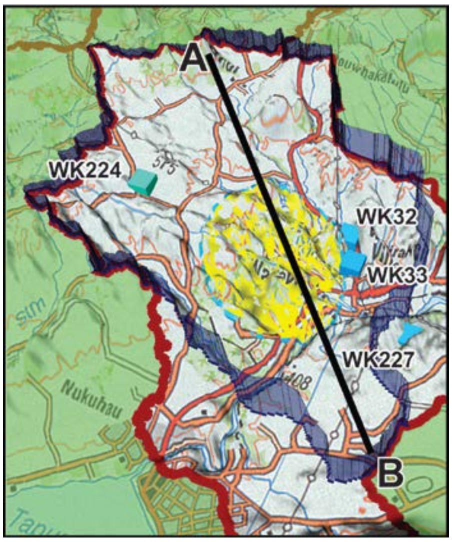


**Figure 4: Possible groundwater catchment (shaded blue) with surface extent of Wairakei geothermal field (yellow), location of WRC catchment boundary (thick red line) and location of wells with consistently low temperatures.**

A water budget separates the Wairakei groundwater catchment into three areas: Wairakei west, the area of cold ground west of the Waikato River; the geothermal field; and Wairakei east (Table 1). This water budget aims to represent flows before development of the geothermal field, i.e., cold and hot water discharge of approximately 1.2 $m^3/s$ measured in 1951 which includes surface water in Wairakei Stream and Kiriohineki Stream in the Wairoa Valley (Greg, 1958). In addition, the use of geothermal fluid was assumed as zero.

**Table 1: Water budget for three areas in the catchment of the Wairakei geothermal field.**

| Geographic area | Inflow ($m^3/s$) | | Outflow ($m^3/s$) | | |
|---|---|---|---|---|---|
| | P | $Q^{GW}_{IN}$ | AET | $Q^{SW}_{OUT}$ | $Q^{GW}_{OUT}$ |
| Wairakei west | 2.8 | 0 | 1.6 | 0 | 1.2* |
| Wairakei geothermal area | 0.6 | 1.2 | 0.4 | 1.2 | 0.2 |
| Wairakei east | 0.4 | 0 | 0.3 | 0 | 0.1 |

*assumed to all flow to the geothermal area.

This is because P – AET is only 0.2 $m^3/s$ in the geothermal area, which is a small proportion of $Q^{SW}_{OUT}$ for the area. In addition, the Wairakei west area probably provides a large portion of geothermal fluid that discharges from the field with surface water (an estimated 0.4 $m^3/s$ in 1951/52; Fisher, 1964) because this flow is also less than P – AET in the geothermal area. Therefore, groundwater recharge in the west follows shallow and deep pathways from the west to the Wairakei geothermal field (Figure 5). The Wairakei west area provides most of the surface water outflow in the geothermal area. Groundwater flows in the west are generally towards the thermal area as shown by the piezometric contours calculated here (Figure 6) and by Bromley et al. (2000).

Vertical groundwater flow is typically downwards in the west which is consistent with temperature logs where near-isothermal, or decreasing, temperatures are observed in wells (Figure 4). For example, temperatures in deep wells drilled by the Ministry of Works outside the field were typically: 11 °C at approximately 70 m and decreasing in the depth range 70 m to 270 m in well WK32 (Studt and Thompson, 1969); less than 30 °C to 430 m in WK33; less than 25 °C to 560 m in WK224; and less than 45 °C to approximately 530 m in WK227.

Within the Wairakei field, groundwater flow can be vertically upwards and downwards (Figure 5 and Figure 6). Vertically-upwards flows are indicated the presence of geysers before development (White and Hunt, 2005). Downwards flows in the geographic area of the field that are sourced from rainfall recharge to groundwater are indicated by cold water inflows to geysers and springs after development (White and Hunt, 2005). The geothermal field is bounded to the east by the Waikato River and “hot seepages” were observed on the left bank of the river by Fisher (1964) which is consistent with a low rate of outflow estimated by the water budget.

A low rate of cold groundwater outflow is also calculated for the Wairakei east area. Therefore, this area has a low potential to contribute cold groundwater flow to the Wairakei geothermal field. This area may be outside the Wairakei geothermal field as the shallow Oruanui Formation aquifer is possibly pinched out by the relatively low-permeability Huka Falls at the Waikato River and all cold groundwater recharge from the area may discharge to the Waikato River.

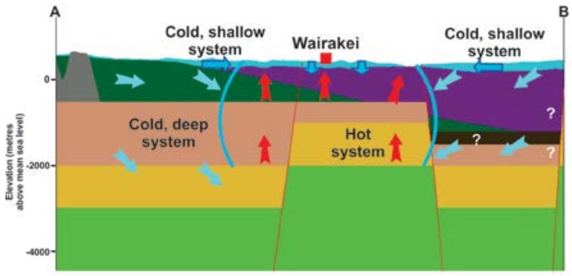


**Figure 5: Cross section A – B showing schematic of cold flow (blue arrows) and hot flow (red arrows) with geological model units including basement (green) pre-Whakamaru volcanics (ochre) and Whakamaru Group (pink); and shallow units (see Figure 7). The location of the section is shown in Figure 4.**

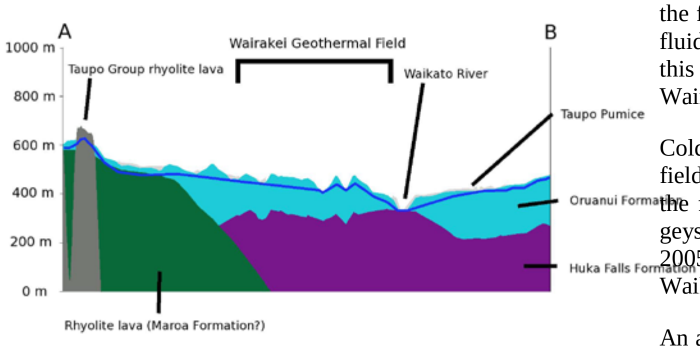


**Figure 6: Cross section A – B with shallow geology and piezometric surface (dark blue line).). The location of the section is shown in Figure 4.**

The estimate of groundwater outflow from the western area and geothermal fluid outflow to the surface from the geothermal field (1.2 $m^3/s$ and 0.4 $m^3/s$, respectively) possibly provide a guideline for groundwater allocation in the western area. For example, WRC may only aim to preserve cold, deep inflows to the geothermal system, in which case the groundwater allocation limit could be 0.8 $m^3/s$ (i.e., 1.2 - 0.4 $m^3/s$) in the western area. Alternatively, WRC may aim to preserve all surface water outflows from the geothermal field, in which case the groundwater allocation limit could be 0 $m^3/s$ in the western area. Typically, WRC aims to preserve a portion of surface low flow through minimum flows (e.g., Waikato Regional Council, 2012). For example, groundwater allocation could be 0.08 $m^3/s$ in the western area should WRC set minimum flow at 10% of the cold water flow from the geothermal field (i.e., 10 % of 1.2 - 0.4 $m^3/s$).

## 5. CONCLUSIONS

Geothermal fields in the Upper Waikato River (UWR) catchment are strongly associated with topographic lows and with structural features (i.e., grabens, calders and faults). This occurrence of fields in topographic lows shows that the groundwater catchments of geothermal systems generally include higher ground in the catchment. Therefore, an understanding of the groundwater circulation system that provides recharge to the fields, and groundwater circulation within the fields themselves, is relevant to the characterisation and modelling of geothermal systems in the Taupo Volcanic Zone (TVZ).

This paper developed a method to assess the size and characteristics of cold groundwater catchments of geothermal systems in the TVZ. This method, which included a 3D geological model of the UWR with a piezometric map and water budgets, was demonstrated with the example of the Wairakei geothermal field.

The cold groundwater catchment of the Wairakei geothermal field extends to the west and includes Waikato Regional Council catchment 3039804. The western area provides an estimated 1.2 $m^3/s$ of recharge to the area of the Wairakei geothermal field. This recharge contributes to the estimated pre-development surface water discharge from the field of 1.2 $m^3/s$ which includes 0.4 $m^3/s$ of geothermal fluid. The western area also provides some, possibly all, of this geothermal fluid because groundwater recharge on the Wairaki geothermal field is less than this discharge.

Cold groundwater also flows into the Wairakei geothermal field from rainfall recharge within the geographic area of the field. This was demonstrated by cold water inflows to geysers and springs after development (White and Hunt, 2005). The field is probably bounded to the east by the Waikato River.

An area to the east of the river was considered for inclusion within the Wairakei geothermal field catchment. However, most cold groundwater flow east of the river is probably in the shallow Oruanui Formation which probably discharges to surface water through the right bank of the Waikato River.

Potential applications of the method were summarised with the example of the Wairakei geothermal field. For example, the estimate of groundwater outflow from the western area and geothermal fluid outflow to the surface from the geothermal field (i.e., pre-development flows of 1.2 $m^3/s$ and 0.4 $m^3/s$, respectively) possibly provide a guideline for groundwater allocation in the western area. For example, groundwater allocation could be 0.08 $m^3/s$ in the western area should Waikato Regional Council set minimum flow at 10% of the cold water flow from the geothermal field.

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