GROUNDWATER CIRCULATION SYSTEMS OF HIGH-TEMPERATURE GEOTHERMAL FIELDS IN THE UPPER WAIKATO CATCHMENT, TAUPO VOLCANIC ZONE, NEW ZEALAND

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ABSTRACT

Groundwater circulation systems provide recharge to high-temperature geothermal fields in the Upper Waikato catchment, Taupo Volcanic Zone (TVZ), and are integral to surface hydrology as they provide baseflow to the Waikato River and its tributaries from springs (hot and cold) and seeps. This paper calculated some characteristics (i.e., catchment location and water budget) of groundwater circulation systems associated with 14 geothermal fields in the Upper Waikato catchment.

These characteristics were identified with: a three-dimensional geological model that included 17 hydrogeological units (e.g., basement greywacke, major ignimbrite groups, volcanic cones and domes, lake sediments and faults); a piezometric map that represented static groundwater elevation; and groundwater budgets that identified major flows, e.g., rainfall recharge and groundwater outflows that were associated with the catchments of geothermal fields.

The groundwater catchments showed where the geothermal fields were linked geographically, and probably hydraulically. Two types of links were identified: inflows to some geothermal fields that may share a common 'deep' groundwater source, e.g., the major cluster of fields located on the flanks of the Paeroa Range (i.e., Reporoa, Waiotapu, Waikiti, Te Kopia and Orakei Korako); and where groundwater catchments may be linked by outflows (e.g., the Tauhara and Wairakei fields).

Together, the characteristics of the groundwater catchments indicated some factors controlling geothermal field location. Therefore, this paper has identified groundwater hydrology as a valuable tool for the investigation of geothermal fields at local, and regional, scales.

1. INTRODUCTION

Groundwater circulation systems provide recharge to 14 high-temperature geothermal fields in the Upper Waikato catchment (White et al., 2015), Figure 1. These systems are also crucial to surface water flows that are dominated by baseflow which is provided by many cold springs and seeps. The extent of groundwater catchments, and water budget (including hot - and cold- water components) was demonstrated for the Wairakei geothermal field; Figure 2 and Figure 3. The catchment area of this field was shown to provide sufficient groundwater recharge to supply surface water flows (hot and cold) in the pre-development field.

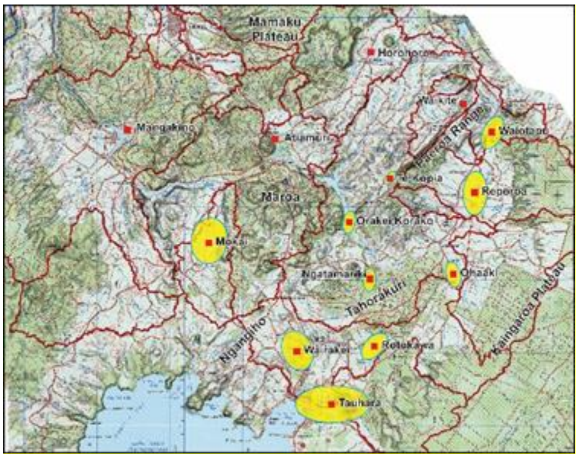

Figure 1: The Upper Waikato catchment with: location of 14 high-temperature geothermal fields (red squares); area of surface geothermal activity associated with high-temperature geothermal fields (yellow ellipses); and sub-catchments (red lines), White et al. (2015).

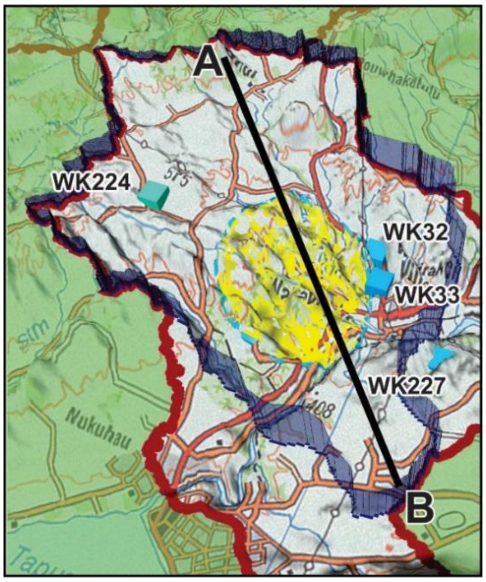

Figure 2: Wairakei geothermal field groundwater catchment boundary (shaded blue) and surface extent of the field (yellow) with location of wells outside the field that have consistently low temperatures (White et al., 2015).

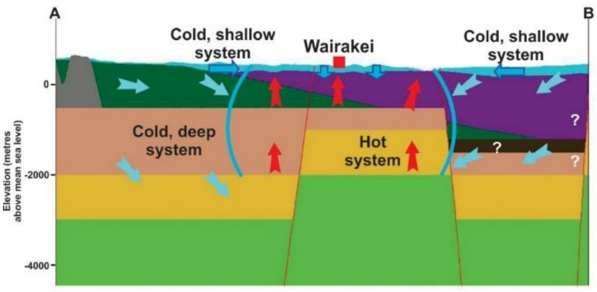

Figure 3: Section A – B of the Wairakei geothermal field groundwater catchment (Figure 2) showing: schematic of cold flow (blue arrows) and hot flow (red arrows); and geological model units including basement (green), pre-Whakamaru volcanics (ochre), Whakamaru Group (pink) and shallow units (White et al., 2015).

This paper maps groundwater catchments of high-temperature geothermal fields in the Upper Waikato catchment, and assesses water budgets of these catchments using a similar approach to White et al. (2015). The paper also discusses controls on the location and formation of geothermal fields, hydraulic links between geothermal fields and the potential implications of these results for high-temperature geothermal systems.

2. METHOD

The method to identify the groundwater catchments of geothermal fields follows White et al. (2015). A general water budget equation was used to describe the relationships between steady-state water inflow and water outflow within the catchment, to the nearest 0.1 m3/s:

$P + Q_{IN} = AET + Q_{OUT}$, where:

P precipitation

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

Q^{SW}_{IN} surface water inflow, including quick flow and baseflow,

Q^{GW}_{IN} groundwater inflow

AET evapotranspiration

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

Q^{SW}_{OUT} surface water outflow

Q^{GW}_{OUT} groundwater outflow.

In addition, GRR (groundwater recharge from rainfall) is approximated as P – AET. In this paper, the water budgets include hot and cold water flow (i.e., deep recharge and shallow recharge, respectively) within catchments, unlike White et al. (2015).

P was estimated from the nationwide National Institute of Water and Atmospheric Research (NIWA) dataset based on the rainfall measurements at individual climate stations and averaged for the period 1960–2006 (derived from Tait et al., 2006). Mean annual AET was estimated 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 (derived from Woods et al., 2006). Surface flows were derived from historic gauging measurements made by Waikato Regional Council (Jenkins, 2015). Groundwater inflows and outflows were calculated by assuming that water budgets balance in each area. Eight catchments have a discharge boundary on the Waikato River. However, Waikato River flows are not included in the water budgets because these flows are not measured at catchment boundaries.

Areas for water budget calculation include surface catchments relative to the locations of surface geothermal activity associated with the high-temperature geothermal fields (Figure 1). These fields include: Wairakei, Tauhara, Rotokawa, Ohaaki, Ngatamariki, Reporoa, Waiotapu, Waikiti, Te Kopia, Orakei Korako, Mokai, Horohoro, Atiamuri and Mangakino. The extents of these fields in three dimensions were estimated by geometric volumes, i.e., prolate spheroids truncated by the ground surface (White et al., 2015). Each spheroid intersects the ground surface as an ellipse. The shape and area of these boundary ellipses represent the perimeter of geothermal activity associated with each field; the base of the spheroid was truncated by the basement. Groundwater catchments of the geothermal systems were primarily characterised with surface catchment boundaries, groundwater budgets, the 3D geological model and a piezometric map of the Upper Waikato area. Geological characterisation of the catchments is not reported in this abstract.

3. RESULTS

The locations of high-temperature fields and the groundwater catchments of these fields show some relation to deep geological structure (Figure 4 and Figure 5). High-temperature fields are commonly associated with caldera, i.e., Reporoa, Atiamuri, Mangakino, Mokai, Orakei Korako, Rotokawa, Wairakei and Tauhara. Fault blocks are also relevant to the location of high-temperature fields. Six groundwater catchments (i.e., Reporoa, Waiotapu, Waikiti, Te Kopia, Ngatamariki and Orakei Korako) are geographically associated with the Paeroa Range fault block and three groundwater catchments (i.e., Ngatamariki, Rotokawa and Wairakei) are associated with a Whakamaru Caldera fault block which is the south-western extension of the Paeroa Range fault block (Figure 5).

The distribution of high-temperature fields, and their groundwater catchments, are also influenced by groundwater flow. The long axes of the boundary ellipses are mostly aligned in the direction of groundwater flow identified in the piezometric map suggesting that groundwater flow, at depth, broadly reflects general piezometric gradients. Most ellipses are located at, or near, local topographic lows where groundwater is likely to be flowing to the surface. The general shape of the boundary ellipses may also be explained by sub-horizontal piezometric gradients that separate surface expressions of an up-gradient 'source' and a down-gradient 'sink'. However, groundwater flows may be close to vertically-upwards where the boundary ellipses are near-circular (e.g., Horohoro, Ngatamariki and Mangakino) because the source is vertically below the sink.

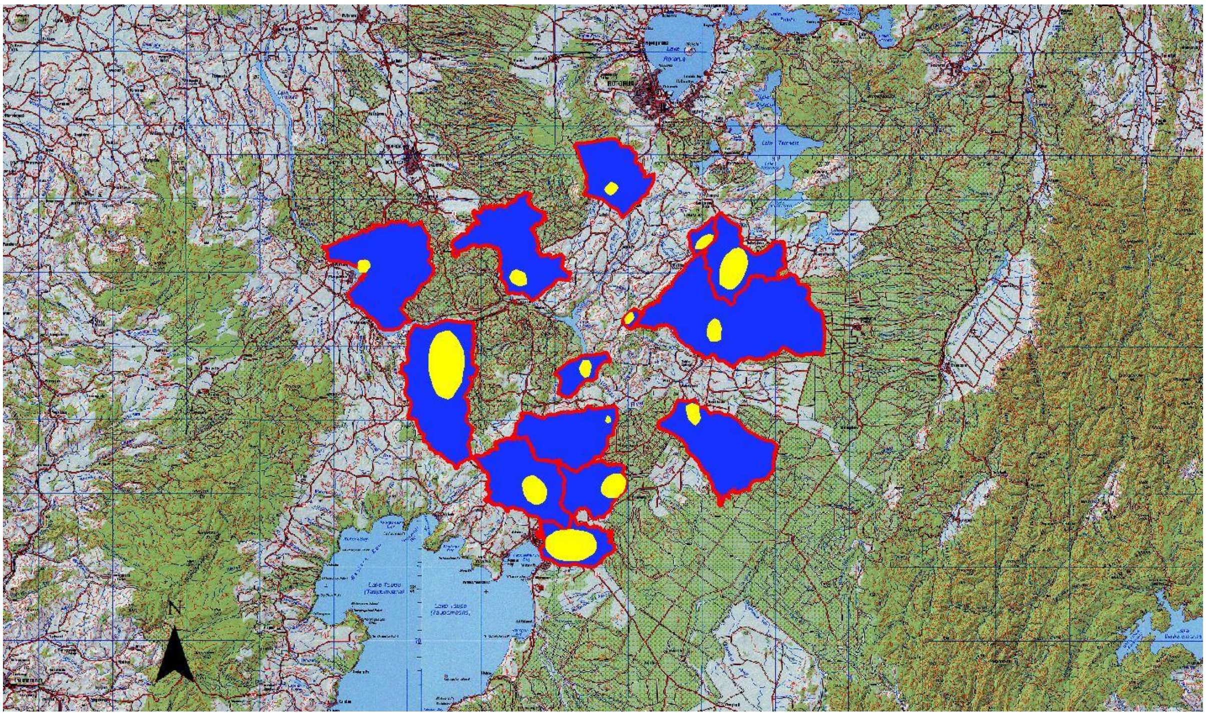

Figure 4: Groundwater catchments of 14 high-temperature fields in the Upper Waikato catchment (blue) and the boundaries of surface geothermal activity associated with these fields (yellow ellipses).

The grouping of fields on the flanks of the Paeroa Range suggests that relatively high GRR in the area (White et al., 2012) is important for local heat transport. In addition, the grouping of groundwater catchments suggests that some high-temperature fields may have a common source because the groundwater catchments are linked on inflows. Some groundwater catchments are possibly linked by outflow, e.g., Wairakei and Tauhara may share a common outflow boundary.

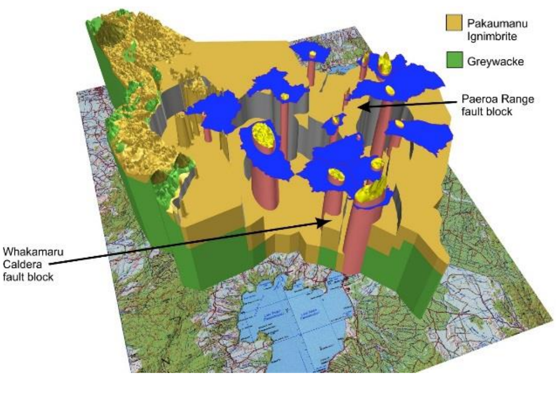

Figure 5: Groundwater catchments, three-dimensional spheroids that represent the high-temperature fields at depth and basement units in the 3D geological model.

Commonly, most inflow leaves the groundwater catchment via surface water. For example, surface water discharge is 100% of inflows to four Paeroa Range fault block catchments (i.e., Reporoa, Waiotapu, Waikiti and Te Kopia). Groundwater outflow from the catchment occurs where Q^{SW}_{OUT} is a small proportion of inflow, e.g., Q^{GW}_{OUT} is 0.6 m^3/s from the Orakei Korako field because Q^{SW}_{OUT} is zero; hot water probably dominates this outflow as demonstrated by geothermal features on the banks of the Waikato River. Outflows from the Atiamuri catchment are generally unknown because a surface inflow discharges into a hydropower reservoir within the catchment.

Table 1. Water budgets of groundwater catchments associated with high-temperature geothermal fields.

Geothermal field	Groundwater catchment surface area (km^2)	Inflow (m^3/s)			Outflow (m^3/s)		
		P	Q^{SW}_{IN}	Q^{GW}_{IN}	AET	Q^{SW}_{OUT}	Q^{GW}_{OUT}
Mangakino	128	6.2	0	0	3.1	3	0.1
Mokai	146	6.9	0	0	3.4	1.8	1.7
Atiamuri	104	4.9	2.6	0	2.5	?	?
Horohoro	68	3.5	0	0	1.6	1.2	0.7
Orekai Korako	23	1.2	0	0	0.6	0	0.6
Ngatamariki	81	4.3	0	0	2.1	0.9	1.3
Waikite	11	0.5	0	0.1	0.3	0.3	0
Te Kopia	4	0.2	0	0	0.1	0.1	0
Waiotapu	68	3.1	0	0.4	1.7	1.8	0
Reporoa	197	8.4	1.8	0.3	4.9	5.6	0
Ohaaki	112	4.3	0	0	2.7	1.5	0.1
Rotokawa	51	2	0	0	1.3	0.1	0.6
Wairakei[1]	94	3.8	0	0	2.3	1.2	0.3
Tauhara	48	1.9	0	0	1.2	0.3	0.4

[1] White et al. (2015).

4. DISCUSSION

Several implications result from the calculation of groundwater catchments and water budgets in the Upper Waikato area. These include: the location and evolution of geothermal fields; the hydraulic links between geothermal systems; the hydraulic links between fields and surface features (i.e., hot and cold springs); and geothermal field management.

Hydrogeology is an important control on the location of geothermal fields, in addition to geology. Clearly, at the scale of the TVZ, heat and geology are key factors in determining the presence of volcanism and geothermal activity. However, at the sub-catchment scale, the presence of groundwater is an essential factor in heat transport. Groundwater is supplied by rainfall, and so variations in rainfall (partly controlled by topographic elevation) and groundwater flow (largely determined by the hydrogeological properties of formations) probably influence the distribution of geothermal fields. This was demonstrated by the large number of geothermal fields that surround two fault bocks (i.e., the Paeroa Range fault block and the Whakamaru Caldera fault block). The importance of hydrogeology was also demonstrated by the location of bounding ellipses representing the surface features of fields. These ellipses were predominantly located at, or near, local topographic lows, where groundwater is likely to be flowing to the surface. By implication, hydrogeological controls are probably important to the evolution of geothermal fields. Natural evolution of fields may be associated with variations in the water budget because heat transport may vary with GRR. Therefore, assessments of GRR over time (e.g., the influence of climate and elevation) and formation permeability are relevant to the calculation of pre-historic heat flows.

The location of groundwater catchments and bounding ellipses suggested that geothermal fields may be linked in two ways. Firstly, fields associated with the Paeroa Range may be linked at source, meaning that a topographic driving head supplies groundwater recharge to a common reservoir and then moves heated groundwater towards the thermal features. This explanation provides a unified model to explain the distribution of geothermal fields around the Paeroa Range because it integrates cause (i.e., the driving head and heat source) with effect (i.e., the geothermal fields). Other explanations for the distribution of these fields (e.g., localised zones of high groundwater pressure) require more complex explanations of the origins of the driving pressure associated with geothermal fields. In addition, the bounding ellipses (i.e., the orientation of the major axes and the up-gradient location of the source) is also consistent with the unified model. Future work in the vicinity of the Paeroa Range will explore groundwater catchments and hydraulic pressures including development of the model in three dimensions.

Secondly, fields are possibly linked by outflow. Here, relatively shallow groundwater, possibly including geothermal fluid, may travel between groundwater catchments. For example, groundwater may travel between the Tauhara and Wairakei fields or may meet at the boundary (i.e., the Waikato River) of the two systems. These circumstances provide possible explanations of surface resistivity measurements which demonstrate that the two field are linked across the boundary (Hunt and Graham, 2009).

Hydrogeological assessments associated with the cold groundwater system are also useful for the management of geothermal fields. For example, tools (e.g., catchment boundaries, water budgets, piezometric maps, 3D geological models and aquifer hydraulic properties) could be used to characterise the effects of geothermal fluid withdrawal such as the ingress of cold groundwater and the local reduction in high temperature outflows that was observed in the Wairakei field (White and Hunt, 2005). These tools would also be useful for the assessment of the effects of fluid withdrawal at sub-catchment, and larger, scales.

5. CONCLUSIONS

Groundwater circulation systems provide recharge to high-temperature geothermal fields and to spring-fed streams in the Upper Waikato catchment. Maps of the groundwater catchments of geothermal fields and water budgets of these catchments indicated that groundwater flow and deep geological structure are important controls on the location of the fields.

For example, the Paeroa Range fault block, and the groundwater circulation system that flows from the Range, are relevant to the location of adjacent geothermal fields (i.e., Reporoa, Waiotapu, Waikiti, Te Kopia, Ngatamariki and Orakei Korako). These fields may be linked at source, meaning that the circulation system (which includes rainfall recharge on the Paeroa Range, a topographic driving head that supplies groundwater to a common reservoir and then causes the movement of heated groundwater towards surface geothermal features) provided a unified model to explain the distribution of geothermal fields around the Paeroa Range.

The importance of hydrogeology was also demonstrated by the location of bounding ellipses representing the surface features of fields. The long axes of these ellipses were mostly aligned in the direction of groundwater flow identified in the piezometric map, i.e., groundwater flow, at depth, broadly reflects general groundwater gradients. The orientation of the long axes generally indicated up-gradient sources for geothermal fluid with down-gradient discharge at surface geothermal features

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