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Computer Modelling of the Chemistry of the Rotorua Geothermal System

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ABSTRACT

The Rotorua Geothermal System is located in the southern margin of Rotorua caldera in the Taupo Volcanic Zone, New Zealand. The system has a hot temperature aquifer (220°C) at very shallow depth (50 – 300m). In 1986, a wellbore closure program was deployed due to a pressure decline caused by a large increase in production from the 1950's onwards. According to monitoring reports the activity of some geysers and geothermal hot springs has recently been rejuvenated.

A new computational model of Rotorua Geothermal System is presented which includes chloride and carbon dioxide. The simulator used is the EWSG version of AUTOUGH2, the University of Auckland's extended version of TOUGH2. The permeability structure and mass and heat inflows used are adopted from the latest computer model of the Rotorua Geothermal System developed at the University of Auckland, named UOA model III (Ratouis *et al.*, 2014). Adjustments of the deep inflows of chloride and CO_2 are made to calibrate the model against the available chloride data, CO_2 emission data, and the location of natural geothermal features.

1. Introduction

Rotorua Geothermal System (RGS) is located within the Taupo Volcanic Zone (TVZ) which is formed by subduction, with the Australian Plate overlying the Pacific Plate (Wood, 1992). The tectonic setting of the TVZ, results in the occurrence of many geothermal systems within the region. The RGS underlies much of Rotorua city, which is located in the southern margin of Rotorua caldera. The caldera is a nearly-circular which is formed during the eruption of Mamaku ignimbrite (225 ka) and covers 20-21 km^2 (Milner *et al*., 2003).

As Rotorua hosts abundant natural geothermal features, it is a well-known tourist attraction, particularly as the site of one of New Zealand's few remaining geysers, namely Pohutu geyser. Geothermal surface manifestations in the RGS are concentrated in four main regions: Kuirau Park, Ngapuna, Government gardens and Whakarewarewa. Based on resistivity data, the RGS covers 18-28 km^2 and extends at least 2 km northward from the city, under the Lake Rotorua (Bibby et al., 1992).

The exploitation of the RGS was started in 1920, and from 1950s to 1986 there was a large increase in terms of exploitation as shown by the number of wells drilled and the mass withdrawn (Scott and Cody, 2000). During that time it was possible to take fluid from the aquifer for private use, with no control on the amount of fluid being taken and no requirement to reinject the waste geothermal water. By the 1980s, this increase in use was believed to have caused a pressure drop and a consequent decline in the activity of natural features.

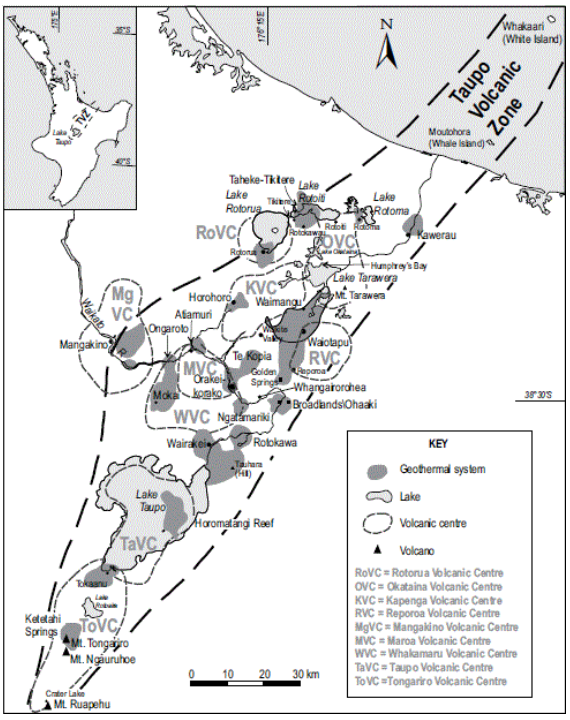


Figure 1: Location of Rotorua caldera within Taupo volcanic zone (from Cody, 2007)

In order to maintain the reservoir pressure, the Bay of Plenty Regional Council (BoPRC) introduced a bore closure program in 1986, requiring all wells within a 1.5 km radius of Pohutu Geyser and all the wells owned by the Government to be closed. In addition, the BoPRC also encouraged the use of reinjection wells instead of the discharge of waste fluid to the surface or to shallow holes. Recent monitoring studies have shown that the pressure has recovered and has been increasing over the years.

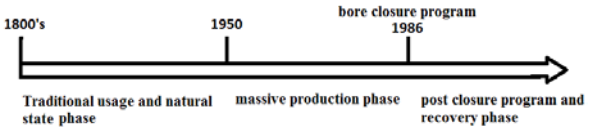


Figure 2: Fluid extraction time line in the RGS

The hydrology of the Rotorua geothermal system is mainly controlled by three geological features. First the Mamaku ignimbrite forms an aquifer extending from the south to the east, with a rhyolite dome overlying it in the west. Then there is a sedimentary basin sequence which lies at the base of the Mamaku ignimbrite and the rhyolite dome and provides a lower permeability aquifer (Wood, 1992). The ignimbrite and rhyolite are characterized with high permeability and porosity. Finally, a number of faults which control the vertical permeability have been proposed. Some of them are the Ngapuna fault which provides permeability in the east, the Rotoatamaheke fault in the south, close to Whakarewarewa region, the Kuirau Fault in the west, and the Inner Caldera Boundary Fault (ICBF) (Wood, 1992).

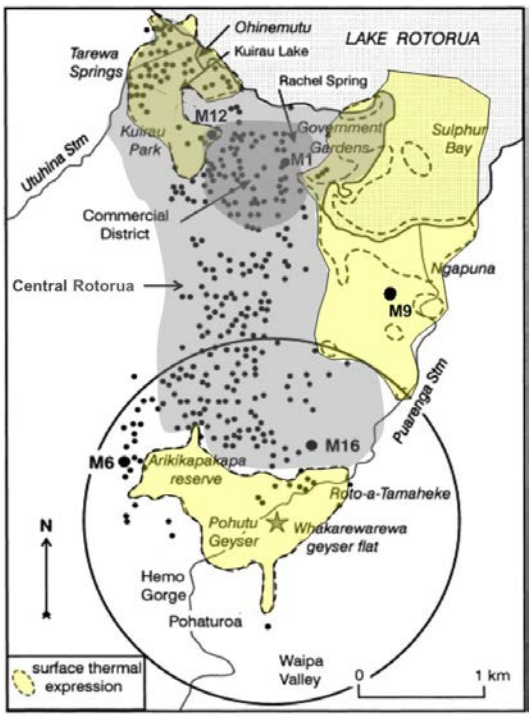


Figure 3: Surface features and geothermal wells in the RGS (from Scott and Cody, 2000)

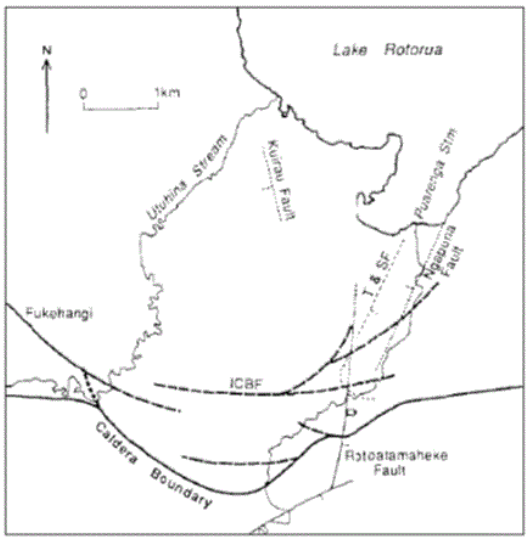


Figure 4: Inferred faults in the RGS (from Wood, 1992)

The model in this paper aims to match distribution of the chloride and CO_2 mass flow through the surface of the RGS associated with the hydrology of the system and is calibrated against measured chloride and CO_2 field data. UOA model III (Ratouis *et al*., 2014) which assumes a pure water system is used as the basis for the current model.

2. Geochemistry Studies

Several chemical surveys had been conducted to infer field hydrology and to provide a general guide for determining fluid flow paths within the RGS. Using chemical measurements for water and gas in the RGS, Giggenbach and Glover (1992) inferred that there are two main upflow zones within the field. The main upflow zone is located in the eastern part of the field where high chloride waters were measured. The second upflow, which is characterized by high bicarbonate-chloride water, occurs in the north-western part of the system.

By contrast, Stewart *et al*. (1992) suggested that three upflows can be identified based on tritium and sulphate measurements. The main upflow which is located in the east has similar chemical characteristic to the alkali chloride water discharged from many other geothermal system in New Zealand. The secondary upflow which feeds the southeast of the RGS is characterized by dilute alkali chloride with some bicarbonate. This water escapes near the Whakarewarewa and Arikipakapa zone. The other upflow, supplying the rhyolite dome in the west, has a high chloride and high bicarbonate content and is affected by rock-fluid interaction.

Chemical measurements were also conducted by Stewart *et al.,* (1992) in 69 wells within the RGS. Even though the feed zone elevations of eastern and western wells are different, the chloride content shows clearly different concentrations of chloride. The high concentration of chloride (more than 1300 mg/kg) is mostly located in the east, with lower concentrations (450 mg/km) of chloride in the west (with high bicarbonate content).

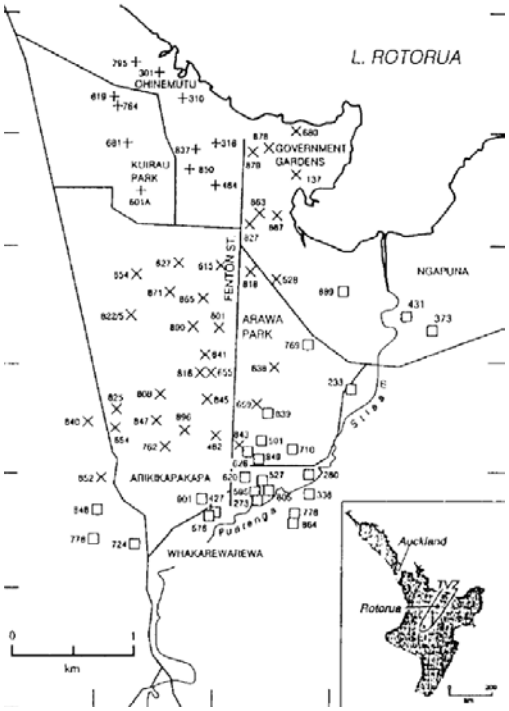


Figure 5: Location of sampling sites (from Stewart *et al*., 1992)

A recent study (Werner and Cardellini, 2006) proposed that the highest concentration of chloride occurs at the east (Ngapuna) where the highest temperature exists. The chloride concentration in this region is 800mg/kg. They assume that chloride distribution in the RGS follows the temperature contours

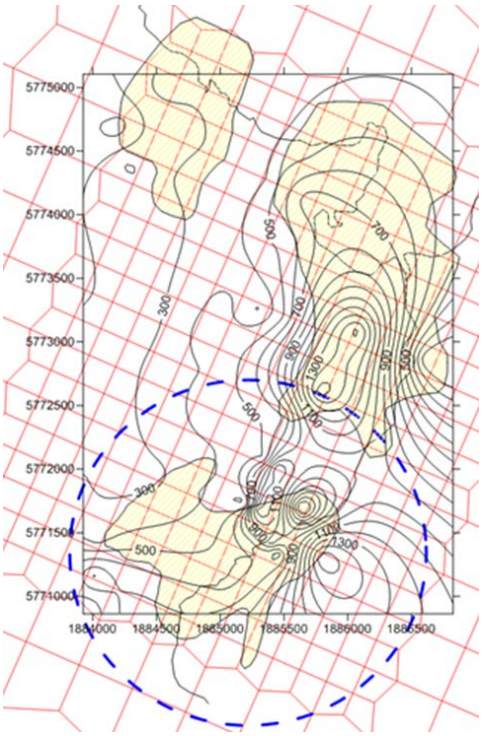


Figure 6: Chloride contour in the RGS (from Stewart *et al.*, 1992)

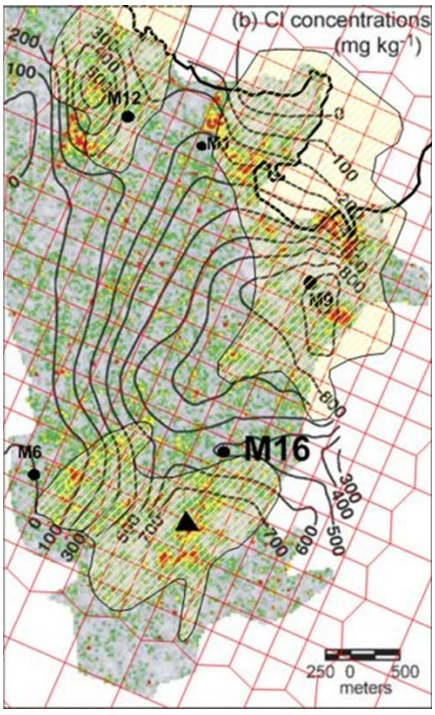


Figure 7: Chloride contours model (from Werner and Cardellini, 2006)

CO_2 flux measurement at 952 locations were conducted and analysed using the sequential Gaussian simulation algorithm (sGs) by Werner and Cardellini (2005). Measurement spacing varied between 25-50 m and they were concentrated in Kuirau Park, Ngapuna, Government garden, Arikipapa golf course and Whakarewarewa.

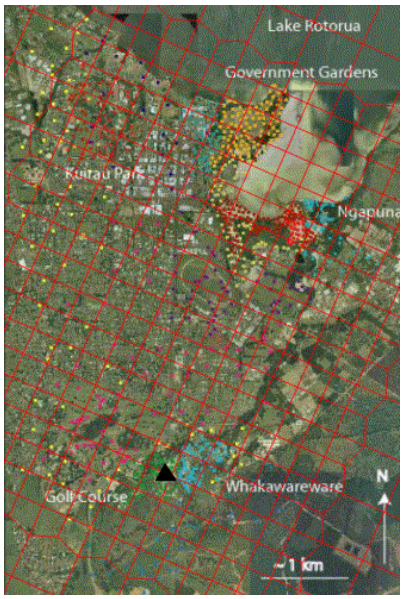


Figure 8: Location of CO_2 Flux measurements across Rotorua city (from Werner and Cardellini, 2005)

The CO_2 flux measured ranged from not detectable to 11535(g/day)/m^2. The CO_2 fluxes across the study area are spatially variable, but higher within known thermal areas, especially in the Ngapuna area (Werner and Cardellini, 2005). This finding confirms the general flow pattern of the RGS and is consistent with the level of fluxes in other volcanic and geothermal area. The following table is a list of maximum CO_2 flux in the previously defined thermal areas.

Area	CO2 Flux (g/day.m^2)
Ngapuna	11535
Government Garden	350
Kuirau Park	2094
Whakarewarewa	2835
Arikipapa Golf Course	2618

Table 1: Maximum CO_2 flux measurement within the four thermal areas at Rotorua

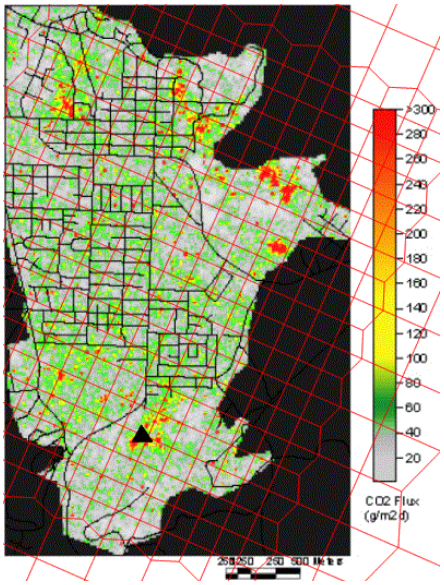


Figure 9: CO_2 Flux measurements across Rotorua city (from Werner and Cardellini, 2005)

3. Conceptual Model

Various important data (lithology, temperature, pressure, fluid chemistry, CO_2 emission) for the geothermal wells and surface features were gathered prior to bore closure program as part of Rotorua Geothermal Monitoring Programme. Those data provide valuable information at the shallow zone of the system because most data were taken at 300m and above. These informations are used to describe the conceptual model of the system:

- The feedzones of production wells are located in the Rhyolite dome aquifer and Mamaku ignimbrite aquifer:
  - Near boiling , medium chloride (~400 ppm) and bicarbonate in the Rhyolite formation which consist of pumiceous, brecciated with high permeability (Wood, 1992).
  - Boiling, high enthalpy, and high chloride fluid (~100ppm) in the ignimbrite formation with high permeability (Finlayson, 1992; Stewart et al., 1992; Werner & Cardellini, 2006; Wood, 1992).
- Well/spring chemistry and CO_2 measurements delineated three major upflows: along Pueranga stream (Ngapuna), Kuirau Park, and Whakarewarewa which are correlated to faults across the RGS (Stewart *et al.*, 1992),(Werner and Cardellini, 2006), (Finlayson, 1992).
- Rotorua sediment sequence act as an aquitard which overlays both the rhyolite and ignimbrite formations.

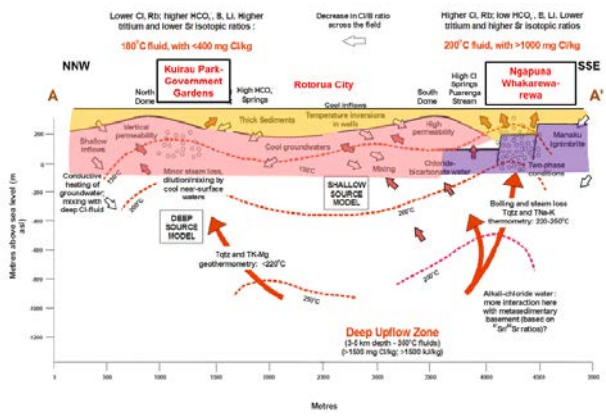


Figure 10: Cross section (NW-SE) of the RGS conceptual model (from Gordon *et al.*, 2005)

4. Computer Model

A computer model which provide a detailed representation of the shallow unsaturated zone at Rotorua has been developed by Ratouis *et al.*, (2014), and is named here: UOA model III. It was run using the air/water equation of state in the numerical simulator AUTOUGH 2 (Yeh *et al.*, 2012), the University of Auckland's version of TOUGH2 (Pruess, 1991). UOA model III gives a good overall match to the natural state of the field and to the response to the 1986 bore closure programme (Ratouis *et al.*, 2014). In order to represent the chloride distribution and CO_2 flow in the model, the EWSG EOS was used. EWSG describes aqueous fluid of variable salinity as a mixture of water, chloride and non-condensible gas (CO_2) (Battistelli, Calore, & Pruess, 1997). The model presented in this paper used parameter choices in EWSG (NK, NEQ, NPH, NB) = (3, 4, 4, 6) appropriate for three phase behaviour in non-isothermal environment of porous media. The chloride in this model is assumed to be conservative, non-reacting phase and mainly present in the liquid phase (Kissling *et al.*, 1996). Thus, incorporating chloride into the model will provide a better understanding about the system since chloride will be more concentrated when boiling occurs, and diluted when mixing occurs with other, less saline water. On the other hand, CO_2 is dissolved in the liquid phase and will also appear in the vapour phase when boiling occurs. Information about the model in this paper is presented in the following table.

category	the model
grid area	12.4 km x 18.3 km
grid depth	2,000 m
blocks	11,302
orientation (angle N-S)	23.7°
rainfall rate	1m/year
infiltration rate	10%
layers	23
surface	follows topography &lake bathymetry
Equation of state	EWSG (water, salt, and non-condensible gas)
deep mass inflow	Kuirau Park : 6,400 t/day
	Ngapuna stream : 15,670 t/day
	38,500 t/day
bottom temperature (2000m)	Kuirau Park: 255°C
	Ngapuna stream : 270°C
	Whakarewarewa : 24°5

Table 2: Summary of model parameters

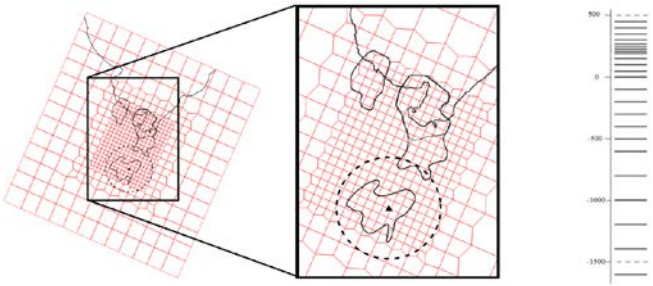


Figure 11: Grid Layout and layer structure of UOA model III (Ratouis *et al.*, 2014)

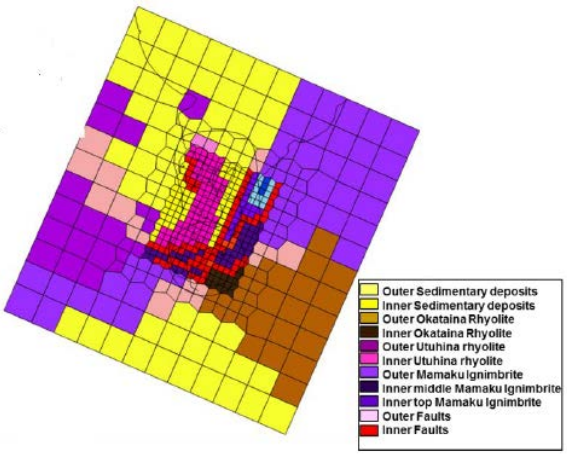


Figure 12: Geological setting at layer 10 UOA model III (Ratouis *et al.*, 2014)

Note that most of the parameter listed in the above table are adopted from UOA model III (Ratouis *et al.*, 2014) except for the EOS (EWSG).

5. Boundary Conditions

Model in this paper consists of certain boundary condition:

Top boundary:

The top surface of the model is set to be at atmospheric conditions where the pressure is 1 bar and temperature is 15^0C. At the base of Lake Rotorua, the temperature is set to be 10^oC and pressure follows the hydrostatic pressure. An annual rainfall is set to 1,000 mm/year and an infiltration rate is set to be 10%. This is expressed by cold water injection on the surface.

Side boundary:

Each side of the model is assumed to be closed, meaning that there is no heat or mass flow into or out of the system.

Base boundary:

Inflow of high enthalpy water together with chloride and CO_2 through the inferred faults and a conductive flow of heat is 80mW/m^2.

5. Result and Discussion

5.1 Natural State Model

The model is run until steady state where the result corresponds to the pre-exploitation state of the RGS. Unfortunately, there is very little data available for this period. However, from isotopic and chemical data, Stewart *et al*. (1992) have postulated the chloride concentration in the system prior to exploitation. Stewart's contours show a high concentration of chloride in the east and south, and decreasing concentration to the west (Figure 12). This distribution of chloride suggests that the principal upflow feeding the system lies to the east and south, and that there is another low chloride upflow in the west.

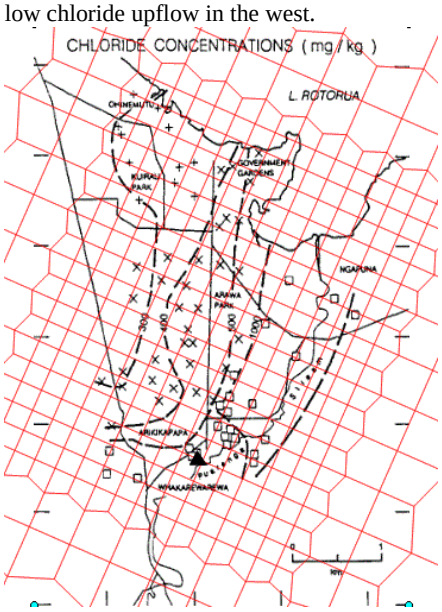


Figure 14: Natural state chloride concentration inferred by Stewart *et al.* (1992)

The chemistry model at natural state is obtained by adding chloride and CO_2 to the deep inflow, and running it up to 0.3 x 10^9 years. After natural state is achieved, we compare the temperature and pressure contour results with those from UOA model III to ensure that is no difference between temperature and pressure distributions between the EWSG EOS and the EOSl with water and air. The chloride contour at natural state in this model shows a similar chloride pattern to Stewart's natural state distributtion. The high chloride concentration is in the east and south and it decreases to the west. Since the side boundary in this model is closed, meaning that there is no mass coming into the system there, we assume that this model overemphasizes boiling relative to dilution. This is one reason why the chloride concentration in the west near Kuirau Park in the model is a bit high compared to values inferred from Stewart's contours. Another reason causing the concentration in the west to be a bit higher is that Stewart's are based on feed zones, which are vary in elevation across the system. Our model results are for layer 9 (~180 m.a.s.l).

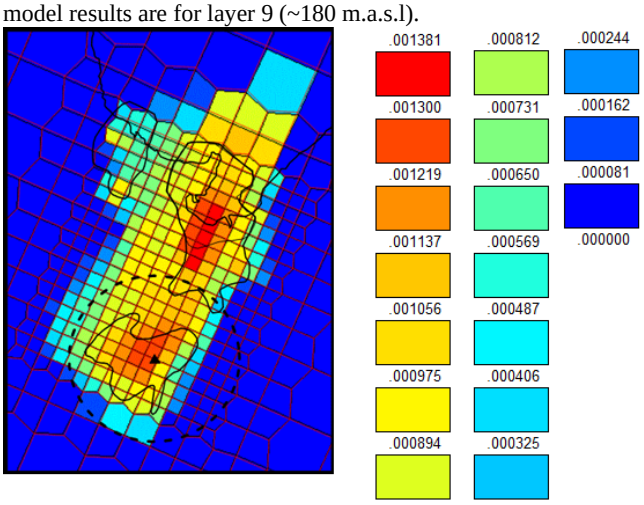


Figure 15: Chloride concentration (mg/kg) at natural state in layer 9

5.2 Production Model

The model was run for 42 years (up to 1992) to match with measured chloride data (Stewart *et al*., 1992) and the up to 55 years (up to 2005) to match with recent CO_2 flux measurement (Werner and Cardellini, 2005) using the production and injection schedule associated with the bore closure program which was discussed by Ratouis *et al*., (2014). The chloride concentration results are compared to measured data presented by Stewart *et al.* (1992) (Figure 6), and CO_2 flux is compared to data from Werner and Cardellini (2005) (Figure 9).

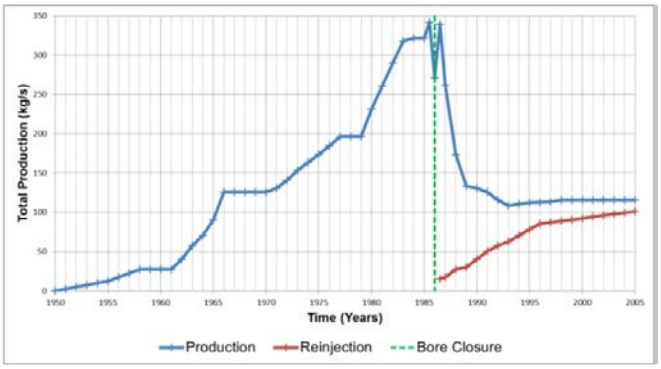


Figure 16: Rotorua production history (from Gordon *et al*., (2005) as cited in Ratouis *et al*., (2014))

After the exploitation period from 1950 to 1992, there is a samll decrease of chloride concentration from the natural state conditions (Figure 15). The model in this exploitation period has predicted the decrease in chloride concentration caused by an injection period during the bore closure programme. There is a good agreement between the model and Stewart's measured data. The maximum chloride measurement in Ngapuna, Whakarewarewa, and Kuirau Park respectively is approximately 1300 mg/kg, 1220 mg/kg, and 450 mg/kg. Chloride concentration at Kuirau Park in the model is slightly higher, but this may be because the model has a closed boundary so that there is insufficient dilution at shallow levels by low chloride water. Also the measured data contours show the distribution of chloride at

feed-zone depths of the wells whereas results from the model show the chloride distribution at layer 9, in which most of wells in the east have their feed-zones.

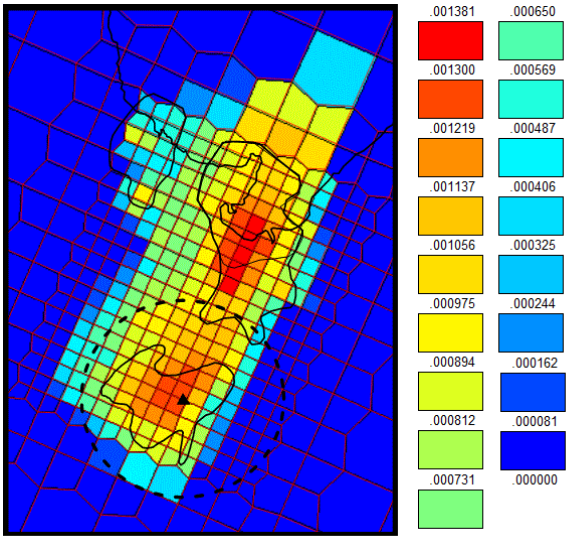


Figure 17: Chloride contour in 1992 at layer 9

The highest chloride (~1381 mg/kg) and temperature in Ngapuna is consistent with the characterization of the zone as the main upflow for the RGS. A secondary upflow in the south (1219 mg/kg) near Whakarewarewa correlate with the dilution of deep geothermal water with a low-temperature, chloride-free fluid, which is presumably shallow ground water (Glover and Mroczek, 1998). In the west, the chloride concentration is not as high as in the east, however chloride concentration in this region follows the HCO_3 concentration suggesting that deep CO_2 is converted by water-rock interactions before the water has a chance to boil at shallow depths (Giggenbach and Glover, 1992; Stewart *et al.*, 1992). Generally, there is a good correlation between chloride contour and subsurface temperature in this model.

Table 2 summarizes the comparison of model results and measured data for the chloride distribution in the RGS. Generally, the agreement is reasonably good except at Kuirau Park, where the model concentration is too high, as discussed above.

Location	Stewart's measured data	Current Model	
		Chloride Concentration	Chloride Fraction (%)
Ngapuna	more than 1300 mg/kg	1381 mg/kg	0.13
Whakarewarewa	1205 mg/kg	1219 mg/kg	0.12
Kuiaru Park	450 mg/kg	894 mg/kg	0.08

Table 2: Comparison between measured data from Stewart and model results

The results on the NW-SE vertical section show that there are several blocks where boiling occurs (Figure 19). This boiling causes the chloride concentration to increase (Figure 20). The temperatures on the NW-SE vertical section show that lateral geothermal fluid flow exists across rhyolite dome.

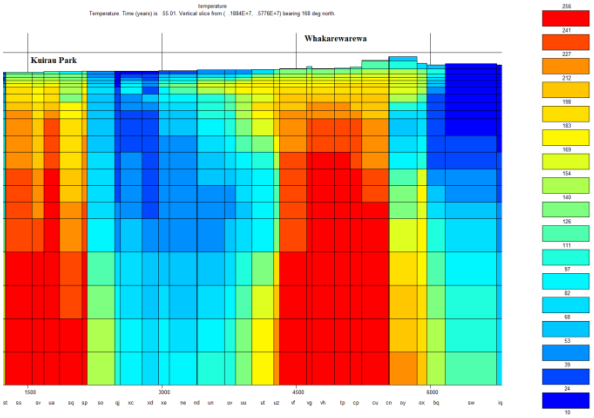


Figure 18: NW-SE Cross section of temperture in the model

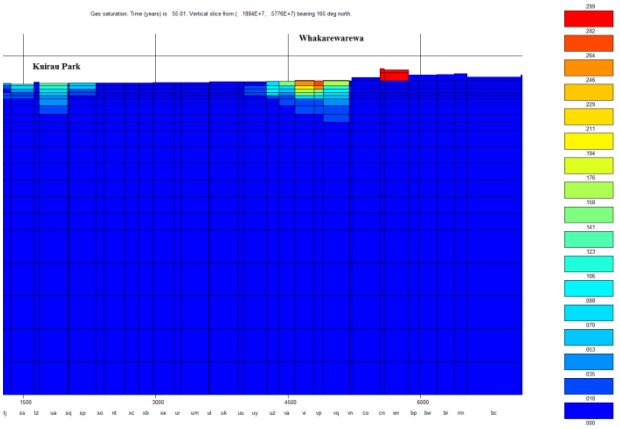


Figure 19: NW-SW Cross section of vapour saturation in the model

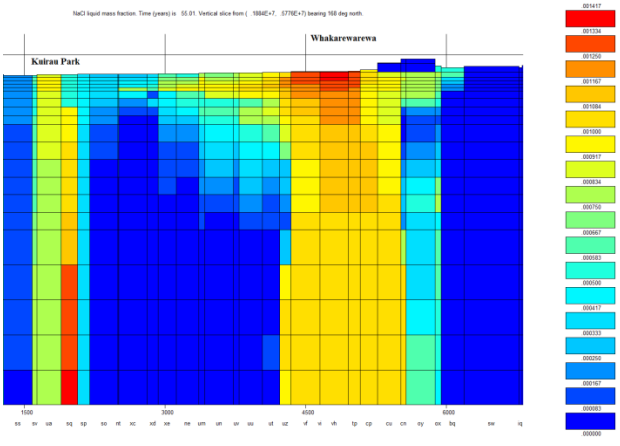


Figure 20: NW-SE Cross section of chloride distribution in the model

Measured CO_2 emission data has been provided by Werner and Cardellini (2005). The model results are consistent with fluid flow patterns in the RGS where measured high fluxes of CO_2 are found in the known thermal areas: Kuirau Park, Ngapuna, and Whakarewarewa. The CO_2 flux of more than 300 g/m^2.d found in these areas is consistent with the amount of CO_2 emission in other geothermal and volcanic areas.

In order to obtain a good match with the data from Werner and Cardellini (205) the model was first run until steady state, and the a production run was simulated for 55 years (up to 2005). The flow through the top surface of the model is then converted to the units provided for the measured data (kg/m^2.d). After calibration against the amount of CO_2 flux to the surface, the CO_2 mass flow from deep reservoir is found to be more than 0.3 kg/s. The CO_2 fractions in the deep upflow in the RGS thermal area: Kuirau Park, Ngapuna, and Whakarewarewa are 1.5%, 2.5%, and 2% respectively.

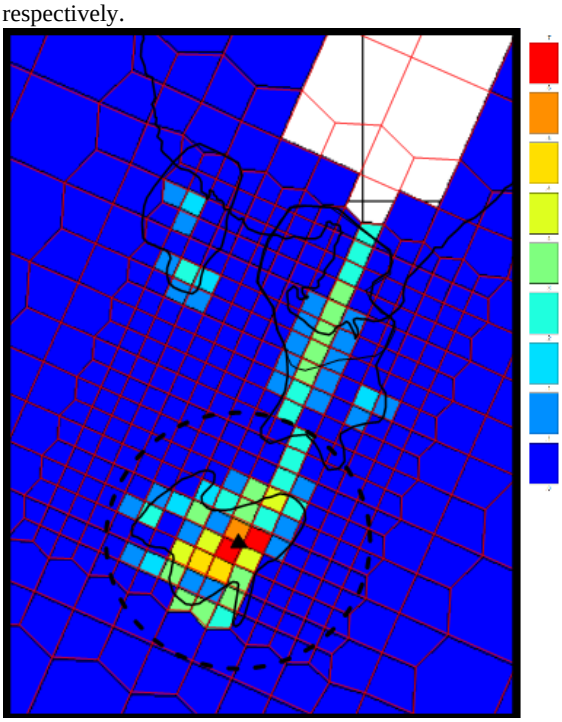


Figure 21: CO_2 flow through top layer 4 in the model

The model is able to produce a CO_2 flow to the surface across the system which is consistent with the fluid flow pattern discussed previously. However, the maximum flux in the model did not match the data. For example the flux in the model did not capture peak value of 12000 g/m^2.d as given by Werner and Cardellini (2005). However the data were for spot measurements at very small areas whereas the model values are for block averages Thus, the model have to have smaller blocks to improve the match to peak measurements of CO2 flux.

6. Conclusion

The Rotorua Geothermal System has been modelled using EWSG, one of EOSs available with TOUGH2 for representing chloride and CO_2 flow through a geothermal system. The model was developed from the latest Rotorua model developed at the University of Auckland (Ratouis *et al*. 2014) which gives a good overall match to the natural state of the system and to the response to the 1986 bore closure program.

Overall a good match with to measured chloride and CO2 data was obtained, however the model should be developed further to improve its accuracy by using a finer grid and finer layer structure.

The inclusion of chloride and CO_2 in the model provided a deeper understanding of the Rotorua geothermal system.

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