NUMERICAL EXPERIMENTS WITH COMPUTER MODELS OF GEYSERS

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ABSTRACT

Simple computer models of geysers have been set up that consist of a chamber linked to a cold recharge block and a deeper hot recharge block. The chamber also has an outlet to the surface through a narrow channel. The TOUGH2 simulator is used to carry out many numerical experiments to determine how parameters such as the size of chamber, cold recharge pressure, hot recharge pressure and permeability of the channel affect whether or not the model produces geysering behaviour and how they affect the period of the eruptions.

The aim is to produce a simple model of a geyser that can be embedded into a larger reservoir model of a system such as Rotorua and used to investigate the long-term variability of the behaviour of geysers.

1. INTRODUCTION

1.1 Geysers

Geysers are rare geothermal surface features with less than 1000 worldwide, most of which occur in one of the five major geyser fields at:

- Yellowstone Park, Wyoming, USA
- Valley of Geysers, Kamchatka, Russia
- El Tatio, Chile
- Taupo Volcanic Zone, New Zealand
- Iceland

Two geysers at Rotorua, Taupo Volcanic Zone, New Zealand are shown in Figure 1.

Figure 1: Geysers flats, Rotorua, New Zealand

One of the features of geysers is their irregular behaviour. This is discussed for the Yellowstone geysers by Hurwitz *et al.*, 2014 and Rojstaczer *et al.* 2003. These authors point out that significant changes occurred in the eruption interval of Old Faithful and other geysers as a result of large earthquakes, however the response to earth tides and weather is not clear.

The literature on the variability of geyser behaviour up to the mid-1990s in New Zealand was summarized by Saptadji *et al.*, 1994. The information for Pohutu is reproduced here as Table 1.

Table 1: Summary of the activity of Pohutu

Period	Eruptions per day	Source
1888-1889	2	Lloyd (1975)
Exploitation of the Rotorua geothermal field began		
1936	More than 5	Donaldson (1985)
1959	5	Lloyd (1975)
1967-1969	10-18	Donaldson (1985)
Half 1979	10-18	Donaldson (1985)
1985	5-25	Cody & Simpson (1985)
Bore closures began		
1986-1987	30-40	Bradford *et al.* (1987)
18/9/1988	22	Weir *et al.* (1992)
22/9/1988	30-40	Weir *et al.* (1992)
23/8/1993	~130	Saptadji (1995)
1996-97	60-80	Scott *et al.* (2005)
>2001	Continuous play	Scott *et al.* (2005)

As shown in Table 1 the activity of Pohutu has varied over the years. However there was a steady decline in geothermal surface activity, including geysers, at Whakarewarewa, Rotorua from the 1960s through to the 1980s. This is attributed to, first, a pressure decline resulting from the large scale exploitation of the adjacent hot water reservoir under Rotorua City (New Zealand Ministry of Energy, 1985) and, secondly, to a decline in the groundwater level caused by a decrease in rainfall in the early 1970s and in the 1980s (Bradford, 1992).

One of the aims of the present study is to produce models of geysers that, when embedded in our 3D model of Rotorua geothermal system (e.g. Ratouis *et al.*, 2015) can reproduce these observed changes in activity.

1.2 Conceptual models of geysers

The subsurface structure of a geyser is generally conceptualized as a chamber connected to the surface by a narrow channel, with the chamber recharged laterally by cold water and from depth by hot water and/or steam (Allen and Day, 1935; Benseman, 1964; White, 1967; Rinehart, 1980; Steinberg, 1981a-d; Bryan, 1986, Saptadji *et al.*, 1994; Saptadji, 1995; Ingebritsen and Rojstaczer, 1996).

The model parameters given by Weir *et al.* (1992) for Pohutu are listed in Table 2. Similar parameters for the

Feathers and Waikorohihi geysers were also given by Weir *et al*. (1992).

Weir *et al*. (1992) also developed a more complex, multi-geyser, conceptual model with connections from Te Horu to Pohutu, the Feathers and Waikorohihi.

Table 2: Parameters for the Pohutu geyser, Rotorua, NZ

Parameter	Value	Derivation
Chamber temperature	118 °C	calculated
Chamber depth	9 m	calculated
Eruption rate (Cody)	50 kg/s	estimated
Eruption rate	98 kg/s	calculated
Total mass discharged	100 tonnes	calculated
Chamber volume	100 m^3	assumed
Temperature of hot feed	180 °C	assumed
Temperature of cold feed	60 °C	assumed
Inflow of cold water	17 kg/s	calculated
Inflow of hot water	16 kg/s	calculated
Av. interval of eruption	51 mins	measured
Av. duration of water play	17 mins	measured
Av. height of eruption	20 m	measured
Vent area	0.12 m^2	measured

1.3 Previous modelling studies

Steinberg et al. (1981 a) considered the geyser activity in three stages: filling of the chamber, filling of the channel, heating of the water in the channel to boiling. They developed a mathematical model for each stage in the form of simple ordinary differential equations. Saptadji *et al*. (1994) applied these models to three geysers at Rotorua (Pohutu, the Feathers and Waikorohihi) and obtained a good match to the field data. The trouble with the Steinberg model is that it represents each stage separately and does not explain why geysering occurs.

Saptadji (1995) set up a numerical model of a geyser using the TOUGH2 simulator and the model configuration shown in Figure 2.

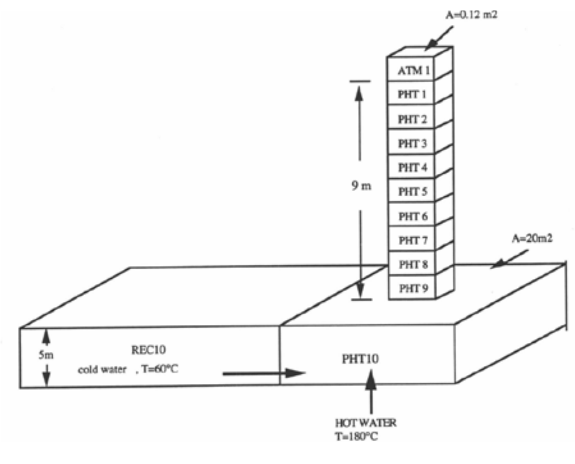

Figure 2: Geyser model of Saptadji (1995)

With the correct choice of parameters this model was able to reproduce the performance of the Rotorua geysers and a similar model was able to match the performance of a physical model of a geyser.

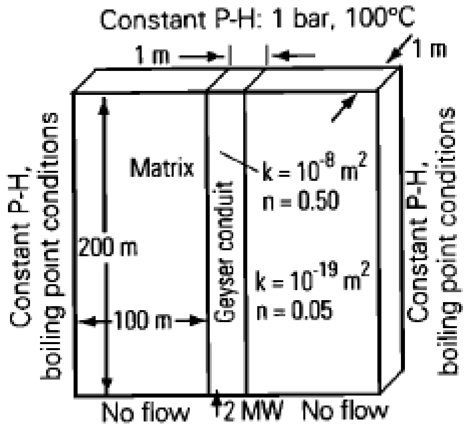

Figure 3: Geyser model of Ingebritsen and Rojstaczer

A similar numerical simulation with the HYDROTHERM code (Hayba and Ingebritsen, 1994) was used by Ingebritsen and Rojstaczer (1993, 1996) to model a geyser. Their model was 2D and consisted of a channel and surrounding rock (see Figure 3). It was able to produce geyser-like behaviour.

2. PRESENT GEYSER MODEL

2.1 Constant hot recharge

The first model used in the current study is essentially the same as that used by Saptadji (1995) and shown in Figure 2. However all the parameters for the model were not provided by Saptadji (1995) and some numerical experimentation was required to recalibrate the model.

The block names (different to Figure 2), rock types and volumes are given in Table 3.

Table 3: Model block parameters

Block	Rock type	Volume
AT1	ATMOS	1.0E30
AA1 to II1	CHANL	0.12
JJ1	CHAMB	100.0
RE1	RECH	1.0E20

The chamber volume of 100 m^3 is the same as recommended by Weir *et al*. (1992) and is one of the options used by Saptadji (1995). Similarly the area of the vent at 0.12 m^2 is the same as used before. The very large volumes used for the atmosphere block, AT1, and the cold recharge block, RE1, ensure that the pressure and temperature remain constant in those blocks.

The connection parameters used in the model are given in Table 4. The distances from the interface between the blocks to the block centres are called "D1" and "D2".

Table 4: Model connection parameters

Block 1	Block 2	D1	D2	Area
AT1	AA1	1.0E-6	0.5	0.12
AA1 to HH1	BB1 to II1	0.5	0.5	0.12
II1	JJ1	0.5	3.0	0.12
RE1	JJ1	5.0	5.0	20.0

Extensive numerical experiments showed that the most important parameters in terms of the period of eruptions are the amount of hot inflow and permeability connecting the cold recharge to the chamber. Figure 4 shows plots of eruption period versus hot inflow for four values of cold recharge permeability (170 to 300 Darcys).

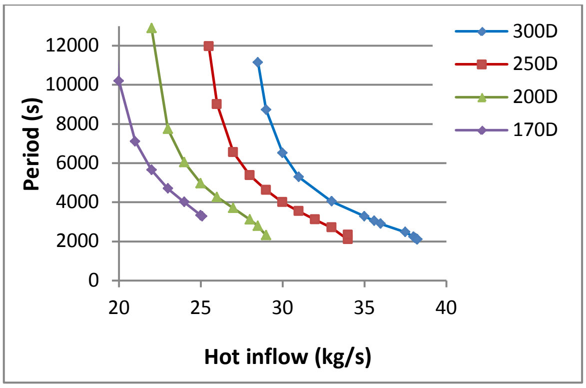

Figure 4: Eruption period versus hot inflow for four values of cold recharge permeability

Each graph shows the approximate range of hot inflow for which geysering occurs. Outside that range other types of behaviour occur as shown in Table 5 (for the case where the cold recharge permeability is 250 Darcys).

Table 5: Types of behaviour of a geyser

Hot inflow (kg/s)	Type of behaviour
0 - 25	Constant flow warm spring
25.5 - 34	Approximately periodic geysering
34.01	Irregular geysering
34.1 - 35.5	Continuous spouting
>35.7	Constant flow hot spring

Two eruption cycles are shown in Figure 5 for a model where the period matches the value of 51 mins given by Weir *et al*. (1992). For this case the hot inflow is 32kg/s.

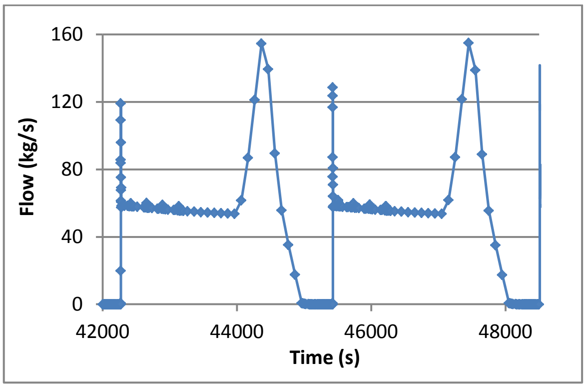

Figure 5: Two cycles of eruption. Period 51 mins, hot inflow 32kg/s.

The parameters for the model whose results are shown in Figure 5 are given in Table 6 and the rock properties in Table 7.

Table 6. Model parameters (51 mins eruption interval)

Parameter	Value
Cold recharge pressure	2.45 bar
Cold recharge temperature	60 °C
Hot recharge flow	32 kg/s
Temperature of hot recharge	180 °C

Table 7. Rock properties (51 mins eruption interval)

Rock-type Parameter	CHAMB	CHANL	RECH	ATMOS
Density(kg/m^3)	2500	2500	2500	2500
Porosity	0.999	0.999	0.3	0.999
x-permeability (m^2)	25.E-11	-	25.E-11	-
z-permeability (m^2)	3.5E-7	3.5E-7	-	3.5E-7
Thermal conductivity	2.0	2.0	2.5	2.0
Specific heat	900	900	1000	900

For the model results shown in Figure 6 the hot inflow is increased to 34kg/s and the period is reduced to 35 mins.

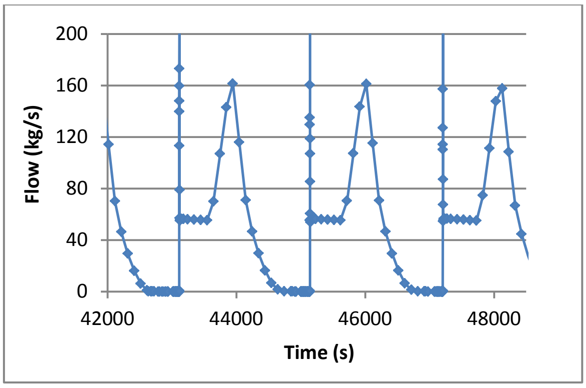

Figure 6: Three cycles of eruption. Period 35 mins, hot inflow 34 kg/s.

A very small further increase of hot inflow to 34.01 kg/s produces the irregular behaviour shown in Figure 7.

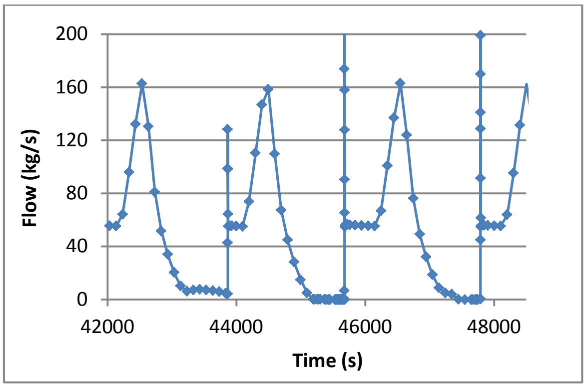

Figure 7: Irregular eruptions. Hot inflow 34.01 kg/s.

A further increase in hot inflow produces the continuous spouting behaviour shown in Figure 8. This persists for values of the hot upflow increasing up to 35.5 kg/s. For values of hot inflow of 35.7kg/s and above constant flow, hot spring behaviour, is obtained (not shown).

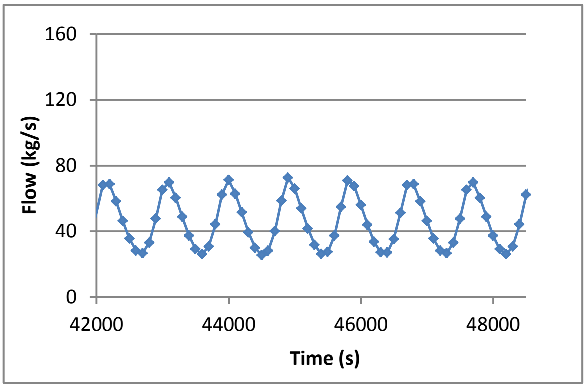

Figure 8: Continuous spouting. Hot inflow 34.1 kg/s.

The results above were obtained using a chamber volume in the model of 100 m^3, the value given by Weir *et al.* (1992).

For the maximum eruption height at Pohutu Weir *et al.* (1992) estimated a flow rate of 98 kg/s. For the model whose results are shown above in Figure 5 the calculated maximum flow rate is higher at 155 kg/s. This value is relatively insensitive to the choice of model parameters, as shown in Figure 9.

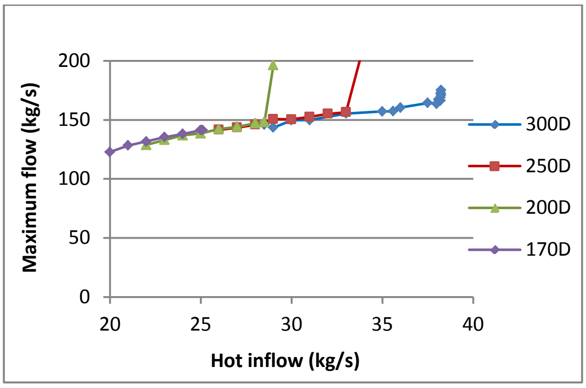

Figure 9: Maximum eruption flow for various hot inflows and cold recharge permeabilities

As shown in Figure 4, none of the models considered produced a period of eruption less than ~2000s, much larger than the value of 652 s measured by Saptadji (1995).

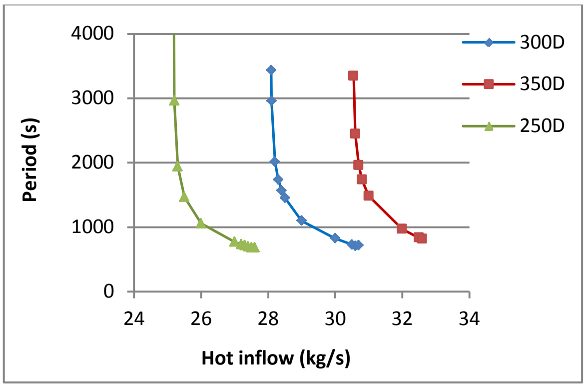

Figure 10: Eruption period versus hot inflow for three values of cold recharge permeability. Chamber volume 12.5 m^3

In order to investigate this matter further a model with a smaller chamber volume of 12.5 m^3 was set up. The plot of geyser period vs hot inflow rate (analogous to Figure 4) is shown in Figure 10. This plots shows, with a cold recharge permeability of 250 Darcys, it is possible to obtain a period of eruption of ~51 mins (see Figure 11). This happens for a hot inflow of 25.2 kg/s, only a little more than the value at which geysering no longer occurs (25.15 kg/s). With this same model it is possible to obtain an eruption period of ~710 s with a relatively small increase of hot inflow to 27.3 kg/s (see Figure 12). These model results are consistent with a small increase in hot inflow occurring between 1988 and 1993 and causing the decrease in eruption period from 51 minutes (Weir *et al.*, 1992) to 652 seconds (Saptadji, 1995).

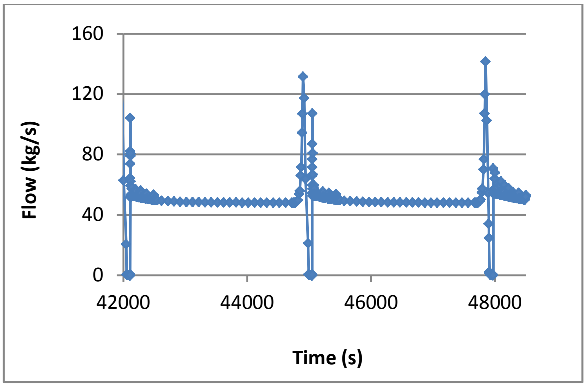

Figure 11: Model of geyser eruption. Period ~51 mins, hot inflow 25.2 kg/s, chamber volume 12.5 m^3.

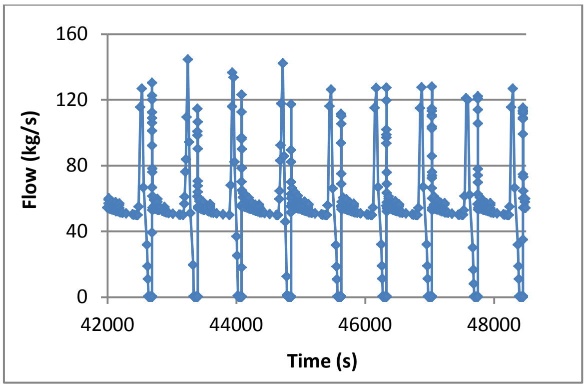

Figure 12: Model of geyser eruption. Period ~710 s, hot inflow 27.3 kg/s, chamber volume 12.5 m^3.

Although the periods of eruption shown in Figures 11 and 12 match observations other features of the model results are not satisfactory. For example, the long period of play before full column eruption and the very short quiet period in both figures do not match the observed behaviour (Weir *et al.*, 1992; Scott *et al.*, 2005).

Saptadji (1992) separated the behaviour of a geyser into four stages: quiet, pre-play, rising eruption and falling eruption. The average values she measured for these times on 20th August 1993 are listed in Table 8 together with values for a typical modelled eruption shown in Figure 12.

Table 8: Values for times of the stages of a geyser

Stage	Measured time	Percent	Modelled time	Percent
Quiet	221	34	54	7
Pre-play	123	19	570	74
Rising	224	34	79	10
Falling	84	13	65	8
Total	652	100	768	100

There is a clear mismatch between the model results and the observations. In particular the model has a much shorter quiet time than that observed by Saptadji in 1993. It is possible that the porous medium representation of flow (possibly two-phase) up the channel is not sufficiently accurate and makes it too easy for the pre-play flow to occur. Further research with a coupled well-bore/reservoir model (e.g. Pan and Oldenberg, 2014) is required on this issue.

Also the assumption of a vertical channel linking the chamber to the surface may be too simple. The actual plumbing of the geyser may be more complex with a dog-leg channel which would offer more resistance to flow and perhaps extend the length of the modelled quiet period.

2.2 Pressure-dependent hot recharge

The assumption used with the model, discussed in Section 2.1, of a constant hot inflow is not physically realistic and it was decided to improve the model by adding a channel below the chamber connected to a hot source (at constant pressure and temperature). This allows the hot inflow to vary as conditions in the chamber change which is probably more physically correct than a constant flow. Also such a model is suitable for embedding in a large reservoir model. The conditions in the hot and cold recharge blocks for the geyser model could be directly extracted from suitable blocks in a reservoir model.

The amended model was set up with a bottom channel of length 90 m.

Using all the same parameters as in Tables 6 and 7 but with the hot inflow of 32 kg/s replaced by a hot recharge pressure of 11.41 bar (and again a temperature of 180°C) an almost identical period of eruption was obtained. A different permeability was required for the channel connecting the hot recharge zone to the chamber, i.e. 1.0E-7 m^2 (compared with 3.5E-7 m^2 in the top channel). A typical part of the eruption results is shown in Figure 13.

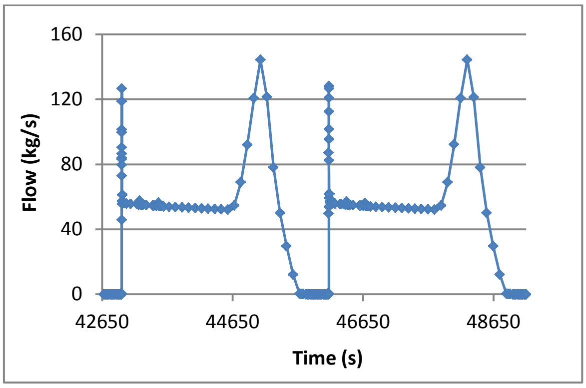

Figure 13: Two cycles of eruption. Period ~51 mins, hot recharge pressure 11.41 bar.

The results shown in Figure 13 are very similar to those shown in Figure 5. The main different is in the slightly lower level of discharge in the period of play before full eruption begins. The length of quiet period is not changed significantly.

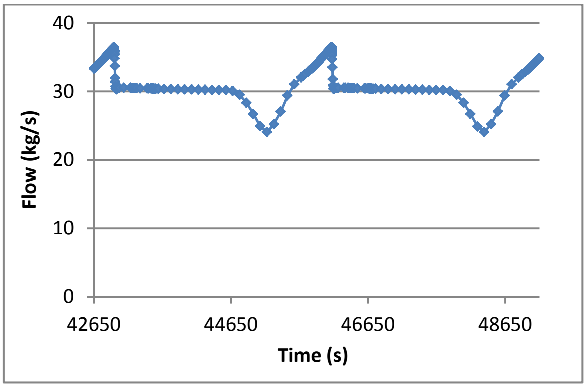

Figure 14: Hot recharge flow. Period of eruption ~51 mins, hot recharge pressure 11.41 bar.

The recharge flow is shown in Figure 14. It varies by only a small amount and is similar to the constant value of 32 kg/s used in the model whose results were shown in Figure 5.

For the model with pressure-dependent recharge there is quite a narrow range of hot recharge pressures, $P_{HotRech}$, for which geysering occurs, namely 11.18 bar $\leq P_{HotRech} \leq$ 11.51 bar. At $P_{HotRech}$= 11.512 bar continuous spouting occurs, but by $P_{HotRech}$= 11.52 bar constant flow hot spring behaviour occurs. Figure 15 shows a plot of period versus hot recharge pressure for the range of values for which geysering occurs. As for the constant hot inflow model with a chamber of 100 m^3, the period of eruption does not drop below ~2000s and it appears that to match the period of 710 s observed by Saptadji in 1993 a smaller chamber is required.

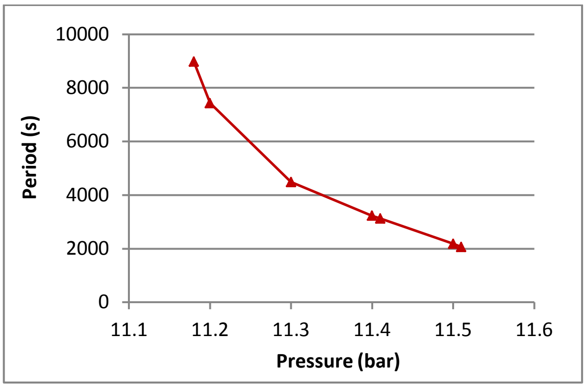

Figure 15: Eruption period vs. hot recharge pressure.

2.3 Pressure of cold recharge

Bradford (1992) pointed out that some of the changes in activity in the Rotorua geysers during the 1960s and 1970s could have been related to changes in rainfall and therefore to changes in water table levels. In the present model this corresponds to a change in the pressure of the cold recharge. The effect of varying this parameter is shown in Figure 16. Geysering only occurs for a fairly narrow range, i.e. 2.246 bar $\leq P_{ColdRech} \leq$2.514 bar. For pressures just below the lower limit perpetual spouting occurs and for pressures above the upper limit a constant flow hot spring is obtained.

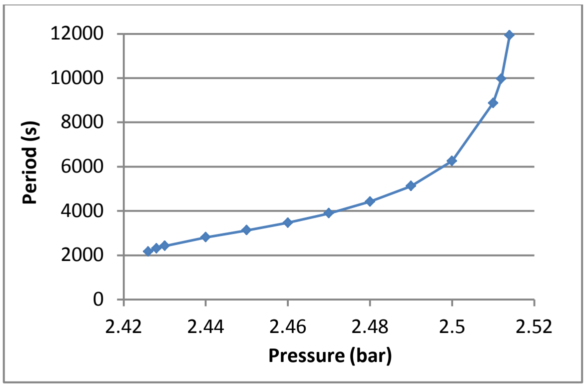

Figure 16: Eruption period vs. cold recharge pressure.

2.4 Atmospheric pressure

Saptadji (1995) investigated the effect of changes in atmospheric pressure. This sensitivity study was repeated here for the model with deep hot recharge. Leaver and Unsworth (2007) also reported that changes in barometric pressure affect geyser behaviour.

The model results in Figure 17 show that the period of eruption decreases as the atmospheric pressure increases, but it is a small effect.

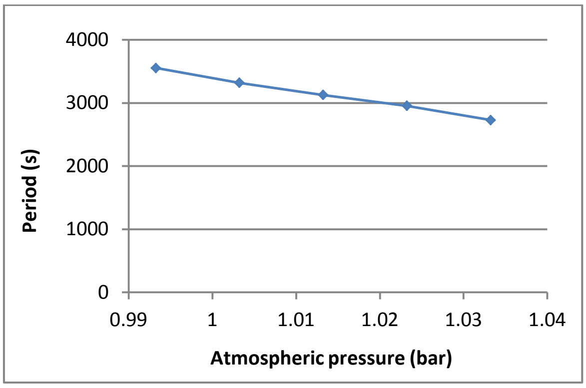

Figure 17: Eruption period vs. atmospheric pressure.

2. CONCLUSION

The type of models we have produced can match the types of behaviour observed with the Rotorua geysers and the changes in the behaviour observed as the deep pressures have recovered since the bore closures in the mid-1980s. However, the observed behaviour of Pohutu is more erratic (see Weir *et al.*, 1992, for example) than our models can predict. There are several reasons for this:

(i) The several geysers at geyser flats in Rotorua may be linked and thus the single geyser model discussed here is not adequate.

(ii) Several of the effects discussed above (e.g. changes in deep pressure and cold recharge pressure) may be occurring together.

(iii) The representation of two-phase flow in the channel by a porous medium model may not be accurate enough.

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