Geothermics 64 (2016) 401–409

Contents lists available at ScienceDirect

Geothermics

journal homepage: www.elsevier.com/locate/geothermics

Numerical modelling of Pohutu geyser, Rotorua, New Zealand

Nenny Saptadji[b], John O'Sullivan[a], Wojtek Krzyzosiak[a], Michael O'Sullivan[a,*]

[a] Department of Engineering Science, University of Auckland, Private Bag, 92019 Auckland, New Zealand
[b] Institut Teknologi Bandung, Bandung, Indonesia

ARTICLE INFO

Article history:
Received 9 May 2016
Received in revised form 28 June 2016
Accepted 30 June 2016
Available online 16 July 2016

Keywords:
Geyser
Computer modelling
Pohutu

ABSTRACT

The Rotorua geothermal field (RGF) in the North Island of New Zealand is renowned for an abundance of natural geothermal manifestations and contains one of New Zealand's last remaining areas of major geyser activity at Whakarewarewa. Close proximity of the geothermal resource to a population centre and ease of access for end-users resulted in intensive drilling and fluid abstraction from shallow bores for domestic and commercial usage from the 1950s onwards. Increasing concern about the effect of geothermal fluid withdrawal on the activity of springs and geysers led to the establishment of the Rotorua Geothermal Monitoring Programme (RGMP) in 1982. By 1986, aquifer pressures declined to the lowest levels since the monitoring programme began, and to prevent further deterioration of spring and geyser activity, a Bore Closure Programme was enforced. By 1988, the programme contributed to a 75% decrease in net withdrawal and an immediate increase in reservoir pressures was observed. During the ensuing years recovery of some surface features has also been observed.

Thus, although the geysers at Rotorua, New Zealand have shown some natural variation in their behaviour, they have also been significantly affected by human interference. The aim of this study is to quantify the past response of geyser activity to human-induced changes in the state of the Rotorua geothermal reservoir and to provide a tool for predicting the future behaviour of the geysers. The study is based on a simple computer model of a geyser that consists of a chamber linked to cold recharge and deeper hot recharge. 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 model successfully matches the observations that: (i) geysering ceases if hot recharge diminishes, (ii) the frequency of eruption increases if hot recharge increases and (iii) if hot recharge increases enough, then geysering turns into continual spouting.

1. Introduction

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, and
- Iceland

Pohutu geyser at Rotorua, Taupo Volcanic Zone, New Zealand is shown in Fig. 1.

It has been noted that Old Faithful Geyser, Yellowstone, had remarkably regular behaviour from 1870 to 1947 (Fix, 1949), but one of the features of many geysers is their irregular behaviour, discussed for the Yellowstone geysers by Rojstaczer et al. (2003) and Hurwitz et al. (2014). 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 the smaller effects of earth tides and weather is non-existent to variable.

The literature on the variability of geyser behaviour in New Zealand up to the mid-1990s was summarized by Saptadji et al. (1994). Information for Pohutu geyser from that source and from the more recent study of Scott et al. (2005) is reproduced here as Table 1.

* Corresponding author.
E-mail address: m.osullivan@auckland.ac.nz (M. O'Sullivan).

http://dx.doi.org/10.1016/j.geothermics.2016.06.019
0375-6505/

Fig. 1. Pohutu Geyser, Rotorua, New Zealand. Alexander Turnbull Library, Whites Aviation Collection, WA-03139-F. http://natlib.govt.nz/records/30644169.

Table 1
Summary of the activity of Pohutu geyser.

Period	Eruptions per day	Reference
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)
1979	10–18	Donaldson (1985)
1985	5–25	Cody and 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)
1996–1997	60–80	Scott et al. (2005)
>2001	Continuous play	Scott et al. (2005)

2. Present study

For this study four computer models of Pohutu were set up. All consist of a chamber linked to the surface by a narrow channel (according to the conceptual model shown in Fig. 2). For Models 1a and 1b the hot recharge occurs at a constant rate, whereas for Models 2a and 2b it is pressure dependent. For all models the cold recharge is pressure dependent. The ‘a’ models have a larger chamber (100 m^3) than ‘b’ models (12.5 m^3). Model 1a uses parameters from previous studies of Pohutu (e.g., Weir et al., 1992) and is treated as the base-case for sensitivity studies, however, Model 1b, with the smaller chamber, better matches the 1988–2015 behaviour of Pohutu.

The computer models of geysers presented below are generic and could be applied to any geyser. Here Pohutu geyser, Rotorua, is used as a test case, first because there are data available from previous studies (see Table 1), and secondly because Pohutu has exhibited interesting changes in activity over the last 25 years (see Table 1).

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 (NZ 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, 1992a). Then, since the bore closure programme in 1986 there has been some recovery of surface activity (Bradford, 1992b; Scott et al., 2005).

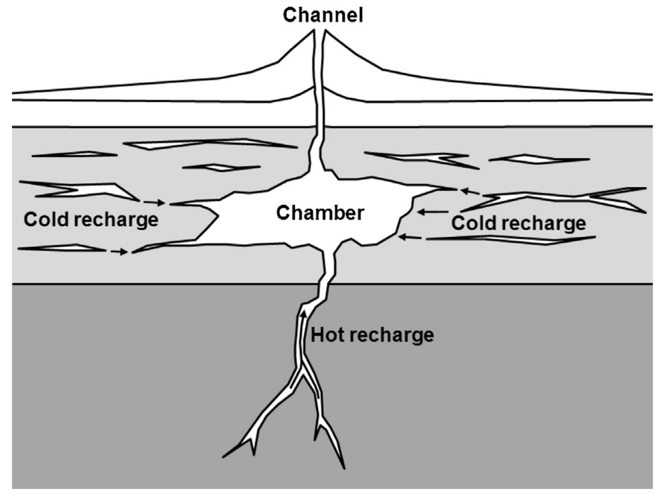

Fig. 2. Conceptual model of a geyser.

After the bore closure programme the behaviour of Pohutu geyser changed (see Table 1). First the period of eruption decreased and recently it has begun to erupt continuously, in an oscillatory fashion but with no quiet, non-eruptive, stage. This mode of behaviour is referred to as “continual or perpetual spouting”.

Presumably the changes in Pohutu, from 1986 onward, are related to an increase in the geothermal reservoir pressures at Rotorua resulting from the large decrease in mass withdrawal after bore closures took place. By 1988, the programme contributed to a 75% decrease in net withdrawal (Bradford, 1992a). In turn, the increase in reservoir pressures will have stimulated an increase in hot recharge to the geysers, including Pohutu, thus affecting their behaviour.

No measurements of the deep geothermal aquifer pressures have been made, but pressures are available for several shallow monitor wells. Typical results in Fig. 3 for well M12 (cased to a depth of 80 m) show an increase in water level of 2 m between 1988 and 2015 (Kissling, 2014).

The main aim of our study is to match the qualitative behaviour of Pohutu geyser with a computer model. A secondary aim is to produce models of Pohutu and other geysers that, when embedded in our 3D model of Rotorua geothermal system (Ratouis et al., 2015, 2016) can reproduce the observed changes in activity.

3. Conceptual model of a geyser

As shown in Fig. 2, 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 steam (Allen and Day, 1935; Benseman, 1965; White, 1967; Rinehart, 1980; Steinberg et al., 1981a,b,c,d; Bryan, 1986; Saptadji et al., 1994; Saptadji, 1995; Ingebritsen and Rojstaczer, 1996; Vandemeulebrouck et al., 2013; Munoz-Saez et al., 2015).

In situ observations of Old Faithful (Hutchison et al., 1997) generally support this conceptual model, showing a narrow channel, 7.3 m in length, connecting to an irregular shaped chamber extending down to 13.8 m. However it has been suggested (Vandemeulebrouck et al., 2013) that there is a much larger cham-

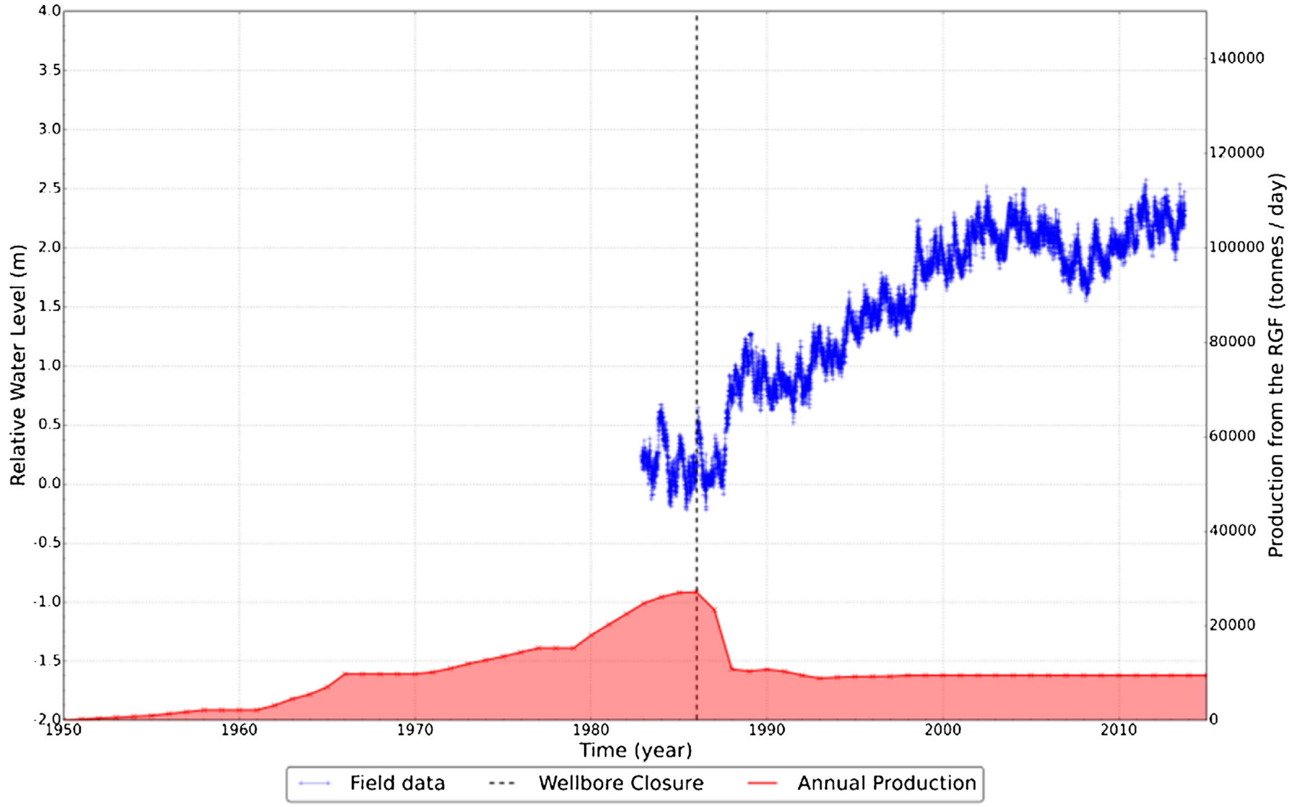

Fig. 3. Water levels in monitor well M12, with annual production from the Rotorua geothermal field (RGF) also shown.

Table 2
Parameters for the Pohutu geyser, Rotorua, NZ, mostly from Weir et al. (1992.

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 t	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 min	measured
Av. duration of water play	17 min	measured
Av. height of eruption	20 m	measured
Vent area	0.12 m^2	measured

ber below 13.8 m and the whole of the top zone should be regarded as the channel.

Model parameters for Pohutu, mostly taken from Weir et al. (1992), are listed in Table 2. Similar parameters for the Feathers and Waikorohihi geysers were also given by Weir et al. (1992).

A more complex, multi-geyser, conceptual model has been suggested for Geyser Flats (Weir et al., 1992), with connections from Te Horu to Pohutu, the Feathers and Waikorohihi, but is not considered here.

Geysering can occur from a conduit with no pronounced chamber (Ingebritsen and Rojstaczer, 1993, 1996). Chamberless models have been used to simulate geysering in a geothermal well, induced by the presence of carbon dioxide gas (Lu et al., 2005), and as the basis of a physical model of Old Faithful (O'Hara and Esawi, 2013).

'Geysering' refers to the approximately periodic discharge of water and steam from a vent in a geothermal area. Typically geyser activity consists of four stages: quiet, pre-play, rising eruption and falling eruption. The duration of each stage and the period between eruptions varies from one geyser to the next.

The behaviour of geysers can vary with changes of subsurface conditions. If hot recharge decreases or cold recharge increases then periodic eruption of hot water can change to a constant flow of warm water. Alternatively if cold recharge decreases or hot recharge increases then nearly-periodic geysering can become much more erratic or turn into continual spouting, or even a constant flow of hot water. One of the aims of the present study is to set up a computer model that can reproduce this diversity of behaviour.

4. Previous modelling studies

Steinberg and co-workers (Steinberg et al., 1981a) considered geyser activity in three stages: filling of the chamber, filling of the channel, and heating of the water in the channel to boiling. They developed mathematical models for each stage in the form of simple ordinary differential equations. In an earlier study (Saptadji et al., 1994) we applied these models to three geysers at Rotorua (Pohutu, the Feathers and Waikorohihi) and obtained a good match to the field data. The Steinberg model was also recently used to obtain a reasonable fit to data from the El Tatio geyser field in Chile (Munoz-Saez et al., 2015). However a limitation of 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, very similar to the model described below, using the TOUGH2 simulator and the model configuration shown in Fig. 4. With the correct choice of parameters this model was able to reproduce some of the performance of the Rotorua geysers, and a similar model was able to match the performance of a physical laboratory model of a geyser.

Saptadji carried out an extensive sensitivity study on her Pohutu model, investigating the effects of changes in the following param-

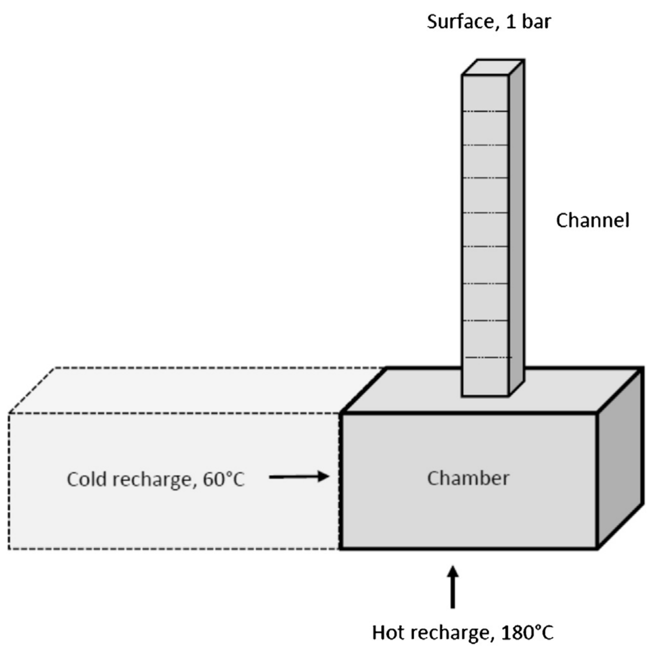

Fig. 4. Schematic of the geyser model.

Table 3
Model block parameters.

Description	Model number	Number of blocks	Rock type	Volume (m^3)
Atmosphere	1&2	1	ATMOS	1.0E20
Channel	1&2	9	CHANL	0.12
Chamber	1&2	1	CHAMB	100.0 or 12.5
Cold recharge	1&2	1	RECH	1.0E20
Lower channel	2	9	CHANX	1.08
Hot recharge	2	1	RECHX	1.0E20

Table 4
Model connection parameters.

Description of connections	Model #	D1	D2	Area (m^2)
Atmosphere to top of channel	1&2	1.0E – 6	0.5	0.12
Between channel blocks	1&2	0.5	0.5	0.12
Bottom of channel to the chamber	1&2	0.5	3.0	0.12
Cold recharge to the chamber	1&2	5.0	5.0	20.0
Chamber to lower channel	2	3.0	4.5	0.12
Between lower channel blocks	2	4.5	4.5	0.12
Lower channel to hot recharge	2	4.5	4.5	0.12

eters: rate of hot upflow, temperatures of the hot and cold recharge, pressure of the cold recharge, atmospheric pressure and temperature, area of the channel, size of the chamber, permeability of the channel and the chamber, relative permeability. From Saptadji's results and some further, recent numerical experiments it was decided that the two key model parameters influencing the behaviour of Pohutu are the rate of hot recharge and the permeability of the cold recharge connection. In the present study a very detailed sensitivity investigation was carried out, accurately delineating the values of these two parameters for which the various types of behaviour occur (mentioned above and listed in Table 7). In the sensitivity study carried out by Saptadji (1995) three or four values of each parameter were used, whereas in the present study twenty to thirty values are tested.

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. It was also able to produce geyser-like behaviour.

Recently, Kiryukhin (2015) set up a radially symmetric (r–z) model of the Velikan geyser in Kamchatka. The model geometry, with a conical shaped channel and no chamber, was based on subsurface measurements and tracer testing. Downhole temperatures at two depths in the Velikan channel were available as observations and were used by Kiryukhin for inverse modelling, using iTOUGH2 (Finsterle, 1999), to optimise the choice of parameters in his model. He matched his model parameters to data from one eruption cycle at a time, for nine sets of data and achieved a good match to the measured temperatures.

5. Present geyser model

Four versions of a model shown in Fig. 4 are considered here. The first two, Model 1a and Model 1b, have a constant rate of hot recharge, while the second two, Model 2a and Model 2b, have a variable, pressure dependent hot recharge. The only difference between Models 1a, 2a and Models 1b, 2b is the size of the chamber, at 100 m^3 and 12.5 m^3, respectively.

Model 1 in the current study is essentially the same as that used by Saptadji (1995). It consists of a 9 m deep channel subdivided into 9 blocks connected to a single large chamber block, which is connected laterally to a cold recharge block.

For Model 2, a lower channel, 90 m in length, connects the bottom of the chamber to a deep, hot recharge block at 180 °C. In the lower channel, ten blocks were used, each 9 m deep and with the same area of 0.12 m^2 as in the top channel. The pressure of the hot recharge block was one of the parameters varied in the numerical experiments. This type of model was not considered by Saptadji (1995).

The rock types and volumes used in the TOUGH2 data file are given in Table 3. TOUGH2 is a finite volume code (Pruess et al., 1999) that solves mass and heat balance equations together with Darcy's law for flow in a porous medium. The grid for the model is relatively coarse, but it is probably not worth trying to improve accuracy by mesh refinement while the approximation is being made of using Darcy's law to represent flow up a channel with a relatively large cross sectional area. Also a model with a small number of blocks (say 10–100) was required so that it could easily be embedded in a larger reservoir model.

For each simulation the run-time was long enough so that 50–100 eruptions were covered. The simulations were started from an approximate post-eruption state and usually a "burn-in" time of 5–10 eruptions were required to dissipate the effect of the initial conditions.

The chamber volume of 100 m^3 used in Model 1a 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 and the cold recharge block ensure that the pressure and temperature remain constant in those blocks. The connection parameters used in the models are given in Table 4. The distances from the interface between the blocks to the block centres are called "D1" and "D2".

The first aim with each model was to find the parameters that gave a period of eruption close to 51 min, the 1988 value given by Weir et al. (1992). The parameters for Model 1a that produced geysering with a period of 51 min (a sample of results for two eruptions are shown below in Fig. 6) are given in the next section in Table 6 and the rock properties in Table 7.

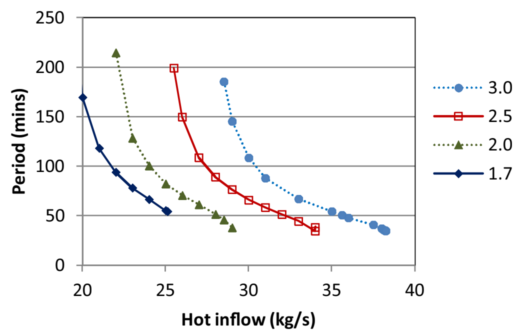

Fig. 5. Eruption period versus hot inflow for four values of cold recharge permeability (units E-10 m^2) for Model 1a, with a chamber volume 100 m^3.

Table 5
Types of behaviour of a geyser, Model 1a.

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

6. Model results

6.1. Geysering or not

For Model 1a, extensive numerical experiments showed that the most important parameters in terms of the period of eruption are the amount of hot inflow and permeability connecting the cold recharge to the chamber. Fig. 5 shows plots of eruption period versus hot inflow for four values of cold recharge permeability (1.7E – 10 to 3.0E – 10 m^2).

Each graph is limited to the approximate range of hot inflow for which geysering occurs. Numerical experimentation showed that outside that range other types of behaviour occur, as shown in Table 5 (for the case where the cold recharge permeability is 2.5E – 10 m^2).

The important result is that the types of behaviour shown in Table 5 are qualitatively consistent with what happened to Pohutu after bore closure in 1986, i.e., when reservoir pressures increased and hot recharge to the geysers increased. As shown in Table 1, the period of eruption of Pohutu decreased (more eruptions per day) after 1988 and by 2001 it was erupting continuously (continual spouting).

6.2. Geysering with a period of 51 min (1988 conditions)

Two eruption cycles are shown in Fig. 6 for Model 1a where the period matches the value of 51 min for 1988 reported by Weir et al. (1992). For this case the cold recharge permeability is 2.5E – 10 m^2 and the hot inflow is 32 kg/s.

As can be seen from Fig. 6, the model results are not exactly periodic, but for the 25 eruptions simulated the period and the shape of the eruption cycle are quite stable, showing no long-term systematic trend. The period of eruption varied by less than ±1 min.

The initial brief, large pre-play and the few small pulses, shown in Fig. 6, are qualitatively correct as they are seen in the eruption of Pohutu and other geysers. The parameters for the version of Model 1a whose results are shown in Fig. 6 are given below in Tables 6 and 7.

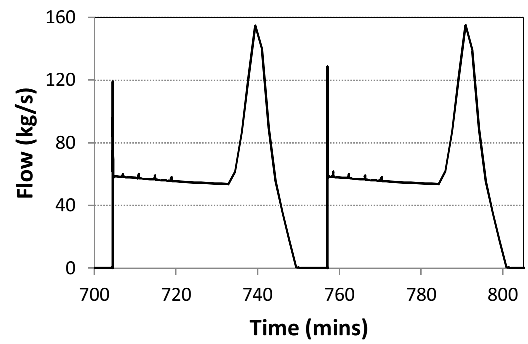

Fig. 6. Two cycles of eruption for Model 1a with a period of 51 min, cold recharge permeability 2.5E-10 m^2 and hot inflow 32 kg/s.

Table 6
Model 1a parameters (51 min 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 for Model 1a (51 min 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)	2.5E – 10	–	2.5E – 10	–
z-permeability (m^2)	3.5E – 7	3.5E – 7	–	3.5E – 7
Thermal cond. (W/m K)	2.0	2.0	2.5	2.0
Specific heat (J/kg K)	900	900	1000	900

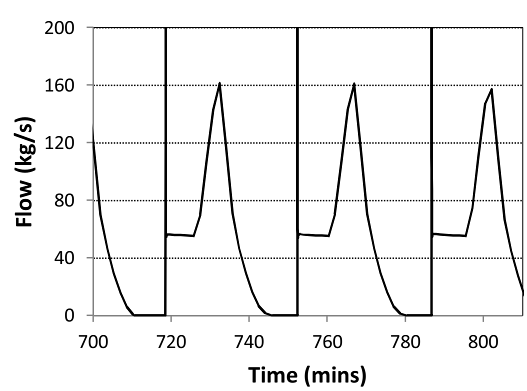

Fig. 7. Three cycles of eruption for Model 1a with a period of 35 min and hot inflow of 34 kg/s.

6.3. Geysering with a shorter period (post-1988 conditions)

For the next sequence of simulations the rate of hot recharge was increased, eventually up to 34 kg/s, with the aim of matching the shorter period of eruption of 10.9 min measured by Saptadji in 1993. These numerical experiments were only partly successful: the period of eruption was reduced, but only down to ~35 min (see Fig. 7).

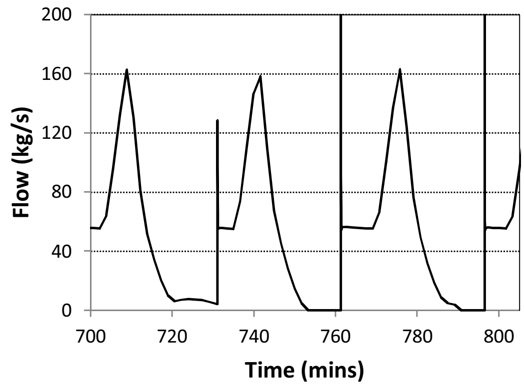

Fig. 8. Irregular eruptions for Model 1a with hot inflow of 34.01 kg/s.

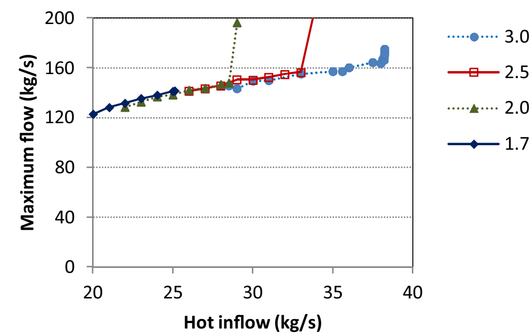

Fig. 10. Maximum eruption flow for Model 1a with various hot inflows and cold recharge permeabilities (units E-10 m^2).

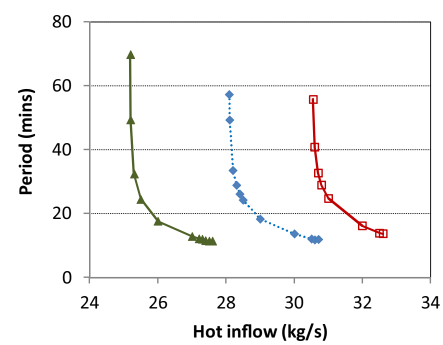

Fig. 11. Eruption period vs hot inflow for Model 1b with a chamber volume of 12.5 m^3 for three values of cold recharge permeability (units E-10 m^2).

6.4. Irregular geysering and continuous spouting (after late 1990s)

A very small further increase of hot inflow to 34.01 kg/s produces the irregular behaviour shown in Fig. 8 and a further increase in hot inflow produces the continual spouting behaviour shown in Fig. 9. Spouting persists for values of the hot upflow increasing up to 35.5 kg/s. For values of hot inflow of 35.7 kg/s and above, constant flow is obtained (not shown), i.e., the geyser turns into a hot spring.

6.5. Maximum eruption flow, Model 1a

From the maximum eruption height at Pohutu, Weir et al. (1992) estimated a flow rate of 98 kg/s. For the 1988 version of Model 1a, whose results are shown above in Fig. 6, the calculated maximum flow rate is higher at 155 kg/s. This value is relatively insensitive to the choice of the key model parameters, as shown in Fig. 10.

6.6. Smaller chamber volume, Model 1b

The results above were obtained using a chamber volume of 100 m^3, the value given by Weir et al. (1992). As shown in Fig. 5, none of the versions of Model 1a considered produced a period of eruption less than ~33 min, much larger than the value of 10.9 min measured by Saptadji in 1993.

In order to investigate this matter further, after much experimentation, Model 1b with a smaller chamber volume of 12.5 m^3 was set up. The resulting plot of geyser period vs hot inflow rate (analogous to Fig. 5) is shown in Fig. 11.

Thus with a smaller chamber and a cold recharge permeability of 2.5E – 10 m^2, it is possible to obtain the 1988 period of eruption of ~51 min (see Fig. 12). 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 Model 1b it is possible to obtain an eruption period of ~12 min with a relatively small increase of hot inflow to 27.3 kg/s (see Fig. 13). The results shown in Figs. 12 and 13 are consistent with a small increase in hot inflow to Pohutu geyser occurring between 1988 and 1993, causing the decrease in observed eruption period from 51 min (Weir et al., 1992) to 10.9 min (Saptadji, 1995).

6.7. Stages of eruption, Model 1b

Although the periods of eruption shown in Figs. 12 and 13 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).

It is common to separate the behaviour of a geyser into four stages: quiet, pre-play, rising eruption and falling eruption. The

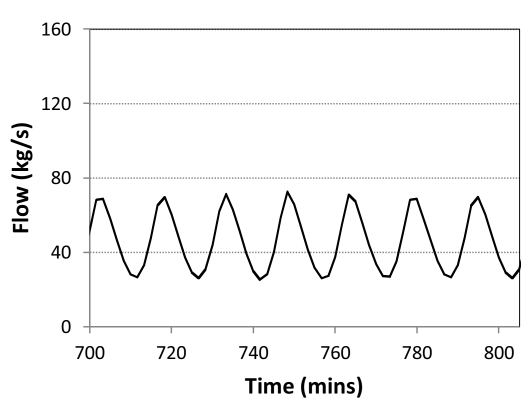

Fig. 9. Continual spouting for Model 1a with hot inflow of 34.1 kg/s.

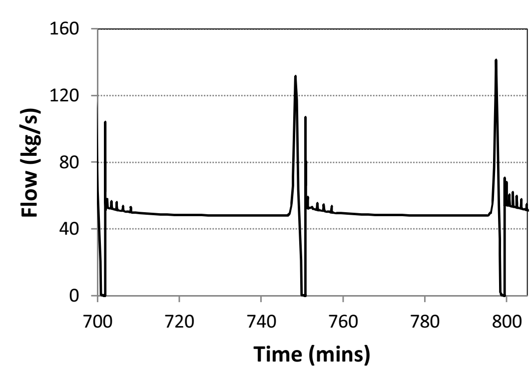

Fig. 12. Model 1b results for geyser eruption with a period ~51 min, hot inflow 25.2 kg/s and chamber volume 12.5 m^3.

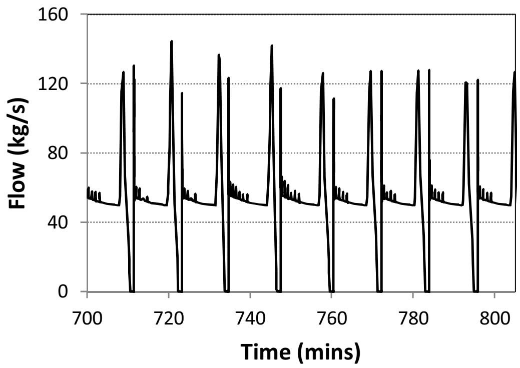

Fig. 13. Model 1b results for geyser eruption with a period 11.8 min, hot inflow 27.3 kg/s and chamber volume 12.5 m^3.

Table 8
Duration of the stages of a geyser, Model 1b.

Stage	Measured time (min)	Percent	Modelled time (min)	Percent
Quiet	3.7	34	0.9	7
Pre-play	2.1	19	9.5	74
Rising	3.7	34	1.3	10
Falling	1.4	13	1.1	8
Total	10.9	100	12.8	100

average values measured (Saptadji, 1995) for the lengths of these stages in August 1993 are listed in Table 8, together with values for a typical modelled eruption for Model 1b shown in Fig. 13.

There is a clear mismatch between the model results and the observations. In particular, Model 1b 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 Oldenburg, 2014) is required to resolve 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.

Saptadji (1995) found that the behaviour of her generic geyser models depended on the choice of relative permeability functions but with her Pohutu model she was unable to obtain geysering behaviour when she changed the immobile water fraction, k_{rl}, from 0.0 to 0.3 and the immobile steam fraction, k_{rv}, from 0.3 to 0.05 (using the Corey curves). The current models all use the Corey relative permeability curves with $k_{rl} = 0.0$ and $k_{rv} = 0.3$ (the same as Saptadji). For Model 2b (see below) we tried other values and found the maximum flow was changed but not the timing of the stages of the eruption (see Fig. 14). Further experimentation with other relative permeability curves may produce better results.

6.8. Pressure-dependent hot recharge, Model 2

The assumption of a constant hot inflow used with Model 1 may not be 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 (Shteinberg et al., 2013; Rudolph et al., 2012). Further, 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 larger reservoir model.

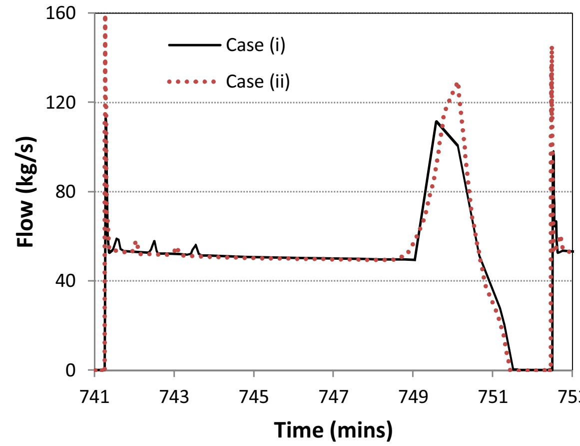

Fig. 14. One period of eruption for Model 2b, with chamber volume 12.5 m^3. Case (i) $k_{rl} = 0.0$ and $k_{rv} = 0.3$, Case (ii) $k_{rl} = 0.13$ and $k_{rv} = 0.35$.

As mentioned above, Model 2, the pressure dependent recharge model was set up with a bottom channel of length 90 m. The chamber volume for Model 2a was set to be 100 m^3, and for Model 2b it was 12.5 m^3.

Using the same parameters as listed in Tables 6 and 7 but with the hot inflow of 32 kg/s replaced by pressure dependent hot recharge, sourced from a block at a pressure of 11.41 bar (and again a temperature of 180 °C) an almost identical period of eruption was obtained with Model 2a as for Model 1a. A different permeability was required for the lower 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 results is shown in Fig. 15.

The results shown in Fig. 15 are very similar to those shown in Fig. 6. The main difference is in the slightly lower level of discharge in the period of play before full eruption begins. The length of the quiet period is not changed significantly.

The recharge flow is shown in Fig. 16. It varies by only a small amount and is similar to the constant value of 32 kg/s used in the version of Model 1a whose results were shown in Fig. 6.

As shown in Fig. 17, for both models with pressure-dependent recharge there is quite a narrow range of hot recharge pressures, $P_{HotRech}$, for which geysering occurs. The types of behaviour observed with Model 2a are given in Table 9.

For Model 2a, as with Model 1a, with constant hot inflow and the same chamber volume (100 m^3), the period of eruption does not drop below ∼33 min. For Model 2b a change in period from 51 min down to 10.8 min can be achieved by increasing the deep recharge pressure. However, for a period of 51 min (1988 conditions) the deep pressure is almost at the lower bound for which geysering

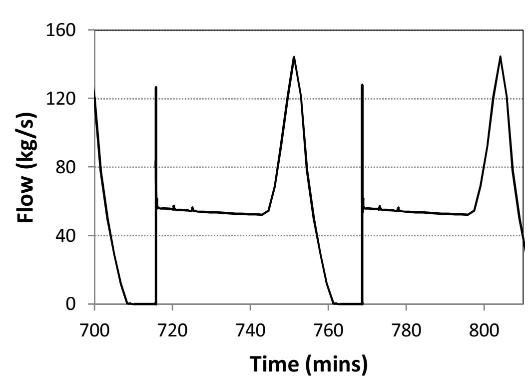

Fig. 15. Two cycles of eruption for Model 2a, with period ∼51 min, hot recharge pressure 11.41 bar and chamber volume 100 m^3.

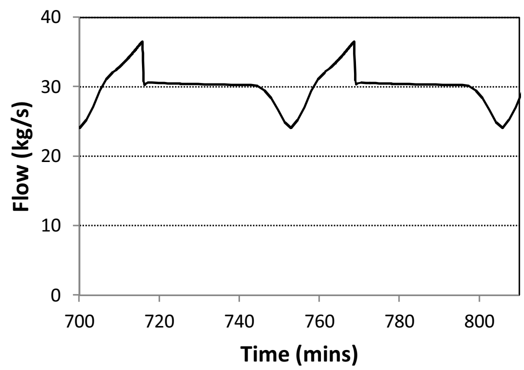

Fig. 16. Hot recharge flow for Model 2a, with period of eruption ~51 min, hot recharge pressure 11.41 bar and chamber volume 100 m^3.

Table 9
Behaviour of Model 2a for various values of hot recharge pressure.

$P_{HotRech}$	Behaviour
<11.18	Constant flow, warm spring
11.18–11.51	Geyser
11.512	Continual spouting
>11.52	Constant flow, hot spring

occurs for Model 2b. It is not clear whether or not Pohutu was on the verge of failure in 1988, or perhaps a chamber volume of 12.5 m^3 is not correct.

It is interesting to note that Fig. 3 shows an increase in shallow pressure equivalent to a water level change of ~2.0 m occurred at Rotorua between 1988 and 2015. This corresponds to a pressure increase of ~0.2 bar, which is consistent with the order of change in $P_{HotRech}$ for Model 2a that produces a change from geyering to continual spouting.

6.9. *Pressure of cold recharge, Model 2a*

Bradford (1992a) 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 models this corresponds to a change in the pressure of the cold recharge. The effect of varying the cold recharge pressure while keeping the hot recharge pressure constant, for Model 2a, is shown in Fig. 18 as Case (i). Geysering only occurs for a fairly narrow range, i.e.,

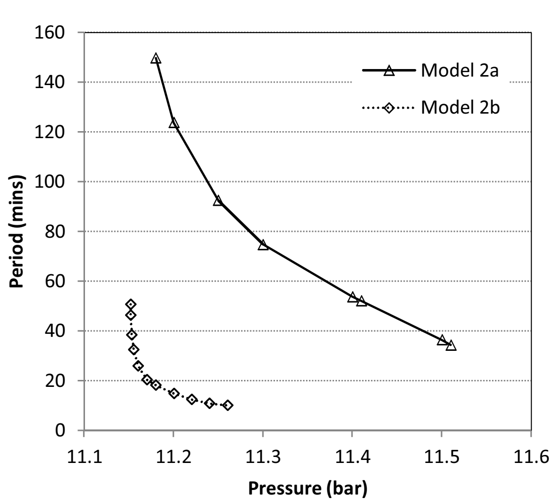

Fig. 17. Eruption period vs. hot recharge pressure, Models 2a and 2b.

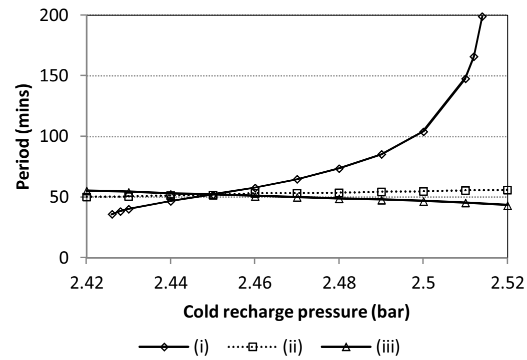

Fig. 18. Eruption period vs. cold recharge pressure, Model 2a. Three ratios for change in hot recharge pressure to change in cold recharge pressure: (i) 0, (ii) 3, (iii) 4.

2.426 bar ≤ $P_{ColdRech}$ ≤ 2.514 bar. For pressures just below the lower limit continual spouting occurs, and for pressures above the upper limit constant flow is obtained, i.e., hot spring behaviour.

The variation of hot recharge pressure and cold recharge pressure independently, as discussed above, may not be realistic as a recovery of the deep pressure is likely to be accompanied by some recovery of the shallow pressure. A check on our model of Rotorua (Ratouis et al., 2015, 2016) showed that the modelled pressure recovery between 1988 and 2015 at ~100 m depth near Whakarewarewa (where Pohutu is located) was approximately three to four times the recovery at 10 m depth. However there are no data to confirm these results. The results of simulations linking changes in the cold and hot recharge pressures are shown in Fig. 18. For a value of three for the ratio of the change in hot and cold recharge pressures the period of eruption increases slowly as the cold recharge pressure increases whereas for a factor of four it decreases, but not fast enough to match the observed 1988–2015 behaviour of Pohutu. Further experimentation varying the relative change of hot and cold recharge pressure is required to improve the model.

6.10. *Atmospheric pressure effects, Model 2a*

It has been previously reported that changes in barometric pressure can affect geyser behaviour (Saptadji, 1995; Leaver and Unsworth, 2007; Nikrou et al., 2013). This effect was tested for Model 2a by varying the pressure in the surface atmosphere block. The results in Fig. 19 show that the period of eruption decreases as the atmospheric pressure increases, but it is a small effect.

7. Conclusions

Our model results are qualitatively good as they show long-term, stable and approximately periodic eruptions. They correctly predict the transition from periodic geysering to irregular gey-

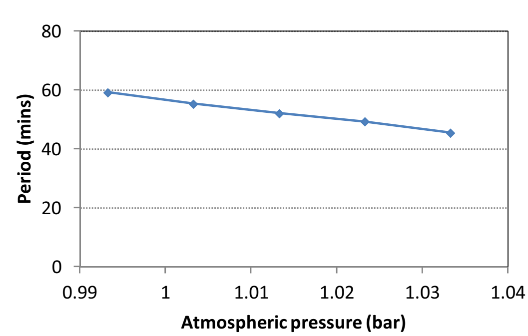

Fig. 19. Eruption period vs. atmospheric pressure, Model 2a.

sering, to continual spouting and then to hot spring behaviour. Thus the models we have produced can match the changes in the behaviour observed at Pohutu geyser as the deep pressures have recovered since the bore closures in the mid-1980s. However the quantitative details are not correct, first, because the observed behaviour of Pohutu is more erratic (Cody and Simpson, 1985) than our models can predict and, secondly, because the details of the eruption cycle predicted by the models are incorrect. 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.
(iv) The relative permeability functions, controlling the relative movement of water and steam, used in the models may not be correct and more experimentation with them is required.
(v) Recent statistical analysis (Langrock, 2012; Vicari and Van Dorp, 2013) of eruption data for Old Faithful and a dynamical system approach for modelling geysers (Raye, 2005; Landa and Vlasov, 2009) both suggest that a model with more degrees of freedom than that considered here may be required to represent geyser dynamics accurately. It may be necessary to have more than one chamber, more than one hot and/or cold recharge areas, or even distributed recharge as in the model of Kiryukhin (2015).
(vi) The models discussed do not include any non-condensible gases, such as carbon dioxide. At Rotorua there is a significant amount of carbon dioxide in the geothermal aquifers (up to ~1000 mg/kg at Whakarewarewa) whose presence affects boiling conditions (Ratouis et al., 2015, 2016). In the future gases will be included in our geyser model.

Therefore the models discussed here are a good first step towards understanding geyser behaviour, but more research is required to fully understand and to accurately model geothermal geysers.

References

Allen, E.T., Day, A.L., 1935. Hot Springs of the Yellowstone National Park. Carnegie Institution of Washington, Publication No. 466, 525 pp.

Benseman, R.F., 1965. The components of a geyser. N. Z. J. Sci. 8, 24–44.

Bradford, E., Cody, A.D., Glover, R.B., 1987. Rotorua Hot Spring Data 1982–1987. Geothermal Report 11. New Zealand Department of Scientific and Industrial Research, Wellington, 160 pp.

Bradford, E., 1992a. Pressure changes in Rotorua geothermal aquifers, 1982–1990. Geothermics 21, 231–248, Special Issue: Rotorua Geothermal Field, New Zealand.

Bradford, E., 1992b. Flow changes from lake Roto-a-Tamaheke, Whakarewarewa. Geothermics 21l, 249–260.

Bryan, T.S., 1986. The Geysers of Yellowstone. Colorado Associated Press, Boulder, Colorado, 299 pp.

Cody, A.D., Simpson, B., 1985. Natural hydrothermal activity in Rotorua. In: Technical Report of the Rotorua Geothermal Monitoring Programme. Ministry of Energy, pp. 227–273.

Donaldson, I.G., 1985. Long term changes in thermal activity in the Rotorua-Whakarewarewa area. In: Technical Report of the Rotorua Geothermal Monitoring Programme. Ministry of Energy, pp. 83–225.

Finsterle, S., 1999. iTOUGH2 User's Guide. Rep. LBNL-40040. Lawrence Berkeley National Laboratory, Berkeley, California.

Fix, P.F., 1949. Regularity of Old Faithful Geyser, Yellowstone National Park, Wyoming. Am. J. Sci. 247, 246–256.

Hayba, D.O., Ingebritsen, S.E., 1994. The computer model HYDROTHERM, a three-dimensional finite-difference model to simulate ground-water flow and heat transport in the temperature range of 0–1200 °C, U.S. Geological Survey, Water Resources Investigations Report, 94–4045, 85 pp.

Hurwitz, S., Sohn, R.A., Luttrell, K., Manga, M., 2014. Triggering and modulation of geyser eruptions in Yellowstone National Park by earthquakes, earth tides, and weather. J. Geophys. Res. Solid Earth 119, 1718–1737.

Hutchison, R.A., Westphal, J.A., Kieffer, S.W., 1997. In situ observations of Old Faithful Geyser. Geology 25 (10), 875–878.

Ingebritsen, S.E., Rojstaczer, S.A., 1993. Controls on geyser periodicity. Science 262, 889–892.

Ingebritsen, S.E., Rojstaczer, S.A., 1996. Geyser periodicity and the response of geysers to deformation. J. Geophys. Res. 101 (B10), 21891–21905.

Kiryukhin, A., 2015. Modeling of geyser response to 3.06.2007 and 3.01.2014 catastrophic landslides-mudflows (Kronotsky nature reserve, Kamchatka, Russia). In: Proceedings 40th Workshop on Geothermal Reservoir Engineering, Stanford University, California, USA.

Kissling, W., 2014. Rotorua Geothermal Bore Water Level Assessment-2014. GNS Science Consultancy Report 2014/199.585, 39 pp.

Landa, P., Vlasov, D., 2009. The geyser as a self-oscillatory system. Randomness or dynamical chaos? J. Mech. Eng. Sci. 223, 1103–1111.

Langrock, R., 2012. Flexible latent-state modelling of Old Faithful's eruption inter-arrival times in 2009. Aust. N. Z. J. Stat. 54 (3), 261–279.

Leaver, J.D., Unsworth, C.P., 2007. Fourier analysis of short-period water level variations in the Rotorua geothermal field, New Zealand. Geothermics 36, 539–557.

Lloyd, E.F., 1975. Geology of Whakarewarewa Hot Springs. A.R. Shearer, Government Printer, Wellington, New Zealand, 23 pp.

Lu, X., Watson, A., Gorin, A.V., Deans, J., 2005. Measurements in a low temperature CO2-driven geysering well, viewed in relation to natural geysers. Geothermics 34, 389–410.

Munoz-Saez, C., Manga, M., Hurwitz, S., Rudolph, M.L., Namiki, A., Wang, C.-Y., 2015. Dynamics within geyser conduits, and sensitivity to environmental perturbations: insights from a periodic geyser in the El Tatio geyser field, Atacama Desert, Chile. J. Volcanol. Geotherm. Res. 292, 41–55.

New Zealand Ministry of Energy Oil and Gas Division: The Rotorua Geothermal Field, 1985. Technical Report of the Geothermal Monitoring Programme 1982–1985. Ministry of Energy, 522 pp.

Nikrou, P., Newson, J., McKibbin, R., Luketina, K., 2013. Geothermal spring temperature analysis. In: Proceedings 35th New Zealand Geothermal Workshop, Rotorua, New Zealand, 17–20 November.

O'Hara, K.D., Esawi, E.K., 2013. Model for eruption of the Old Faithful Geyser, Yellowstone National Park. GSA Today 23 (6), 4–9.

Pan, L., Oldenburg, C.M., 2014. T2Well—an integrated wellbore-reservoir simulator. Comput. Geosci. 65, 46–55.

Pruess, K., Oldenburg, C., Moridis, G., 1999. TOUGH2 User's Guide, Version 2.0. Lawrence Berkeley National Laboratory, Earth Sciences Division, Berkeley, California.

Ratouis, T.M.P., O'sullivan, M.J., O'sullivan, J.P., 2015. An updated numerical model of Rotorua geothermal field. In: Proceedings World Geothermal Congress 2015, Melbourne, Australia.

Ratouis, T.M.P., O'sullivan, M.J., O'sullivan, J.P., 2016. A numerical model of Rotorua geothermal field. Geothermics 60, 105–125.

Raye, J.K., 2005. Using nonlinear dynamics to predict Old Faithful. Math. Comput. Model. 41, 679–687.

Rinehart, J.S., 1980. Geysers and Geothermal Energy. Springer-Verlag New York Inc, 233 pp.

Rojstaczer, S.A., Galloway, D.L., Ingebritsen, S.E., Rubin, D.M., 2003. Variability in geyser eruptive timing and its causes: Yellowstone National Park. Geophys. Res. Lett. 30 (18), 2-1–2-4.

Rudolph, M.L., Manga, M., Hurwitz, S., Johnson, M., Karlstrom, L., Wang, C.-Y., 2012. Mechanics of Old Faithful Geyser, Calistoga, California. Geophys. Res. Lett. 39, L24308.

Saptadji, N.M., O'Sullivan, M.J., Freeston, D.H., 1994. Mathematical models of some geysers at Rotorua geothermal field, New Zealand. Geotherm. Sci. Technol. 4 (l), 37–75.

Saptadji, N.M., 1995. Modelling of Geysers. PhD Thesis. University of Auckland, Auckland, New Zealand.

Scott, B.J., Gordon, D.A., Cody, A.D., 2005. Recovery of Rotorua geothermal field, New Zealand: progress, issues and consequences. Geothermics 34, 159–183.

Shteinberg, A., Manga, M., Koolev, E., 2013. Measuring pressure in the source region for geysers, Geyser Valley, Kamchatka. J. Volcanol. Geotherm. Res. 264, 12–16.

Steinberg, G.S., Merzhanov, A.G., Steinberg, A.S., 1981a. Geyser process: its theory, modelling and field experiment. Part 1. Theory of the geyser process. Mod. Geol. 8, 67–70.

Steinberg, G.S., Merzhanov, A.G., Steinberg, A.S., Rasina, A.A., 1981b. Geyser process: its theory, modelling and field experiment. Part 2. A laboratory model of a geyser. Mod. Geol. 8, 71–74.

Steinberg, G.S., Merzhanov, A.G., Steinberg, A.S., 1981c. Geyser process: its theory, modelling and field experiment. Part 3. On metastability of water in geysers. Mod. Geol. 8, 75–78.

Steinberg, G.S., Merzhanov, A.G., Steinberg, A.S., 1981d. Geyser process: its theory, modelling and field experiment. Part 4. On seismic influence on geyser regime. Mod. Geol. 8, 79–86.

Vandemeulebrouck, J., Roux, P., Cros, E., 2013. The plumbing of Old Faithful Geyser revealed by hydrothermal tremor. Geophys. Res. Lett. 40, 1989–1993.

Vicari, D., Van Dorp, J.R., 2013. On a bounded bi-modal two-sided distribution fitted to the Old-Faithful geyser data. J. Appl. Stat. 40 (9), 1965–1978.

Weir, G.J., Young, R.M., McGavin, P.N., 1992. A simple model for geyser flat. Geothermics 21, 281–304.

White, D.E., 1967. Some principles of geyser activity, mainly from steamboat springs, Nevada. Am. J. Sci. 265, 641–684.