Effects of reinjecting diluted mineral pool water into the Rotorua Geothermal System

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ABSTRACT

This work presents the results of a geochemical modelling study into the potential effects of reinjection of dilute geothermal brine (i.e. dilution by bathing waters) into the geothermal aquifer of the Rotorua Geothermal System (RGS). It also summarizes the potential environmental effects from reinjection or discharge to surface waters, from both the release of pathogenic microorganisms, and the potential for biochemical changes to the environment by microbes.

The results of this study show that reinjection will have a small effect on the water composition of the shallow geothermal aquifer fluid proportional to the reinjection rate. At reinjection rates of 50 and 100 t day^{-1} (both at fluid temperatures of 120°C and 150°C) changes to the aquifer chemistry are minimal. Changes in the concentration of conservative elements will be insignificant as these are modelled to be within the ± 2% uncertainty of the aquifer brine composition. Less mineral precipitates are expected when injecting diluted brine compared to undiluted

A measurable change in pH is found only at high reinjection rate (800 tonne day^{-1}) up to 800 m from the well. There will be a measurable pH change and substantial decrease in the SiO_2 concentration, which could impact surrounding wells and surface geothermal features.

Reinjection of water from mineral pools, or discharge to surface waters, poses a risk of release of human pathogens. Pathogens may infiltrate groundwater or surface water and present a hazard through inhalation, skin contact, or ingestion of contaminated food. Microorganisms identified in nearby surface features indicate that there may also be environmental risks from the natural geothermal microbial populations. These range from increased biofilm formation leading to reduced permeability, to the production of toxic and corrosive H_2S. The gradient of risk depends on the types of microorganism, volumes and dilutions of water reinjected, and the receiving environment, particularly temperature and pH. Filtration is recommended to remove the natural microbial population and pathogens and reduce the risk of adverse effects from their metabolic processes.

PART 1: GEOCHEMISTRY

1. INTRODUCTION

The Rotorua Geothermal System (RGS) is a globally unique geothermal system that has been extensively utilized over last 50 years. The RGS, like other geothermal systems in the Rotorua-Taupō area, is a product of large-scale volcanism and rifting. It is coincidentally within a modern city in which brine extraction is occurring and numerous surface manifestations are found including geysers, hot springs, mud pools and pots, and warm ground (Scott et al., 2016).

Only the shallow Rotorua geothermal aquifer has been used for extraction, therefore, the RGS brine composition is known only from shallow commercial wells and natural springs. No deep wells (>500 m) have been drilled in the RGS thus the precise composition of the deep fluid is not well known (Scott et al., 2021). The shallow fluid chemistry is inhomogeneous and varies throughout the RGS (Scott et al. 2016). According to the different in fluid chemistries, the RGS can be divided into three separate zones: Kuirau Park in the north-west; Ngāpuna in north-east; and Whakarewarewa in the south (Figure 1).

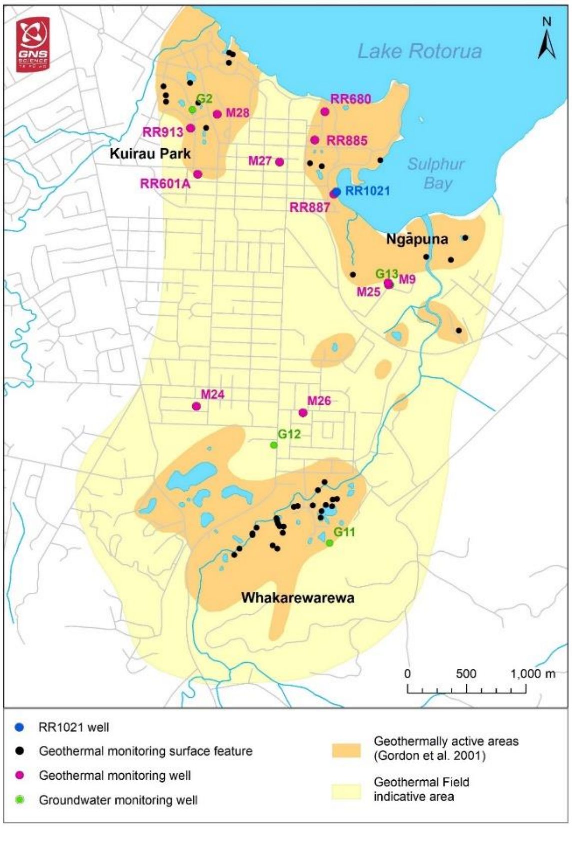

Figure 1: Locations of currently monitored sites in the RGS by BOPRC

Bay of Plenty Regional Council (BOPRC) has commissioned GNS Science (GNS) to investigate potential chemical, biological and physical effects of reinjection of diluted geothermal brine into the shallow part (100–300 m depth) of the Rotorua Geothermal System (RGS). Geothermal brine is used extensively in the RGS as a source of fluid for bathing in motels, hotels, public pools, and private pools. It is common practice for geothermal brine to be diluted with town water in order to cool it down for bathing purposes. The diluted fluid is then reinjected into the RGS.

The goal of the present study is to investigate the geochemical and biological effects reinjecting diluted brine on the RGS. The outcome of this work will broaden the knowledge on potential effects of reinjection and will help inform decisions on sustainable management.

2. THE MODEL

2.1 Methodology

In order to investigate the physical and chemical effects of reinjection of diluted geothermal brine on the aquifer fluid and surface features, we use multicomponent reaction modelling. The software tool REACT (Geochemist's Workbench® 2021) was employed to simulate multicomponent reactions (i.e. fluid mixing). The presented model is idealized but is considered representative of the reinjection process in the RGS.

The model is divided into three steps. Each step represents part of the brine flow-path (Figure 2). The first step is the extraction of the brine, at aquifer temperature and pressure, from the production well and boiled at atmospheric pressure where it loses most of its non-condensable gases (mainly CO_2 and H_2S). The boiled fluid is further aerated to remove any remaining toxic H_2S. In the next step, the degassed fluid is mixed with town water.

For purpose of this study a ratio of brine to town water of 1:1 (the highest ratio) has been used. This mixture comprises the bathing pool fluid (40°C). The residence time of the pool fluid is set to four hours. The final step is the reinjection of the diluted brine back into the aquifer via a reinjection well where it mixes with the original geothermal brine. This three-step model has some limitations which are discussed below.

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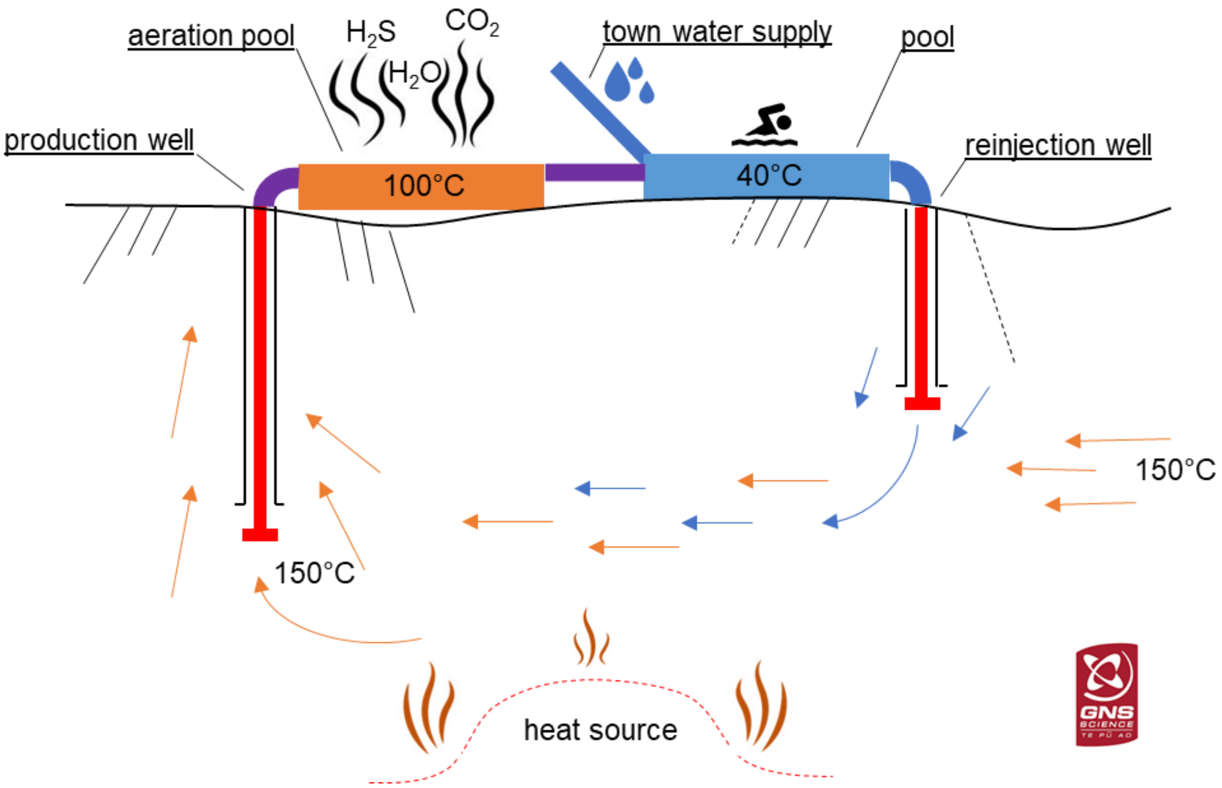

Figure 2: A simplified diagram showing the flow path of the geothermal brine as it is extracted and degassed, mixed with town supply and used for bathing, followed by reinjection back into the aquifer.

2.2 Model Parameters

Production wells of the RGS are characterized by a range of temperatures, with a minimum of ~30°C and up to a maximum of ~160°C. The average production temperature is 110°C. For this study, two representative temperatures of aquifer fluid have been selected; 120°C and 150°C. Lower temperatures (< 100°C) have been omitted from this study, as at these low temperatures silicate mineral reactions are generally too slow to induce any significant changes in chemistry of fluid.

Consented maximum mass discharge values have been used to model the reinjection rates as there are no measurements of actual fluid reinjection rates available. The consented values are up to 800 tonne day^{-1} and as low as 50 tonne day^{-1}. Note that, the actual reinjection rates might be lower than the consented values. The following discharge rates have been considered in the model: 50, 100, 300 and 800 tonne day^{-1}.

Water chemistry in the aquifer will depend on the amount of mixing that occurs between the reinjected fluids and the aquifer water. We expect that more mixing will occur as the reinjected fluids move away from the reinjection point.

It is not trivial to predict the spatial mixing of the two fluids. The dynamics of mixing is dependent on the flow rates of the fluids and the permeability of the aquifer including width, spacing, and orientation of fractures. For this reason, some assumptions are necessary.

Previous numerical modelling has shown that the majority of the RGS fluid flows from the south to the north at a flow rate of 10 kg sec^{-1} (Burnell, 2020). Therefore, if the reinjection rate of the pool fluid is 10 kg sec^{-1} then the mixing ratio is the assumed maximum value of 1:1. Whereas, if injection rate was equal 50 tonnes day-1 (~0.6 kg sec^{-1}) the mixing ratio has is 1:17 (Table 1.1).

Table 1: Conversion of injection flow rates used in this study. It has been assumed that the aquifer flow rate is 10 kg sec^{-1} (~800 ton day^{-1}).

Injection Rate		Ratio
tonne day^{-1}	kg sec^{-1}	Injection fluid: Aquifer Fluid
800	9.26	1:1
300	3.47	1:3
100	1.16	1:9
50	0.58	1:17

The direction of flow of the aquifer fluid and the reinjected brine is dependent on the local geology. However, for this study it has been assumed that the aquifer and reinjected fluid mixture travel in one direction.

To estimate mixing rates with distance from the reinjection point, we use a previously developed model of tracer dispersion in the RGS that was employed by Burnell (2020) (Figure 3). We assume that the injected fluid can be considered to behave similar to a tracer and will follow this dilution model.

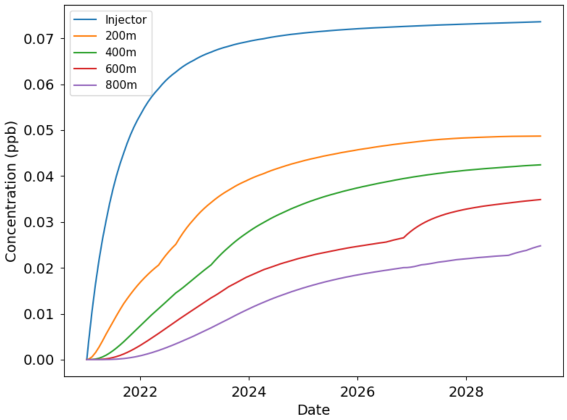

Figure 3: Model of dispersion of a tracer injected into the RGS (Burnell 2020).

2.3 Fluid Compositions

In this study town supply water was used to dilute the geothermal fluid in the ratio 1:1 (town water: geothermal fluid). The town supply composition is characterized by low cation and anion concentrations and a near neutral pH (Table 2).

Table 2: Town water composition used in this work.

Analyte		Town Water
pH		7.3
Chloride	mg L^{-1}	5.4
Sulphate	mg L^{-1}	2.8
Calcium	mg L^{-1}	2.3
Boron	mg L^{-1}	0.01
Sodium	mg L^{-1}	10.01

The RGS is tapped from a series of shallow production and reinjection wells. The majority of wells are located in the north part of Rotorua City (Figure 1). The individual fluid compositions of these bores are variable and depends on local geology and the depth of the well. The purpose of this study was to examine a hypothetical scenario of reinjection which can be applied to the whole RGS. Hence, for the purposes of this study, the chemistry of a production well RR1021 has been employed (Table 3). Well RR1021 is located in Government Gardens. The well has a long history of regular sampling and shows a stable composition. It has been assumed that the fluid from this well is near equilibrium with respect to production and natural recharge (Mroczek et al., 2011).

The mineral pool fluid is derived from flushed geothermal brine. In the chemical model the geothermal brine utilized is assumed to have the composition of well RR1021. In order to obtain the input boiled brine chemistry, it is necessary to adjust the composition for boiling to 100°C.

The recent chemical analysis for selected components in well RR1021 is available (Table 3). This sample was collected at the wellhead pressure of ~3 bar using a separator. The mineral pool is filled with brine that has boiled to 100°C. In order to obtain its composition, the software programme WATCH was used to simulate the boiling of the fluid from 3 bar and 145°C to 1 bar and 100°C (Appendix 3). The results for selected components are shown in Table 1.3.

After boiling to 100°C, the brine passes to the aeration pool, an example of which is pictured in Figure 1.6. In this pool the concentrations of H_2S and CO_2 are reduced, and temperature decreases due to aeration. Assuming the highest efficiency of aeration, the lowest value for H_2S obtained from analysis of the aeration pool (11.5 mg L^{-1}) has been used in the modelling. The concentrations of the remaining analytes from the analysis of the aeration pool fluid were not used due to lack of information on its exact sampling location. Instead, the concentrations of these analytes generated in WATCH were used.

Table 3: RR1021 well chemistry composition from 6 February 2019 (complete details in Appendix 2) and composition obtained from WATCH after boiling to 100°C.

Analyte		Measured	WATCH
pH		8.3	8.5
Chloride	mg L^{-1}	379	414
Sulphate	mg L^{-1}	46	50
Calcium	mg L^{-1}	8.7	9.5
Boron	mg L^{-1}	5.5	6.0
Sodium	mg L^{-1}	482	527
SiO_2	mg L^{-1}	285	312

The temperatures of the shallow aquifer in the RGS are variable. These are mostly dependent on the depth of the well and its location. For deeper wells (~130 m) temperatures reach 150°C (Scott et al., 2021). In this study, two geothermal aquifer temperatures (120°C and 150°C) have been considered.

The chemical composition of the aquifer fluid also changes across the RGS. Due to this variability, it is challenging to select one representative brine composition for the whole RGS. The composition of the RR1021 fluid has been employed, because of availability of quality of data and relatively long history of sampling. It is also assumed that the geothermal aquifer fluid (at 120°C and 150°C) is at chemical equilibrium with geothermal aquifer rock mineralogy and not supersaturated with respect to common rock-forming minerals. Using the above assumptions, the compositions of the geothermal aquifer fluid at both temperatures have been calculated using REACT. These are shown in Table 4.

Table 4: Aquifer composition recalculated in GWB® using RR1021 well chemistry.

Analyte		120°C	150°C
pH		7.7	7.7
Chloride	mg L^{-1}	371	371
Sulphate	mg L^{-1}	45	45
Calcium	mg L^{-1}	1.6	0.7
Boron	mg L^{-1}	5.4	5.4
Sodium	mg L^{-1}	472	472
SiO_2	mg L^{-1}	184	272

2.4 Descriptions of Model Scenario

For each scenario run with the model (Figure 1.7), the following steps were taken:

1. Calculate the initial composition of the boiled geothermal brine (Fluid A) using WATCH.

2. a) Mix boiled geothermal brine with town supply (Fluid B) in 1:1 ratio using GWB® to give pool water composition (Fluid C); b) reference scenario with no dilution (i.e. no town water is mixed with geothermal brine) using town supply.

3. Mix pool water (Fluid C) back into geothermal aquifer fluid (Fluid D) at required ratios (Table 1.1) which results in Fluid E.

4. Re-dilution of Fluid E further away from the injection point with Fluid D.

Additional assumptions include:

1. There is no mineral precipitation in the mineral pool fluid (Fluid C).

2. The geothermal aquifer fluid (Fluid D) is in chemical and thermal equilibrium with the aquifer at 120°C or 150°C.

3. Only the minerals anhydrite ($CaSO_4$), amorphous silica (SiO_2), calcite ($CaCO_3$), cristobalite (SiO_2), pyrite (FeS_2) and Ca-Saponite clay ($Ca_{0.165}Mg_3Al_{0.33}Si_{3.67}O_{10}(OH)_2$) are considered as possible precipitates in the geothermal aquifer.

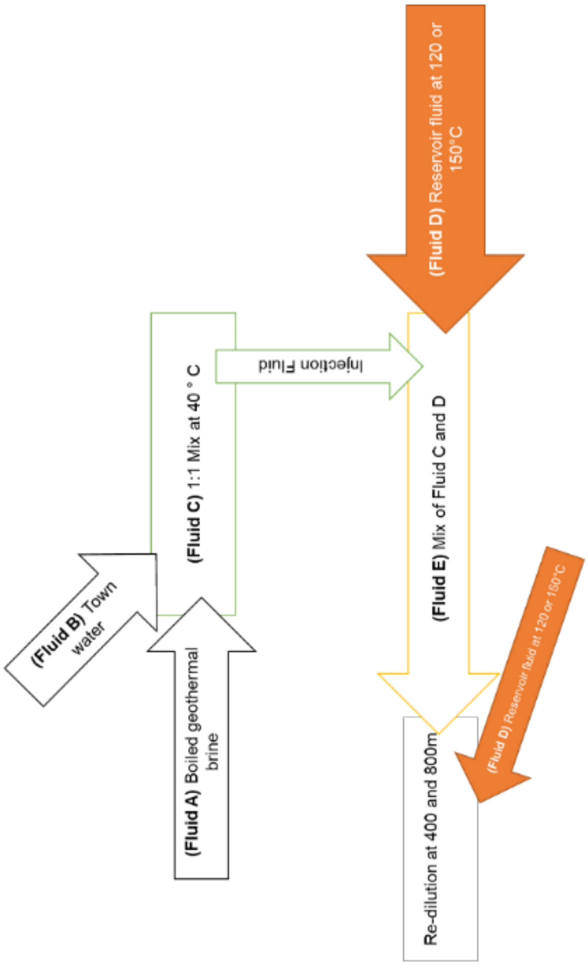

Figure 4: The conceptual flow chart of the model.

3. MODEL RESULTS

3.1 Reinjection into a 120°C Aquifer

Geothermal brines contain many different dissolved components. Some of these are often considered as conservative (e.g. Cl). Conservative elements do not take part in mineral reactions and their concentrations remain unchanged except during processes such as boiling and mixing. For example, the proportions of mixing of diluted mineral pool fluid (low Cl concentration) with geothermal aquifer fluid (high Cl concentration) can be determined based on the mixed fluid's Cl concentration.

Figure 5 shows the Cl and B concentration changes during reinjection of diluted fluid and, for comparison, undiluted geothermal brine (Figure 5b & d) versus the distance from reinjection point. At distance 0 m, the fluid is a mixture of reinjection fluid and aquifer fluid presented as Fluid E on Figure 4. The dotted line shows the original geothermal aquifer concentration ± 2% uncertainty (dashed lines). It is assumed that all calculated concentrations falling within ± 2% of the original concentration are the same within uncertainty.

The results show that injection of diluted brine at rate 50 and 100 t day^{-1} results in little change to the geothermal aquifer fluid composition. At injection rates of 300 t day^{-1} and 800 t day^{-1}, when diluted fluid is reinjected, the composition change of the geothermal aquifer is considerable for both Cl and B. At 300 t day^{-1} and 800 m from the reinjection point, the mixed composition lies slightly below the original brine. At 800 t day^{-1} the mixed composition is noticeable below the original and it will take another several hundred of meters for the brine to reach the original composition. For the injection of undiluted geothermal brine at all rates there are no significant changes in geothermal aquifer composition > 800 m from the reinjection point.

The concentrations of non-conservative species are altered due to changes in temperature, pH, fluid mixing and fluid-rock interaction. Such changes can induce mineral precipitation and/or mineral dissolution. For example, dissolved SiO_2 concentration can increase or decrease depending on the temperature of the fluid as it equilibrates with silica minerals. Dissolved cations such as Na, K, or Ca or gases (e.g. H_2S, CO_2) can also be non-conservative. In order to determine the behaviour of non-conservative species it is necessary to model changes in temperature, pH, and fluid composition due to mixing or fluid-rock interaction.

In the present model, it has been assumed that the aquifer fluid, when cooled down by reinjection of diluted brine, is not reheated by the geothermal aquifer rock and only gains temperature by mixing with further hotter geothermal aquifer fluid. Figure 6 shows the modelled temperature, pH, and SiO_2 concentration changes with the distance from the reinjection point at the four injection rates. It is possible that reheating of the aquifer by the geothermal aquifer rock would minimize the SiO_2 concentration changes and enhance calcite precipitation.

The results show that a measurable pH increase (+ 0.25 log units) will occur only at 800 t day^{-1} and only adjacent to the rejection well (Figure 6a,&6b). In the remaining cases, the pH shift is approximately +0.1 log units. This is likely to be close to the estimated errors given the challenges of calculating highly accurate pH values under these conditions.

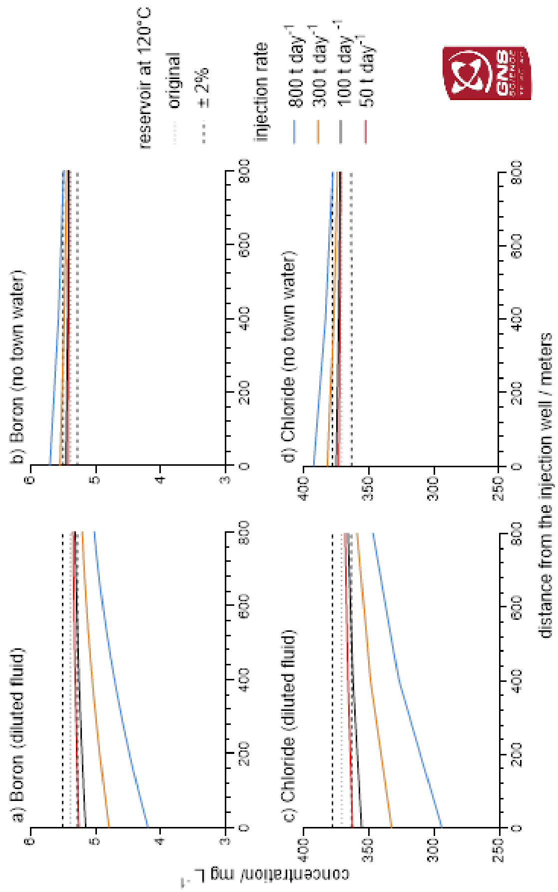

Figure 5: Concentration (mg kg^{-1}) of B (a,b) and Cl (c,d) versus distance (m) from a reinjection well at a geothermal aquifer temperature of 120°C at four reinjection rates (t day^{-1}). The left diagrams show the results for diluted brine and the right diagrams are for undiluted brine. Dotted lines are the original geothermal aquifer composition. Dashed lines are ± 2% of this concentration.

In contrast, the temperature of the mixed fluid will decrease significantly, especially at reinjection rate of 300 and 800 t day-1 (Figure 6c). Also affected are the concentrations of dissolved species. For example, mixing the diluted brine with the geothermal aquifer fluid causes a decrease in SiO_2 concentration (Figure 6d). The change in temperature also causes SiO_2 to re-equilibrate with the silicate phases which also results in an additional decrease. The temperature of the geothermal aquifer may change over a long distance and thus affect the surrounding features.

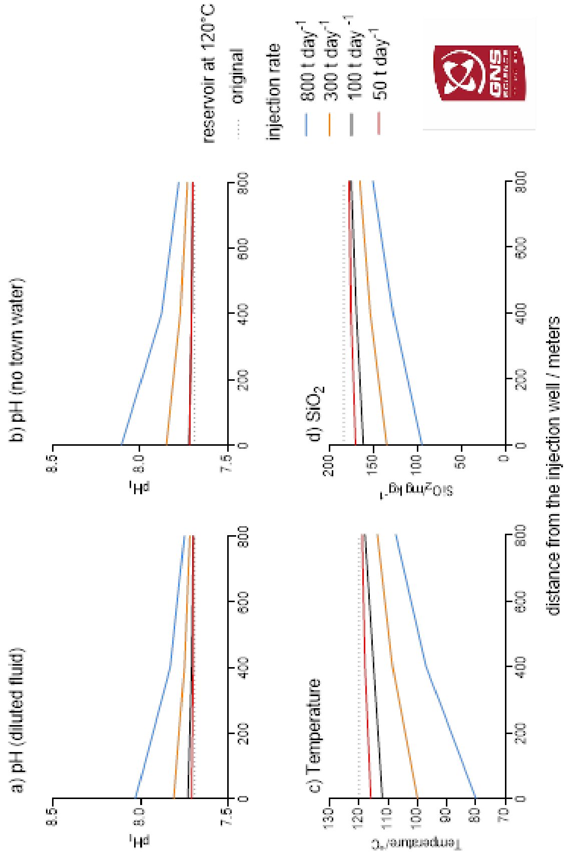

Figure 6: pH at temperature (pHt) (a,b), temperature (c), and silica concentration (d) versus distance (m) from the reinjection well at a aquifer temperature of 120°C at four reinjection rates. For comparison, reinjection of undiluted geothermal is shown in (b).

Ca concentration is also dependent on changes in temperature and fluid composition. This is due to its concentration being controlled by Ca-bearing minerals. In the present model these are calcite, anhydrite, and Ca-saponite. The results show that during diluted fluid reinjection, Ca concentration should increase (Figure 7a), however, this does not consider the saturation state of Ca-bearing minerals.

Figure 8a and b show the saturation state of the minerals considered in this study and Figure 8c and d show the calculated amount of these minerals in grams per tonne of fluid reinjected. The results show that the diluted brine, when mixed with the aquifer fluid, becomes slightly oversaturated with respect to calcite and cristobalite, and oversaturated with respect to Ca-saponite and pyrite (Figure 8a). A similar result is found when undiluted brine is reinjected, however the saturation indices for these minerals are higher (Figure 8b).

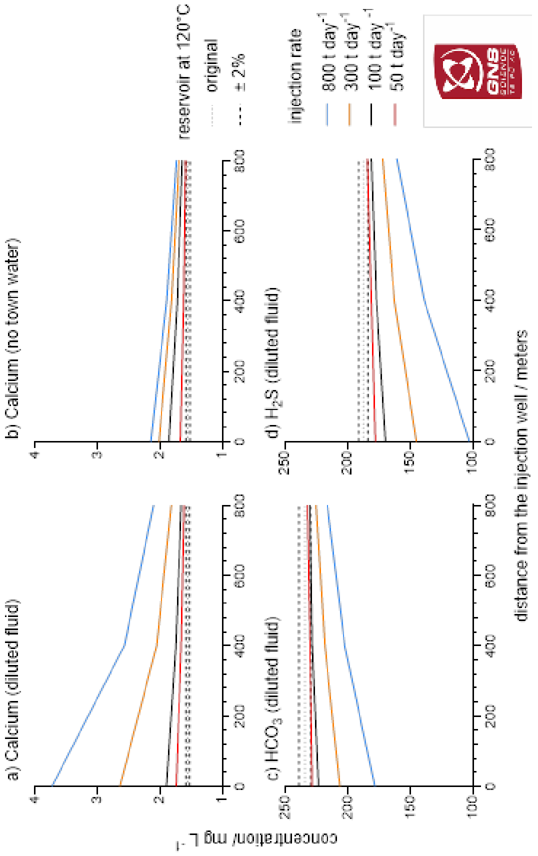

Figure 7: Ca (a,b), HCO3 (c), and H2S (d) concentration versus distance (m) from the reinjection well at an aquifer temperature of 120°C at four reinjection rates. For comparison, the effect on Ca of the reinjection of undiluted geothermal is shown in (b).

Oversaturation with respect to some minerals indicates that these minerals will precipitate. Because of the low temperature (120°C), the precipitation rates will be slow. Nevertheless, the small changes in concentration mean that the amount of precipitated minerals is minor. The estimated maximum amount of precipitated mineral is for calcite is 0.24 g t^{-1} brine at a reinjection rate of 100 t day^{-1} (Figure 8c). For the undiluted brine, a much larger amount of calcite is precipitated because of the brine's higher Ca concentration. Maximum calcite precipitation of 8.5 g t^{-1} brine occurs at a reinjection rate of 800 t day^{-1} while 0.8 g t-1 brine is precipitated at a reinjection rate of 50 t day^{-1} (Figure 8d).

The reinjected fluid (either diluted or not diluted) has a lower concentration of HCO_3 and H_2S when compared to the aquifer fluid. This results in a decrease in concentrations of these species which is most notable at high injection rates (Figure 7c,d). The lowering in concentration of these species indicates that there might be an impact on acid-sulphide features which depends on H_2S presence in the aquifer.

Because pyrite is highly insoluble at the pH values encountered, the small amounts of Fe and H_2S in the mixed fluid would result in pyrite precipitation (Figure 8c). The presence of Al, Ca and SiO_2 in the mixed fluid also indicates that Ca-saponite clay precipitation is also expected (Figure 8c). However, the amounts of these two minerals is minor, both in the diluted and undiluted brine.

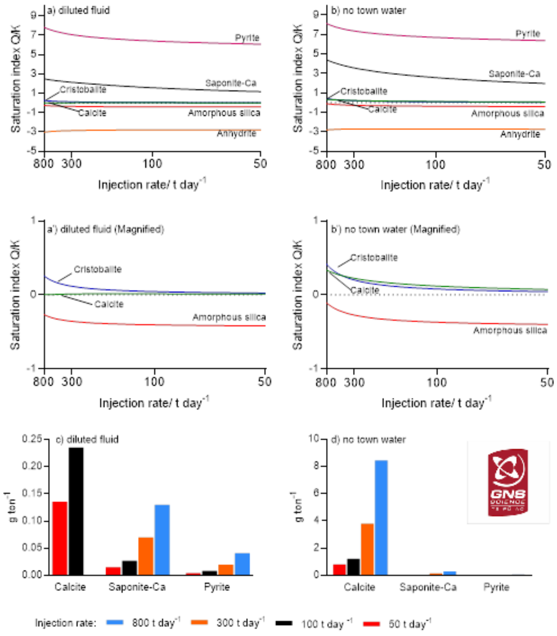

Figure 8: a,b) Mineral saturation index versus reinjection rate calculated using GWB. The fluid is saturated with respect to a mineral when its saturation index is greater than zero (dashed line) and undersaturated when less than zero. c,d) Calculated mass of precipitated minerals in grams per tonne of brine.

3.1 Reinjection into a 150°C Aquifer

Figure 9 shows the Cl and B concentrations during reinjection of diluted and undiluted brine (no town water) versus distance from the reinjection well. The dotted line shows the original aquifer concentrations. The dashed lines are ± 2% of the aquifer concentration, considered the uncertainty. Because the concentration of conservative species is not dependent on temperature, the concentration profiles of these species are the same as those modelled at 120°C. As before, only at high reinjection rates (300 tonne day^{-1} and above) are large changes observed (for example decrease in concentration of Cl- by 77 mg L^{-1}).

The concentration of non-conservative elements will be affected by changes in temperature and pH, and by mineral precipitation or dissolution. As at 120°C, at 150°C calculated pH change will be measurable only at 800 t day^{-1} and only near the rejection well (Figure 10a,b).

Figure 10c shows the temperature profile versus distance from the reinjection well. Substantial decreases in temperature are observed especially at 300 and 800 t day^{-1} reinjection rate (for example drop to temperature below 100°C at 800 t day^{-1}). Decreases in SiO2 concentration also result from reinjection (Figure 10d).

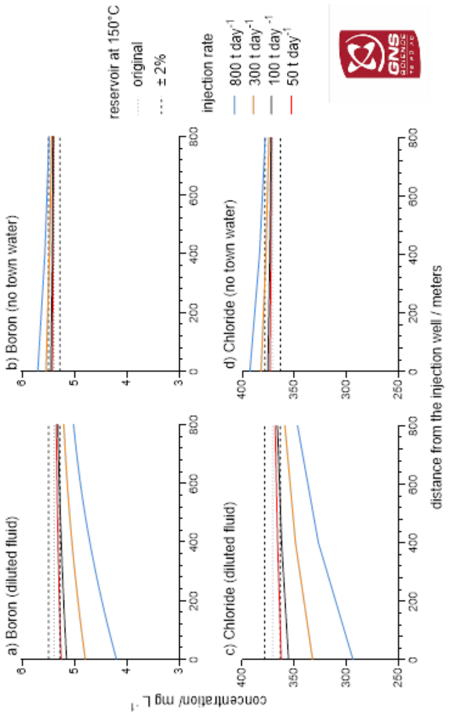

Figure 9: pHt (a), temperature (c), and silica concentration (d) versus distance (meter) from the reinjection well at the aquifer temperature of 150°C. For comparison, the effect on pHt (b) is shown for undiluted brine.

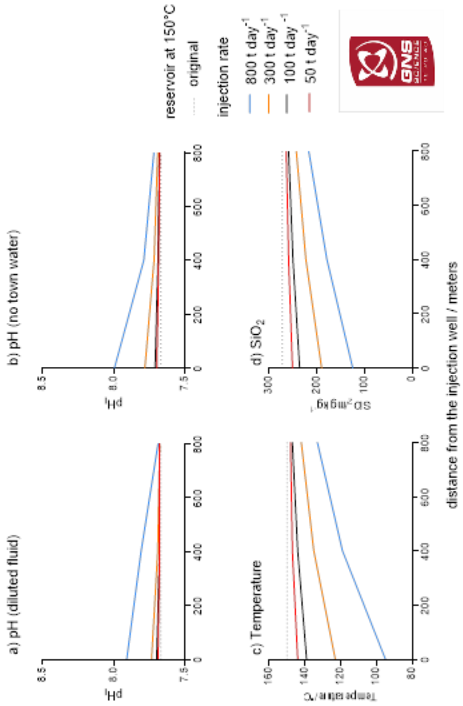

Figure 10: Ca (a) and HCO3 (c) changes versus distance (meter) from a reinjection well at aquifer temperature (150°C). For comparison, the effect on Ca (b) is shown for undiluted brine.

Figure 11a shows that when diluted brine mixes with the re aquifer fluid the mixture is slightly oversaturated with respect to calcite and significantly oversaturated with respect to Ca-saponite. When undiluted brine is reinjected, calcite saturation is marginally higher (Figure 11b). The calculated amounts of precipitated minerals are shown in Figure 11c and d. With diluted brine, the only noteworthy precipitate is calcite ranging from 0.5 g t^{-1} brine at reinjection rates of 50 t day^{-1} to 2 g t^{-1} brine at reinjection rates of 800 t day^{-1}. With undiluted geothermal brine the amount of calcite is considerably higher with about 1 g t^{-1} brine at reinjection rates of 50 t day-1 to 8 g t^{-1} brine at reinjection rates of 800 t day^{-1}. This is 2–4 times greater than undiluted brine. This shows that with diluted brine at the high temperature there is considerably more calcite precipitated, 25 g to 1600 g per tonne of brine reinjected. The latter is a substantial amount of calcite; however, it is not clear exactly where this would precipitate within the aquifer and will depend of the permeability and fracture network around the well. These precipitates may reduce permeability around the well over time.

The amounts of Ca-saponite and pyrite are lower as these minerals have a higher solubility at higher temperature (Figure 11).

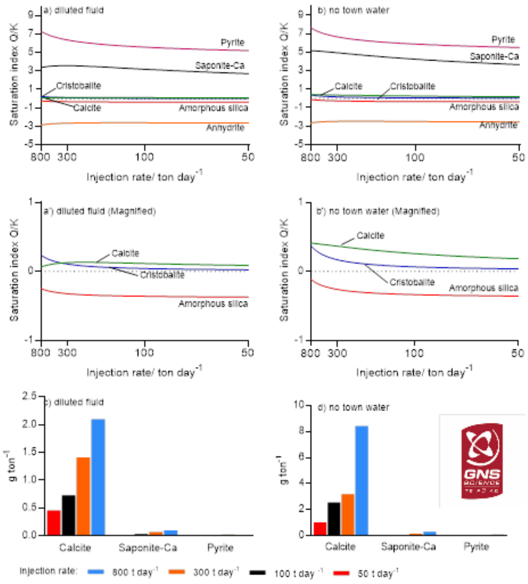

Figure 11: a,b) Mineral saturation index versus reinjection rate calculated using GWB. The fluid is saturated with respect to a mineral when its saturation index is greater than zero (dashed line) and undersaturated when less than zero. c,d) Calculated mass of precipitated minerals in grams per tonne of brine.

4. LIMITATION OF THE STUDY

The present geochemical model is representative of only one combination of chemistries; however, it does give a measure of the effect of reinjection. There following limitations should be considered when interpreting the model results: The geothermal brine chemistry can vary within the RGS and this will affect the amount of minerals expected to precipitate. Note, that it is not possible to predict where exactly the precipitate will occur. If the respective brine chemistries are different, the model would have to be modified.

1. It has been assumed that the geothermal aquifer fluid flows at 10 kg sec-1 towards the north This is a reasonable assumption, however, there are parts of the RGS where the flow rate differs. A different flow rate will result in a different proportion of mixing and will also affect the results.

2. The geochemical model assumes that the proportion of geothermal aquifer fluid during flow and mixing will increase with distance from the well. However, the degree of mixing is dependent on local geology and permeability.

3. Modelling the long-term temperature change in the geothermal aquifer was not part of this study. The present geochemical model assumes that sufficient heat is provided by the flowing geothermal aquifer fluid to maintain a temperature equilibrium.

The results from this modelling approach provide a reasonable understanding into the likely effects on the geothermal aquifer due to reinjection of brine. Note, however, to increase confidence in the predictions, or to target a specific brine combination, additional chemical data and further modelling are required.

5. CONCLUSIONS – GEOCHEMISTRY

The results of this study show that:

1. Reinjection of the diluted fluid will influence the composition of the geothermal aquifer fluid with the impact being proportional to the reinjection rate.

2. At reinjection rates of 50 and 100 t day-1 (both at 120°C and 150°C) changes to the geothermal aquifer chemistry are minimal.

3. Changes in the concentration of conservative elements (Cl, B) will be insignificant as these are within the ± 2% uncertainty of the reservoir brine composition.

4. For conservative elements, the effect of reinjection on the geochemistry is even less notable when undiluted brine is reinjected.

5. In most cases the pH change of the reservoir fluid is minor (~0.1 log units) and is independent of reinjection rate, fluid type or reservoir temperature.

6. The only measurable change in pH will be at 800 t day^{-1} up to 800 m from the well.

7. There will be a major decrease in SiO_2 concentration at 300 and 800 t day^{-1} which could impact surrounding wells and surface features.

8. The decreases in SiO_2 concentration are dependent both on mixing and temperature due to re-equilibration with silica minerals (at 150°C from 275 mg kg^{-1} to 125 mg kg^{-1}).

9. At both 120°C and 150°C, when injecting diluted brine, fewer mineral precipitates are expected than when injecting the same amount of undiluted brine (for example, at 800 t day^{-1} almost four times less of calcite will be precipitated).

10. The amount of calcite precipitation expected at 150°C is substantial, particularly at 800 t day^{-1} of undiluted brine

(6736 g per day) and could pose an issue for long-term injectability.

The geochemical model suggests that at a mixing ratio of 1:1 brine to town supply, and at slow to moderate injection rates (≤ 100 t day-1), there will be minimal effect on the reservoir. However, when the reinjection rate is greater (≥ 300 t day-1) there could be noticeable changes in reservoir fluid composition. These would be expected to be more notable near the reinjection well. It is also worth to note that extraction of the geothermal brine and subsequent boiling results in loss of water vapour. The loss of water results in an increase of concentration of most dissolved components (e.g. Cl, SiO_2) in the bathing fluid. Therefore, dilution of the geothermal brine with the town water brings the concentrations of components closer to a natural state before boiling occurred. The amount of added town water must be equal to water lost as steam.

PART 2: MICROBIOLOGY

6. INTRODUCTION

This Section outlines the potential environmental impacts of reinjecting bathing pool water or discharging bathing pool water to surface water, based on the microbiology of the pool water. There are two possible groups of adverse effects; the release of pathogenic microorganisms into the reinjection site and surrounding environment, and the potential for chemical changes induced by microorganisms. Social and cultural concerns are out of scope for this report. While drinking water sources are generally safeguarded through the use of source protection zones and filtration, it is important to note that pathogens may be harmful not only in drinking water but also in water used for irrigation, recreation or when interacting with surface water connected to mahinga kai. The aim of this report is to allow the development of a risk matrix for the treatment or disposal of post-bathing water, depending on the microorganisms present and the site chosen for reinjection or discharge.

6.1 Pathogens in Bathing Water

Most of the risk of infection associated with geothermal mineral pools is due to faecal contamination of the water, either from residual faecal material from bathers' bodies, from contaminated source water, or from birds and rodents. These enteric pathogens may be bacterial, viral or protozoan in origin (Table 5) (World Health Organisation 2006). Enteric viruses are a particular risk, as they are excreted in high numbers (up to 10-11 viral particles per gram of faeces) and many have a low infectious dose (10–100 particles) (Horn et al. 2016). Viruses cannot reproduce in water without host cells but can be very stable in the environment.

Bathers may also contaminate waters and the surfaces of objects by shedding non-faecal pathogenic organisms, particularly bacteria, viruses and fungi, which may lead to skin and other infections. In addition, some free-living bacteria and amoebae can grow in natural mineral waters as well as wet surfaces in heating and air-conditioning systems (World Health Organisation 2006).

Most bathing pool developments are required to monitor at least *E. coli* and *Enterococcus*, often known as faecal indicator bacteria or FIB (EPA 2012). The control of bacteria and viruses in mineral pools is usually achieved through filtration, disinfection with chlorine or other anti-microbial agents, or temporary pH adjustments. However, some pathogens such as *Pseudomonas aeruginosa*, *Cryptosporidium* and *Giardia* are resistant to disinfectants (World Health Organisation 2006), and an accidental faecal release with high pathogen contamination of the water may not be controlled by normal disinfectant levels. In these cases, heat treatment may be applied in order to decontaminate water.

Table 5: Potential microbial hazards in mineral bathing pools[1] spp., multiple species.

Pathogen	Illness	Health Significance	Transmission Pathway[2]	Likelihood of Infection[3]
Bacteria				
Campylobacter spp.*[4]	Gastroenteritis, fever	High	Ingestion	Moderate
*Enterococci**[5]	Bloody diarrhoea, abdominal cramp, respiratory illness	High	Ingestion	Low
*Escherichia coli * (pathogenic strains)*	Bloody diarrhoea, abdominal cramp	Moderate	Ingestion	High
Legionella spp.	Pneumonia, gastroenteritis	High	Inhalation	Low
Leptospira spp.	Fever, headache, vomiting, jaundice	Moderate	Ingestion, contact	Low
Mycobacterium spp.	Respiratory disease, pneumonia, skin diseases	Moderate	Inhalation, contact	Low
Pseudomonas spp.	Ear infections, skin diseases	Low	Contact	High
Salmonella spp.*	Gastroenteritis	High	Ingestion	Low
Shigella spp.*	Bloody diarrhoea, abdominal cramp	Moderate	Ingestion	Moderate
Staphylococcus spp.	Ear infections, skin rashes, wound infections	Low	Contact	Moderate
Viruses				
Adenoviruses*	Gastroenteritis, respiratory disease, conjunctivitis	High	Ingestion, inhalation	High
Enteroviruses*	Gastroenteritis, respiratory infections	Moderate	Ingestion	High
Hepatitis A*	Liver disease	High	Ingestion	Moderate
Molluscipoxvirus	Skin diseases, warts	Low	Contact	Moderate
Noroviruses (Norwalk viruses)*	Diarrhoea, vomiting	High	Ingestion	High
Papillomavirus	Plantar warts	Low	Contact	High
Rotavirus	Gastroenteritis	High	Ingestion	High
Protozoa				
Acanthamoeba spp.	Universally fatal granulomatous encephalitis, corneal inflammation	High	Ingestion	Low
Cryptosporidium spp.*	Diarrhoea, abdominal pain, fever	High	Ingestion	High
Entamoeba histolytica	Amoebic dysentery	High	Ingestion	High
Giardia spp.*	Diarrhoea, abdominal cramp	High	Ingestion	High
Naegleria fowleri	Almost invariably fatal amoebic meningoencephalitis	High	Contact	Low
Fungi				
Epidermophyton spp.	Athlete’s foot	Low	Contact	Moderate
Trichophyton spp.	Athlete’s foot	Low	Contact	Moderate

1 Data taken from (World Health Organisation 2006; NHMRC 2008; Tiwari et al. 2021).

2 The amount of water ingested by swimmers and bathers will depend upon a range of factors, including age, experience, skill and type of activity. Inhalation exposure will be largely associated with aerosols, within a hot tub (for example), or where there is significant splashing. Contact may involve water coming into contact with skin, mucus membranes or cuts in the skin, or physical contact with wet surfaces, edges of pools, shared towels etc.

3 Likelihood of infection depends on the number of organisms needed for an infectious dose, as well as length and type of transmission and the age and health status of individuals.

4 * May be faecally-derived.

5 Enterococci is defined as “members of the genus Enterococcus that show growth at least between 10°C and 45°C, at pH 9.6 and at 6.5% NaCl; are able to reduce 0.1% methylene blue; and show resistance to 60°C for 30 minutes” (World Health Organisation 2009). However, as the most common faecally-derived organisms also fulfil these criteria, the terms “enterococci”, “intestinal enterococci”, “the Enterococcus group” or “faecal streptococci”, are in practice interchangeable.

6.2 Heat Treatment, D Values and Sterilisation Methods

D values are used to indicate the heat resistance of contaminants, which is the time needed at a specific temperature in order to kill 90% of the organisms. D values for viruses indicate a reduction of at least 3 log units for complete inactivation (Bozkurt et al.,2015), associated with an acceptable risk reduction for human contact. Table 6 shows D values for common contaminants, including faecally-derived pathogens, in mineral pools. Bacteria, protozoa, and fungi often produce resting stages such as spores and cysts, which are more resistant to heat and other stresses than active cells. D values for these resting stages have been included in Table 6 where known.

The exposure of microorganisms for a short time to temperatures above their maximum growth temperature is known as heat shock. If the heat shock is not lethal, it can lead to tolerance of more severe stress (Richter et al., 2010). After repeated heat shocks, strains of Legionella pneumophila were heat resistant to 70°C with up to 85% of cells viable after 60 minutes at this temperature (Allegra et al. 2011). Many bacteria, including faecal coliforms, show not only recovery but increased growth after heat shock (Davenport et al., 1976). The abundance of *Vermamoeba vermiformis*, a known *Legionella* host, also increased after heat shock (Ji et al., 2018). Resistance to heat shock is highest during the stationary phase of growth (White,1953), which would be expected for pathogens sitting in thermal pools for prolonged periods.

Recovery after heat shock depends on a range of environmental factors, including temperature, nutrient availability, alkalinity and the presence of trace elements such as Al, Mo and Sb (García-Gil et al. 2018). Resistance to heat shock is difficult to predict and is organism-dependent.

Reinjection of post-bathing water poses a potential hazard to the environment if pathogens are not eliminated. Depending on the temperature of the receiving geothermal reservoir, the ratio of water reinjected and the estimated residence time, pathogens could be inactivated by heat. However, this would need exposure to a suitably high temperature for a long enough period to kill the majority of pathogens. For example, more than two minutes at 90°C is required if *Acanthamoebae* are present, or heating to 100°C if *Noroviruses* or *Hepatitis A* virus are present. The risk from pathogens will be lower if water is reinjected into zones where temperatures and flow paths have been previously measured or modelled at higher temperatures (> 100°C). Concentrations of microorganisms will be naturally attenuated through processes including dispersal and dilution, soil filtration and adsorption, and die-off, although microbes may also multiply if conditions are conducive to growth.

The pH of the receiving environment is unlikely to assist in the control of pathogens. While the optimum pH of most pathogens is generally from neutral to mildly alkaline (in line with their hosts), many are resistant to at least short periods of more extreme pH. Food borne or enteric pathogens are acid resistant in order to cope with exposure to gastric acid (pH 1.5 to 5) in the human digestive system. These include the bacteria *M. paratuberculosis, E. coli, S. aureus* and *Streptococcus* and *Salmonella* species (Audia et al. 2001; Cotter and Hill 2003). Resistance to low pH increases with concentration of cells, starvation, and being in a stationary phase or in a biofilm (Cotter and Hill 2003). In addition, many viruses are also resistant to low pH (Lee et al. 2015).

For alkaline conditions, the outlook is more promising. High pH (pH > 10.5) has been shown to kill some bacterial pathogens, including *S. aureus*, *E. coli* and *Salmonella typhimurium* (Mendonca et al. 1994), as well as the amoeba *N. fowleri* (Sykora et al. 1983). However, compounds which increase pH to this level are often corrosive and may have unintended effects on the environment. For example, if water from the geothermal reservoir mixes with groundwater, the effect of an increase in pH on the naturally present microbes which provide essential ecosystem services such as denitrification (conversion of nitrate to dinitrogen gas) is not known.

Other methods of sterilisation could include treatment with UV or disinfectants, although some viruses are resistant to UV (Bozkurt et al. 2015), and *Acanthamoebae* are resistant to chlorine (Gabriel and Panaligan 2020). *P. aeruginosa, Cryptosporidium* and *Giardia* are resistant to several disinfectants (World Health Organisation 2006), and again, the downstream effects of these compounds are not known.

Filtration has been shown to be highly effective in an Australian hot spring bathing facility where post-bathing water is filtered before being reinjected, removing *E. coli* and *Pseudomonas* which were the only pathogens identified (Aburto-Medina et al. 2020).

6.3 Rotorua Geothermal Water in Mineral Pools

Geothermal takes for thermal pools often have outflow temperatures conducive to pathogenic microbial growth. In the Rotorua area, several consented geothermal takes were identified which currently discharge post-bathing water potentially contaminated with pathogens into surface water or reinject it into the geothermal system (Table 7). The microbial risk from these discharges will depend on the number of bathers, volume of water used each day and the ratio of geothermal water to town water. Consented takes which currently discharge into sewers where water will be transported to a Waste Water Treatment Plant are not considered here. There will also be customary takes not requiring a consent which are not recorded here.

In addition, other sites which reinject post-bathing water into geothermal systems may pose a risk if the mean residence times of microorganisms at temperatures below their D-value allow continued growth or survival until infiltration into groundwater or surface water. The distance microbial pathogens may travel could be modelled if geological and hydrological data is available for the reinjection area.

There has been some research done on the transport of viruses through groundwater in e.g. alluvial sand and gravel (Pang et al. 2021). There are also national guidelines on separation distances for wells from potential contamination (Moore et al. 2010) and methods for determining capture zones based on either set distances or time-of-travel (Moreau et al. 2014), which may assist with risk assessment and mitigation.

6.4 Chemical Changes Induced by Microorganisms

Geothermal water is not sterile, harbouring natural microbial communities which includes a diversity of non-harmful microorganisms as well as potential pathogens. Many mineral waters used for bathing are not filtered or otherwise treated in order to protect the natural physical and chemical

Table 6: Heat resistance values of common contaminants. spp., multiple species.

Bacterium/Bacterial Groups	Temperature (°C)	*D* range or maximum (minutes)	Reference
Campylobacter jejuni/coli	55	0.2–3.2	(Sörqvist 2003)
	60	0–0.5	
	65	0–0.9	
	72	0–0	
Enterococcus faecalis	55	3.7–146.9	(Sörqvist 2003)
	60	1.1–43.2	
	65	0.3–12.9	
	72	0.1–2.4	
Enterococcus faecium	55	17.4–232.8	(Sörqvist 2003)
	60	5.3–69.4	
	65	1.6–20.9	
	72	0.3–4	
Escherichia coli	55	0.9–22.3	(Sörqvist 2003)
	60	0.1–3.2	
	65	0–0.5	
	72	0–0	
Legionella pneumophila	58	18	(Dennis et al. 1984)
Legionella spp.	80	2.1	(Stout et al. 1986)
Mycobacterium paratuberculosis	72	0.25	(Juffs and Deeth 2007)
Pseudomonas aeruginosa (cells)	60	> 30	(Ricker et al. 2018)
	80	5–30	
Pseudomonas aeruginosa (biofilms)	60	> 30	
	80	> 30	
Salmonella spp.	55	1.1–12.9	(Sörqvist 2003)
	60	0.1–1.4	
	65	0–0.2	
	72	0–0	
Shigella sonnei	65	0.2	(Spinks et al. 2006)
Staphylococcus aureus	50	104–128	(Kennedy et al. 2005)
	55	13–21	
	60	4.8–6.6	
Streptococcus faecalis	60	2.5– > 30	(White 1953)
Adenovirus 5	70	21	(Maheshwari et al. 2004)
Enteroviruses	60	30	(Mocé-Llivina et al. 2003)
Hepatitis A virus	50	56.2–385	(Bozkurt et al. 2015)
	60	2.7–74.6	
	70	1.1–3.8	
	85	1.0	
	100	0.3	
Human norovirus (Norwalk) GI.1	60	> 30	(Horn et al. 2016)

Bacterium/Bacterial Groups	**Temperature (°C)**	***D* range or maximum (minutes)**	**Reference**
Human norovirus GII	56	100	(Bozkurt et al. 2015)
	63	25	
	72	3.3	
	85	1.1	
	100	0.3	
Acanthamoeba spp.	71	18.3	(Gabriel and Panaligan 2020)
	76	9.3	
	81	7.4	
	86	4.5	
	91	1.8	
Cryptosporidium parvum	60	5	(Fayer 1994)
	72	1	
Giardia	56	15	(Sauch et al. 1991)
	70	15	(Ongerth et al. 1989)
Naegleria spp. (cells and cysts)	51	25–120	(Chang 1978)
	55	7.5–75	
	63	0.5–9	
	65	< 0.5–3	
Trichophyton mentagrophytes	80	4	(Essien et al. 2009)
Trichophyton rubrum	80	3.2	
Epidermophyton floccosum	80	4.4	(Essien et al. 2009)

Table 7: Consented Rotorua geothermal takes used for mineral pools with high potential for microbial contamination (outflow temperature < 60°C (data supplied by BOPRC).

Consent	**Location**	**Well Number**	**Mineral Pool Discharge Temperature (°C)**	**Maximum Consented Discharge (m^3/day)**	**Geothermal Water in Outflow (%)**	**Current Discharge Site**
RM17-0752	The Boulevard Motel	RR872	37–42	45	25	Soak hole
66393	1 Kuirau St	RR447/ BN20-0094	37–42	2	50	Soakage trench
67531	Spa Lodge	BN20-0103	37–42	20	50	Soakage trench
67177	Aura Accommodation	RR10649	42–47	25	50	Stormwater
RM18-0384	Polynesian Spa	RR887, RR1067, RR12184, BN19-0156	37–42	300	100	Lake Rotorua
RM20-0571	QE Health and Wellness Spa	RR858, RR1012, RR12751	40	800	75	Reinjection/ WWTP
68238	Cosy Cottage Thermal Holiday Park	RR1000014	37–42	43.2	100	Stream

properties of the water and their therapeutic effects (Valeriani et al. 2018). If this is the case with the proposed source for re-injection, the natural microbes present and their potential effects need to be considered.

During reinjection of geothermal water, microbial metabolism may result in bio-clogging, reducing the hydraulic conductivity by several orders of magnitude (Feng et al. 2021). This has halted operations in several geothermal plants around the world (Filippidou et al. 2016; Croese 2018b; Dinkel et al. 2018). Bio-clogging may be caused by an accumulation of cells into a biofilm, held together by extracellular polysaccharides (EPS); or by precipitation of carbonates or iron hydroxides by bacteria (Vetter et al. 2010; Feng et al. 2021). These processes are mediated by a range of bacteria and are affected by temperature, pH, nutrient availability, and redox status as well as the type of bedrock surrounding the reservoir.

Although the specific microbial communities of the takes in this project are not known, the microbial diversity of a large number of geothermal springs in the Kuirau Park has been previously investigated (One Thousand Springs 2013), and these surface feature populations may be used as a proxy for bathing pools. The major taxa (none pathogenic to humans) found in 25 sites close to the monitoring sites RRF913 and RRF0601 are shown in Table 8. These sites covered a range of temperature (22–97°C) and pH (1.38–8.72).

Table 8: Major microbiological taxa identified at Kuirau Park sites.

Bacterial/Archaeal Species or Group	**Known Metabolism**	**Specific Issues**
Acidithiobacillus	Sulphur, sulphide, ferrous iron	Produces H_2SO4, corrodes concrete
Alkalibacter	Fermentation	Produces H_2, CO_2
Aquifex	Sulphur, thiosulphate	Produces H_2S
Thiobacter	Sulphur, thiosulphate, sulphide	Produces H_2S
Caldisericum	Sulphur, sulphite, tetrathionate	-
Cryptomonadaceae	Photolithotrophy	-
Desulfurella	Sulphur, thiosulphate	Produces H_2S, CO_2
Fervidicoccus	Peptides	-
Hydrogenobacter	H2-O2-CO2	-
Hydrogenobaculum	H2-O2-CO2	-
Hydrogenophilus	H2-CO2, organic acids	-
Hydrotalea	Heterotrophy	Forms biofilms
Ignavibacterium	Fermentation	Forms biofilms
Methylomonas	Methane oxidation	-
Micrococcineae	Probably saprotrophic (detritus)	-
Ohtaekwangia	Heterotrophic	Forms biofilms
Peptoniphilus	Peptone	-
Persephonella	Sulphur, thiosulphate, H2	Produces H_2S
Salinisphaera	Thiosulphate, CO_2, organic acids	Produces H_2S
Sediminibacterium	Heterotrophic	Forms biofilms
Sideroxydans	Ferrous iron	-
Sphingobacteriales	Heterotrophic	Produces H_2S, forms biofilms
Sulfurihydrogenibium	Sulphur, thiosulphate, CO_2	Produces H_2S
Sulfurimonas	Sulphur, thiosulphate, sulphide, sulphite, H_2	Produces H_2S, sulphate
Thermodesulfobacterium	Sulphate, H_2	Produces H_2S
Thermogymnomonas	Heterotrophic	-
Thermoplasmata	Sulphur	-
Thermus	Heterotrophic	Forms biofilms
Thiobacillus	Sulphur, tetrathionate, sulphide	Produces H_2S
Thiobacter	Sulphur, thiosulphate, sulphide	Produces H_2S, sulphate

Bacterial/Archaeal Species or Group	Known Metabolism	Specific Issues
Thiomonas	Thiosulphate, tetrathionate	Produces H_2S
Thiovirga	Sulphur, sulphide, thiosulphate	Produces H_2S
Venevivibrio	Sulphur, thiosulphate, H_2	Produces H_2S

Many of the microorganisms identified from surface features located close to known takes for mineral pools are capable of producing biofilms, trapping suspended particles and reducing the porosity and permeability of the reinjection area (Feng et al. 2021). Most of these microbes are heterotrophic, obtaining carbon and energy from a wide variety of sources likely to be found in bathing water, including sugars, organic acids and amino acids and peptides. These come from shed skin and hair cells as well as residual material from bathers' bodies, and plant or insect materials which fall into open pools. However, no bio-clogging has been reported at the RR sites following field-scale re-injection, so this may be a minor issue under the current environmental conditions.

A large number of sulphur oxidizing and sulphate reducing bacteria and archaea were also identified from the geothermal springs. Sulphur oxidizers can use either elemental sulphur (S^0) or sulphide (HS- or H_2S) to produce sulphate, and usually fix CO_2 to obtain carbon. *Acidithiobacillus*, which dominated five of twenty-five sites with up to 78% of all DNA sequences, is of particular note as it produces H_2SO_4 and is known to corrode even concrete (Li et al. 2017). Sulphur oxidizers are often filamentous and may also form biofilms, in addition to the heterotrophs noted in the table.

Sulphate-reducing organisms convert sulphate, and sometimes thiosulphate, into the toxic and corrosive gas H_2S, using either dissolved carbon compounds or CO_2 for their carbon source. These bacteria are known to cause issues in geothermal systems. In 2018, a geothermal plant in the Netherlands experienced bio-clogging and used sodium bisulphite as an oxygen scavenger to prevent corrosion, but this increased growth of sulphate-reducers and led to dangerously high levels of H_2S being released (Croese 2018a). Sulphate reducing bacteria can also induce calcium carbonate precipitation, both by increasing alkalinity and through acting as nucleation sites (Lin et al. 2018). The increase in alkalinity will also increase pH buffering of the system, supporting growth of more microorganisms (García-Gil et al. 2018).

Microorganisms involved in the formation of iron hydroxides (e.g. *Gallionella, Shewanella, Geothrix*) (Dinkel et al. 2018) were not detected in the 25 springs used in this report.

7. CONCLUSIONS – MICROBIOLOGY

Reinjection of post-bathing water poses a risk of pathogen release to the environment, therefore monitoring and appropriate treatment (e.g. filtration) is recommended before this water is returned to the geothermal reservoir or discharged to surface water. Pathogens may infiltrate groundwater or surface water used for purposes other than drinking water and present a hazard through inhalation of aerosols, skin contact, or ingestion of contaminated food. There is a gradient of risk depending on the volume of water, the types of microorganisms present and the temperature, pH and permeability of the geothermal aquifer.

Filtration will remove the natural microbial population as well as pathogens from the water and reduce the risk of adverse effects from their metabolic processes. Other methods of decontamination, such as chlorination or chemical disinfection, may be employed but care must be taken that resistant pathogens (e.g. *P. aeruginosa, Cryptosporidium, Giardia*) and abnormally high levels of other pathogens are controlled.

The microbial populations in nearby geothermal surface features can be used as a proxy for the microorganisms likely to be introduced into bathing pools. Many of the microorganisms identified from surface features located close to known takes for mineral pools are capable of producing biofilms which may reduce the porosity and permeability of the reinjection area. Sulphur – oxidising and – reducing microbes were identified in nearby surface features, and these may produce corrosive and toxic substances such as H_2SO_4 and H_2S. Growth of some of these microbes may be stimulated by energy sources found in post-bathing water such as sugars, organic acids, amino acids and peptides.

8. FURTHER POTENTIAL WORK

The following workstreams were identified if the matter is to be investigated more in-depth:

1. The geochemical model presented in this work represents a single combination of brine chemistries, however, the natural diversity in reservoir composition and the variation in local permeability and fracture network geometry needs to be considered. A tracer test could be done to investigate the connectivity between the production well, re-injection wells, and the surface features.

2. Modelling using a larger range of fluid chemistries that represent other parts of the RGS.

3. The results do not consider long-term effects on the geothermal aquifer temperature (and hence mineral dissolution and precipitation). A separate modelling study should be undertaken if long term changes to the geothermal aquifer and connected surface features temperature are required.

4. Water from mineral pools should be monitored for the presence of pathogens. It is recommended that this monitoring covers a wide range of potentially pathogenic microorganisms and is more extensive than enterococci or faecal indicator bacteria.

5.Water from mineral pools should be appropriately treated before reinjection or discharge to surface water. Filtration is recommended as this will remove the natural microbial population as well as pathogens from the water and reduce the risk of adverse effects. Other methods of decontamination, such as chlorination or chemical disinfection, may be employed but care must be taken that resistant pathogens are controlled, as well as abnormally high levels of other pathogens (e.g. after an accidental faecal release).

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