Estimates of sustainable pumping in Hot Sedimentary Aquifers: Theoretical considerations, numerical simulations and their application to resource mapping

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A method for a spatial analysis of potential sustainability for the early stage of exploration in Hot Sedimentary Aquifers (HSA) is presented here. Our analyses are based on well established estimations for the thermal breakthrough in a doublet well setting. We consider two significantly different scenarios: the placement of a well doublet in an aquifer without significant natural flow, and the case where a natural groundwater flow exists.
We integrate these two analytical estimations into one workflow with geological modelling and geothermal simulation. As a result, we obtain spatial analyses of theoretical sustainable pumping rates for a whole resource area. These maps are specifically suitable for the early stage of exploration where a potential target area has to be determined based on limited information.
We present the application of our method to a geothermal resource area in the North Perth Basin, from geological modelling, to the simulation of fluid and heat flow, and finally to map the analysis of sustainable pumping rates for one aquifer. The results contain a high degree of uncertainty, but indicate the distribution of future prospective areas. These maps can be combined with other spatial datasets, e.g. infrastructure. Also, as they are integrated into one workflow, an update of the analyses is directly possible when new data become available.

Keywords: Hot Sedimentary Aquifer (HSA); Resource Analysis; Sustainable Pumping Rates; Geothermal Simulation; Geological Modelling

Introduction

This paper presents a novel exploration method to identify geothermal prospects based on thermal and hydraulic properties of the subsurface. We combine estimates of sustainable pumping rates with simulations of fluid and heat flow, and derive maps of estimations for sustainable pumping rates.

Our work regards estimates of sustainability for well doublet systems. After a certain time t_B, the reinjected cold water front may reach the extraction well and cool down the extracted temperature (Fig. 1, red curve). This will affect the geothermal application and, at some stage, rule out further effective usage of the site. An estimation of this breakthrough time t_B is required to evaluate the sustainability of a project.

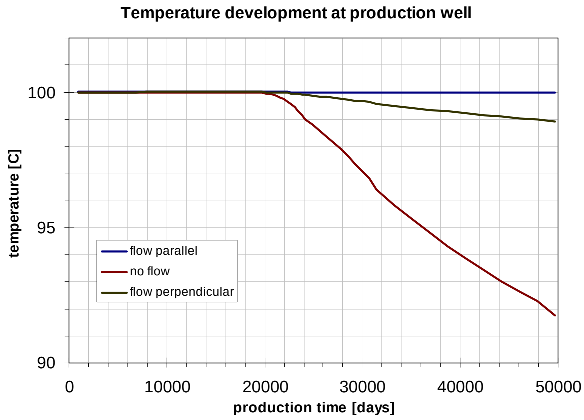

Figure 1: Comparison of temperature development at the extraction well for three different scenarios: i) If no advective flow is present, the cold reinjected water may reach the production/ extraction well (red curve) and the temperature of the pumped water will decrease; ii) For advective groundwater flow perpendicular to the wells, the temperature decrease is significantly slower (green curve); and iii) For the case that the reinjection well is directly downstream of the production well, no thermal breakthrough occurs (blue curve).

Analytical estimates of a sustainable long-term use for geothermal installations have been applied for many years (e.g. Gringarten, 1978, Lippmann and Tsang, 1980). Most of the approaches are based on many simplifications and assumptions. They nonetheless deliver an important insight into the distribution of promising areas for sustainable flow in the subsurface, especially in the early exploration phase, as not only available temperature and heat in place are considered, but also hydraulic parameters like permeability and porosity.

Another standard tool in geothermal exploration is numerical simulation of subsurface fluid and heat flow. (See e.g. O'Sullivan et. al. 2001 for a detailed revision of applications.) A thoroughly performed study can deliver detailed insight into fluid and heat movement in the subsurface, within the usual limitations of data availability and model accuracy.

One problem with both estimations, analytical and numerical, is that they are usually only performed at one location, i.e. at a previously identified target, to evaluate its long term behaviour. We propose here that it is useful to perform a raster analysis of sustainable pumping rates. This can be applied from the very first stages of geothermal exploration and subsequently refined during ongoing exploration, when more data become available.

We present here a method to perform these spatial analyses. Our approach is implemented in a complete framework covering geological modelling and fluid and heat flow simulations. The results we obtain have to be analysed critically as the many assumptions that go into the analysis prohibit an absolute interpretation of the results. For example, an estimated average pumping rate of 80 m^3/s for a lifetime of 30 years may contain a high degree of uncertainty. But even if the total values might vary, we consider the general distribution of the analysis to be a valuable representation of potential target areas in a resource area.

Theoretical considerations and simulated examples

Here, we briefly review some of the commonly applied theoretical estimations of sustainability studies. All the presented estimations below are suitable for application in Hot Sedimentary Aquifer/ porous media systems. The situation is much more complex in fractured systems (EGS) and special considerations are necessary. For more detailed information, see the recent review of Banks (2009).

Analytical estimations

The longevity of a doublet well can be defined as the time it takes for the reinjected cool water to reach the extraction well indicated at the point when the extracted temperature starts to decrease (e.g. Fig. 1). We are applying this definition here, but it should be noted that this time defines the lower end of the usability. After the thermal breakthrough, the extracted temperature will decrease but possibly the application will still be usable (e.g. Lippmann and Tsang, 1980, Banks, 2009).

In this paper, we consider two cases for the estimation of a sustainable pumping rate, with and without advective background flow.

Well doublet without advective background flow

We firstly consider the case of hydraulic breakthrough. This is the time t_{hyd} the reinjected water takes to reach the extraction well. For simple cases (flow along the shortest path, homogeneous aquifer, no dispersion) the hydraulic breakthrough time (e.g. Hoopes and Harleman, 1967) can be evaluated for a pumping rate Q, an aquifer with porosity ϕ , a thickness h and a spacing D between extraction and reinjection wells as:

$$t_{hyd} = \pi \phi h \frac{D^2}{3Q}$$

The hydraulic breakthrough (i.e. the time when the reinjected water reaches the extraction well) is not equal to the thermal breakthrough (the time when the cold temperature front reaches the extraction well). The temperature front is delayed by a retardation factor R_{th} (Bodvarsson, 1972) that depends on the thermal properties (specific heat c and density ρ) of the aquifer rock (a) and the water (w):

$$R_{th} = \frac{1}{\phi} \frac{\rho_a c_a}{\rho_w c_w}$$

Therefore, the time for the arrival of the thermal front at the extraction well can be calculated as:

$$t_{the} = \frac{\pi}{3} \frac{D^2 h}{Q} \frac{\rho_a c_a}{\rho_w c_w}$$

Interestingly, the thermal breakthrough time in this case does not depend on the hydraulic conductivity / permeability of the aquifer, but only on geometric and thermal properties.

This estimation is based on many assumptions; the most important are:

1) Fluid properties are constant and do not depend on temperature.
2) The flow itself is steady-state, injection rate and temperature are constant and there is no mixing between the reinjected fluid and the native water.
3) The geometry of the aquifer is very simple: constant thickness, constant porosity and it is assumed to be horizontal.
4) Cap rock and bedrock of the aquifer are impermeable.

(For a further detailed discussion see e.g., Gringarten and Sauty, 1975.)

Apart from these conditions, another common assumption is that there is no heat transport from the aquifer into the surrounding rocks by conduction. This assumption is reasonable in many cases (see Gringarten and Sauty, 1975, for accurate criteria) and we will adopt it here as well.

Well doublet with advective background flow

If a native hydraulic gradient is present in the aquifer, the situation is more complex. It is now important to consider the well placement with respect to the natural advective groundwater flow

v_0 (Fig. 2). An analytical estimation for the thermal breakthrough can be derived for the case that the reinjection well is placed downstream of the extraction well (Lippmann and Tsang, 1980):

$$t_{the} = (D/v_0)\frac{1}{\phi}\frac{\rho_a c_a}{\rho_w c_w}\left[1+\frac{4A}{\sqrt{-1-4A}}\arctan\frac{4A}{\sqrt{-1-4A}}\right]$$

where

$$A = \frac{Q}{2\pi h D v_0}$$

This equation does not have a real solution when the natural groundwater velocity is above a critical value

$$v_0 > \frac{2Q}{\pi \phi h D}$$

In this case, no thermal breakthrough will occur and the system is, in principle, completely sustainable and can be operated without time limitations.

Validity of the analytical solution

The analytical estimations of hydraulic and thermal breakthrough depend on many assumptions (see above). In a realistic setting, some effects might reduce the breakthrough time (hydraulic dispersion, heat conduction in the fluid phase) while others might lead to longer breakthrough times (heat resupply from surrounding beds, stratification). A careful examination of these effects is possible with numerical simulations of pumping and reinjection.

Consideration of pressure drawdown

In both cases presented above, with and without natural groundwater flow, we can consider a maximum pressure drawdown *s* at the extraction well as another criterion for the determination of a sustainable pumping rate. Gringarten (1978) presented a relationship obtained from potential theory:

$$s = \frac{Q}{2\pi T}\ln\frac{D}{r_w}$$

We can see from this equation that the pressure drawdown *s* depends on pumping rate *Q*, aquifer transmissivity *T* and well diameter r_w, as can be expected, but also on the well spacing *D*, as the two wells interact and a smaller spacing leads to less drawdown.

Combined analysis

For a complete sustainability analysis for the well doublet, we might consider the thermal breakthrough time and a maximum pressure drawdown in the reservoir. Concerning the temperature breakthrough time, we want to have a large well spacing *D*, but if we consider the pressure drawdown, a smaller spacing is more beneficial. The optimal value of *D* cannot be determined analytically, but numerical solutions can be applied (e.g. Kohl et al., 2003, Wellmann et al., 2009).

Numerical simulations

The theoretical estimations described above deliver a very useful estimation about potential geothermal targets. We therefore consider them as ideal for the early exploration stage. But as they depend on many assumptions and simplifications, numerical simulations of subsurface fluid and heat flow have to be applied to derive a more realistic insight into the sustainability of the system.

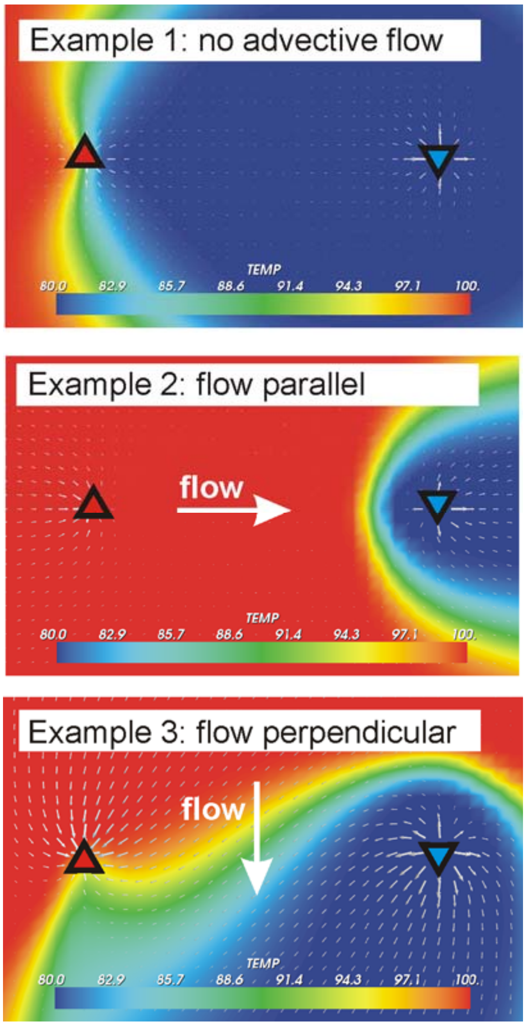

Figure 2: Fluid and heat flow representations for the three example scenarios described below, and presented in Fig.1. In the first example, without advective flow, we can see that the reinjected cold water (reinjection well: blue triangle) reaches the extraction well (red triangle) after a certain time, and the produced temperature decreases. Example 2: for natural advective flow in the direction of the injection well, the cold temperature fan does not reach the extraction well, and the system is completely sustainable. Example 3: for flow

perpendicular to the wells, less cold water reaches the extraction well, and the temperature decrease is reduced.

A variety of software codes exists to perform these simulations (see O'Sullivan et al., 2001). We used SHEMAT (Simulator of HEat and MAss Transfer, Clauser and Bartels, 2003) for the resource scale simulations presented in this paper (e.g. Fig. 3). To test the validity of the analytical estimation of breakthrough times, we simulated a well doublet (extraction and reinjection well) with SHEMAT and, additionally, with the petroleum reservoir engineering software Tempest/More from Roxar.

The plots in Fig. 2 show the temperature distribution (colour map) and fluid flow vectors (grey arrows) in the subsurface. The three examples given relate to temperature decrease at the extraction well for three different scenarios, as given in Fig. 1.

In summary:

1) Well doublet in an aquifer without groundwater flow, after thermal breakthrough occurred. We can see that the flow field affects a wide area perpendicular to the direct connection between the wells.
2) Natural groundwater flow, the reinjection well is in the downstream direction of the extraction well. The temperature field is now disturbed by the natural groundwater flow. For the same pumping rate, well spacing, and simulation time, the cold temperature field does not reach the extraction well. No thermal breakthrough occurs.
3) Natural groundwater flow perpendicular to the connection line of the well doublet. The temperature field is again clearly affected by the groundwater flow field and the temperature decrease at the extraction well is slowed down.

Example: North Perth Basin

Geological model

We applied the analytical estimations presented above to exploration-scale simulations of fluid and heat flow. For the first stage of exploration, we consider these analytical assumptions as a valuable indication of potential geothermal target areas.

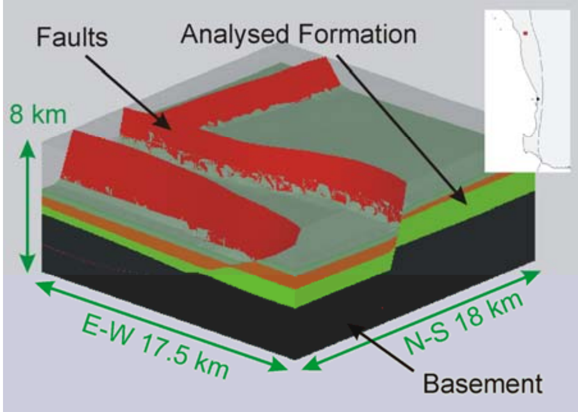

Figure 3: 3-D Geological model for a part of the North Perth Basin (In inset picture: model location=red square; black circle=Perth). Sedimentary formations are overlying basement which is offset by normal faults.

As an example here, we show the application of the method to an area in the North Perth Basin. The geology is characterised by thick sedimentary formations cut by normal faults in a graben setting (Fig. 3). The geological model was created with an implicit potential-field approach (Lajaunie, et. al. 1997), implemented in the GeoModeller software (Calcagno et al., 2008). The model is a simplified version of a more complex regional model.

Geothermal simulation

The geological model is directly processed to an input file for fluid and heat flow simulation with SHEMAT (see Clauser and Bartels, 2003). Rock properties (permeability, porosity, thermal conductivity and heat capacity) were assigned according to samples in this region where available. A strong anisotropy (horizontal / vertical = 10) was applied to all permeability values to achieve a more realistic model.

Figure 4 is a representation of the simulated fluid and heat flow field for the North Perth Basin model. The effect of fluid flow on the temperature distribution is clearly visible. The resulting temperature gradients appear reasonable and qualitatively in accordance with measured values in the area.

For a quantitative analysis of the results, the model has to be refined and adjusted further, especially at the borders (boundary conditions, see discussion). Respecting these current limitations to model verification, we next apply our resource analysis methods to this model. As all steps are integrated into one workflow, it is easily possible to update the model and all analyses later, when more data become available.

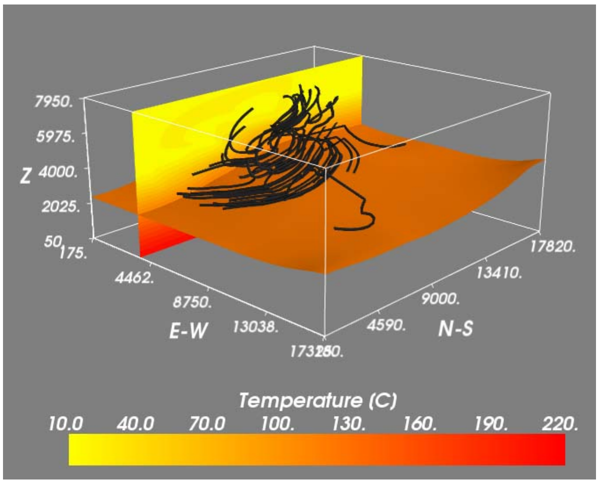

Figure 4: Visualisation of the temperature and fluid flow field simulated for the 3-D geological model of the North Perth Basin. The orange isosurface shows the depth to 120°C. The black lines indicate fluid flow pathways. General flow direction is N-S.

Novel resource analysis methods

Next we use the simulated fluid and heat flow field to estimate different aspects of geothermal resource sustainability. All the examples here are performed for the oldest sedimentary formation (see Fig. 3, light green unit). The minimum lifetime to consider a geothermal project site as "sustainable" is assumed to be 30 years for the following analyses.

Key novel aspects of all our analyses are:

1) We perform the analyses directly on the basis of the simulated fluid and heat flow field for the resource area, linked to the 3-D geological model.

2) All aspects (maximum sustainable pumping rate, heat in place, pressure drawdown) are evaluated on a spatial basis, i.e. we derive 2-D maps of these properties showing their distribution.

3) All relevant steps are integrated into one workflow, it is therefore readily possible to update the geological model and the geothermal simulation when more data become available.

Maximum sustainable pumping rate, without consideration of advective flow

Following the definition of the theoretical breakthrough time for the thermal front given above, we estimate a maximum pumping rate that could be expected for a doublet system. Spatial analysis is performed step-by-step at every point in space (Fig. 5).

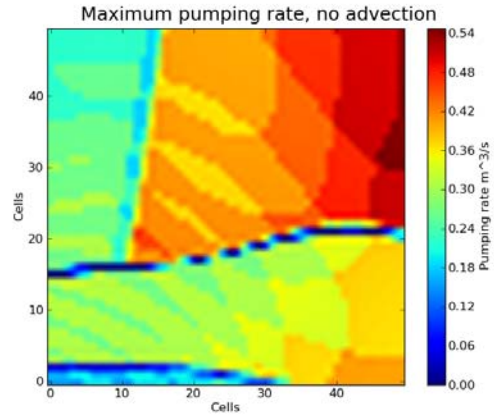

Figure 5: Maximum pumping rates for a doublet system with 800 m spacing and a lifetime of 30 years. All other properties required for the estimation of the pumping rate (see equations above) are directly taken from the simulation (e.g. density) and the model (e.g. formation thickness).

Consideration of natural groundwater flow

In Fig. 4 we can see from the distribution of the streamlines that groundwater flow is present at the regional scale for this specific model. So, if we hypothetically intelligibly place a well doublet in one of the flow areas, it is possible to determine a pumping rate where a thermal breakthrough will, theoretically, never occur (see Example 2 in Fig. 2). If we then apply this analysis again at every point in our model, we can derive a spatial analysis of these pumping values (Fig. 6) for which thermal breakthrough will never occur.

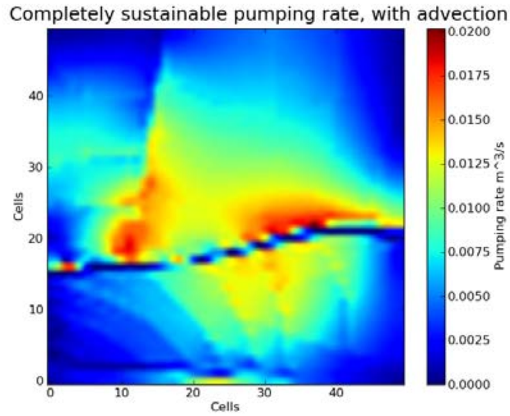

Figure 6: Estimation of a maximal pumping rate for the theoretical case of no thermal breakthrough (Example 2 in Fig. 2), in the presence of advection. This is of practical significance as areas with a high value can also be expected to allow a higher sustainable pumping rate (for a project durance less than infinity).

Combination with other important factors

These spatial analyses can now be used in combination with other relevant factors for geothermal exploration, e.g. mean temperature at depth for a target formation, or maps of local heat in place (Wellmann et al., 2009). Heat in place is referred to as one absolute number characterising the geothermal potential of a geothermal reservoir volume. We define the local heat in place as the heat in place of a tiny subdivision of the reservoir. A local heat in place map gives crucial information on the connectivity of the geothermal reservoir and therefore is of high interests for reservoir engineering studies. As all results are in map view, they can easily be included in a GeoInformationSystem (GIS) and combined with, for example, infrastructure considerations.

Discussion

We have shown that it is possible to combine analytical considerations of resource sustainability, with geothermal fluid and heat flow simulations. Our approach enables a direct spatial analysis of relevant factors for geothermal exploration in Hot Sedimentary Aquifers. The major advantage is that geothermal prospects can be identified based on physical reasoning (in the context of geological modelling), geothermal simulation, and ideally, all available data. We propose that this method is a step forward for the identification of geothermal target areas from a regional analysis.

The example presented above for the North Perth Basin is performed for a resource-scale model, representative for an early stage of geothermal exploration. It contains a high degree of uncertainty and the determined numbers for sustainable pumping rate are probably not quantitatively correct. But as they are based on a full 3-D integration with geological knowledge, physical simulation and all available data, we can interpret the results spatially, i.e. identify areas which should be analysed more carefully. This is a major advantage to standard resource estimation methods, e.g. heat in place, where only one value for the whole resource area is determined.

In a realistic project scenario, the next steps would be to refine the model and adjust boundary conditions carefully to the local setting. But as we have integrated all relevant modelling, simulation and resource analysis steps into one workflow, an update at every stage is easily possible.

We recognise that the results are subject to a large degree of uncertainty. Two ways we will address this in future work, will be to combine this workflow with an uncertainty simulation of geological modelling (Wellmann et al., 2010), and with sensitivity studies of the geothermal simulation to derive a quantitative evaluation of the sustainability map quality.

Acknowledgements

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