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MODELING THE THERMAL EFFECTS OF GROUND SOURCE HEAT EXCHANGE AT STANFORD UNIVERSITY: A PRELIMINARY STUDY

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ABSTRACT

The possibility of implementing an open-loop Ground Source Heat Exchanger (GSHE) for heating and cooling on the Stanford University campus is currently being investigated. As part of this preliminary investigation, modeling was performed to estimate the thermal effects of GSHE operation for a hypothetical heating and cooling scheme and well layout. It was found that groundwater temperature in the model experience a small increase due to imbalanced heating and cooling loads after 30 years of operation. However, the thermal plume remains near the GSHE wells after 30 years.

INTRODUCTION

An open-loop Ground Source Heat Exchanger (GSHE) could be used to meet a portion of Stanford University's heating and cooling needs. Analysis is being performed to address the feasibility of GSHE implementation for both heating and cooling on the Stanford University campus.

One concern that affects the feasibility of such a system is its possible impact on groundwater temperature. In order to address this concern, numerical simulation of mass and heat transport was carried out for a hypothetical GSHE scenario described by Luhdorff & Scalmanini Consulting Engineers (2011). The work described here is a first pass at determining the thermal effects of GSHE operation and should be viewed as preliminary analysis.

METHODS

Numerical simulation of single-phase transport of groundwater and of heat transport was carried out. TOUGH2 software was used to model a hypothetical GSHE scenario and estimate its impact on groundwater temperature (Pruess et al. 1999). The software PetraSim was used as an interface for TOUGH2 (Thunderhead Engineering 2007). This scenario is described here, including a summary of the most important model parameters and assumptions.

The spatial dimensions of the model are provided in Table 1.

Table 1: Basic structure of model.

Model Dimension	**Value**
Depth at top of model	23 m
L_x	2000 m
L_y	3000 m
L_z	184 m
NX	44 elements
NY	66 elements
NZ	8 elements

These dimensions were chosen based on the hypothetical well layout in the modeled scenario (Luhdorff & Scalmanini 2011). The depth of 23 m that was used to define the top of the model corresponds to the depth of the water table (Luhdorff & Scalmanini 2011).

The rock properties used in the model are given in Table 2.

Table 2: Rock properties used in model.

Rock Property	**Value**
Lateral permeability	55 darcy
Vertical permeability	5.5 darcy
Porosity	20%
Density	2600 kg/m^3
Thermal conductivity	1.7 W/m-°C
Specific heat capacity	872 J/kg-°C

As detailed geological information was lacking for the modeled location, these properties were taken to be homogeneous throughout the model for this initial analysis. Values of rock porosity, permeability, and density were based on estimates provided by Tom Elson of Luhdorff & Scalmanini Consulting Engineers (2011). While a range of permeability values (30 to 55 darcy) and porosity values (20 to 25%) were provided, the high value of permeability and low value of porosity were used such that the flux velocity of the fluid in the aquifer (and thus the velocity of the thermal front in the aquifer) would be the highest value obtainable from these estimates. Thus, the case considered here is intended to be a conservative estimate with regards to thermal interference in neighboring wells. However, it is important to keep in mind that heterogeneity of the flow properties in the aquifer could lead to a much different result than this simple homogeneous case.

Values of rock thermal conductivity and specific heat capacity were based on estimates provided by Haley & Aldrich (2010).

The approximate geographic location of the model is shown in Figure 1. These model boundaries were chosen based on the hypothetical well layout in the modeled scenario as well as the locations of existing neighboring groundwater wells downstream of the GSHE. The hypothetical well layout used in the model is given in Figure 2.

An approximation of natural regional groundwater flow was included in the model. Under present-day conditions, the natural regional groundwater flow direction is northeast, originating in the coastal hills and discharging in the San Francisco Bay (Luhdorff & Scalmanini 2011). The flow direction in the model was taken to be parallel to the y-axis (see Figure 1). The total rate of natural groundwater flow into and out of the segment of the aquifer of interest in the GSHE scenario was estimated to be between 400 and 800 acre-ft/yr by Luhdorff & Scalmanini Consulting Engineers based on transmissivity estimates and published gradient values (2011). The midpoint of this range was used in the model and was converted to a mass flowrate of 31.3 kg/s using a water density of 1000 kg/m^3.

Regional groundwater flow was assumed to be distributed homogeneously with respect to depth. In other words, each gridblock on the southwestern face of the model was given an equal portion of the total mass flowrate (and correspondingly so for the northeastern face of the model). Finally the temperature of the groundwater flowing into the southwestern face of the model was given a value of 17.78°C, which is based on an estimate provided by Haley & Aldrich (2010).

The initial temperature distribution was assumed to be homogeneous with a value of 17.78°C (Haley & Aldrich 2010). The initial pressure gradient was assumed to be hydrostatic. The initial value of confining pressure at the top of model used in the natural state simulation was 311 kPa. This estimate was provided by Casey Meirovitz of Luhdorff & Scalmanini Consulting Engineers and was based on pressures in wells on the Stanford University campus which were measured at the depth of interest (2011).

The well configuration in the hypothetical GSHE scenario includes 8 producers and 18 injectors with flowrates scaled so that the injection and production rates at any given time are equal. (Luhdorff & Scalmanini 2011). All wells in the model were vertical and specified to allow flow at depths from 46 – 92 m, which was as close to the depths of 150 – 300 ft specified by Luhdorff & Scalmanini Consulting Engineers as discretization allowed (2011). The locations of injection and production wells in this scenario were chosen for high expected well yields as supported by aquifer test data (Luhdorff & Scalmanini 2011).

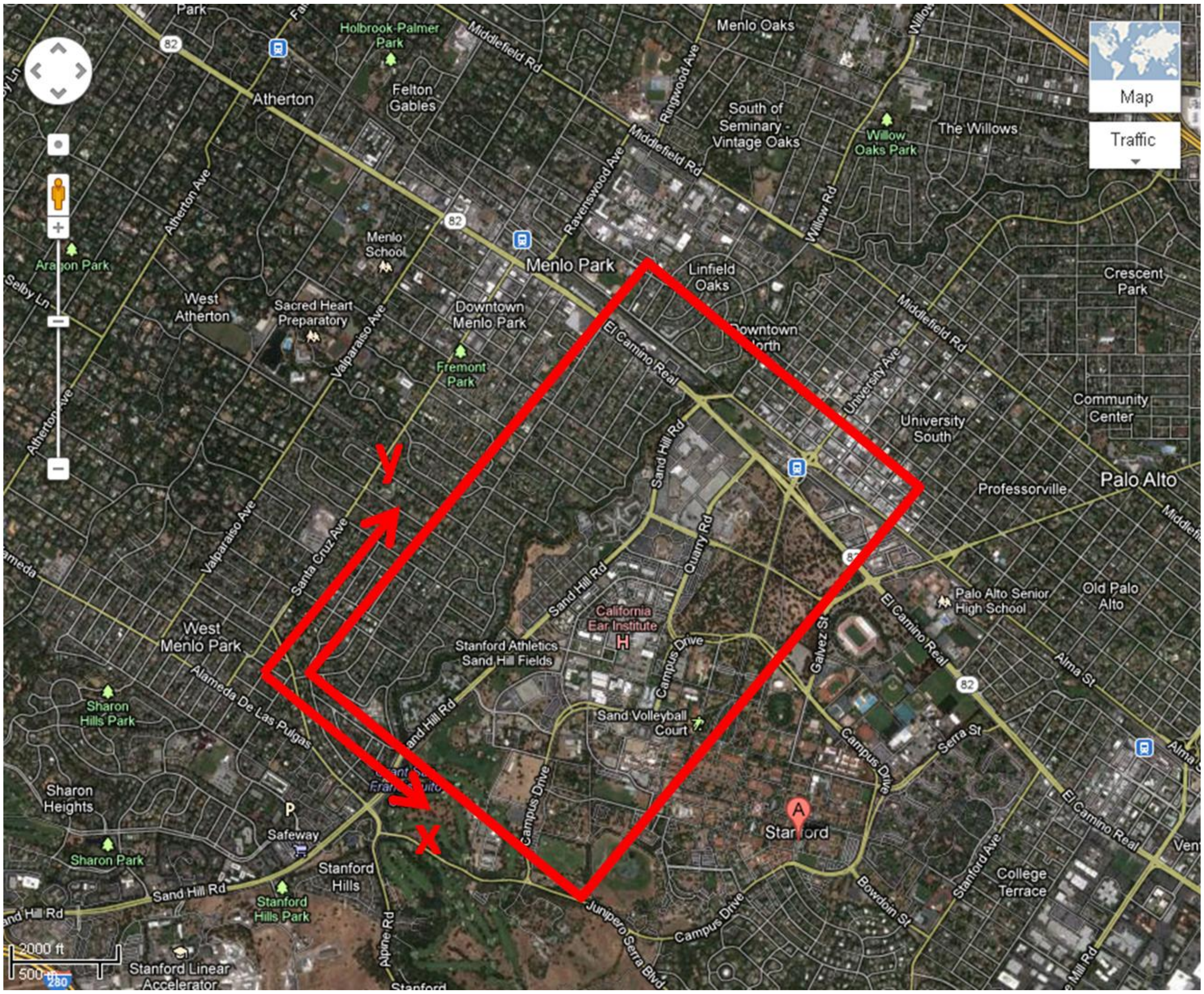


Figure 1:   Approximate geographic location of GSHE model (Google maps).

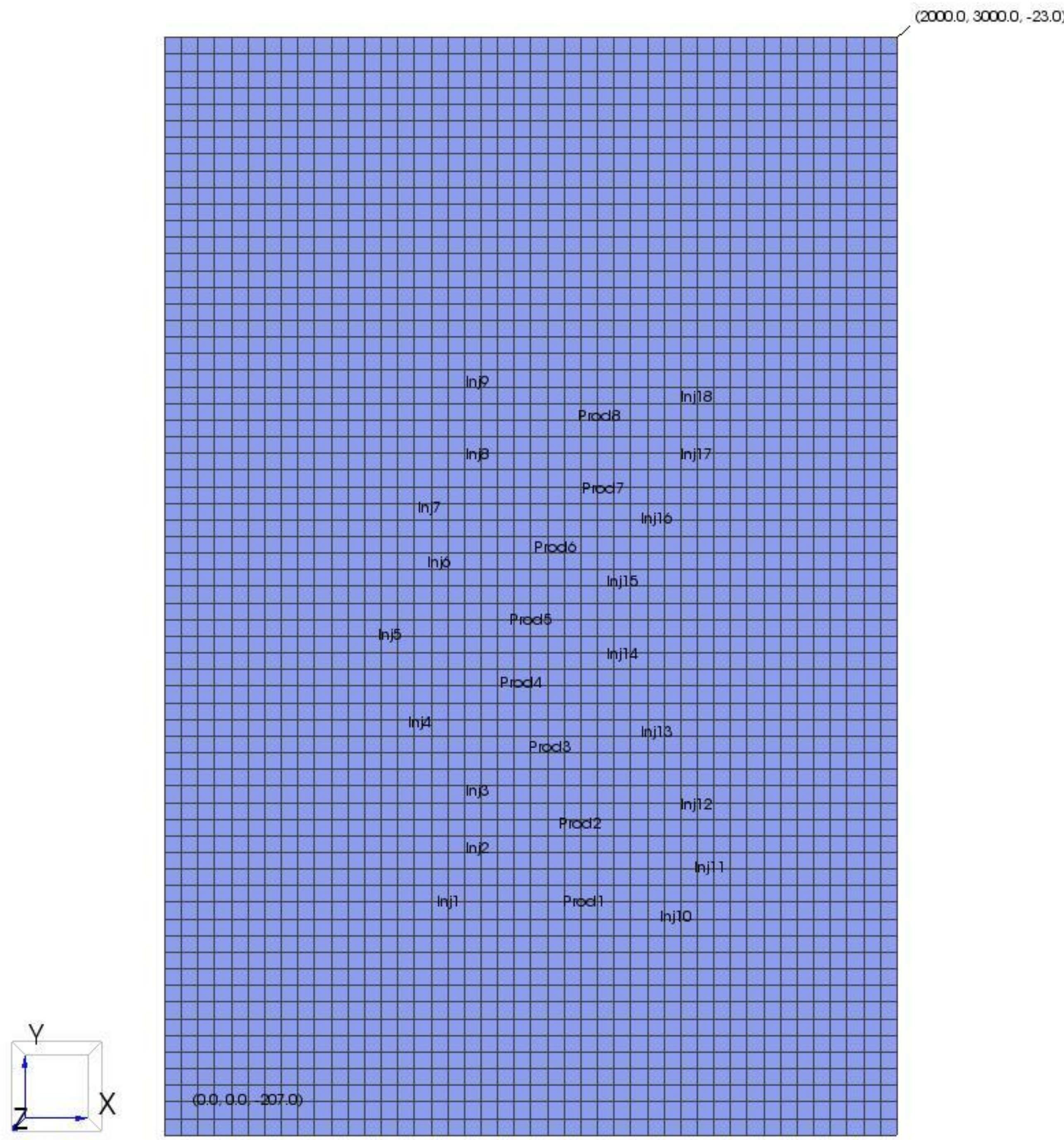


Figure 2: Hypothetical well layout used in GSHE model.

The average monthly groundwater production flowrates and reinjection temperatures for the scenario considered are shown in Figure 2 (2011). These values were output from the Stanford University Central Energy Plant Optimization Model (CEPOM) (2011). The figure also specifies which months correspond to the heating season (October – April) and the cooling season (May – September). These flowrates represent the total production rates of the well field. They are based on expected heating and cooling requirements and the maximum expected production yield for this well configuration as determined by aquifer test data and data from existing wells on the Stanford University campus (Luhdorff & Scalmanini 2011).

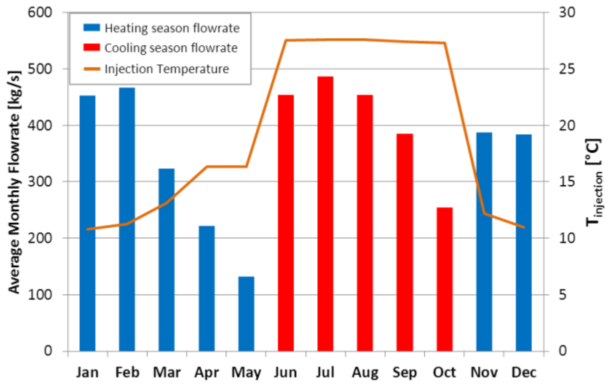


Figure 3: Average monthly GSHE (A) temperatures and (B) flowrates (Luhdorff & Scalmanini 2011).

RESULTS

The temperature distribution in the reservoir at different stages of GSHE operation is illustrated in Figures 4 – 6. It is apparent that some heating of the aquifer occurs, with local temperature increases of up to 2.3°C after 30 years of operation. While the spatial extent of the thermal plume increases with time, the heated region remains relatively close to the GSHE wells after 30 years of operation.

The overall heating of the aquifer near the wells is likely a result of imbalanced heating and cooling loads: there is a net heat addition into the aquifer of approximately 4.3 TJ for a given year (assuming the heat capacity of water is constant at 4180 J/kg-°C). This is despite the fact that the amount of cool water injected during the heating season exceeds the amount of warm water injected during the cooling season by 0.8 megatonnes/yr. In other words, the temperature difference during the cooling season exceeds the temperature difference during the hating season. The estimated heat flow into the aquifer is illustrated in Figure 7.

It should also be noted that there would actually be cold spots very close to the wells (inside of the hot spots) after 10, 20, and 30 years of operation, since each year ends during a heating season. This detail was most likely missed due to a relatively coarse discretization near the wells.

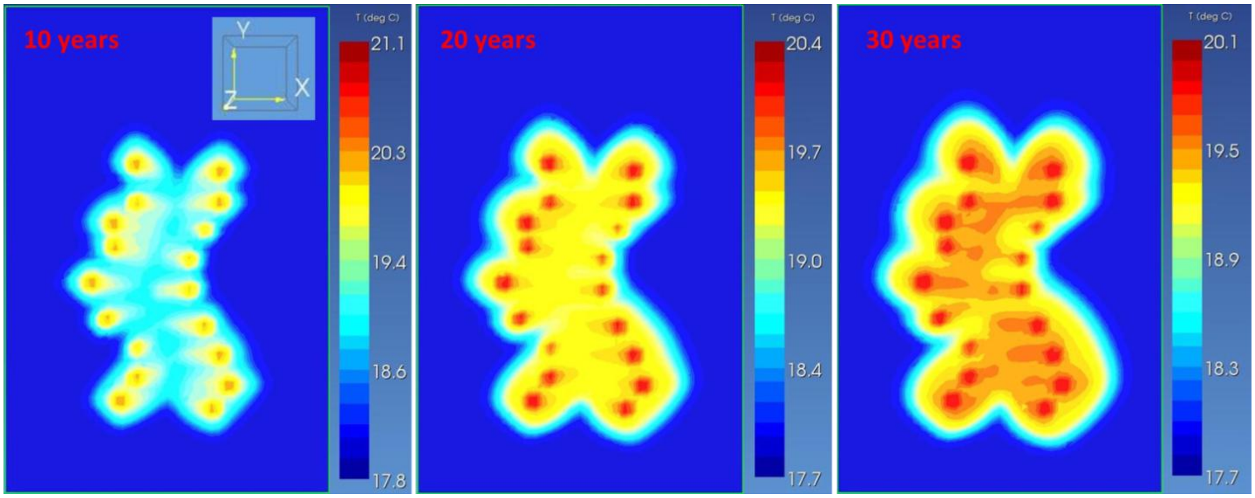


Figure 4: Temperature distribution in aquifer at a depth of 23 meters.

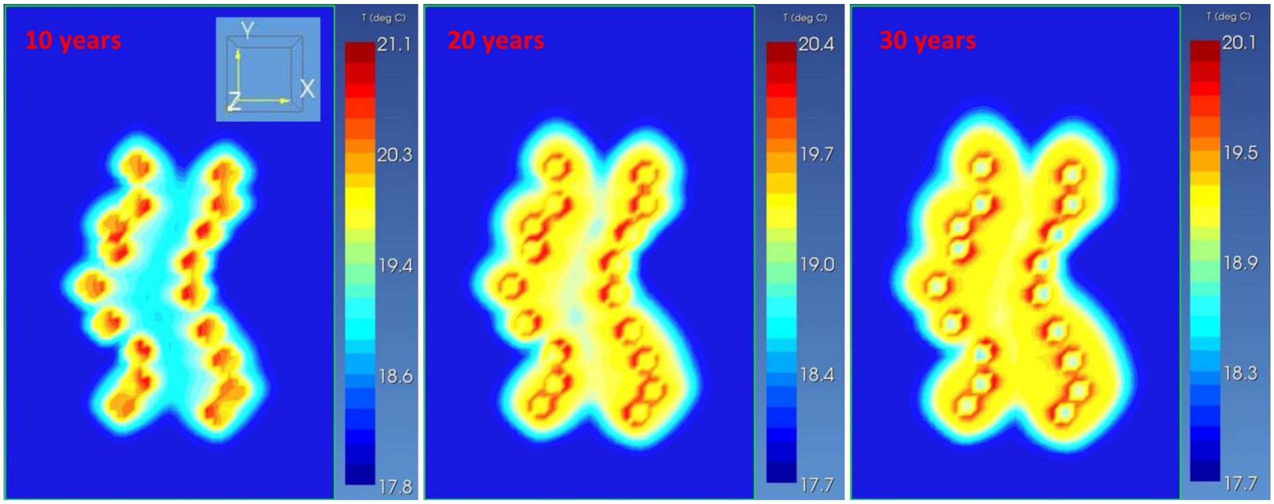


Figure 5: Temperature distribution in aquifer at a depth of 70 meters.

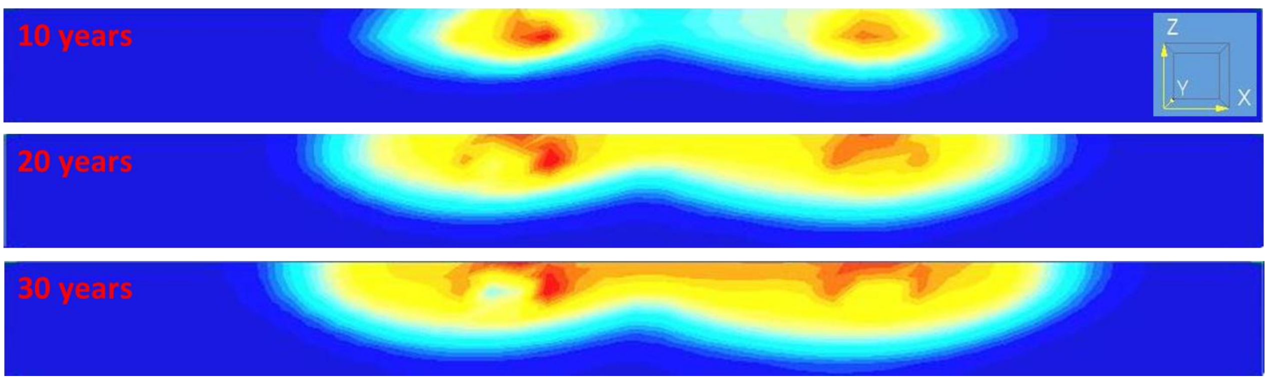


Figure 6: Temperature distribution in aquifer at a y-position of 700 meters (legends same as in Figures 3 and 4 for corresponding times).

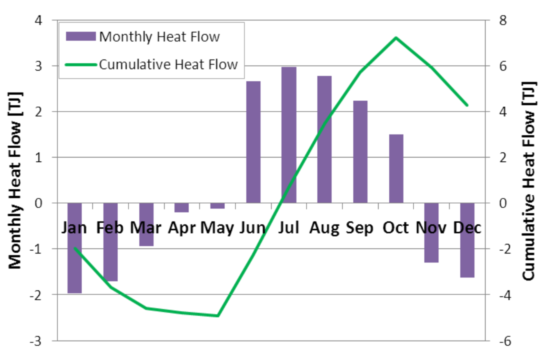
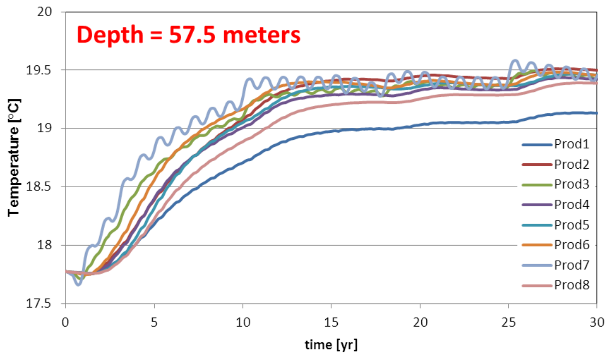


Figure 7: Estimated heat flow in the aquifer for a given year.

The evolution of temperature over time at the locations of the GSHE production wells is given in Figure 8. All eight production wells exhibit similar a similar increasing trend. This will ultimately change the temperature at which produced water can be reinjected as time progresses, a detail that will be incorporated into future modeling.

Additionally, all eight production wells exhibit periodic fluctuations in temperature associated with the switch between the heating and cooling seasons (i.e. these fluctuations have a period of 1 year). This periodic behavior is most pronounced in Producers 3 and 7, probably because these wells are positioned closest to the thermal plume coming from the injection wells in this particular well layout. An initial temperature drop can be observed in Producers 3 and 7, which is due to the fact that the simulation began in January, which is during a heating season.



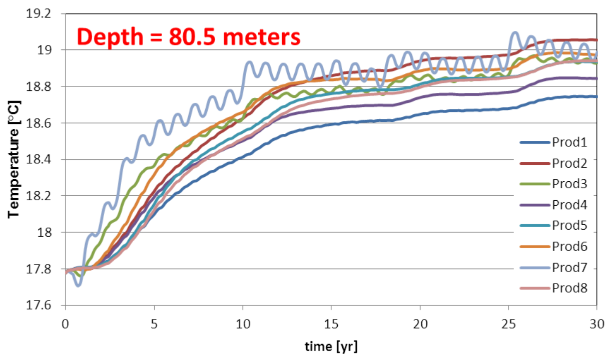


Figure 8: Evolution of temperature over time at different depths in GSHE production wells.

CONCLUSIONS

Numerical simulation of mass and heat transport was performed to estimate how the implementation of an open loop GSHE for heating and cooling may impact groundwater temperatures. The results of this simulation for one hypothetical well layout and production plan indicate that the GSHE scenario considered would have a relatively small impact on groundwater temperatures. After 30 years of operation, groundwater temperatures in the region near GSHE wells experience local temperature increases of up to 2.3°C, but the thermal plume remains relatively close to the wells.

More detailed modeling which includes subsurface heterogeneity, the effects of the variability of production temperature on the reinjection temperature, and the influence of the operation of existing neighboring wells (injection and/or production) will be performed in the future to provide a more complete picture of possible impacts on groundwater temperatures. Sensitivity analysis will also be performed on flow properties, thermal properties, and natural groundwater flowrate.

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