Numerical simulation of Borehole Heat Exchanger Fields for long-term storage in combination with groundwater utilization in an artificially regulated aquifer for urban district planning

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ABSTRACT: Especially in expanding cities like Vienna, the task of energy supply and management for new urban expansion areas with renewables is of great importance. The actual energy concept for the new urban extension area “Nordwestbahnhof” is to use all local waste heat and geothermal resources in the quarter, cross link all buildings with a geothermal heating and cooling network and further improve the energy with decentralized heating pumps. The temporally shift of heating and cooling demands should be stored in borehole heat exchanger fields. In addition also the shallow aquifer is used as basic load heat source and solar collectors and waste heat are balancing the annual heat and energy deficit. For dimensioning reasons a 3D numerical simulation is set up including BHE fields and groundwater usage to specify the energy and storage potential to deliver the areal heating and cooling network. Of special interest is the local groundwater situation of an artificially regulated aquifer near the Danube since the hydroelectric power station is operating and the natural groundwater situation is preserved by several pumping stations.

INTRODUCTION

At the former freight terminal “Nordwestbahnhof” a new urban district is currently in planning progress and will enrich the attractive location between the city and the Danube with mainly residential buildings combined with office, cultural and social service buildings, see Figure 1. In three stages, until 2025, the new district should create space for about 7200 inhabitants, 5100 workplaces next to schools and a cultural center (Puscher et al., 2008). To reach the goal of a sustainable and renewable energy supply a geothermal utilization is considered to combine the local heat supply and demand. The geological conditions are quite good, as the urban extension area is located above Quartenary, high conductive gravels from recent deposits from the Danube above low conductive layers of sand and silt. Since the hydroelectric power plant “Freudenau” was built the entire aquifer between Danube and Danube Canal is regulated artificially with 27 pumping wells along an 11.5 km long slurry wall to conserve the natural groundwater level, see Figure 1.

The geothermal concept is planned to use groundwater as a basic heat load for the warm water demand in combination with a seasonal geothermal heat storage realized with borehole heat exchangers (BHE). The buildings, the BHE fields, the groundwater heat exchanger and the heat surplus are connected with a local heat distribution network, see Figure 2. The network consists of a cold and a warm pipe at a low temperature level and acts as short-term storage to balance heat inputs and outputs at similar times. The BHE storage will balance the seasonal caused shifts of heat supply (summer) and demand (winter). It is a priority to look at a balanced annual heat supply and demand for the underground storage. Geothermal utilities based on this concept are known as “Kalte Fernwärme” or “Anergienetze” (Sulzer et al., 2014).

For dimensioning reasons and to estimate the environmental impact and the interaction between the geothermal components a three dimensional numerical simulation with Feflow was requested. Similar geothermal simulations at the Geological Survey of Austria can be found at Brüstle et al. 2015.

DIMENSIONING AND MODEL SET UP

For setting up the three dimensional model a lot of underground information was available. Figure 3 gives a summary of the average layer levels and important boundary conditions and material properties.

The model consists of two main layers. The Quaternary layer represents an unconfined aquifer with an average thickness of 12 m, whereas about 5.6 m are fully saturated with groundwater. The boundary nodes of this layer are set to a constant head boundary condition (BC), representing the average groundwater level of the last 10 years. The underlying Neogene layer mainly consists of clay and marl with some embedded sand lenses and represents the main layer for seasonal storage.

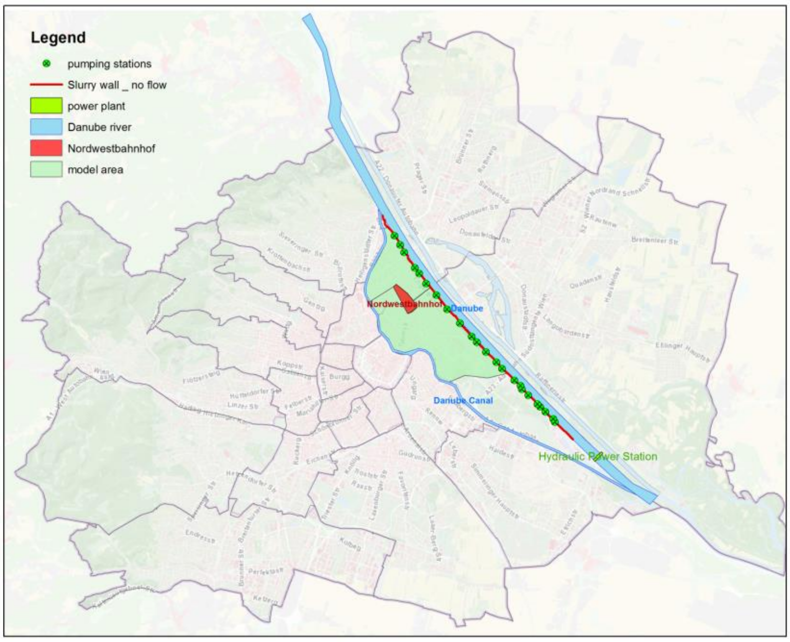


Figure 1: Location Overview – The unconfined aquifer between Danube and Danube Canal is regulated artificially with several pumping station and a slurry wall due to the backwater of the hydroelectric power plant.

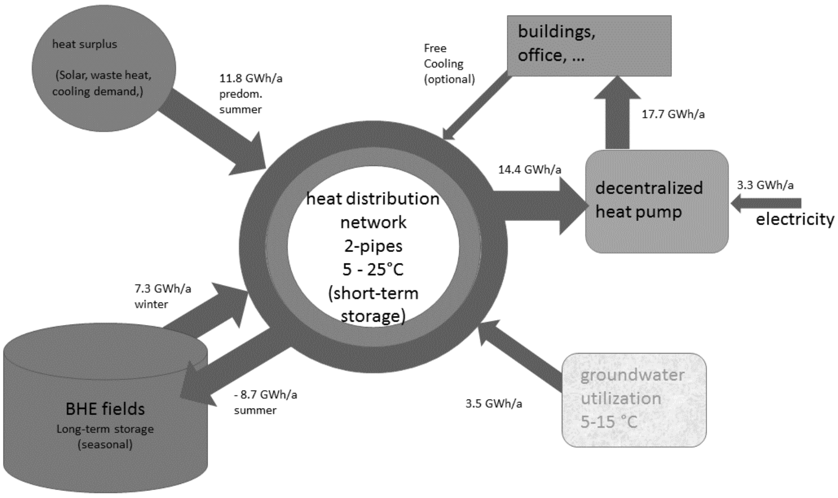
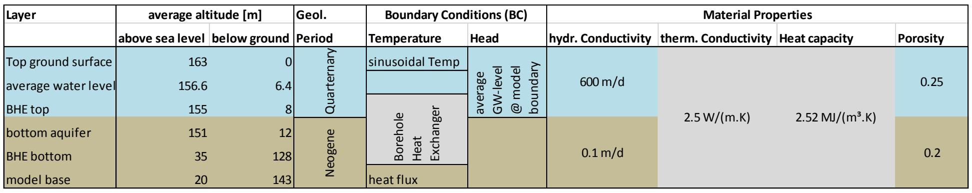


Figure 2: Concept of the geothermal heat distribution network with specification of the energy flow

A sinusoidal temperature BC is set at the surface, representing the idealized surface temperature derived from a nearby weather station with ground temperature measurements. On the base of the model a constant heat flux of 0.055 W/m² was set. The depicted boundary conditions was taken to get the start conditions in temperature distribution and groundwater flow before the geothermal utilities are operating for 20 years in a temporal simulation, see Figure 7.

Of special interest is the setting of the varying surface temperature, which effects also the groundwater temperature due to its shallow location and is illustrated in the left diagram of Figure 5. There was a good accordance to the comparison of a nearby groundwater temperature measurement. The phase shift of the temperature wave has a positive effect for the groundwater utilization, since the peak is shifted about 3.5 month at groundwater level and about 5.5 month at the aquifer base.



Layer	average altitude [m]		Geol.	Boundary Conditions (BC)		Material Properties			
	above sea level	below ground	Period	Temperature	Head	hydr. Conductivity	therm. Conductivity	Heat capacity	Porosity
Top ground surface	163	0	Quarternary	sinusoidal Temp	average GW-level @ model boundary	600 m/d	2.5 W/(m.K)	2.52 MJ/(m³.K)	0.25
average water level	156.6	6.4							
BHE top	155	8		Borehole Heat Exchanger					
bottom aquifer	151	12	Neogene			0.1 m/d			0.2
BHE bottom	35	128							
model base	20	143		heat flux					

Figure 3: Summary of important model layers, boundary conditions and material properties

Total number of BHEs	1000	
Number of BHE fields	2	
BHEs per field	500	
BHE spacing	4	m
BHE depth	120	m
geometry of one BHE field	25 x 20	
geometry dimension	96 x 76	m x m
area	7296	m²
active storage volume	875520	m³
BHE type	2 x U-pipe	
BHE refrigerant	water	

Combined flow and heat process
Darcy (Saturated)
Unconfined condition with phreatic top layer
Automatic Time Step Control with limited time step size of 2d
Maximum Error Norm of 0.05
Iterations per time step: 1
No Upwinding
3 Dimensions
1,565,840 mesh elements
821,472 mesh nodes
24 Slices / 23 Layers

Figure 4: BHE field set up (left) and general model settings (right)

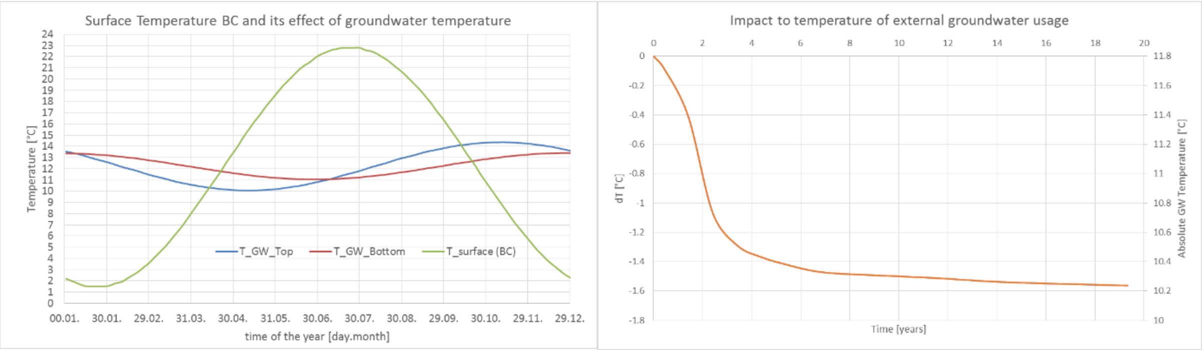


Figure 5: Surface Temperature as Boundary Condition and its effect to the groundwater temperatures without geothermal utilization (left); Impact of the geothermal utilization to the annual minimum groundwater temperature to the nearest external groundwater usage (right)

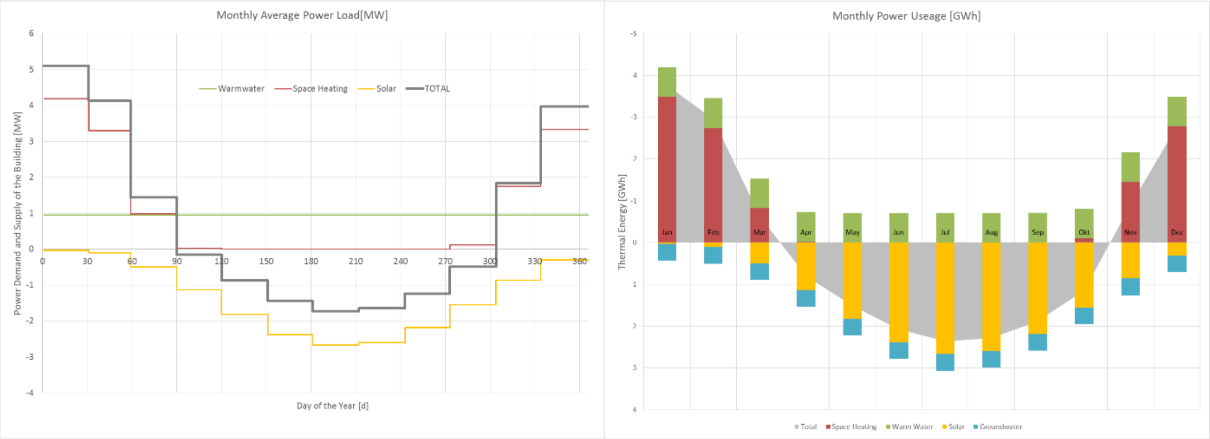


Figure 6: Power Demand of the buildings (left) and seasonal energy demand for the BHE storage with groundwater usage (right)

After a rough analytical dimensioning some basic parameters were specified. Therefore the groundwater wells are set to 20 l/s with 2 extraction and one injection well with a temperature difference of 5 Kelvin which complies with 400 kW of permanent power load. Further 120 km borehole heat exchanger (BHE) are split up to 2 BHE fields each with 500 BHEs with 120 m depth. The exact BHE field settings are given in the left column of Figure 4 and the positions in Figure 7. The simulation settings and mesh properties are given additionally in the right column of Figure 4.

Figure 6 shows the assumed power and energy demand of the buildings of the “Nordwestbahnhof” area which are adopted to the operation function of the BHE fields with an assumed COP (coefficient of performance) of the heat pump to 3 (for warm water) and 5 (for space heating). The gray marked curve at the right diagram of Figure 6 has to be handled from the BHE Fields.
All 500 BHEs of a field are connected parallel and the circulation rate was calculated so that the temperature difference between BHE-field input and output are 1.5 Kelvin in winter and 4 K in summer.

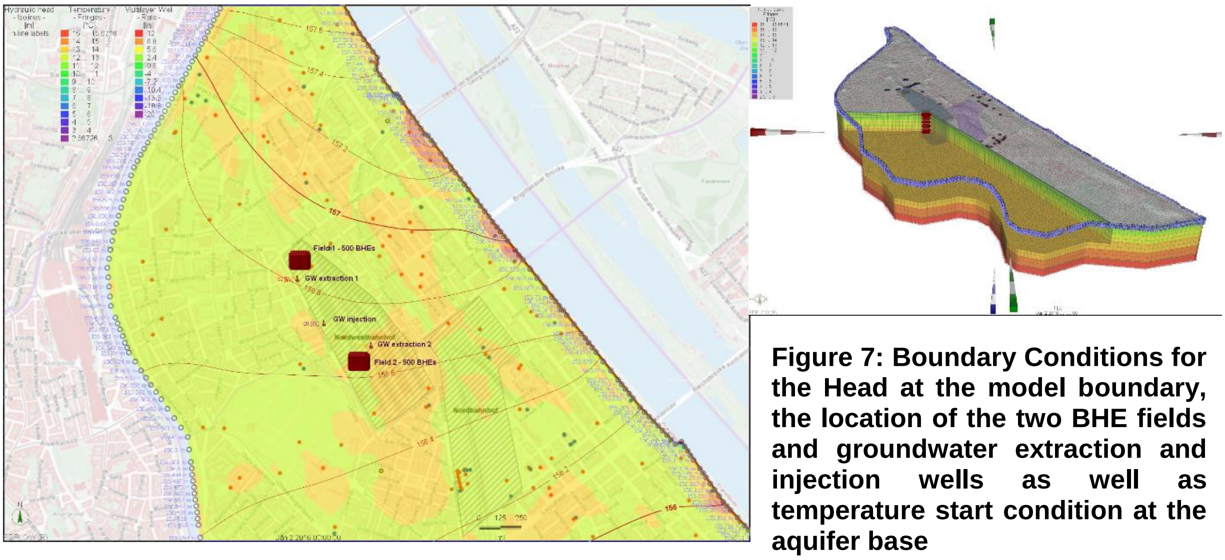


Figure 7: Boundary Conditions for the Head at the model boundary, the location of the two BHE fields and groundwater extraction and injection wells as well as temperature start condition at the aquifer base

RESULTS

The temperature distribution after 20 years of virtually operating the geothermal utilities is given in Figure 8. The power function of the BHE fields was set in a way that more energy is injected (8.7 GWh/a) than extracted (7.3 GWh) which yields to a surplus of 1.4 GWh/a. The usage of groundwater extracts 3.5 GWh/a so the total deficit for the earth are 2.1 GWh/a. The heat losses of the BHE fields are lowered by the groundwater wells since they are pulling the heated water. In addition the phase shift effect brings the highest groundwater temperature in December, see Figure 9 below.

The external groundwater use, about 150 m in the southwest of the Nordwestbahnhof is affected by the cold temperature wave of the groundwater well (Figure 8). The temperature drop of the annual minimum is illustrated in the right diagram of Figure 5. It seems, that the temperature disturbance will have its maximum at 1.6 °C which may be acceptable for the operator. Alternatively the operator can connect to the heat distribution network of the Nordwestbahnhof.

Due to the heat surplus of the BHE fields the BHE outlet temperature rises from 5.5 °C in the first year to 11.5 °C in the 20th year, see Figure 9. This is good for the heating period in winter and for the groundwater usage, but may be too warm for free cooling in summer.

In general the simulation shows the feasibility of the local energy concept. The decision whether the concept is economical efficient will take place at Vienna’s city administration. We are looking forward to do a more detailed simulation with more precise power functions and an improved positioning of the geothermal systems.

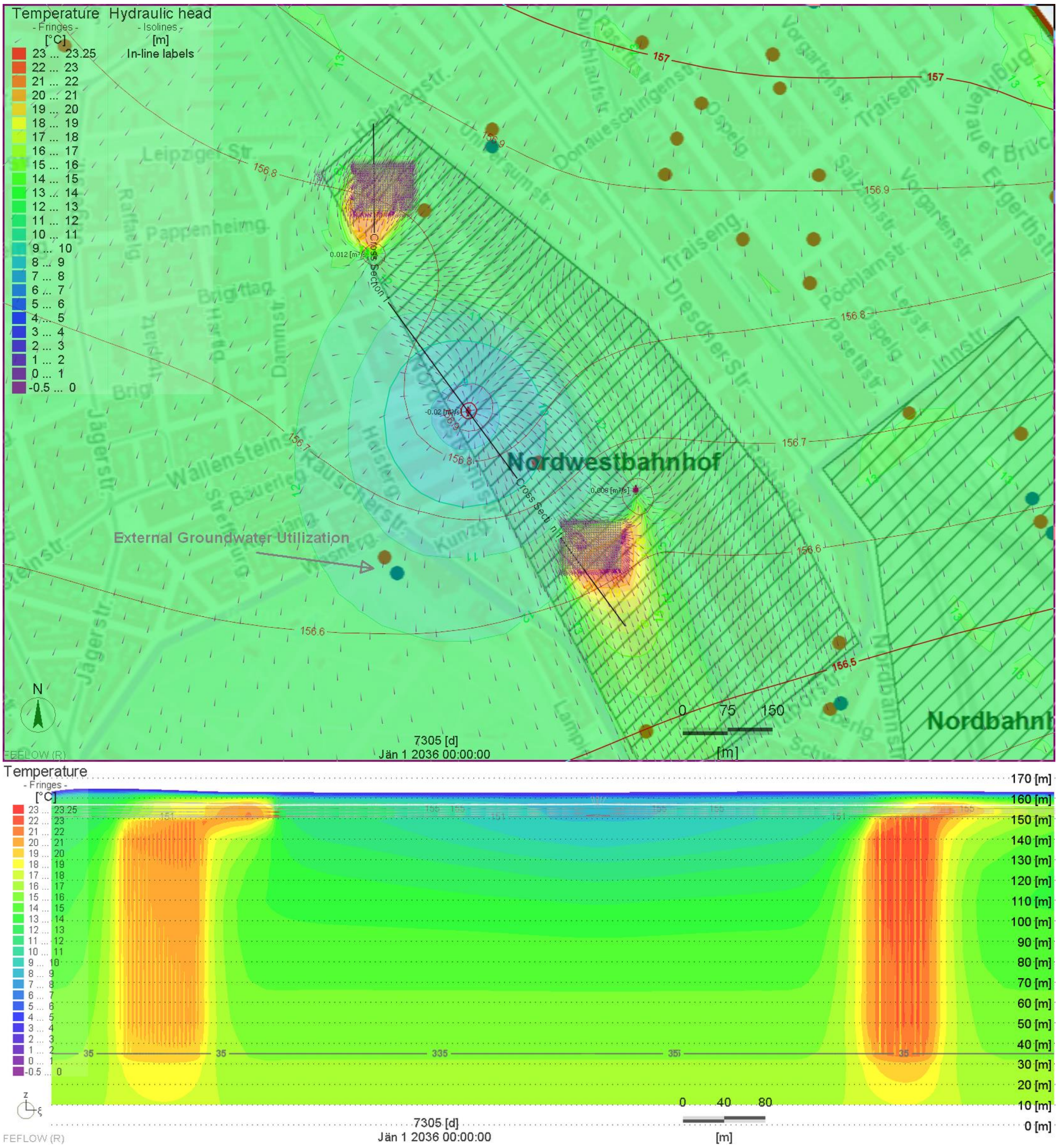


Figure 8: Simulation Results after 20 years of operation at a horizontal slice at 153 m in the aquifer (top) and a cross section (bottom). Temperature Fringes, Hydraulic Head, Darcy flux, Position of two extraction and one injection well, BHE positions and external groundwater utilizations (blue and red dots) are plotted.

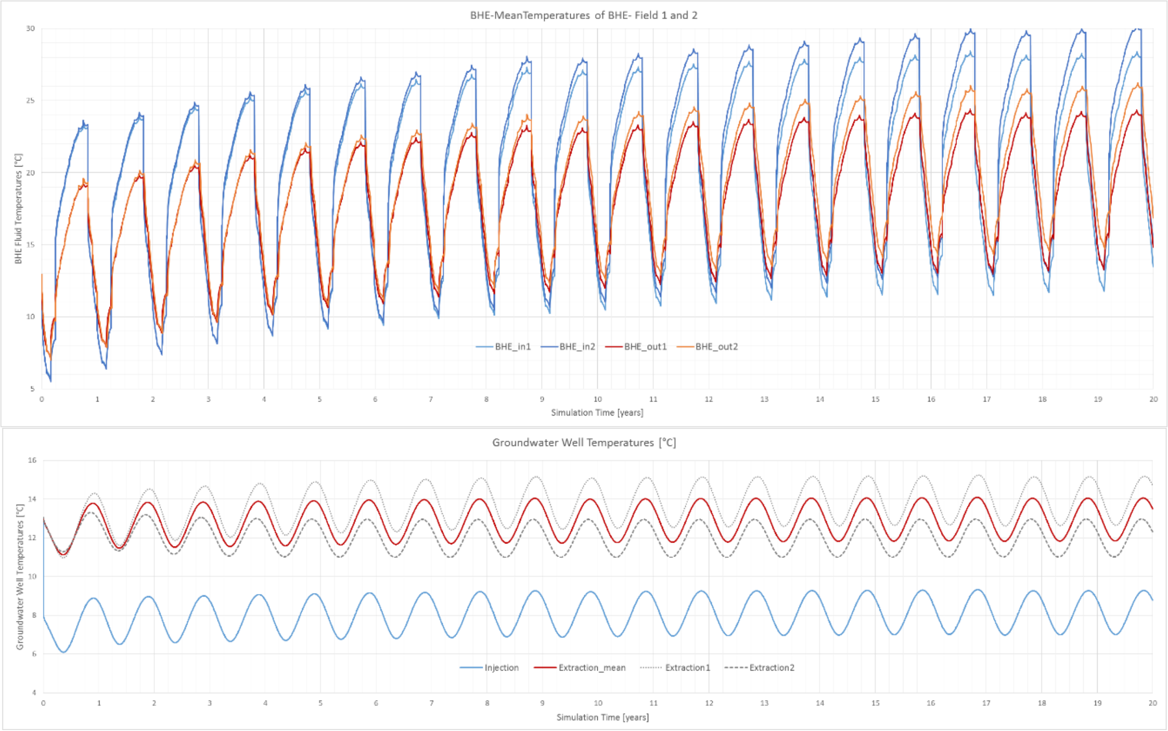


Figure 9: BHE inlet and outlet temperatures (top) and groundwater well temperatures (bottom) as a result of the simulation

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