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Coupling Dynamic Heat Demands of Buildings with Borehole Heat Exchanger Simulations for Realistic Monitoring and Forecast

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ABSTRACT

We present results of building performance simulations coupled with borehole heat exchanger (BHE) simulations for modeling the response of BHE-fields to varying heating power demands. We apply this method to an existing settlement in the Lower Rhine Embayment in Germany, called Neu-Teveren. Buildings in this former military settlement were built in the 1950s and will be extensively retrofitted in the coming years. Thus, it is a prime opportunity to model the impact of retrofitted buildings on the performance and longevity of BHEs. Our simulation results based on multi-year outdoor temperature records show that the cooling effect of the BHEs in the subsurface is about 3 K lower for retrofitted buildings. Further, a layout with one borehole heat exchanger per building can be efficiently operated over a time frame of 15 years, if the BHE-field layout considers regional groundwater flow. Due to northward groundwater flow, thermal plumes of reduced temperatures develop at each BHE, showing that BHEs in the southern part of the model affect their northern neighbors. Changing the layout of the BHE-field increases the performance of individual BHEs.

1. INTRODUCTION

Major renewable energy sources are characterized by natural transient fluctuations in energy supply. Therefore, their increasing exploitation requires flexible distribution systems and load management of consumers. For improving load management, it is important to study how transient changes in a consumer's energy demand can affect a nearby baseload energy source, e.g. a geothermal borehole heat exchanger (BHE). The implications of transient fluctuations in thermal energy demand on a BHE can be adressed by dynamic simulation of said demand on a flexible timescale. In some cases, BHE field simulations use estimated values of the energy demand averaged over longer time frames as model input parameter (e.g. Mottaghy and Dijkshoorn, 2012). In contrast, we present results of BHE field simulations, where the prescribed energy demand itself is the result of a building performance simulation (BPS), which can model the heating demand of a prescribed building in user-defined time frames, and in different modes (Bode et al., 2018). For this, we use TEASER (Tool for Energy Analysis and Simulation for Efficient Retrofit), an open framework for urban energy modeling of building stocks (Remmen et al., 2018). Results of the scalable BPS are thermal power curves, which can be used as input for modeling a realistic mix of energy input for heating. For instance, results of such a simulation can be used to model the response of a BHE in combination with or without other sources of thermal energy. In this manuscript, we present results of a case study, where we applied this coupled approach of building-specific simulated heating demand provided by a modelled BHE. The study area, the settlement "Neu-Teveren", is a former military housing settlement at the NATO-Airbase Geilenkirchen, Germany. Houses in this settlement share a similar layout, making it a well-controlled study environment. Thus, direct implications for the entire settlement can be derived from results of exemplarily simulated parts of the settlement. We further examine the impact of retrofitting buildings to newer energy standards on the heat demand and the response of the BHE.

2. STUDY AREA

The investigated study area is a settlement near the city of Geilenkirchen, located in the region north of Aachen, Germany (Fig. 1 A). Here we had the opportunity to interact with stakeholders from the city of Geilenkirchen who are planning the reconstruction of the settlement next to the NATO-Airbase in Geilenkirchen-Teveren. The buildings in this former military housing complex *"Fliegerhorstsiedlung Teveren"* (further called Neu-Teveren) were built in the 1950s and are planned to be extensively retrofitted in the coming years. Additionally, the construction of new houses is planned in some areas of the settlement. Figure 1 shows a map indicating the location of Neu-Teveren (blue polygon in B and C) within the area of a regional, calibrated flow model (turquoise polygon in B). Small grey rectangles depict positions of existing houses, further colors illustrate the surface topography.

Geologically, the study area is situated in the Lower Rhine Embayment, an active subsidence site characterized by NW-SE striking normal faults, which can form hydraulic barriers due to clay-smearing (Bense and van Balen, 2004). This normal fault system yielded the development of a Horst-Graben-system, which created accommodation space for siliciclastic sediments from the Tertiary onwards with major lignite formation in the Miocene (Lücke et al., 1999). The sedimentary successions consist of alternating sequences of relatively unconsolidated marine and continental deposits. The fine-grained, shale-rich marine sediments are generally less permeable than the continental deposits. In terms of the hydrogeological system, several aquifers (sandy continental deposits) are divided by less permeable units, i.e. aquitards (shaly marine deposits and lignite seams). The Tertiary sediments unconformably overlie consolidated Carboniferous and Devonian sediments that were affected by the Variscan orogeny and are folded significantly with fold axis predominantly striking NE-SW. The system of normal faults, which developed from the Tertiary onwards, also dissects the Palaeozoic units.

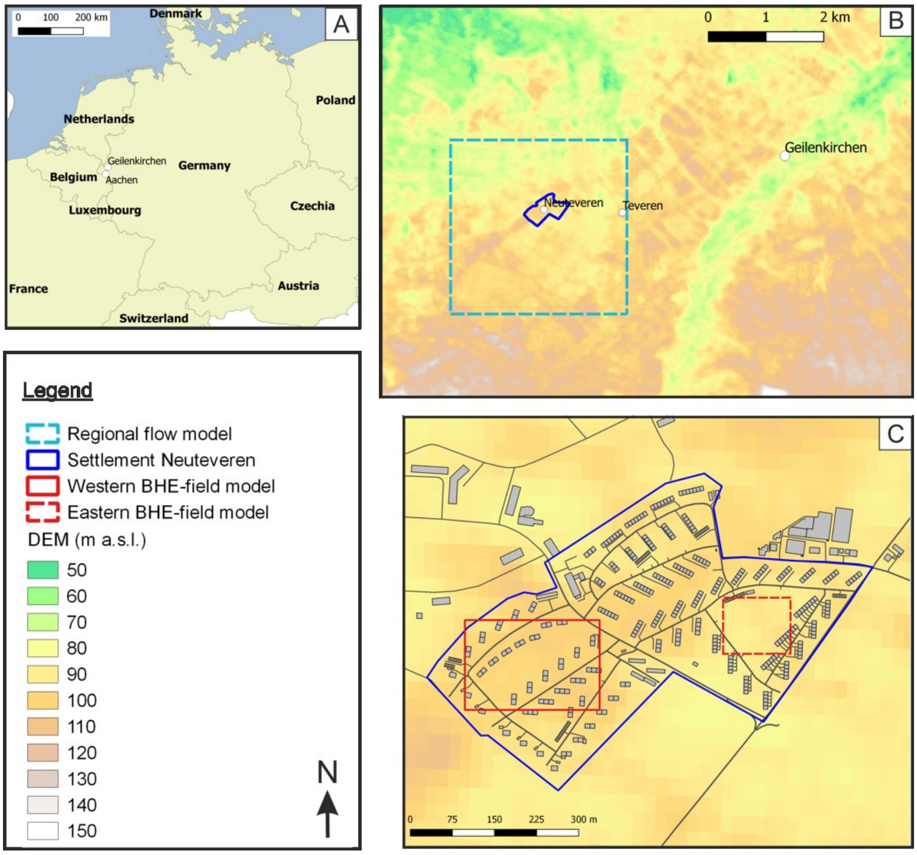

Figure 1: A: Overview maps of the study area within Germany. B: Outlines of a calibrated flow model (cyan) and the studied settlement (blue). C: Within the settlement, two exemplary but representative BHE-models were created (red boxes). Maps B and C are colored by topography, grey boxes in C mark locations of existing buildings.

The geological model focuses on detailed representation of Tertiary sediments in subsurface of the study area (Fig. 2). Paleozoic units beneath the basal Tertiary unconformity are grouped in one unit in the model (grey unit in Fig. 2). Tertiary lithologies in the geological model were grouped into aquifers and aquitards depending on their hydraulic properties. Main aquifer units in the model are the Liegendsande Aquifer, the Hauptkies Aquifer, and the Quaternary sediments. Lithological units are displaced by normal faults which predominantly strike NW-SE. Faults are modelled just as displacement, as there is no data on hydraulic properties of the faults available.

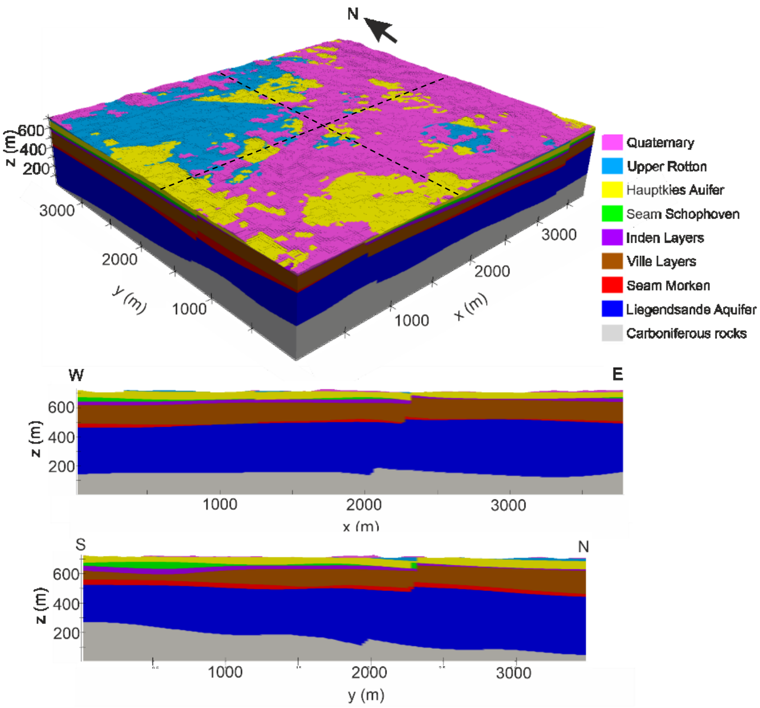

Figure 2: Geological model of the Tertiary sediments in the study area. Paleozoic sediments are depicted in gray. The model covers an area of 16 km². Location of the cross sections are marked as dashed lines in the 3D model.

3. BHE-FIELD MODELS

Two representative areas within the settlement were chosen for modelling BHE-fields based on information available in a confidential planning report provided by representatives of the city of Geilenkirchen. The choice was based on parameters such as available building retrofitting parameters (building area, date of construction, number of floors), and advantageous location for probable investors. Those parameters were combined with results of a regional reservoir model for deciding on model locations for BHE-fields. The western model area (Fig. 3 A, solid red square in Fig. 1 C) contains houses, which are planned to be retrofitted. Here, we simulated a BHE-field for two scenarios: original-state and retrofitted houses. In the eastern area (Fig. 3 B, dashed red square in Fig. 1 C), new single-family houses or semi-detached houses may be built according to information provided by city representatives.

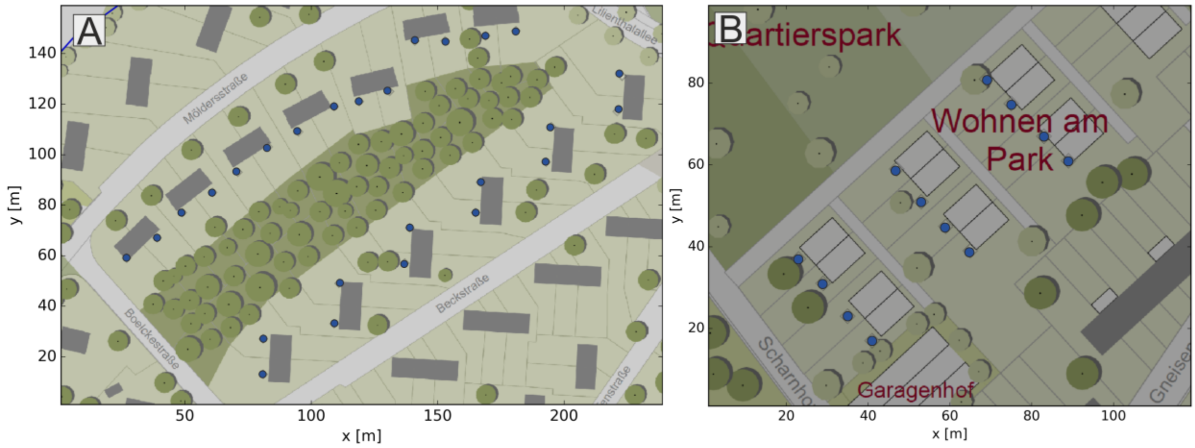

Figure 3: Positions of borehole heat exchangers (blue circles) in the numerical models (A: western model, solid red square in Figure 1 C, B: eastern model, dashed red square in Figure 1 C, after Geilenkirchen, 2018). Each BHE is assigned to a housing unit.

In the chosen layout, one borehole heat exchanger is assumed to be installed per housing unit, yielding 26 BHEs in the western model (Fig. 3 A) and twelve BHEs in the eastern model, according to a planned construction scenario (Fig. 3 B; Geilenkirchen, 2018). Further existing development scenarios differ in the layout of newly built houses. However, due to the relative continuous geology in the subsurface of Neu-Teveren, simulation results of one scenario are generally representative for BHE operation in the area. All BHE units extend to a depth of 100 m below ground surface. This is a regular depth for geothermal BHEs, since depths greater than 100 m require more extensive reviews based on the German mining law.

4. SIMULATION TOOLS

4.1 TEASER

For estimating the sustainability of a geothermal direct heat usage via BHEs, knowledge about the transient thermal energy demand of residential buildings is essential. We use TEASER (**T**ool for **E**nergy **A**nalysis and **S**imulation for **E**fficient **R**etrofit) (Remmen et al., 2018) for generating time series of the heating power demand for the specified number of residential buildings. TEASER uses **R**educed **O**rder **M**odels (ROMs) whose input parameters are defined by the user and data enrichment functions, based on statistics of the German building stock. By using those functions, the necessary user-input is reduced to a minimum, summarized in Table 1.

Table 1: Building-specific input parameters for a TEASER simulation.

BUILDING PARAMETER	***VALUE***	***UNIT***
BUILDING USAGE TYPE	Residential	-
YEAR OF CONSTRUCTION	1953 (original)	-
	2016 (retrofitted)	
NUMBER OF FLOORS	2	-
FLOOR HEIGHT	2.8	m
NET LEASED AREA	104 (western model)	m²
	158 (eastern model)	m²

In addition to building-specific input parameters, TEASER requires specific weather data (outdoor temperature, solar irradiation) over the time-frame to be simulated. We use data of the year 2014, measured at a weather station near the study area.

4.2 SHEMAT-Suite

For modelling heat and mass transport in a porous medium, we use coupled balance equations for energy, mass, and momentum. These conservation equations are implemented in the code SHEMAT-Suite (Rath et al., 2006), which is derived from the SHEMAT code presented in Clauser (2003). The mass transport equation is based on Darcy's law and the mass balance equation.

The code models heat- and mass-transport in a porous medium, by solving coupled balance equations for energy, mass, and momentum. The transient flow equation is based on Darcy's law and mass conservation:

$$S_s \frac{\partial h}{\partial t} = \nabla \cdot \left[\frac{\rho_f \, g \, \boldsymbol{k}}{\mu_f} \left(\nabla h_0 + \rho_r \nabla z \right) \right] + W \tag{1}$$

Where S_s is the specific storage coefficient [m^{-1}], h the hydraulic potential [m], and t is time [s]. ρ_f is the fluid density [kg m^{-3}], g the gravity [m s^{-2}], $\boldsymbol{k}$ the permeability tensor [m^2], μ_f the dynamic viscosity of the Fluid [Pa s], ρ_r is the relative density change compared to atmospheric temperature, z the vertical space coordinate [m], and W a volume source term [s^{-1}]. Analogue, the heat transport equation is derived from Fourier's law of heat conduction and energy conservation:

$$(\rho c_p)_B \frac{\partial T}{\partial t} = \nabla \cdot \left[(\lambda_B \nabla T) - (\rho c_p)_f \boldsymbol{v} \nabla T \right] + K \tag{2}$$

Where (ρc_p) are the thermal capacities of the *bulk* and *fluid* phase respectively [J m^{-3} K^{-1}], T is Temperature [°C], λ_B is the *bulk* thermal conductivity [W m^{-1} K^{-1}], $\boldsymbol{v}$ the Darcy velocity [m s^{-1}], and K the radiogenic heat production [W m^{-3}]. Values for the bulk porous rock parameters are calculated using the appropriate mixing laws, e.g. geometric mean for the thermal conductivity.

5. NUMERICAL BHE-FIELD MODEL

In this section, we present important characteristics of the numerical model, such as discretization, boundary- and initial conditions. After describing the heating demand curves from TEASER, which serve as input for the BHE simulations, we present simulation results comparing the BHE performance of retrofitted buildings versus buildings in original state.

For simulating a field comprising several individual BHEs, we translate power demand into an effective heat source term (heat sink term respectively), an approximation described in Mottaghy and Dijkshoorn (2012). By applying this approximation, BHE simulations are more efficient, reducing the computational cost of, for instance, the western model, which comprises 26 BHEs in total. This allows for considering heterogeneous geological models and the influence of groundwater flow (i.e. advective heat transport) on the BHE performance. The approach is computationally feasible for whole BHE fields and long-term simulations without the need for simplifications in operation time or temporal resolution of the BHEs.

5.1 Implementing Heating Demand

BHEs are implemented into our model as effective heat source or sink terms. For providing the correct values for these sources and sinks, the total thermal power demand in the model has to be known. The power curves resulting from TEASER simulations, however, are building specific. Due to its original design as a military housing settlement, the majority of buildings in Neu-Teveren have the same layout. This is advantageous for our simulation approach, as the total power demand is then simply a multiple of the building-specific results provided by TEASER.

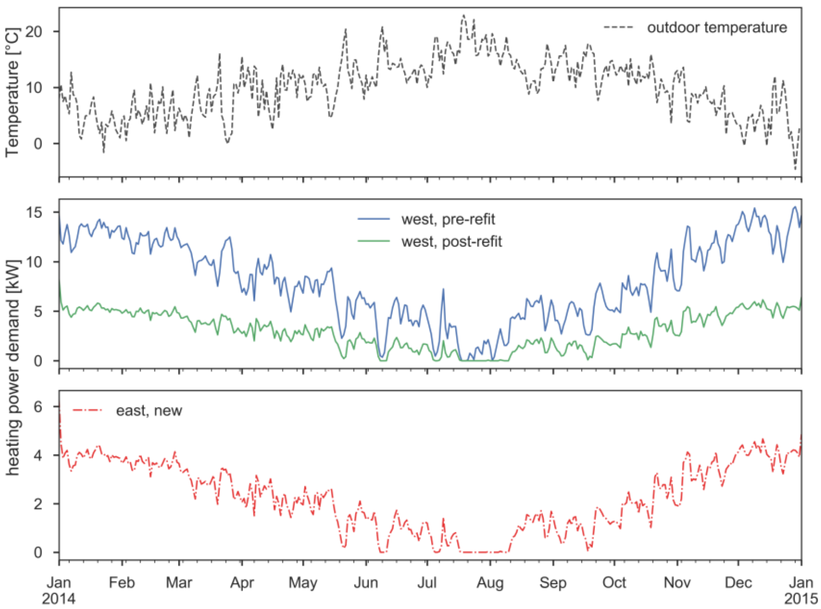

Figure 4: Top: Measured air temperature at a station near Jülich, Germany, in 2014. Mid: heating power demand for a twin-house in the western model, in original (blue) and retrofitted (green). Bottom: heating power demand of a house in the eastern model, assuming it is newly built.

For instance, we calculate the transient heating power demand for one twin house in the western model (gray rectangles in Fig. 3), and multiply it by 13 (26 houses arranged as 13 twin houses) to yield the total heating power demand. The thermal power demand is predominantly a function of the outdoor air temperature. Unless specified differently, TEASER uses a representative annual temperature curve, together with parameters specified in Table 1. Based on these input parameters, TEASER creates a building model used for calculating the transient thermal energy demand of the specified building.

Here, we specify the local annual temperature curve from 2014 (Figure 4, top). The middle and lower plots in Figure 4 present the resulting transient heating demands calculated by TEASER for specified buildings based on the respective outdoor temperature. The middle plot in Figure 4 depicts heating demands of an original house (blue curve) versus a retrofitted house (green curve) in the western model, whereas the bottom plot shows the heating demand curve of a newly built house in the eastern model. Increased energy efficiency of retrofitted buildings compared to their original state is clearly visible during winter months, and only to a lesser effect during summer. Note that we only consider heating demand in this study. Thus, the minimum heating power demand is 0 kW_e. Cooling would be modeled with negative heating power demand.

5.2 Boundary and Initial Conditions

Both BHE-field models, the western and the eastern one, are extracted from a bigger, calibrated regional reservoir model (cyan rectangle in Fig. 1 B), which was simulated with SHEMAT-Suite based on a cut-out of the subsurface model shown in Figure 2. Hydraulic head and temperature distributions used in the BHE-field models were extracted from the calibrated reservoir model and downscaled to the finer grid of the BHE-field models. Figure 5 shows in the top row a map view of the initial hydraulic head within the two BHE-field models. Both models show a gradient in the hydraulic head from south to north, indicating a northward groundwater flow. Such a northward flow agrees with measured groundwater level data (Erftverband, 2015). These initial values are kept constant at the lateral boundaries (i.e. Dirichlet boundary conditions).

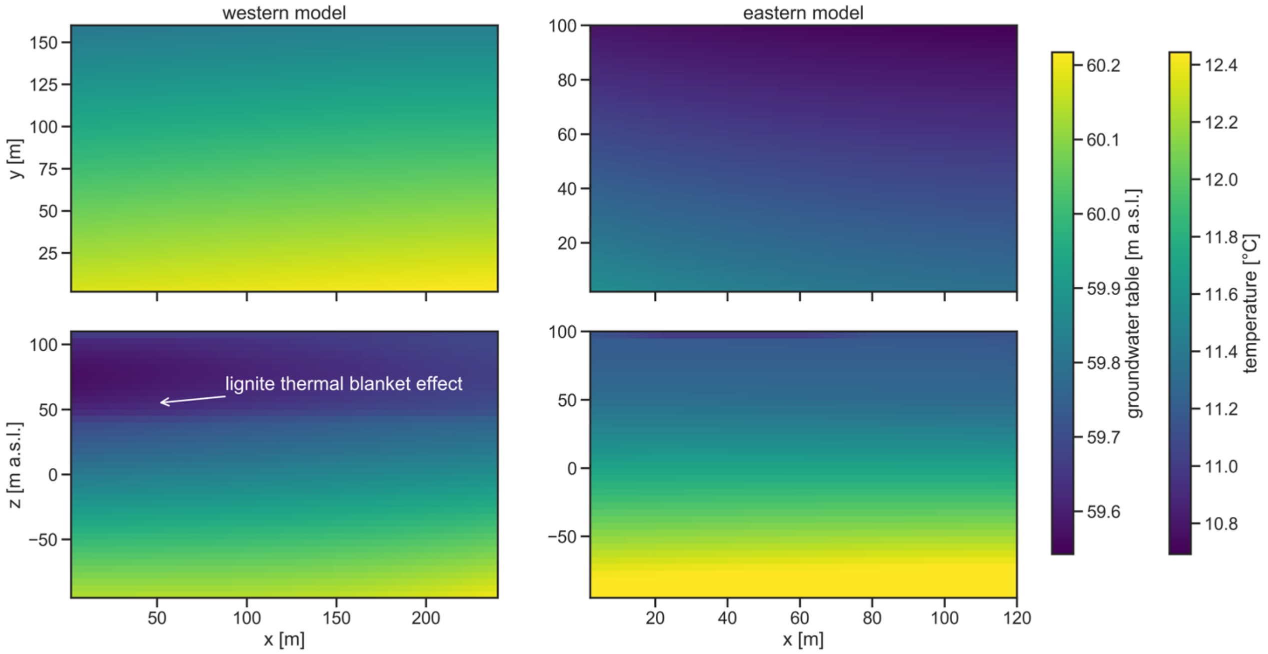

Figure 5: Top: Map view of the hydraulic head (in meter above sea level) in the western (left), and the eastern BHE model (right) at about 70 m depth. The values of hydraulic head at lateral boundaries are kept constant, thus working as Dirichlet boundary conditions. Bottom: vertical cross section through the western (left), and eastern BHE model (right) colored by initial temperature.

Temperature values are applied accordingly to the hydraulic head values. Vertical temperature profiles through the model are shown in the bottom row of Figure 5. In the western model, a distinct drop in temperature can be observed. This drop is caused by a lignite seam, which works as a thermal blanket due to its low thermal conductivity (less than 1 W m^{-1} K^{-1}, Jorand et al., 2015).

6. RESULTS

Operation of the BHE-fields in the western, as well as in the eastern model, was simulated over the timeframe of one year in order to assess the impact of seasonal heating demand and groundwater flow on the BHE-field. Simulation results of the western and eastern model are presented as 2D snapshots, i.e. horizontal cross-sections at a depth of 50 m below surface.

6.1 Western model

We designed the western BHE-field model around existing buildings which are representative for the settlement Teveren (Fig. 3 A). Already existing buildings provide the possibility for assessing the impact of retrofitting buildings on the BHE-field. Therefore, we generated two scenarios for the western model: One scenario using an estimated heating power demand of the buildings in original state (Fig.4, blue curve) and another scenario which assumes retrofit of buildings based on newest energy standards (Fig. 4, green curve).

Figure 6 shows simulated temperature in three representative months during the year at a depth of 50 m below ground surface assuming retrofitted buildings (left) or buildings in original state (right). The latter have a significantly higher heating power demand due to less thermal insulation. This in turn causes lower temperatures in the BHEs compared to energetically renovated buildings. Temperatures around BHEs in the original scenario are around 2 °C lower than in the renovated scenario.

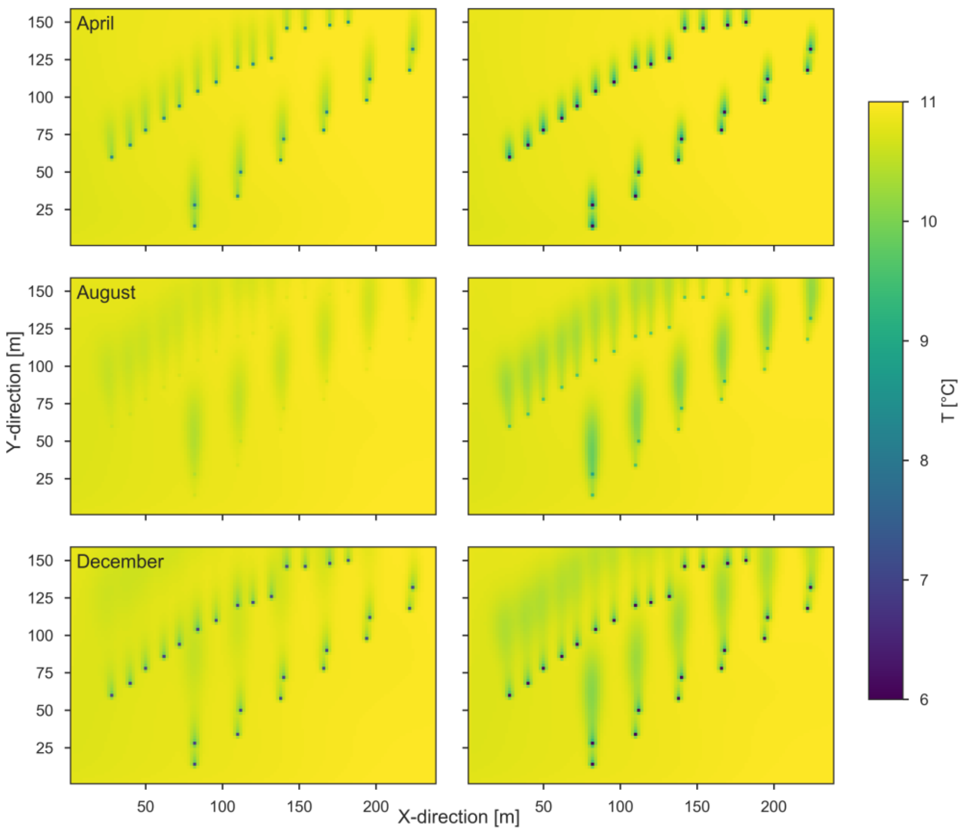

Figure 6: Map view of the temperature at 50 m depth in the western BHE model in retrofitted (left) and original state (right). Cooling of the subsurface is stronger for buildings in original state, with more developed thermal plumes.

Depending on aquifer permeability, groundwater flow shows a significant impact on temperatures around the BHE-field, as plumes of relatively lower temperatures are transported northward along the local groundwater flow direction. As heating power demand for buildings in the original scenario is higher, the thermal plumes are more pronounced. Consequently, the interaction between single heat exchangers is stronger, as BHEs in northern part of the model are affected by thermal plumes coming from neighboring installations. Furthermore, the simulations demonstrate that aligning BHEs in a north-south direction is not advantageous, as this is parallel to the direction of propagation of thermal plumes (see southern pairs of BHEs in Fig. 6). For assessing how much a transported thermal plume affects neighboring borehole heat exchangers, we study the temperature development over time of two BHEs in the southern part of the model. Temperature differences between neighboring borehole heat exchangers in the model peak around day 180 in our simulations, which translates to end of June. In Figure 7 we plot a north-south temperature profile at 50 m below ground level at day 180. Undisturbed simulated temperatures at that depth are around 10.9 °C.

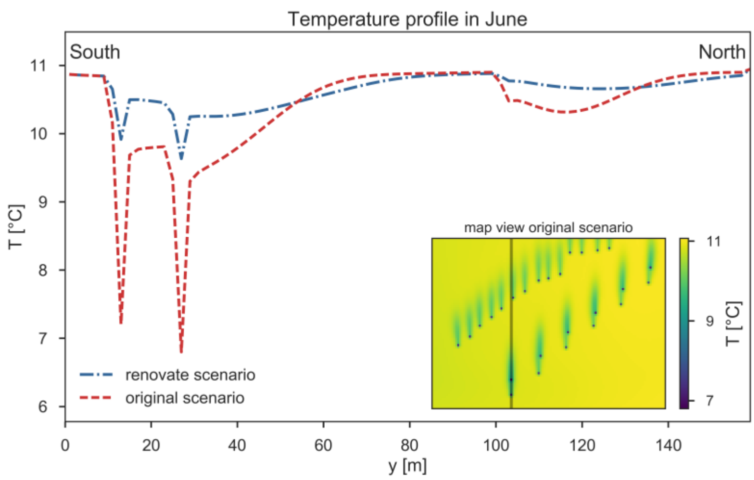

Figure 7: North-South trending plot of temperature at 50 m depth below sea level in June. Temperatures in a northern BHE are decreased due to a cooling influence of its southern neighbor.

Pronounced peaks in temperatures mark fluid temperatures in a borehole heat exchanger. Between the two BHEs in the south, temperatures are lower than the undisturbed temperatures, marking the influence of a thermal plume. The signal of the plume extends from the most southern BHE until around 80 m along the profile. The temperature difference between the two borehole heat exchangers is relatively small with around 0.3 °C. In the scenario with buildings in original conditions, temperature differences are significantly larger. Here, the plume of the most southern BHE causes a temperature drop of about 1 °C. This in turn affects the thermal energy rate which can be provided by a BHE installation. A slight decrease in temperature at around 100 m in both scenarios is a thermal signal of a BHE adjacent to the profile. By offsetting the southern BHEs in an EW direction, the performance of BHEs in the southern part of the western model improves slightly, as thermal plumes do not directly cross neighboring installations.

Seasonal changes in heating power demand are reflected by northward migrating thermal plumes. If heating power demands decrease to zero (as in July/August in our simulation), temperatures in BHEs re-equilibrate with surrounding temperatures. Therefore, the formation of thermal plumes of decreased temperatures caused by higher heating power demand in winter ends, once heating power demand decreases, and eventually gets zero during summer.

6.2 Eastern Model

Such seasonal variations can be well observed in the eastern model. Figure 8 shows map views of temperature in the eastern model at a depth of 50 m below sea level every three months. High heating demand in the first four months yields thermal plumes of decreased temperatures. The extent of these plumes grows with continuous heating power demand (Fig. 8, June). If the demand equals zero over a longer time frame, temperatures around BHEs increase again, confining the plume of decreased temperatures. This plume is transported northward and exits the model domain via the northern lateral boundary (Fig. 8, September). This cycle repeats annually, as it correlates with seasonal temperature changes via heating power demand.

As stated before, visible thermal plumes are just observed in more permeable units, namely Hauptkies Aquifer and Quaternary Aquifer. Maximum simulated groundwater velocities in these aquifers are in the range of 70 m per year. In less permeable, deeper lithological units, such as the Inden and Ville Layers, no thermal plumes are observed and the heat transport towards BHE installations is dominated by conduction, causing a stronger temperature reduction in the BHE at those depths.

Different building scenarios exist for the eastern model, i.e. six single buildings (Fig. 3 right) or twelve semi-detached houses. The latter would cover approximately the same area as six single houses. Accordingly, our simulation results can be evaluated for both scenarios, as the heating power demand is a function of net leased area. This parameter does not vary significantly between the two scenarios.

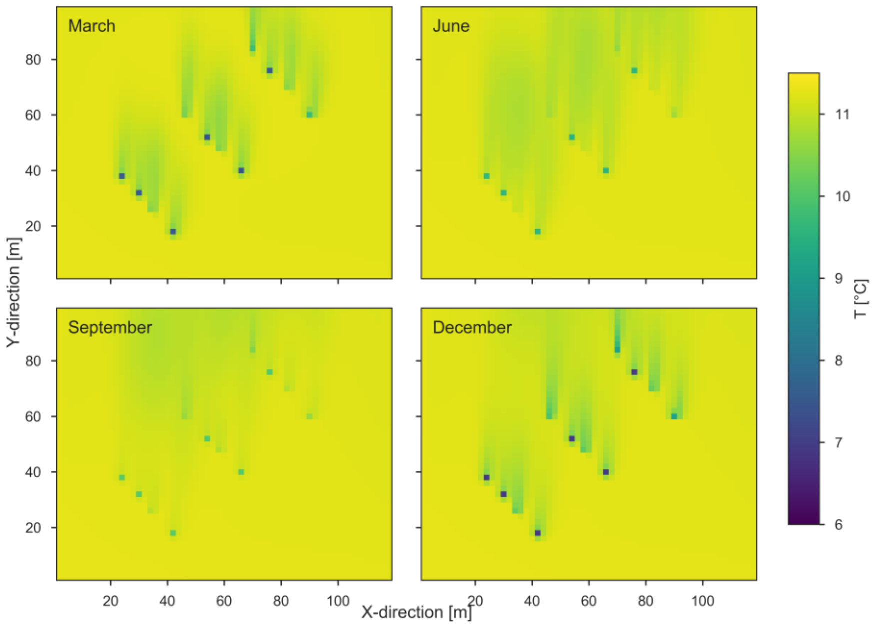

Figure 8: Map view of the temperature at 50 m depth in the eastern model during different times of a year. The cooling effect of BHEs is most pronounced during winter months.

6.3 Simulation over 15 years

Simulations over a timeframe of one year do not suffice for estimating the sustainability of a BHE-field. Mottaghy and Dijkshoom (2012) simulate a BHE-field for 15 years of operation in order to analyze sustainable operation of the simulated BHE-field. Further, such a long-time simulation will allow for analyzing possible cooling of the subsurface caused by using geothermal heat supply for space heating only.In order to evaluate the sustainability of the BHE-field, we extended the simulation time to 15 years for the western model, assuming retrofitted buildings.

For assessing the magnitude of cooling in more detail, we plot in Figure 9, the temperature profile in June for each year, at the same location as in Figure 7. Temperatures along the profile significantly decrease from higher initial conditions over the first three years, due to the effect of groundwater velocity. However, temperatures stabilize at around 10 °C for the rest of the simulation. Accordingly, impact of thermal plumes also stabilizes.

It should be noted that the temperature curves underlying the heating power demand for the BHE-field do not comprise extreme events, such as long cold spells during winter. Instead, we assume a more regular, sinusoidal seasonal temperature pattern. Accordingly, temperatures stabilize at certain values, due to repeating boundary condition values, i.e. seasonally repeating heating power demands.

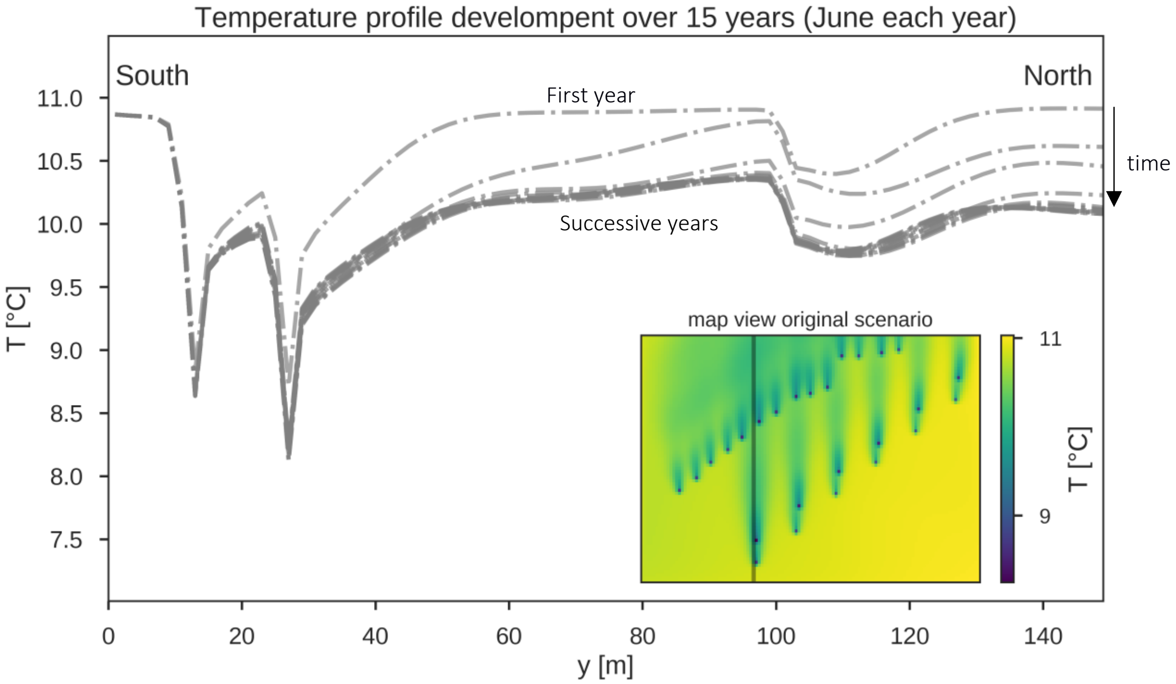

Figure 9: North-South trending temperature profiles of each year (month June) for a simulation time of 15 years. Temperatures decrease for the first 4 years, but then stabilize.

However, a stabilization of temperatures under the assumed conditions suggests, that the simulated BHE-field could be operated sustainably. In our simulations, we just assumed heating power, not cooling during summer. Incorporating cooling would likely improve the BHE-field performance, as storing heat undergorund during summer would counteract the cooling effect.

A combination of heating and cooling, where surplus heat gets stored in the subsurface during summer, most likely increases a sustainable operation of a BHE-field.

7. DISCUSSION AND CONCLUSION

Based on a calibrated, regional reservoir model around the settlement Neu-Teveren, Germany, we generated two representative models for simulating the operation of BHEs for direct heating. In a western model, we compare BHE responses to thermal power demand in two scenarios: an original scenario, where buildings from the 1950s are assumed to remain in original conditions, and a renovated scenario, where buildings are assumed to be retrofitted to current energy standards. Heating power demand was simulated using TEASER instead of assuming average or normative values.

We simulate permanent BHE operation over a timeframe of one year. Simulation results suggest that the thermal power demand of retrofitted buildings can likely be met by BHEs. Temperatures within a modelled BHE decrease to around 6 °C in winter due to high thermal power demand, and rise to around 10 °C in late summer.

Simulations further show that groundwater flow should be considered in layout of BHE-fields, as high permeability in the Hauptkies Aquifer and Quaternary Aquifer enable northward groundwater velocities of up to 70 m per year. Groundwater flow causes the development of thermal plumes, emanating from the borehole heat exchangers. Thermal plumes are transported by advective heat transport and increase thermal interaction between BHEs. However, simulation results suggest that this thermal interaction is relatively small and does not decrease the capacity of BHE installations affected by thermal plumes of neighbouring BHEs.

Prolonged simulations over a timeframe of 15 years yield stabilized temperatures around 1 °C below initial conditions at a depth of 50 m below surface. Temperatures around single BHE-units suggest that a sustainable operation of the simulated BHE-field is possible for a longer time. Sustainable operation can be improved by coupling heating and cooling of buildings, and using the subsurface as heat storage, i.e. store heat during cooling in summer and use this heat in winter.

However, only one to two percent of modern residential buildings in Germany have an air conditioning system available, and rather cool by insulation and ventilating systems. Thus, BHE fields should be planned to be sustainable and operational with heating alone. On the other hand, around half of office- and administrative buildings in Germany have air conditioning systems installed. Thus, cooling of the building, and corresponding heat-storage in the subsurface, should be considered when modelling these types of buildings.

The comparison between original and retrofitted buildings showed the importance of incorporating realistic heating power demand of buildings into the BHE-field simulation. Building performance simulation, such as provided by TEASER, is an efficient tool for obtaining realistic building specific heating power demand as input for BHE-field simulations.

Our simulations can represent realistic scenarios for district heating and results may have a direct application in the renewed city quarter. Additionally, the study area in the Lower Rhine Embayment reveals results of more general interest for geothermal applications in sedimentary basins facing medium to high groundwater flow rates.

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