The favourable contribution of advective recharge to the BHE performances makes BHEs another site-specific geothermal resource that is out of the scope of this study. Here, we investigate a case with no advection by focusing solely on diffusive heat transfers.

Injecting excess solar heat energy collected from solar panels in summer into the ground was view by the authors as a potential solution to compensate for the geothermal heat extracted in winter and guarantee the long-term viability of such installations.

We therefore here attempt to quantify the rate of heat production in the subsurface as well as the potential recovery rate from solar and geothermal heat flux, based on a typical temperature and geological profile in the Midlothian Coalfield in Scotland.

The effect is that the yearly average temperature can be assumed for a first approximation to be a Dirichlet boundary. However, ignoring the cooling effect overestimates how much heat is available, and will maintain the near surface temperature artificially high.

Choosing the ∆*T* at the heat pump to calculate the required volume however neglects what the actual temperature of the rock is. To account for the heat content of rock sections, Raymond and Therrien (2008) suggested to define in Eq. 2.1 according to the initial rock temperature , with *z* the average depth of the considered rock section and the mean geothermal gradient. In such scenario, , ∆*T* would be reduced to 2°C. Assuming an average borehole depth z = 70 m and a geothermal gradient *α* = 31 ◦*C/km*, the volume of rock required for cooling would be increased to an area of 180 *m*2 for 1 year and 5500 m² for 30 years. In that case, considering a lower geothermal gradient and thus a lower at the borehole would require greater rock volume to provide the necessary heat load.

Using 133 Bottom-Hole temperature (BHT) acquired from depth >1.5 km in 72 offshore wells in the North West Margin area (Gatliff et al., 1996 in Gillespie et al., 2013), the authors however noted the increase in the deep geothermal gradient from about 35.8◦C/km at 1 - 3.5 km to 46.7◦C/km at 3.5 - 5 km, relatively consistent across Scotland, and independent of the location (i.e. onshore or offshore) and the type of rock (i.e. sedimentary, crystalline basement) in which measurement were taken. Plotted together, onshore and offshore temperature measurements for the whole depth range (0-5km) indicated an average geothermal gradient of 31.9 ◦C/km.

Below that depth, the ground temperature is mainly controlled by the upward geothermal heat flux and tends to follow the trend of the local geothermal gradient (Hein et al., 2016).

Although solar heat flux is an order of magnitude higher than the geothermal heat flux, it is expected to decrease exponentially with depth due to 1) an increase in temperature and 2) a dissipation of the effects of solar radiation and atmospheric condition with depth depending on the diffusivity of the soil (Ozgener et al., 2013). Therefore, the estimated solar recharge might be constrained to shallow depth and overestimate the heat recharge to the borehole. Additionally, energy losses might also occur at the surface in situations where the ground gets warmer than the surface.

The large temperature decline at the borehole i.e. ΔT = 10.8°C in the finite model) relative to the one observed at distance x = 4.5 m after 1 year (ΔT = 1.1 °C) after 1 year or at x = 26. 5 m after 30 years (ΔT = 1.3 °C) suggests the presence of a cone of thermal drawdown, where the effects of heat extraction are damped and delayed with distance from the borehole.

This comparison suggests the importance of lateral heat recharge in reducing the amplitude of the temperature decline in the zone of impact of the borehole. Although quasi-steady-state situation tend to be reached in the model.

This suggests that although a quasi-steady-state temperature tends to be reached at the borehole, this does not correspond to the spatial steady-state temperature conditions due to the poor heat generation and recharge potential of this system.

## Axial recharge

We first attempt to quantify the axial affects induced by heat extraction from the 40-m long borehole over time by comparing the temperature profiles obtained from the 1D finite (F) and semi-infinite (SI) models. In both scenarios, a total heat load of 1200 W regularly distributed along the line source of finite length is abstracted from the 73 m² and 2200 m² models for durations of 1 year and 30 years, respectively, according to the analytical model described in part XXX.

We therefore calculate the integrated temperature difference in the borehole depth interval between the finite and semi-infinite models for both time periods in order to evaluate the effects of axial heat recharge on the observed temperature profile. This is done based on the following equation:

Where subscript F and SI refers to the finite 40-m long model and 1000-m long semi-infinite model, respectively, and the integrand limits represent the model depths. Results indicate that after 1 year (73-m² model), about 10% of the heat extracted in the semi-infinite model is sourced from the area available above and below the borehole. Over 30 years, although the model used dispose of a greater rock volume (i.e. 2200-*m*2 model), the temperature drop within the borehole depth interval is considerably reduced, with the rocks situated above and below providing up to ~50% of the heat required by the borehole. The amplification of axial effects over time therefore permits the reduction in the temperature drop at the borehole, given that the model disposes of the appropriate lateral extent.

## Three-dimensional study of radial recharge

Assuming that 1D models represent far field conditions, we extract data along polylines situated at distances x = 4.5-m and x = 26.5-m from the borehole location (x = 0 m) after at 1-year and 30-years of simulation. Those distances correspond to the radii of the areas required for BHE utilisation after 1 and 30 years of heat extraction (73-m² and 2200-m²), respectively, and used in the 1D analysis.

* Using Eq. XXX, we calculate the relative proportion of axial heat recharge and compare it to results obtained from the 1D models
* We deduce the relative contribution from radial heat recharge after 1 and 30 years of production based on the difference in temperatures measured at 4.5-m and 26.5-m in the 3D model and the temperatures in the 1D model, integrated within the borehole depth interval.
* We calculate the axial fluxes induced at x = 0-m and at 4.5-m and 26.5-m in the 3D model after 1 and 30 years of heat extraction

The comparison between the temperature profiles extracted in the 3D models at x = 4.5-m and x = 26.5-m with the corresponding 1D profiles (i.e. 73m² and 1D 2200m² models, respectively) after 1 and 30 years of heat extraction suggests a smaller thermal drawdown in the far field of the 3D model than in the corresponding 1D model (Fig. 4). However, results from the calculations indicate that at those distances from the line source, the contribution from axial flux is in the order of those estimated from 1D scenarios, that is about 10% ± 0.3% after one year and ~50% ± 3.9% after 30 years. On the contrary, a greater temperature decline is observed at the borehole location (i.e x = 0-m), interpreted to result from the effects of lateral spatial discretisation. In the finite models (i.e. red profile), the temperature at the mid-borehole declines by 6.2°C after 1 year ( 5 °C) and by 10.8°C after 30 years (0.35 °C). Although, the 3D semi-infinite model (i.e. pink profile) sees the same decline in temperature after 1 year of production, the effects of recharge after 30 years allow reducing the thermal drawdown at the borehole location, with a decline of 9.8°C is measured after 30 years (.35 °C). Applying Eq. XXX at x = 0 m shows that axial effects only contribute to less than 5 % of the recharge after 1 year and up 17 % after 30 years. This suggests that although axial fluxes also allow reducing heat depletion in the borehole depth interval, they do not provide sufficient recharge in the area directly surrounding the borehole where the amplitude of the drawdown is the highest.

We then quantify the relative contribution of radial heat fluxes to the heat recharge to the borehole over time, using the relative temperature difference between data extracted at distances x = 4.5 m and x = 26.5 from the 3D finite model and the corresponding 1D finite temperature (Eq. XXX). Results indicate that when no axial recharge is allowed, radial heat fluxes contribute up to 70% of the recharge at the model boundary (i.e. 4.5 m for the 1-year model and 26.5 m for the 30-year model). In a case with axial recharge, they would contribute up to 63% of the recharge after 1 year and 35% after 30 years.

We finally calculate both vertical (axial) and radial (horizontal) heat fluxes along 2D vertical profiles extracted from the finite and semi-infinite 3D models at t = 1, 10, 30 and 100 years of heat extraction (Fig. XXX).

Table XXX

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | Finite model 3D |  | Semi-infinite model 3D |  |
|  |  |  | corr |  | corr |
| 1 year  (x = 4.8) | Top BHE  Mid BHE  Bottom BHE | -1.072 -0.067  **-1.003** -0.063  -1.072 -0.056 | -0.003  0  0.008 | -0.537 0.197  **-1.003** **-0.063**  -0.537 -0.328 | 0.261  0  -0.264 |
| 30 year  (x = 26.5) | Top BHE  Mid BHE  Bottom BHE | -0.145 **-0.064**  -0.144 **-0.064**  -0.145 **-0.064** | 0  0  0 | -0.067 -0.030  -0.100 **-0.063**  -0.067 -0.096 | 0.034  0  -0.032 |

After 1 year (x = 4.8 m), the radial heat flux in the semi-infinite model reaches ~ 1 W/m² at the mid-borehole depth (i.e. -70 m), in accordance with the analytical model presented in section XXX. At the borehole ends, is reduced by half to a value of 0.537 W/m². There, the axial heat fluxes contribute to the heat recharge, reaching ~0.26 W/m² after correction for the effects of the geothermal heat flux. After 30 years of heat extraction, the heat fluxes induced at x = 26.5-m in the semi-infinite model are an order of magnitude lower, with values for of only 0.1 W/m² and 0.067 W/m² at the mid-BHE and borehole ends, respectively, and ~0.03 W/m². In the finite model, radial heat fluxes are increased to compensate for the lack of axial recharge and constant along the borehole. Those equals 1 W/m² at x = 4.8 m after 1 year of production (similarly to the mid-borehole value in the semi-infinite model) and 0.15 W/m² at x = 26.5 m (t = 30 years).

From XXX years, quasi-constant radial heat fluxes are reached throughout the model, in accordance with the steady rate of temperatures decline highlighted by the temperature time series (Fig. XXX). As a result, the area of impact will keep expanding slowly over time, if no additional heat recharge is provided.

Discussion:

We then verify our model through different cyclical injection/production scenario using the 3D full-extent model.

## Heat balance analysis

Here, we perform simple heat balance analysis to evaluate the amount of annual recharge that would allow constraining the area of impact to 70-100 m² over 30 years.

We suggested earlier that radioactive heat production, solar recharge and geothermal heat cannot compensate for the heat extracted on a yearly average under the considered geological and climatic context, without considering an unrealistically large volume of rock. For a defined heat extraction rate and production period, the footprint area of mined heat is highly dependents on the conductivity of the medium. Our analysis shows that lateral heat flux, which defines the rate at which heat is provided to the borehole by the surrounding area, can reach steady state after < 10 years in a homogeneous system. Axial fluxes tend to increase over time, depleting the volume of rock available above the borehole in heat while expanding the zone of influence below and around it, to an extent that depends on the conductivity of the ground.

In addition, this study showed that in geographical areas with low geothermal heat flux and low in-situ heat production, artificial heat recharge is required to ensure sustainable heat extraction and constrain the footprint area impacted by heat mining. 3D analysis showed that the areal impact of heat mining can be minimized by performing cyclical production with periods of no production, while adding cyclical recharge allow ensuring heat balance in the system, decrease the peak in temperature drop at the borehole and ensure sustainability from the heat resource perspective.

Next step will be to assess the relative contribution from heat convection and conduction through the porous medium, using 2D advection-diffusion models (i.e. with groundwater flow). We will also extend this study by using mine-water heat source as a way to disperse heat injected from artificial sources.

References

Numerical investigation on the performance, sustainability, and efficiency of the deep borehole heat exchanger system for building heating of Chen et al. (2019)