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<https://escholarship.org/uc/item/4hc232sp>

Authors

Doughty, Christine

Liu, Xiaobing

Stumpf, Andrew

et al.

Publication Date

2026-02-10

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Coupled Groundwater Flow and Heat flow Modeling for Detroit Arsenal

Christine Doughty

Lawrence Berkeley National Laboratory

Xiaobing Liu

Oak Ridge National Laboratory

Andrew Stumpf and Yu-Feng Lin

Illinois State Geological Survey

James Tinjum, Alicia Leubbe, and David Hart

University of Wisconsin, Madison

February 10, 2026

Abstract

An efficient means of modeling coupled groundwater flow and heat transport for an entire borefield making up the Ground Heat Exchanger (GHE) for a Ground Source Heat Pump (GSHP) is demonstrated, using the numerical simulator TOUGH, incorporating the “Extra Grid Block” method. A realistic thermal load taken from an EnergyPlus simulation provides inlet temperature and loop flow rate for the borefield. The thermal load is nearly balanced between winter heating demand and summer cooling demand. TOUGH then simulates subsurface heat transport, assuming three different magnitudes of regional groundwater flow: none, small – deemed plausible for Detroit Arsenal, and large – 10 times the small value, to illustrate a more extreme effect. The small groundwater flow has a negligible effect on GHE performance, and the large groundwater flow has only a minor effect. An alternative case using a hypothetical unbalanced thermal load with cooling demand all year showed greater effect of groundwater flow. The implication of the coupled groundwater flow/heat transport model results presented here is that the usual practice of assuming subsurface heat transport occurs by thermal conduction only is valid for the proposed GHE design at Detroit Arsenal. A large hydraulic head gradient, high-permeability strata over most of the borehole length, and a highly unbalanced thermal load are all necessary for groundwater flow to have a significant effect on GHE performance, and none of these is present at Detroit Arsenal.

Introduction

The FedGeo project helps government installations determine how to use shallow geothermal resources such as ground source heat pumps (GSHP), borehole or aquifer thermal energy storage, and direct use for building heating and cooling (both residential and industrial) and hot-water heating.

Typical analysis methods for GSHP systems go into great detail in describing buildings' geometries and composition, energy loads, and HVAC systems, but treat the subsurface very simply, by assuming heat transfer between boreholes and ground occurs by thermal conduction through a homogeneous geologic medium. Not considered are heterogeneities in geology that impact thermal properties and the presence of groundwater flow that enables heat transfer by convection.

This report describes numerical modeling of coupled groundwater flow and subsurface heat transport for a borefield (i.e., GHE) that would be part of a potential GSHP system for a building at Detroit Arsenal, conducted as part of the FedGeo project. The goal is to assess whether groundwater flow is likely to impact GSHP performance.

Detroit Arsenal Setting

Building and GSHP Borefield

We consider a hypothetical GSHP for a large multi-story office building at Detroit Arsenal (Figure 1). Considering results of an initial GHE design analyses done with Oak Ridge National Laboratory's GSHP screening tool based on EnergyPlus simulation, 116 vertical boreholes, each 100 m long, are used. Each borehole contains a single u-tube, and boreholes are connected in parallel. Boreholes are arranged in a rectangular pattern consisting of four North-South rows, with 29 boreholes in each row. This elongated rectangular shape was chosen to fit into available open land to the West of the building (Figure 1), and to make optimal use of East to West groundwater flow. Borehole lateral separation is 6 m.

Hourly load, temperatures, and flow rate for one year of operation of the GSHP are taken from an EnergyPlus analysis that considers heat transport in the subsurface to be purely by conduction (Figure 2). Over the course of one year (Figure 2a), the load is reasonably balanced, with similar amounts of heat taken out of the ground in the winter and heat put into the ground in summer. Note that daily temperature variation is smallest in the spring and fall, and largest in the summer. Figure 2b and Figure 2c show the same variables as Figure 2a, but for just a few months during the winter and summer, respectively. Daily and weekly variability is apparent in Figure 2b and Figure 2c. During the winter, loop flow rate is nearly constant, with short peaks during the coldest part of each night and short dips during the warmest part of each day. Gentle dips in heat use on the weekends are also visible. During the summer, loop flow rate shows a distinct on-off pattern, as air conditioning is not used at night or on the weekends.



Figure 1 Satellite view of Detroit Arsenal. The hypothetical borefield location is the blue box adjacent to the office building shown outlined in red. Bear Creek is shown as a light blue line. Expected groundwater flow direction through the borefield is from right to left, toward the creek

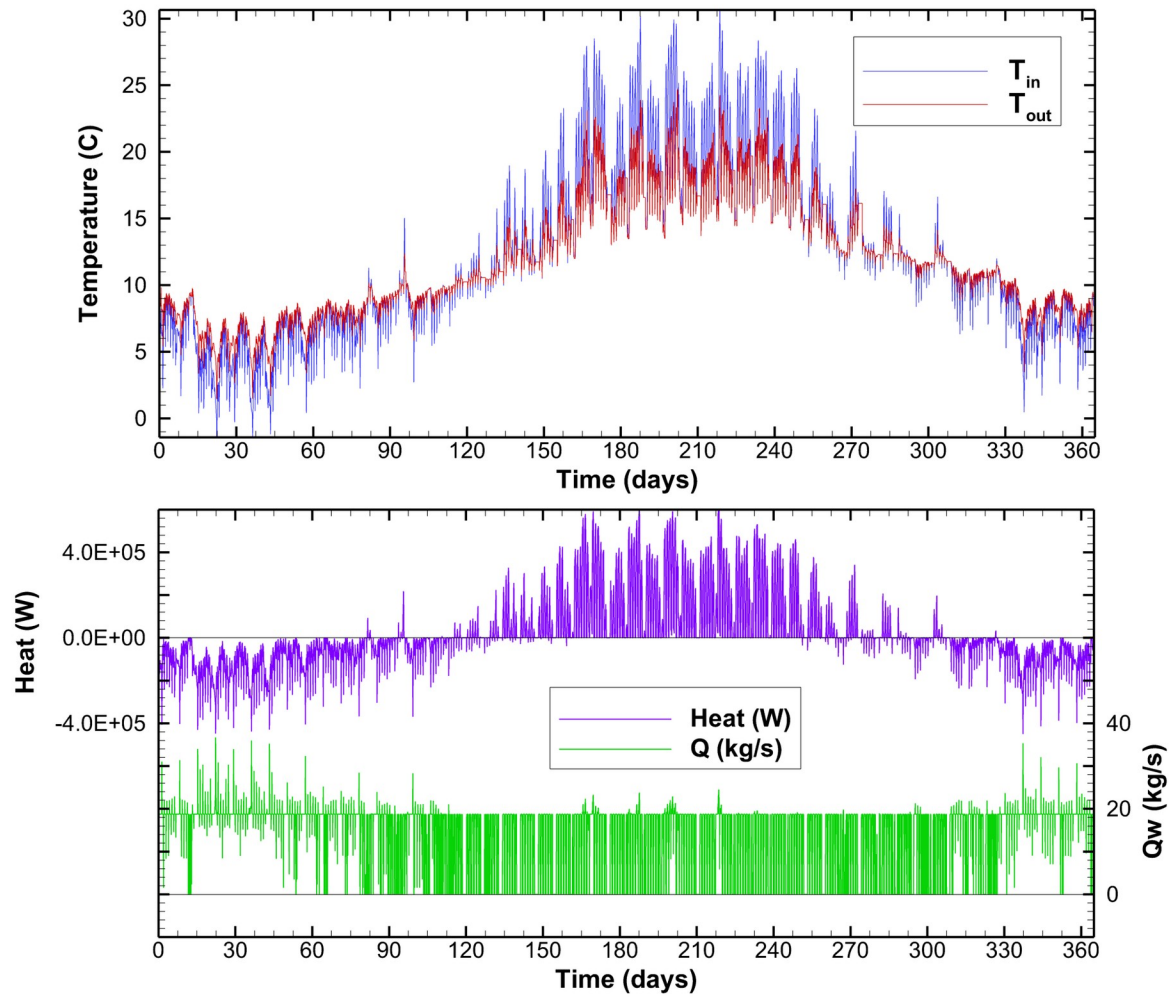


Figure 2a. Top frame: inlet and outlet temperatures for the borefield. Bottom frame: heat transferred from the boreholes to the subsurface (positive - into the subsurface, negative - out of the subsurface), and loop flow rate. Calculated with EnergyPlus assuming heat transport in the subsurface is purely by conduction.

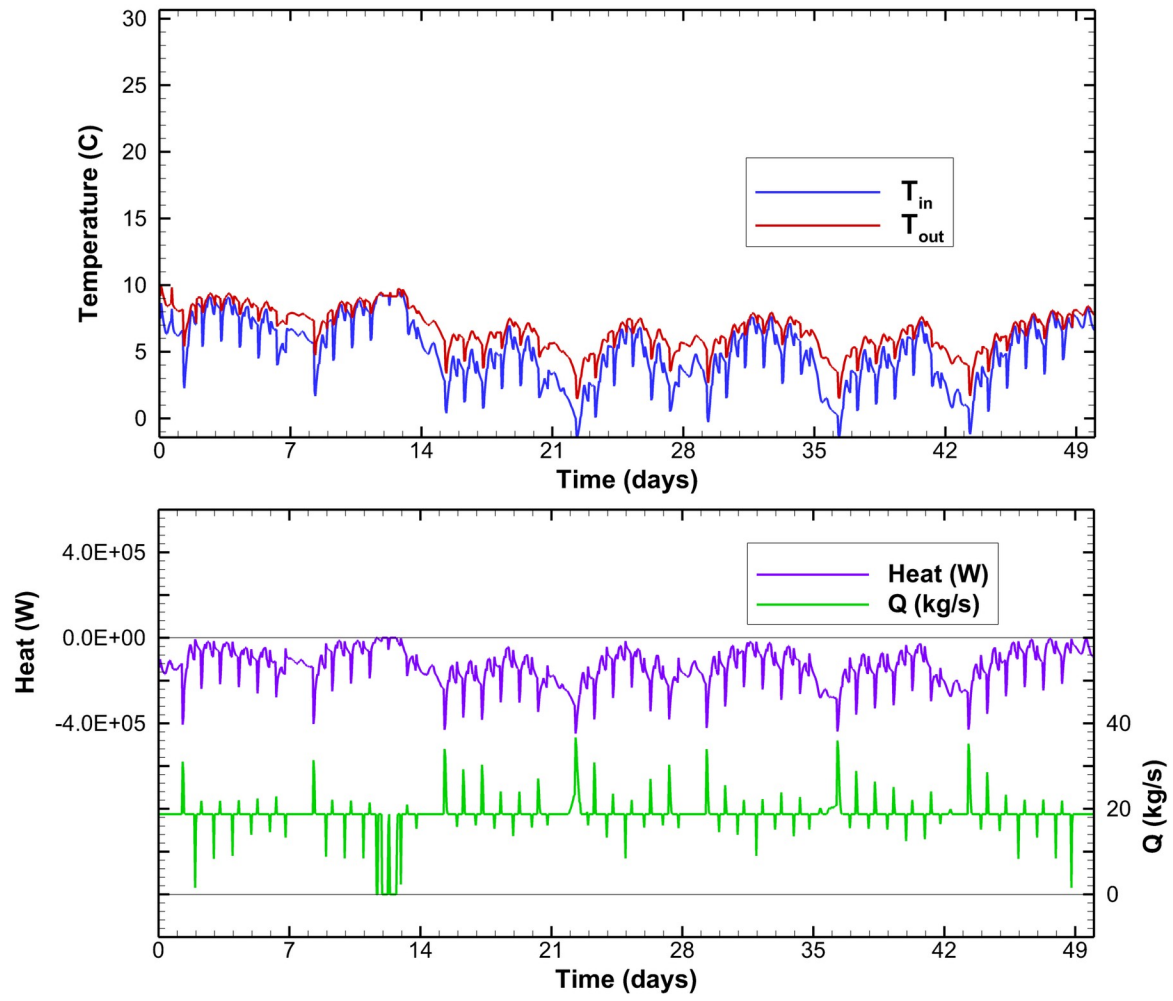


Figure 2b. Same variables as in Figure 2a, but for a few winter months. Top frame: inlet and outlet temperatures for the borefield. Bottom frame: heat transferred from the boreholes to the subsurface, and loop flow rate.

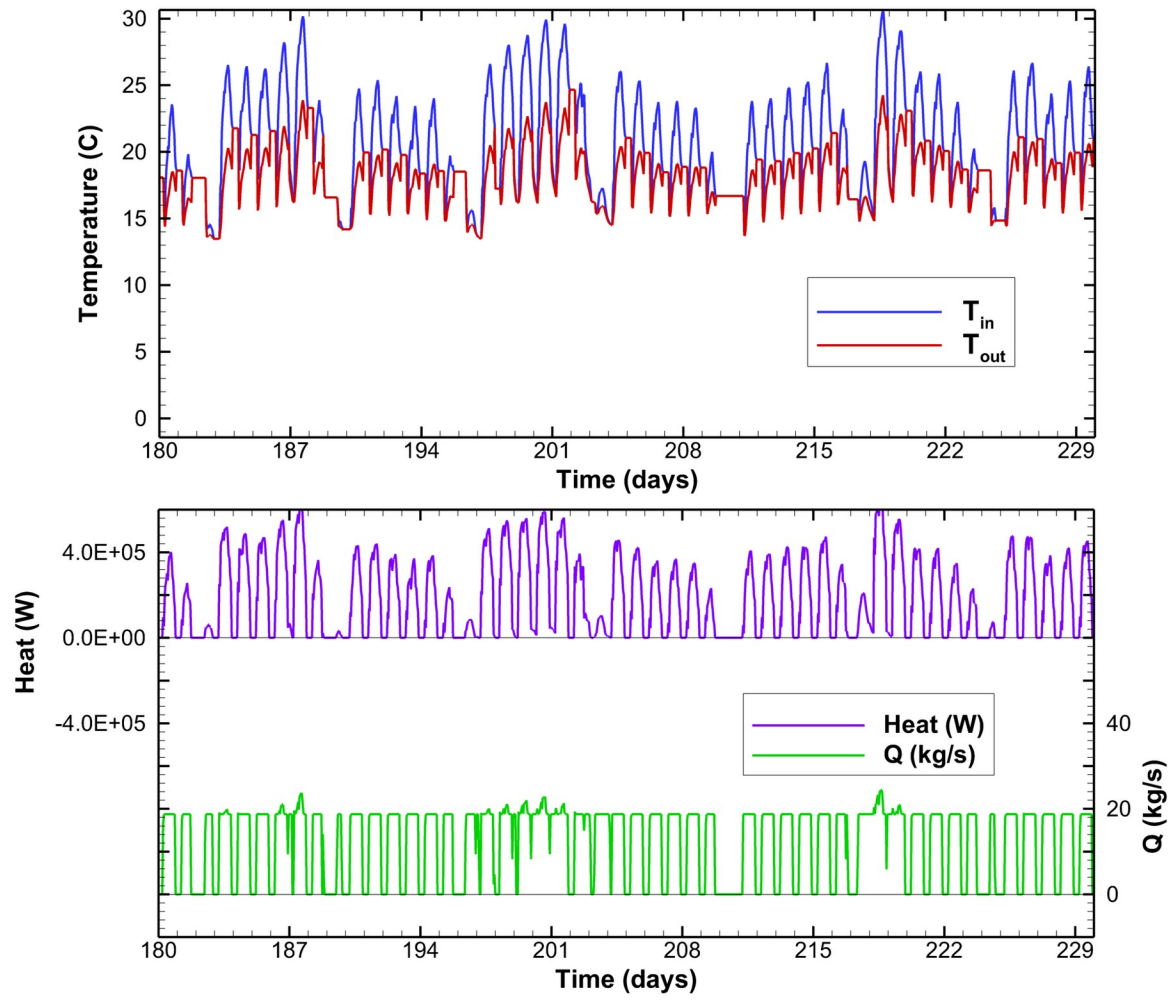


Figure 2c. Same variables as in Figure 2a, but for a few summer months. Top frame: inlet and outlet temperatures for the borefield. Bottom frame: heat transferred from the boreholes to the subsurface, and loop flow rate.

Geological setting

The regional geological setting at Detroit Arsenal consists of 40-50 m of glacial till overlying layered shales and limestones. In the bedrock beneath the till, layers are continuous over large regional extent. The topography is generally flat. Surface elevation is 189 m (620') above sea level. Figure 3 shows geophysical logs (gamma, resistivity, caliper, temperature, and self-potential) and interpreted lithology for DE-TRT1, a 152-m (500') deep well located at latitude 42.492521, longitude -83.044424, drilled at Detroit Arsenal for the FedGeo project. In the glacial sediments, high gamma and low resistivity indicate more clay, and low gamma and high resistivity indicate more sand and gravel. In the bedrock, high gamma and low resistivity indicate more shale, and low gamma and high resistivity indicate more dolomite/limestone.

The interpreted lithology is consistent with regional understanding, obtained from many wells in the region around Detroit Arsenal. Shallower perched water is observed in some wells, but the regional water table is generally taken to be about 20 m below ground surface. The hydraulic gradient at Detroit Arsenal is not well established, but is hypothesized to be from East to West, toward Bear Creek, which runs along the western boundary of the property. An alternative hypothesis is that groundwater flow is from South to North, paralleling the creek. Topographic elevation is used as a proxy for groundwater level to estimate an upper limit for the hydraulic gradient of approximately 0.0046 m/m.

Model Development

TOUGH Simulator

The numerical simulator TOUGH (Transport of Unsaturated Groundwater and Heat; Jung et al., 2018), a multi-phase, multi-component simulator for fluid flow and heat transport through porous or fractured geologic media, is used to model coupled groundwater flow and subsurface heat transport for the GHE. TOUGH has a modular architecture, wherein different Equation of State (EOS) modules can be employed to represent different combinations of fluid components and phases. Here EOS3 is used, which considers two mass components (water and air), two fluid phases (gas and liquid), and the transport of heat. In general, EOS3 can represent both the saturated zone and the vadose zone, and include phase transitions such as would accompany a changing water table. For the present application, the water table depth (20 m) is small compared to the length of the boreholes (100 m), so the small vadose-zone thickness is neglected, and the entire subsurface is considered to be water-saturated.

TOUGH uses the Integral Finite Difference Method (IFDM; Edwards, 1972; Narasimhan and Witherspoon, 1976) for spatial discretization. In the IFDM there is no need for a global coordinate system, rather the user specifies grid-block volumes and material types and connections between neighboring grid blocks (defined by the distances from the grid-block centers to their mutual interface d_1 and d_2 , interface area A , and the cosine of the angle between the line connecting the grid blocks and the direction of gravity, β).

TOUGH has been extensively verified against analytical solutions (Moridis and Pruess, 1992, 1995; Pruess et al., 1996) and other simulators (Pruess et al., 2004; White et al., 2016), and validated against laboratory and field data (Geller et al., 1995; Doughty et al., 2008; Doughty and Freifeld, 2013). It is widely used for a variety of applications including geologic sequestration of CO₂ and nuclear waste, environmental remediation, oil and gas production, conventional geothermal, EGS, and shallow geothermal (Blanco-Martin et al., 2015).

TOUGH has been used for detailed GSHP studies involving one or a few boreholes (Hu et al, 2020, 2022; Doughty et al., 2021) and simplified GHE studies involving a borefield consisting of many boreholes (Doughty et al., 2025).

Grid

The numerical model consists of 12 horizontal, uniform-thickness layers, and 975 grid blocks per layer grid arranged in a 25x39 rectangular array. Lateral resolution is 6 m in the finest part of the grid, surrounding the borefield, then it gradually coarsens. Figure 4 shows the full grid and a cut-away view that shows the borefield. The spatial extent of the model is 248 m in the x (East-West) direction, 332 m in the y (North-South) direction, and 200 m in the z (vertical) direction with the top of the model coinciding with the ground surface. The borefield is 24 m wide, 174 m long, and boreholes are 100 m deep.

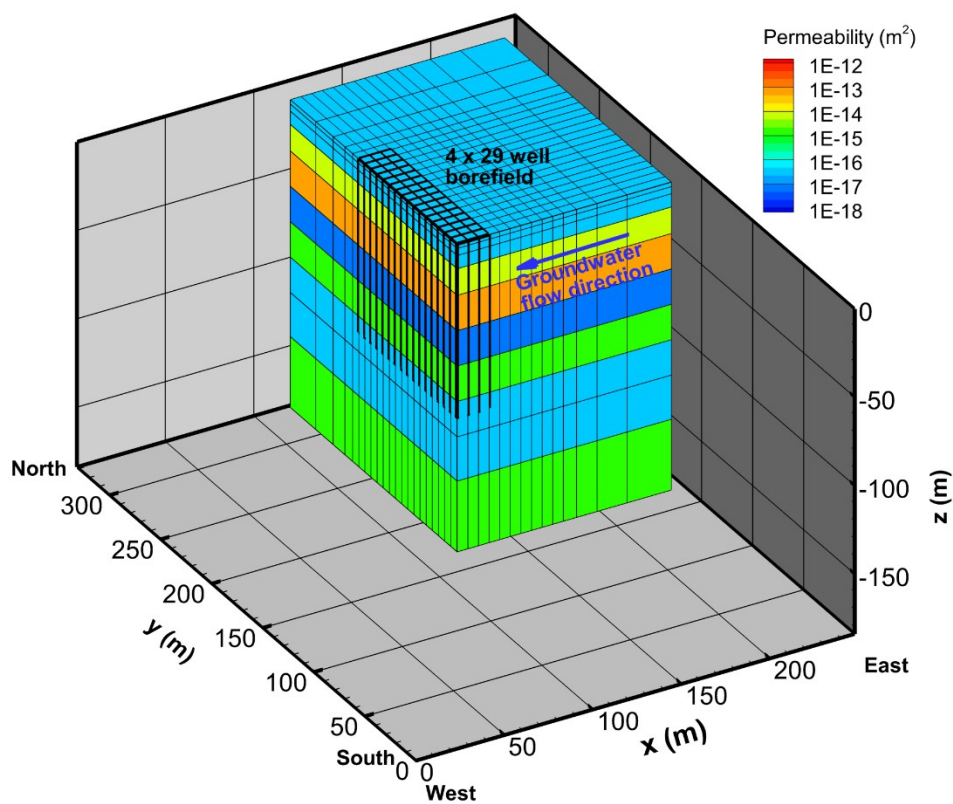
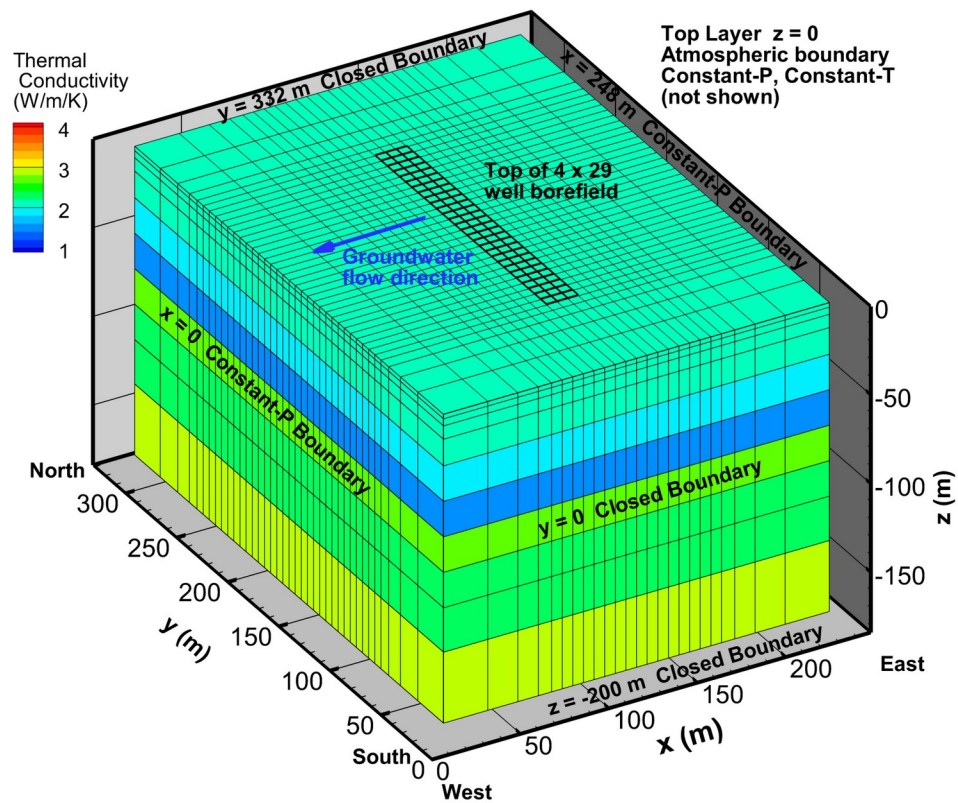


Figure 4. Top frame: complete grid showing layered thermal conductivity values and boundary conditions. Bottom frame: cut-away view showing borefield and layered permeability values.

Material Properties

Material properties, shown in Table 1, are uniform within each layer and are taken from literature values for the lithologies shown in Figure 3. Layer permeabilities are used as is, but layer thermal conductivities are scaled so that the thickness-weighted average of thermal conductivity over the length of the boreholes matches the thermal conductivity provided by a thermal response test at the Detroit Arsenal, which is 2.25 W/m/K. Additionally, the porosity of each layer is taken to be 0.35.

Initial and Boundary Conditions

Model initial conditions are fully water saturated (i.e., the water table coincides with the ground surface), a uniform temperature of 11°C, and a hydrostatic pressure distribution, with atmospheric pressure at the top of the model.

The top boundary of the model ($z = 0$) is the atmosphere, which is held at a constant temperature of 11°C and atmospheric pressure, and is represented by model layer 1. The bottom ($z = -200$ m), North ($y = 332$ m), and South ($y = 0$ m) boundaries of the model are closed. At the East ($x = 248$ m) and West ($x = 0$ m) boundaries, pressure is held constant, with a pressure difference applied to create a hydraulic gradient of 4.6E-3 m/m and a resulting groundwater flow from East to West.

Table 1. Lithology descriptions and key material properties (thermal conductivity and permeability), for the materials in the model.

Geological Material	Material Description	Thickness m	Thermal Conductivity* W/(m-K)	Permeability mD	Model Layers
clayey glacial deposits 1	clayey diamicton, silt and clay, stiff	12.2	2.10	0.4	2,3,4
clayey glacial deposits 2	silty to sandy diamicton, soft to stiff, may include interbedded lake sediment	10.1	2.10	100	5
sand and gravel 1	sand and gravel, saturated	10.7	1.90	1000	6
glacial till	diamicton, sandy, hard	8.8	1.90	50 but use 1000**	6
Antrim Shale	black shale	25.0	1.50	0.1	7
Birdsong Bay Limestone	limestone and shale, contains pyrite	10.4	2.80	5 but use 10**	8
Traverse Limestone (includes the Ten Mile Creek Dolomite)	limestone and dolostone	16.2	2.80	10	8
Bell Shale	shale and mudstone	46.9	2.30	0.3	9,10
Dundee Limestone	cherty limestone	12.2	2.90	10	11,12
Total		152.4			

* Values adjusted to be consistent with TRT test value for entire borehole: 2.25 W/(m-K)

**Due to coarseness of model resolution

Extra Grid Block Approach to Represent Boreholes

The borefield consists of 116 vertical boreholes, each 100-m deep, arranged in a 4 by 29 rectangular array, plumbed in parallel, so that the total flow rate of the above-surface loop is split into 116 equal parts for each borehole. The borehole spacing is 6 m. We do not model the details within each borehole (a u-tube embedded in grout), or make a highly resolved radial grid representing the region around each borehole, but make use of the flexibility of the IFDM employed by TOUGH for spatial discretization, which allows boreholes to be represented in a simple way following the approach of Falta et al. (2023). Specifically, one new “extra grid block” is introduced to represent each borehole. Because the grid spacing is the same as the borehole spacing, every original grid block column within the footprint of the borefield has one extra grid block associated with it. Each extra grid block is 100-m long and connected laterally to all the grid blocks of the original grid block column over that 100-m interval (model layers 2-9). The parameters of these lateral connections are specified in a particular way so that the details within the borehole and the radial geometry for heat transfer outside the borehole are represented. In the IFDM, each connection between two grid blocks requires four parameters to be specified: the distances d_1 and d_2 from the nodal point of each grid block to their common interface, the area A of the interface, and the orientation of the interface with respect to gravity. Here we specify

$$d_1 = 2 \square \square r_w \text{ BTR}$$

$$d_2 = r_w \ln(r_e/r_w)$$

$$A = 2 \pi r_w \Delta z$$

$\pi = 0$ for horizontal connections

where $\pi = 2.182$ W/m/K is thermal conductivity of the grout, $r_w = 0.07$ m is the borehole radius, BTR = 0.1 is borehole thermal resistance (an integrated representation of the details within the borehole), $r_e = 0.2086$ m = 1.25 m is the effective radius of the original grid block column connected to the extra grid block, and Δz is the thickness of the original grid block. More details of the extra grid block approach may be found in Falta et al. (2023) and more details of the IFDM may be found in Jung et al. (2018).

Each extra grid block contains a mass source, with strength equal to the fluid flow rate through the borehole ($1/116^{\text{th}}$ of the loop flow rate shown in Figure 2) and specific enthalpy equal to $C_w T_{\text{in}}$, where $C_w = 4184$ J/kg/K is the specific heat of water and T_{in} is shown in Figure 2. Each extra grid block also contains a mass sink, with strength equal to the opposite of that of the mass source. The specific enthalpy of the mass sinks is calculated internally by TOUGH, and is averaged over all boreholes, divided by C_w , and compared to T_{out} in Figure 2. For a simulation with no groundwater flow, the T_{out} values should agree, to verify that TOUGH is representing the GHE correctly (See Appendix A). For a simulation with groundwater flow, comparison of the T_{out} values indicates the importance of groundwater flow on GHE performance.

Model Application

The main application of the model is based on the realistic thermal load shown in Figure 2. Flow rate and inlet temperature values are averaged over one-week time periods to provide input to TOUGH. Previous studies have shown that because heat transfer is slow in the subsurface, averaging out short-term variability in thermal load does not impact subsurface temperature distributions, and allows TOUGH to run much more efficiently. Appendix B shows results of a series of TOUGH simulations using different time-averaging periods, to verify the one-week averaging approach. Note that daily temperature variation, in particular the difference between minimum and maximum daily temperature, is a key parameter used for sizing GHE systems. But the purpose of the modeling presented in this report is not to size GHE system, but to examine the effect of groundwater flow on a GHE designed assuming that there is no groundwater flow, and heat transport in the subsurface is purely by thermal conduction.

The one-year record shown in Figure 2 is replicated 20 times, to provide input conditions for a 20-year TOUGH simulation. The main outputs of the TOUGH simulations are (1) the spatial distributions of temperature in the subsurface at various times, which illustrate the coupled groundwater and heat flow, and (2) the difference between the inlet and outlet temperatures, $DT(t) = T_{\text{in}}(t) - T_{\text{out}}(t)$, which is proportional to the net heat transferred between the boreholes and the subsurface, and indicates how effectively the GHE is running.

Because the thermal load shown in Figure 2 is nearly balanced, little net heat or chill builds up in the subsurface, meaning the long-term temperature change in the subsurface is small.

Groundwater flow alternately sweeps warmer and cooler water away from the borefield, and thus its overall effect on GHE performance is small. Therefore, we consider a second application with a completely unbalanced thermal load, modeled simply by specifying a constant inlet temperature $T_{in} = 20^{\circ}\text{C}$ (significantly higher than the undisturbed subsurface temperature 11°C) and constant loop flow rate of 13.5 kg/s . Under these conditions, heat will build up in the subsurface. If groundwater flow sweeps this heat away from the borefield, it will have a large positive impact on GHE performance.

For each of these two cases, we consider three regional groundwater flow magnitudes: none, small (representative of the flat topography at Detroit Arsenal), and large (10 times bigger than small, just to illustrate a more extreme effect). Each case is run for 20 years.

Additionally, Appendix C shows a few additional TOUGH simulations of Case 1, to illustrate the effect of some design choices on GHE performance.

Case 1. Actual-Load Model Results

Figure 5, Figure 6, and Figure 7 show modeled spatial temperature distributions at a series of times for no, small, and large groundwater flow, respectively. The plots show E-W vertical cross-sections through the center of the borefield, and show both ground temperature and borehole temperature. The top row of plots shows temperature distributions at selected times during the first year of operation, and the bottom row shows the same times during the 20th year of operation. Despite the nearly balanced load, a gradual heating of the subsurface over time is apparent.

Figure 6 shows that the effect of small regional groundwater flow is barely visible after 20 years: there is a slight downgradient movement of heat at $z \sim 20 - 40 \text{ m}$, where glacial sediment permeability is high.

Figure 7 shows that the effect of large regional groundwater flow is barely visible after 1 year, and more apparent after 20 years. Downgradient movement of heat, while larger than in the previous figure, is still mainly limited to $z \sim 20 - 40 \text{ m}$, where glacial sediment permeability is high.

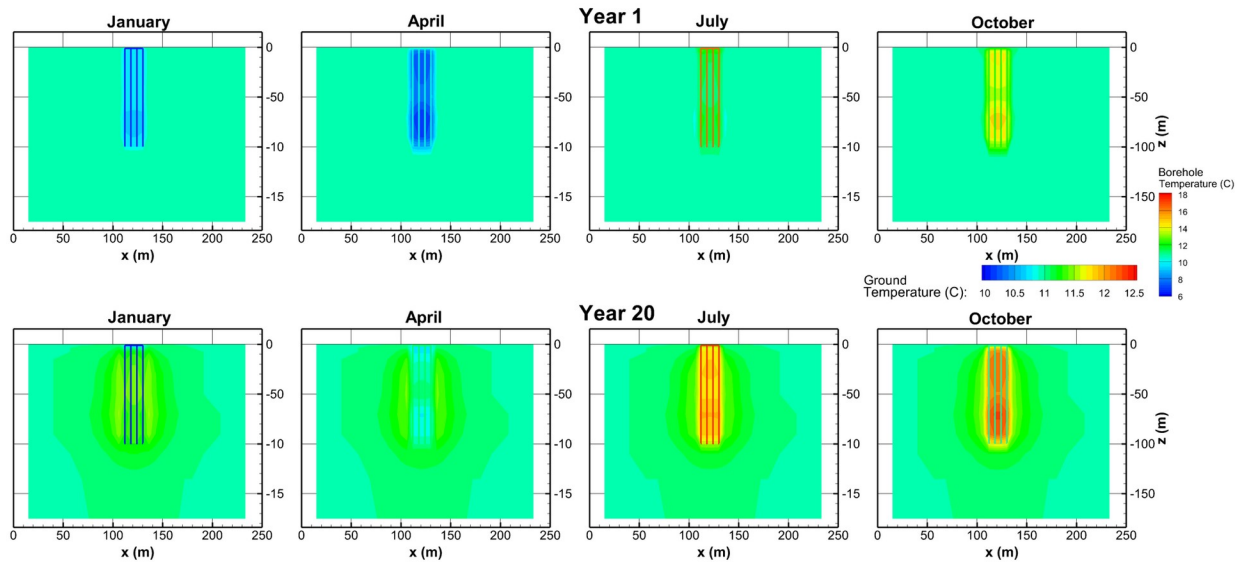


Figure 5. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 1 with no groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results. Note that the ground and the borehole temperature fields use different color scales.

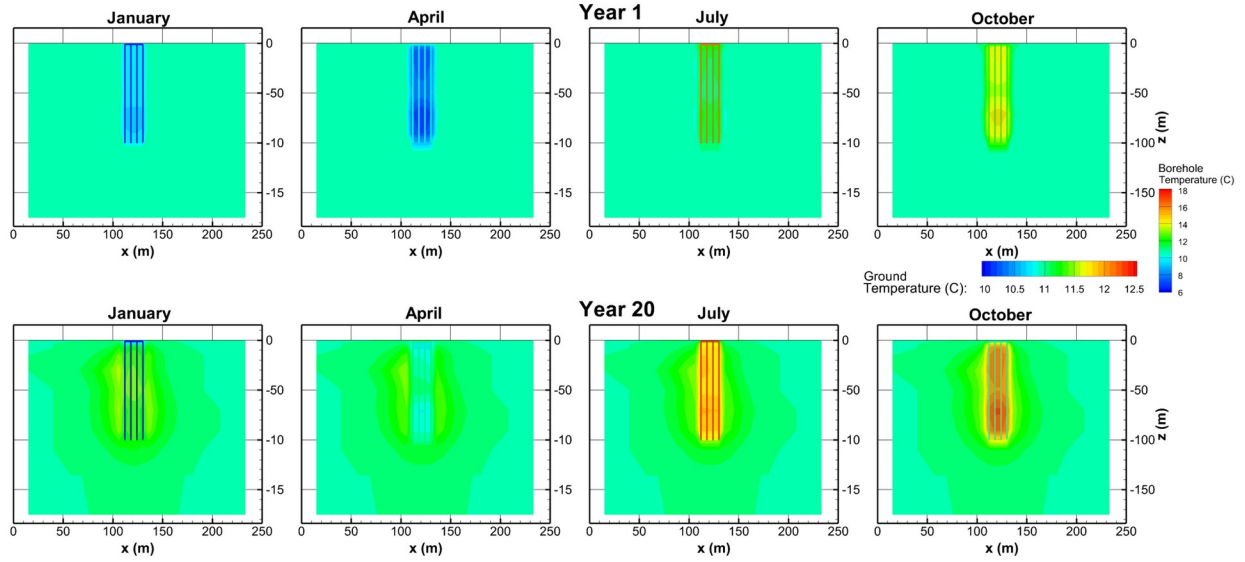


Figure 6. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 1 with small groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results. Note that the ground and the borehole temperature fields use different color scales.

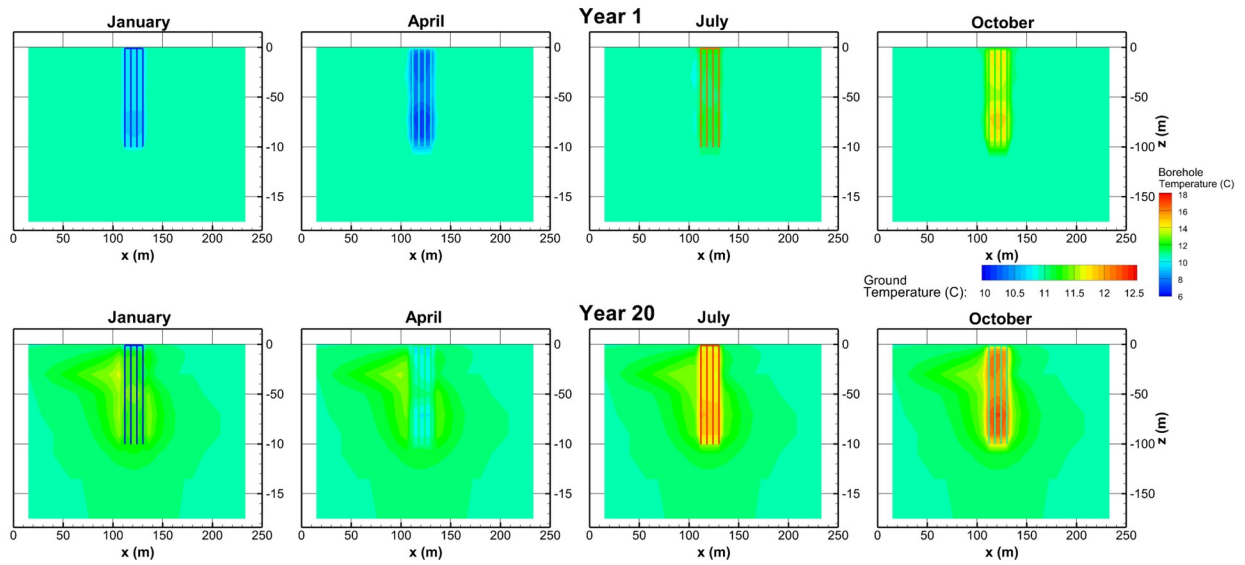


Figure 7. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 1 with large groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results. Note that the ground and the borehole temperature fields use different color scales.

Figure 8 summarizes the performance of the GHE for Case 1. The top plot shows power (heat) transferred to the subsurface, and cumulative energy, which is the time integral of heat, for 20 years of GHE operation. The near-balanced nature of the load is visible in the symmetry above and below 0 for the heat curve for each year, and the unchanging nature of the heat curves from year to year. The cumulative energy does show a gradual increase, indicating that each year slightly more heat is added to the subsurface during summer than is removed during winter.

Results for all three groundwater flow strengths are shown in the heat/energy plot. For heat there is no difference visible. For energy, a small difference grows with time. For the large groundwater flow case, slightly more heat is added to the subsurface during summer, and slightly less heat is taken from the subsurface during winter, because the ground temperature in the borefield is slightly lower (compare Figure 5 and Figure 7).

The bottom plot in Figure 8 shows the temperature into and out of the borefield for two-year periods at the beginning and end of the 20-year simulation, for the no groundwater flow case. The early- and late-time T_{out} curves agree closely, indicating that, as for the heat plot, there is no visible change between the beginning and end of the 20-year operation, due to the nearly balanced load. Moreover, T_{in} and T_{out} for the small and large groundwater flows (not shown) are indistinguishable from the curves shown. This is expected as heat is proportional to $T_{in} - T_{out}$.

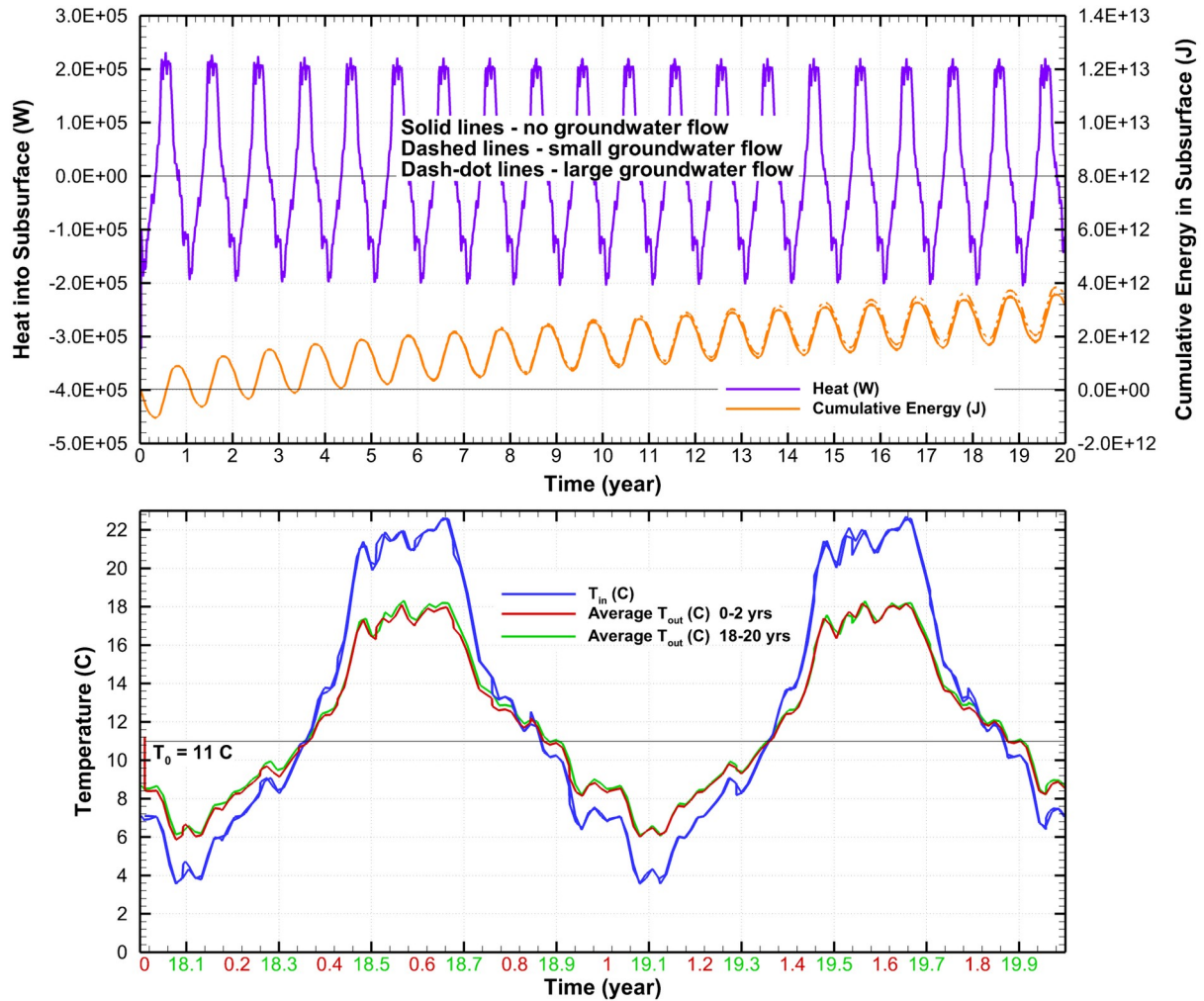


Figure 8. Case 1, seasonally variable load GHE performance. Top plot: heat transferred into the subsurface and cumulative energy stored versus time for no, small, and large groundwater flow. Bottom plot: T_{in} and average T_{out} with 0-2 years and 18-20 years overlain, for the no groundwater flow case (small and large groundwater flow results are indistinguishable from these).

Case 2. Cooling-Only-Load Model Results

Figure 9, Figure 10, and Figure 11 show modeled spatial temperature distributions at a series of times for no, small, and large groundwater flow, respectively. Note that the temperature color scale is very different from that of Case 1, where no ground temperature is more than 2°C higher or lower than the initial temperature of 11°C. A steady heating of the subsurface is apparent over time, with ground temperature in the borefield nearing $T_{in} = 20^{\circ}\text{C}$ after 20 years.

Figure 10 shows that the effect of small regional groundwater flow is clearly visible after 20 years, with a small downgradient movement of heat at $z \sim 20 - 40$ m, where glacial sediment permeability is high.

Figure 11 shows that the effect of large regional groundwater flow is barely visible after 1 year, and strong after 20 years. Downgradient movement of heat, while larger than in the previous figure, is still mainly limited to $z \sim 20 - 40$ m, where glacial sediment permeability is high.

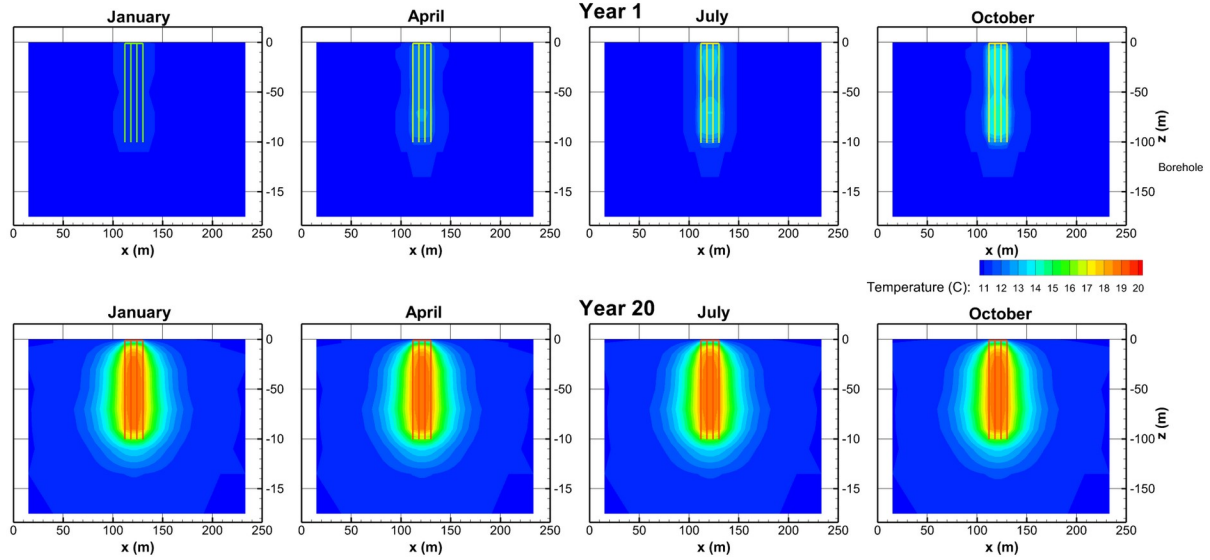


Figure 9. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 2 with no groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results.

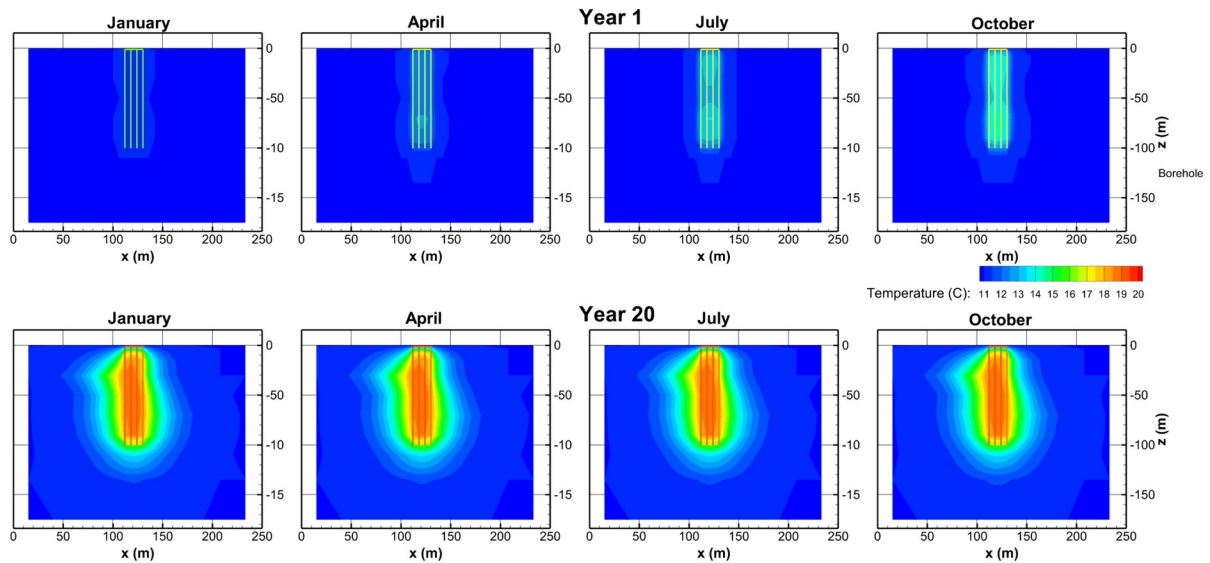


Figure 10. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 2 with small groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results.

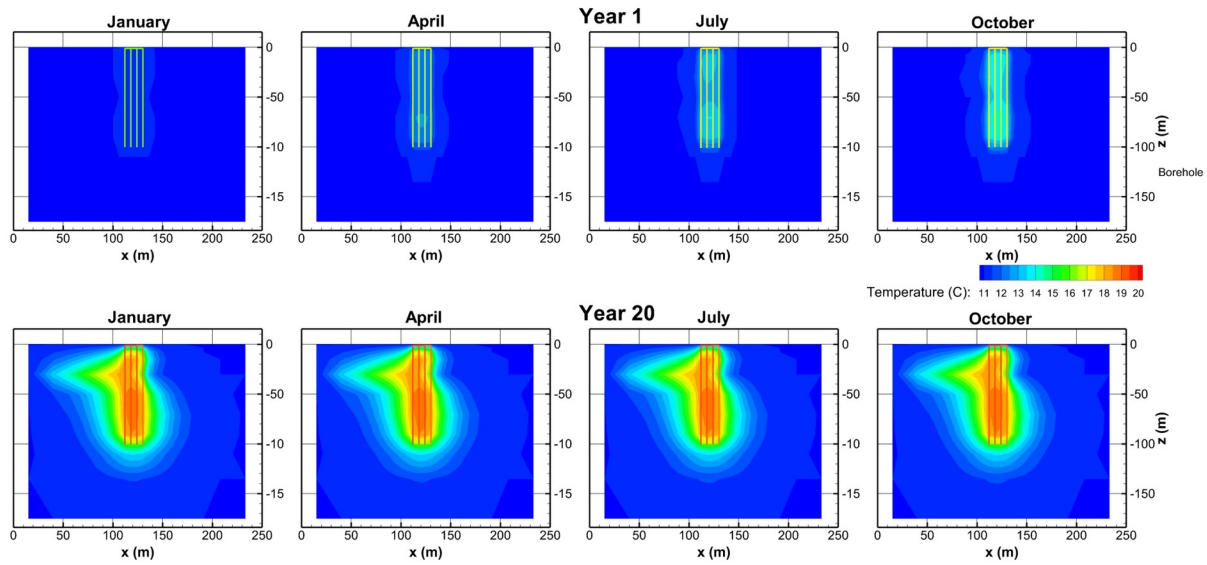


Figure 11. Snapshots of modeled temperature distributions for E-W cross-sections through the borefield for Case 2 with large groundwater flow. The top row shows first-year results and the bottom row shows 20th-year results.

Figure 12 summarizes the performance of the GHE for Case 2. The top plot shows that, in sharp contrast to Case 1 (Figure 8), here heat transferred to the subsurface steadily decreases over the years. By 5 years, performance is already significantly degraded, and the trend continues throughout the 20-year operation period. The bottom plot shows the cause of the heat-transfer decline: as T_{out} steadily increases over time, the difference $T_{\text{in}} - T_{\text{out}}$ decreases, resulting in less heat transfer into the subsurface. As groundwater flow increases, T_{out} increases more gradually, due to subsurface heat being swept downgradient. In addition to showing average T_{out} for the borefield, Figure 12 also shows T_{out} for selected locations within the borefield. As expected, for the no-groundwater-flow case, T_{out} increases more rapidly at the center of the borefield and more slowly at the corners, as heat dissipates laterally around the borefield. Moreover, T_{out} at upgradient and downgradient corners of the borefield are identical (Figure 12, bottom plot, solid lines). But when groundwater flow is large, T_{out} at an upgradient corner of the borefield grows more slowly than T_{out} at a downgradient corner of the borefield (Figure 12, bottom plot, dash-dot lines), demonstrating the effect of downgradient sweep of stored heat.

Discussion

The impact of groundwater flow is much greater for the unbalanced load of Case 2 than for the nearly balanced load of Case 1, because for a balanced load, there is little long-term buildup of heat or chill. Recall that even for the large groundwater flow case, only the upper third or so of the borehole length, where glacial sediments have much higher permeability than underlying bedrock, sees significant groundwater flow (Figure 7 and Figure 11). For geology with more extensive high-permeability zones, the impact of groundwater flow would be greater.

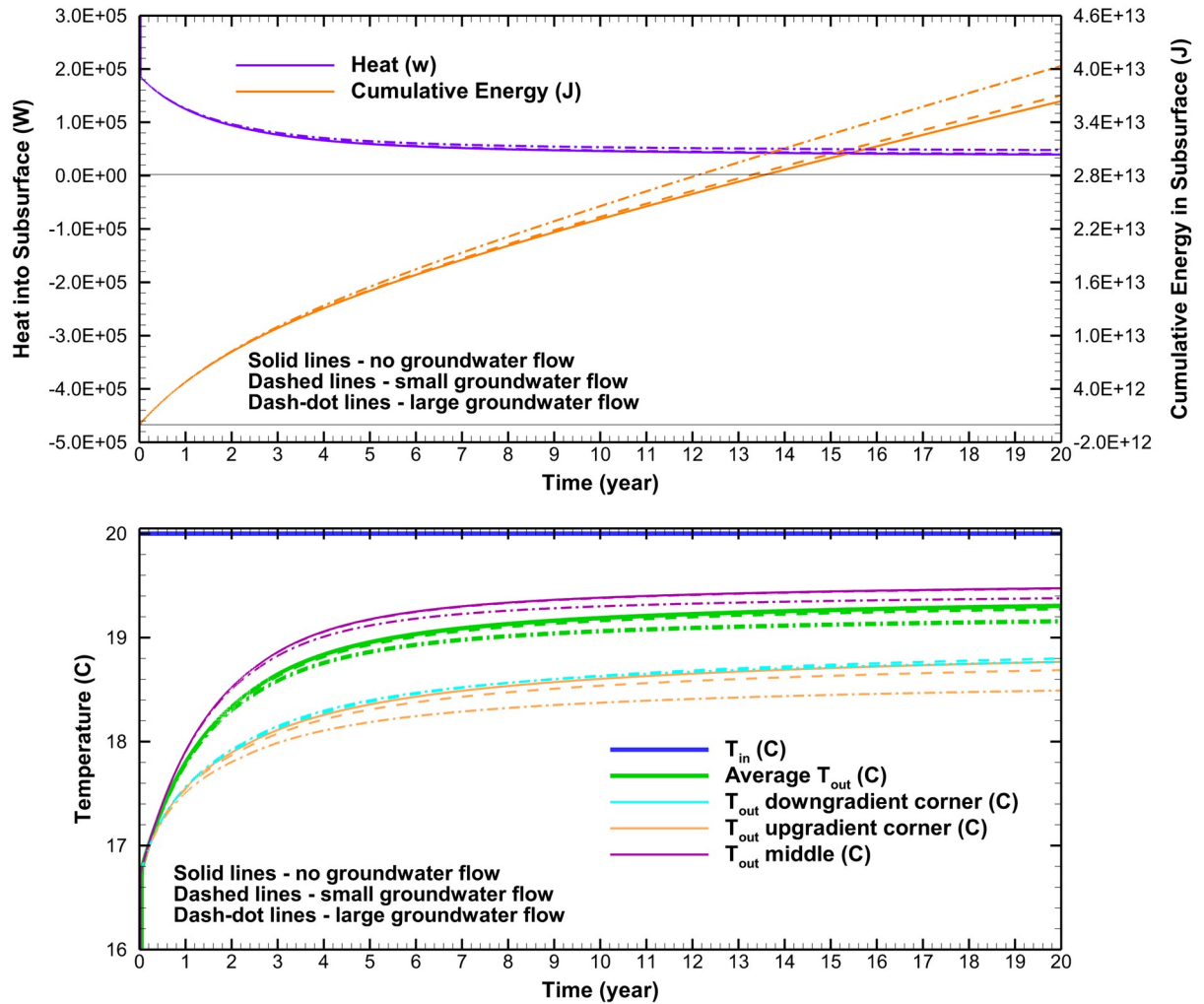


Figure 12. Case 2, constant all-cooling load GHE performance for no, small, and large groundwater flow. Top plot: heat transferred into the subsurface and cumulative energy stored versus time. Bottom plot: T_{in} , average T_{out} , and T_{out} at select borefield locations versus time. Note that the cumulative energy and temperature scales are very different from those in Figure 8.

Conclusions

An efficient means of modeling coupled groundwater flow and heat transport for an entire borefield making up the GHE of a GSHP for a large multi-story office building at Detroit Arsenal has been demonstrated, using the numerical simulator TOUGH, incorporating the “Extra Grid Block” method of Falta et al. (2023). A realistic thermal load taken from an EnergyPlus simulation of the building provides inlet temperature and loop flow rate for the borefield. TOUGH then simulates subsurface heat transport, assuming three different magnitudes of

regional groundwater flow: none, small – deemed plausible for Detroit Arsenal, and large – 10 times the small value, to illustrate a more extreme effect. The small groundwater flow has a negligible effect on GHE performance. Groundwater flow is small because hydraulic head gradients that drive groundwater flow are small due to flat topography, and because bedrock permeability is small. Glacial sediments have highly variable permeability, but high-permeability layers have limited thickness, constituting only a small fraction of the borehole length. Moreover, the actual lateral extent of high-permeability materials within the glacial sediments is likely to be smaller than the model-wide extent used here, decreasing the potential for large groundwater flow. Even if groundwater flow were high, the nearly balanced thermal load serves to minimize the effect of groundwater flow. The ultimate implication of the coupled groundwater flow/heat transport models presented here is that the usual practice of assuming subsurface heat transport occurs by thermal conduction only is valid for sizing GHE at Detroit Arsenal.

Acknowledgements

Thank you to the entire FedGeo team for discussion and support. Shannon Bergt (Energy Manager, Installation Management Command, U.S. Army Garrison – Detroit Arsenal) was instrumental in championing the FedGeo effort, and in managing site access, coordination, and logistics. This work was supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), Geothermal Technologies Office, Federal Geothermal Technical Assistance Framework for Low-Temperature Geothermal Technologies, under Award Number DE-AC02-05CH11231 with Lawrence Berkeley National Laboratory.

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Appendix A. Comparison of TOUGH Results to EnergyPlus Results

In order to verify that the “extra grid block” approximation for handling multiple boreholes in a TOUGH simulation is reasonable, TOUGH results for Case 1 with no groundwater flow are compared to EnergyPlus results based on the g-function approach, for a one-year simulation. As in the main part of this report, loop flow rate Q and borefield inlet temperature T_{in} taken from EnergyPlus are used as source terms for TOUGH. However, no time-averaging of Q or T_{in} is done, so detailed comparisons of T_{out} , the borefield outlet temperature, for TOUGH and EnergyPlus can be made, as shown in the left hand frames of Figure A-1. Other important output parameters to compare are heat transferred from the borehole to the subsurface, which is proportional to $Q \cdot (T_{in} - T_{out})$, and the time-integral of heat transfer rate, the cumulative energy stored in the subsurface, as shown in the right-hand frames of Figure A-1. Figure A-1 shows 10-day segments in winter, spring, and summer, when the load, and consequently the behavior of the system, are rather different. Note that during the summer, flow rate is often zero during the weekends, so T_{in} and T_{out} are not meaningful then, and are not shown.

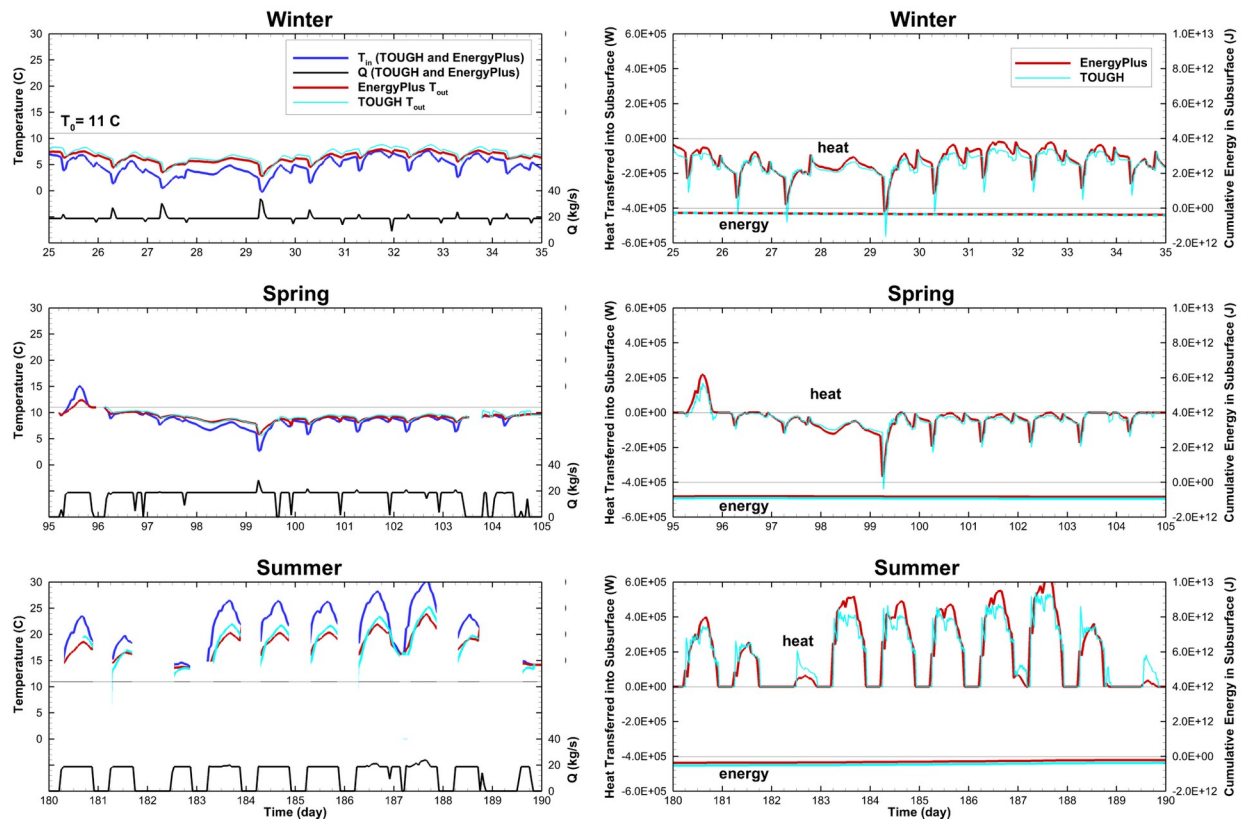


Figure A-1 Comparison between TOUGH and EnergyPlus results for a one-year simulation with no groundwater flow. The three rows show 10-day segments during different seasons. Left column: borefield inlet and outlet temperatures and loop flow rate; Right column: heat transferred into the subsurface and cumulative energy stored.

During winter, $T_{in} < T_{out}$, so heat and cumulative energy are negative, indicating heat is being extracted from the subsurface. The agreement between TOUGH and EnergyPlus is good for T_{out} , heat, and cumulative energy.

During spring, T_{in} and T_{out} are nearly the same and consequently heat transferred to the subsurface is near zero and cumulative energy in the subsurface is nearly constant. TOUGH and Energy Plus agree very well.

During summer, $T_{in} > T_{out}$, so heat is positive and cumulative energy is increasing, as heat is added to the subsurface. T_{out} for TOUGH shows more variability than EnergyPlus: highs during the day are too high and lows during the night are too low, but for most of the time T_{out} for TOUGH is a little too big, i.e., too close to T_{in} . Thus, the TOUGH daily heat peaks, which are proportional to $(T_{out} - T_{in})$, are a little too low. However, when the daily variability is integrated to obtain the cumulative energy, the agreement between TOUGH and EnergyPlus is again good.

Figure A-2 shows results for the entire one-year simulation, indicating that the agreement between TOUGH and Energy Plus is generally good, but that cumulative energy growth in the subsurface is a little slower for TOUGH than for EnergyPlus.

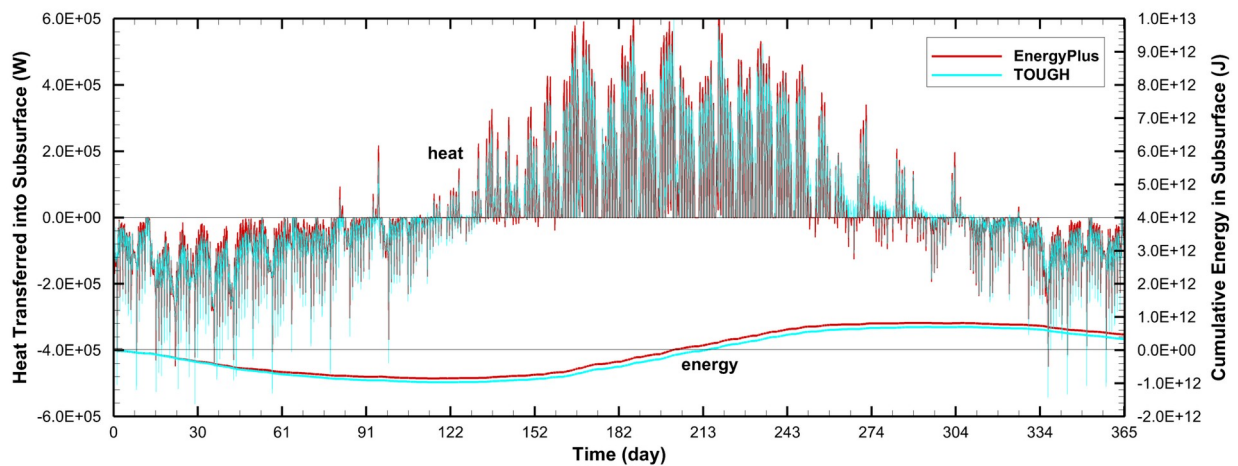


Figure A-2 One-year comparison between TOUGH and EnergyPlus for heat transferred into the subsurface and cumulative energy stored.

Appendix B. Effect of Different Time-Averaging Periods

The Detroit Arsenal thermal load data is provided at 1-hour intervals. Because temperature changes occur slowly within the subsurface, in the main TOUGH simulation results shown in this report, borefield inlet temperature T_{in} and loop flow rate Q are time-averaged to 7-day intervals before being provided as source terms to TOUGH. This averaging removes diurnal and synoptic temperature variations, but enables TOUGH to take multi-day time steps as opposed to 1-hour time steps, significantly reducing required computation time. To verify that this averaging does not produce systematic errors in the TOUGH simulation results, 10-year simulations of Case 1 with no groundwater flow were done using 1-day and 4-hour averaging, and with no averaging, directly using the 1-hour data. These results are compared to the 7-day averaged results in Figures B-1 through B-3. Figure B-1 shows simulation results for 10-day segments during different seasons of the first year. Using 4-hour averaging enables diurnal variations to be represented, while still providing a reasonable usage of computer time. Daily peaks are slightly better resolved with no averaging, and in particular, the periods when the GSHP is off during summer are resolved, as identified by the time segments when $Q = 0$ and T_{out} is not shown. Generally, the relationship between the 1-hour, 4-hour, 1-day, and 7-day average results is as expected, with diurnal and synoptic variations being smoothed out in a reasonable way.

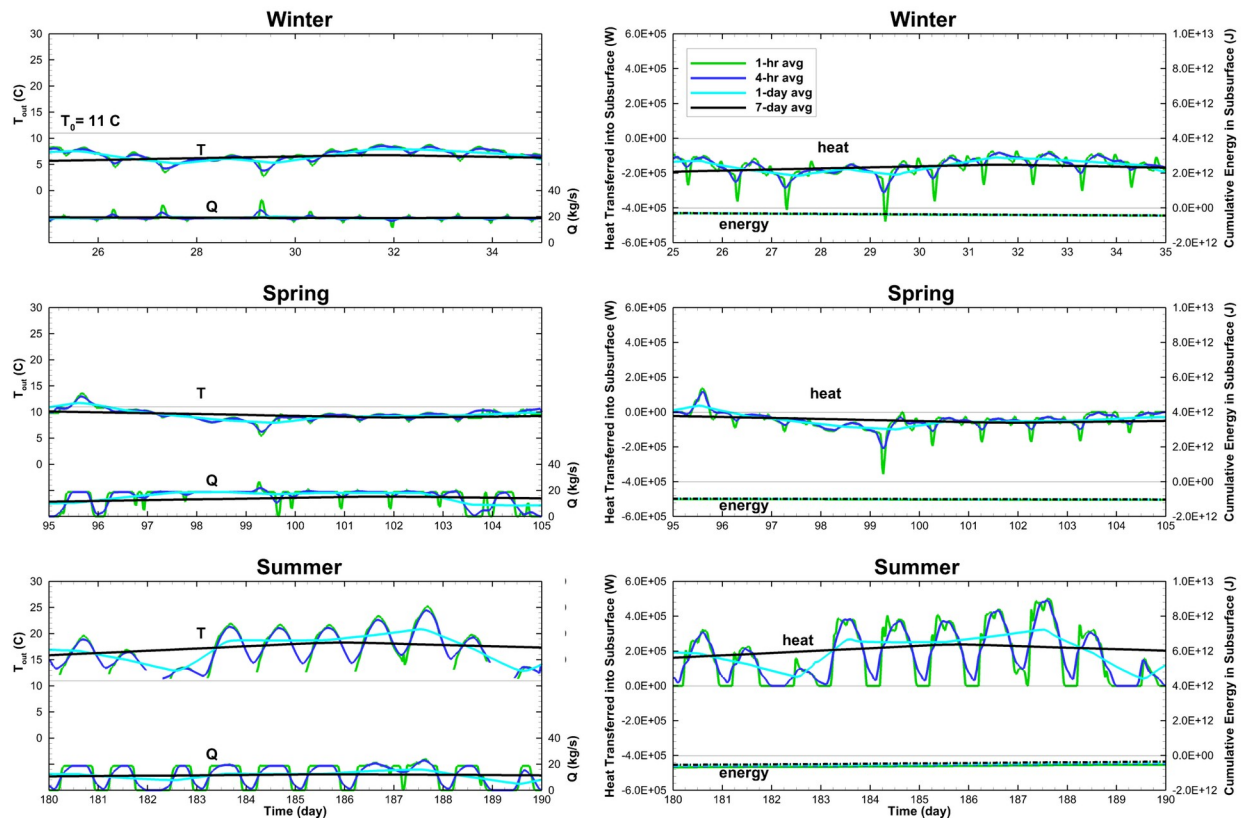


Figure B-1. Comparison of TOUGH simulation results for different time-averaging periods of T_{in} and Q , for a ten-year simulation with no groundwater flow. The three rows show 10-day segments during

different seasons of the first year. Left column: borefield outlet temperature T_{out} and loop flow rate Q ; Right column: heat transferred into the subsurface and cumulative energy stored.

Figures B-2 and B-3 show T_{out} , Q , heat transferred, and cumulative energy for one- and ten-year periods, respectively. Cumulative energy shows good agreement between 1-hour and 4-hour averaging, and a slowly growing overprediction for 1-day and 7-day averaging periods. The spatial temperature distributions for all time-averaging periods (not shown) are indistinguishable from those shown in Figure 5 for the 7-day averaging period.

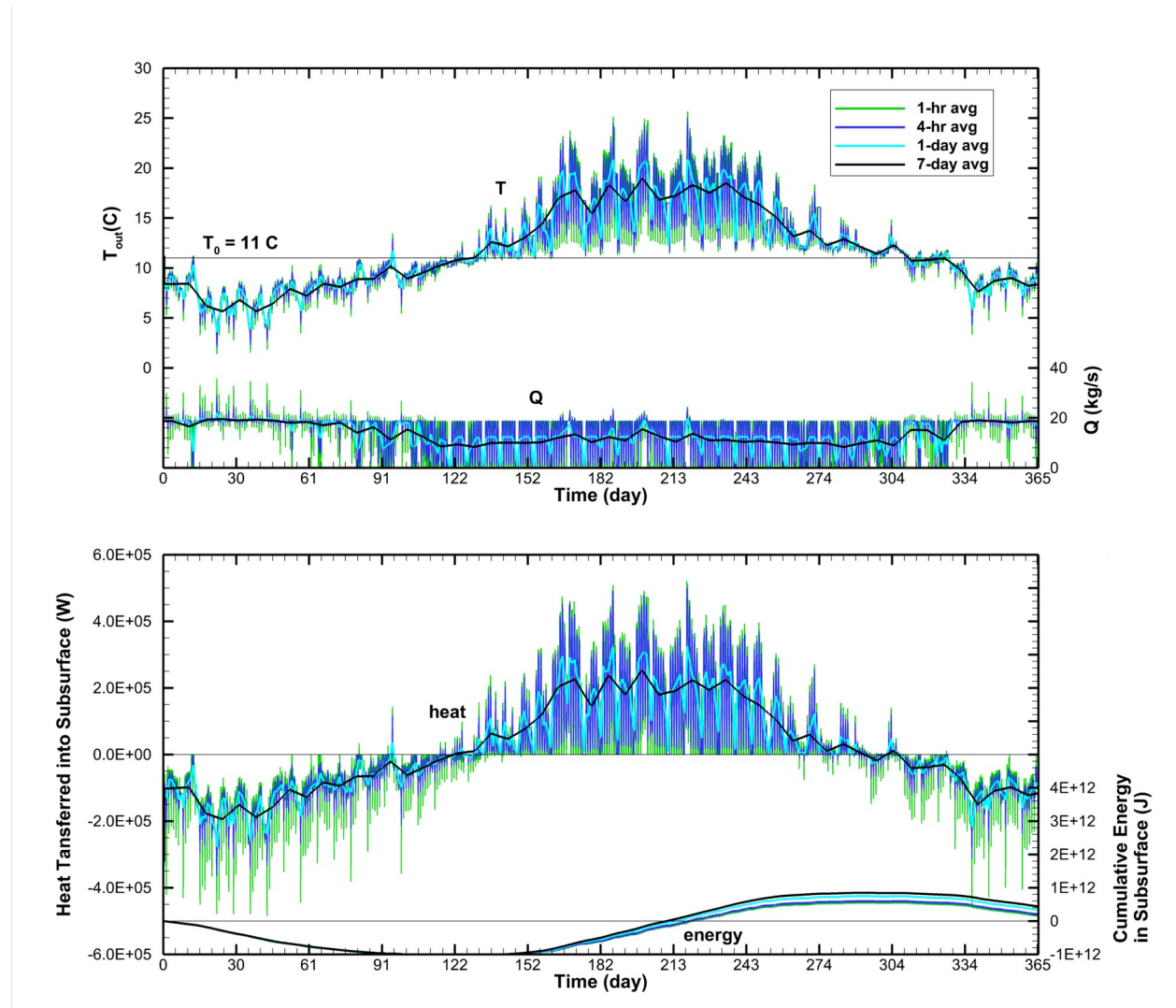


Figure B-2. One-year comparison of TOUGH simulation results for different time-averaging periods of T_{in} and Q , showing borefield outlet temperature T_{out} and loop flow rate Q (top frame) and heat transferred into the subsurface and cumulative energy stored (bottom frame).

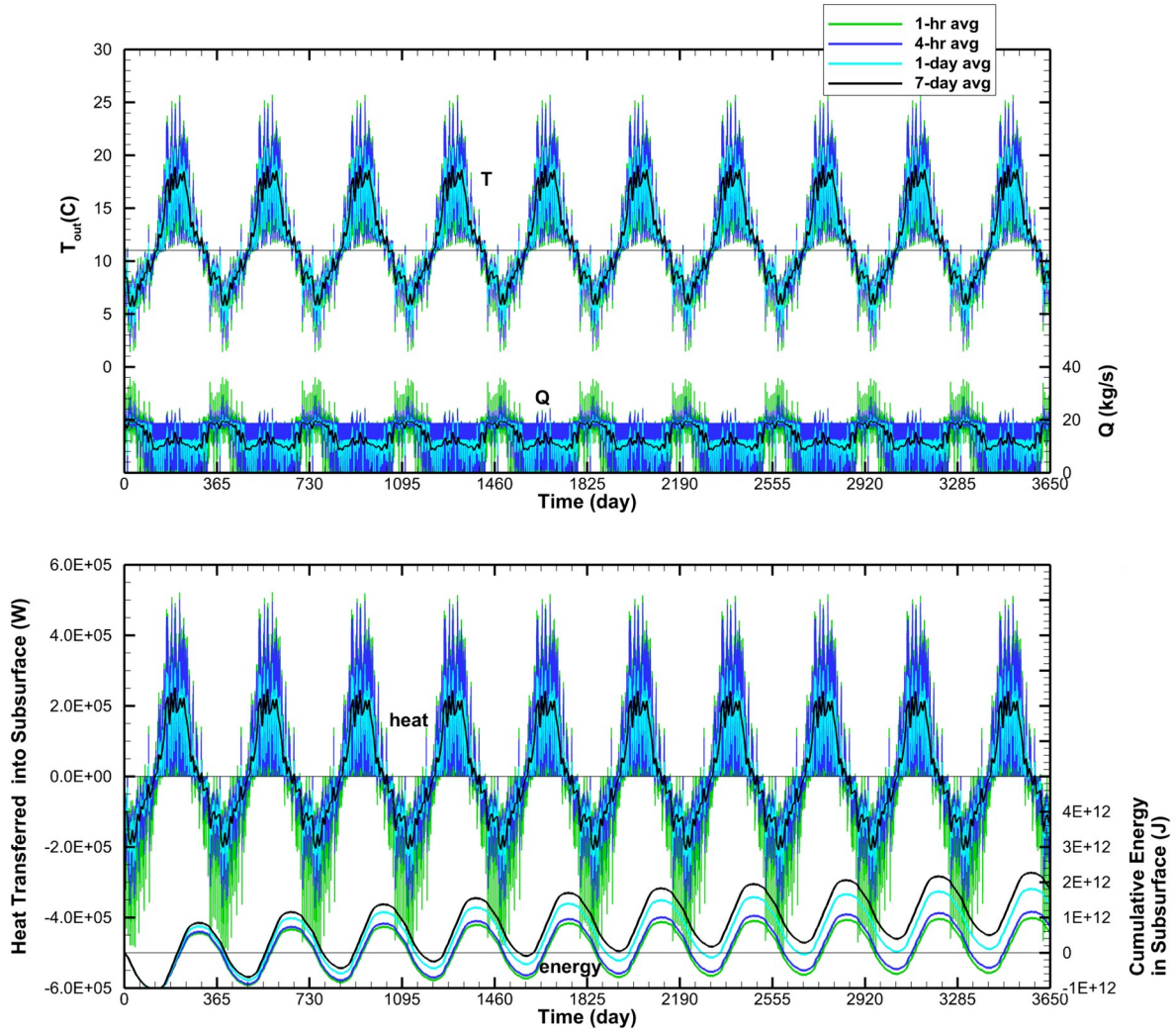


Figure B-3. Ten-year comparison of TOUGH simulation results for different time-averaging periods of T_{in} and Q , showing borefield outlet temperature T_{out} and loop flow rate Q (top frame) and heat transferred into the subsurface and cumulative energy stored (bottom frame).

To investigate the overprediction of cumulative energy observed for long time-averaging periods evident in Figures B-2 and B3, detailed studies of cumulative energy were conducted using synthetic thermal loads in which $Q(t)$ and $T_{in}(t)$ are represented by analytical expressions.

$Q(t)$ is either constant or varies sinusoidally with a one-day period:

$$Q(t) = Q_0 + Q_1 \sin((t-t_{0q})/2\pi\tau_d).$$

$T_{in}(t)$ varies with both an annual and daily sinusoidal variation:

$$T_{in}(t) = T_0 + T_1 \sin((t-t_0)/2\pi\tau) + T_d \sin((t-t_{0d})/2\pi\tau_d)$$

Figure B-4 shows $Q(t)$ and $T_{in}(t)$ for $Q_0 = Q_1 = 10 \text{ kg/s}$, $t_{0q} = 0 \text{ day}$, $\tau_d = 1 \text{ day}$, $T_0 = 16 \text{ C}$, $T_1 = -8 \text{ C}$, $T_d = 5 \text{ C}$, $t_0 = 296 \text{ days}$, $\tau = 365 \text{ days}$, and $t_{0d} = 0 \text{ day}$. Note that the annual average of $T_{in} = T_0$. The initial temperature of the subsurface is taken as T_0 also. At any time, power into the subsurface is proportional to the product $Q(T_{in} - T_0)$, and cumulative energy is the time-integral of power, so for constant Q , at the end of each year cumulative energy will be zero.

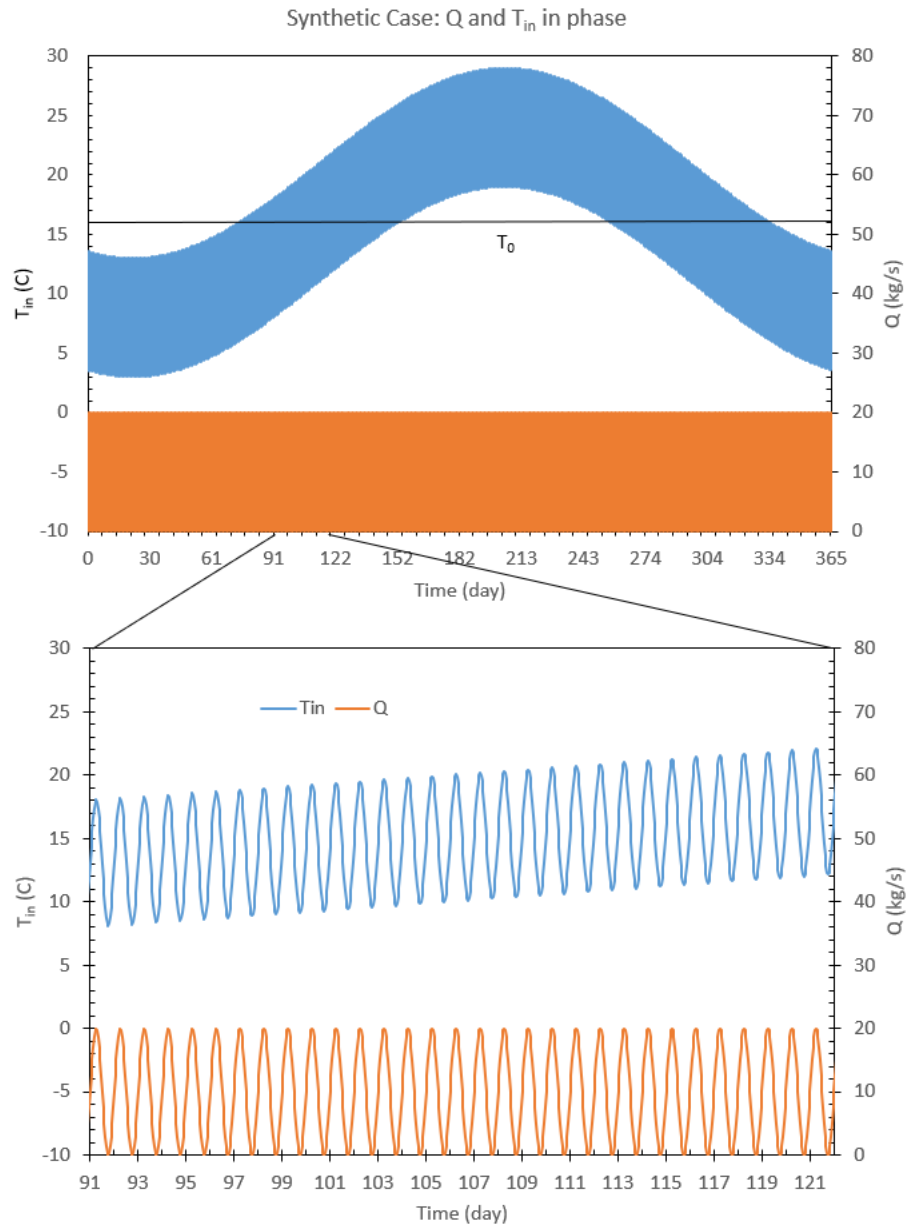


Figure B-4. $T_{in}(t)$ and $Q(t)$ for the synthetic case with the daily variability of Q and T_{in} in phase. In the top frame, the daily variation cannot be resolved.

TOUGH simulation results with constant Q and $T_{in}(t)$ given at 1-hour intervals (Figure B-5, dark-green curve) verify that cumulative energy is zero after one year. Doing 1-day averaging of $T_{in}(t)$ produces identical results (light-green curve). But when Q varies in phase with the T_{in} daily variation ($t_{0q} = t_{0d}$), and both are given at 1-hour intervals, cumulative energy shows a net increase over one year (dark-blue curve), and doing 1-day averaging of T_{in} and Q shows an even greater increase (light-blue curve). In contrast, when Q varies out of phase with the T_{in} daily variation ($t_{0q} = 0.5$ day, $t_{0d} = 0$ day), and both are given at 1-hour intervals, cumulative energy shows a net decrease over one year (red-curve), and doing 1-day averaging of T_{in} and Q shows an even greater decrease (orange curve).

The increase and decrease for the 1-hour interval (no averaging) cases are real physical effects. When Q and T_{in} are in phase, large values of T_{in} are weighted by large values of Q , so have a bigger contribution to cumulative energy than do small values of T_{in} . In winter, when $T_{in} < T_0$, less energy is removed from the subsurface, while in summer, when $T_{in} > T_0$, more energy is added to the subsurface, compared to the case with constant Q . When Q and T_{in} are out of phase, the opposite occurs: small values of T_{in} are weighted by large values of Q , in winter more energy is removed from the subsurface, and in summer less energy is added to the subsurface. Thus, despite the fact that the annual average of $T_{in}(t)$ equals T_0 , cumulative energy stored in the subsurface can remain constant, increase, or decrease, depending on how Q varies relative to T_{in} .

The greater increase and decrease for the 1-day averaging cases are erroneous results, introduced by the averaging process. Thus, if the absolute value of cumulative energy is important, averaging out daily variation should not be done. However, for the present studies, we are interested in verifying that the difference between cumulative energy for cases with different groundwater flows is small (Figure 8), and as long as the same averaging period is used for cases being compared, the conclusions remain valid.

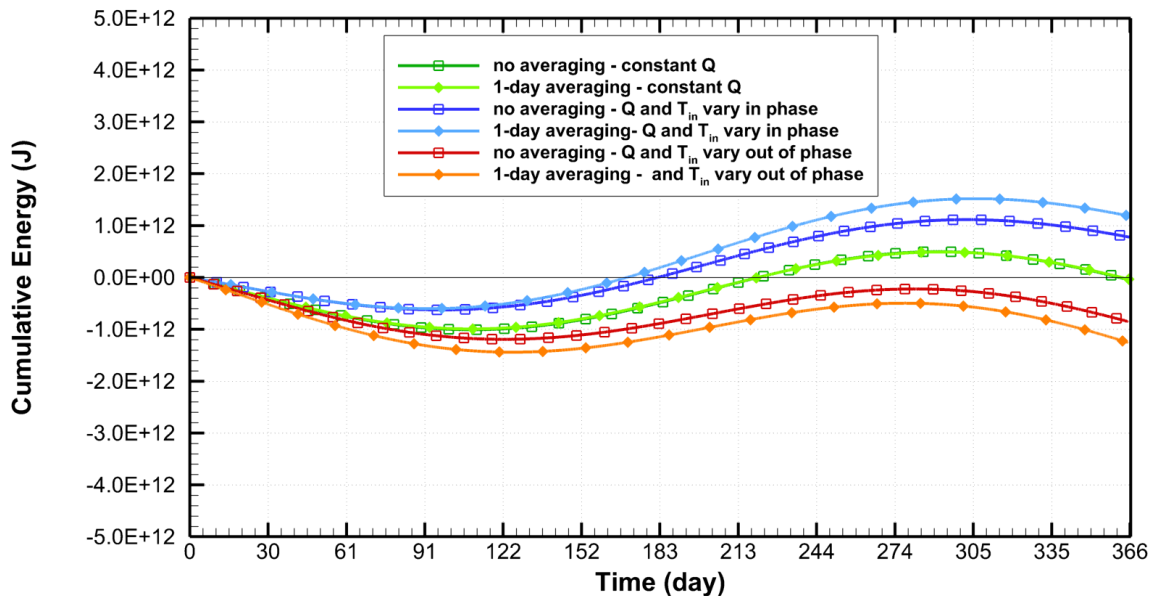


Figure B-5. TOUGH simulation results for the synthetic cases showing cumulative energy for one year.

Appendix C. Parameter Sensitivity Studies

The effect of different choices in GHE design are illustrated for Case 1 with no groundwater flow.

Borehole Thermal Resistance

Borehole Thermal Resistance (BTR) is an integrated representation of the thermal resistance of the components within the borehole, including fluid in the u-tube, the u-tube itself, grout filling the borehole, and borehole casing, if present. Of the components making up BTR, grout thermal conductivity is likely to show the most variability, with high-thermal-conductivity grouts available to enhance GHE operation by reducing BTR. A value of $BTR = 0.1 \text{ (W/m/K)}^{-1}$ is typical and is used for the present report. Figure C-1 illustrates heat, energy, and T_{out} for a range of BTR values. As BTR increases, heat is less effectively transferred from the borehole to the surroundings, so the difference between T_{in} and T_{out} decreases, resulting in less heat transferred to the ground in summer and removed from the ground in winter.

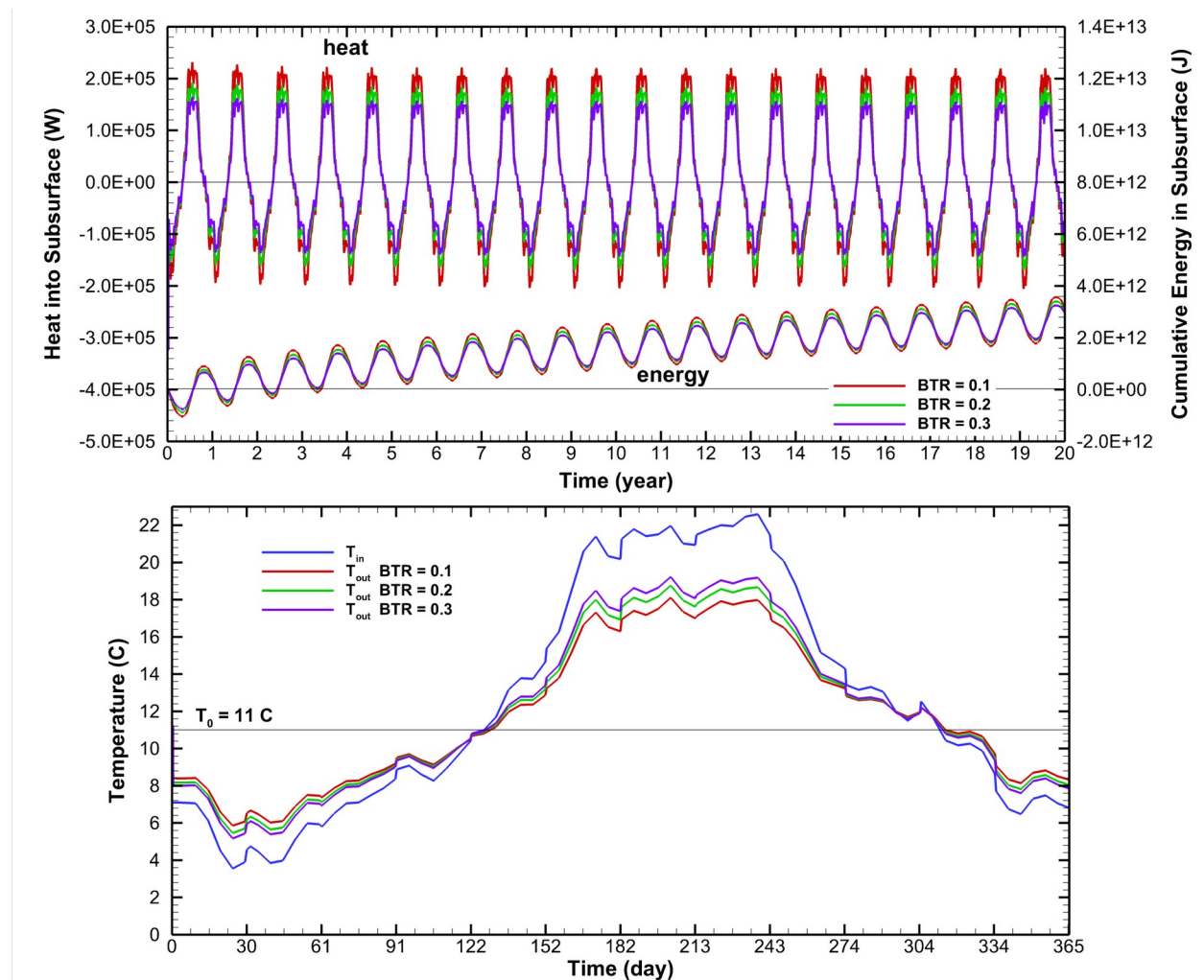


Figure C-1. Twenty-year comparison of TOUGH simulation results for different values of BTR. Top frame: heat transferred into the subsurface and cumulative energy stored; bottom frame: T_{in} and T_{out} during the first year.

Number of Boreholes in the Borefield

We consider borefields in which the total loop flow is divided equally among all boreholes in the borefield. Thus, the fluid flow through each borehole is inversely proportional to the number of boreholes. When fluid flow is smaller, there is more time for heat transfer between the borehole and the surrounding ground, so $(T_{in} - T_{out})$ is bigger, and the magnitude of heat and cumulative energy increase. Figure C-2 compares TOUGH simulation results for borefields consisting of 116 and 232 boreholes.

This trend of increasing heat transfer as the number of boreholes increases would continue, with $T_{in} - T_{out}$ continuing to grow, until T_{out} equaled T_0 throughout the year, indicating that all the thermal energy in the borehole fluid had been transferred to the ground.

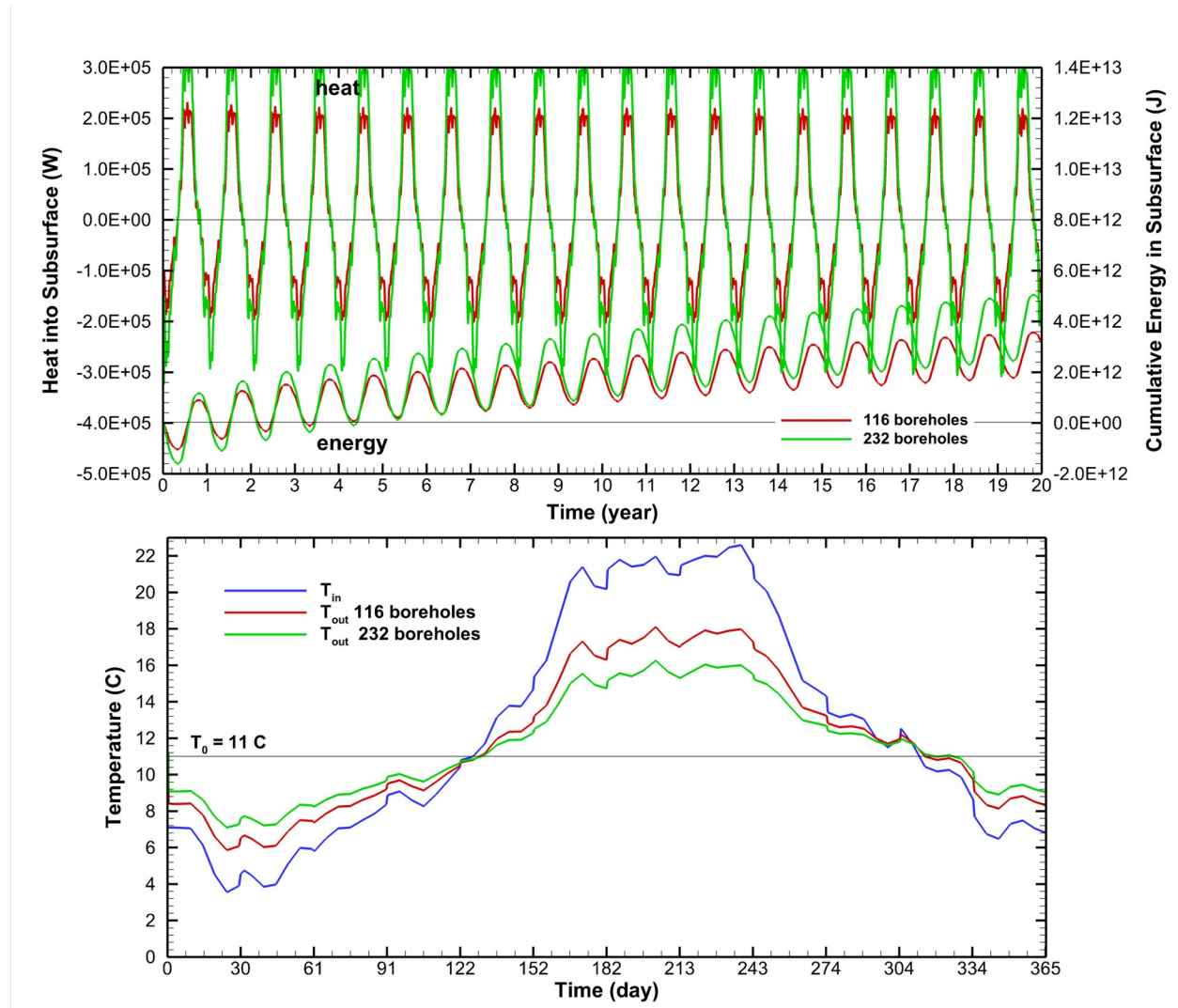


Figure C-2. Twenty-year comparison of TOUGH simulation results for different numbers of boreholes in the borefield. Top frame: heat transferred into the subsurface and cumulative energy stored; bottom frame: T_{in} and T_{out} during the first year.

Borehole Length

For longer boreholes, there is more opportunity for heat transfer between the borehole and the surrounding ground, so $(T_{in} - T_{out})$ is bigger, and the magnitude of heat transferred and cumulative energy stored increase. Figure C-3 compares TOUGH simulation results for borefields consisting of 100-m and 150-m long boreholes. This trend of increasing heat transfer with borehole length would continue until T_{out} equaled T_0 throughout the year, indicating that all the thermal energy in the borehole fluid had been transferred to the ground.

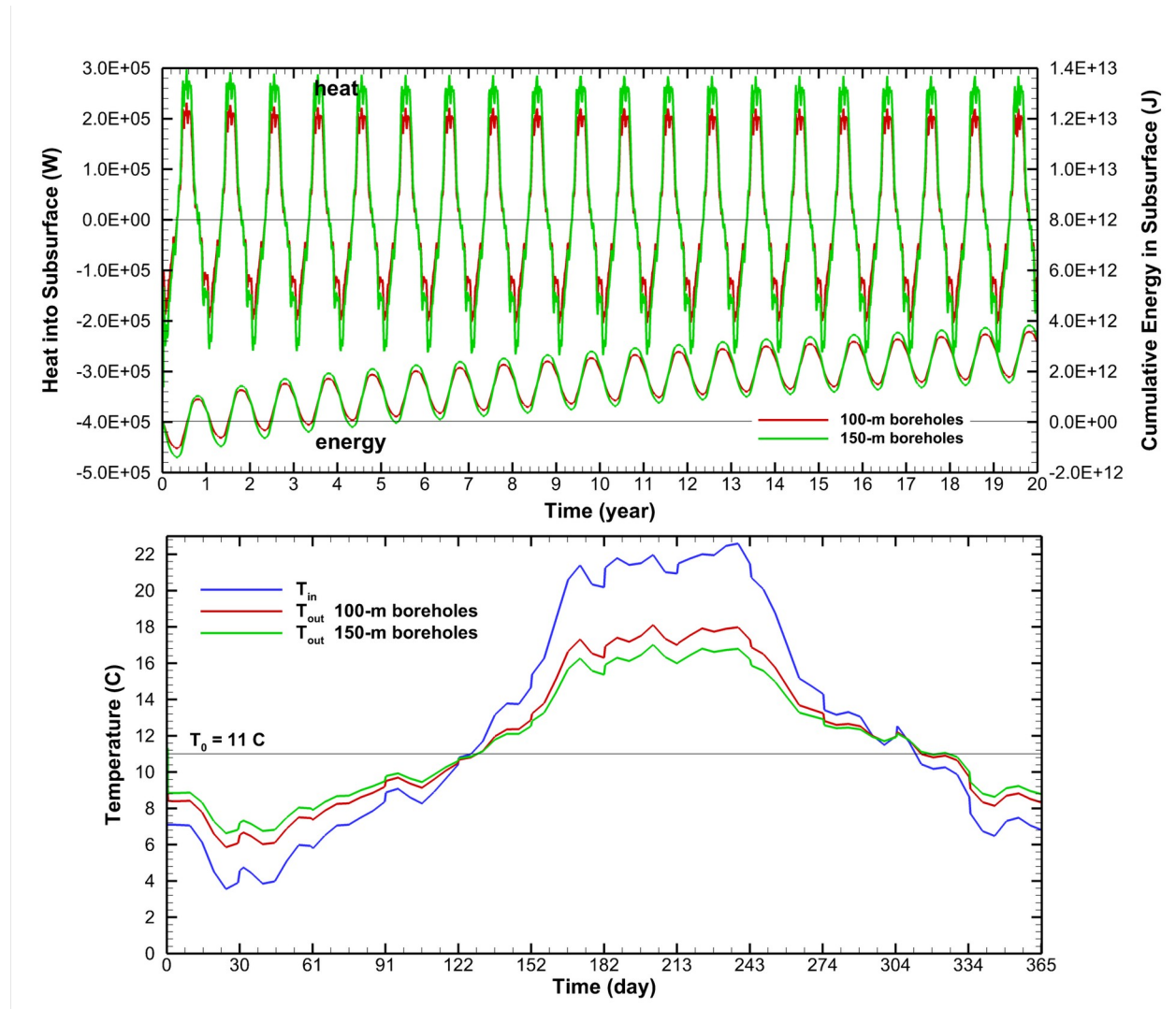


Figure C-3. Twenty-year comparison of TOUGH simulation results for different length boreholes. Top frame: heat transferred into the subsurface and cumulative energy stored; bottom frame: T_{in} and T_{out} during the first year.

