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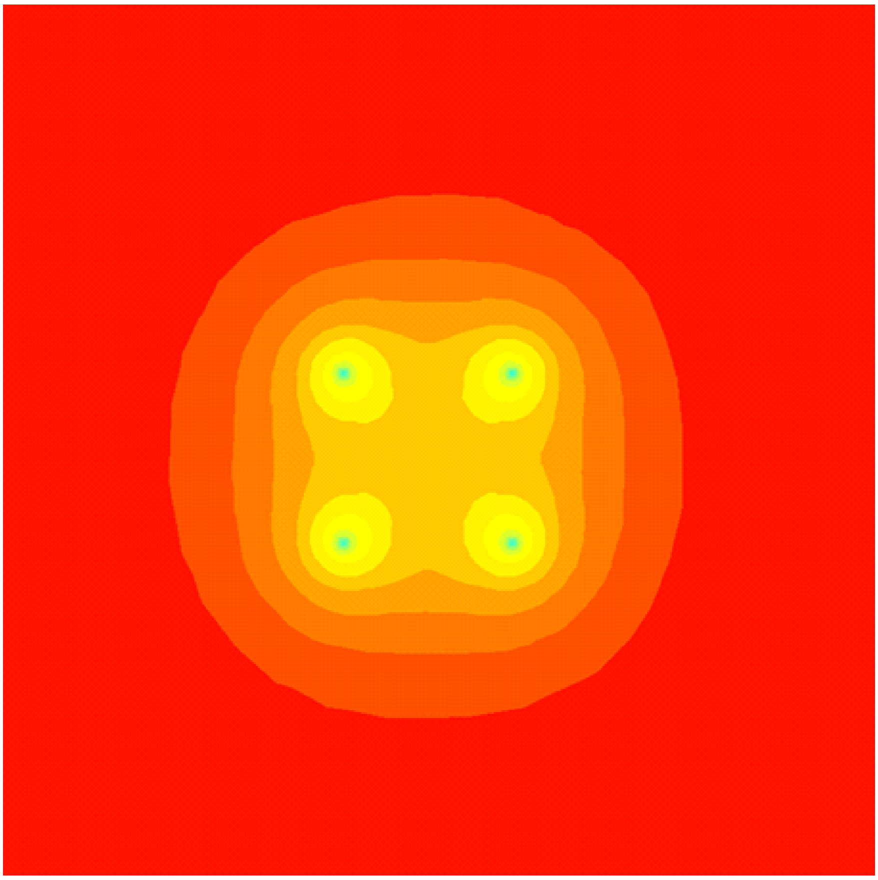
A modelling study using Feflow to examine the feasibility and sustainability of closed-loop ground source heat pump systems

Energy Science Programme

Open Report OR/11/022



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A modelling study using Feflow to examine the feasibility and sustainability of closed-loop ground source heat pump systems

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Four well image from Feflow model

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Summary

The work presented in this report is part of the Thermogeology project. Ground source heat pumps are becoming an increasingly popular method of heating/cooling in the UK. However, little work has been published on the long term sustainability of such schemes, partly because insufficient time has elapsed to allow long term data to be collected but also because closed-loop schemes are not required to be regulated. The aim of the work was to determine which factors, geological, hydrogeological and scheme-specific e.g. size, spacing and operating regime were most important in ascertaining whether a vertical closed-loop ground source heat pump scheme would be successful and sustainable. The impact of interference effects when a number of boreholes are located in close proximity were also considered. Guideline values for borehole spacing are typically of the order of 5 to 10 metres but modelling studies were used to demonstrate whether such values are appropriate. The work presented in this report comprises three parts – a review of the current application of closed-loop GSHPs in the UK, an assessment of the range of parameters required for a successful scheme and scenario modelling using the heat transport model Feflow®.

1 Introduction

Ground source heat pumps are becoming increasingly popular in the UK. This report presents the results of a modelling study that was used to make initial assessments of the feasibility of UK aquifers for (vertical closed-loop) GSHP installations and the sustainability of such schemes.

Closed-loop ground source heat pump (GSHP) systems do not require the abstraction or re-injection of groundwater and may comprise a horizontal coil (sometimes referred to as a slinky) in a trench or vertical installation in a borehole. The most popular closed-loop system in Europe is an indirect circulation scheme which uses a carrier fluid circulating in a closed-loop of pipe. In a heating system the chilled carrier fluid exiting the heat pump absorbs heat by conduction from the subsurface and conveys it back to the heat pump, where it is abstracted. The carrier fluid is therefore chilled and the process can begin again. The converse happens for a cooling system. The closed-loop GSHP may therefore be thought of as a subsurface heat exchanger (Banks, 2008).

Closed-loop schemes are not currently regulated because no groundwater is abstracted or re-injected. This report will seek to address the issue of what size and number of schemes can be sustained by different rock types. It brings together information about the use of closed-loop GSHPs in the UK and about the parameters required to undertake a programme of scenario modelling. The overall aim of the scenario modelling is to allow statements to be made about the suitability of different UK geological materials to support different scales and designs of heat pumps.

2 History of development of closed-loop GSHP in the UK

The earliest known champion of ground heat pump technology in the UK was John Sumner who was commissioned in 1948 to install ground source heat pumps in 12 houses (Banks, 2008). Curtis (2001) reports that between "1970-1994, perhaps a dozen or so horizontal closed-loop systems were installed – all domestic". The first use of a vertical closed-loop system was in 1994 in Devon in a newly built house (Curtis 2001). A single closed-loop borehole was connected to an American reverse-cycle water-to-air unit. Warm or cool air was distributed around the house via ductwork which was also connected to a fresh air/heat recovery unit. Curtis (2001) reports that for several years a Scottish utility promoted the introduction of small DX-based systems (i.e. ground loops containing refrigerant) for remote housing, off the national grid, that would otherwise have been electrically heated. The first 1.4 kW units were installed in Lerwick in late 1994. On the basis of promising results a further 40 units were installed using 1.4 and 2.5 kW units between 1998 and 1999. The early installations used horizontal, refrigerant-filled, copper ground loops and the later ones used boreholes in a range of ground conditions (Millar, 2001).

Curtis (2001) provides a table of more recent (primarily non-domestic) installations of closed-loop type – see Table 1. The list includes installations ranging from 4 kW to 200 kW thermal capacity using a variety of heat sources/sinks (borehole arrays, single pipe trenches, horizontal coils and pond loops) with a range of within-building distribution systems.

According to Banks (2008), large scale interest in the use of ground source heat pumps only really took off around 2003. Ó Dochartaigh (2009) states that most of the ground source heat pumps already installed in the UK are thought to be small closed-loop systems installed in individual houses. The Department for Business Enterprise and Regulatory Reform (BERR) estimate that around 3000 ground source heat pumps (open- and closed-loop) have been installed in individual family homes between 1992 and 2008 (BERR 2009). BERR also estimate that at the start of 2009, around 250 ground source heat pumps were being installed annually in the UK, increasingly including larger, usually open-loop, systems in larger residential, commercial and public buildings (BERR 2009).

Table 1 UK geothermal closed-loop heat pump installations 1998-2001 – primarily non-domestic. After Curtis 2001.

Metropolitan Housing Trust - Office Headquarters, Raleigh Square, Nottingham - 30-hole array coupled to two heat pumps mounted in the roof of a new-build four-storey office block. One heat pump for heating, one for cooling. The heat pumps are coupled through a common buffer tank, which supplies four pipe fan coils distributed throughout the building. Boreholes drilled Autumn 2000. Commissioned July 2001.
Ascom UK Headquarters, Croydon - A 30-hole closed-loop borehole array is part of a hybrid system supplying reverse-cycle console units distributed through this new multi-story office block. These particular console units incorporate economizers that provide passive cooling. Installed and commissioned during 2000.
Dunston Innovation Centre, Chesterfield - 32-hole array coupled directly to reverse-cycle console units distributed throughout this newly- built, three-story, low-energy office block building, housing fully-serviced startup units. Each office unit has its own heat pump and metering arrangement. The common conference facility has a water-source heat pump supplying fan coils. The ground loop installation was completed in Winter 2000 and commissioning took place in early-2001.
Cotswold Water Park near Cirencester - The visitor centre is using pond-loop system to provide heating and cooling. The pond-loop heat exchanger has been installed in the adjacent lake and is connected to eight reverse-cycle console-type heat pump units. The system was commissioned in November 2000.
National Forest Millennium Discovery Centre, Moira, Leicestershire - 32-borehole based hybrid system. The ground heat exchanger is coupled to a heat pump, which feeds hot and cold buffer tanks that are also serviced by supplementary boilers and chillers. Borehole array installed Spring 2000. System commissioned early-2001.
Nature's World Visitor Centre, Middlesborough - The centre incorporates a coupled solar/geothermal system. An array of 30 metre deep, concentric heat exchangers, supply individual reverse-cycle water-to-air heat pumps installed around the building. Commissioned during 2000.
Stover Country Park - Newton Abbot, Devon - A shallow pond loop heat exchanger provides heating and cooling to the visitor centre. The pond loop system is coupled, through 100-metre headers from the lake, to a reverse-cycle heat pump. The heat pump delivers energy to an underfloor system via a buffer tank. This is believed to be the first example of a closed –pond-loop system in the UK.
Bryce Road - Phase 2A, Dudley, Nottingham - Four high profile eco-friendly terraced houses have had a small borehole-based system installed to provide partial heating and cooling to a wet underfloor system. Commissioned in November 2000.
Minehead Community College, Minehead, Somerset - A slinky-based system is installed in a new IT teaching block. The ground heat exchangers are installed in horizontal trenches in the adjacent sport field and are coupled to a reverse-cycle heat pump and supplied connected to a separate air handling unit. Loops installed during Summer 2000. Commissioned during 2001.
Charlestown J&I School - St. Austell, Cornwell - This 1960-school building has been retrofitted with a 10 borehole-based system with the ground loop array installed in the school grounds. A fully-integrated roof-mounted air handling unit has replaced the original air handling system that used direct electric heater batteries and a chiller. The new roof-mounted heat pump unit incorporates twin reverse cycle water-source heat pumps supplying the integrated DX-to-air coils. System installed in Summer 1999.
Health Centre - St. Mary's, Isles of Scilly - The new health centre on St. Mary's uses a four borehole closed-loop array to supply heating and cooling, using a reverse-cycle water-to-water heat pump to the underfloor system and to provide domestic hot water using a superheater. Commissioned in December 1998. This is thought to be the first non-domestic closed-loop installation in the UK.
The Royal Zoological Society Millennium Project, London - The new Invertebrate House at the London Zoo in Regents Park is designed as a high-profile, low-energy building. The small closed-loop system provides cooling to the air supply being used to control the temperature of the high mass TermoDeck floors and ceilings. The boreholes were drilled and completed in early-July 1998 and the system was commissioned in early-1999.
Sheltered Housing Development, Marazion, Cornwall - These four small bungalows, developed by a housing association, use slinky coils connected to individual heat pumps to provide domestic hot water and heating via conventional radiators. Commissioned 1998.

Botallack Count House, Pendeen, Cornwall - The National Trust restored this old mining Count House. A closed-loop borehole system provides underfloor heating for the main exhibition hall and warm air heating for the warden's office. Commissioned 1999.	
Millennium House, Building Research Establishment, Garston, Watford - This futuristic, low-energy house is fitted with a small two hole closed-loop system to supply the heating and cooling to the convective underfloor system in this Intelligent House of the Future.	

Note: About 20 private domestic installations have taken place between 1995 and 2001 ranging in size from 4 to 30 kW. These are in addition to the 30 or so small DX systems installed in the North of Scotland. There are possibly up to 10 or 20 other trenched-based closed-loop systems that have been installed between 1980 and 2000 by various individuals using a variety of imported heat pumps.

3 Design considerations for installation of vertical closed-loop GSHPs in the UK

3.1 FACTORS AFFECTING PERFORMANCE

The performance of a vertical closed-loop GSHP system will depend on:

1. Size and nature of the scheme

- The number and proximity of boreholes
- The heating and/or cooling requirements of the scheme (capacity and seasonal variations)
- The operating temperature of the ground loop. In heating mode this is typically around or just below 0 ^{o}C, in cooling systems there is no natural upper limit.

2. Thermal properties of the ground

- Thermal conductivity (how well a body of rock conducts heat)
- Specific heat capacity (how well a body of rock stores heat, specific heat capacity is related to porosity)
- Mean annual ground temperature is reasonably consistent for a given region although may be significantly higher in urban areas.

3. Hydrogeological factors

- Depth to groundwater
- Porosity
- Hydraulic gradient

3.1.1 Size and nature of the scheme

An average house typically requires 10-18 kW of heating capacity. The heating load which a scheme can deliver is proportional to the number of drilled borehole metres. Installed capacity per borehole ranges from 2 kW to 17 kW, where the lowest capacities relate to the shallowest borehole (40 m) and the highest to the deepest borehole (180 m). Dividing installed heat pump capacity by the total number of drilled borehole metres gives a range of specific installed thermal outputs of between 50 and 104 W per drilled metre (i.e. an average 75 W m^{-1}). Assuming that a heat pump scheme has a typical co-efficient of performance of 3.4, these figures equate to specific peak heat absorption rates (i.e. heat abstracted from the ground) of 35-73 W m^{-1} (average 52 W m^{-1}) (Banks 2008).

Larger schemes often include cooling requirements and additional performance-influencing factors become important:

- Thermal interference between boreholes.
- Cooling systems may need greater borehole lengths than a comparable heating system to deliver a particular load.
- Complex heating and cooling loads. Seasonally-reversible schemes may require shorter/fewer boreholes than heating-only schemes. Where heating and cooling loads are not balanced i.e. schemes with a dominant heating or cooling load, borehole spacing of a minimum of 10 m is recommended. For balanced, reversible schemes, smaller spacing may be adequate.

When designing a scheme a number of guidelines need to be considered. The mean temperature of the carrier fluid under average 'base-load' conditions should not drop significantly below 0^{o}C over the design life of the system. Operational carrier fluid temperatures of -4 to 0^{o}C are typical. The return temperature of the carrier fluid should not be more than 11^{o}C lower than undisturbed ground temperature under base-load conditions (weekly average) and not more than 17^{o}C lower than undisturbed ground temperature under peak load conditions.

It is therefore important to consider the duration of peak load, the percentage of peak load that represents average base load (depending on occupancy) and the minimum acceptable carrier fluid temperature. Larger spacing and linear arrays appear to perform better (Banks, 2008).

It is also important to note that steady state conditions may not occur for several decades, typically 30 years (Banks 2008), and simulation periods should reflect this. In heat storage schemes i.e. schemes injecting heat during the summer and abstracting it during winter, many of these conditions do not apply. In these schemes temperatures may reach a steady state relatively quickly and borehole spacing may not need to be as wide. Low hydraulic gradients are preferable as are higher peak temperatures.

3.1.2 Thermal properties of the ground

Thermal conductivity does not vary greatly between lithologies and is typically between 1.5-6 Wm^{-1} K^{-1}, heat capacity varies even less. In terms of the thermal conductivity of the ground the range in most British rocks lies within a factor of 3, which roughly reflects the variability in calculated specific heat absorption rates. Thermal conductivity is often anisotropic due to primary sedimentary or crystalline structure. Most rocks have relatively consistent thermal properties and their behaviour is not strongly lithologically dependent. This allows rules of thumb, such as 60-100 W m^{-1} of peak installed GSHP capacity in heating mode, to be applied (Banks 2008).

European experience supports these values (Rosen et al, 2001). For example, in Austria the recommended peak specific heat absorption rates range from 30 W m^{-1} for dry sediments to 70 W m^{-1} for granites, for a temperature difference of 10^{o}C between the carrier fluid and the undisturbed ground. In Germany peak specific heat absorption rates of 20-25 W m^{-1} are recommended for low conductivity (<1.5 W m^{-1} K^{-1}) strata, 50-60 W m^{-1} for medium conductivity strata and 70 to 84 W m^{-1} for high conductivity (>3 W m^{-1} K^{-1}) strata. In each of these ranges, the lowest value applies to systems with high operational use (2400 h yr^{-1}) and the highest to systems with lowest use (1800 h yr^{-1}). Across Europe the average peak specific heat absorption rate is estimated at 62 W m^{-1} for systems with operating times of 1600 -2400 hr yr^{-1}.

Borehole design and construction can affect the thermal efficiency. Just as a water abstraction borehole may suffer reduced efficiency due to well loss, thermal resistance may occur due to the conductivity of the material filling the annulus (typically grout), thermal short circuiting or transfer of heat from grout through the U-tube to the carrier fluid.

The mean annual ground temperature is reasonably consistent for a given region although may be significantly higher in urban areas.

3.1.3 Hydrogeological factors

Depth to groundwater table, porosity and hydraulic gradient influence groundwater storage and flow and subsequently the rate at which heat is dissipated in the ground. For individual aquifers values can be estimated based on borehole records, hydrogeological maps and aquifer property measurements. The thermal properties relevant to heat transfer are a combination of the rock, air and water properties. Closed-loop heat pumps usually operate most efficiently in saturated ground (i.e. when installed below the water table rather than in the unsaturated zone) because water has a higher thermal conductivity and thermal capacity than air. The porosity of the aquifer is also an important factor as it determines the relative volumes of water and rock and their associated thermal properties.

The top of an aestifer (heat storing body) can in the long term be considered a constant temperature boundary at the average annual surface temperature. Therefore, if heat is pumped from a closed-loop borehole a zone of depressed temperature develops around the borehole. Heat stored in the surrounding rocks will be conducted radially towards the borehole and eventually, when the ground cools further, heat will be increasingly induced from the surface as steady state conditions develop. The heat flow induced from the surface balances the heat abstracted from the ground.

Table 2 Summary table of factors influencing performance of closed-loop GSHP

Parameter	**Typical values**
Thermal Conductivity	1.5 to 6 $Wm^{-1} K^{-1}$, most UK rocks <3 $Wm^{-1} K^{-1}$
Specific Heat Capacity (related to porosity)	2 kW (40 m deep borehole) -17 kW (180 m deep borehole, 50 -104 W per m (average 75 W per m)
Ground temperature	9-12 ^{o}C
Operating temperature of ground loop	around 0^{o}C (for heating systems)
Borehole spacing	>10 m for heating and cooling systems, possibly less for just heating/cooling
Typical co-efficient of performance	3.4
Specific peak heat absorption rates	35 to 75 Wm^{-1} (average 53 Wm^{-1})

4 Modelling studies

4.1 MODEL SETUP

The aim of the modelling was to assess the sustainability of closed-loop GSHP schemes, i.e. what size, in terms of heat requirement and number of closed-loop GSHPs, can be supported by a given volume of rock with defined characteristics. The sensitivity of the model to the different parameters which are thought to influence scheme performance was tested to identify factors that affect model performance. The fundamental question to answer in assessing whether a scheme will be successful in the short and long term is how fast does the heat (or coolness) dissipate?

A simple 2-D steady state flow, transient heat transport model was set up to simulate a vertical closed-loop ground source heat pump used for heating.

Modelling was undertaken using FEFLOW® (5.3), Finite Element and Subsurface Flow and Transport Simulation System, by DHI-WASY which allows heat transport simulations to be made. The model dimensions were set as a 1 km square with the well at the centre so that boundary effects were minimised. A non-uniform grid was used with grid refinement in the vicinity of the well. Grid cell dimensions varied from 1m in the vicinity of the well to 50 at the boundaries of the model (Figure 1). Initially the simulation was run for a 10 year period (with 365 time steps each lasting 10 days).

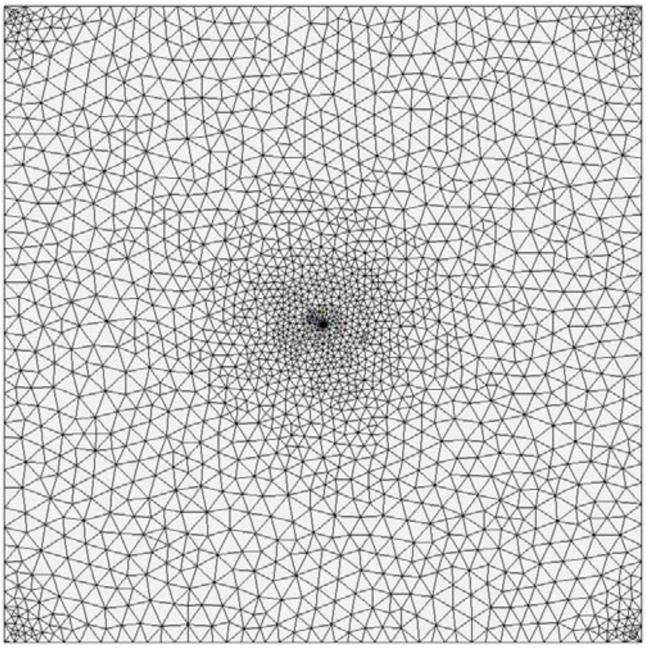

Figure 1 Mesh used for Feflow model. The well is in the centre of the refined mesh.

The model was fully saturated. A hydraulic gradient of 1 m was set up across the model with groundwater flowing from south to north. The initial thickness of the model was 30 m. Porosity was initially set to be 30% and transmissivity to 0.001 m^2/s. Hydraulic gradient and transmissivity of the aquifer are not directly relevant to the operation of a closed-loop GSHP. However, they determine the local groundwater velocity and hence affect the rate at which heat dissipates. Thickness of the aquifer was changed during some of the simulations and transmissivity was changed accordingly to maintain a constant groundwater flow velocity.

The initial heat conditions across the model were set to be 10^oC with no-flow heat boundaries on all sides. The groundwater flowing in to the model from the south is given a temperature of 10^oC but this is assumed to have little or no effect on the thermal balance around the GSHP due to the size of the model area. This means that all the heat energy abstracted by the GSHP will come from the ground and no ‘extra’ energy flow is induced from the ground surface. Therefore the model will never reach a steady state. This is considered to be a realistic modelling scenario as it will give a ‘worst-case’ scenario for temperature change in the ground. Also it is not at present clear exactly how GSHP schemes affect the transport of heat from the surface. The thermal properties used for the initial model runs were: thermal conductivity 3 W m^{-1} K^{-1} (rock), 0.65 W m^{-1} K^{-1} (water); specific heat capacity 2.5 MJ m^3 K^{-1} (rock) and 4.2 MJ m^3 K^{-1} (water).

To monitor temperature change in the aquifer a series of observation nodes were set up around the well, one at the well itself, 4 at 5 m distance, 4 at 10 m distance, 4 at 20 m distance and 4 at 40 m distance. The nodes were located radially to the north, the east, the south and the west.

4.2 MODEL RESULTS

4.2.1 Model sensitivity

The sensitivity of the model to different parameters was investigated. The range of values used to test sensitivity for heat load, aquifer thickness, porosity, thermal conductivity and specific heat capacity are given in Table 3.

Table 3 Range of parameter values used in the modelling study

Parameter	Values used in model
Size of scheme (heat load)	1, 2, 5 and 10 kW
Aquifer thickness	30, 50 and 100 m
Porosity	10, 20, 30 and 40 %
Thermal Conductivity	1.5, 3 and 4.5 J/m/s/K
Specific heat capacity	2, 2.5 and 3 MJ/m^3/K

HEAT LOAD

The amount of energy abstracted from the ground was varied. Base load for a small domestic scheme is typically in the region of 1.5 kW, with peak load reaching 4.5 kW. Simulations were run using a heat abstraction rate of 1, 2, 5 and 10 kW. The results for observation nodes at the well itself (A) and 40 m north of the well (E) are presented in Figure 2.

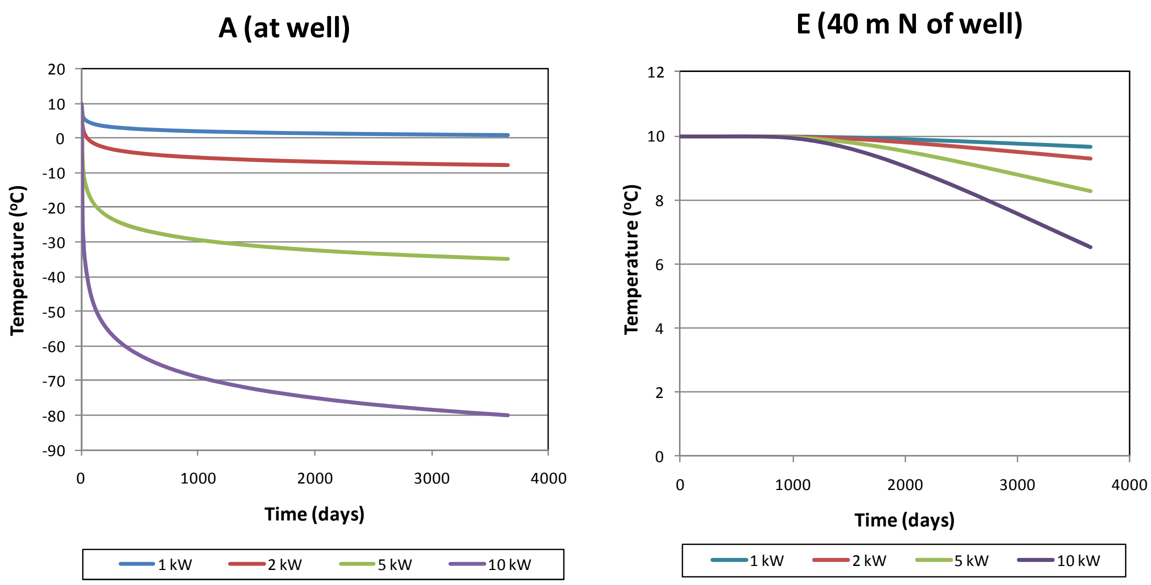

Figure 2 Time-heat curves for varying heat requirements at the well and at 40 m distance from the well. Note the different vertical scales for temperature.

At the well itself, heat abstractions of greater than 10 kW resulting in large reductions in temperature at the well (down to -80^{o}C for a 10 kW abstraction), which would be too great for a successful GSHP scheme. For an abstraction of 1 kW, the temperature at the well remains above 0^{o}C. At distance from the well, here seen at 40 m north of the well, the impact of heat abstraction is much less but can still be observed even for small base loads.

Effect of aquifer thickness

It would appear that a 30 m thick aquifer is too thin, in fact most closed system GSHP schemes tend to be in excess of 75 m deep. The model was therefore adapted to see how temperature over time varied with aquifer thickness (Figure 3). Aquifer thicknesses of 30 m, 50 m and 100 m were modelled and compared. A heat requirement of 2 kW was assumed (an approximation of peak load at 4 kW for a few hours a days and base load of 1.5 kW for the rest of the time). Transmissivity was altered accordingly, to give the same groundwater velocity in all models.

Figure 3 shows that the smallest reduction in temperature occurs in the thickest aquifer, and that only the 100 m thick aquifer gives positive temperatures at the well itself. At distance from the well the least thick (30 m) aquifer displays not only a larger reduction in temperature but the temperature drop occurs earlier than in the thicker aquifers. There is less variation in temperature reduction and timing between the 50 m thick and 100 m thick aquifer at distance from the well.

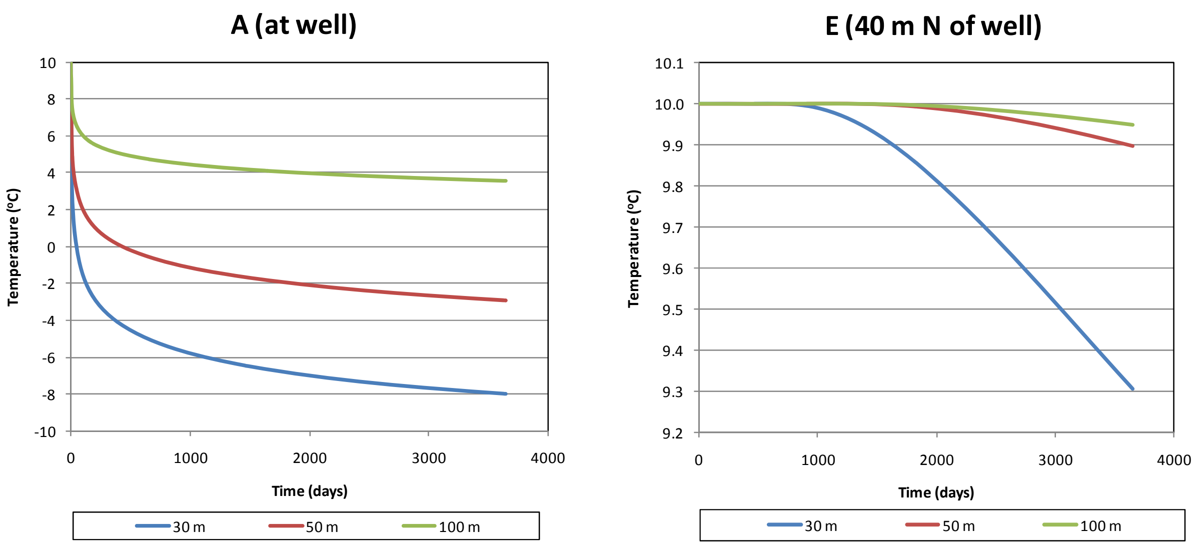

Figure 3 The effect of aquifer thickness of temperature with time. Note the different vertical scales for temperature.

Impact of varying aquifer porosity

The impact of aquifer porosity was also considered. Using a 50 m thick aquifer and a heat requirement of 2 kW, porosity was varied from 30% to 10%, 20% and 40% (Figure 4). The thermal properties of the water and rock were not changed, so that the change in porosity gives a change in specific heat capacity and thermal conductivity of the bulk aquifer material. The transmissivity and the head gradient were also kept constant so the change in aquifer porosity will also result in a change in groundwater velocity past the GSHP (for a given gradient and transmissivity water will flow faster in a lower porosity material). Varying porosity has a linear impact on ground temperature. Reducing porosity to 10% produces the least reduction in temperature at the well but the most and earliest reduction at distance from the well.

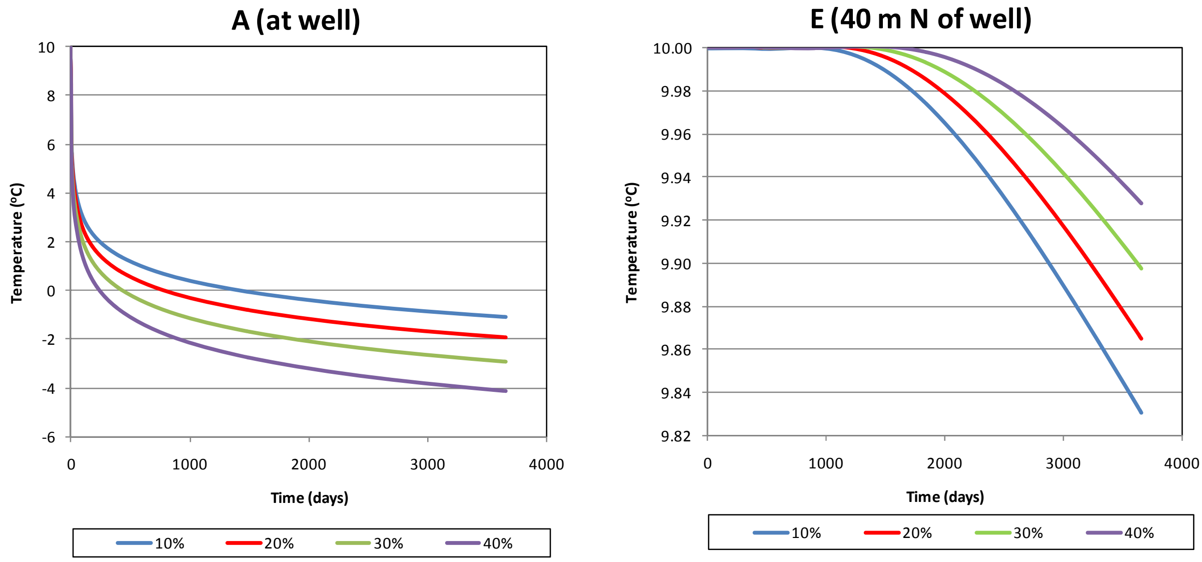

Figure 4 The impact of aquifer porosity on temperature with time.

SENSITIVITY TO VALUE OF THERMAL CONDUCTIVITY AND SPECIFIC HEAT CAPACITY

Finally, the effect of different thermal properties of the rocks on the model outputs were considered using the same 50 m thick aquifer model. Thermal conductivity and specific heat capacity were varied to 1.5, 3 and 4.5 J m^{-1} s^{-1} K^{-1} and 2, 2,5 and 3 MJ m^{-1} K^{-1} respectively. Figure 5 shows the impact of thermal conductivity of the rocks at observation nodes at the well itself, at 5 m distance and at 20 m distance. This suggests that the effects are greatest at the well and are minimal at 20 m distance. The lowest thermal conductivity (1.5 J m^{-1} s^{-1} K^{-1}) material results in the greatest reduction in temperature at the well and the ground rapidly freezes. For a thermal conductivity of 4.5 J m^{-1} s^{-1} K^{-1} the ground does not freeze. The effects become less pronounced with distance from the well.

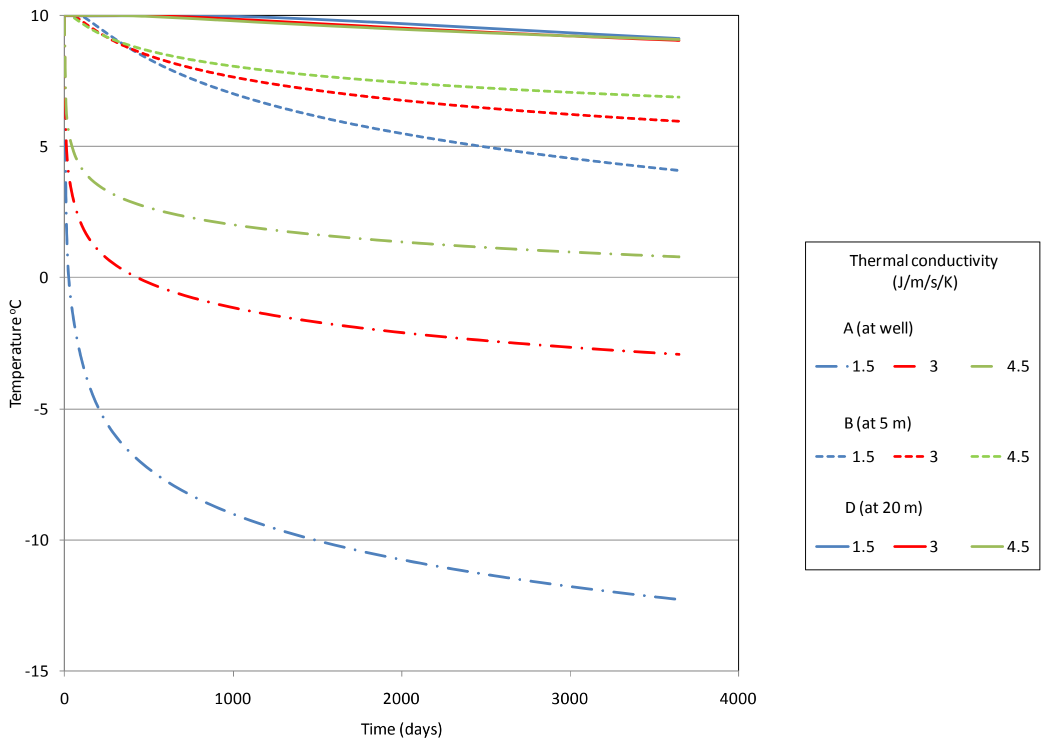

Figure 5 The effect of thermal conductivity on temperature with time and distance from the well (0 m, 5 m and 20 m).

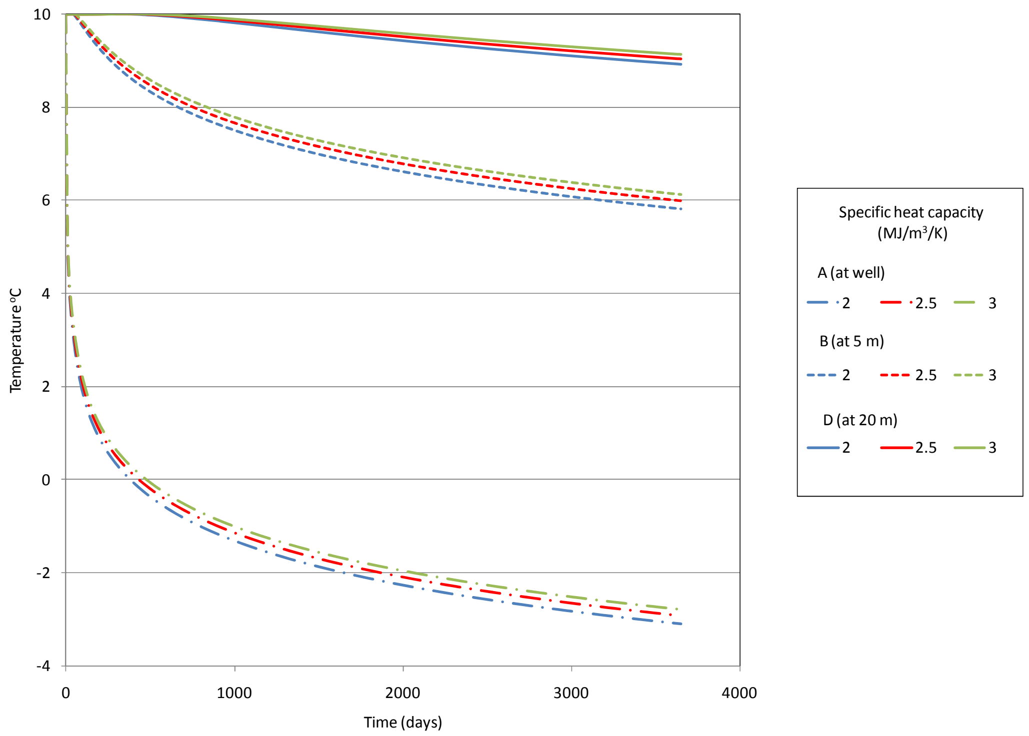

Figure 6 The effect of specific heat capacity on temperature with time and distance from the well (0 m, 5 m and 20 m).

Figure 6 shows that the impact of changes in the specific heat capacity of the rocks has relatively little impact on temperature with time.

4.2.2 Temporal variations

Variations with time were also considered. A 30 year model was run but the results were found to be very similar to the 10 year model suggesting that a 10 year modelling interval is sufficient for pseudo steady-state temperatures to be reached for the conditions denoted in this model.

The model was then used to investigate the impact of a closed-loop GSHP heating system which runs for only 5 months of the year (Figure 7). A 50 m thick, 2kW heating scheme with an aquifer porosity of 30% was used.

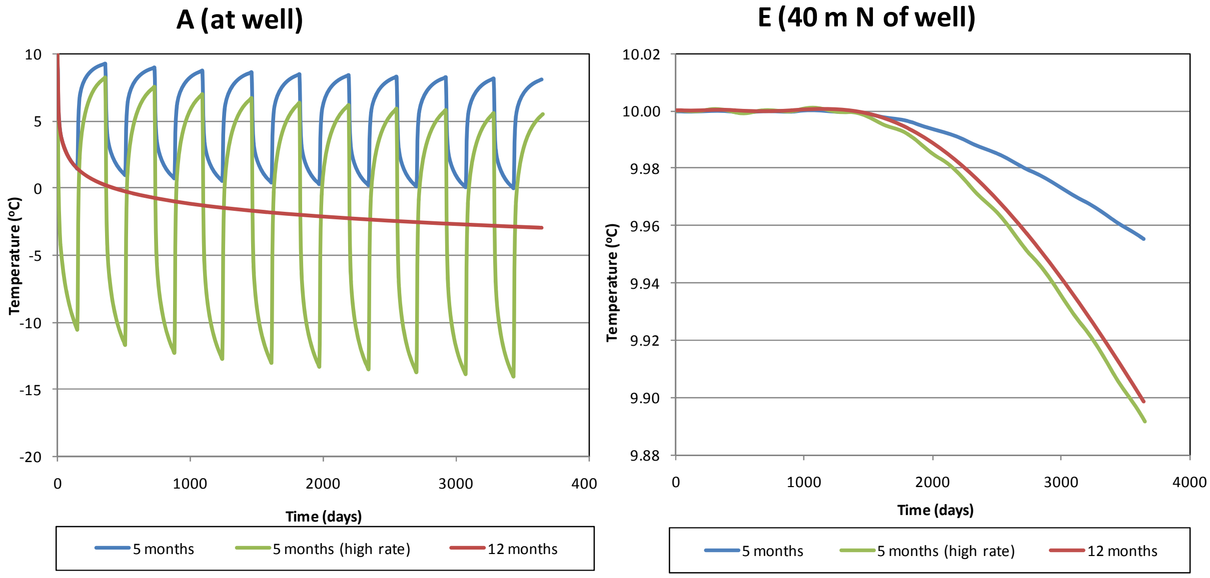

Figure 7 The impact of 5 months heating per year compared with 12 months heating.

Reducing the length of time during which the scheme is operational during the year from 12 to 5 months has an ameliorating impact on the total temperature reduction at the well. Operating the scheme for 5 months on and 7 months off reduces the mean temperature to around 4 ^{o}C (with a range from 0 to 8 ^{o}C after 10 years) compared with -3^{o}C if the scheme runs continuously. However, these results are not surprising as, in the first scenario, the total amount of heat abstracted from the system over a year is much less. Therefore, another 5-month operation scenario was run with the same total heat requirement as the 12-month model (i.e. 12 months worth of heat abstracted in 5 months). The results of this run are shown in green in Figure 7. As would be expected this model results in a greater temperature fluctuations at the well, but the average temperature reduction is similar to the 12-month scenario.

The 5-month model was also used to examine how the temperature change moves away from the well. The variations with distance from the well are shown in Figure 8.

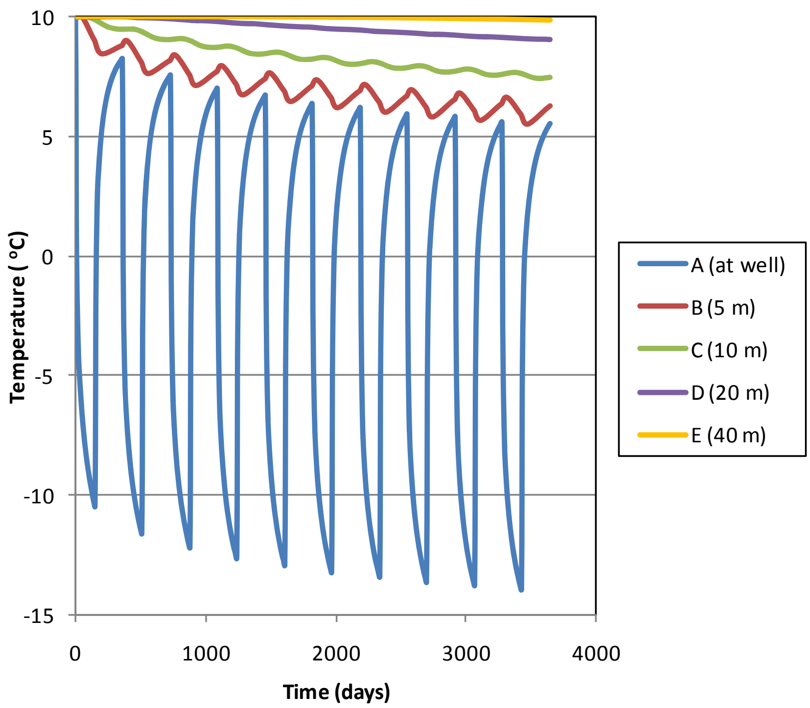

Figure 8 Variation of temperature over time with distance from well.

At 10 m distance, the temperature variations with time are significantly damped, and at 20 m the time variations are insignificant. This means that the large-scale effects of a GSHP scheme (i.e. at distances greater than 50 m) can be modelled as if the load is equally distributed in time. This is an important finding as it implies that total GSHP potential of an area can be investigated from the annual heat loads (distributed over 12 months) and do not require monthly load data.

This results of this model also has implications for interference effects between closely spaced wells and seems to support the recommended spacing of boreholes of 5 to 10 m. The heat signal is not only damped as it moves from the well, it is also lagged. The maximum temperature drop 10 m from the abstraction well occurs several months after the maximum change at the abstraction. Therefore, the performance of a second well 10 m away would not be greatly affected by the first well.

4.2.3 Multiple wells

To test interference between wells another model was set up with the potential to have up to four wells (spaced at 10 m apart at each corner of a square). Initially only two wells were activated, each extracting 1 kW each. The aquifer thickness was set to 50 m and porosity at 30 %).

A four-well model (Figure 9) was also established with the same aquifer thickness and porosity but with the total heat extraction of 2 kW shared between the four wells (i.e. each well extracting 0.5 kW).

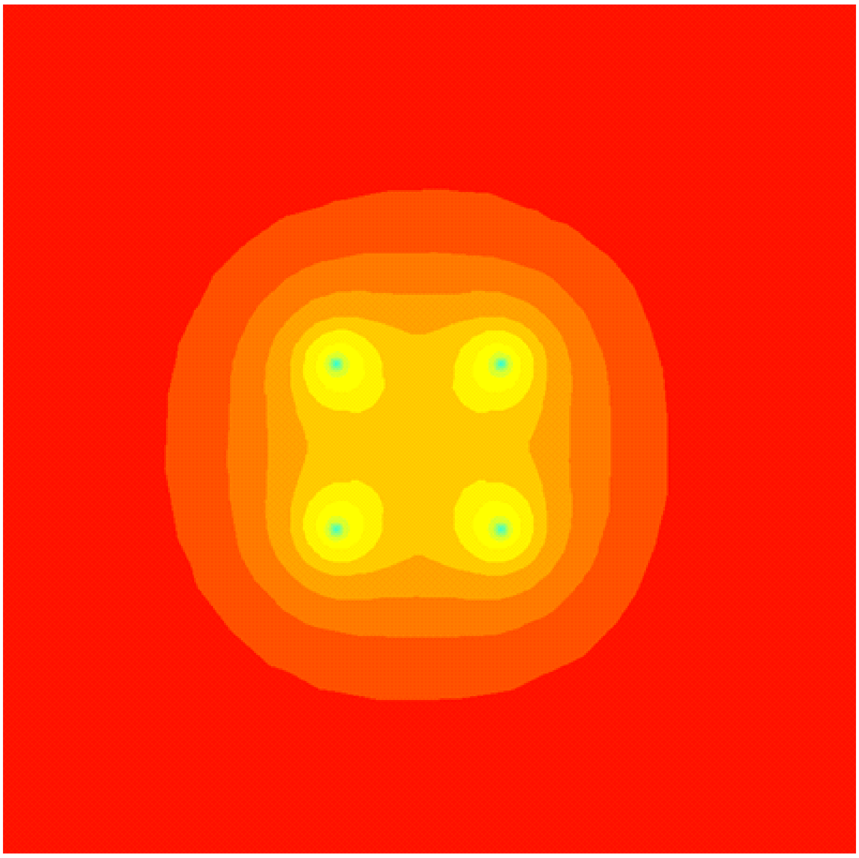

Figure 9 Four-well model

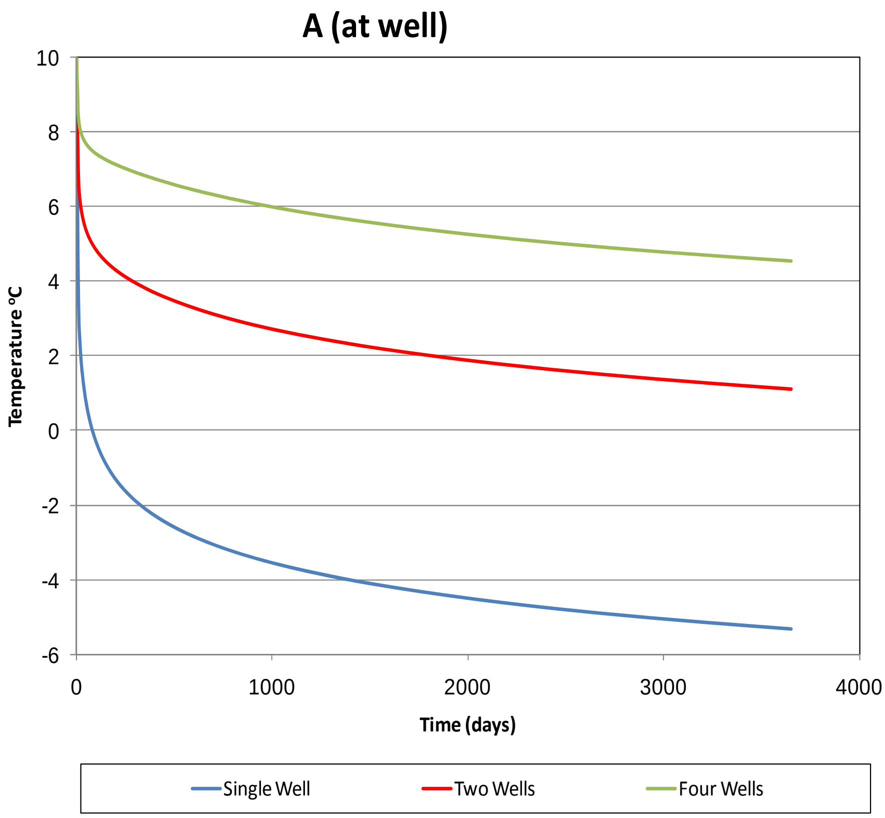

Figure 10 Variation of temperature over time at the GSHP well.

At the well itself there is a reduction in drawdown of temperature as the number of wells increases (which reflects the reduced rate of heat extraction at the initial well). For a single-well extracting 2 kW the ground rapidly freezes, however if two wells each abstracting 1 kW are used conditions remain above 0^{o}C. For four wells extracting 0.5 kW each conditions are less cold still. Therefore, for single well schemes where the heat requirement would result in frozen conditions, using more than one borehole would be more successful and sustainable. When extraction rates were doubled (100% increase) for the four-well model the ground became frozen at around 2600 days. However, a 50% increase from 0.5 kW each to 0.75 kW (giving a total output of 3 kW) does not result in freezing.

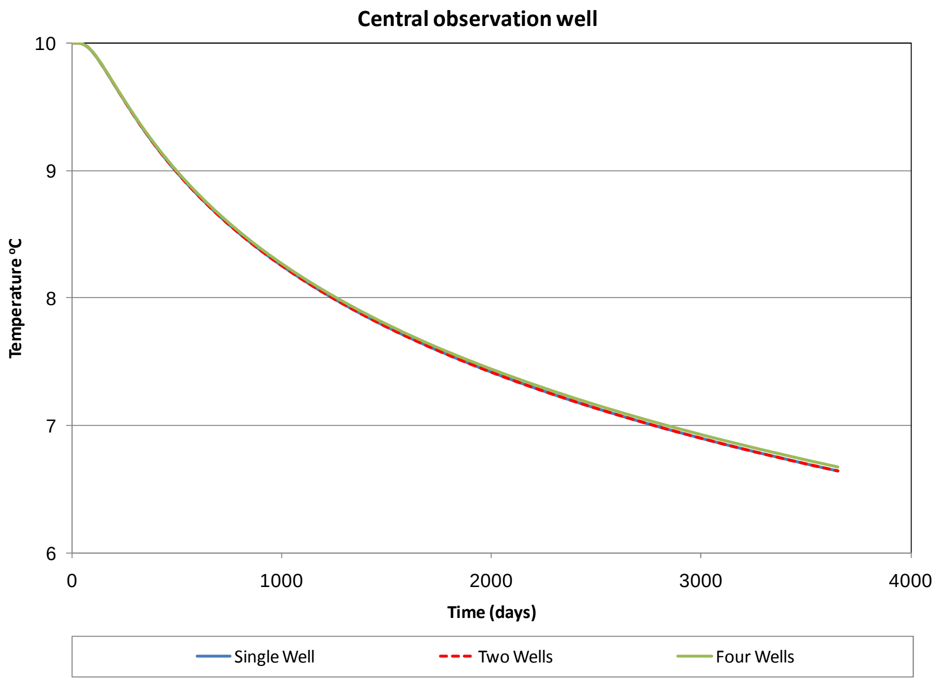

Figure 11 Variation of temperature over time at an observation well between 4 GSHP wells.

At a site located in the centre of the square of four wells, the drawdown remains more or less constant regardless of whether one, two or 4 wells are pumping (because it is the same total amount of heat being extracted), so for modelling purposes, a single-well feature could be used to model schemes with more than one well in a similar hydrogeological setting.

5 Conclusions and recommendations

1. Using numerical modelling can give a good insight into how closed-loop GSHPs affect the temperature in the ground close to the scheme. This is useful as there are very few (if any) monitoring data in the vicinity of such schemes
2. The sensitivity analysis carried out in this work has shown that the impact of a scheme on ground temperature is dependent on many variables – particularly on aquifer thickness and porosity. The modelled scenarios are, by their nature, idealised and can only give an indication of what might happen in the real world. To ensure that schemes are correctly designed, models must use site-specific parameters to get appropriate results for the selected site.
3. The modelling shows that the 'rule-of-thumb' separation distance for the installation of boreholes (5-10 m) is appropriate. However, for a small site this is a large range and can have a significant effect on the number of boreholes that can be installed in a given area. Modelling studies could be used to refine this range for specific ground conditions.
4. Large scale impacts can be modelled using annual loads
5. Further modelling work should include:
    - Consideration of the impact of solar radiation and the geothermal gradient on scheme effectiveness
    - Simulate the effect of a higher hydraulic gradient on the time variant behaviour of a scheme
    - Testing with some real data

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