Observations from shallow geothermal modelling case studies in Canada and the UK

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C. Abesser[1], R. Schincariol[2], J. Raymond[3], A. Garcia-Gil [4], J. Busby[1], R. Drysdale[2], A. Piatek[2], N. Giordano[3], N. Jaziri[3], J. Molson[5]

[1] British Geological Survey, UK; [2] Department of Earth Sciences, University of Western Ontario, Canada; [3] Institut national de la recherche scientifique, Québec, Canada; [4] Área de Hidrogeología Aplicada, Instituto Geológico y Minero de España, España, [5] Département de géologie et de génie géologique, Université Laval, Canada.

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1. INTRODUCTION

Ground source heat pump (GSHP) systems benefit from the thermal inertia of the subsurface, i.e. a constant ground temperature all year long, which permits its use of these systems for both heating and/or cooling. This fragile equilibrium between the heat pump system's thermal loads and the rate of thermal renewal in the subsurface needs to be maintained over the life of the system to ensure sufficient energy savings. With increasing deployment of these systems in the subsurface of urban areas, there is growing potential (and risk) for these systems to considerably impact the subsurface thermal regimes and also to interact with other heat-sensitive subsurface infrastructures, such as tunnels, building foundations or with other shallow energy abstraction / storage systems. This study details three modelling-based case studies that investigate the changes in the performance of typical Ground Coupled Heat Pump (GCHP) systems (different designs and operational pattern) in response to perturbations in the hydrogeological and/or thermal regimes. The specific objectives vary for the different case studies, but the overall aim of this investigation is to: (1) ***compare GCHP response to changing state or process variables within different hydrogeological / thermal systems*** and (2) ***assess the impact of interferences with other subsurface uses on the GCHPs operational efficiency.***

2. METHODOLOGY

Modelling within all three case studies is performed using FEFLOW® which offers different approaches for simulating heat transport around BHEs (Diersch et al. 2010):

(1) via a **Heat Nodal Sink/Source Boundary Condition** within a fully discretized 2D or 3D model. This approach simulates BHE thermal exchange with the surrounding soil/rock, while thermal transfers within the BHE configuration are not explicitly considered. **[Used in modelling study II]**

(2) via **built-in modules**, based on numerical (Al-Khoury and Bonnier, 2006) or analytical (Eskilson and Claesson, 1988) methods, where the BHE is represented by a simplified 1-dimensional (1D) element, inserted at the centre node of the BHE and coupled with the rest of the model domain. FEFLOW® solves the governing flow and heat transport equations for the area surrounding the BHE; a BHE solution is coupled with the rest of the model domain through the temperatures at borehole nodes. **[Used in modelling studies I and III]**

3. CASE STUDIES

Modelling Study I: University of Western Ontario campus, Canada

Objectives:

(1) To assess how a functioning GCHP system could be expanded

(2) To investigate effects of installing upstream system on the efficiency of the existing system

(3) To assess importance of fully accounting for near surface thermal disturbances in the modelling.

Approach: 3-D model (Fig. 1)

Two active vertical BHEs (90 m) and two horizontal ground exchangers (= 4 discrete linear elements) (Fig. 1)

Thermal loads (nearly balanced): 6 months (May to October) cooling only, 2 month (April and November) alternate heating and cooling, 4 month (December to March) heating only.

Simulation period: 20 years

Model calibration: using average BHE inlet temperatures + thermistor data from 3 monitoring boreholes

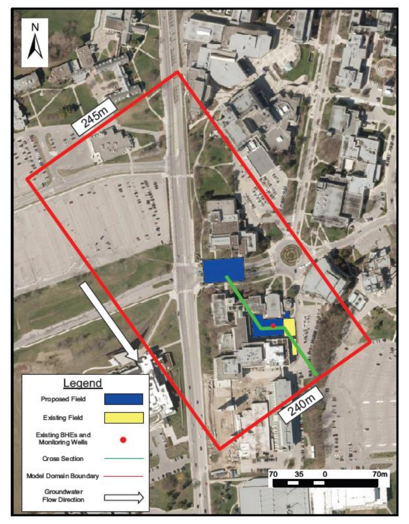

Figure 1: Site conditions showing locations of BHEs, infrastructure and ground conditions, and model lateral boundaries

Scenarios: (1) expansion of BHE field with 10 m spacing (18 BHEs) and 5 m spacing (69 BHEs); (2) installation of upstream 18 BHE system; (3) model sensitivity to surface thermal disturbances

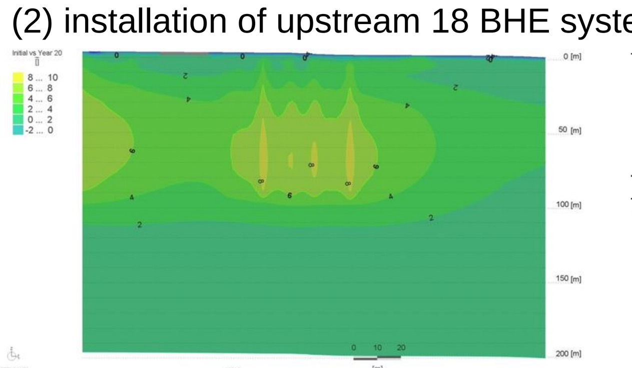

Figure 2 : Difference plot for 10m spaced BHE, with upgradient 10m spaced BHE field, comparing initial conditions to 20 years of operation. Thermal plume from upgradient system is seen entering plot from the left.

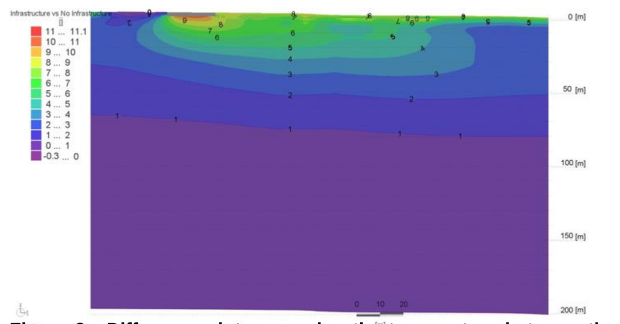

Figure 3 : Difference plot comparing the temperature between the infrastructure and no infrastructure models prior to BHE activation.

	10 m	10 m No Infrastructure	10 m No Infrastructure or unsaturated zone	10 m No Infrastructure, unsaturated zone, or groundwater flow	10 m with upgradient 18-BHE field	5 m
Annual Average (MWh)	400	408	412	337	398	1471

Table 1. Comparison of infrastructure, unsaturated zone, groundwater flow, upgradient field on energy exchange for 10m spaced BHE field, and energy exchange for 5m spaced BHE field.

Results

- Current GCHP system is expandable with little loss in efficiency per borehole
- Equivalent GCHP system operating 100 m upgradient has minimal impact on the existing field (Fig. 2, Tbl. 1)
- It is important to apply the correct initial conditions by assessing the appropriate level of model spin-up
- Accounting for infrastructure and unsaturated zone effects on thermal transport influenced BHE energy exchange by 2% and 3% (Fig. 3, Tbl. 1)
- Removing groundwater flow reduced BHE energy exchange by 16% (Tbl. 1)

Modelling Study II: London Road, Reading, UK

Objectives:

(1) To assess interactions between systems at high-density deployment

(2) To investigate the impact of hydrogeological conditions and heating loads on system performance

Approach: 2-D model (Fig 4)

Fully-saturated Chalk aquifer with a saturated thickness of 100 m and regional groundwater flow (hydraulic gradient 0.005 m m^{-1})) (Fig 4b)

Heat extraction at 58 nodes (nodal sink/source BC) (Fig 4c), representing vertical BHE systems (100 m) installed within two blocks of semi-detached houses at distances between 5 m and 18 m and 65 m between the blocks (unbalanced loads, heating only)

Simulation period: 25 years

Model calibration: none

Scenarios: (1) different thermal load scenarios corresponding to total annual heating loads of 3.3 MWh, 6.2 MWh and 10.1 MWh per dwelling; (2) model sensitivity to various operational/ hydrogeological parameters

Scenarios		Average consumption (MJ/year) - all systems	Change relative to reference case
Reference case	*HD =median; Hydraulic gradient = 0.005 m m^{-1}; GW temp = 12 °C*	*396*	-
Heat extraction	low HD	200	49%
	high HD	680	-72%
Thermal inteference between systems within field	difference between most and least efficient scheme in field	0.32	-5%
Thermal interference with external system	2 °C increase in gw tempature	369	7%
	1 °C reduction in gw tempature	411	-4%
	2 °C reduction in gw tempature	426	-8%
Hydraulic gradient	0.025 m m^{-1}	417	-5%
	0.001 m m^{-1}	447	-13%
	0 m m^{-1}	533*	-35%

*final year of operation

Table 2: Energy consumption under different operational and interference scenarios

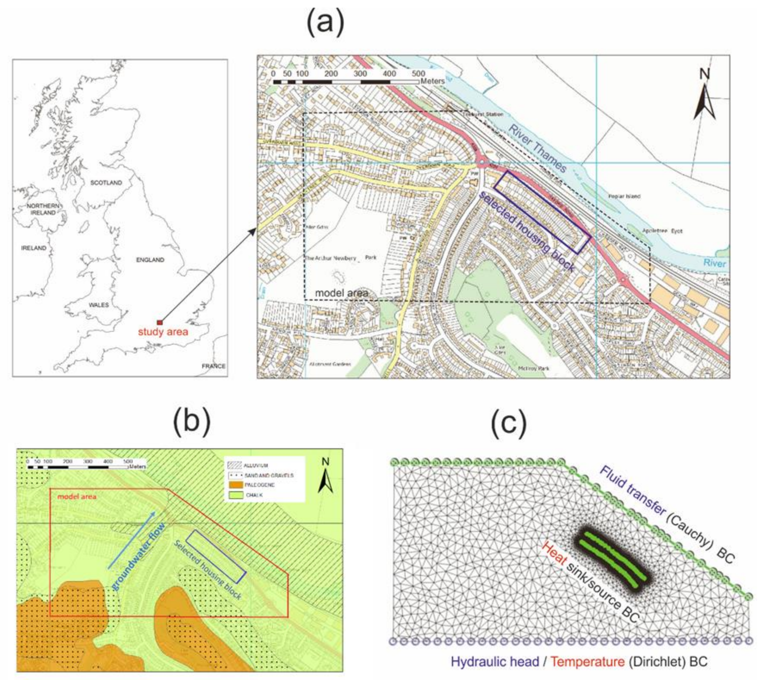

Figure 4 : Location (a), bedrock (Chalk-green) /superficial (clay & sand - brown) geology (b) and finite element model mesh / boundary conditions (c) of the study area (Contains Digital geological data, British Geological Survey ©UKRI. Contains Ordnance Data © Crown Copyright and database rights [2017]. Ordnance Survey Licence no. 100021290)

Results

- System performance is mostly a function of heating loads to ground and groundwater flow/ hydraulic gradient (Tbl. 2)
- Thermal interference between neighbouring systems is unavoidable in high density settings, but efficiency reductions are small for intermediate HD (Tbl. 2)
- Thermal influence of upstream schemes has potentially larger impact on system efficiency than near-field interferences (Tbl. 2)
- Risk of far-field interactions declines with reducing groundwater flow / thermal dispersion
- Even small groundwater flows improve overall system performance, highlighting importance of advection in harmonising unbalanced loads

Modelling Study III: Carignan-Salières elementary school, Montréal, Canada

Objectives:

(1) To predict the long-term performance of BHE field affected by variable groundwater flow

(2) To anticipate potential operational interference with dewatering of a nearby quarry.

Approach: 3-D model (Fig 5)

Direction of groundwater flow is locally oriented toward the active quarry (at distance of <1 km) due to dewatering

31 BHEs (152 m) connected to 50 heat pumps

Heating and cooling annual energy consumption of 290 MWh; peak heating loads: 494 kW (January); peak cooling loads: 253 kW (July) (unbalanced loads)

Simulation period: 20 years

Model calibration: using large-scale heat injection test (305 kW total)

Scenarios: (1) low groundwater flows (hydraulic gradient: 0.0006 m m^{-1}) and (2) high groundwater flows (hydraulic gradient: 0.008 m m^{-1}) (dewatering);

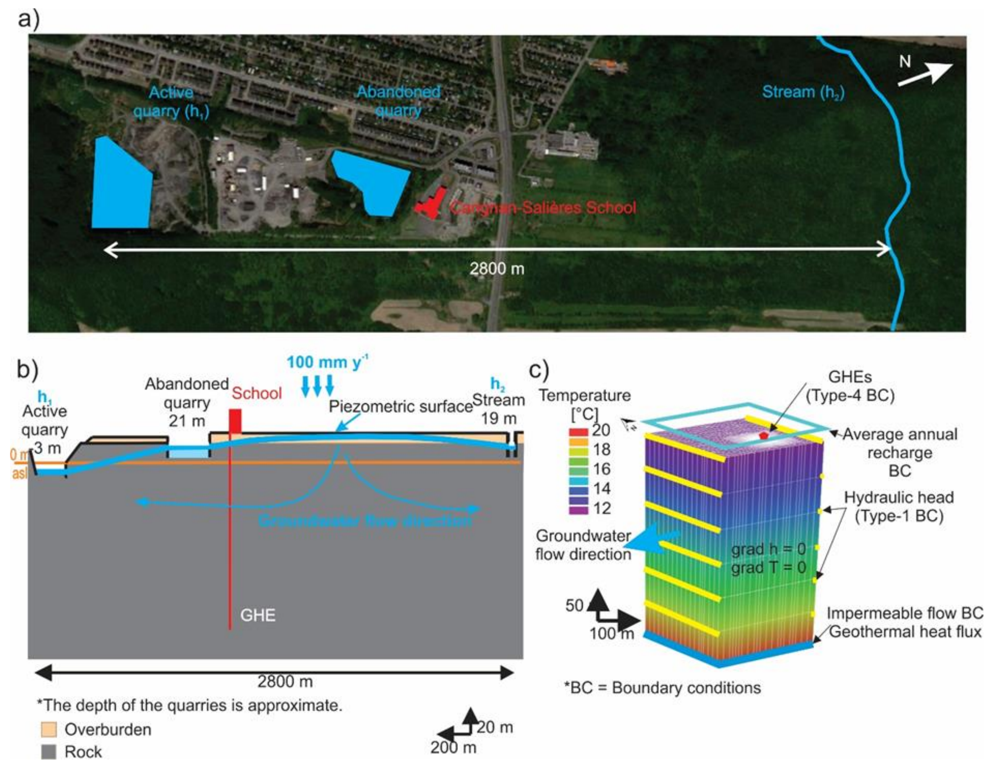

Figure 5: (a) location of the study site with hydraulic boundary conditions (h1 and h2); (b) conceptual geological model; (c) 3D numerical model showing the boundary conditions and initial temperature for each layer (Redrawn from Jaziri et al., 2020).

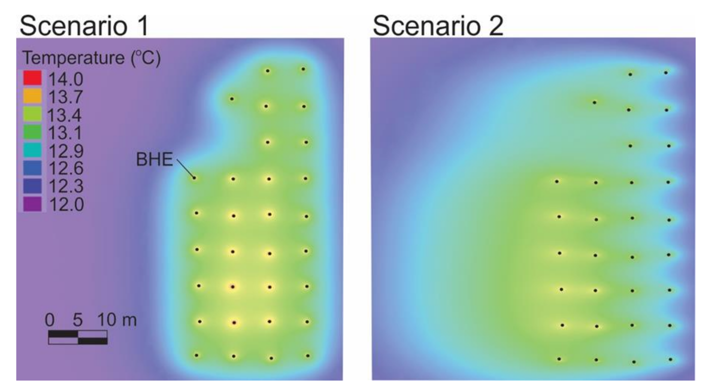

Figure 6: Plan view of one-year underground thermal perturbation at the peak of the cooling season (July) for simulation cases with a low (Scenario 1) and high hydraulic gradient expected locally (Scenario 2).

Results

- Performance of a GCHP system is clearly affected by dewatering activities in a nearby active quarry (< 1 km from the BHE) (Fig. 6)
- Heat exchange capacity of GCHP system enhanced by groundwater advection when the specific Darcy velocity changes from 6×10^{-8} m s^{-1} (no dewatering) to 8×10^{-7} m s^{-1} (high dewatering)
- Even low groundwater flow conditions are beneficial for avoiding progressive cooling of the ground around the system due to unbalanced thermal loads
- Dispersion of hot and cold front around the BHEs due to heat transfer enhanced by advection improves operational temperatures for unbalanced systems

4. Summary of key findings & recommendations

►Three modelling case studies have shown that GCHP ***system efficiency can be considerably impacted by changes in the thermal and hydrogeological regimes***. ► While the risk of thermal interference is widely recognised and modelled, interferences caused by groundwater abstraction or injection on GCHP systems is rarely considered. ► ***Changes in hydrogeological regime*** were confirmed as ***one of the key controls on GCHP performance*** in all three studies, and especially for study III where GCHP system is interacting with a dewatered quarry showing efficiency improvements even at small groundwater flow rates. ► This highlights **the *need for subsurface activities that can change subsurface groundwater flows to be considered*** in the design and operation of BHEs as these activities have potential to interfere with / impact on nearby GCHP schemes.

► The studies have further shown that thermal interference is unavoidable where individual systems are installed in close proximity, and that ***far-field interferences from operations at distances of 100-1000m can have equal or higher impacts*** on system efficiency than systems interacting within the BHE field. ► This supports the argument of *needing some regulation that requires registration of such GCHP systems* with records of locations and approximate heat pump capacity – even though these systems do not abstract or inject groundwater. ► Additional regulation can be put in place to ensure the ***subsurface thermal equilibrium is maintained*** around GCHP systems, possibly using a threshold temperature yet to be defined. ► ***Regulations*** like this currently ***do not exist in the UK or Canada*** and there is ***potential for interference problems*** to arise as numbers of installations rapidly increase. ► As part of such regulations, a critical evaluation of system efficiencies and CO_2 saving must be undertaken, and this must include a ***requirement for better monitoring these systems*** to provide data set that enable a better understanding of the ground temperature fields around such installations and that support the quantification of interference risks.

References: **Al-Khoury, R. and P. G. Bonnier (2006).** International Journal for Numerical Methods in Engineering 67(5): 725-745.; **Diersch, H. J. G., et al. (2010).** WASY Software FEFLOW White Paper 5: 5-96.; **Eskilson, P. and J. Claesson (1988).** Numerical Heat Transfer 13(2): 149-165; **Jaziri, N., et al. (2020).** Energies 13(1): 96.

Contact information

Dr Corinna Abesser | cabe@bgs.ac.uk