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7   **Influence of Geology and Hydrogeology on Heat Rejection from Residential Basements in**
8   **Urban Areas**

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40   **Abstract**

41   Urbanization and limited land availability have resulted in the increased utilization of underground structures
42   including residential basements in largely populated cities such as London, with an average addition of 200
43   basements per year in some boroughs. Residential basements kept at a comfortable temperature level throughout
44   the year significantly contribute to heat fluxes in the subsurface as well as an increase in ground temperature.
45   Understanding the ground thermal status is crucial in managing the significant geothermal energy potential in
46   urban areas as well as the sustainable development of the urban underground, and in maintaining the energy
47   efficiency of underground structures. In this proof-of-concept study, a 3D finite element approach accounting for
48   coupled heat transfer and fluid flow in the ground was used to investigate the influence of ground conditions on
49   the heat rejection rate from basements. A detailed analysis was made of ground, above ground and underground
50   built environment characteristics. This study demonstrates that the amount of heat from basements rejected to the
51   ground constitutes a significant percentage of the total heat loss from buildings, particularly in the presence of
52   groundwater flow. The extent of thermal disturbance in the ground varies depending on the ground characteristics.
53   The volume of ground thermal disturbance inversely correlates with the groundwater flow rate in the ground
54   mainly consisting of granular (highly permeable) material. However, a direct correlation exists when the thickness
55   of the granular layer decreases. A larger horizontal to vertical ratio of ground thermal disturbance is observed
56   when the thickness of the permeable layer increases.

57   **List of Notations**

A_s	annual air swing [°C]
$C_{p,f}$	groundwater specific heat capacity [J/kgK]
$C_{p,m}$	solid material specific heat capacity [J/kgK]
$\mathbf{g}$	gravitational acceleration vector [m/s^2]
K	ground permeability [m^2]
k_h	ground hydraulic conductivity [m/s]
k_v	vegetation coefficient [-]
n	porosity [-]
p_f	pore pressure [Pa]
t	time of the year [day]
t_0	coldest temperature day from January 1st [day]
$T_{ground,\ mean}$	ground annual average temperature [°C]
T_m	temperature field in the ground [°C]
$\mathbf{v}_f$	groundwater velocity [m/s]
z	depth in the ground [m]
α	ground thermal diffusivity [m^2/s]
λ_{eff}	effective thermal conductivity of porous ground [W/mK]
λ_f	groundwater thermal conductivity [W/mK]
λ_m	solid material thermal conductivity [W/mK]
μ_f	groundwater dynamic viscosity [Pa.s]
ρ_f	groundwater density [kg/m^3]
ρ_m	solid material density [kg/m^3]

58   **Keywords**

59   geothermal energy, basements, groundwater, geology, finite element modelling, urban subsurface.

1. Introduction

Current rates of urbanization predict that 70% of the world's population will live in cities by 2050 (Un-Habitat, 2012). In addition to the above-ground landscape, underground built environments are an important feature of urbanization. In densely populated cities, where land is precious and planning laws constrain residential extensions above ground, underground spaces are attractive for different purposes, most commonly for transport and residential purposes. A review of recent planning applications for residential basements in London shows that basements which were used as cellars, storerooms and/or kitchens, are now mainly retrofitted to self-confined living flats or as an extension to the rest of the house providing additional living/leisure spaces[1][2][3][4]. These residential basements are likely to be kept at a comfortable temperature (18°C)[5] throughout the year. Given London's climate, where the annual average ground temperature is relatively low (12°C-14°C, (Price et al., 2018)) it is likely that residential basements continuously reject heat to the ground. A large increase in the number of heated basements in an urban area can thus result in a rise in temperature in the surrounding ground in the long term, especially in the presence of groundwater flow as it dissipates the heat away from the basements in the direction of groundwater flow affecting a greater volume in the ground. The heat flux from a large number of basements into the ground accelerates the creation of an Urban Underground Heat Island (UUHI), where the ground is significantly warmer than its surroundings. The elevated ground temperature can be economically and environmentally advantageous in terms of geothermal energy exploitation. It is shown that the geothermal potential of urban areas is on average about 50% higher than in rural areas and can exceed the annual residential thermal demand in many urban areas (Zhang et al., 2014). Therefore, understanding the ground thermal disturbance in the urban underground is crucial to facilitate and manage geothermal energy exploitation in a sustainable manner (Arola and Korkka-Niemi, 2014, Zhu et al., 2010, Benz et al., 2015a, Menberg et al., 2013, Zhang et al., 2014, Herbert et al., 2013, Barla et al., 2018).

UUHI and its impact on underground climate, in particular, groundwater flow network and temperature have been studied in varies cities (Attard et al., 2016a, Epting and Huggenberger, 2013, Menberg et al., 2013, Benz et al., 2015b, Attard et al., 2016b, Taniguchi et al., 2009, Ferguson and Woodbury, 2007, Ferguson and Woodbury, 2004, Epting et al., 2017, Epting et al., 2013). The heat flux into the subsurface as the heat input into shallow urban aquifers is caused by various anthropogenic heat sources. This includes increased ground surface temperature, solar radiation, buildings and basements, road tunnels, sewage networks, subway systems, reinjections of thermal wastewater and other geothermal energy systems such as ground source heat pumps (GSHPs). Buildings and basements are reported to have a significant impact on subsurface temperature with the maximum heat flux of between 10 W/m^2 and 16 W/m^2 (Menberg et al., 2013, Epting and Huggenberger, 2013, Mueller et al., 2018).

Despite detailed studies on underground structures and heat rejection to the subsurface in various cities (Rivera et al., 2017, Ferguson and Woodbury, 2004, Ferguson and Woodbury, 2007), the focus of most past research has been on identifying anthropogenic heat sources and quantifying the heat flux to the subsurface, as well as the consequent subsurface temperature increase via analytical and numerical approaches. Underground structures are significant contributors to subsurface temperature increase, and heat loss from these structures to the ground largely varies in different studies. However, to what extent ground conditions influence heat flux from underground structures to the subsurface has been mostly overlooked. This is due to the lack of detailed knowledge of the subsurface (e.g., limited ground temperature measurements, spatial heterogeneity of thermal conditions of the ground, the scale and complexity of the problem, etc.) (Vázquez Suñé et al., 2016). The lack of reliable knowledge about urban underground has led to energy inefficiency in a number of structures. The high

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[1] Arup 2008. Royal Borough of Kensington and Chelsea Town Planning Policy on Subterranean Development: Phase1-Scoping Study. London, UK.

[2] Baxter, A. 2013. Royal Borough of Kensington and Chelsea Residential Basement Study Report. London, UK.

[3] RBKC 2014. Basements Development Data: Partial Review of the Core Strategy. London, UK.

[4] RBKC 2009. Subterranean Development: Supplementary Planning Document. London, UK.

[5] Lane, M. 2011. How warm is your home. BBC Magazine. UK.

102 temperature in some underground train lines around the world and the passengers' thermal discomfort as a result
103 represents one of the many problems which could have largely been prevented with a better understanding of the
104 ground (Furfano et al., 2018, Ampofo et al., 2004, Cockram and Birnie, 1976, Barla et al., 2016). The aim of this
105 paper is to investigate the extent to which thermally disturbed ground around heated basements is influenced by
106 different geological and hydrogeological conditions. To what extent heat loss from basements and hence their
107 thermal energy demand varies in different ground conditions are also investigated. The heat rejection rate from a
108 set of heated residential basements in three districts with different geological and hydrogeological conditions was
109 numerically modelled. In this study, we selected a representative London borough – The Royal Borough of
110 Kensington and Chelsea (RBKC) – known for its high density of existing residential basements[6] (Baldwin et al.,
111 2018). The LSOA[7] sub-divisions of RBKC were examined for their ground geology, the number of residential
112 basements, and hydrogeological properties. From these sub-divisions, three representative areas were selected for
113 analysis and comparison. Each area has a similar number of basements, relatively similar surface area and similar
114 hydraulic head differences. However, each has distinct combinations of geology types (varying between sand,
115 gravel and clay), hence different hydraulic and thermal properties. The dominant building typology and the
116 number of existing basements in RBKC were obtained from a detailed geo-mapping dataset[8]. The basement type
117 and characteristics corresponding to the most dominant building type in the borough were corroborated through
118 a comprehensive and time-consuming review of basement development applications submitted to RBKC planning
119 and building control portal[9].

120 The geology and hydrogeology of the studied areas were extracted from a complex 3D geological model of RBKC
121 aggregated at relevant resolutions. In this 3D model, the 2D ground hydro-thermal properties were spatially
122 integrated into the model based on the geological classifications. Groundwater flow rate and direction play a key
123 role in the temperature distribution of the ground (Angelotti et al., 2014, Hecht-Méndez et al., 2013). Therefore,
124 representative groundwater level contours were extracted from the groundwater model developed for superficial
125 deposits in RBKC accounting for the lost rivers (i.e., Fleet and Westbourne) as well as the River Thames (British
126 Geological Survey, 2017).

2.   Above and underground characteristics of the Royal Borough of Kensington and Chelsea

2.1.1   Location and typology of basements

129 The Royal Borough of Kensington and Chelsea (RBKC) is known for large utilization of underground spaces,
130 particularly as residential basements. High land price and construction constraints on above ground extensions
131 have resulted in a significant appetite for underground expansion for residential purposes. Figure 1 shows that
132 about 4,600 basement development proposals were made in seven boroughs in London between 2008-2017
133 (derived from the information provided by each borough's planning portal). About 1,022 approved basement
134 development applications were extracted from RBKC's planning portal between these years (out of 1,300
135 basement development proposals made) demonstrating one of the highest basement development rates per
136 household in the country (see Figure 1). These applications included around 676 standard basements (single
137 storey, mostly under terraced houses), 279 large basements (double storey) and around 67 mega basements (triple
138 storey or more- up to the depth of 18m), where basement developments are spread across the whole borough
139 (Baldwin et al., 2018).

[6] D. Batty, C. Barr & P. Duncan, (2018). What lies beneath: the subterranean secrets of London's super-rich, The Guardian, UK.

[7] Lower Layer Super Output Areas (LSOAs) are a geographic hierarchy designed to improve the reporting of small area statistics in England and Wales and are generated to be as consistent in population size as possible. The Minimum population is 1000 and the mean is 1500.

[8] GeoInformation, (2017a). UK Buildings. Verisk Analytics.

[9] RBKC, (2018). Planning and Building Control Portal/Planning Search.
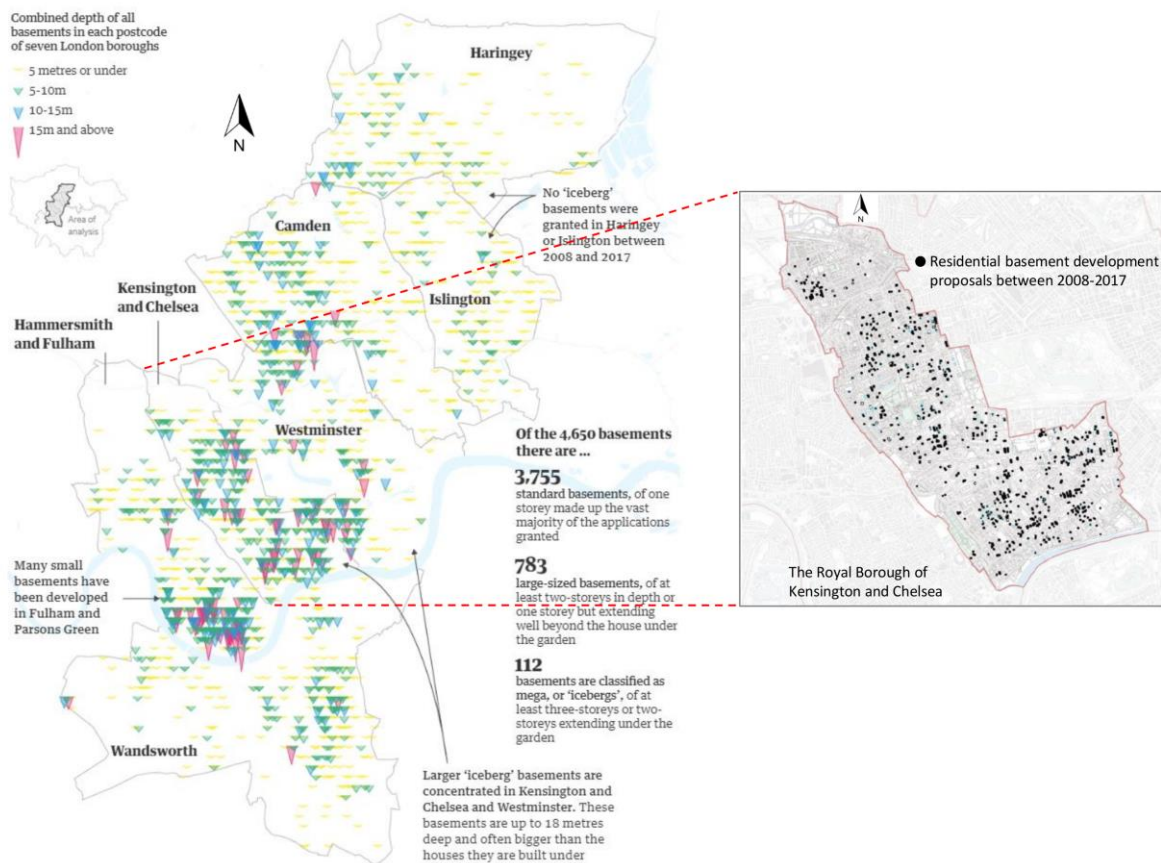
Figure 1. Basement proposals made in seven boroughs in London between 2008-2017 (Baldwin et al., 2018).

Reviewing the geo-mapping dataset confirmed the existence of 13,000 known residential basements in RBKC. Building typology, age, material and building height were some of the parameters analysed in this study to gain further insight into the characteristics of residential basements. About 22,000 residential buildings were identified in RBKC, mainly varying between detached and semi-detached houses, flats and terrace houses (see Figure 2).

Terrace houses are the most dominant building typology in this borough (i.e., 80%) owning 75% (10,000 out of 13,000) of the residential basements in RBKC. Knowing the most dominant building typology (terrace houses) in the borough and their corresponding building age, the characteristics of their basements were investigated by reviewing the basement development applications submitted to the planning and building control portal.

A comprehensive review of RBKC's planning and building control portal revealed that for most of the terrace houses, basements are single level and their floor area is similar to the building footprint. Even though RBKC possesses a large number of mega basements (around 200 according to (Baldwin et al., 2018)), these extra-deep basements (~18 m depth) were not the focus of this study as their overall impact on ground temperature on a district scale is negligible (in comparison to 13,000 standard, single-level basements in the borough). In this study, the floor area per standard basement was assumed to be about 50 m^2, reflecting the basement of a typical two-bedroom terrace house and an average ceiling height of 3 m. A wall and slab thickness of 0.4 m, made of concrete, could be considered standard for these basements. The basements were assumed to be kept at a comfortable temperature level of 18°C throughout the year.

Building with basement
Building without basement

0   0.5   1.0   1.5 km

159

160   Figure 2. Residential building distributions in RBKC.

161   A 3D digital geological framework model of London, UK was developed by the British Geological Survey (BGS)
162   (Burke et al., 2014, Mathers et al., 2014). The geological model was constructed at a scale equivalent to a 1:50 000
163   scale of 2D geological maps and comprises bedrock, superficial (Quaternary) deposits and artificial ground. It
164   was constructed using GSI3D modelling software using the modelling procedures described by Kessler et al.
165   (2009). Existing geological data derived from ground investigation boreholes were digitised using the method
166   described by Burke et al. (2014).

167   The model developed by BGS for the area of RBKC was based on the 3D geolanduse layer that was a modified
168   version of the 3D shrink-Swell clays dataset (Jones and Hulbert, 2017), which spans the surface to the top of the
169   Chalk Group (shown in Figure 3-a). However, the geological layers extending from the surface to the top of the
170   Lambeth Group was of interest to this work (60-100 m below the ground surface). The 2D hydro-thermal datasets
171   relevant to the geological classifications of the area were spatially integrated into the 3D model. Each grid cell of
172   the model contains several characteristics of the ground such as geological units, ground elevation, groundwater
173   level, hydro-thermal properties, etc. Figure 3-b shows the geological variations within the borough at different
174   depths from the surface to 20 m depth (reaching the consistent London Clay Formation) using the 50 m x 50 m
175   grids. Within the first 5 m below the surface, the southern part of the borough mostly consists of permeable River
176   Terrace Deposits, whereas the northern part sits on impermeable London Clay Formation. However, it is observed
177   that from about 10 m below the ground surface, the London Clay Formation dominates within the entire borough.
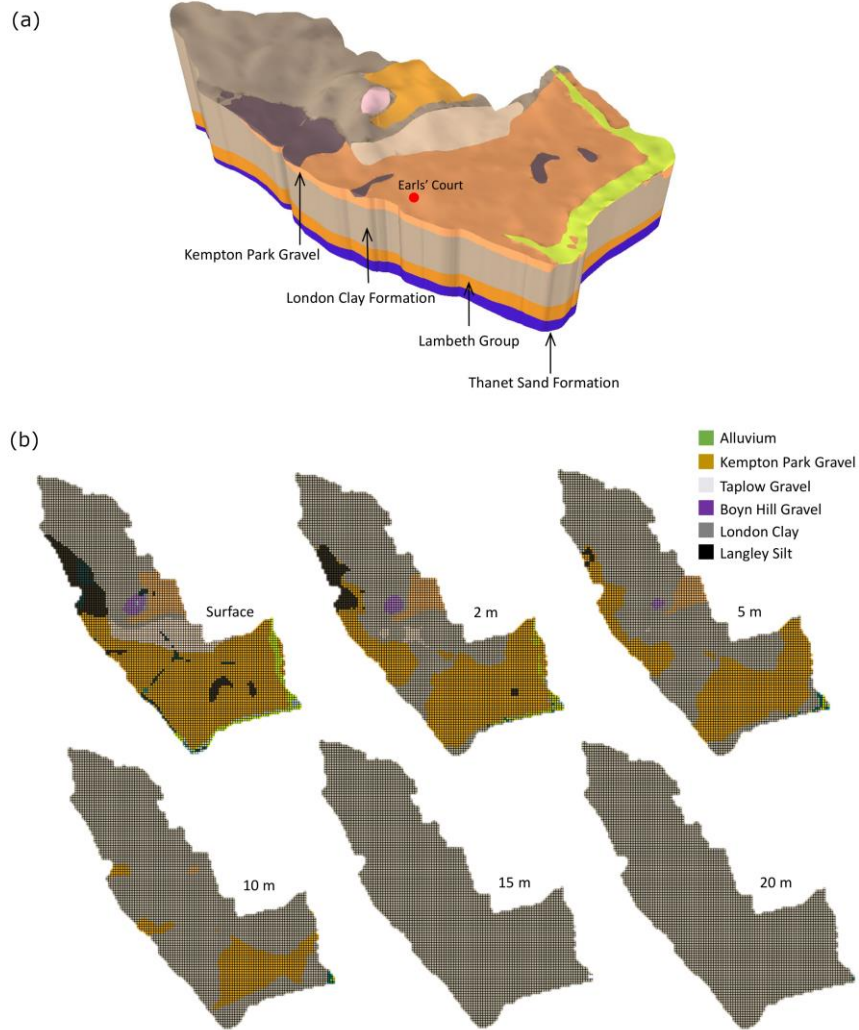
7

Figure 3. RBKC geology-50 m x 50 m grid (a): 3D geological model, (b): geological variations at different depths (not to scale).

The geology of RBKC is relatively consistent (the most significant variation occurs between the south and north part of the borough), therefore, LSOA subdivisions were used as cell grids in this study merging the attributes of 50 m x 50 m grids within each LSOA. By analysing the geological variations of each LSOA at different depths, one dominant geology was selected for each LSOA at a certain depth. Figure 4 shows a summary of the most dominant geological units for different areas of the borough varying by depth at the LSOA level, which shows a similar distribution within the borough as in the 50 m x 50 m grid model (Figure 3).
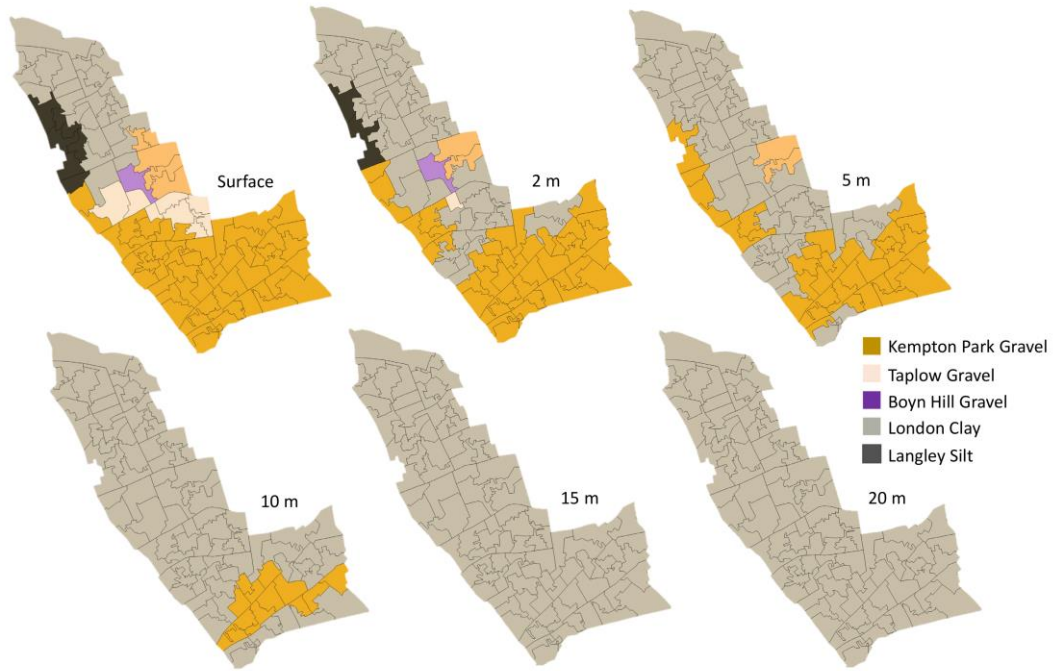
Figure 4. RBKC geological classification at LSOA level (not to scale).

Different archetypes for the entire Kensington and Chelsea is defined based on the variations in ground geological conditions. According to Figure 4, four archetypes with various geological classifications by depth have been identified in the borough as follow:

- 10 m of River Terrace Deposits underlain by London Clay Formation,
- 5 m of River Terrace Deposits underlain by London Clay Formation,
- 2 m of River Terrace Deposits underlain by London Clay Formation,
- London Clay Formation outcropping at the surface.

The River Terrace Deposits are deposits of sands and gravels, which can be up to 10m thick. They are named differently and have slightly varying characteristics but can all generally be classified as sands and gravels (e.g., Kempton Park Gravel).

For the purpose of this study and according to the identified geological archetypes, three areas each comprising LSOAs with similar geology (as shown in Figure 5) were selected as the geological representatives of the borough. Even though four geological archetypes were initially identified, the area with 2 m of River Terrace Deposits underlain by London Clay Formation was not studied herein as it was expected to show similar results to the area where the London Clay Formation outcrops. The three selected areas in RBKC possess similar ground volume and accommodate almost the same number of residential basements as shown in Figure 5. This was essential to achieve a consistent $V_{basement}/V_{ground}$ (m^3) ratio in all areas and therefore a meaningful comparison within the areas.

The three selected areas of RBKC were studied independently by developing a three-dimensional numerical model of each area with simplified underground heat sources distribution (i.e., basements). The thermal interaction between neighbouring areas was neglected in order to meet the objective of this paper, which was to examine the extent of ground temperature disturbance surrounding heated basements as well as the amount of heat loss variations from the basements to the ground in different ground conditions.
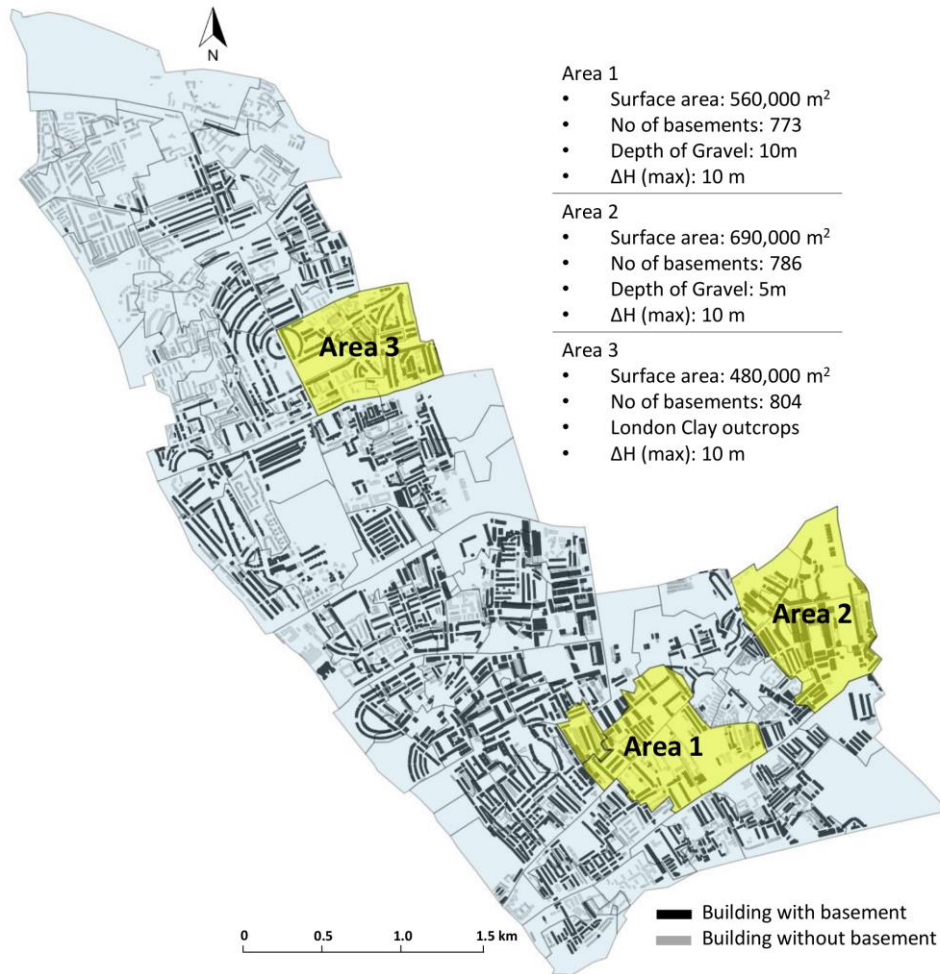
9

Figure 5. Three different areas of Kensington and Chelsea selected for modelling.

2.1.2 Hydrogeology

The groundwater regime across the borough is generally characterised by two distinct aquifers which are separated by the relatively impermeable London Clay:

- the Upper Aquifer is perched water sitting in gravelly soils that overlie the London Clay;
- the Lower Aquifer within the sandy soils and chalk that lie deep below the London Clay.

For basements in the borough, the Upper Aquifer is the relevant aquifer as the extent of ground thermal disturbance due to its exposure to underground heat sources does not reach the deep aquifer. This is the water table that would be encountered when digging a basement.

The groundwater levels within the shallow aquifer can be extracted from the 3D geological model of RBKC. Considering the hydraulic conductivity of the superficial deposit and taking into account the lost rivers of Fleet and Westbourne and the River Thames (with an average recharge rate of 0.12 m/day- derived form BGS' Thames Basin recharge model), the resulting groundwater level contours are shown in Figure 6 (McKenzie, 2015).

According to the groundwater contours, for the southern part of the borough (permeable superficial deposits) containing studied areas 1 and 2, a slight groundwater flow (around 0.25 m/day with a hydraulic gradient of 0.005) can be identified. Even though the ground is relatively flat in the southern part of the borough, the water on this upper aquifer tends to flow slowly on the surface of the London Clay due to the high permeability of River Terrace Deposits. The northern part of the borough, containing area 3, mainly consists of impermeable London Clay Formation with negligible groundwater flow in that area.

231   This paper studied the effect of groundwater flow on ground temperature variations and the amount of heat loss
232   from basements to the ground for different thicknesses of the permeable. Groundwater flow rate is a highly
233   uncertain parameter, which plays a key role in ground temperature distribution. Therefore, to highlight the
234   importance of groundwater flow rate on the thermal interaction between basements and the ground, several
235   groundwater flow rate scenarios varying between 0 m/day (no flow), 0.5 m/day and 1 m/day were considered in
236   this study by assigning various hydraulic gradient to the models. The extent to which thermally disturbed ground
237   around a heated basement and the amount of heat loss from basements to the ground are influenced by different
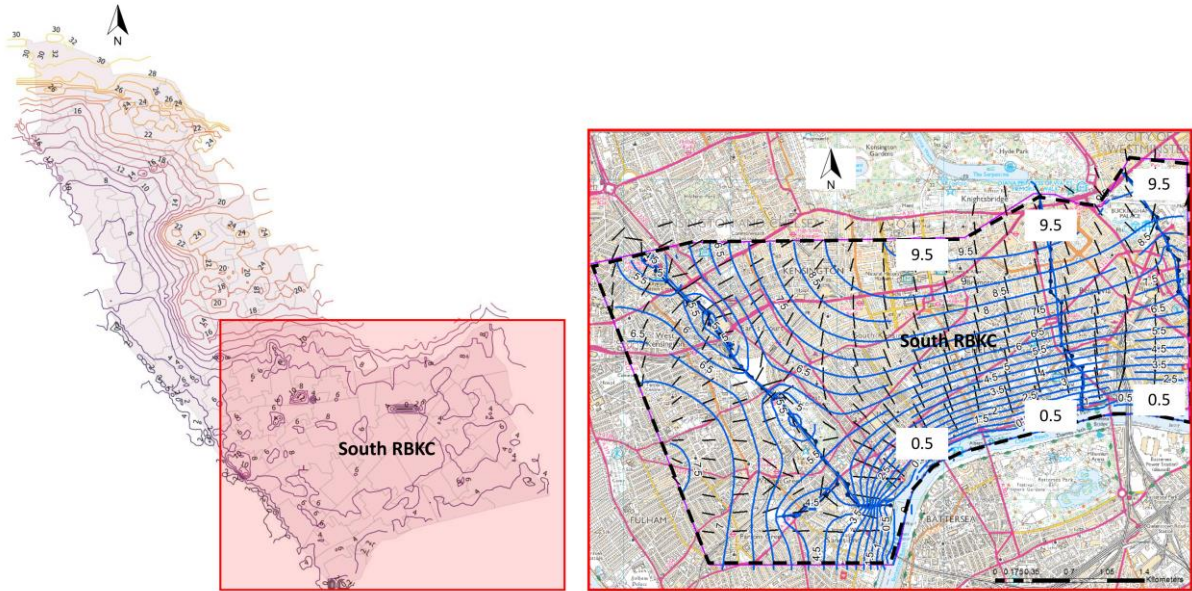238   hydrogeological conditions was numerically investigated in detail.

239

240   Figure 6. Groundwater level contours for the southern part of RBKC (British Geological Survey, 2017).

241   **2.1.3   Ground hydro-thermal properties**

242   Ground thermal properties are one of the most critical parameters for an accurate estimation of ground thermal
243   disturbance due to their exposure to heat sources. Ground thermal conductivity and diffusivity used in this study
244   were obtained from the 3D geological model for RBKC, where the general 2D thermal data classified for different
245   geological units (mostly gathered from Thermal Response Tasting results around the UK) are spatially integrated
246   into the model (Price et al., 2018, Busby et al., 2009, British Geological Survey, 2017). The estimated values of
247   thermal conductivity and diffusivity for Superficial Deposits and London Clay Formation are shown in Table 1.

248   In the presence of groundwater flow, ground hydraulic conductivity plays a significant role in the extent of heat
249   propagation in the ground exposed to different sources of heat. In this study, the hydraulic conductivity of the
250   superficial deposit was taken from a case study on the Thames Basin, UK. A conceptual model of superficial
251   deposits across the Thames Basin was used to define different lithostratigraphic classes of superficial deposits
252   including River Terrace Deposits. Hydraulic conductivity of the superficial deposits was estimated from grain-
253   size distribution data, originally collected for mineral resource assessments, using the Kozeny–Carman method
254   (Burke et al., 2014). The results are shown in Table 1. A relatively low hydraulic conductivity (1×10^{-9} m/s) was
255   assumed for the impermeable London Clay.

256   Table 1. Estimated thermal/hydraulic conductivity and thermal diffusivity for some of the geological units in RBKC.

Geology		λ [W/(mK)]	α[m²/s]	k_h[m/s]
Kempton Park Gravel	0-2m depth	0.77	4.5×10^{-7}	4.2×10^{-5}
Kempton Park Gravel	2-10m depth	2.5	9.1×10^{-7}	5.6×10^{-4}
London Clay Formation	Various depths	1.79	9.7×10^{-7}	1×10^{-9}

11

3.   Thermal modelling of ground exposed to heated basements

Using a 3D finite element approach, the three selected areas of RBKC were modelled, accounting for the heated residential basements, ground surface cover, geological variations, and groundwater regime. The finite element package COMSOL Multiphysics was used to couple and solve the equations for conductive and convective heat transfer between the basements and the porous ground. The presented model is a representative of the selected areas in the borough. Each model (three models with the geometry presented in Figure 7) represents one of the three selected areas shown in Figure 5, each with a similar number of basements, similar ground surface area and similar geological and hydrogeological conditions to the real conditions. It should be noted that the exact spatial distributions of basements in each area are simplified into a regular grid consisting of a similar number of basements (800 basements as presented in Figure 7) in the three numerical models. The impact of basements density and distribution on ground temperature elevation is not the focus of this study, hence an even distribution of basements is considered in all three models.

3.1.1   Geometry and Meshing

Figure 7 shows the finite element representation of the ground exposed to heated basements and the initial and boundary conditions. Each model accommodates about 800 basements in a volume of 1.5 km by 1.5 km by 90 m ground domain. To account for an even distribution of the basements in all models, four batches of 200 basements were considered in this study. The configuration of basement batches was selected randomly. The number of basements assumed in each model was taken from the approximate number of basements currently existing in the three areas shown in Figure 5. These, and their floor areas, were derived from an extensive geospatial database containing footprint information per building and their use, age, and building type[10].

A depth of 3 m, including 0.4 m of slab thickness, and wall thickness of 0.4 m were considered for each basement. The floor area per basement was assumed to be 50 m^2, reflecting a typical two-bedroom terrace house. The entire surface area is meshed by triangular elements consisting of 210,000 elements. To implement efficient swept mesh (prisms) in vertical direction, the model is partitioned in depth into several layers with varying thicknesses, for which the thickness increases by depth when a coarser mesh is required in the model (Figure 7). The whole model consists of 1,200,000 elements including triangular elements and triangular prisms.

Figure 7. Schematic of 3D meshing and initial and boundary conditions.

3.1.2   Governing Equations

Heat transfer between the basements and the surrounding ground was captured by coupling and solving the equations for heat transfer and fluid flow in a porous medium (ground). The governing equations, coupling techniques and initial and boundary conditions used in this study were previously validated against experimental data in a similar problem where heat transfer between the tunnel wall and the porous ground with groundwater flow was investigated. Further details on validation of the coupling techniques and governing equations can be found in Bidarmaghz (2014), Bidarmaghz and Narsilio (2018), Bidarmaghz et al. (2017), Makasis et al. (2018).

Heat conduction occurs in the ground and in the wall/floor of the basements. Unlike most of the literature considering a higher ground thermal conductivity (effective thermal conductivity) representing the effects of groundwater, the groundwater flow was numerically modelled in this study using Darcy's Law and heat convection occurring in the ground due to the presence of groundwater and its flow is modelled in details. The conductive-convective heat transfer equations can be expressed as follows (COMSOL, 2018a, Vahab et al., 2018):

$$\left(\rho C_p\right)_{eff}\frac{\partial T_m}{\partial t} + \left(\rho C_p \boldsymbol{v}_f\right)\nabla T_m + \nabla.q = 0 \tag{1}$$

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[10] GeoInformation, (2017a). UK Buildings. Verisk Analytics.

12

$$q = \lambda_{eff} \nabla T_m \qquad\qquad\qquad\qquad\qquad\qquad\qquad 2$$

$$\left(\rho C_p\right)_{eff} = (1-n)\rho_m C_{p,m} + n\rho_f C_{p,f} \qquad\qquad\qquad 3$$

$$\lambda_{eff} = (1-n)\lambda_m + n\lambda_f \qquad\qquad\qquad\qquad\qquad 4$$

296   where ρ_m represents the material density (i.e., ground, concrete, air), and $C_{p,m}$ and λ_m represent the specific heat
297   capacity and thermal conductivity of the material respectively. Above, λ_f represents the thermal conductivity of
298   the groundwater and λ_{eff} is the effective thermal conductivity of the porous ground. Note that other estimations
299   may be used for λ_{eff} in Eq. 2; here we choose Eq. 4 for this. $C_{p,f}$ is the groundwater specific heat capacity, n is the
300   porosity, and ρ_f is the groundwater density.

301   Single phase fluid flow in a porous medium (groundwater flow) is usually described by Darcy's law, which states
302   that the Darcy velocity field, $\mathbf{v_f}$, is determined by the total head gradient, the fluid dynamic viscosity, μ_f, and the
303   structure of the soil (Bear, 2012, COMSOL, 2018b, Todd, 1959):

$$\boldsymbol{v_f} = -\frac{K}{\mu_f}\left(\nabla p_f - \rho_f g \nabla Z\right) \qquad\qquad \frac{K}{\mu_f} = \frac{k_h}{\rho_f g} \qquad\qquad 5$$

304   where K is the isotropic permeability of the ground, p_f represents the pore pressure in the ground, ρ_f is the
305   groundwater density, k_h is the hydraulic conductivity of the ground, $\mathbf{g}$ is the gravitational acceleration vector, and
306   μ_f is the groundwater dynamic viscosity.

307   Inserting Darcy's Law into the continuity equations produces the generalized governing equation:

$$\frac{\partial}{\partial t}(n\rho) + \nabla.\rho\left[-\frac{K}{\mu_f}\left(\nabla p_f - \rho_f g \nabla Z\right)\right] = 0 \qquad\qquad 6$$

308   Eqs. 5 and 6 are solved for $\mathbf{v}_f$ and p_f in the ground and are coupled to Eq. 1 via $\mathbf{v}_f$.

3.1.3   Initial & Boundary Conditions

310   To solve the above system of equations, appropriate initial and boundary conditions are required as shown in
311   Figure 7 and are summarized as follows:

312   • The groundwater velocity of 0.25m/day is assigned to the model by introducing a hydraulic head gradient
313   to the ground farfield boundaries. This is taken from the available groundwater level contours reflecting
314   the average hydraulic head difference in the southern part of the borough. A hydraulic head difference
315   of about 10 m over 2 km of horizontal distance (i_h=0.005) is shown in RBKC's southern part (Figure 6).
316   In the numerical models (with a horizontal distance of 1.5 km), the hydraulic head difference is adjusted
317   to represent the same hydraulic gradient. To further study the effect of groundwater flow rate on heat
318   transfer between the basements and the ground, flow rates of 0m/day (no flow), 0.5m/day and 1m/day
319   are also considered[11] (Burke et al., 2014). The variations in groundwater flow rate is implemented by
320   changing the hydraulic gradient in the models (from no flow to i_h=0.01 (0.5 m/day) and the extreme case
321   of i_h=0.02 (1m/day).
322   • The basements' wall and floor are kept at the average indoor temperature in the UK (18°C) throughout
323   the year[12].
324   • Thermal insulation is assigned to the building footprint on the surface to represent the thermally insulated
325   building floor.

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[11] Arup 2008. Royal Borough of Kensington and Chelsea Town Planning Policy on Subterranean Development: Phase1-Scoping Study.
London, UK.
[12] How warm is your home, BBC Magazine, UK

326   •   The undisturbed ground temperature is set at 12.5°C based on the temperature monitoring experiment in
327   Earls's Court, London (Price et al., 2018).

328   •   The seasonal changes in ground temperature are modelled as a time and depth varying temperature. This
329   temperature is applied as a depth varying initial temperature to the entire model including the farfield
330   ground boundaries and as a time-varying temperature to the ground surface to account for surface
331   temperature fluctuations (Baggs, 1983, Jensen-Page et al., 2018, Bidarmaghz et al., 2016):

$$T_{ground}(z,t) = T_{ground,mean} - 1.07.k_v.A_s.\exp(-0.00031552.z.\alpha^{-0.5}).\cos\left(\left(\frac{2\pi}{365}\right).(t - t_0 + 0.018335.z.\alpha^{-0.5})\right)$$

         7

334 where $T_{ground,mean}$ is the ground annual average temperature, (12.5°C). k_v is the vegetation coefficient set at
335 0.5 accounting for 50% vegetation cover for each area. A_s, 8.3°C, is the annual air swing temperature. t is the
336 day of the year. z indicates the depth in the ground [m]. α is the ground diffusivity equal to an average value
337 of 9.65×10^{-7} m²/s, calculated based on physical and thermal properties of the soil presented in Table 2. t_0 is
338 the coldest temperature day from January 1st (British Geological Survey, 2017, Price et al., 2018).

339   •   The ground farfield boundary is set as thermal insulation instead of a time-depth varying temperature. In
340   reality, the ground at farfield is also thermally disturbed when considering basements or other heat
341   sources in adjacent areas. However, such thermal interference was not the focus of this proof-of-concept
342   study.

343 A summary of the geological, physical and hydrothermal characteristics of the ground for the three areas
344 modelled are presented in Table 2 (Busby et al., 2009, Price et al., 2018, British Geological Survey, 2017).

345   Table 2. Geological, physical and hydrothermal properties of the three areas shown in Figure 5.

	Model 1						
	Geology	*λ [W/(mK)]*	*ρ [kg/m³]*	*C_p [J/(kgK)]*	*Porosity[-]*	*k_h[m/s]*	*α[m²/s]*
0-2m	Kempton Park Gravel (unsaturated)	0.77	1,600	1,100	0.35	4.2×10^{-5}	4.5×10^{-7}
2-10m	Kempton Park Gravel (saturated)	2.5	1,900	1,440	0.35	5.6×10^{-4}	9.1×10^{-7}
10-90m	London Clay	1.7	2,000	870	0.5	1×10^{-9}	9.7×10^{-7}

	Model 2						
	Geology	*λ [W/(mK)]*	*ρ [kg/m³]*	*C_p [J/(kgK)]*	*Porosity*	*k_h[m/s]*	*α[m²/s]*
0-2m	Kempton Park Gravel (unsaturated)	0.77	1,600	1,100	0.35	4.2×10^{-5}	4.5×10^{-7}
2-5m	Kempton Park Gravel (saturated)	2.5	1,900	1,440	0.35	5.6×10^{-4}	9.1×10^{-7}
5-90m	London Clay	1.7	2,000	870	0.5	1×10^{-9}	9.7×10^{-7}

	Model 3						
	Geology	*λ[W/(mK)]*	*ρ [kg/m³]*	*C_p [J/(kgK)]*	*Porosity*	*k_h[m/s]*	*α[m²/s]*
0-90m	London Clay	1.7	2,000	870	0.5	1×10^{-9}	9.7×10^{-7}

4.   Results and Discussions

Figure 8 shows the heat loss (W) from the wall and slab of one basement (10L×5W×3D) to the ground and its comparison to the heat loss from the above-ground structure of the buildings (house of 50m² floor area and 125m² of the exposed wall (from The Building Regulations, 2016). Depending on the thickness of the permeable layer and groundwater flow rate, the heat rejection rate from the basements to the ground may be significant and comparable to the amount of heat loss from the above-ground structure of a newly built building to the air. These results are within the range of heat fluxes reported in the work of Epting et al. (2013) and Menberg et al (2013), where basements are constructed in saturated ground (~10 W/m² on average) (Epting and Huggenberger, 2013, Menberg et al., 2013).

Groundwater flow rate has less influence on the amount of heat losses from the basements to the ground, when the ground mainly consists of permeable material (model 1). However, when the thickness of the permeable layer decreases (model 2), faster groundwater flow leads to larger heat loss from basements and can become a significant percentage of the total heat loss from a building.

Underground structures constructed in impermeable soil, for example, most of the London Tube line constructed within London Clay Formation, have a consistent heat rejection rate into the ground due to minimal to negligible groundwater flow. However, heat transfer between the underground structures and the ground becomes more complex when groundwater flow is present. Heat rejection from heated basements constructed in the shallow ground with groundwater flow (permeable sand and gravel) varies significantly based on the geological distribution, and thickness of the permeable layer as shown in Figure 8. Therefore, the thermal energy demand for basements also varies and it is necessary to gain a better understanding of the ground thermal status in order to develop an efficient energy system design for underground structures.
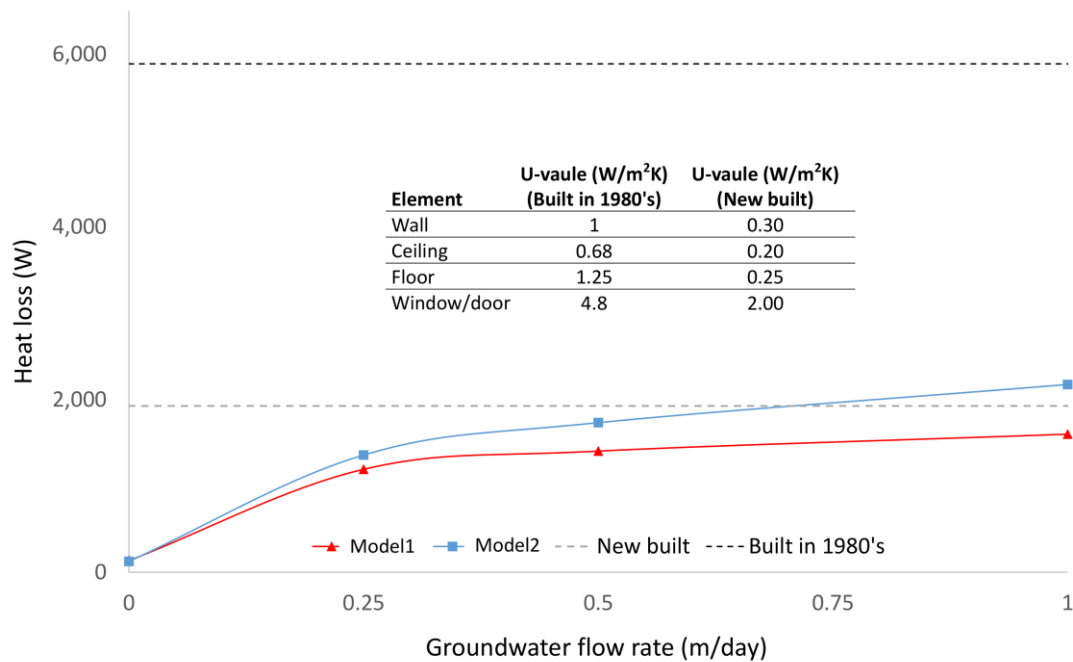

Figure 8. Heat loss from basement wall and floor (one basement - 10L×5W×3D) for models 1 and 2 and for typical double storey building (50 m² of floor area and 125 m² of the exposed wall) based on recommended U-values in 1980's and 2016[13].

Figure 9 shows the extent of the thermally affected ground with a temperature gradient of 1°C to 5.5°C with respect to the ground's annual average temperature (around 12.5°C) in vertical and horizontal directions in 25 years. For example, in model 1, the deepest point in the ground with a temperature gradient (T>12.5°C) occurs

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[13] The Building Regulations 2016. Conservation of Fuel and Power in New Dwellings. England.

373 further away from the basement footprints in the direction of the groundwater flow and at the depth of 32m (Figure
374 9-a). The high permeability of the ground in model 1 affects the concentration of the thermal disturbance around
375 the basements and leads to a faster heat dissipation to the farfield. However, in model 2 and 3, the deepest point
376 in the ground affected by the heated basements occurs at the depth of about 35m and 31m respectively (Figure
377 9-b and c). The combination of permeable layer thickness and groundwater flow rate in model 1 results in a larger
378 horizontal extent of the disturbed ground (~400m from edge of basements) in comparison to model 2 (~250m)
379 and model 3 (~10m) over 25 years, due to its significantly low permeability, hence negligible groundwater
380 movement. These results also show that the geothermal potential, its spatial concentration and extent also varies
381 in the ground with different characteristics.
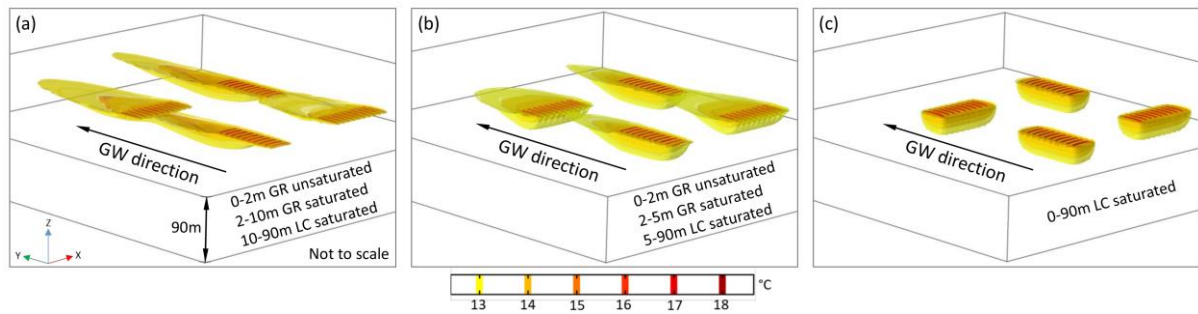
382

383 Figure 9. Thermally affected ground for 25 years with groundwater flow rate of 0.25m/day.

384 The modelled depth varying ground temperature profile - after 25 years of simulation - clearly shows the
385 differences in ground temperature distributions for different models (see Figure 10). The variations in ground
386 temperature gradient (thermal discharge rate) are related to the permeable layer thickness. The highest temperature
387 gradient (0.5°C/m) is observed for model 1 within the superficial deposit as shown in Figure 10. For model 2
388 where the permeable layer thickness is smaller, the temperature gradient is about 0.3°C/m for the first 5m
389 (permeable layer). The temperature gradient is shown to be around 0.1°C for model 3, where the model consists
390 of impermeable London Clay. It is also worth noting that depending on the thickness and thermal properties of
391 the (superficial layer) permeable layer, the temperature gradient within the London Clay varies. This is due to the
392 fact that the extent of thermal disturbance in the Clay is also dependent on the characteristics of the layer above.
393 This is captured in the differences between temperature gradients in London Clay Formation for different models.

394 The limited available ground temperature measurements in Earl's Court, London is shown in Figure 10 (triangular
395 marks (Price et al., 2018)). The Experimental ground temperature profile illustrates the general ground
396 temperature trend by depth, which shows a relatively similar trend to the modelled temperature profile of models
397 2 and 3. The geological variation of the field located in Earl's Court consists of about 4-5m of River Terrace
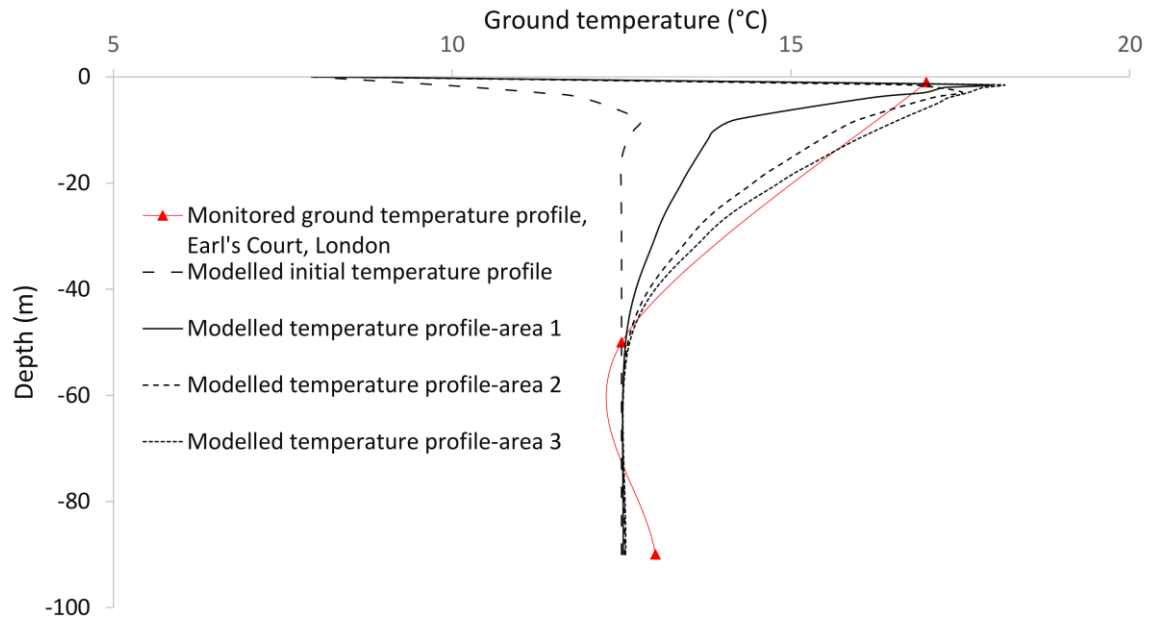398 Deposits underlain by London Clay. The exact location of the field is shown in Figure 5.

Figure 10. Measured and modelled temperature profiles.

Figure 11-a shows the volume of the ground with 1°C to 5.5°C temperature increase within 100m^2 of the basement footprint in 25 years. The volume of the thermally disturbed ground shows a non-consistent trend with an increase in groundwater flow rate. When the groundwater flow rate increases above 0.25m/day in model 1, the heat generated around the heated basements dissipates by the fast flow. In model 2, on the other hand, the volume of the disturbed ground consistently increases for faster flows as the ease of heat transport in the ground is affected by the smaller volume of granular material leading to the accumulation of heat in the ground surrounding the basements. As expected, the groundwater flow rate does not have a significant effect on model 3 due to the very low permeability of the clay material.

Figure 11-b shows the difference between model 2 and model 1 in terms of the maximum extent of the heated ground (with a temperature higher than the ground annual average temperature, 12.5°C) in the horizontal and vertical directions. In the horizontal direction, there is a significant difference with a relatively slow flow (0.25m/day) as model 1 extends 72% more in the horizontal direction than model 2. However, this difference decreases with an increase in groundwater flow rate, and at an extreme groundwater flow rate (1m/day) the difference is only about 3%. In ground with a large volume of permeable layer (e.g., model 1), any two points at certain horizontal distances from the basements show a smaller temperature gradient than in model 2 where the thickness of the granular layer decreases. This is because the heat rejected from the basements is carried further away from the basement structure, resulting in a maximum temperature gradient (18°C-12.5°C=5.5°C) occurring at a larger length of the ground at any depth. However, in the case of an extreme groundwater flow rate, this effect is minimised. Therefore, model 1 and 2 show a smaller difference in the horizontal extension of the thermally disturbed ground.

In the vertical direction, rejected heat from the basement is continuously dissipated in the direction of the groundwater flow in model 1 with largest volume of permeable material resulting in a shallower penetration depth of the heated area in the ground, which also decreases for faster groundwater flows (Figure 11-b).
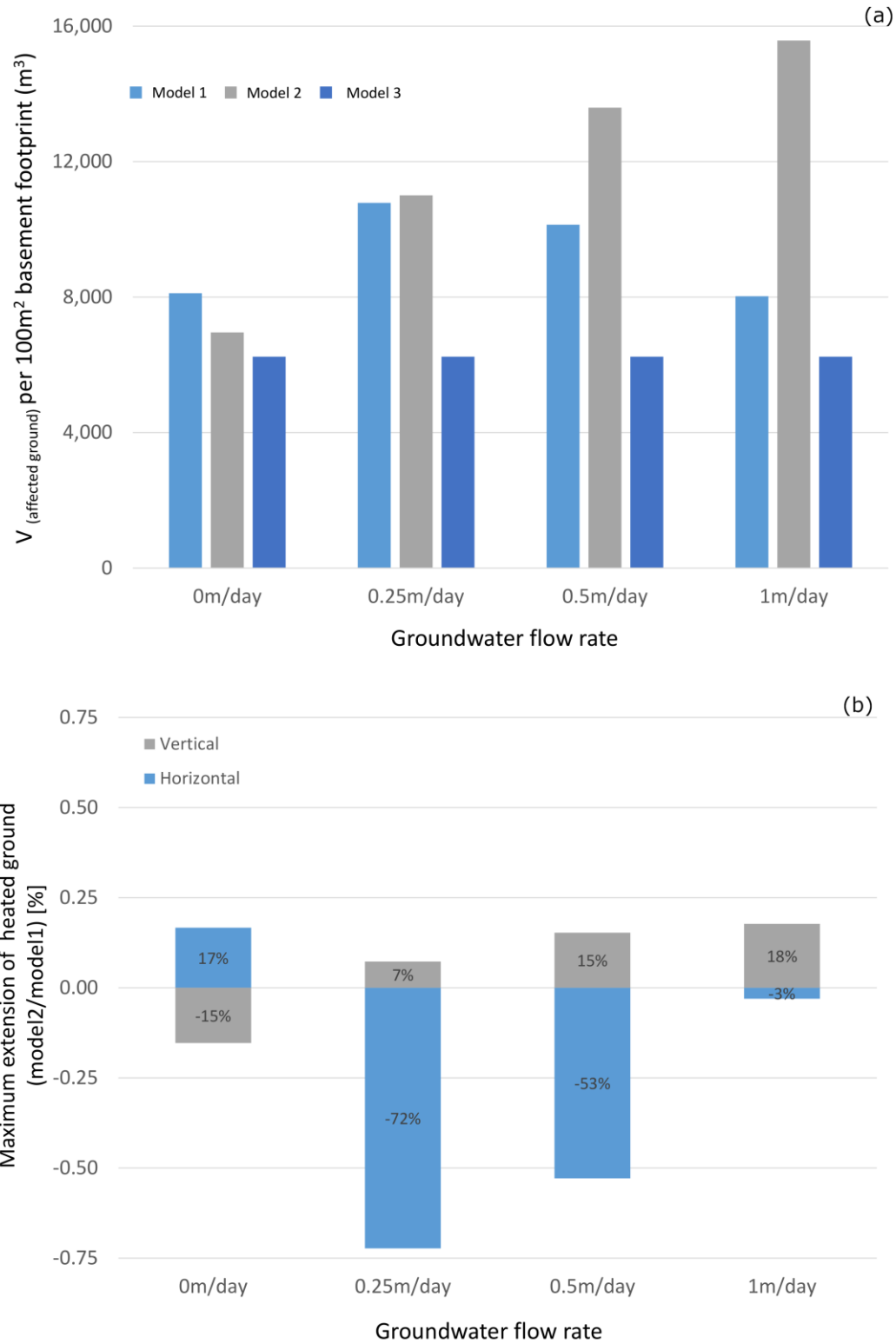
Figure 11. The thermally affected volume of the ground per $100m^2$ of basement footprint (a), The difference between the extension of the heated ground in horizontal and vertical directions between the model 1 and model 2 (b).

5. Conclusions

Reliable knowledge of ground thermal status in urban areas is crucial for 1) the sustainable development of underground structures, 2) the optimal utilization of geothermal sources and 3) efficient energy system design for

underground structures. To achieve such understanding, not only are the built environment and external contributors (anthropogenic heat fluxes) to ground temperature rise important for consideration and study, but also analysis that is based on a good understanding of the local geological and hydrogeological conditions is required. The aim of this proof-of-concept study was to highlight the impact of geology and hydrogeology on heat rejection rate from underground structures, and thus the extent of ground thermal disturbance. Numerical analysis of a sample of selected areas shows that thermal losses from heated basements to the ground can constitute a significant percentage of the total heat loss from a building, particularly in the presence of groundwater flow. However, this is not a consistent trend. Results show that the influence of groundwater flow on thermal loss from basements is less in ground with a large volume of permeable material. In addition, the extent of thermal disturbance in the ground is also dependent on the combination of geological and hydrogeological characteristics. In ground mainly consisting of permeable material, the volume of thermally affected ground shows an inverse correlation with the groundwater flow rate. However, a direct correlation exists when the thickness of permeable layer decreases. A larger horizontal to vertical ratio of ground thermal disturbance is observed when the thickness of permeable layer increases.

The widely used assumption of constant annual average temperature for ground is demonstrated to be incorrect by this study. This incorrect assumption of the ground temperature has a direct impact on the evaluation of the energy requirements for basements. By using the ground as a source of geothermal energy, an accurate estimation of the ground temperature facilitates and improves the sustainable utilization of geothermal energy sources.

The understanding of the evolution of ground temperature necessitates a large-scale study on the thermal interaction between underground spaces and the surrounding ground. A city-scale model including different underground sources of heat (basements, train tunnels, etc.) is therefore required and will be the focus of our future work.

6.   Acknowledgement

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