Preliminary assessment of optimum sustenance potential for geothermal systems within the London Basin 1: Development of groundwater flow model

Oladeji Olayinka Simeon¹, Adegbola Adebayo Ayolele²
1- Environment Agency, Groundwater, Hydrology and Contaminated Land Team, Apollo Court, Hatfield, AL10 9EX
2- Department of Civil Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.
dayomos2002@yahoo.com
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ABSTRACT

The sustainability of the geothermal systems where heat exchanger is utilized to extract and discharge differential heat from, or into groundwater for heating and cooling during the winter and summer periods, largely depends on obtaining consistent temperature difference between the groundwater abstraction and re-injection locations. However, occurrence of such systems at close proximity can potentially cause derogatory effects between the individual systems, as well as the systems and the environment. The aim of this paper is to present the development of a flow model that underpins the framework upon which the overall assessment of the capability of the London Basin in supporting geothermal systems is based. This includes the characterization of the study area, as well as transformation of an existing Integrated Catchment Management Model into a Feflow model, which is thought to offer a more robust capability for use as a tool in the subsequent assessment.

Keywords: Geothermal systems, London Basin, Sustainability, Groundwater modeling.

1. Introduction

The high thermal inertia of the soil coupled with time lag between the temperature fluctuations at the surface and subsurface, presents differential heat reservoir that can be utilized using heat exchanger for heating and cooling during the winter and summer periods. This technology is commonly referred to as Ground Source Heating and Cooling (GSHC) system or simply geothermal system, and has widely been accepted as sustainable form of energy source both in the industries as well as in the Government circles across the world. Generally, there are two types of GSHC schemes, namely Open loop and Closed loop systems. The Open loop systems utilize abstracted groundwater as a medium for heat circulation through pipe network and heat exchanger in the heating or cooling of space, while Closed loop systems circulate refrigerant through heat exchanger and network of pipes buried in trenches to achieve similar space heating and cooling effects. The two systems have their respective advantages and disadvantages, and these are widely documented in the literature (Omer, 2008; Florides and Kalogirou, 2007).

Converse, the non-renewable sources of energy such as the fossil fuels that produce greenhouse gases and increase effects associated with climate change, GSHC systems are renewable sources of energy and their use have largely been promoted by governmental
bodies at various levels. These motivations have led to their global increase. Lund et. al. (2005) reported that as at 2005, GSHC systems have the largest worldwide energy installed capacity as well as use, accounting for 54.4 % and 32.0 %, respectively. The majority of the installations occurs in North America and Europe, and increased from 26 countries in the year 2000 to 33 countries in the year 2005.

In the United Kingdom, the capability of GSHC systems to deliver low carbon space heating and cooling has recently led to high increase in their applications. The annual growth in demand for geothermal systems has been estimated to be between 50 – 100% (Younger, 2007). Of particular interest is the central part of London, where GSHC systems are currently been proposed at proximal distance of less than 200 m (see Figure 1). The records of the installation of the GSHC systems contained in the database of the Environment Agency shows that the numbers of the GSHC schemes which are at different levels of completion within the central London increased from 2 to 226 between 2002 and 2011. The development planning initiatives in the London City for large projects to achieve 10 – 20 % renewable energy source has partly been responsible for this surge. The increasing public interest, as well as the government’s drive to mitigate the effects of climate change through promotion of utilization of renewable energy sources may further increase this growth rate, with potential to cause secondary environmental derogatory effects if not properly regulated. Some of these secondary effects may include reduced efficiency caused by interactions of proximal systems, creation of conduits that connect distinct aquifer systems, thereby causing undesirable flows, as well as local and regional aquifer pollution by both heat and refrigerant liquids.

This situation has therefore placed greater demand on the Environment Agency as a responsible and modern environmental regulator to evolve and ensure more effective and efficient methods to regulate these systems. The rate of increase and clustered-spreading of GSHC systems within the central London particularly necessitated the need for tools to assess the interactions between the individual GSHC systems, as well as between the systems and the environment at large. Further discussions in this work are concerned mainly with the Open loop systems. The overall aim of this paper is to assess the number of GSHC systems that can optimally be supported by the hydrogeological conditions within the central part of the London Basin, without derogating the groundwater quality, as well as the efficiency of the individual systems. The results of the assessment are intended to be presented as a serial publication, and this paper represents the preliminary work where characterization of the area and development of the flow model are presented.

2. Methodology

This work involves setting up and calibration of a flow model within a Feflow modelling software environment for the study area. The conceptualization as well as the initial and boundary conditions of the existing Integrated Catchment Management Model (ICMM), developed by Mott MacDonald (2000) as part of the London Basin Groundwater Modelling Study, constitutes the basis for the formulation of the current work. The model re-development was required because unlike the ICMM, Feflow possesses enhanced modelling capabilities for coupled (i.e. flow, solute and heat), reactive multi-species transport, including varying density flow conditions, as well as 2D and 3D display, both areal and in cross-sections. The transformation of the required data format, as well as the presentation of the modelling output were facilitated by manipulation within the Microsoft Excel, MS WordPad and customized FORTRAN utility programs.
2.1 Description of the study area

The study area is presented in figure 1, which shows the solid geology as well as the boundary of the model.

Figure 1: Description of the study area

The study area covers the central London, with the north-west and south boundaries delineated by the unconfined Chalk of the Chilterns and the North Downs, respectively. The Chalk Formation is made up of very-fine grained limestone formed during the late Cretaceous Period. The chalk forms a massive syncline geological structure beneath the central London, with the fold axis trending SW - NE direction, with the Chalk outcropping both at the Chilterns and North Downs. The stratigraphy of the synformal structure at the central part of the area indicates that the Chalk Formation is overlain by the Thanet Sand, consisting a brownish-grey, fine-grained sand, which in turn is overlain by the Lambeth Group, made up of mottled clay with fine-grained sand, laminated clay, flint pebble beds and shelly clay layers. This geological succession is overlain by the confining London Clay, which in general are made up of a very silty clay material.

The basal Chalk Formation has hydraulic connectivity with the overlying Thanet Sands, and these two geological units form the major aquifer beneath the London Basin. A groundwater divide which occurs between the River Hogsmill and Mole (see figure 1) delineates the south western boundary of the model, while the south eastern boundary is delineated by River Cray. River Thames flows in a W - E direction, extending across the entire model area, but largely
over the confining London Clay, and hydraulically connecting with the Chalk only at the unconfined portions in the eastern patch of the model. A more detailed description of the area is presented by ESI (2010).

2.2 Model setup and run

The model is setup as a 5-layer model. The model layers from the top are the London Clay, Lambeth Group, Thanet sands, and the Chalk. The upper part of the Chalk aquifer is more extensively fractured, and therefore exhibits distinctive hydraulic conductivities compared to the bottom parts of the Chalk aquifer. Hence, the Chalk aquifer is further sub-divided into two layers, namely Top Chalk and Bottom Chalk. The length of simulation period is set to span from January 1965 to December 2005. The simulation period is divided into 492 stress period, and the length of each stress period is 30.42 days. Each stress period is further subdivided into three time steps. The study area is discretized into 178,074 mesh nodes and 294,540 elements, compared to the ICMM with 3732 nodes.

The model is delineated by six external boundary conditions which are represented by transient groundwater heads and fluxes across the boundaries for each of the layers. These boundary conditions are presented in Figure 2.

![Figure 2: Boundary conditions](image)
The boundary conditions include Stepped Head Boundary, Constant Head Boundary, Stepped Head Boundary, No Flow Boundary, Fixed Flow Boundary, and Constant Head Boundary, respectively. Each of the boundary conditions is represented by transient data using the power function capability of the Feflow software package. The boundary conditions 1, 2, 3, 4, and 6 (see Figure 2) are the same the Thanet Sands and the two layers of the Chalk aquifer. These respectively corresponds to layers 3, 4 and 5 of the model. The Fixed Flow boundary condition are the same for the Thanet Sand and Top Chalk aquifer (layers 3 and 4), but different for the Bottom chalk aquifer (layer 5). The London Clay and the Lambeth Group (layers 1 and 2) are defined using no flow boundary conditions because of their relatively low permeability, and their absence in certain places. The regional groundwater flow pattern is from the Chilterns and the North Downs towards the depression area of the London Basin. The ranges of values for the initial conditions for the hydraulic conductivities (both horizontal and vertical), the confined and unconfined storage coefficients, as well as the initial values for the groundwater elevation are interpolated from the 3732 nodes of the ICMM model.

The rivers included in the model are Rivers Thames, Wandle and Ravensbourne (Figure 1). The parts of the rivers that have hydraulic connections with the upper part of the Chalk aquifer are incorporated within the third model layer, by using the transfer boundary condition of the Feflow capability. The reference hydraulic head along the rivers is set to be 0.0 m OD, and the bottom of the rivers is set to be -5 m OD, with the river bed conductance value of $1.16 \times 10^{-7}$ m/s. There are 25 spring sources that are incorporated into the model (Figure 1). Springs flow is assumed to be induced when the rate of recharge exceeds the rate at which the groundwater flows towards the central London depression. The transient spring flow data is represented in the model, using power function capability of the Feflow. Also, there are Low Permeability Barriers which are linear structures occurring within the Thanet Sand and the Chalk aquifer. The barrier is thought to impede the regional flow of the groundwater and accounts for the sudden change in observed water levels within Central London. The locations and orientations of the barriers were obtained from the ICMM setup, and incorporated into the Feflow model using quadrilateral 2D vertical elements of the Fracture Editor capability. The barrier was originally defined using initial hydraulic conductivity values obtained from the ICMM, and the values were subsequently adjusted during the model calibration process. Also, transient groundwater abstraction data from 900 boreholes (Figure 2) are incorporated using power functions capability of the Feflow model.

In order to apply recharge flux onto the model domain, the study area is divided into six catchment areas (Figure 3), based on the geology and rate of infiltration. Pre-calculated transient recharge flux rates based on the Environment Agency (EA) Soil Moisture Model is linked to corresponding recharge polygons using power functions. Most of the recharge flux calculated by the EA Soil Moisture Model is rejected at the central part of the study area where the chalk aquifer is confined by the London Clay Formation (recharge polygon 5). This is because the flux value exceeds the rate at which leakages occur through the London Clay Formation. Also, there are 85 observation boreholes with water level monitoring data incorporated into the Feflow model. These data were used for comparison with the simulated data during the calibration of the flow model. The model area is subdivided into 9 zones and the observation data are distributed among the zones (Figure 3). The time taken to run the Feflow flow model on a Desktop computer with specification of 2.07 GHz and 1.50 GB of RAM is approximately 4 hours.
3 Results and discussions

The conceptual model was setup based on the understanding of the geology, hydrology and hydrogeology of the study area, and forms the numerical framework of the model. The model was setup as a five layered model, and calibrated over a 41-year period spanning January 1965 - December 2005. The calibration of the model was based on minimizing the residuals by comparing the measured groundwater heads obtained from the 85 observation boreholes, and the simulated equivalents. The observation boreholes are divided into 9 zones in order to facilitate comparison between different regions. Since the monitoring boreholes are completed within the Chalk aquifer, calibration efforts were largely focused on the refining of the hydraulic parameters within the two chalk model layers and the overlying Thanet Sand. The overall model volumetric balance for the simulation is presented in Figure 4. The percentage numerical error associated with the volumetric balance is less than 0.01 % throughout the duration of the simulation. Typical representations of the comparison between the measured and simulated groundwater heads for each of the delineated zone are presented in figure 5.

![Figure 3: Locations of observation boreholes](image_url)
Figure 4: Volumetric budgets for the calibrated flow model

Figure 5: Measured and simulated groundwater heads
Generally, a sufficient degree of match was obtained between the measured head observations and the simulated equivalents in all the monitoring points. The simulated data are within ± 5 m of the observed data, though majority of the simulated data falls below this deviation. Generally, the starting groundwater heads within the Chalk aquifer appears to be low, however the final calibrated values of the hydraulic parameters for each of the model layer are similar to that obtained for the ICMM model. The first model layer corresponds to the London Clay.

The simulated horizontal and vertical hydraulic conductivities are $1.16 \times 10^{-6}$ and $5.79 \times 10^{-11}$ m/s, respectively. The modelled specific yield is 1.0 %. The same horizontal hydraulic conductivity value was obtained for the underlying Lambeth Group, with corresponding vertical hydraulic conductivity and storage coefficient values of $2.32 \times 10^{-9}$ m/s and 10 %, respectively. The base of the London Clay Formation is sandy, and forms an erosive contact with the underlying Lambeth Group. This therefore explains the similarities in their horizontal hydraulic conductivities. The range of simulated values obtained for the horizontal hydraulic conductivity of the underlying Thanet Sands is $6.95 \times 10^{-6}$ – $1.30 \times 10^{-4}$ m/s. The corresponding vertical hydraulic conductivity is $1.16 \times 10^{-6}$ m/s, and this value is thought to be low because of the presence of clayey materials at the lower part of Thanet Sand. It is thought that the presence to this clayey material tends to reduce the hydraulic connection with the underlying Chalk aquifer (ESI, 2010). The corresponding values simulated for the confined and unconfined storage coefficients for the Thanet Sand are 0.01 and 6 – 15 %, respectively. The top of the Chalk aquifer, assumed to be approximately 50 m thick, and corresponds to the layer 4 of the model. This layer is characterized by open-fractures, which gives rise to the development of significant secondary porosity and increased hydraulic conductivity. The range of simulated values for the horizontal hydraulic conductivity for the top of the Chalk aquifer is $1.16 \times 10^{-6}$ – $2.90 \times 10^{-3}$ m/s. The corresponding values for the bottom part of the chalk aquifer are $1.16 \times 10^{-7}$ – $3.12 \times 10^{-4}$ m/s. The vertical hydraulic conductivity, as well as the confined and unconfined storage coefficients are the same for the chalk aquifer, and are modelled as $5.78 \times 10^{-7}$ m/s, 0.05 % and 0.02 %, respectively.

4. Conclusion

The aim of this paper is to present the development of a flow model that will underpin the framework upon which the overall assessment of the capability of the London Basin in supporting geothermal systems is based. The sustainability of the geothermal systems largely depends on obtaining consistent differential temperature in groundwater between the abstraction and re-injection points. However, close proximity of these systems can potentially cause derogatory interactions between the individual systems, as well as between the systems and the environment, thereby impacting on the functional efficiency of the system. This paper presented the preliminary work in the development of a flow model that underpins the required overall assessment tool. Characterization of the study area, as well as transformation of an existing ICMM model into a Feflow model, which is thought to offer more robust capability is also presented.

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