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The open loop ground source heat pump screening tool for England and Wales

Corinna Abesser, Melinda Lewis

British Geological Survey, Crowmarsh Gifford, Wallingford, Oxon, OX10 8BB, UK

mlewis@bgs.ac.uk

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ABSTRACT

The British Geological Survey (BGS) in collaboration with the Environment Agency (EA) of England and Wales, has developed a web-based screening tool that provides an indication of where conditions may be suitable for installing commercial scale (>100 kW heating/cooling demand) open loop ground source heat pump (GSHP) systems. The tool considers both, *hydrogeological* and *economic* factors, including the presence and productivity of an aquifer, the minimum depth of borehole required, as well as potential restrictions (e.g. location within protection zones). It also provides information on the volumes of water currently licensed to be abstracted as well as water quality information (corrosion, scaling and iron precipitation) for locations where such data are available.

Data are collated, grouped and summarised within a GIS environment and viewed via WebGIS. Viability for open loop GSHP installations is displayed in the form of a screening map which shows all areas where the basic requirements for successful GSHP installations are met. More detailed information on the underlying hydrogeological and economic factors is available from summary data tables and through exploration of the underlying thematic maps. As such, the tool provides an effective method for the initial assessment of the subsurface conditions and the suitability for open loop GSHP installations.

1. INTRODUCTION

The UK Government expects that by 2020 12% of the UK's heat demand will come from renewable sources, and is providing incentives to help achieve this. Ground source heat pumps (GSHP) could make a substantial contribution towards reaching this goal as they offer an economical and clean alternative to conventional heating and cooling technologies. They use the subsurface as a natural heat source/sink to provide space heating/cooling and can significantly reduce operating costs [Kulcar *et al.*, 2008; Ozgener *et al.*, 2007] as well as CO_2 emissions [Nagano *et al.*, 2006].

A wide variety of GSHP systems are available that use the ground (soil and rocks) (closed loop system) or water, including groundwater, (open loop system) for exchanging heat. Groundwater-based open loop systems exchange heat directly with the groundwater and therefore are generally more efficient for larger buildings (e.g., multi-storey offices, shopping centres and swimming pools) than closed loop systems. Uptake of GSHP for space heating/cooling in the UK has rapidly increased over the past five years [Lund *et al.*, 2010], but high upfront capital costs, insufficient levels of government support and lack of public awareness have been quoted as barriers to uptake [ENDS, 2012; Le Feuvre, 2007] as well as the perception of risk associated with unknown hydrogeological and economic conditions at the installation site.

This paper presents the development of a web based screening tool which maps hydrogeological and economic factors relevant for larger groundwater-based open loop GSHP installations.(>100 kW heating/cooling demand) in England and Wales. It is intended to provide a first-pass screening that shows where the basic hydrogeological and economic requirements for open loop GSHP installations are met. The tool was developed in collaboration with the Environment Agency of England and Wales and with representatives from the ground source heat pump industry and is freely accessible on the BGS website at http://www.bgs.ac.uk/research/energy/geothermal/gshp.html.

2. PILOT STUDY

A pilot study was carried out to develop the methodology for mapping the suitability of the subsurface for open loop GSHP installations by considering the main hydrogeological and economic constraints. The study area is the West Midlands county in England and suitability is mapped at the 1:50,000 scale. The resulting tool considers the availability of bedrock aquifers and borehole productivity as well as the estimated ground temperatures at 100 m depth, depth to the aquifer at the given location and the availability of other potential groundwater sources (i.e. superficial deposits).

Data are collated, grouped and summarised within a GIS environment and the suitability for GSHPs is displayed in the form of a map. Ranking and weighting of the data is deliberately avoided as these methods require assumptions about the size (and the economics) of the scheme and hence can only be applied to a scheme of a specific size. In this pilot study, the final map is designed such that it is applicable to schemes of all sizes (Figure 1). Clicking on the map brings up a table with more detailed information on the hydrogeological and economic conditions at the selected location and also provides a graphical summary of these subsurface attributes in the form of a "Chernoff face" (Figure 2).

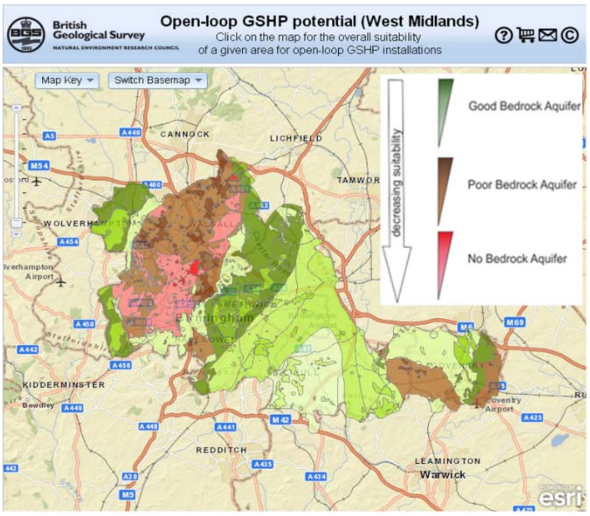


Figure 1: Suitability for open loop GSHP systems in the West Midlands, UK (suitability reduces from green to red)

Chernoff faces are derived by translating the mapped criteria into facial features. Here, eyes and mouth represent the availability and productivity of an aquifer, respectively, and the length of nose gives the approximate depth to the source (i.e. the minimum drilling depth). The tool also includes information about the ground temperature at 100 m depth (face colour) and the presence of superficial deposits of (at least) 10 m in thickness (hair). The latter parameters are included in the pilot study but are not considered in the national screening tool as they are less relevant for schemes of larger size.

3. SCREENING TOOL FOR ENGLAND AND WALES

This screening tool is developed for the whole of England and Wales at the scale of 1:250,000 to show where suitable subsurface conditions exist for open loop GSHP installations of >100kW heating/cooling output. The tool development is based on the methodology described above which was modified to account for the specific requirements of larger schemes. The tool comprises five thematic data layers: (1) Bedrock aquifer map, (2) Depth to source map, (3) Protected areas map, (4) Groundwater chemistry data and (5) Abstraction licence data which with the screening map are integrated in a web viewer.

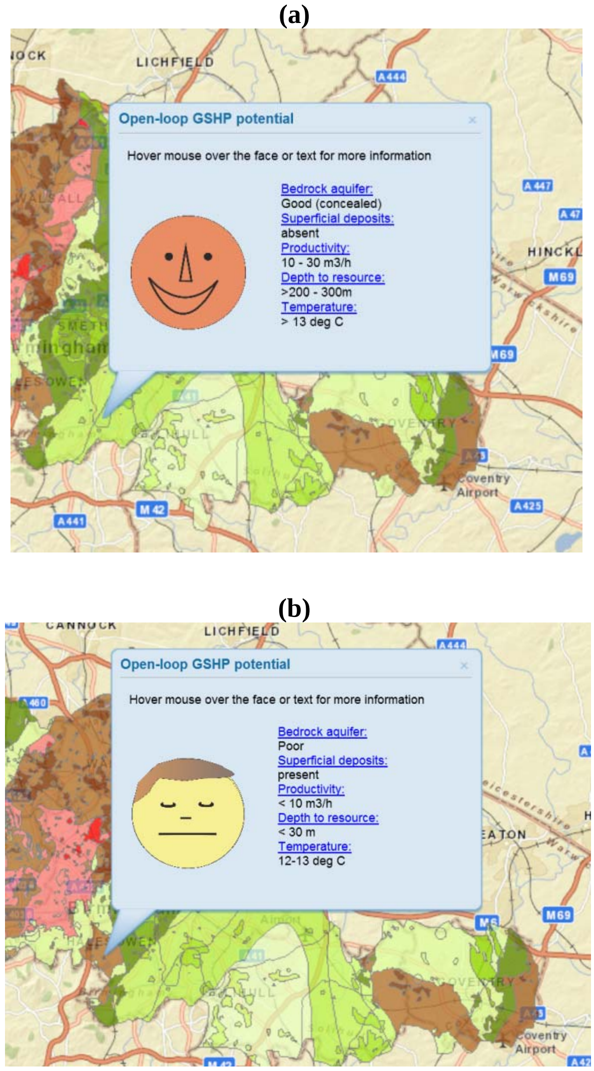


Figure 2: Chernoff faces representing the presence of (a) a good (concealed) aquifer of medium productivity located at 200-300 m depth and (b) a poor, low productivity aquifer at shallow depths which is covered by superficial deposits

On opening the tool, it displays the initial screening map (Figure 3) which is derived from the *bedrock aquifer* and *depth to source* maps (see below). The screening map shows areas that are 'favourable' or 'less favourable' for the installation of open loop GSHP systems (>100 kW). Areas are considered 'favourable' where one (or more) productive bedrock aquifer (i.e. with yields of at least 1 L s^{-1}) is present within 300 m beneath the ground (topographic) surface. In some areas, aquifers are present at depths of more than 300 m, but these are shown as 'less favourable' in this tool as the high costs associated with drilling, borehole installation and pumping would render a GSHP installation uneconomic. Furthermore, aquifers generally become less productive with increasing depth compared with nearer to the surface.

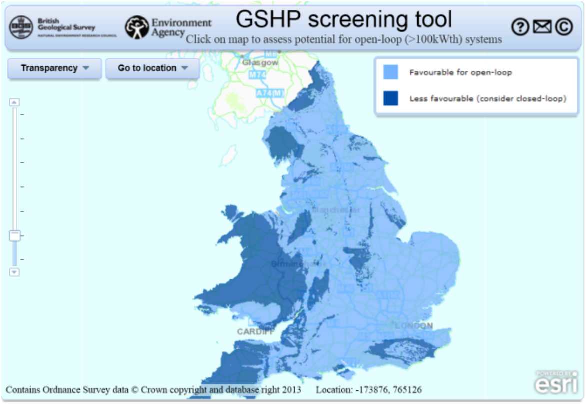


Figure 3: Initial screening map showing viability for open loop GSHP installation > 100kW in England and Wales (light blue = favourable, dark blue = less favourable)

Clicking on the map opens a table which displays details of the underlying data layers and allows access to the thematic maps (Figure 4). Information on groundwater chemistry and existing licensed abstraction volumes are also shown in the table (where available) but these cannot be accessed directly due to restrictions related to data confidentiality and national security concerns. Instead, clicking on the map returns all data values that occur within a search radius of 600 m around the search location. The search returns all data available within this radius up to a maximum of 10 data values. The data are displayed in the results table in a random order and can refer to sampling points/abstractions from different aquifers and depths.

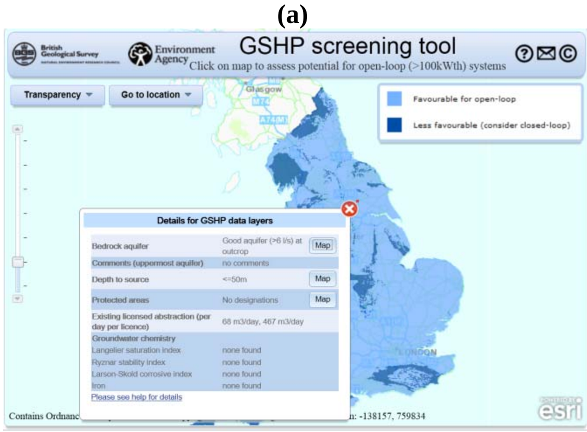
3.1 Thematic data layers

The following section provides a brief summary of the underlying thematic maps and data sources. A more detailed description of these layers is available in (Abesser, 2012; Abesser *et al.*, in prep).

(1) Bedrock aquifer map

This layer (Figure 5) shows the areas where suitable bedrock aquifers are present at rockhead (at outcrop or subcrop beneath superficial deposits) or at depth (i.e. concealed by less permeable bedrock formations). The layer is derived from two key BGS data sets: the digital bedrock geology map and contour data of the main geological formations for Great Britain. The 1:250,000 bedrock map (DiGMapGB-250) distinguishes about 600 geological units in England and Wales and these were attributed according to their potential to form aquifers capable of providing a certain level of water supply (yield) to a borehole. Aquifers with potential yields of less than 1 L s^{-1} were considered unsuitable for use as commercial (100kW) open loop GSHP sources. Those over 1 L s^{-1} were subdivided into moderate (1-6 L s^{-1}) and good (> 6 L s^{-1}) aquifers. Additionally, the downdip (i.e. concealed) extents of the main UK aquifers (Chalk, Lower Greensand, Corallian, Great Oolite, Inferior Oolite, Sherwood Sandstone and Magnesian Limestone) were mapped using the Atlas GIS contour data. The aquifer outcrop and concealed aquifer maps were then combined to produce the bedrock aquifer map.

(a)



(b)

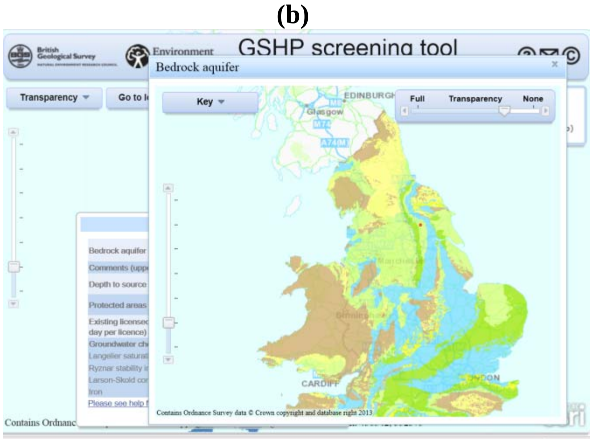


Figure 4: More detailed information on the subsurface conditions in form of a data table (a) through which the underlying thematic maps, such as the bedrock aquifer map (b) can be accessed, are brought up by clicking on a location.

Comments are provided regarding the uppermost aquifer where it comprises karstic limestone and hence yields are both very variable and also the likelihood of designing a working open loop system is reduced.

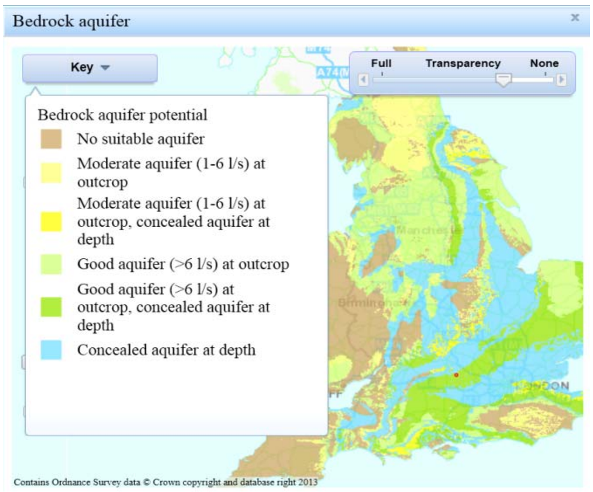


Figure 5: Bedrock aquifer layer

However, there are other geological situations that could also affect the viability of a system and care must always be taken when attempting to utilise soluble rocks (limestone, chalk, dolomite, salt and gypsum). In these situations, caves, cavities and open fissures may be present which permit material from the surface to either collapse or be washed into them causing surface subsidence and damage to infrastructure. In highly soluble rocks, such as salt and gypsum, fluctuations in groundwater levels, caused by the addition and removal of groundwater are likely to exacerbate this. In areas where gypsum is present, it is important that drilling does not introduce water into the underlying anhydrite, and that the sulphate content of the abstraction and drilling water is similar. Hence an open loop GSHP system may not be viable where salt and gypsum are known to be present.

Other factors that should be taken into consideration are: location of mine workings and shafts, locations with known or suspected contamination and areas where geohazards such as landslips and cambering may occur.

(2) Depth to source map

This layer (Figure 6) estimates the drilling depth required to reach the water in an aquifer. This does not necessarily coincide with the depth to the water table/potentiometric surface, but in some areas represents the thickness of superficial sediments or overlying bedrock formations that overlie the aquifer. Where more than one aquifer is present, the depth refers to the shallowest bedrock aquifer, closest to the surface. The layer is derived from BGS groundwater level data, superficial thickness data and AtlasGIS contour data and is classified in 50 m intervals up to a maximum depth of 400 m. For most aquifers it is rarely economic to drill to depths of more than 300 m as yields decrease with depth and water quality also often deteriorates. Hence, while the presence of aquifers in this map layer is mapped to a depth of up to 400 m (where appropriate), the screening map only considers aquifers located at depths of 300 m or less to provide a suitable source for open loop GSHP installation.

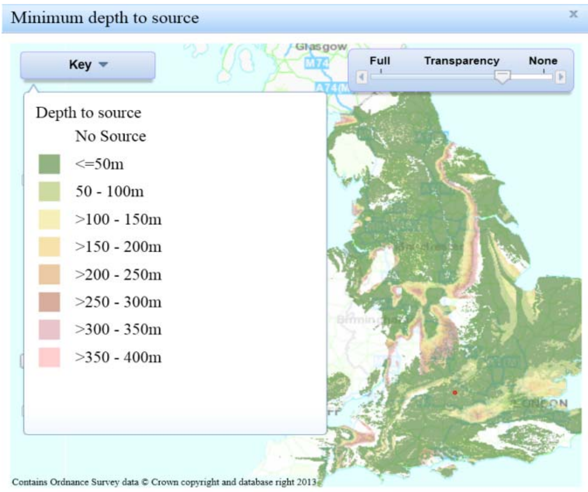


Figure 6: Depth to source layer

(3) Protected areas map

A number of protection zones are defined in England and Wales to protect individual groundwater sources or to preserve a unique array of plants, wildlife, geology or landscape. A location within a protected zone does not necessarily imply limitations for the operation of a GSHP scheme, unless the zone relates to water- or temperature-dependent features, but may require additional permissions and/or planning consents from the relevant authorities.

This layer (Figure 7) outlines the distribution of protection zones in England and Wales, including Source Protection Zones (SPZ), National Parks and Sites of Special Scientific Interest (SSSI). It is derived from GIS data sets from the Environment Agency of England and Wales (EA), the Countryside Council of Wales (CCW) and Natural England (NE).

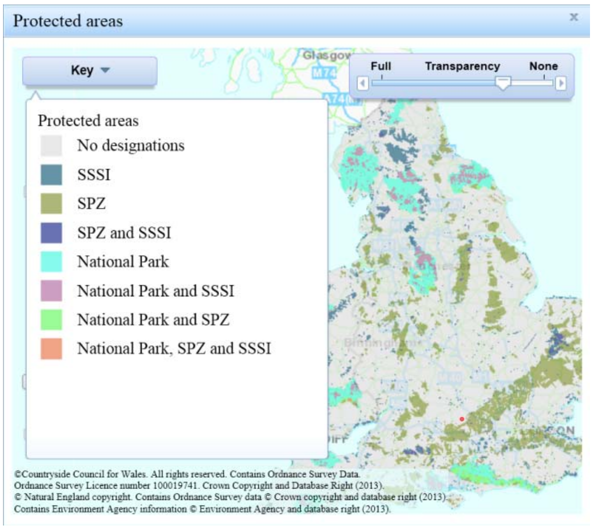


Figure 7: Protected Area layer

(4) Abstraction licence data

In England and Wales all sources abstracting 20 m^3 day^{-1} or more, have to be licensed by the Environment Agency. This data set shows the maximum daily abstraction volumes that are licensed by the Environment Agency (at the time of the tool development and can refer to any of the available aquifers in the area) and located within a radius of 600 m around the search location. The returned values are not the actual abstraction volumes but the maximum daily amount that a licence holder is permitted to abstract. This information is included here as (1) it provides an indication of the rates and volumes that can be abstracted (from one or multiple boreholes) within the area of interest, (2) it highlights areas where large abstractions exist and, hence, where water availability may be limited, reducing the likelihood of a permit being issued and (3) it shows areas where there is an increased risk of interference between abstractions, potentially impacting on the efficiency of the scheme.

(5) Groundwater chemistry data

Open loop GSHP systems exchange heat directly with the groundwater and hence, they are susceptible to problems caused by poor groundwater quality. The principal concerns are scaling, corrosion and encrustation as they can affect the well performance as well as the life of the heat exchanger. This data set includes a set of empirical indices and concentration thresholds that estimate (1) the tendency of the groundwater to deposit or dissolve calcium carbonate (Langelier Saturation Index, Ryznar Stability Index), (2) the corrosiveness of the groundwater (Larson Skold Corrosive Index) and (3) the potential for encrustation associated with high dissolved iron (Fe) concentrations. The indices were calculated for in-situ groundwater temperatures (as measured on sample collection). Altering the temperature of the water may alter the solubility of different minerals and hence affect the scaling/corrosion behavior of the water. Spatial coverage of chemical analyses suitable for calculating these indices is low, hence groundwater chemistry data are only available for about 2% of the total mapped area.

3.2 Application and validation of the screening tool

The tool was validated by comparing the outputs of the screening tool with borehole records and aquifer data for sites where commercial scale GSHP systems are known to be in operation. A total number of 99 locations were tested and all were found to lie within areas mapped as "favourable" by the tool. However, two of these schemes are known to have experienced thermal feedback within their systems. The resulting reduction in efficiency caused the operation of these schemes to become unsustainable and led to their abandonment after only a few months of operation.

Information on depth to water table and/or depth to aquifer was available for 73 locations and generally compared well with the depth ranges estimated by the tool. Only 72 (out of 99) locations indicated licensed abstractions existed within a 600 m radius of the search location. Therefore, the remaining locations must either abstract from superficial deposits (which are not considered in this tool) or they were licensed after the tool was created.

4. DISCUSSIONS

The tool aims (1) to support the identification of areas where it is worth carrying out site specific investigations to prove the hydrogeological and economic viability of a scheme at the early planning stage and (2) to provide a communication tool that raises awareness of GSHP technology by highlighting areas that may be feasible for open loop GSHP installation.

It is developed at the 1:250,000 scale and maps the most relevant hydrogeological and economic requirements for GSHP installation, i.e. the presence of a sufficiently productive aquifer within a reasonable depth beneath the topographic surface. As such, the tool does not provide definitive answers at the site scale and cannot replace more detailed desk studies or site specific investigations (Banks, 2011).

Considerations such as the direction and gradient of groundwater flow and potential for both hydraulic and thermal interference between the proposed abstraction and reinjection boreholes and the assessment of likely economic costs and benefits based on predicted life expectancy of a scheme have to be investigated at the site-scale and take into consideration the size, design and operational requirements of the scheme.

The tool is applicable to both, schemes with consumptive groundwater use (rejected waste water is disposed of via sewers) and schemes with non-consumptive groundwater use (rejected waste water is returned to the same aquifer it is abstracted from via injections wells). However, the tool does not assess how much water would be available for groundwater abstractions (or consider the discharge of water) in a particular area. Environmental permissions would be required for abstraction and discharge and the tool gives no assurances in this respect.

Similarly, the tool does not consider the ability of the subsurface to accept a given flux of water (i.e. rejected water from the scheme) back into the aquifer. This mainly depends on the hydraulic properties and depth of the receiving aquifer and on the design and construction of the injection well(s) and hence, needs to be considered specifically for each site and scheme. It is also possible that the injection borehole will not accept water at the same rate that it was abstracted, due to air entrapment and/or borehole clogging by particulate matter or growth of biofilms.

Validation of the tool against locations of existing open loop GSHP schemes and borehole data has shown that the tool produces reliable results. However, it highlighted two important issues, (1) sustainability of GSHP schemes and (2) the need for regular updates of the tool's thematic data layers.

Sustainability of open loop GSHP schemes is largely controlled by the scheme's design and operational pattern as well as by interactions with neighbouring GSHP schemes (open loop and closed loop). If a system is used solely for heating or cooling, thermal interference is likely to become a problem and in aquifer thermal energy storage schemes it is important that the thermal load is balanced. Aquifers that are excessively utilised by a large number of end users have, naturally, a higher risk of thermal and hydraulic interference and hence, sustainability in these areas is often reduced (Ferguson and Woodbury, 2005; Fry, 2009). In some aquifers, local fracturing may provide pathways for rapid groundwater flow between boreholes and this can further diminish the sustainability of this and/or neighbouring schemes (Gropius, 2010). Sustainability is not explicitly addressed within this tool, but the risk of interference can be inferred from the abstraction licence data set which is included in this tool and shows existing abstractions around the location of interest. Interference from closed loop systems can also affect the performance of open loop systems but is very difficult to access or quantify. Currently, there is no requirement in England and Wales to obtain permission for drilling a closed loop borehole (unless located in areas of underground mining or coal-bearing strata) or to register the installation of closed loop systems. Hence, locations and numbers of closed loop schemes and installed capacities in any given area are largely unknown as is their impact on groundwater temperatures and/or on nearby open-loop GSHP schemes.

Validation of tool performance also highlighted the importance of updating the tool data sets, in particular the abstraction licence data. This is a very dynamic data set with new licences being added constantly (the Environment Agency receives an average of 1000 licence applications per year (Environment Agency, 2009)) and expired licences being removed. Considering the rising uptake of open loop GSHP technology in the UK, it is important that this data set is kept up-to-date to ensure that the tool remains relevant for users. Currently, there are no plans for updating the tool and this decision needs to be revised.

5. CONCLUSIONS

This study developed a web based screening tool that highlights areas where conditions may be suitable for installing commercial scale (>100 kW heating/cooling demand) open loop GSHP systems in England and Wales. Validation of the tool showed that the tool produces reliable results but that key data sets, such as the abstraction licence data need to be updated in order to keep the tool relevant.

In addition to the basic requirements for open loop GSHPs, i.e. the availability of a sufficiently productive aquifer within a reasonable depth beneath the surface, the tool also includes information on existing abstractions, water chemistry and the location of protected areas. Hence, the tool helps identifying areas where problems of scaling/encrustation, water availability/sustainability and/or licensing restrictions may occur.

Developed at the 1:250,000 scale, the tool does not provide definite answers at the site-scale, and users will still have to obtain more detailed, site-specific information before committing to the scheme. However, it provides an effective instrument for the initial assessment of suitability of a location (at the given scale) thereby increasing confidence at the early planning stage.

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