Technical Note

Mapping suitability for open-loop ground source heat pump systems: a screening tool for England and Wales, UK

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Abstract: 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. Open-loop ground source heat pumps (GSHP) could make a substantial contribution. A web-based screening tool has been developed that highlights areas where conditions may be suitable for installing commercial-scale (>100 kW heating or cooling demand) open-loop GSHP systems in England and Wales. In addition to the basic requirements for open-loop GSHP (i.e. the availability of a sufficiently productive aquifer within a reasonable depth beneath the surface) the tool provides information on existing abstractions, water chemistry and the location of protected areas. Validation and tool application show that it produces reliable results and provides an effective method for the initial assessment of subsurface conditions and suitability for GSHP installations. Hence, the tool can help to reduce uncertainty at the early planning stage, and also to promote GSHP technology to a variety of audiences.

Ground source heat pump (GSHP) systems exchange heat with the subsurface to provide space heating or cooling. Groundwater-based open-loop systems exchange heat directly with groundwater and can be more efficient than closed-loop systems owing to the water generally maintaining a constant temperature, whereas in closed-loop systems the ground is affected by heat extraction or injection. They could make a substantial contribution to meeting the UK's heating or cooling demands while reducing CO_2 emissions, but this depends on overcoming obstacles to GSHP uptake. Two of these obstacles are the lack of public awareness of GSHP technology (Enviros Consulting Limited 2008; Roy & Caird 2013) and the higher uncertainty (compared with conventional heating or cooling systems) regarding the economic viability of a planned scheme owing to unknown (hydro)geological conditions at the installation site.

To address these issues, the British Geological Survey (BGS) (with support from the Environment Agency (EA) and advisors from the GSHP industry) is developing methods for identifying favourable (hydro)geological conditions for the installation of GSHP systems at the local administration or regional scale. Developed in a geographic information system (GIS), the results are made available as simple-to-use, web-based tools intended for use in first-pass assessments of the potential of a given locality for GSHP installation and/or for use in resource assessments. This paper presents the development of the open-loop GSHP screening tool for England and Wales, which maps hydrogeological and economic factors relevant for groundwater-based open-loop GSHP installations.

Construction of thematic maps and data layers

Data sources

The screening tool has been developed for England and Wales at a scale of 1:500000 and is freely available on the BGS website (http://www.bgs.ac.uk/research/energy/geothermal/gshp.html). It is based on national datasets available from the collaborators in this study or sourced under an Open Government licence from Natural England and Natural Resources Wales. Some layers, such as the protected area map, were derived by combining existing maps and reattributing them to fit the purpose of this tool. The bedrock aquifer map and the underlying data layers have been specifically created as part of this project, based on the evaluation and mapping of aquifer productivity at the national scale. (The term 'bedrock' is used by BGS to refer to deposits of approximately Pliocene age and older. It includes unconsolidated sediments such as Palaeogene sands and the Crag, which is Pliocene to Pleistocene in age.) The data layers are briefly described below. A more detailed description of the tool and the underlying mapping method has been given by Abesser (2012).

Simplifications and assumptions

The tool was developed based on the following assumptions.

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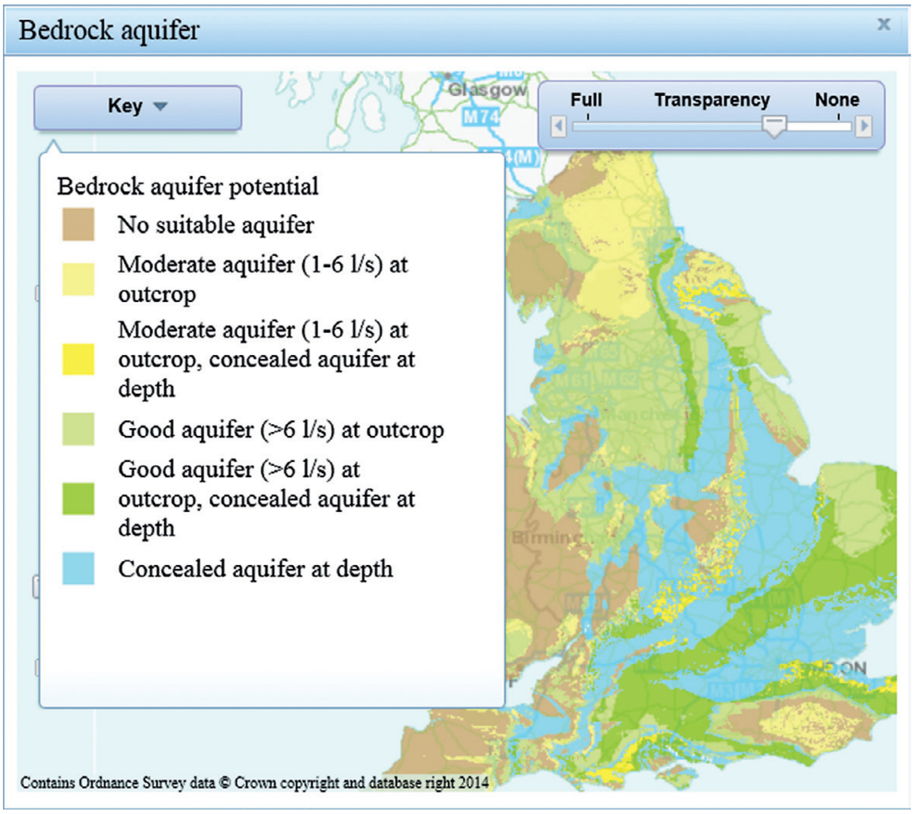


Fig. 1. Bedrock aquifer map.

(1) The tool is used for the initial screening of subsurface conditions for schemes with peak heating or cooling loads of 100 kW or more.

(2) The area that is evaluated is 0.25 km^2 or larger (i.e. appropriate to the scale at which the tool and maps were developed).

(3) The temperature differential ΔT (K) resulting from the heat exchange lies between 5 K (which is a typical value for many heat pump systems; Banks 2012) and 10 K (the maximum ΔT recommended by the Environment Agency for discharge to groundwater; Environment Agency 2011).

(4) The minimum required water flow rates Q ($l\,s^{-1}$) for schemes with peak loads $q \geq 100$ kW are 2–5 $l\,s^{-1}$.

(5) Installation of multiple abstraction wells is viable for open-loop GSHP schemes >100 kW to achieve the required operational yields.

(6) All aquifers with estimated yields of >1 $l\,s^{-1}$ are considered a suitable groundwater source for open-loop GSHP schemes with peak loads ≥100 kW, as more than one borehole could be utilized.

Assumptions (3) and (5) are supported by published abstraction or injection temperatures and abstraction well numbers for open-loop GSHP systems with capacities >100 kW (Abesser 2010; Carbon Trust 2011). Assumption (6) follows from (4) and (5), and agrees well with proposed design values of 0.018–0.045 $l\,s^{-1}\,kW^{-1}$ for optimum groundwater flow rates for open-loop systems (Rafferty 2001).

Bedrock aquifer map

The primary requirement for groundwater-based open-loop systems is the availability of a suitable aquifer that can yield the required volume of water and instantaneous flow rate. This layer is illustrated in Figure 1. It shows the areas where suitable bedrock aquifers are present at the surface (at outcrop or beneath superficial deposits) (the term 'superficial deposits' is used by BGS to refer to Quaternary deposits; that is, Pleistocene age and younger) or at depth (i.e. concealed by younger bedrock formations that are generally, but not always, less permeable) and classifies these according to their potential to provide the following levels of productivity (yields): no suitable aquifer (yield <1 $l\,s^{-1}$), moderate aquifer at outcrop (yield 1–6 $l\,s^{-1}$), good aquifer at outcrop (yield >6 $l\,s^{-1}$), concealed aquifer at depth (yield >1 $l\,s^{-1}$) or combinations of an aquifer at outcrop and a concealed aquifer at depth. Examples of aquifers included in the yield categories 1–6 $l\,s^{-1}$ and >6 $l\,s^{-1}$ are shown in Table 1. This layer includes only the main hydrogeological units (Table 2) that form important concealed aquifers at depth, with the maximum depths to which these formations are considered to form aquifers. These are 400 m for the Chalk, Lower Greensand and Sherwood Sandstone and 150–200 m for the remaining formations (UKTAG 2011). However, in the overall suitability assessment (as described in the section 'Implementation of the thematic layers in the web-based screening tool') aquifers beneath 300 m are considered to be 'less suitable', as high costs associated with borehole drilling and completion as well as possible water quality problems would probably render a GSHP installation at depths >300 m uneconomic.

The tool does not include aquifers that potentially provide deeper geothermal resources; for example, the Sherwood Sandstone Group of Humberside and the Hampshire Basin.

Depth to source map

Drilling, completion and pumping costs are important considerations when assessing the viability (and economics) of open-loop GSHP installations. This layer estimates the drilling depth required to reach the uppermost (i.e. nearest the surface) potential aquifer. This does not necessarily coincide with the depth to

Table 1. *Typical formations classified as being moderate and good aquifers*

Aquifer class	Typical yield	Examples
Moderate aquifer	1–6 $l s^{-1}$	Tunbridge Wells Sand
		Ashdown Beds
		Corallian
		Bridport Sand
		Permian breccias (SW England)
		Fell Sandstone
Good aquifer	>6 $l s^{-1}$	Crag
		Chalk
		Lower Greensand
		Sherwood Sandstone
		Permian sandstones
		Magnesian limestones
		Great Oolite (Cotswolds)
		Inferior Oolite (Cotswolds and Lincolnshire)
		Warwickshire Group
		Carboniferous Limestone

Table 2. *Geological units mapped as concealed aquifers and the maximum depths at which they are considered to form aquifers (after* UK TAG *2011)*

Aquifer unit	Maximum depth of aquifer (m)
Chalk	400
Lower Greensand	400
Corallian	200
Great Oolite	150
Inferior Oolite	200
Sherwood Sandstone	400
Magnesian limestones	200

the potentiometric surface, but in some areas represents the thickness of superficial deposits or less permeable rock formations that overlie the aquifer. Depth values are grouped into eight categories ranging from (1) <50 m to (8) 350–400 m. The resulting map is illustrated in Figure 2.

Protected areas map

A number of protection zones are defined in England and Wales to protect groundwater sources or to preserve wildlife, geology or landscape. GSHP schemes located within a protection zone may require additional permissions and/or planning consents from the authorities managing the protection. This layer (Fig. 3) shows the distribution of protection zones in England and Wales. It combines GIS datasets from the EA, Natural Resources Wales and Natural England into eight categories covering the various possible combinations of Source Protection Zone (SPZ), Site of Special Scientific Interest (SSSI) and National Park.

Groundwater quality data (point data)

Open-loop GSHP systems exchange heat directly with the groundwater and hence they are susceptible to problems induced by poor groundwater quality. The principal concerns are corrosion and scaling or fouling. This dataset provides empirical indices and concentration thresholds that estimate (1) the tendency of the groundwater to deposit or dissolve calcium carbonate (Langelier saturation index, LSI; Ryznar stability index, RSI) (Rafferty 1999), and (2) the corrosiveness of the groundwater (Larson–Skold corrosive index, LSCI) (Larson & Skold 1958). These indices are often used conjunctively and interpreted according to the guidelines in Table 3. They were calculated using *in situ* groundwater temperatures and, hence, represent the temperature at which the water would be delivered from the borehole. This dataset also includes concentrations of dissolved iron (Fe), hence indicating the predisposition of the water for iron (hydr)oxide precipitation (encrustation). Data are grouped into waters with dissolved Fe concentrations less than or more than 500 $\mu g\, l^{-1}$ to indicate a low or high tendency for iron (hydr)oxide formation.

Existing licensed abstractions (point data)

In most countries, the operation of open-loop GSHP systems and the associated groundwater abstraction and reinjection is regulated under water resources legislation. In England and Wales, groundwater abstraction is regulated by the Environment Agency and Natural Resources Wales, respectively, and any abstraction over 20 $m^3\, day^{-1}$ (equivalent to a continuous rate of 0.23 $l s^{-1}$) requires a licence. This dataset comprises point data (single abstraction licences) and is derived from the EA's National Abstraction Licensing Database (NALD). The dataset shows the maximum daily licensed quantity (as of 12 August 2011) that is permitted to be abstracted by the licence from one or several sources, and covers all aquifers. It is included to provide an indication of the rates and volumes that can be abstracted within the area of interest (from one or more boreholes) but also highlights areas where large abstractions exist and, hence, where water availability may be limited, reducing the likelihood of a permit being issued.

Implementation of the thematic layers in the web-based screening tool

All thematic layers were developed in ArcGIS 9.3.1 and integrated into a WebGIS viewer to create the web-based screening tool. The function of the web viewer is to provide the screening map interface through which the underlying thematic layers can be explored (without allowing direct access to the data).

The screening map (Fig. 4) is derived from the bedrock aquifer map (see above) and the depth to source map (see above). It 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 borehole yields ≥1 $l s^{-1}$) is present within 300 m of 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 possibly pumping and poor water quality would render a GSHP installation probably uneconomic. Furthermore, aquifers generally become less productive with increasing depth compared with those nearer the surface.

Clicking on the map opens a table that displays details of the underlying data layers and allows access to the thematic maps (Fig. 5). Information on groundwater chemistry and existing licensed abstraction volumes in the vicinity are shown in the table (where they exist) but these cannot be accessed directly owing to restrictions relating to data confidentiality and security. Instead, the table displays all data values (up to a maximum of 10) that occur within a search radius of 600 m around the chosen location. These can refer to sampling points or abstractions from different aquifers and

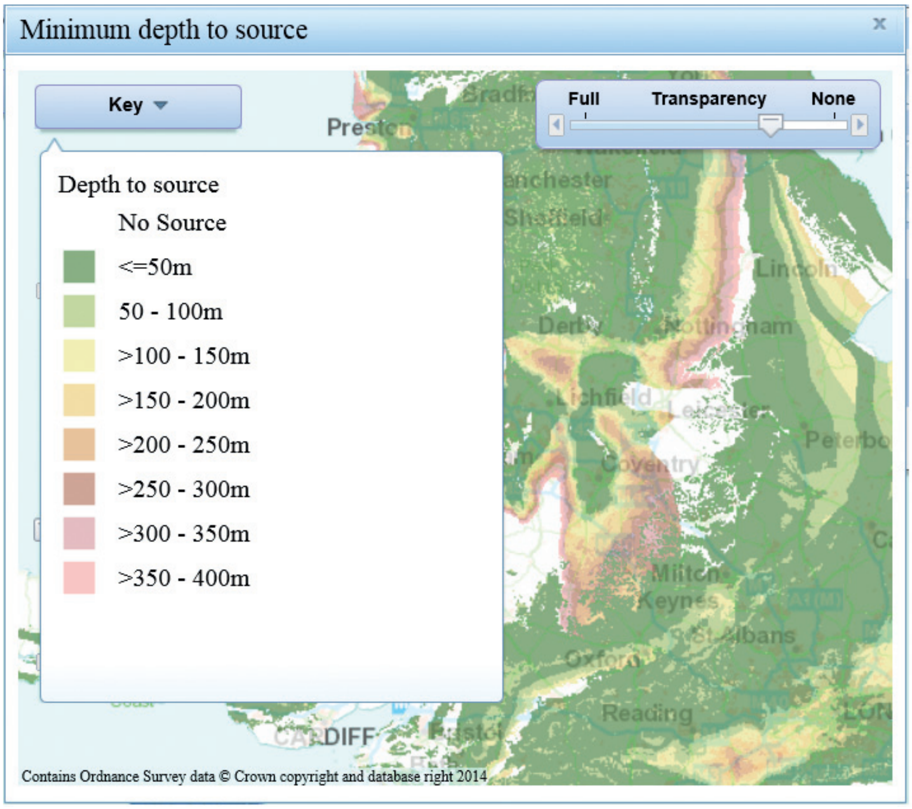


Fig. 2. Depth to source map.

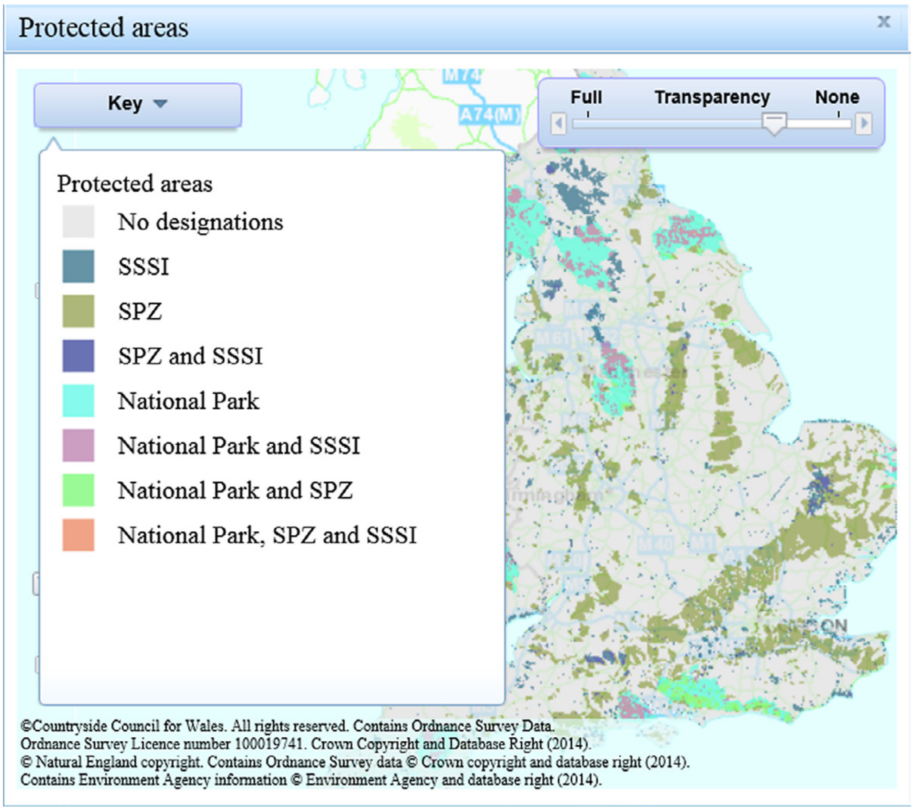


Fig. 3. Map of protected areas.

Table 3. *Interpretation of scaling and corrosion indices*

Langelier saturation index (LSI)	Ryznar stability index (RSI)		Larson–Skold corrosive index (LSCI)	
LSI > 0.4	RSI < 6	→ Ca-carbonate precipitation = scaling likely	LSCI < 0.8	→ No corrosion
0.4 > LSI > −0.4	6 < RSI < 7	→ No dissolution, no precipitation	0.8 < LSCI < 1.2	→ Some corrosion possible
LSI < −0.4	RSI > 7	→ Ca-carbonate dissolution	LSCI > 1.2	→ Corrosion likely

depths, and can include multiple boreholes forming part of the same abstraction licence.

Testing and application of the screening tool

The performance of the screening tool was tested by applying the tool to locations where commercial-scale GSHP systems are known to be operational. For each location, predictions of the overall viability were obtained, and predicted minimum depth ranges were compared with existing data from aquifer tests and borehole records. The list of existing licence abstractions (as returned by the tool for each location) was also checked to ensure that the GSHP abstraction was itself shown by the tool.

A total number of 99 locations were tested and all found to lie within areas mapped as 'favourable' by the tool. However, two of these schemes are known to have experienced thermal interference between the boreholes. 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. Such problems of 'thermal interference' are, however, due to issues with borehole spacing, scheme size and management (Younger 2014), rather than due to the fundamental unsuitability of the (hydro)geology. Information on the depth to water and/or depth to aquifer was available for 73 locations and generally compares well with the depth ranges estimated by the tool. Only 72 (out of 99) of the locations were identified as licensed abstractions by the tool. Abstractions at the remaining 27 locations may have been licensed after the tool was created or, in a few cases, the schemes abstract from superficial deposits (which are not considered in this tool).

The screening map layer is available for downloading (in web map services format) on the BGS website and can easily be incorporated into existing GIS projects. As well as being used for point assessments (e.g. to assess suitability at single map locations), the tool can also be applied in regional-scale (administrative-scale) assessments. In England, for example, local authorities need to quantify the naturally available renewable energy resource within their geographical boundary (SQWenergy 2010). The utility of the tool to support such regional or area resource assessments has been tested for a pilot area, the West Midlands (13000 km^2). This study estimated that about 56% of the area is suitable for open-loop installations with a capacity of 100 kW or more. For England and Wales as a whole, the estimate is higher, with 67% of the total area being mapped as favourable. This estimate is based on a minimum yield requirement of 1 l s^{-1} (assumption (6)). Assuming a minimum yield requirement of 6 l s^{-1} reduces the estimated favourable area to 52% for the West Midlands and to 57% for England and Wales.

Discussion and conclusions

The GSHP screening tool has been developed at the 1:250000 scale for use at the 1:500000 scale. This provides a 500 m ground resolution, which is similar to that of other regional- or national-scale tools (Bezelgues *et al.* 2010). The scale was selected to reflect the purpose of the tool (i.e. to be used as a screening tool, not for site-specific assessments) and the reliability of the underlying data. The tool maps the most relevant hydrogeological and economic requirements for GSHP installation, namely the presence of a sufficiently productive aquifer

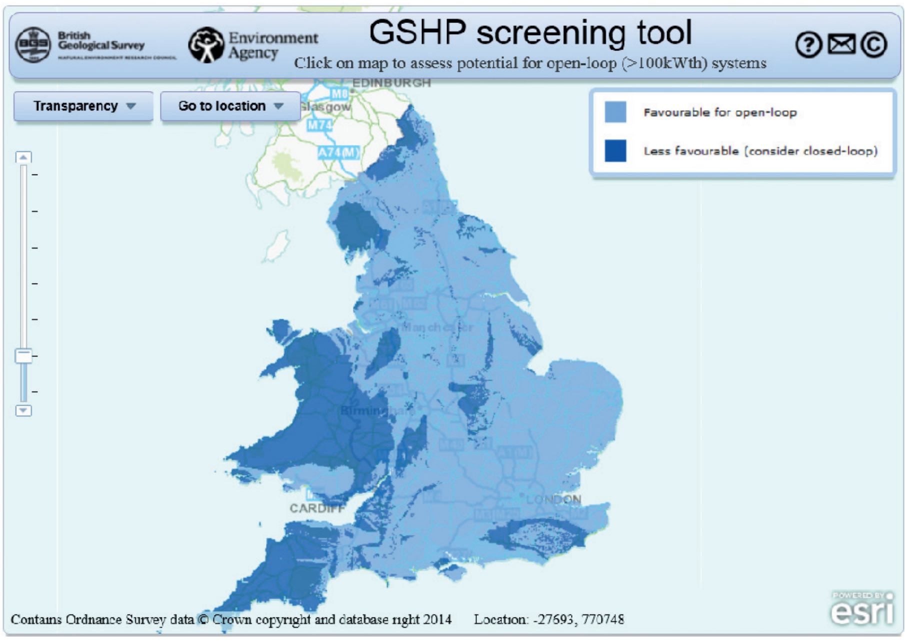
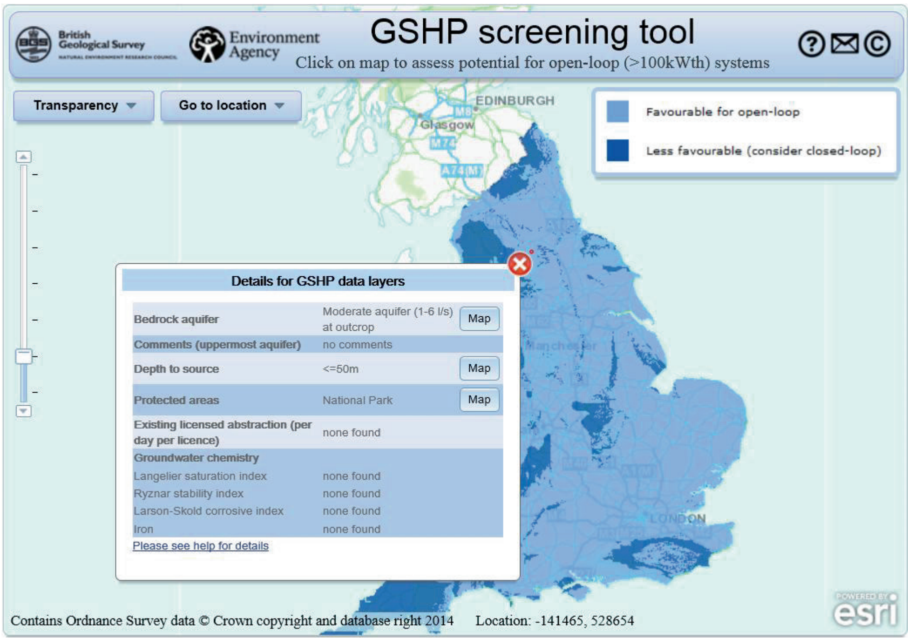


Fig. 4. Initial screening map showing viability for open-loop GSHP installations >100 kW in England and Wales.

(a)



(b)

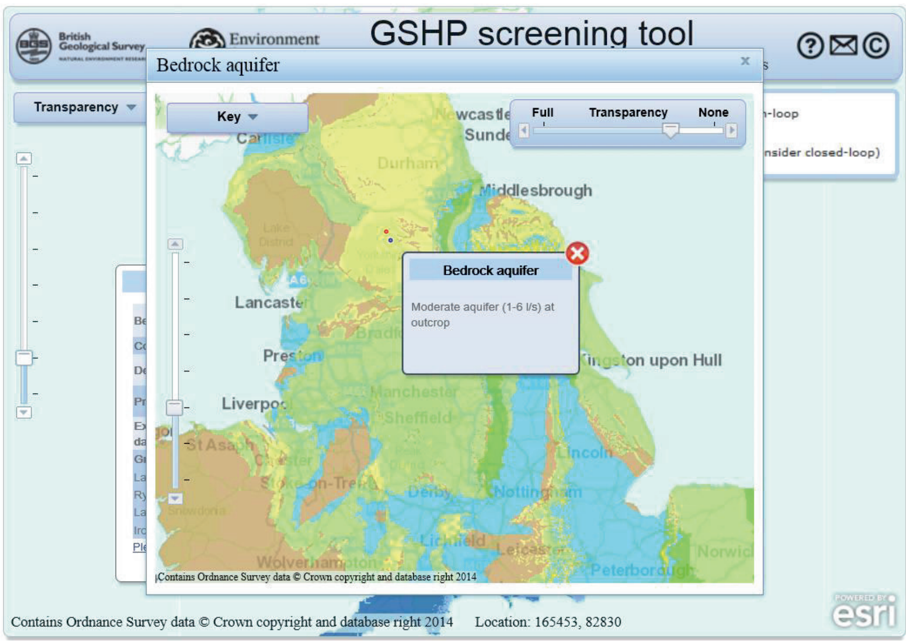


Fig. 5. More detailed information on the subsurface conditions in the form of a data table (**a**), through which the underlying thematic maps such as the bedrock aquifer map (**b**) can be accessed, is brought up by clicking on a specific location (marked as dot on map).

within a reasonable depth beneath the surface. As such, it identifies areas where it is worth carrying out more detailed site-specific investigations to prove the hydrogeological and economic viability of a scheme at the early planning stage. Although reducing the uncertainty associated with unknown subsurface conditions, the tool does not provide definitive answers at the site scale and cannot replace more detailed desk studies or site-specific investigations (Banks 2011).

A limitation of the tool is that it considers only the major hydrogeological units to form useable aquifers at depth (Table 2). Therefore some areas underlain by concealed aquifers at relatively shallow depths are excluded (e.g. Permian sandstones below Aylesbeare Mudstone in SW England) even though, locally, they can provide an important resource. This is because the subsurface extent of these formations is not generally known and hence their distribution has not been mapped. A more detailed presentation of the subsurface geology (including geological volumes and units) is currently being developed as part of a 3D national geological model (NGM) (British Geological Survey 2014). This will provide the necessary data required for more detailed mapping of concealed aquifers.

The tool does not consider superficial deposits, even though, at some locations, they can form moderately productive aquifers

(O'Dochartaigh *et al*. 2011) and have potential for supporting medium- to large-scale groundwater heating and cooling applications (Birks *et al*. 2013). However, the inherent heterogeneity of superficial deposits means that their properties as aquifers (e.g. permeability, thickness and lateral extent) can change significantly over short distances even within the same lithological unit. Maps of superficial deposits and their thicknesses are available but these tend to be classified by their mode of origin (e.g. 'Glacial Deposits', 'River Terrace Deposits' or 'Blown Sand') rather than lithology. Permeability within these classes can vary hugely (Bricker & Bloomfield 2014; MacDonald *et al*. 2012), and their productivity will also depend on the lithology of the deposit, areal extent (which is often small) and saturated thickness, making it difficult to distinguish between deposits that form aquifers and those that do not. There are also currently no superficial deposits maps available at the scale of 1:250000.

Validation of the tool against locations of existing open-loop GSHP schemes and borehole data shows that the tool produces reliable results. It also highlights two important issues: (1) the fact that the tool cannot address the sustainability of a scheme (which depends on spacing, mode of operation and load balance); (2) the need for regular updates of the thematic data layers.

Sustainability is not explicitly addressed within this tool, and the tool uses yield rather than specific capacity data. However, proximity to, and hence the risk of interference from, existing abstractions can be inferred from the abstraction licence dataset, which shows existing abstractions near the location of interest. Intergranular aquifers generally have smaller zones of influence and hence interference effects are likely to be more limited, but in fractured aquifers, local fractures may provide pathways for rapid groundwater flow between boreholes, diminishing the sustainability of this and/or neighbouring schemes (Gropius 2010). This is more likely to be a problem in aquifers that are utilized excessively by a large number of users and, naturally, have a higher risk of thermal and hydraulic interference (Ferguson & Woodbury 2006; Fry 2009). Thermal interference from closed-loop systems can, theoretically, also affect the performance of open-loop systems but is unlikely to be a problem unless the closed-loop scheme is very large. It should be noted that closed-loop schemes are currently unregulated in England and Wales.

The need for updating applies in particular to the abstraction licence data used within this tool. This is a dynamic dataset with new licences being added constantly and expired licences being removed. Considering the expected rise in uptake of open-loop GSHP technology in the UK, it is important that this dataset is kept up-to-date to ensure that the tool remains relevant for users.

The tool provides information on the economic viability and deployment constraints for open-loop GSHP installations. A recent review of the regional assessments of renewable energy capacity in England concluded that such information is required to improve existing resource assessments and to support the development of local (and regional) energy plans (Stoddart & Turley 2012). Hence, it can be expected that this tool will play an important role in future assessments and target setting for shallow geothermal resources in England (and Wales).

Developed for use at the 1:500000 scale, the tool does not give definite answers at the site scale and cannot replace more detailed site-specific investigations. Even so, it does provide (1) a valuable instrument for the initial assessment of the suitability of an area, (2) data and information relevant for (regional and local) renewable resource assessments and (3) a tool to communicate where suitable subsurface conditions for the installation of open-loop GSHP systems may exist. As such, the tool can reduce uncertainty at the early planning stage and also help to promote GSHP technology to a variety of audiences.

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