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Open-loop ground source heat pumps and the groundwater systems: A literature review of current applications, regulations and problems

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Summary

This report presents a literature study that was carried out to collect data and information required for developing a strategy to assess the suitability and sustainability of UK aquifers for (open-loop) GSHP installations. Developing such a strategy requires a good hydrogeological understanding but also a good knowledge of what GSHP systems are currently in use, how they are used, what problems are associated with their use and how they are regulated. Once this is understood, a methodology can be devised that assesses the suitability of an aquifer/location for GSHP installations and considers its sustainable use. Considering the complexity of influencing factors and processes, this is likely to include the use of numerical models and/or data management tools, such as GIS.

This report collects and summarizes the information available in the contemporary literature on open-loop ground source heat pump (GSHP) applications. Chapter 1 provides a brief introduction and background information on the subject. In Chapter 2, information on the general use of open-loop GSHP technology within the UK are gathered together with statistics on the number of installations and capacities. Chapter 3 gives specific examples of schemes that are currently in operation in the UK and worldwide. Where available, this includes system-specific data such as abstraction rates, thermal capacities and information on the system's design. Chapter 4 summarizes available information and data on the cost-effectiveness of GSHP installations while Chapter 5 discusses potential problems associated with the running of such schemes. Chapter 6 is concerned with the regulation of GSHP systems. It gives a brief outline of existing regulatory approaches as currently employed within different European countries as well as the US. Finally Chapter 7 examines existing modelling approaches that have been used to investigate how GSHP schemes impact on the source aquifer. The chapter also reviews GIS-based tools that evaluate the suitability and sustainability of an aquifer for GSHP installations.

1 Introduction

Groundwater temperatures are relatively constant at depths of 10-15m below ground surface (approximating the mean annual air temperature at that location) and with further depths increase according to the geothermal gradient (average 2.6ºC per 100m depth). As a result, there is a temperature difference between above-ground (air) temperatures and groundwater temperatures for most of the year, with groundwater being colder than air during summer and warmer during winter. Ground source heat pump (GSHP) systems exploit this natural temperature difference for heating or cooling demands. In open-loop systems, groundwater is abstracted at ambient temperature from one or more abstraction boreholes, passed through heat exchangers or heat pumps before being discharged back into the aquifer through one or more injection borehole(s). The water will have undergone a temperature change and the discharged water will be cooler (if used for heating of the building) or warmer (if used for cooling of the building).

The use of GSHP systems for heating or cooling is widespread in the US and Canada and certain European states (e.g., Germany, France, Switzerland and Sweden). In the UK, it is an emerging technology. The number of UK installations has increased rapidly since 2000, from about twelve systems installed between 1970 and 1994 to approximately 3,500 systems (all system types) in 2008[1] (2009). The reasons for this rapid development include the increased awareness of climate change issues, rising fuel prices as well as the introduction of the Merton Rule and similar policies in 2003, which require new developments above a certain size to generate 10% of their energy needs from on-site renewable sources. Currently, open-loop systems are a relatively small sector in the overall GSHP market in the UK, but demand for use in larger scale commercial/public buildings in urban environments is expected to increase. Market growth scenarios published by the Environment Agency (Le Feuvre and St John Cox, 2009), for example, predict that between 7,750-29,000 open loop systems will be operational by 2020 in the UK.

This rise entails increasing pressures on natural resources such as groundwater and there is increasing concern over the sustainability of such abstraction-reinjection (open-loop) systems and their impact on the aquifer’s thermal budget (Kelly, 2009). Successful management of these new pressures and demands requires a good understanding of the short-term and long-term impacts, hydraulic and thermal, of individual schemes on the groundwater system as well as their long-term sustainability and efficiency. Such information is very important for regulators, such as the Environment Agency in England and Wales, to target the regulation of these resources appropriately. Changes to the legislation may be required to establish the regulation of heat, or to adapt existing regulatory tools.

Sustainability of ground source heat resources, heat propagation through rock and water, and the effect of temperature changes on groundwater chemistry are the principal areas where gaps in knowledge and understanding exist (Kelly, 2009). Numerical heat transport models (as well as geochemical models) are indispensable tools to support research in these areas. They are not only valuable for verifying the conceptual understanding of an aquifer system, but can also help to predict the operational performance of a GSHP system, its impacts on other potential groundwater users and to simulate long-term thermal interference effects.

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[1] This figure is estimated from a number of sources, including European Heat Pump Statistics, 2008; Kensa Partner Newsletter, 2008; see Le Feuvre and St John Cox, 2009 for details

2 Use of GSHP (open-loop) in the UK

Since 2000, the number of installations of GSHP in the UK has increased rapidly. In London, for example, 179 proposals and applications for open-loop GSHP were received between 2000-2009 (Fry, 2009).

Registration of GSHP installations is not required (or possible) and hence, there is no definitive figure for the total number of systems currently installed in the UK. A recent review by the Environment Agency (Le Feuvre and St John Cox, 2009) estimates that approximately 3,500 systems (all system types) were in operation in the UK in 2008. The accuracy of this figure is uncertain and estimates in various literature sources for installations in 2008 range between 1,500 and 4,000[2]. Most GSHP installations are microgeneration schemes (<45kWth capacity); between 745 and 2000 were estimated to be operational in the UK in 2007 (Element Energy, 2008). As part of the EA review, stakeholders were asked to produce a best estimate for UK installations in 2009. Predictions ranged from 3,000 to 10,000 (all systems), with 8,000 being considered the most reasonable figure for the UK (Le Feuvre and St John Cox, 2009). The figure has not been confirmed and seems rather high considering that it implies an increase of almost 130% within one year.

The main applications (70-90%) for GSHP systems (all types) in the UK are domestic, heating-only systems (Le Feuvre and St John Cox, 2009). In urban areas, the proportion of commercial/public installations appears to be higher, as is the demand for cooling. In Central London, for example, 62% (111) of all open-loop installations use combined systems (that allow for heating and cooling) while 36% (64) use cooling systems (Fry, 2009). These systems will discharge higher temperature water into the natural environment and may affect local ecology and aquifer structure.

There are very few industrial applications of GSHP (<1%) in the UK as waste heat is a more suitable heat source and provides higher temperatures than those available in the ground. However, GSHP are often used for cooling and refrigeration and installations of open-loop industrial cooling systems are likely to increase, especially in the foods and drinks industries, as popular refrigerants are being phased out (Le Feuvre and St John Cox, 2009).

Table 1. Typical capacity of different GSHP systems (all types) (from Le Feuvre and St John Cox, 2009)

Application	**Capacity/Range**	**Reference values**
Residential/Domestic	2-15 kW	Small (e.g. terraced house): 5kW Large (e.g. detached house): 11 kW
Housing association/Council residential	20-100kW	Dependent on number of housing units and configuration
Commercial	50kW-MW scale	Small (e.g., small office): 55kW Large (e.g., large office): 330kW
Public Sector	50kW-MW scale	For offices: similar to commercial For schools, bespoke depending on size and amenities Hospitals: MW scale

[2] See Le Feuvre and St John Cox (2009), p. 11 for references

Capacities of GSHP installations vary from system to system; typical values (for all system types) are listed in Table 1. The average capacity of GSHP systems in the UK is estimated as 6.5kW per installation, confirming that domestic systems and microgeneration technology (<45kW capacity) predominate. However, larger installations of between 100kW and 300kW are becoming increasingly common. In spite of their low numbers (Table 2), these larger scale systems are very important in terms of the energy they generate. An industrial scale installation, for example has a similar output to more than 200 domestic units (Le Feuvre and St John Cox, 2009).

An estimate for the current total installed UK capacity is given in Table 2. These figures are based on the best estimate of 8,000 GSHP systems installed in the UK in 2009 as well as on assumed average sizes and percentages given in columns 2 and 3.

Table 2. Estimates of the current GSHP capacity in the UK (after Le Feuvre and St John Cox, 2009)

Sector	Average size of units*	Percent of installation*	Number of systems	Total capacity
Domestic	5 kW	90	7,200	36 MW
Commercial/Public	100 kW	9.5	760	76 MW
Industrial Scale	1 MW	0.5	40	40 MW

* these are the assumptions that were used for calculating the capacity

3 Examples of open-loop schemes

Technical details regarding the design, capacity and abstraction rates of open-loop GSHP schemes are not readily available, except for a few schemes. These include Galt House East Hotel in Louisville, Kentucky, which was the largest operational scheme in the US in 2004 (Lund et al., 2004). The scheme has a capacity of 15.8MW for cooling and 19.6 MW for heating, providing heat and air conditioning for 600 hotel rooms, 100 apartments, and 89,000 square meters of office space for a total area of 161,650 square meters.

In the UK, detailed information on the design of schemes and abstraction quantities required for running these schemes are only available for London. Here, a typical scheme consists of two wells, non-consumptive abstraction (77% of all schemes[3]) and is operated for combined heating and cooling (62% of schemes). Abstraction quantities are usually 10-20 L s^{-1} but can exceed 50 L s^{-1} in some of the larger installations (Fry, 2009).

Data for other schemes (worldwide) is available from various sources and summarised in Table 3.

[3] This includes operational schemes as well as schemes undergoing investigation

Table 3. Technical details for selected schemes

	Heating / Cooling	Number of production wells	Well depth, (m)	Abstraction rate (L s^{-1})	Discharge to/ Number of injection wells	Mean abstraction Temperature (° C)	Injection temperature (° C)	Heat pump capacity (kW)	Source of information and comments
Galt House East Hotel, Louisville, Kentucky, US	H + C	4		177	?	14		15.8MW (C) 19.6 MW (H)	(Lund et al., 2004)
Inn of the Seventh Mountain, Oregon, US	H + C	1	122	72.5	1	10		1758 (total of 2 heat pumps)	(Bloomquist, 2005a)
Kestrel Building, Wallingford, UK	C	1	25	< 1	1	14		72	Paul Middleton, Technical Services Manager, HR Wallingford Ltd,
Portcuillis House- HoP, London, UK	C	2	150	22	sewer	13.5	19-21	765	(Ampofo et al., 2006)
Royal Festival Hall, London, UK	C	2	140	25	River Thames	14	20	1200	(Ampofo et al., 2006) (Clarkson et al., 2009)
Sundown M Ranch , Yakima, Washington, US	H + C	2	61 57	22.7 16.4	1	13.9		1523 (total of 302 heat pumps)	(Bloomquist, 2005b), pumped 24hrs a day
The City Hall, London, UK	C	2	100	30	sewer	12-14	20-22	1000	(Ampofo et al., 2006)
The Queen's Gallery, Buckingham Palace, London, UK	C	1	150	29	sewer	13.4	22-23	700	(Ampofo et al., 2006)
The Sadler's Wells Theatre, London, UK	C	1	200	12	sewer	11-12	22	500	(Ampofo et al., 2006)
The Zetter Hotel, Clerkenwell, London, UK	C	1	130	1.4	sewer	13-14	22	47	(Ampofo et al., 2006)
Selby factory, UK	C	1	70	12	1	11	20	450	(Todd and Banks, 2009)

4 When does GSHP system become cost-effective

With escalating fuel costs and diminishing resources, GSHP's are considered to provide a cost effective alternative to traditional heating and cooling systems. Among the benefits, stated by energy savings-websites and installers, is the potential to lower fuels bills (Energy Saving Trust, 2010) and to become cost-effective within a few years after installation. Many of the figures/statements on installation costs and cost-effectiveness refer to residential, closed-loop schemes. In some cases, these figures are quoted in this report as a general reference but also because similar figures for open-loop and/or commercial system are rare.

Cost-efficiency and the amount actually saved will depend on a number of factors, including

- Installation costs of system
- GSHP system efficiency/ coefficient of performance
- Current heating system efficiency
- Electricity or gas tariff
- Available grants for GSHP installations

Local climate is also of importance, as heating season savings are more significant in colder climates, while cooling season savings will likewise be greater in hotter climates. Depending on the factors above, typical returns on investment are quoted as 6%-15% a year (Green Energy 360, 2010), which implies a payback period of 17-7 years.

Installation costs vary greatly depending on the size of the system and local geological/hydrogeological settings which determine borehole depths and drilling costs. The Energy Saving Trust states the expected costs of a typical GSHP system to fall between £4,500 and £14,000 installed (Energy Saving Trust, 2006), although it is not clear from the publication if this includes open-loop systems. Also, this figure probably only applies to residential schemes. Installation costs for commercial schemes are expected to be considerably higher. Actual figures are difficult to find as many of these buildings are newly-built and costs are hidden within the total cost of construction (e.g. The Environment Centre in Wales, closed-loop, £5.8M (ECW, 2010)). However, some figures are available for retrofitted systems. The cost of the (closed-loop) heating system at Buckingham Palace, for example, is estimated to have been around £50,000 (Lund, 2005) while the installed HVAC[4] capital costs for retrofitting an (open-loop) system to a hotel/resort (22 buildings) in Oregon are given as $3M (Bloomquist, 2005a).

The efficiency of a GSHP system depends on the power-consumption of the well pump, the heat pump and the building loop pumps. Usually, the greater the groundwater flow the more favourable is the temperature at which the heat pump operates. However, the improvement in heat pump performance at higher groundwater flow is compromised by the rising consumption of the well pump to a point where the total system performance begins to decline. This needs to be considered in the design of the GSHP system which should be such that system's efficiency (i.e. balance between energy consumption and heat pump performance) are optimised (Rafferty, 2001). The heating performance of the system is defined by the coefficient of performance (COP). In simple terms, this is the heating output produced by the unit divided by the power input (required by the heat pump, the well pump and the loop pump). A similar measure exists for the cooling performance, which is called energy efficiency ratio (EER) (Rafferty, 2008). Typical values will be in the range of 2-4 for

[4] HVAC stands for Heating, Ventilation and Air-Conditioning

COP (Energy Saving Trust, 2006) and 12-18 for EER (Rafferty, 2008), where larger values indicate higher efficiencies (i.e., less energy input).

The remaining factors (as listed above), namely efficiency of the current heating system, the electricity/gas tariff and available grants will vary for each scheme and location and investigations need to be made locally as well as at the time of application to get a representative overview of the savings that can be made.

In terms of overall cost-effectiveness, residential GSHP systems are generally more expensive to install than a conventional heating system. However, they will be cost-effective in locations where mains gas is not available and where other energy-saving measures (e.g., cavity wall and loft insulation) have already been taken (Energy Saving Trust, 2006). In other locations, the installation of a heat pump system, especially at the residential scale, will probably reduce the CO_2 emissions, but may not necessarily lead to cost savings. In fact, calculations of annual heating costs (Pither and Doyle, 2010) for a semi-detached house (solid walls, no insulation, a room in the loft) have shown that a GSHP system (type not specified, CoP 3.15, Economy 7 tariff) is more expensive (£813/year) to run than a mains gas condensing boiler system (£801 pa). According to this study, significant savings could be made by converting from electric storage heaters (£1,470/year) to a GSHP system (£813/year), although a similar reduction in costs (£883/year) could be achieved by insulating the walls and roof of the property.

Another study by ESD (now part of CAMCO) compared monitored fuel consumption from two developments of small, well insulated Housing Association bungalows of different sizes (60m^3 and 100m^3). The dwellings were fitted with different-style heating systems including a (closed-loop) GSHP system (Powergen Heat Plant) to cover the total annual thermal energy requirement of 8000kWh and 12500kWh. The results suggest that there is only a small difference in annual fuel cost between the GSHP system (£210/£305) and gas condensing boiler (£235/£350), although larger differences are seen for traditional electric (£510/£760) or solid fuel heating (£805/£1230). More significant savings were made with regards to the annual CO_2 emissions, which was reduced by almost 1tonne/year if converting from a gas-heating to almost 7tonnes/year if converting from a solid-fuel-based system (Parker, 2006).

Large commercial GSHP systems generally have lower unit pumping energy requirements compared to residential systems (Rafferty, 2007), which makes the running of these systems more cost-effective. Additional cost benefits occur when utilised in buildings that also require cooling as there is no need to expend further capital on a second system. Some additional costs may arise in (office) buildings that have insufficient natural ventilation and where GSHP cooling is complimented by air cooling systems to maintain the circulation of fresh air.

5 Problems associated with operating open-loop GSHP

Most GSHP in the UK are domestic systems that are used for heating (Le Feuvre and St John Cox, 2009). However, there are approximately 500 commercial-scale GSHP systems in the UK that are used, at least partially, for cooling (Le Feuvre and St John Cox, 2009). These systems will discharge higher temperature water into the natural environment and may affect local ecology and aquifer structure.

Regulations are in place in most countries that regulate the water abstraction from and discharge to the 'host' aquifer. Problems may occur where schemes are designed without considering limitations imposed by these regulations, e.g., limits on temperature of discharging water. This appears to have been a problem at the Shrewsbury store of the UK supermarket chain Tesco where "the geothermal heat load generated by the store was greater than expected, and so the system is now unable to meet the operating criteria set by the Environment Agency. As a result, the geothermal system is not currently operating." (Energy and Climate Change Committee, 2010).

During operation of the scheme, problems can occur where a considerable proportion of returned (injected) water is drawn towards the abstraction borehole (as a result of the forced hydraulic gradient caused by the operation of the scheme) causing thermal interference and reducing the effectiveness of the scheme. Ferguson and Woodbury (2005), for example, reported that open-loop installations in the carbonate aquifer of Winnipeg, Canada experience temperature rises of a few degrees due to thermal "feedback". The temperature rise occurs only a few years after commissioning the schemes and modelling of the area suggested that the use of groundwater in cooling applications is not sustainable under current development schemes.

The risk of thermal interference and hydraulic interference is increased in areas of intense abstractions, such as London where many installations are within 250-500 metres of each other (Fry, 2009). Considering, for example, a well double scheme in a typical aquifer with a transmissivity of $100m^2$/day, a hydraulic gradient of 0.01 and an abstraction rate of 5 L/s, a minimum (well separation) distance (*L*) of 275m[5] between abstraction and injection well is required to ensure that there is a zero risk of thermal feedback (Banks, 2009b). For many densely populated urban areas, this value of *L* is unrealistically large, implying that thermal interferences in these areas are almost inevitable, at least in the long-term. In fact, Banks (2009b) suggests that open-loop GSHP systems have only a finite operational life anyway before thermal breakthrough become too large. Optimised system design and operational strategies can reduce the risk of interference and improve the sustainability of individual schemes to make them economically viable. However, these strategies can only succeed if the source aquifer and its resources (including thermal resources) are managed in an integrated and informed way. Improved risk assessment procedures using several tiers of increased complexity have been proposed (Banks, 2009b) together with steps to improve the life-span of individual open-loop GSHP scheme. These are particularly important for GSHP installations in fissured and fractured rocks where estimation of yields and travel time are much more uncertain compared to porous medium-type aquifers.

In urban areas, problems may occur as a result of schemes impacting on the overall groundwater temperature of an area/region, leading to thermal degradation of the aquifer. However, in urban areas, such as London, for example, more than 130 cooling systems may potentially discharge warm water into the aquifer in the future (within a ~100 km^2 zone), with more than 40 schemes within an area of 7km by 5km (Fry, 2009). Considering individual schemes, the impact on groundwater temperatures is likely to be small and limited to the area around the injection well (within a radius of 30-40m) (Andrews, 1978; Williams and Sveter, 1987). However, where several schemes are present within a small area, the increase in discharge of heated water into the aquifer has the potential to modify the temperature of the groundwater in the surrounding area and may also contribute to the 'urban thermogeological heat island' effect. The effect was observed in Gateshead, where downward conductive heat 'leakage' from long-established urban environments has lead to the modification of subsurface temperatures to a depth of 55m (Banks et al., 2009). At present, GSHP injections are not thought to be a primary cause for this effect (Le Feuvre and St John Cox, 2009), but could be in the future with an increase in the number of heat pumps installations. Regional-

[5] Assuming one abstraction and one injection well, not considering the influence of other nearby schemes

scale numerical modelling of groundwater flow and heat transport may be required to better understand the impacts that GSHP systems have on the regional groundwater system.

Because most GSHP systems are non-consumptive, the quantity of return flow water is generally the same as that withdrawn. Therefore, overall abstraction is not an issue. However, there will be localised draw down around the abstraction well which may affect local users and licence holders. Furthermore, the recharge mound accompanying re-injection of the water may interfere with local user's ability to abstract water where the pumps have not been designed to cope with the additional head (Fry, 2009). The localised groundwater level rise may also cause flooding of tunnels, increased chemical attack on buried steel and concrete as well as increase the loading on tunnel lining (Simpson et al., 1989). High discharge rates and resulting steep hydraulic gradients were , for example, held responsible for increased erosion of underground strata and structures (USEPA, 1997). In the UK, such damage is not a concern of the Environment Agency as it is not the "Agency's responsibility to protect (London's) infrastructure from localized discharge …". Any damage or flooding that is experienced as a direct result of GSHP recharge will be a civil matter between the applicant and the person experiencing the damage (Fry, 2009).

Many of the problems associated with the re-injection of the water into the aquifer are similar to those experienced in artificial recharge installations and are discussed in Bouwer (2002).

When groundwater is brought to the surface a number of chemical processes and reactions may occur, including:

1. CO_2 degassing and associated increase in pH and mineral (e.g., calcite) precipitation;
2. Dissolution of oxygen in the groundwater and oxidation of dissolved metals resulting in the formation of poorly soluble metal precipitates;
3. Formation of biofilms.

These processes have the potential to cause problems, such as clogging, abrasion or corrosion of the pump, the pipe work or the evaporator of the heat pump (Banks, 2008). They can also cause the injected water to differ chemically from the source (abstracted) water. For example, where water is withdrawn from and returned to the same aquifer, dissolved solid and suspended solid contents can differ between the abstracted and the re-injected water. The effect is usually minimal with no implications for human health (USEPA, 1999).

Recirculation of water at pressure and varying temperatures to the receiving groundwater can also lead to chemical interactions between the injected water and the aquifer bedrock, causing the dissolution (or precipitation) of aquifer minerals. Calcite, for example, is more soluble at lower temperatures; solubility decreases four-fold between 0ºC and 50 ºC (Garrels and Christ, 1965). The solubility of gases (CO_2, O_2) also increases with decreasing temperatures. In the case of CO_2, this means that more carbonic acid is present in colder waters (at a given pCO_2), hence more carbonate minerals (such as calcite) can be dissolved. Where CO_2 is lost from the water (degassing due to decrease in temperature or pressure), this can lead to the precipitation of carbonate minerals, provided that sufficient calcium and (bi)carbonates are present in the water (Armitage et al., 1980). Where colder waters are injected into warmer groundwater, for example, this may result in pore clogging in the receiving aquifer. Although limited to the area near the injection site, pore clogging may affect the performance of the GSHP system as well as the infiltration capacity of the injection well. In contrast, dissolution of minerals can result in the creation of new pathways through the aquifer bedrock and overlying strata, and may also impact on the groundwater quality. Within the anticipated range of temperatures, the overall effect of temperature on mineral solubility is likely to be small. Other factors, such as pH are likely to be the dominant control, but these are also affected by temperature changes through the solubility of CO_2.

Temperature also affects the viscosity of water and hence, can influence infiltrations rates. Where cold water is injected into a warmer aquifer, the water's viscosity may increase, resulting in slower infiltration rates. This has been identified as a potential problem for artificial recharge installations (Bouwer, 2002) but the effect on GSHP system is not known (USEPA, 1999).

The infiltration borehole may also experience problems of biological clogging (due to accumulation of algae and micro-organism growth on the infiltrating surface/ aquifer substrate). Algae growth may also induce mineral precipitation by removing CO_2 from the water and lower the pH (Bouwer, 2002). This may further contribute to clogging of the pores resulting in a (localised) reduction of aquifer porosity and hydraulic conductivity.

Depending on the GSHP system and the groundwater hydrochemistry, the injection water may also contain other types of contaminants, such as metals leached from pipes and pumps, bacteria, precipitated iron and manganese hydroxides and/or chemical additives. A study by the Environmental Protection Agency of the United States (USEPA, 1999) has found a few cases where concentrations of copper, lead and chloride in return waters exceeded the water maximum levels for drinking water and caused contamination of the receiving aquifers. The prevalence of this problem is unknown, but is unlikely to be significant. Leaching of metals from GSHP system would only be expected in acidic waters and the use of chemical additives in open-loop systems is expected to be low (USEPA, 1999). However, regulations should be in place, as is the case in London (Fry, 2009) the UK, that require an assessment for each proposed schemes of the potential to contaminate or change the quality of the re-injected water as well as proof that precautions have been taken to prevent such contamination. Regular water quality monitoring of the injected water should also be a legal requirement.

A greater risk of contamination occurs in dual aquifer systems. These systems are used where another formation (different from which source water is withdrawn) is more readily accessible for return flow discharge and is capable of handling the injected volumes. Problems may occur where the geochemistry of the two aquifer systems is largely different or where the source aquifer is contaminated and the water is re-injected into a non-contaminated system. To minimise these risk, regulations in parts of the UK (e.g., London), require that any recharged groundwater must be re-injected into the same aquifer (and to the same depths) from which it was abstracted (Fry, 2009). This implies that dual-aquifer installations are usually prohibited in these areas and this is also the case in other countries (e.g. in Italy, Lo Russo and Civita, 2009).

A number of problems and concerns arise from the improper borehole construction and installation of GSHP systems. These include groundwater contamination from downward leakage along the side of the borehole as well as inter-aquifer flow. To minimise such problems, many countries regulate the borehole placement and construction (USEPA, 1999). However, these problems are not specific to GSHP installations and hence, are not considered in this study.

6 Regulatory approaches in the EU and worldwide

Clear energy and environmental policies and regulations are of paramount importance for the sustainable use of geothermal energy and GSHP systems. Such regulations should provide a framework for managing the use of geothermal resources and, as recommended by the European Geothermal Energy Council (2007) need to serve the following purposes:

1. Secure the environmentally friendly use of geothermal energy, in particular with regards to the protection of underground drinking water resources
2. Regulating competing uses and securing the sustainable use of geothermal energy
3. Granting the investor the right to use geothermal energy in a given area and to a given extent.

At present, the legislative and regulatory framework for geothermal energy is very diverse worldwide as well as within the EU member states (Banks, 2008; European Geothermal Energy Council, 2006). While it is generally recognised that heat can cause pollution and should be controlled, there is no detail in the legislation on how this may be achieved. In many countries, geothermal resources are dealt with within the Mining Law whereas the abstraction/re-injection of the water from the subsurface is regulated by the Water Protection legislation. A survey of the relevant legislation in various European countries has found that regulation of GSHP appears to be different in each country (European Geothermal Energy Council, 2006). A number of countries have been selected for this review and the different regulatory approaches are summarised below.

6.1 REGULATIONS IN THE UNITED KINGDON

In England and Wales (Fry, 2009; Le Feuvre and St John Cox, 2009), the operation of open loop GSHP schemes is regulated by the Environment Agency's abstraction licence and discharge consent (now covered by Environmental permits) requirements. The installation and operation of an open loop GSHP scheme will normally require prior permission from the Environment Agency, in the form of consent to drill and conduct a pump test, an abstraction licence and an environmental permit.

To drill and test-pump a well (borehole), a Consent to Investigate a Groundwater Source (CIG) must be obtained. As part of the application procedure, a number of tests and surveys are carried out, depending on individual circumstances of the proposal. These may include constant rate abstraction and constant rate recharge tests to determine achievable yields and recharge as well as a water features surveys that evaluate the impact of the proposed system on local water features and receptors. The information collected under this consent is vital for a successful abstraction licence application. Abstraction licences are required for all GSHP systems, unless they are very small (abstraction of $<20m^3\ day^{-1}$ for private water use is exempt from licensing). Applications need to include detailed explanation of the proposed system as well as sound justification of the proposed water quantities. Sustainability of the abstraction licence (with regards to yield of the well and sustainable development) is assessed for conditions at the time of application (Fry, 2009), but this assessment does not consider factors that may arise from future conditions at the site (e.g., long-term change in groundwater level).

The return of thermally 'spent' water to surface water or an aquifer used to be regulated via consents to discharge. In April 2010, the regulation regime changed and discharge is now regulated as part of the Environmental Permits regime. Permits are required for all schemes that discharge to ground and are deemed to have the potential to cause pollution. Permits are also required for all schemes that discharge to surface water, with the exception of schemes for heating purposes from a single dwelling. The permits specify conditions controlling the composition and rate of discharge, and may include temperature limits as well as the maximum allowable change in temperature (usually 10ºC) relative to the ambient groundwater temperature to prevent pollution. The permitted discharge rate is in most cases equal to the abstraction rate and monitoring may be required as part of the consent to ensure that the composition conditions are adhered to (Fry, 2009; Hall, 2010).

In addition, any well or borehole that penetrates strata that contain coal deposits or mine working requires consent from the UK Coal Authority. All boreholes > 15m deep must also be reported to the British Geological Survey.

A number of issues related to these regulations were identified by stakeholders in a recent consultation by the Environment Agency (Le Feuvre and St John Cox, 2009). It was suggested that a centralised approach would be more appropriate and that the application process be modified so that a single department processes applications, rather than different departments managing abstraction licences and discharge consents. This has partly been addressed by the introduction of the Environmental Permitting (England and Wales) Regulations 2010. Under these new regulations, operators will be permitted to consolidate a number of waste and Pollution, Prevention and Control (PPC) permits into a single environmental permit.

Furthermore, stakeholders agreed that the potential thermal impacts of open loop systems should be given more consideration in the regulatory process, particularly interference between systems and how thermal impacts effect the environment (Le Feuvre and St John Cox, 2009). The Environment Agency recommends that the applicant establishes the maximum area of influence on water quality, hydraulic head and temperature arising from the operation of the proposed system (Environment Agency, 2008). Thermal assessments and long-term predictions are not a requirement of the licence application, at present, although in some areas applicants are advised to use thermal transport assessments to consider long-term performance of their proposed scheme as well as local interferences. However, the regulatory control of discharges is aimed at protecting groundwater within the aquifer, not guaranteeing that abstracted water (and its temperature) is suitable for use. In that sense, it remains the applicant’s responsibility to understand how the operation of the proposed system will interact with and impact on other local systems and their efficiency (Fry, 2009).

Work is ongoing within the Environment Agency and government departments to improve the regulation of GSHP systems. A recent Legislation and Policy document (Environment Agency, 2008) identified the key issues related to GSHP installations. The document outlines some general policies and makes best practice recommendations. Nonetheless, many of these issues are tackled differently by different regulatory bodies/local offices. This creates confusion within the industry and discourages the adoption of the technology (ESI, 2010a). A recent Select Committee report on low-carbon technology, therefore, recommends that the process for obtaining licenses and the guidelines for the operating criteria of ground source heat pumps are clarified (Energy and Climate Change Committee, 2010).

Open-loop GSHP schemes in Scotland are regulated by the Scottish Environmental Protection Agency (SEPA). It employs a risk-based regulation and authorisation system, the Controlled Activities Regulations (CAR)[6], which includes different authorisation levels for different activities according to their risk to the environment. Open-loop GSHP schemes that abstract and discharge <10 m^3 per day or that abstract and discharge into the same geological formation and where the chemical composition of the water is not altered are considered as low risk to the environment. These activities do not necessitate any authorisation from SEPA,

[6] Water Environment (Controlled Activities)(Scotland) Regulations 2005 (‘CAR’) extended and amended by The Water Environment (Controlled Activities) (Third Party Representations etc) (Scotland) Regulations 2006, The Water Environment (Controlled Activities) (Scotland) Amendment Regulations 2007 and The Water Environment (Diffuse Pollution) (Scotland) Regulations 2008

but require compliance to the General Binding Rules GBR 2 and GBR 17, respectively. Where water is returned to a different geological formation or there is an alteration to the chemical composition of the abstracted water, authorisation from SEPA is required in the form of registration (activities of low but cumulative risk) or licences (higher risk activities). Although not a legal requirement, SEPA also encourages the assessment of the potential environmental impacts of the GSHP system to aid compliance with the GBR and to ensure effective operation of the GSHP system.

6.2 REGULATIONS IN FRANCE

Geothermal installations in France (Jaudin, 2010; Rybach, 2003) are regulated by the Mining Law (Code Minier). Licences are required for all installations where drilling is > 100m deep and where the maximum possible heat extraction rate is > 200 thermal units/hour (232 kW). Where borehole depth exceeds 10m, the borehole must be registered with DREAL[7] (Art.131 of the Mining Code) and any information resulting from the drilling is publicly available from BRGM[8]. Geothermal installations are also regulated by the Environmental code (Code de l'Environment) and by its Water Law (Loi sur l'Eau). For open-loop GSHP installations this means that different declarations or authorizations are required, depending on the system design (e.g., installed flow-rate capacity, reinjection into aquifer) and geographical location (there are protected zones and aquifers). For large flow rates, taxes on water withdrawals from superficial aquifers are charged by the Basin Agencies. Regulations also include standards for good practices for drilling (Norme AFNOR FD X10-999, Norme AFNOR NF X10-980 and NF X10 970) as well as for geothermal ground heat exchangers (currently in preparation) (Jaudin, personal communication).

A summary of the French regulations (which apply at the time of writing) has been provided by Jaudin (2010) and is given in Figure 1.

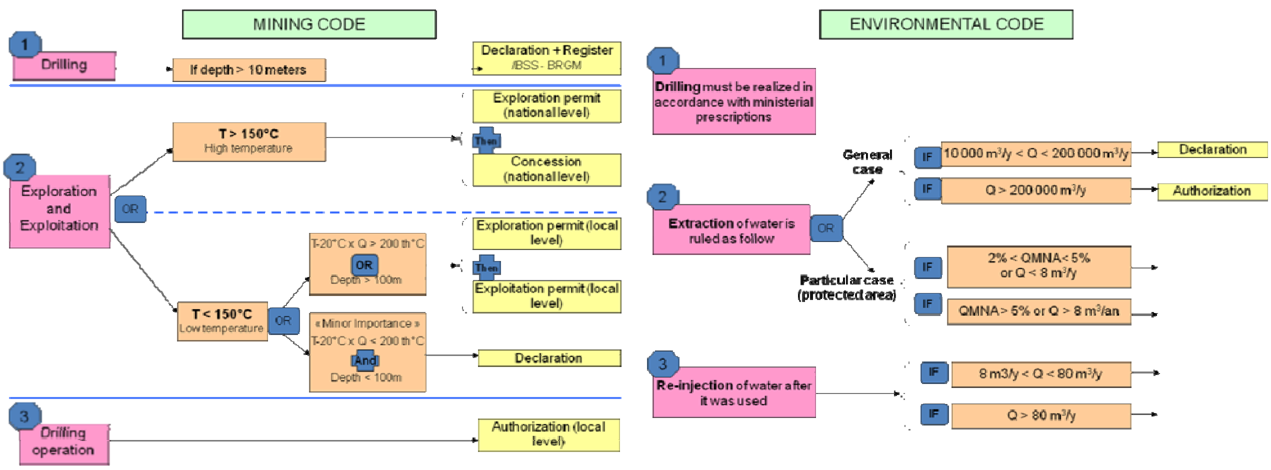

Figure 1. Flow chart of French regulations that are relevant to GSHP systems (Bezelgues, 2008; Jaudin, 2010)

[7] DREAL : Regional Department for Environment, management and accommodation which is responsible for regulating water and mining-related issues
[8] BRGM : Geological Survey of France (Bureau de Recherches Géologiques et Minières) (www.brgm.fr)

6.3 REGULATIONS IN GERMANY

Geothermal energy use in Germany (European Geothermal Energy Council, 2006; Rybach, 2003) is governed by the Federal mining act (Bundesbergbaugesetz). According to this act, geothermal energy is not a property of the land owner, but belongs to the Federal state and its use needs to be licensed by mining authorities. When a mining licence is given, other aspects like water protection and environmental protection are dealt with by the mining authorities and relevant offices, and the necessary approvals are included in the licence. Licensing under the mining act is not required when the resource (e.g., heat) is used wholly on the site where it is abstracted (e.g., residential schemes) and/or if the borehole is less than 100m deep. In these cases, the geothermal scheme is regulated by the water law (Federal Water Household Act) and relevant licenses (e.g., for abstraction, environmental protection) need to be obtained from the state (Länder) authorities.

6.4 REGULATIONS IN SWITZERLAND

In Switzerland, the regulation of geothermal energy is not well defined on the federal or cantonal level. The use of ground-source heat in open-loop systems is largely regulated at the canton-level via water resources laws (Banks, 2008).

6.5 REGULATIONS IN THE US

In the US (Bloomquist, 2003), open-loop systems are typically regulated under normal water-resources law pertaining to well and discharges (Banks, 2008). Nearly all states have statutory and regulatory requirements for GSHP injection boreholes, which regulate the size, design and/or additives used in the system. USEPA also operates an Underground Injection Control (UCI) program for Class V[9] injection and relevant regulation approaches are summarised in USEPA (1997). Much more complex permitting requirements exist for dual-aquifer systems due to the increased risk of contamination.

7 Modelling studies and GIS applications

The following section gives some examples of how models have been used in the context of GSHP. However, this review is by no means comprehensive and many other examples of such model applications have recently been presented to the science community (2nd international FEFLOW User Conference, 2009; Barker, 2007; Gandy and Clarke, 2007; Geological Society, 2007; Todd and Banks, 2009).

Understanding the interaction between ground source heating and cooling systems and the groundwater system is essential to ensure the sustainability of the system and to assess and manage the environmental risk. Analytical/semi-analytical models and methods can be used to assess the risk of hydraulic and/or thermal feedback within one or between several schemes (Banks, 2009a), even in dual-porosity aquifers such as the Chalk (Barker, 2010). However, these algorithms are usually insufficient to handle more complex aquifer settings and GSHP systems and operations. In such cases, numerical modelling is more appropriate using available models such as SHEMAT (Clauser, 2003), HST3D (Kipp, 1997) or FEFLOW® (Diersch, 2005).

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[9] Injection wells used for subsurface disposal (or return) from Heat Pump and Air conditioning (HAC) systems are classified as Class V underground injection wells (USEPA, 1997)

Numerical flow and heat transport modelling can be used to examine existing problems (Ferguson and Woodbury, 2004), to investigate the feasibility of heating/cooling schemes and operational procedures (Gandy et al., 2010), to test scenarios (e.g., such as those suggested in Banks (2009b)) as well as to investigate the likely magnitude of impact of a scheme (Lo Russo and Civita, 2009), in particular where significant potential for impact on water features or existing users has been identified in the feasibility study. Such applications are outlined by Gropius (2010) who used the finite-element package FEFLOW® to simulate interference between existing and planned open- and closed loop GSH schemes in central London. He clearly demonstrated the risk of thermal interference between schemes and emphasised the need for careful planning and resource management. In a second case study, Gropius (2010) simulated groundwater and heat flow at an operational open-loop scheme, where problems of thermal feedback had occurred as noted by a 6.5ºC rise in groundwater temperature within the first year of operation. He applied a conceptual modelling approach which represented the network of fractures and fissures in the Upper Chalk as 1m or 10m thick highly permeable layer (continuum model). Using this approach, he was able to reproduce the general trend of the monitored abstraction temperatures, although absolute temperatures deviated by +25% and -20%, respectively. The modelling results largely improved after calibration of the model with site-specific data (hydraulic transmissivity and permeability, fracture properties). Gropius (2010) concluded that the application of the conceptual modelling approach is applicable at the feasibility stage, where site-specific data are usually not available. However, the model should be revisited once such data become available in order to reduce the uncertainty in the numerical modelling results and to increase the reliability of model predictions.

Another large-scale modelling application, commissioned by Transport for London (TfL), simulated the effects of ground source heat pump schemes on groundwater temperatures in Greater London and identified potential interferences between neighbouring schemes (Arthur et al., 2010; Herbert et al., 2007). "The transport of heat within the aquifer was initially modelled using an adapted version of MODFLOW and MT3D. To account for potential temperature effects on groundwater flow and the influence of the unsaturated zone on heat conduction, the models were also developed in the finite element code FEFLOW®. Results from the different numerical codes were compared to increase the understanding of the influence of the mathematical methods on the calculated solutions and intensive sensitivity analyses were carried out to account for the uncertainty inherent in the aquifer characteristics and thermal properties applied in the models." (ESI, 2010b).

On a smaller scale, Todd and Banks (2009)simulated the migration of a thermal plume from an open-loop well-doublet industrial cooling system using SHEMAT. They found that while groundwater dispersion was not considered in the model, there was evidence that numerical dispersion affected the results. They concluded that the analytical assessment based on hydraulic and thermal travel time calculations was preferable to the numerical model.

Groundwater and heat modelling can also be applied to identify suitable sites for geothermal installation and to generate suitability maps. The approaches to evaluate the suitability of a location/area for GSHP installations differ, depending on data availability and scale of application. Fujii et al. (2007), for example, presents suitability in the form of heat exchange rates for a standard ground-coupled (i.e., closed-loop) heat pump. The maps are derived by constructing a regional groundwater flow and temperature model and simulating the thermal performance of a standard ground heat exchanger system under different scenarios and at different locations in the study area. The modelling was carried out using FEFLOW® and suitability maps were derived by contouring the heat exchange rates. Although this methodology is designed for closed-loop system, it could be adjusted to open-loop applications by simulating groundwater abstraction/injection volumes and temperatures instead of heat exchange. However, such modelling requires good hydrogeological and temperature data and constructing and calibrating the groundwater model can be quite time consuming.

Suitability maps have also been generated by using Geographical Information Systems (GIS) in combination with an aquifer classification/ indexing system. BRGM (and collaborators), for example, employed such a GIS-based approach to map the suitability of mostly superficial aquifers (<100m deep and average groundwater temperature 10-15ºC) in France for GSHP installations (Bezelgues et al., 2010). As part of this exercise a set of GIS maps (accessible at www.geothermie-perspectives.fr) was produced to support the planning of GSHP installations at the feasibility stage, in particular commercial-scale installation (i.e. large supermarkets, office buildings and hospitals). These maps are available for most regions of France, although there seem to be some variations in map contents and mapping methodology between the regions. In the Région Ile-de-France (Schomburgk et al., 2005), for example, the "exploitability" of the main aquifers is mapped based on their hydrogeological and geochemical properties. Parameters like depths to groundwater table, saturated aquifer thickness, transmissivity and hydrochemistry of the aquifer are evaluated and form the basis for aquifer classification. Using the ranges and weight coefficients in Table 4 and Table 5, five classes of "exploitability" are derived ranging from 'very weakly exploitable' to 'very strongly exploitable'. Maps are provided for the individual parameters as well as for potential discharge and exploitability. Groundwater temperatures were also considered in the assessment, but for simplicity were averaged across the region. Hence, temperatures are not included in the index (or maps), instead average values for winter (12ºC) and summer (16ºC) temperatures are provided to be used in calculating the thermal energy resources available for extraction.

Table 4. Parameter ranges and weighing coefficients (after Schomburgk et al., 2005)

Weighing coefficient	1	2	3
Depth to water table	0-5m, >50m	25-50m	5-25m
Saturated aquifer thickness	0-5m	5-20m	>20m
Transmissivity	10^{-5}-10^{-3} m^2/s	10^{-3}-10^{-2} m^2/s	>10^{-2} m^2/s
Hydrochemistry/water hardness (ºf)	>32 (strongly mineralised)	22-32	<22 (weakly mineralised)

Table 5. Exploitability ratings as inferred from parameter weights (after Schomburgk et al., 2005)

Transmissivity	1			2			3		
Saturated thickness	1	2	3	1	2	3	1	2	3
Depth to GWL	1	2	3	1	2	3	1	2	3
Hydrochemistry	1	2	3	1	2	3	1	2	3
Exploitability	**4**	**7**	**10**	**5**	**8**	**11**	**6**	**9**	**12**

⇓

very weakly	**weakly**	**medium**	**strongly**	**very strongly**

In the Région Centre (Martin et al., 2007), the suitability index for GSHP installations is presented as “geothermal productivity”, rather than “exploitability”, and is based on the (estimated) yield of an production well and the minimum aquifer thickness. Ranges and weights were assigned similar to (Schomburgk et al., 2005), and values were regrouped into three classes: “strong”, “average”, “weak”. Groundwater chemistry is not included in this index as it was not thought to affect the geothermal productivity, although it may affect installations (Martin et al., 2007) and hence sustainability (economics) of the scheme. The study also produced a map of the geothermal resource potential which presents the estimated thermal capacity (C_{therm}) that is available from the aquifer. The available geothermal capacity (in kW) for a production borehole was calculated as

$$C_{therm} = 1.16 * Q_y * \delta\mathrm{T} \qquad \text{(Equation 1)}$$

where Q_y is the yield of the production borehole and δT is the temperature difference (which is assumed to be constant =.6ºC).

Data and maps presented in these two studies are intended to help identifying suitable locations for GSHP within the region. It is recommended that, as a first step, “geothermal productivity” (Région Centre) /“exploitability” (Région Ile-de-France) maps are being used in conjunction with maps of individual parameters to check the suitability of a locations for GSHP installations. If found suitable, the maps of the geothermal resource potential (Région Centre) / calculations of thermal energy resources (Région Ile-de-France) can then be consulted (e.g., as part of the feasibility study) to confirm that the thermal capacity at the site is sufficient to support the planned scheme. The outputs of these two studies (as well as those undertaken in other regions of France) are available on CD ROM (www.geothermie-perspectives.fr), which includes the required GIS software, and hence can be used by planners as well as by interested individuals. The authors point out that the maps may include some local incoherencies, resulting from the interpolations of data across the region (e.g., from selected discharge data points) (Schomburgk et al., 2005). Unfortunately, these studies do not provide any measure of model performance (e.g., “strength” of prediction), model uncertainty or error. Such information is essential for the user of these tools to assess the reliability of the predictions and to give confidence in the results.

A GIS-based approach is also presented by Gandy and Younger (2010) who derive a ground source heat potential index (for open-loop installations) using the numerical ranking system DRASTIC (Aller et al., 1985). Ranking, weighting and index calculations are similar to those applied by Schomburgk et al. (2005), but aquifer property data (e.g. transmissivity, yield, specific conductivity) were not available for this study. Instead, basic hydrogeological properties (e.g. aquifer/aquitard, aquifer thickness, depth to aquifer) were inferred from the observed geology and borehole records by means of hydrogeological domain mapping (McMillan et al., 2000). The final data sets considered in the index included (1) aquifer thickness, (2) depth to aquifer, (3) distance to licensed abstraction, (4) thickness of overlying aquitard and (5) thickness of superficial deposits. The selection of these parameters and their relevance for assessing ground source heat potential is debatable as is their weighting and ranking. Parameter 3 (distance to licensed abstraction), for example, seems more related to the sustainability of a scheme rather than to the suitability of the location. Furthermore, it would seem sensible to differentiate between schemes of different types and sizes (e.g. by deriving a set of indices rather than just one). A large-scale commercial installation for cooling, for example, has different requirements/flexibilities to a small scale residential heating scheme (e.g. with regards to abstraction depths, aquifer thickness, yield). This should be considered in the weighting and ranking, as sites that are unsuitable for small-scale installations may still have potential for large-scale installations (e.g., by pumping larger volumes or by accessing a deeper aquifer) and vice versa.

Very little information is available in the literature on geochemical modelling in the context of GSHP applications. This could be because the effect of mineral precipitation (and dissolution) on the long-term performance of the GSHP system is not (yet) appreciated and may only be of concern in certain aquifers or lithologies (e.g., confined aquifers, carbonates, iron-rich formations). Some modelling studies exist for deeper/ high-temperature geothermal applications where dissolution/precipitation reactions are more important due to the high temperatures of these systems. A study of the Berlin Geothermal Field (El Salvador), for example, uses the programs SOLVEQ and CHILLER to model quartz precipitation at the injection borehole. The simulations show that a considerable amount of quartz precipitates on re-injection of the water into the aquifer resulting in a 50% reduction in porosity around the injection well after 10 years of simulation (Castro et al., 2006; Lopez et al., 2006).

A number of geochemical modelling studies have been carried out to investigate the impact of artificially recharging surface water into an aquifer, e.g., as part of Aquifer Storage and Recharge (ASR) research (Katzer and Brothers, 1989; Parkhurst and Petkewich, 2002; Ross-Schmidt et al., 2007). Common problems include the potential for chemical precipitation of calcite and iron oxyhydroxide, increase of iron bacteria and reduction in the efficiency of injection wells or in aquifer storage volume (Drever, 1997; Ross-Schmidt et al., 2007). These are very similar to the problems associated with heat pump discharge and it may be possible to adopt some of the presented modelling approaches.

8 Summary and conclusions

This report reviewed and discussed various aspects related to the installation and running of open-loop GSHP systems. The following points seem most relevant within the context of this study:

The reviewed information shows that there is an urgent need for clear and well-coordinated energy and environmental policies and regulations. It appears that existing regulations of GSHP are mostly concerned with resource and environmental protection, with little consideration for the interference of schemes. Some protection for existing schemes exists in Germany, where mining licences are given for specified licence areas (Erlaubnisfelder) (Rybach, 2003). The right to use the geothermal heat of that area resides with the licence holder and additional installations in that area have to be agreed with the licence holder. This means that owners can protect their installation but they can also prevent the construction of other geothermal schemes, even though the two installations would not influence each other (e.g., shallow borehole heat exchanger vs. deep geothermal plant). Including a depths limit in the licence in addition to the surface area would probably help to prevent such problems.

In London, the problem of interference between schemes is considered when licences are granted and no licence is given when the new scheme is believed to affect existing abstractions. Applicants have to demonstrate the long-term performance of the system is unlikely to result in adverse temperature changes in the groundwater or associated groundwater uses. A similar approach is currently investigated in the Netherlands, which, if implemented, will require a five year prediction of the (groundwater) thermal balance in the vicinity of the GSHP installation (van Beelen, personal communication).

New risk assessment procedures have been suggested which consist of several tiers of increasing complexity (Banks, 2009b) and include increasingly complex risk calculations as well as numerical modelling of heat and groundwater flow. However, they only consider the influence of individual schemes (and perhaps neighbouring abstractions). To guarantee the long-term sustainability of GSHP schemes in densely-populated areas, such as London, a more comprehensive approach may be required that also considers the wider impact that the entirety of operational and proposed schemes has on the aquifer, in particular in the long term. This could be achieved by means of larger-scale (regional-scale) modelling, which simulates changes in groundwater temperatures over the entire area and long time periods under different operational scenarios.

GIS-based methodologies were shown to provide a prospective tool for mapping the GSHP potential/suitability of a region (Bezelgues et al., 2010) or an aquifer (Gandy and Younger, 2010). These approaches use ranking and weighting approaches similar to those proposed by Dee et al.(1973). The selection of parameters as well as the determination of the numeric weight and ranking values is done heuristically. Consequently, the resulting indices are very researcher/research-group specific and difficult to compare. They strongly reflect the assumptions that the research team has made when assigning weights and ranking as well as the availability and quality of the data used for its calculation. To make these indices more comparable, it would be valuable if less subjective methods can be found to assign the different scores. At least, there must be a well-defined basis (or method) upon which these numerical assignments are made. This needs to include clear statements (and justifications) of all underlying assumptions and score assignments. In the case of GSHP applications, this should also state what type of index is produced (suitability or sustainability) and what type/size of schemes it is suitable for. Finally, for any such index (i.e., predictive model) to be valid, it must be reproducible and defensible. Therefore it is important that some model validation and/or evaluation is included in such studies (e.g., testing the effect of changing weights). It also requires a measure of model uncertainty/error and/or model performance (e.g., "strength" of prediction). This information is important for the user of these indices/models to assess the reliability of the predictions and to have confidence in the results.

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