Groundwater heat pump feasibility in shallow urban aquifers: experience from Cardiff, UK

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Highlights:

- Shallow urban aquifers proven suitable for water-water ground source heat pumps
- Whole system monitoring can improve user behavior, lowering CO_2 and running cost
- Seasonal Performance Factor of Ground Source Heat Pump system = 4.5 (GW13/W50)
- Field based monitoring improves confidence in heat flow model results

Abstract

Ground source heat pumps have the potential to decarbonise heating and cooling in many urban areas. The impact of using shallow groundwater from unconsolidated sedimentary aquifers for heating in urban areas is often modelled, but rarely validated from field measurements. This study presents findings from the *'Cardiff Urban Geo-Observatory'* project. This study focuses on an experimental open loop ground source heat pump scheme retrofitted to a school building. Field monitoring for three years between 2015 – 2018 provided data on the environmental impact of the scheme on aquifer conditions. Average aquifer thermal degradation in the first three years was kept below 2 °C, with a maximum change of 4 °C measured during the heating season. The numerically modelled predictions of thermal degradation around the production and injection wells are compared with long-term field monitoring data, providing new insights into both aquifer, and user, behaviour. The Seasonal Performance Factor (SPF_{H4}) of the pilot installation was 4.5 (W13/W50) in the monitoring period. An initial thermal resource estimation of the wider aquifer volume suggests that lowering the temperature of the aquifer by 8 °C could generate equivalent to 26 % of the city’s 2020 heating demand, but achievable heat extraction would in reality, be less. The study concludes that large parts of the aquifer can sustain shallow open loop ground source heat pump systems, as long as the local ground conditions support the required groundwater abstraction and re-injection rates. Future schemes can be de-risked and better managed by introduction of a registration of all GSHP schemes, with open sharing of investigation, design and performance monitoring data, and by managing thermal interference between systems using spatial planning tools.

Keywords: Thermogeology; seasonal performance factor; well doublet; geothermal; sustainability; renewable energy.

1. Introduction

Human interference with the climate is occurring, and adaption to cleaner energy sources is urgently needed to reduce emissions to limit the effects of global warming (IPCC, 2014). In May 2019 the UK government pledged to reduce greenhouse gas emissions to net zero by 2050. The decarbonisation challenge starts in homes and public buildings; space and water heating accounted for around 80 % of UK domestic energy consumption in 2017 (BEIS, 2018), and is currently dominated by carbon-emitting gas-fired heating systems. Space heating therefore needs to be rapidly decarbonised in a cost-effective and environmentally acceptable way. Ground Source Heat Pumps (GSHP) provide an efficient route to reduce gas consumption, but their uptake in the UK has been slow compared with many European countries (Buss, 2009). Reasons for this include low global gas prices, cultural bias towards gas central heating, relatively high installation costs, and low stakeholder awareness and marketing (Tsagarakis 2019).

GSHP can either utilise a closed loop heat exchanger, or an open loop configuration, which directly abstracts heat from a groundwater aquifer. The latter is called a Groundwater Heat Pump (GWHP) and usually involves two wells, one to abstract, and one to reinject groundwater, often called a 'well doublet' (Banks, 2008). Much of the UK enjoys a relative abundance of shallow and deep groundwater resources and GWHP systems are potentially feasible, but untested, in many urban areas (Allen et al., 1997). Investigations for open loop GSHP systems have traditionally targeted 'Principal' sedimentary bedrock aquifer sources at depths in excess of 100 m below ground surface (Birks et al., 2015), with 57 % of England and Wales showing potential to support commercial-scale (100 kW) open loop GSHP installations (Abesser et al., 2014). However, the high yields from deeper aquifers come at an increased drilling cost making open loop schemes too expensive for smaller projects. Shallow open loop options are often overlooked. Where urban areas are underlain by shallow, 'Secondary' aquifers (Jones et al., 2000), for example unconsolidated Quaternary sedimentary deposits, or flooded mine workings, there is potential for shallow low-enthalpy heat use (Allen et al., 1997; Hall et al., 2011), where ground conditions are suitable. Furthermore, urban groundwater systems are often thermally enhanced due to the subsurface Urban Heat Island (sUHI) effect (Allen et al., 2003; Taniguchi et al., 2009; Zhu et al., 2010; Menberg et al., 2013; Attard et al., 2016; Farr et al., 2017).

Open loop GSHP systems were not included in recent analyses of data from UK heat pump field trials (Dunbabin et al., 2013; Lowe et al., 2017), which focused on closed loop GSHP and Air Source Heat Pumps (ASHP). Furthermore, large-scale international reviews have mainly focused on monitoring and anthropogenic thermal impacts of closed loop systems (García-Céspedes et al., 2019; Taniguchi et al., 2009; Attard et al., 2016). Therefore, uncertainty remains regarding the technical feasibility, operational efficiency, and long-term environmental impacts of shallow open loop GSHP systems. Adequate resource planning of systems and regulation will be essential in urban areas as the density of systems increases to meet the UK government's commitment to achieving net-zero carbon emissions by 2050, and will likely require some change to current environmental regulation, policy and planning approaches (Abesser et al 2018). This paper provides a much needed UK case study to address this imbalance, with learnings that are relevant to other urban areas with shallow unconsolidated Quaternary aquifers.

The main hydrogeological uncertainties associated with designing open loop GSHP systems are aquifer yield and recharge capacity (Birks et al., 2015). These technical risks can be reduced by conducting geological and hydrogeological investigations prior to design and installation (Busby et al., 2009). Other identified risks are impacts on groundwater quality, chemical precipitation leading to aquifer clogging (Possemiers et al., 2014), release of heavy metal contamination due to changes in pH, redox conditions, dissolved oxygen and total dissolved solids (García-Gil et al., 2014), and ground stability in karstic and evaporitic rock environments. Thermal interference and thermal feedback between adjacent GSHP systems is also a potential problem for heat pumps used in heating mode, because a reduction in source temperature of 1.5 °C reduces system efficiency by around 5-10 % (Banks, 2008; Banks, 2009; Fry, 2009; Clarkson et al., 2009; Epting et al., 2013; Galgaro and Cultrera, 2013; Abesser et al., 2018). Previous studies have tended to focus on numerical heat flow modelling scenarios and design optimisation (e.g. Freedman et al., 2012; Lo Russo et al., 2014), or the thermal impact of river levels and temperatures on groundwater bodies (García-Gil et al., 2014). Few studies have compared modelling results with long-term field monitoring data collected from open loop GSHP systems.

This paper is focused on the observed impacts of an operational open loop GSHP retrofitted into a building to supply space heating. The study compares real impacts with predictions made from numerical heat flow models, and comments on the environmental sustainability and performance, as well as how upscaling for district heating might be achieved.

2. Study Area

The city of Cardiff, Wales, UK, covers a land area of 140 km^2, has a population of 346,000 and a population density of 2,500 per km^2 (Office for National Statistics, 2012). The city is traversed by the Taff and the Ely rivers which flow south east and discharge into Cardiff Bay, while the Rhymney River drains directly into the nearby Bristol Channel. The main human development is on moderately flat, low-lying, riverine and coastal flood plain, and glaciofluvial terraces (Fig. 1). Locally, the Glaciofluvial deposits are up to 30 m thick in buried valleys under the modern drainage channels (Anderson and Blundell, 1965) and these sediments typically comprise highly-permeable sands and gravels, making them a target for open loop GSHP systems and Aquifer Thermal Energy Storage (ATES). Groundwater levels in the sand and gravel aquifer have been monitored and managed since 1999 by Cardiff Harbour Authority (CHA) in response to the impoundment of Cardiff Bay by a coastal barrage (Edwards, 1997; Heathcote et al., 1997; Heathcote et al., 2003; Williams, 2008). As a result, groundwater levels have stabilised to around 3-4 m below surface across the southern part of the city (Farr et al., 2017). Average annual rainfall is 991 mm/year and average annual air temperatures is 10.3 °C. Shallow groundwater temperatures usually slightly exceed the average annual air temperature (Rybach & Sanner, 2000). The shallow subsurface regularly experiences higher than average annual air temperatures due to a number of reasons including radiative budget and the efficiency of heat transfer in and between soil and atmosphere, slope and aspect of the terrain, vegetation cover, ground permeability, and annual quantity as well as distribution of precipitation (Banks, 2008). Local groundwater temperature mapping suggests average temperatures are 12.6 °C, resulting from the subsurface urban heat island effect (Farr et al., 2017).

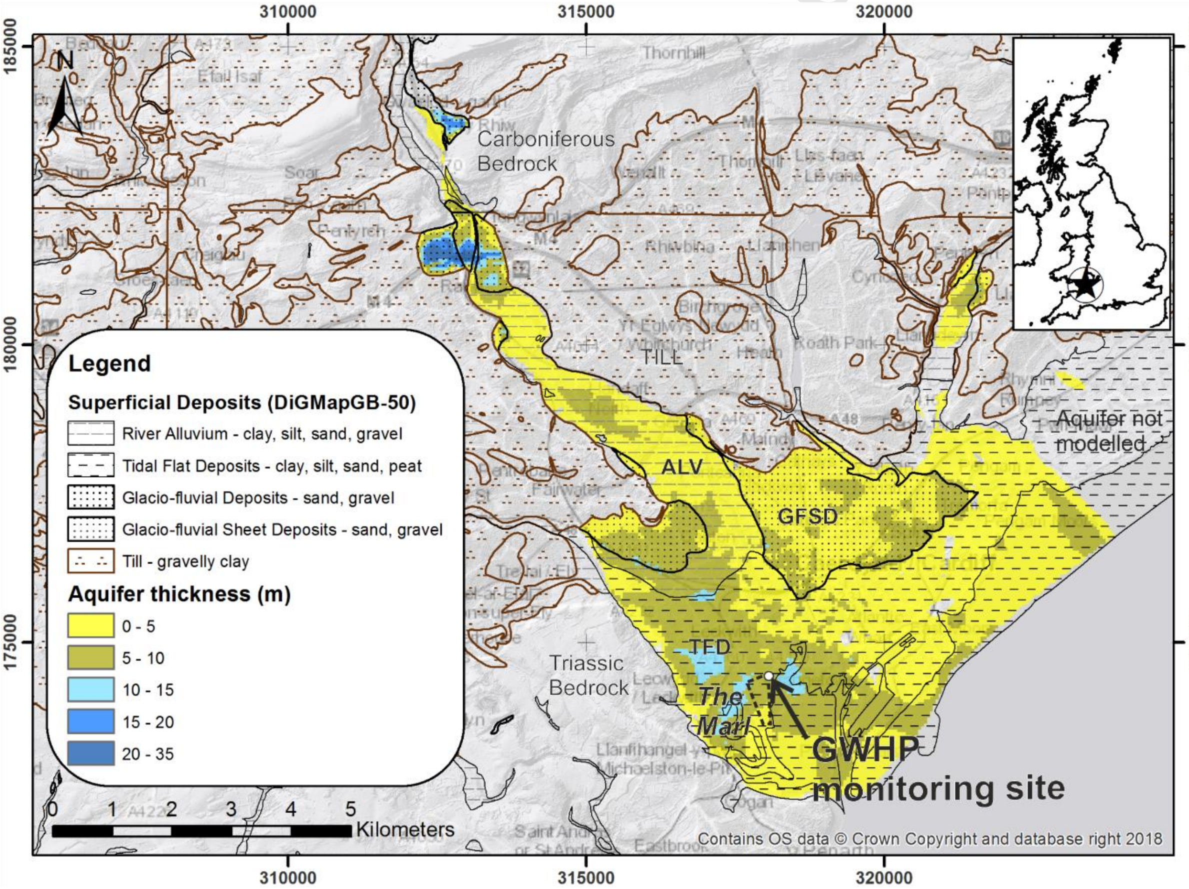

Fig. 1. Map showing the location of the groundwater heat pump monitoring site, regional superficial geology, and gravel aquifer thickness. DiGMap 1:50 000 British Geological Survey © BGS-UKRI. Contains Ordnance Survey data © Crown Copyright and database rights 2019.

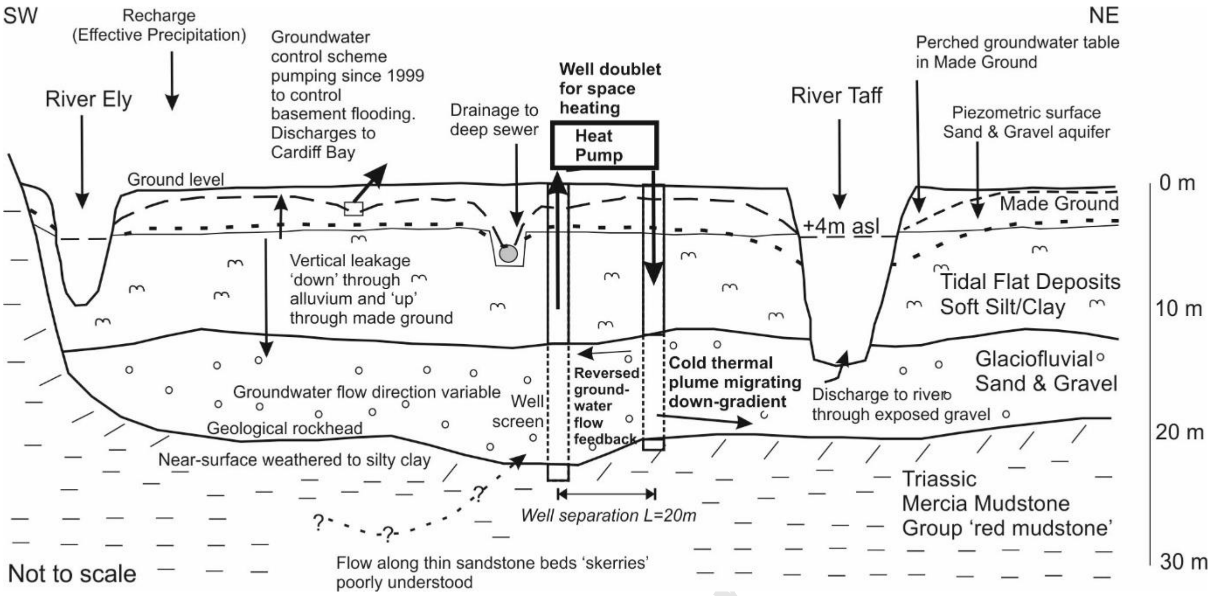

Fig. 2. Hydrogeological conceptual model including well doublet (Modified from Farr et al 2017; adapted from Edwards 1997).

3. Materials and Methods

Assessment of the technical feasibility of using shallow open loop systems in the glaciofluvial sand and gravel aquifer involved investigations at two scales:

(1) 'City-scale' geological and hydrogeological investigations focused on characterising aquifer dimensions and temperature,

(2) 'Site scale' proof-of-concept installation of a pilot open loop GWHP to test technical feasibility, with long-term monitoring of environmental impacts on the aquifer and whole-system performance.

3.1. City-scale investigations

GSHP design requires a good understanding of the geology and groundwater flow regime (Busby et al., 2009). Initial city-scale investigations involved a desk-study of historic land use and geology (Kendall, 2015), collation of approximately 3000 geotechnical and geological borehole records from third party ground investigations, followed by creation of a 3D superficial geology model (Kendall et al., 2018), following the methods described by Kessler et al., (2009). The 3D geological model focussed on defining the extent and thickness of the sand and gravel aquifer units and confining layers (Fig 1). Hydrogeological investigations involved baseline groundwater temperature mapping across the city (Farr et al., 2017).

The potential aquifer heat resource was estimated using an approach introduced by Balke (1977), and later applied by Zhu et al. 2010, based on the following expression:

$$Q=Q_w+Q_s = VnC_w \Delta T+V(1-n)C_s \Delta T \tag{1}$$

where Q (kJ) is the total theoretical potential heat content of the aquifer, V (m^3) is the aquifer volume, calculated from the 3D superficial geology model, n is the porosity, and C_w and C_s (kJ m^{-3} K^{-1}) are the volumetric heat capacity of water and solid, respectively. ΔT (°C) is the temperature reduction in the aquifer. Values and assumptions used for these calculations are listed in Table 1.

Table 1 Aquifer properties used for heat content estimation

Parameter	Value	Reference	Assumption
Volumetric heat capacity solid C_s	2150 kJ m^{-3} K^{-1}	Zhu et al., 2010	Similar to the sandy gravel aquifer in Cologne
Volumetric heat capacity of water C_w	4200 kJ m^{-3} K^{-1}	Zhu et al., 2010	Similar to the water in gravel aquifer in Cologne
Porosity n	0.2 to 0.3	Terzaghi et al., 1996	Similar porosity to typical un-cemented fairly ‘clean’ sandy gravel material
Aquifer volume V	1.4×10^8 m^3	Kendall et al., 2018	Estimated total

			volume of the main glacial gravel aquifer. Aquifer volume is assumed fully saturated.

3.2. Site-scale investigations

Site-scale investigations were focussed on the installation and monitoring of a pilot open loop GSHP scheme at ‘Grangetown Nursery School’ (Fig. 1). For the preliminary site investigation, temperature profiling and falling head tests were conducted in nearby boreholes to determine baseline temperature and to test aquifer recharge capacity. Drilling conditions were anticipated from review of previous ground investigations in the area and the 3D geological model. A conceptual hydrogeological model, shown in Fig. 2, was adapted for the pilot site to understand groundwater flow direction and gradient to inform numerical heat flow modelling aimed at understanding the size of a thermal plume to be expected from the scheme. The production and injection wells were drilled in August 2015, with two additional groundwater monitoring wells in November 2016. Core and samples were collected during drilling and these were analysed in the BGS geotechnical properties laboratory in Nottingham to provide thermogeological characterisation of the geological materials, including index properties and thermal conductivity and diffusivity measurement of the confining layer of cohesive silty tidal alluvium, and particle size distribution analysis on non-cohesive glacial gravel (aquifer) sediments.

3.3. Numerical modelling

Before the installation a numerical 2D groundwater flow and heat transport model was set up using the Finite Element and Subsurface Flow and Transport Simulation System FEFLOW® (Diersch, 2010) to understand the long-term thermal impact of the proposed scheme (Fig. 3).

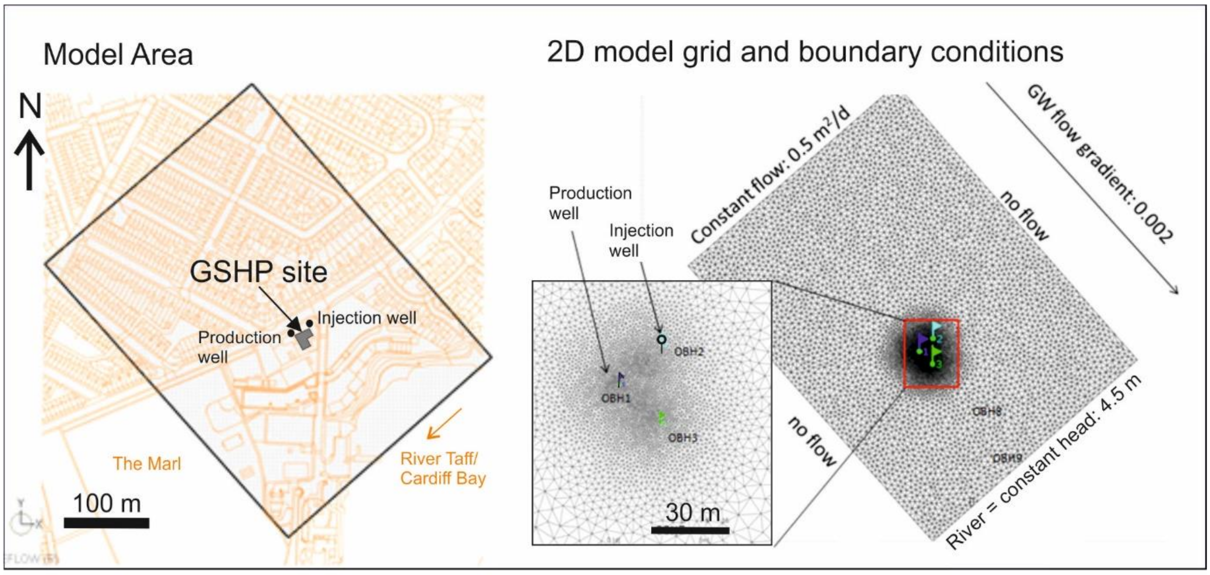

Fig. 3: Numerical model area (left) and FEFLOW 2D model mesh detail with boundary conditions (right)

The 2D model was set up to represent the sand and gravel aquifer and confining fine-grained alluvium, assuming no flow from the Triassic mudstone bedrock. The aquifer is typically 9-10 m thick in the model area, so a 2D model with a constant thickness of 10 m was considered sufficient for this fairly simple geological situation. The aquifer is assumed to be in hydraulic contact with Cardiff Bay to the south east, using base case parameterisation in Table 2, which were selected using FEFLOW default values and expert knowledge from modelling in other UK gravel aquifers. The model was run for a period of 20 years assuming a heating season between 15 October – 15 May with a 35 m^3/d pumping rate. Model sensitivity analysis was tested to address uncertainties in the hydrogeological conceptualisation, including groundwater flow direction and borehole geometry. Different operational scenarios were tested to assess their impact on the surrounding aquifer and to assess the risk of thermal interference between the production and injection wells. The main aim of this preliminary numerical model was to produce a visualisation of the plume to help communicate to stakeholders the importance of groundwater flow and thermal interference issues in the context of future planning for geothermal-based district heat networks.

Table 2 Model parameterisation values for base case scenario

Hydraulic properties		Thermal properties	
Hydraulic conductivity [m/d]	25	Vol. heat capacity (fluid/groundwater) [J m^{-3} K^{-1}]	4.2×10^6
Specific storage	0.001	Vol. heat capacity (solid) [J m^{-3} K^{-1}]	2.0×10^6
River bed counductance (in) [m/d]	10	Heat conductivity (fluid/groundwater at 13 °C) [W m^{-1} K^{-1}]	0.65
River bed conductance (out) [m/d]	5	Heat conductivity (solid) [W m^{-1} K^{-1}]	3
Porosity	0.02	Dispersivity (longitudinal) [m]	1
Groundwater flow direction	Towards SE	Dispersivity (transverse) [m]	0.1
Groundwater gradient	0.002	Ambient groundwater temperature [°C]	13

3.4. Heat pump installation and monitoring

Following initial site investigations, a 22 kW peak output ‘well doublet’ type GSHP system was installed. The buffer tank (water store) is connected to the school building's existing central heating system of radiators (Fig. 4a-c), using a Wilo Yonos Maxo 25/05-12 circulation pump. The production well is 22 m deep and lined with PVC well casing, screened between 8 and 17 m bgl, and grouted between 22 and 17 m, creating a response zone through the aquifer (Fig. 5). The production well was fitted with a fixed-rate submersible borehole pump (Nastec 4H 06/02) that abstracts up to 35 m^3/d (0.42 l/s). The pump was installed at 15 m bgl: to ensure (1) it remains submerged throughout the year, (2) water is abstracted from well below the the zone of seasonal fluctuation (<10 m), as shown in Fig. 4b and Fig. 5, (3) to raise the base of the screen section 2 m above the base of the well to reduce long-term maintenance, as water wells are prone to silting-up over time. The cooled wastewater is reinjected directly back into the aquifer via a pipe with outlet at 10m bgl, via the 18 m total deep injection well, which is also screened throughout the aquifer. This configuration provides the option to switch the production and injection wells, to optimise source temperatures if there is any intolerable thermal interference. To mitigate against damage to the heat exchanger from sediment in the water a particulate water filter was installed to remove sediment and iron. The GSHP system comprises of a a serviceable stainless steel plate heat exchanger, two 11 kW Dimplex high temperature domestic ground source heat pumps (SIH11ME), auxiliary pumps (Wilo Yonos Pico 25/1-8), and 100 litre buffer tank, digital heat meters, and insulated pipe work (Fig. 4a). Real-time power consumption data are collected every 15 minutes for the GSHPs and all circulating pumps, along with in situ borehole temperatures, flow/return temperatures, brine temperatures, building inflow/return temperatures and outside air temperature. Consumption meters record cumulative borehole and central heating system flow volumes, heat flow (heat generated), and electricity consumption for each device.

The monitoring data allows calculation of Seasonal Performance Factor (*SPF*), following the approach of Zottl and Nordman (2009) and Nordman (2012) Eq. (2). The SPF_{H1} boundary includes only the heat pump unit itself, while SPF_{H4} includes the heat pump, borehole pump, circulation pumps, any backup heaters:

$$SPF_{H4} = \frac{Q_{HP} + Q_{back\ up\ heater}}{w_{HP} + w_{heat\ source\ pump} + w_{back\ up\ heater} + w_{heat\ sink\ pump}} \tag{2}$$

Monitoring of the temperature in the production and injection wells started in October 2015, one month before cold water injection commenced, to capture baseline (ambient) conditions.

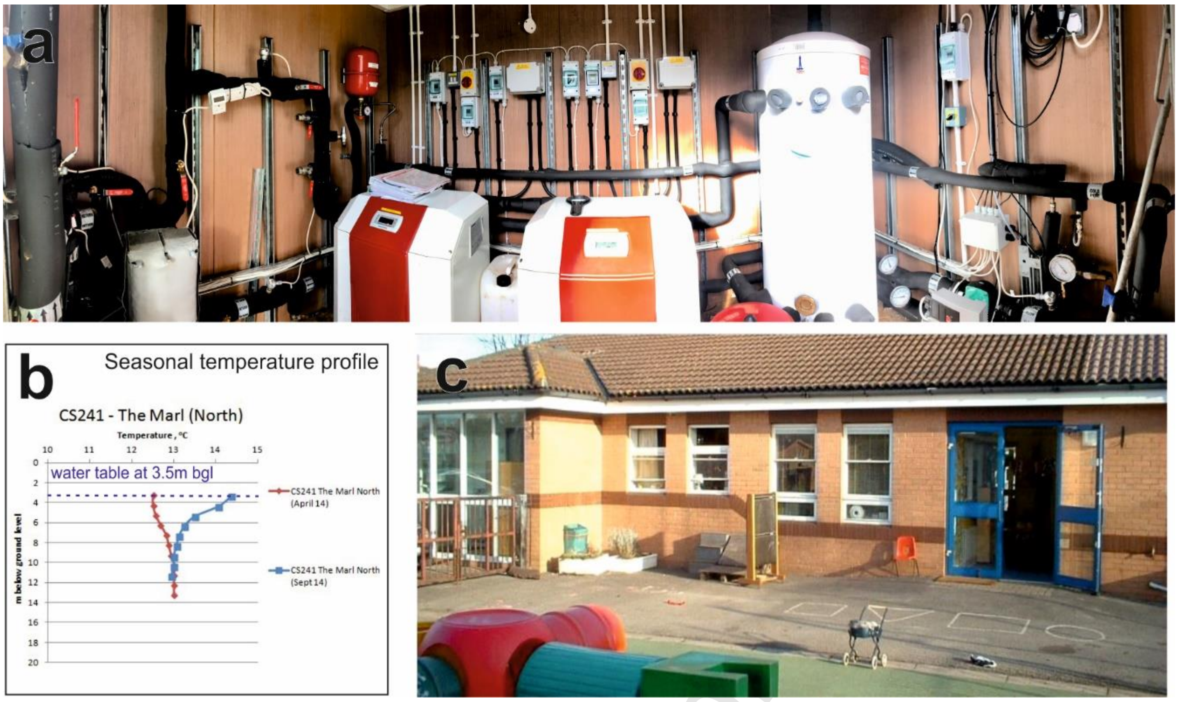

Fig. 4. (a) Photograph showing inside of the plant house showing GSHP units, thermal store, auxiliary pumps and consumption meters (b) Seasonal groundwater temperature profiles taken in 2014 in nearby observation well prior to heat production, showing aquifer (source) temperatures were stable at 13 °C at 10 m depth; (c) photograph of the Grangetown Nursery School building which has a 280 m^2 footprint.

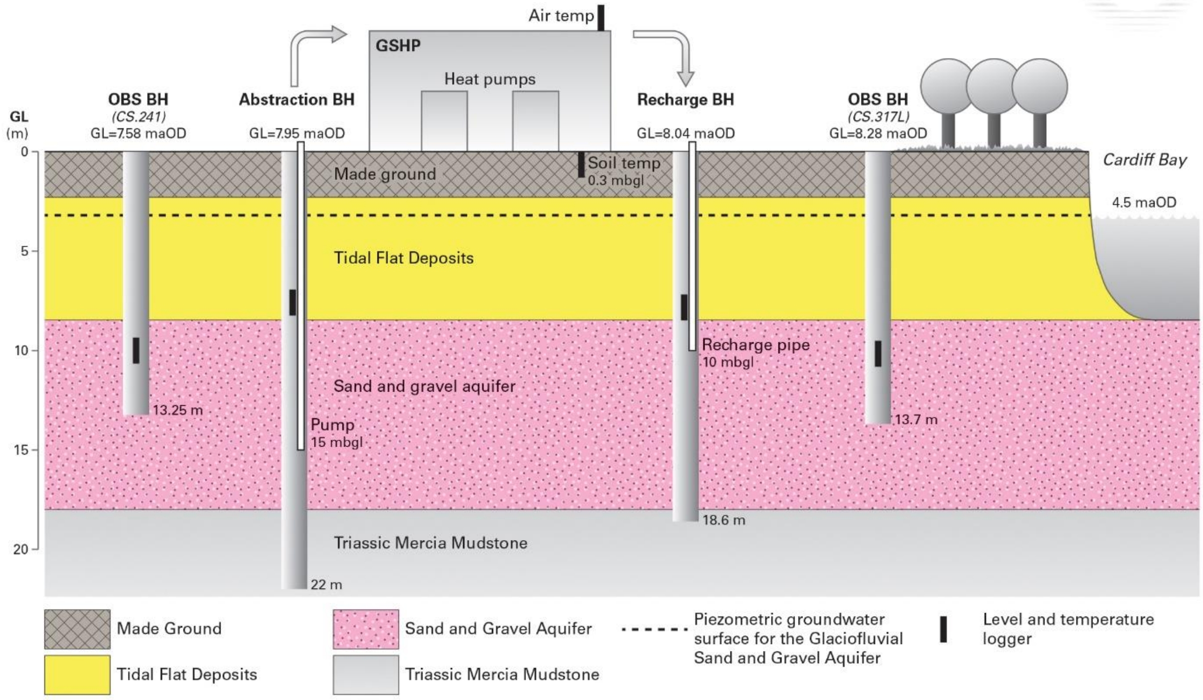

Fig. 5. Schematic of the ‘well doublet’ open loop GSHP system at Grangetown Nursery School in Cardiff, UK (not to scale).

4. Results and Discussion

4.1. Shallow geothermal resource estimates

Based on the values listed in Table 1, we calculate an aquifer thermal yield of 7.70 x 10^{11} kJ thermal energy (213.9 GWh_{th}) and 7.14 x 10^{11} kJ (198.3 GWh_{th}) for upper and lower-bound porosity values of 0.3 and 0.2, respectively. This assumes a reduction in aquifer temperature (ΔT_{gw}) of 2 °C, which also represents the contribution of heat flux from the anthropogenic UHI effect (Farr et al. 2017).

The predicted annual heating demand for the Cardiff city region in 2020 is 3,213 GWh_{th}

(Cardiff Council, 2013), and a change in aquifer temperature of 2 °C represents 6-7 % of this heat demand. Reducing the groundwater temperature from 13 °C to 5 °C (ΔT_{gw} = 8 °C), which would be at the limit of the recommended UK guideline values (Environment Agency, 2011; CIBSE, 2019), is equivalent to 26 % (856 GWh_{th}) of this predicted heat demand. The proven thermal productivity of the small GSHP pilot scheme is 76.8 MWh_{th} of useful heat energy annually (ΔT_{gw} = 2 °C). Upscaling this small-scale GSHP technology solution across the 39 km^2 area of aquifer would require in the region of 40,000 systems to meet 100 % of the city's heat demand, requiring a density of one system shared by every two households. However, this is very theoretical, and we recognise that such a high density of systems would likely not be technically feasible, sustainable, nor cost effective. More likely is a hybrid solution involving a mix of small- (domestic) and large-scale (commercial) abstractions integrated with other renewable heating technologies including closed loop GSHP in non-aquifer units, coupled with solar PVT, Borehole and Aquifer Thermal Energy Storage Systems (BTES, ATES) linked to industrial waste heat capture, water source heat pumps, and distributed via local or district heat networks.

These initial assessments do not consider the subsurface thermal gains from solar radiation and urban infrastructure, which, for the city-scale heat balance can be substantial (e.g. Epting et al 2013). The above method does not account for natural or artificial variations in aquifer hydrogeological properties, groundwater flow processes, thermal interference and thermal degradation of the aquifer associated with high-density installations. Therefore, further investigations and characterisations are required on a case-by-case basis, e.g. stepped pump tests, thermal response tests, with city-scale groundwater flow and heat transport modelling to support urban energy planning and to ensure sustainable management of the subsurface.

4.2. Numerical modelling of groundwater flow and heat flow

Results from the base case scenario numerical modelling are shown in Fig. 6. This scenario is considered to best represent the hydrogeological / geothermal conditions at the pilot GSHP site before the system was installed, and was used to explore and communicate the impact of the proposed borehole layout and pumping schedule on the aquifer (Fig. 6c). Fig. 6a, and b show that after two years of heat pump operation a 60 m wide cold-plume develops around and downstream of the injection well, driven by south east moving groundwater advection. Under these model boundary conditions a maximum temperature drop of 0.5 °C is observed at the production well (Abs. in Fig. 6c) in year 2, coinciding with peak injection rates of 35 m^3/d. During abstraction a wider pulse of cold water, which developed during the previous year, is observed downstream of the current pulse developing around the injection well. During periods of non-abstraction (and therefore no cold injection), as represented in Fig. 6b, this pulse of colder water drifts down the hydraulic gradient towards the SE, merging with the previous years' pulse, and the aquifer source around the injection well recovers to near ambient temperatures.

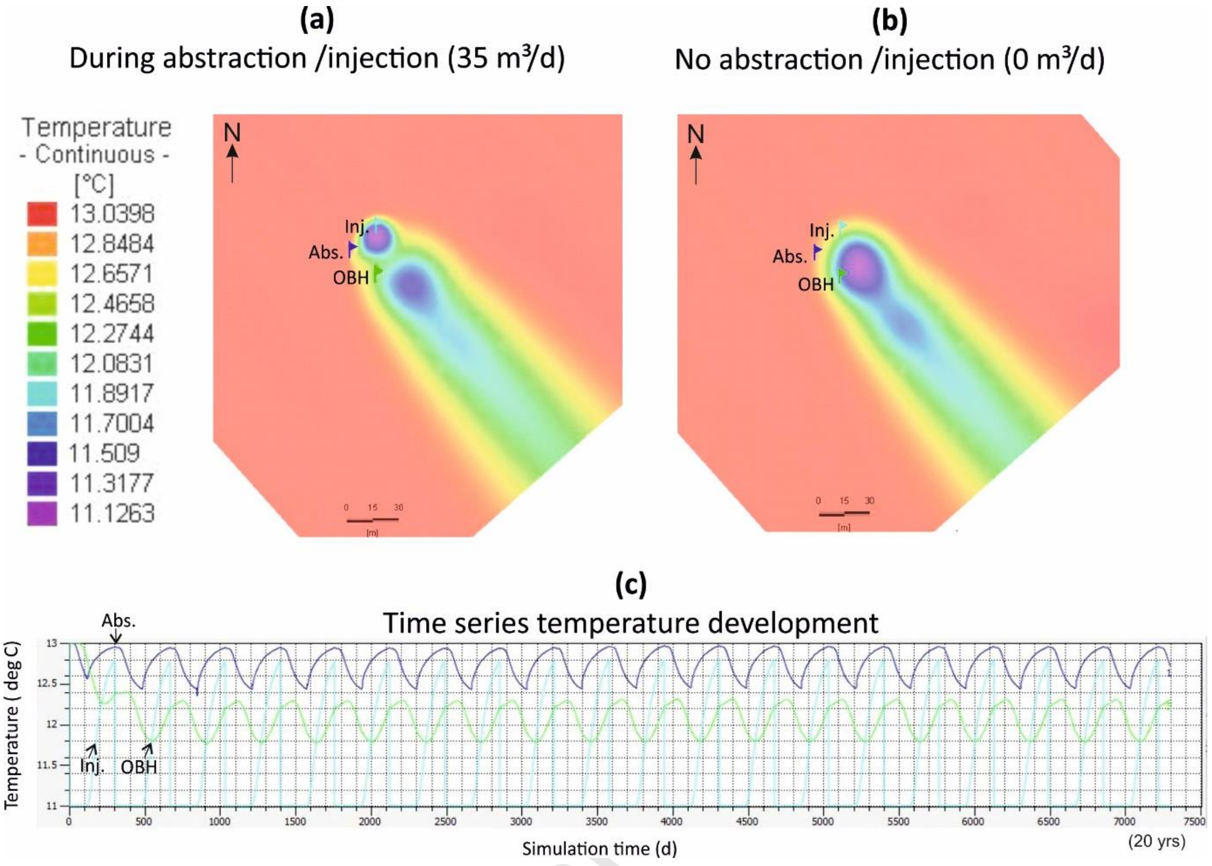

Fig. 6: Base case scenario: Spatial temperature distribution (a) during GSHP operation and (b) during pause in GSHP operation. (c) Time series of temperature development at the production well (Abs.), the injection well (Inj.), and the observation well (OBH) located downstream of the GSHP installation. The simulated pumping and injection period is consistent with the typical local heating season, lasting from 15 October – 15 May.

The sensitivity of the model to the groundwater flow direction was analysed by varying the flow direction. This showed that thermal interference between the production and injection wells increased dramatically when the production well was positioned down-gradient of the injection site. This is unsurprising, but allowed quantification of the maximum expected source temperature reduction if the plume is positioned unfavourably to the production well. The maximum temperature drop was 2.7 °C during peak load injection (35 m^3/d), compared to <0.2 °C for the case where the abstraction well is positioned up-gradient of the injection well, as assumed at the design stage.

Model parameterisation was found to be an important control on the timing of thermal interference and the shape of the resulting cold plume. For example, increasing aquifer transmissivity resulted in a more rapid temperature deterioration and recovery at the production well in response to injection. Similarly, the groundwater gradient controlled how quickly the thermal load was transported away from the injection site, but it also influenced the width of the resulting cold plume (i.e. its spread perpendicular to the direction of groundwater flow), which increases with decreasing gradient. Changes in aquifer thermal conductivity showed negligible impacts on the model outputs, as heat transport within this part of the system is dominated by groundwater advection. In such systems, thermal dispersivity becomes important, determining the shape and spread of the plume, but also influencing the thermal interference and the degree to which the temperatures recover during non-injection intervals.

In all cases, temperature changes at the production well resulting from changes in model parametrisation were in the order 0.4 - 0.8 °C and groundwater temperature recovered to at least 12.8 °C during the pause in GSHP operation. Hence, the modelled impact on temperatures at the production well due to uncertainty in subsurface parameterisation was considerably smaller than that related to changes in well alignment relative to groundwater flow direction (advection). Sub-daily operational patterns were found to have no influence on the modelled temperature deterioration / recovery at the production well, confirming that modelling at (approximately) daily time steps is acceptable.

4.3. Observed impact on the aquifer

Fig. 7 shows the actual thermal impact observed at the production and injection wells during the first three years of GSHP operation. The graph shows a 2 °C net reduction in source temperature during the first year. This behaviour is interpreted as 'thermal feedback' or 'thermal short circuit' (Banks 2009; Galgaro & Cultrera 2013), resulting from the short (20 m) well separation, the relatively flat hydraulic gradient, creation of a local cone of depression caused by down-draw around the production well, and moderately high permeability of the gravel aquifer system. However, at the end of the first summer (August 2016), the source temperature had almost fully recovered to 12.8 °C, as was predicted in the numerical model, confirming aquifer temperature rejuvenates quickly (but not fully) when cold water injection is paused.

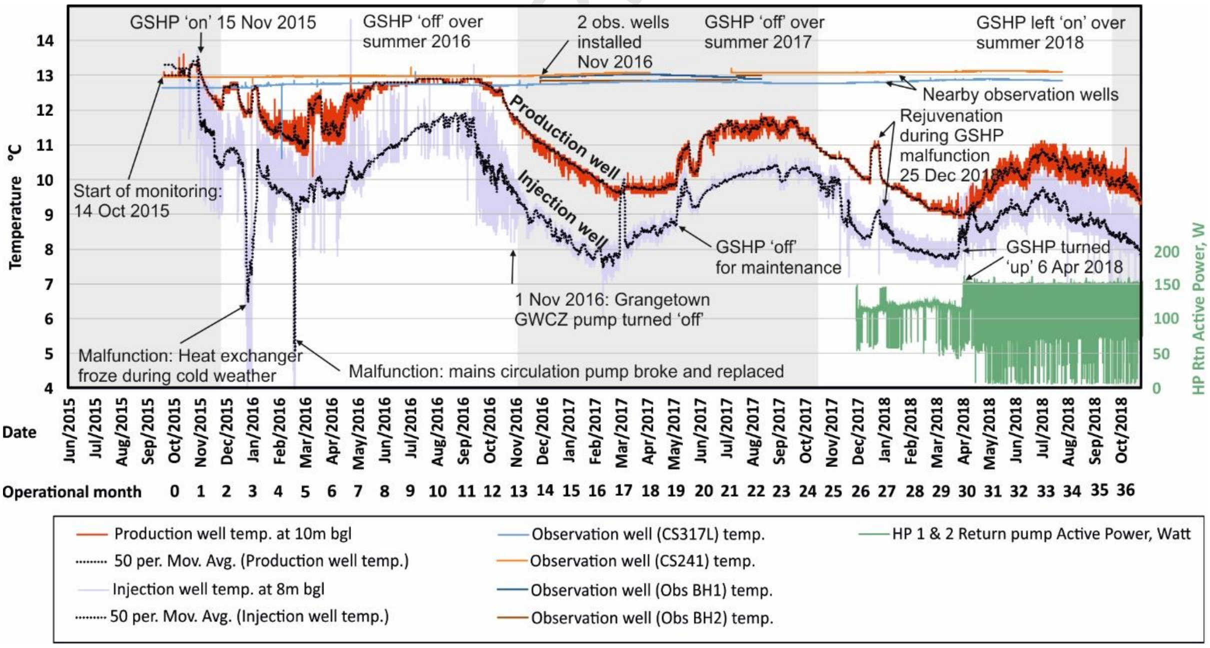

Fig. 7. Observed aquifer temperature evolution in the first three years of GSHP operation.

External events affected the system on 1 November 2016, when early in the second heating season Cardiff Harbour Authority switched off their groundwater control pumps at Grangetown groundwater control zone (GWCZ), located approximately 200 m to the north of the GSHP. This resulted in a 0.30 m groundwater level rise in the wells at the GSHP site. Although immediate changes in groundwater temperature were observed in this event, as evidenced in Fig. 7, it is likely that the regional groundwater gradient and flow regime changed in response. The implication is that the groundwater gradient (and plume direction) was possibly not stable throughout the study period and the plume may have changed in size and shape in the early years of the GSHP scheme. This transience in boundary conditions has not been modelled in detail in the current study, mainly as the input parameters are not yet available, but these events will be explored in future studies.

Over the 2nd and 3rd heating seasons (winters 2016/17 and 2017/18) source temperatures at the production well continued to fall and summer temperatures only recovered to 11.5 °C and 10.5 °C respectively, reaching a minimum of 9 °C by the end of the main heating season (Fig. 7). The observed rejuvenation was significantly lower than the 12.9 °C predicted by the heat flow model. Analysis of the heat pump telemetry data provided an interesting insight into user behaviour during the 3rd heating season; the heat pump's heating curve settings were changed on 6 April 2018, as indicted by a sharp increase in 'heat pump return active power' (Fig. 7) which is the power consumption used by the heat pump return circuit pump which passes water across the heat exchanger plate. The system was 'turned up high' temporarily but then left on a 'high' setting over the summer period, resulting in poorer aquifer thermal rejuvenation, and overall lower efficiency in the following winter.

In shallow groundwater systems where seasonal changes in temperature can be measured several meters below the ground surface, the installation depth and use of fixed depth temperature sensors must be considered if meaningful data is to be measured or used for regulatory purposes. An example of why follows: The groundwater temperature measurements plotted in Fig. 7 are collected from 10 m below surface, but these discrete data do not represent a vertical profile in the aquifer above and below this point. Fig. 8 shows results from repeated 1 m interval temperature profiling in the production well. The August data show the general thermal degradation (from 13.0 °C to 11.5 °C), during the first two years of heat pump operation. This signal is in agreement with the independent static logger data at 10 m below surface, shown in Fig. 7. However, the vertical profile from February 2017 (Fig. 8) shows the aquifer temperatures decreased slightly with depth, fairly linearly, by 1.0 °C, over a distance of 7 m. This data provides an insight into the seasonal thermal structure of this part of the aquifer, suggesting that it may be affected by the cold water injection plume. Monitoring data from the production well and a nearby observation borehole (CS241) suggest the gravel aquifer in the study area is also in hydraulic connectivity with Cardiff Bay / River Taff, and so this deeper cold water may partly originate from winter river water mixing. At present in the UK there is no agreed method for how to measure and report $\varDelta T$°C between production and injection wells of open loop GSHP systems. This comparison of methods, using both fixed depth temperature sensors and repeated downhole temperature, illustrates how the measurement and reporting of $\varDelta T°C$, for example as a requirement of an environmental permit, could easily be incorrectly measured, highlighting the need for a consistently applied methodology for measuring and reporting $\varDelta T$°C.

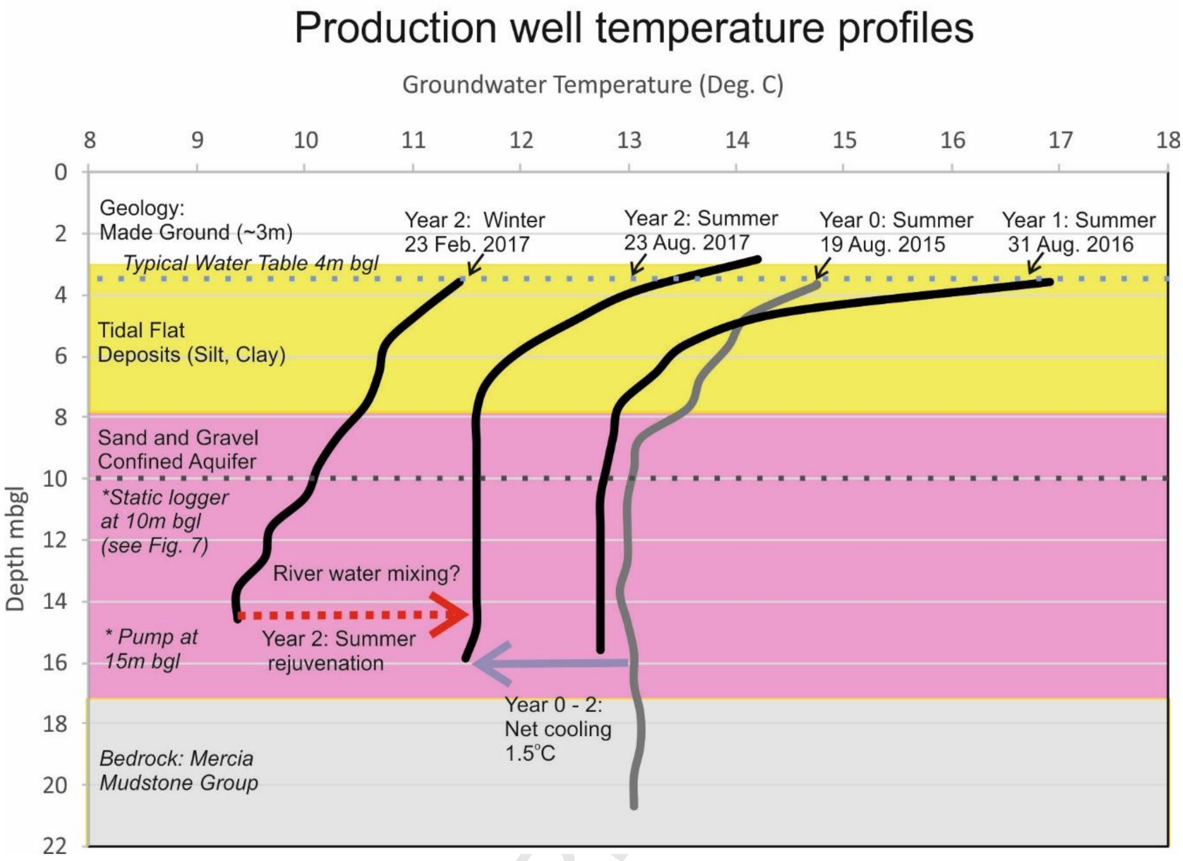

Fig. 8. Groundwater temperature profiles in the production well, before and during GSHP operation.

4.4. Effect of thermal degradation on system efficiency

Performance of GSHP's are commonly assessed by the seasonally-averaged Coefficient of Performance (SCOP), or the Seasonal Performance Factor (*SPF*). The pilot GSHP was found to have a SPF_{H4} of 4.5 (W13/W50) over the study period. Between March 2017 and 2018 the system extracted 77 MWh of useful heat with a net 2 °C change in source temperature, in a year when HDD totalled 1909 (using 15.5 °C baseline from 'Bute Park'). The whole-system efficiency is 450 %, which although is outstanding, was affected by the variable stability of the source temperature during the heating period, as shown in Figs. 7 and 8. For this reason any aquifer thermal degradation is considered undesirable, hence there have been attempts to quantify the impact of thermal degradation on GSHP system efficiency. Sciacovelli et al., (2014) undertook modelling studies that suggested thermal (cold) plumes can reduce the COP of nearby heating schemes by up to 20 %. Anthropogenic thermal enhancements, such as the subsurface urban heat island effect, heat leakage from sewers, tunnels, basements, sustainable urban drainage schemes (SuDS), and industrial heat losses, might all be considered desirable for ground source heating schemes as they raise source temperatures. On the other hand, controlled groundwater cooling may be beneficial for groundwater cooling schemes. The pilot scheme described herein witnessed a temperature drop from 13 °C to 11 °C in the first three years, mainly due to thermal feedback caused by the short well spacing length (20 m). Under GW11/W50 operating conditions, this minor thermal degradation reduced the GSHP COP by 4 %, based on the empirically based relationship from Eq.4 in Staffell et al., 2012. Given the seemingly high system efficiency of the studied system, this loss in efficiency is tolerable, but not optimal, and a wider borehole spacing (e.g. 50 m) would have returned better performance. Unfortunately, the size and configuration of the site prevented a larger borehole spacing, a situation that is not uncommon in urban settings. Another factor affecting efficiency is that the GSHP plant room and pipe work is located in a poorly insulated building, leading to higher heat losses. Future system efficiency and whole-life running costs will be influenced by system operational patterns, building insulation, building and system usage behaviour, climate and heating demand, the unit cost of electricity, and stability of the source temperature including any thermal interference from other schemes. Future CO_2 savings will depend on the source of electricity, which is increasingly from low carbon energy sources (e.g. wind, solar, nuclear). A more detailed analysis of system performance using HDD is currently being undertaken to better understand the lifetime cost-benefit of the system.

5. Conclusions

This study evaluated the below ground environmental impact and performance of an operational open loop ground source heat pump system in the mid-latitude maritime climate setting of the United Kingdom.

The main findings of this study are as follows:

- Shallow urban aquifers can supply very low carbon heating, with tolerable thermal interference.
- 3D geology modelling provided estimation of aquifer volumes for heat content calculations, and context for developing realistic groundwater flow and heat flow models. Models also provide an indication of drilling depths and costs for prospective GSHP schemes and other development projects.
- Assessment of the aquifer volume suggests it's pore water contains a heat resource of between 793 and 856 GWh_{th}, assuming the aquifer temperature is kept above 5 °C; this heat content is equivalent to 26% of the city's predicated 2020 heat demand, but further groundwater investigations are needed to understand the physical limits of abstraction and reinjection across the city.
- Monitoring of groundwater temperatures around the production and injection wells before and during GSHP operation was beneficial for sustainable use, as it supplied evidence-based feedback to the system owners, enabling intervention and optimisation of the system performance, which will reduce thermal degradation of the aquifer and improve efficiency of the heating system.
- Interference between the production and injection well, and neighbouring systems, is anticipated where groundwater flow (advection) and heat production rates are high

and thermal plumes intersect, and these aspects need to be proactively identified and managed by all stakeholders, including design teams, planners, regulators and owner/operators.

- Continuous and high spatial resolution monitoring data, combined with characterisation of the geology and hydrogeological regime, is required to reliably predict and manage the sustainable development of ground source heat pump systems.

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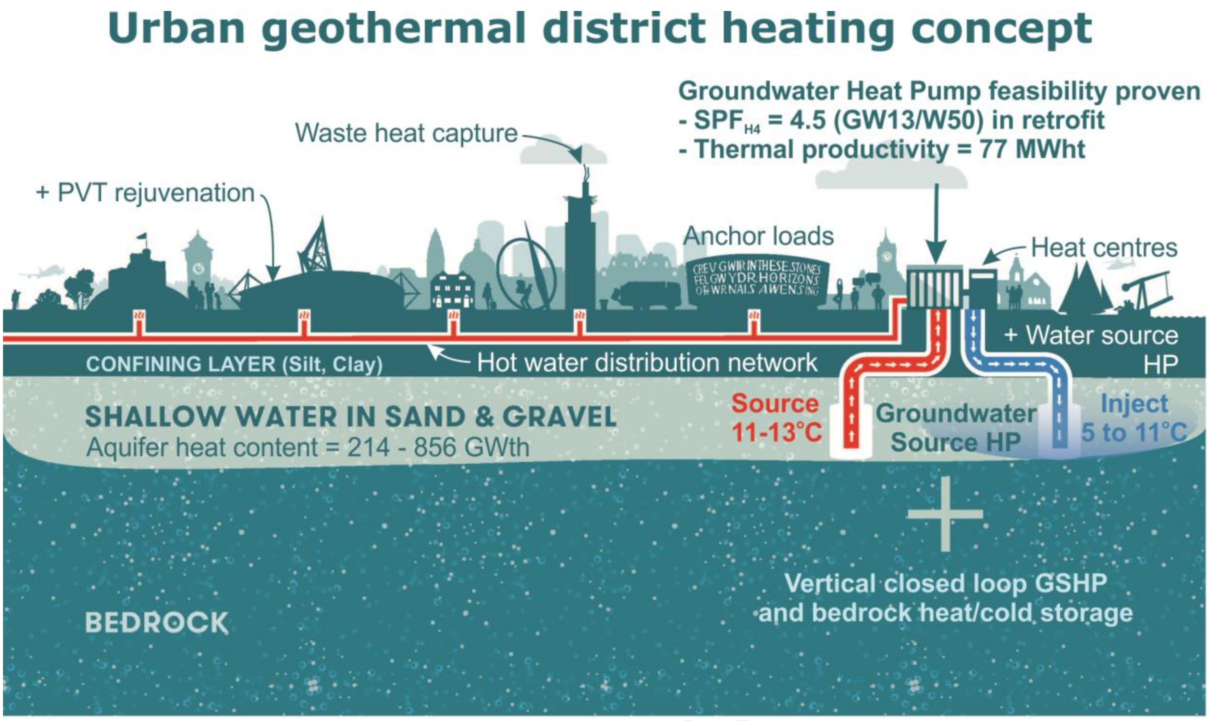

Graphical abstract