#Running header: *'Cardiff Urban Geo-Observatory'*

Case study: Establishing an urban geo-observatory to support sustainable development of shallow subsurface heat recovery and storage

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Abstract

Low-enthalpy ground source heating and cooling is recognised as one strategy that can contribute towards reducing reliance on traditional, increasingly insecure, CO_2-intense thermal power generation, as well as helping to address fuel poverty. Development of this technology is applicable in urban areas where high housing density often coincides with the presence of shallow aquifers. In urban areas groundwater temperatures can be elevated due to the subsurface Urban Heat Island effect. Uptake and development of this technology is often limited by initial investment costs, however, baseline temperature monitoring and characterisation of urban aquifers, conducted in partnership with local authorities, can provide a greater degree of certainty around resource and sustainability that can facilitate better planning, regulation and management of subsurface heat. We present a novel high-density, city-scale groundwater temperature observatory and introduce a 3D geological model aimed at addressing the needs of developers, planners, regulators and policy makers. The Cardiff Geo-Observatory measures temperature in a Quaternary aged sand and gravel aquifer in 61 boreholes and at a pilot shallow open-loop ground source heating system. We show that repurposing existing infrastructure can provide a cost effective method of developing monitoring networks, and make recommendations on establishing similar geo-observatories.

Anthropogenic factors, including land cover, heat loss from buildings, basements and subsurface infrastructure, can result in the warming of shallow groundwater in urban areas, known as the subsurface Urban Heat Island effect (sUHI) (Allen *et al*. 2003; Ferguson & Woodbury 2007; Hayashi *et al*. 2009; Taylor & Stephan 2009; Zhu *et al*. 2010; Menberg *et al*. 2013a; Epting & Huggenberger 2013; Benz *et al*. 2016 & Farr *et al*. 2017; Bidarmaghz *et al*. 2019). Both open and closed loop ground source heat pumps can utilise the shallow urban subsurface which can also be used to provide space heating and cooling for buildings and for thermal storage.

Currently, domestic and industrial heating make up nearly 50 % of all energy consumption across the EU (Sanner *et al*. 2011). In the UK 32 % of energy is used for space heating, which can be broken down into; industrial (19 %) and domestic (13 %) heating (BEIS 2017). In The UK 80 % of space heating is derived from the burning of fossil fuels (DECC 2013), a large contributor to anthropogenic greenhouse gas emissions. The UK Government has committed to the Climate Change Act, 2008, pledging to reduce CO_2 emissions by at least 80 % by 2050 compared to 1990 levels (BEIS 2017). In the UK 83 % of the population (Office for National Statistics 2018) live in urban areas, however development of ground source heat recovery and storage has been on a case-by-case basis with little strategic subsurface planning or policy, and significant challenges, including the regulation and ownership of heat, still need to be fully addressed (Sanner *et al*. 2011; Abesser *et al*. 2018). To reduce our dependency on fossil fuels for domestic space heating, increase long-term energy security and help alleviate fuel poverty there is a need to de-risk the development of a mix of renewable, sustainable, low-carbon technologies so they can be integrated into district heating networks.

Commonly documented risks of shallow geothermal energy systems include thermal interference between unregulated closed-loop systems and the competitive use of subsurface opportunities (e.g. Fry 2009; Herbert *et al.* 2013). Evidence of subsidence associated with open loop ground source heating schemes has been documented in Germany (Fleuchaus & Blum 2017). Conflict may occur between other users of the urban subsurface, e.g. buried services, water abstraction, and sewerage. A paucity of baseline temperature data from shallow urban aquifers could also result in poor system design and performance, which could undermine investor and public confidence. It is already well recognised that subsurface conditions are not considered adequately during the planning stage of heat recovery and storage and that regulation and licencing could benefit from an evidence-base on which decisions can be made (Blum *et al*. 2011; Vienken, *et al*. 2015; Stephenson *et al.* 2019). We propose that a strong evidence-base is one of the key attributes that can help to 'de-risk' shallow urban heat recovery and storage. Such an evidence base could allow policy makers, regulators, investors and developers to implement sustainable projects.

In the UK a lack of information on shallow urban groundwater temperatures has, in addition to high drilling costs and low gas prices, limited the sustainable development of ground source heat recovery and storage systems. Greater understanding of urban groundwater systems will provide the evidence-base needed to de-risk future development (e.g. Blum *et al*. 2011; Vienken *et al*. 2015). Among the pressing challenges to the uptake of the sustainable use of urban aquifers for heat recovery is the over-regulation of open-loop heat recovery operations, which can be a barrier to development, deterring investors (e.g. Bonsor *et al*. 2017; Herbert *et al*. 2013). Under-regulation of closed-loop heat recovery and storage can also have potentially negative consequences as systems can be installed anywhere, which may result in negative feedback between systems and loss of performance (Fry 2009 & Herbert *et al*. 2013). Regulatory challenges are compounded by a lack of consensus on ownership of heat in the subsurface (Abesser *et al*. 2018). Subsurface thermal management policies are therefore required to regulate heat in urban areas (e.g. García-Gil *et al*. 2015a; Epting *et al.* 2018) and these are best addressed before large-scale deployment of ground source heat recovery and storage systems.

Globally, many cities have started to address the challenges of sustainably recovering and storing heat in shallow urban aquifers (Table 1). The sUHI has been characterised in many cities, with elevated groundwater temperatures being recognised as a potential source for low enthalpy heat recovery using heat pump technology (Allen *et al*. 2003; Arola & Korkka-Niemi 2014; Benz *et al*. 2016; Casasso *et al.* 2017; Farr *et al*. 2017; Ferguson *et al*. 2007; Janža *et al*. 2017; Taniguchi *et al*. 2007). 3D heat flow and groundwater models (García-Gil *et al*. 2015a; Mueller *et al*. 2018) have been used in Basel and Zaragoza to sustainably manage subsurface heat resources.

In Berlin, Germany, the Senate Department for Urban Development and Housing integrates ground source heat into their planning regime, and this is complemented by groundwater temperature monitoring programs (e.g. Benz *et al*. 2016). Urban groundwater monitoring networks are required to increase confidence for investors whilst supporting evidence-based regulatory targets (Epting *et al,* 2018). The Common Vision for the Renewable Heating and Cooling sector in Europe lists a need for an observatory to provide better quality data related to renewable heating and cooling as one of its priorities (Sanner *et al*. 2011). However urban areas can be highly geologically variable and it is acknowledged that there is no single design of city-scale monitoring or modelling of groundwater and heat resources appropriate for all cities (Bonsor *et al*. 2017).

To address these challenges the British Geological Survey and City of Cardiff Council have worked in partnership to deliver a high-density, city-scale, urban geo-observatory. The 'Cardiff Urban Geo-Observatory' comprises four years of baseline temperature data, an operational shallow open-loop ground source heat pump, and a 3D geological model of the superficial geology focused on the target unconsolidated sand and gravel aquifer. The observatory is the largest of its kind in the UK, providing open access data though a bespoke web-portal (www.ukgeos.ac.uk/observatories/cardiff). Lessons learned from this approach could be used to benefit the development of other urban geo-observatories, underpinning evidence-based environmental regulation and supporting sustainable development. Groundwater levels and temperatures obtained from the monitoring sites can be used to develop groundwater and heat flow models to support regulation of heat and water recovery. In this paper we present a case study from Cardiff describing a method for establishing a geo-observatory comprising a network of groundwater temperature sensors, 3D geological model, and an introduction to the shallow open loop groundwater heat pump research site. The Cardiff urban geo-observatory is thought to be the UK's first city-wide groundwater temperature network and illustrates the advantages of repurposing existing infrastructure and working in partnership with local authorities to deliver data to underpin low-carbon energy technologies.

Study area

Cardiff, covers an area of 140 km^2 and has a population of 346 000 (Office for National Statistics 2012). The Port of Cardiff once exported one third of the World's coal (Brabham 2009), however following the decline of the coal industry, the area fell into disrepair. In the mid-1980s, as part of the city's redevelopment, the Cardiff Bay Development Corporation (CBDC) was formed to oversee the construction of a tidal barrage across the mouths of the River Taff and Ely. The barrage closed its locks for the first time on the 4th November 1999, creating a 2 km^2 fresh water lake (Hunter & Gander 2002). Due to the possibility of rising groundwater levels impacting underground structures such as basements, the 'Cardiff Bay Barrage Act, 1993' required groundwater monitoring to be undertaken for a period of 20 years following the closure of the barrage. In response, 236 monitoring boreholes, many of which can be seen in Figure 1, and six dewatering schemes were installed to monitor and manage groundwater levels (Edwards 1997; Heathcote *et al*. 1997; 2003; Sutton *et al*. 2004 & Williams 2008). The majority of the boreholes monitor groundwater in the glaciofluvial sand and gravel aquifer.

Cardiff is underlain by bedrock deposits comprising folded Silurian, Devonian and Carboniferous strata and unconformably overlying Triassic rocks, including the Mercia Mudstone Group and its basal Marginal Facies. These are overlain by Devensian glacial deposits and Holocene alluvial and coastal deposits (Waters & Lawrence 1987; Kendall 2015). The target aquifer for this study is the Quaternary aged glaciofluvial sand and gravel that underlies the river valley systems that transect the city and principally comprises dense, poorly sorted sandy gravel with cobbles (Heathcote *et al*. 2003). Edwards (1997) defined the Tidal Flat Deposits to be of low to intermediate permeability overlying the sand and gravel aquifer, generally confining the sand and gravel aquifer in the south of the city centre. However in some localised areas the Tidal Flat Deposits are absent resulting in hydrogeological connections between the sand and gravel and the made ground aquifers (Williams 2008). Groundwater in the sand and gravel aquifer generally flows towards the rivers and the coast (Edwards 1997). Red mudstones of the Triassic aged Mercia Mudstone Group bedrock form a low permeability base to the aquifer (Edwards 1997; Heathcote *et al.* 2003). Post impoundment of the barrage, changes in groundwater levels between 2.5 -3.5 m were measured in the sand and gravel aquifer but were limited to the fringes of Cardiff Bay (Williams 2008). Pumping tests show that the hydraulic conductivity of the sand and gravel aquifer is relatively consistent, with average values of 50 m/d (Heathcote *et al*. 2003) with groundwater levels 3-4 m below the surface.

In partnership with Cardiff Harbour Authority (a department of Cardiff City Council), who maintain the groundwater level monitoring network, temperature profiles at 168 boreholes were undertaken to characterise aquifer temperatures and the sUHI. The study revealed groundwater temperatures exceeded those forecast by the predicted geothermal gradient by up to 4 °C in over 90 % of the boreholes, with the excess heat attributed to the sUHI (Farr *et al*. 2017)

Methodology

Data from the geo-observatory is intended to be used to address some of the key questions relating to the sustainable development of heat recovery and storage in shallow urban aquifers. For the purposes of this study, the extent of the groundwater temperature monitoring area is defined by the +10 m AOD (above ordnance datum) contour line as this was the extent of the original groundwater level monitoring and covers the majority of the city of Cardiff. The step-by-step process for creating and maintaining the 'Cardiff Urban Geo-Observatory' is described.

Geological data acquisition and storage

The first step towards developing the geo-observatory was to collate existing sources of geological data. The British Geological Survey acts as custodian for borehole records, enabling data sharing that can further understanding of the subsurface. Borehole data was submitted by developers or accessioned from site investigation reports held in the public records at the local authority. Ground investigation data can be abundant in urban areas, however these data are often not centrally held and are often distributed between local authorities, consultancies and their clients. The BGS's National Geoscience Data Centre (NGDC) allows for these data to be brought into one central repository. The data were used to underpin the development of a 3D geological model (Kendall *et al.* 2018) and to create a database of information on the geotechnical and hydrogeological properties of the main geological units.

In addition to the data already held in the NGDC, ground investigation data held in Cardiff City Council's planning applications public record were identified and captured. In total, over 1000 borehole logs were acquired and interpreted, including all of the borehole logs for Cardiff Harbour Authority's groundwater monitoring boreholes. These borehole logs are stored in the British Geological Survey's Single Onshore Borehole Index (SOBI) which be viewed online using the BGS 'Onshore GeoIndex'. Boreholes included in this study are identifiable by their co-ordinates in Table 2.

Geotechnical data

Geotechnical data were collated from sites investigation reports stored on the NGDC. These data are intended to help reduce the risk of unforeseen ground conditions for future developments, as well as provide insight into aquifer properties, and are held in the BGS' National Geotechnical Properties Database available from BGS. Material properties can be used to calculate the thermal conductivity of the geological units, and thus could better inform how heat is transported and stored within the subsurface, supporting future thermal management models. In addition, four boreholes drilled specifically for this project (Abstraction, Recharge, OBS1 and OBS2, see Table 2) with full core recovery have been tested for a range of physical properties including bulk density, natural moisture content, thermal conductivity, thermal diffusivity and resistivity. Data stored within the Geotechnical

Properties Database has been summarised and the Glaciofluvial Sand and Gravels were found to be 'cleaner' in the south of the city with an average of 6 % fines (silt and clay) and a higher permeability than that of the city centre where fines averaged 18 %. This may be related to the confinement of these areas, with the former thought to be confined while the latter is considered generally unconfined. The depth of weathering in the Mercia Mudstone Group varies considerably; typically the top 10-15 m are found to be weathered material but this may reach depths of up to 47 m. Standard penetration test (SPT) N values were found to be higher in the unconfined areas of the aquifer but were generally varied, ranging from 1-150. The data shows the heterogeneity of soils across the city, highlighting the importance of site-specific data. Other data recorded in the database but not specifically interrogated at the time of writing include 9576 SPTs, 1538 water strikes, 1213 contaminant and chemical tests, 1099 point load tests, 842 consolidation tests, 593 particle size distributions, 461 fracture spacing data, 312 triaxial tests, 73 in situ vane tests, 50 weathering grades, 2 shrinkage tests, 23 compaction tests, 14 shear box tests, and 6 in situ density tests.

Developing a 3D geological model

To support the use of ground source heat recovery within Cardiff City Council's regeneration plans a city-scale 3D geological model has been produced (Kendall *et al.* 2018). The geological model extends beyond the main urban city centre to encompass some of the surrounding suburbs and the three main rivers. This model describes the vertical and lateral extent of the superficial geology from surface to the underlying geological rockhead (Fig. 2). The following illustrates the main steps used to create the model.

3D geological modelling software

Geological modelling software 'GSI3D™' (Geological Surveying and Investigation in 3 Dimensions) was used to develop a city-scale model to better understand the extent of the target sand and gravel aquifer and its relationship to the adjacent units. GSI3D™ allows the geologist to create an 'explicit' model by developing cross sections constrained by the surface intercept (geological map) and subsurface constraint from interpreting and correlation of borehole information (Kessler *et al.* 2009).

The 3D geological model illustrates the relationship between superficial deposits comprising Alluvium, Tidal Flat Deposits, Glaciofluvial Sheet Deposits and Till and their contact with the underlying bedrock.

Instrumentation

Baseline groundwater temperatures were measured using a variety of sensors installed in the pre-existing borehole network to characterise the thermal regime beneath the city. These data provide a baseline with which to compare the thermal regime after the installation of heating and storage systems and to assess any long-term impacts of their use on the surrounding aquifer. The following subsections describe the various sensors, their locations, and installation depths.

In–situ temperature sensors

In-situ sensors were installed in 61 monitoring boreholes across a range of depths (Table 2 and Fig. 1; 2). The boreholes selected for instrumentation were spatially distributed across the city representing the main geological units and a range of land uses and land cover. In most boreholes one temperature sensor was installed, however in some boreholes multiple sensors were installed both above and below the boundary of the Zone of Seasonal Fluctuation - the depth to which seasonal oscillations in air temperature affect groundwater temperatures - previously characterised at an average depth of 9.5 mbgl (Farr *et al*. 2017). The Zone of Seasonal Fluctuation was delineated to provide information on the most suitable depth of groundwater pumps for open loop systems. Pumps installed and intercepting groundwater derived from greater than 9.5mbgl should encounter more stable groundwater temperatures, whilst abstractions from aquifers less than 9.5mbgl are more likely to experience seasonal temperature variations that could result in a loss of performance. In boreholes where just one sensor has been installed, depths were chosen to include groundwater both within, and those below the base of the Zone of Seasonal Fluctuation. However, the majority of sensors were installed below the base of the Zone of Seasonal Fluctuation as this is where groundwater heat pumps would be sited and thus monitoring of these temperatures is critical to establish baseline temperatures and potential changes which may occur after the development of ground source heating. It is important to monitor groundwater temperatures to establish a baseline and then to be able to quantify and attribute changes from this baseline, both seasonally and over a period of years. This baseline data will allow assessment of any impact of future developments at a local and city-scale.

A network of boreholes were instrumented with Hobo® Temp Pro V2 sensors with a resolution of 0.02°C and an accuracy of ±0.21°C, Solinst Leveloggers, with a resolution of 0.003°C and an accuracy of ± 0.5°C, and OTT® Hydrometry Orpheus Mini loggers with a resolution of ± 0.1°C and an accuracy of ± 0.5°C. Both the Solinst® and OTT® sensors record water pressure and temperature whilst the Hobo® is a dedicated temperature sensor. Sensors used were chosen for their affordability and reliability and record temperature at half-hourly intervals to be consistent with the existing groundwater level monitoring in the network. 3.75 million temperature measurements from boreholes (Fig 1; Table 2) collected over a period of three years are illustrated in Figure. 3. The data show temperatures to vary considerably across the year within the top 10 mbgl, becoming more seasonally stable below this depth which is significant for the proper siting of groundwater pumps so as to avoid inefficiencies caused by temperature instability.

The groundwater temperature data have a greater variation within the Zone of Seasonal fluctuation (0-9.5mbgl) and become less variable with depth, especially below the Zone of Seasonal Fluctuation. However, some boreholes, for example 9/OB1L, show a wide fluctuation in temperature data. The cause of this is unknown but could be related to localised anthropogenic heat loss from subsurface infrastructure or even localised hydrogeological pathways that allow cooler recharge to bypass the low permeability alluvium and recharge the sand and gravel aquifer.

Telemetry

Telemetry allows for real-time monitoring of groundwater temperatures which is useful for monitoring dynamic boreholes, including those associated with the ground source heat pump. To support our decision-making, an initial screening exercise of the borehole network showed that many were unsuitable for telemetry due to practical factors including; poor reception, no power supply or limited security preventing solar panels from being reliably employed. However, telemetry can be useful at ground source heating system sites as it allows automated messages should changes occur that are outside of permitted values. Automated messages make it possible to detect potential issues early on and remedy them promptly to improve the reliability and functionality of the system. Prior characterisation of the aquifer in Cardiff helped in the selection of suitable sites for telemetry where dynamic changes in groundwater temperature may be observed.

Six boreholes were selected for telemetry comprising three monitoring boreholes within the sand and gravel (4/PB2, 5/PB2 and 2/PB2), one borehole in the Mercia Mudstone Group Marginal Facies (Techniquest), and the abstraction and recharge boreholes at the pilot groundwater source heat pump scheme. Each borehole was installed with a sensor connected to an OTT/ADCON® telemetry unit. Data is sent to a gateway where it is stored in a database and can be visualised for remote monitoring of the system and analysed for research and development. Telemetry provides a novel early warning system for the ground source heat pump demonstrator. In the event of a temperature change outside of pre-defined targets, in this case any temperature below 8°C, staff receive e-mail alerts or SMS text messages allowing them to respond by visiting the site, checking for system issues and altering the system controls.

Groundwater Source Heat Pump Demonstrator

As proof of concept that a shallow open loop ground source heat pump could be viable in an urban setting, a pilot scheme, funded by InnovateUK, was constructed at 'Grangetown Nursery School'[GR 318117, 174486] (Boon *et al*. 2019) in partnership with Cardiff City Council and WDS Green Energy. The ground source heating scheme comprising two shallow boreholes (18.6 and 22 m deep) was retrofitted to replace an existing gas central heating system (Fig. 4). Operational since November 2015 it supplies 22 kW of peak heating output. Shallow groundwater from the sand and gravel aquifer is abstracted from a 22 m deep borehole with a pump installed at 15 mbgl. Groundwater is passed through a heat exchanger, which transfers around 2 Kelvin of heat to the heat pump brine circuit, before being returning to the same sand and gravel aquifer via a recharge borehole (18.6 m deep) located 20 m away from the abstraction borehole. An abstraction licence and registration of an exemption to discharge were obtained from Natural Resources Wales, the environmental regulator before the site could become operational. The system abstracts and returns on average 36 m^3/day and is limited by a single speed pump operating on-demand rather than continuously. The system is instrumented with an early warning telemetry system, and monitoring of the surrounding aquifer is provided by boreholes CS241, CS317L, OBS1 and OBS2 (Table 2). We monitored the groundwater levels, temperatures, abstraction volume, as well as all parts of the heat pump system including heat generated and the brine circuit. Changes in groundwater temperatures at the demonstrator site are tracked in reference to baseline temperatures. Observed changes from the baseline are out of scope for this paper but are the subject of Boon *et al*. 2019, however this pilot scheme proves shallow open loop systems in urban areas can be viable.

Open Access Data Portal

Half-hourly temperature data from 2014 onward are available via the open access portal; www.ukgeos.ac.uk/observatories/cardiff (Fig. 5). The decision to make the data open access was made to increase confidence for developers, whilst allowing local authorities, environmental regulators and policy makers to underpin evidence-based decisions. Each monitoring location, or 'node', is attributed with information on the location, depth, sensor ID and measurement properties e.g. temperature or groundwater level. Once downloaded, the data is prepared in .csv format, validated and matched to the individual node.

Groundwater chemistry

Groundwater chemistries, including elevated concentrations of iron and manganese, can result in the fouling of boreholes, groundwater pumps and heat exchangers, leading to the loss of performance of ground source heating schemes. It is not possible to reduce the source of these metals in the sand and gravel aquifer however an understanding of likely concentrations will allow developers to be better prepared to mitigate against possible system damage. To characterise groundwater chemistry, specifically iron and manganese in the target sand and gravel aquifer, data was collated from operational dewatering schemes operated by Cardiff Harbour Authority (Fig. 1) (Williams 2008).

Groundwater chemistry data measured over a period of 12 years are summarised (Fig. 6). The box plots show the range of measured values confirming that iron and manganese are both ubiquitous within the target aquifer. De-oxygenated groundwater high in dissolved iron and manganese can, on interaction with oxygen in the atmosphere, result in precipitation of iron and manganese oxides creating operational problems such as biofouling in heat exchangers, associated pipework, pumps and boreholes. This information shows the value of baseline water chemistry monitoring data as it highlights a system design constraint to reduce the impact of iron and manganese by sealing the systems from the atmosphere where possible. Lessons can be transferred from experience in other aquifers where this is commonly dealt with, e.g. coalfields (Younger 2014; Banks *et al*. 2017).

Discussion

Establishment of the Cardiff Urban Geo-Observatory has given rise to a number of discussion points which are addressed below.

Monitoring strategies

Bonsor *et al*. (2017) identified it to be best practice to have a clear understanding of the monitoring aims before establishing a geo-observatory. Prior to the commencement of monitoring, it is useful to consider the type of data that will be required, the frequency with which it will be measured, how it will be displayed, what method of analysis will be used and how the data will be stored for future use (Bonsor *et al*. 2017). Long-term maintenance, staffing costs and funding are also important considerations to ensure the future security of any monitoring network. Monitoring considerations include; vertical and horizontal distribution of monitoring points, geological setting, land use and cover, site security and access, monitoring frequency and duration. Half-hourly monitoring was chosen to be constant with other groundwater monitoring networks. New borehole networks can be designed specifically to match the purposes of the geo-observatory, however in Cardiff it has proven possible to repurpose existing groundwater monitoring infrastructure. Where existing networks can be repurposed a significant cost reduction can be realised. We therefore recommend that where existing infrastructure is suitable for repurposing that it should be used to establish a geo-observatory or supplement new infrastructure. We recommend that where possible city-scale monitoring should be developed in partnership with the local authority as it may complement their renewable energy strategy and raise awareness within the user community.

Monitoring techniques

Low-cost, reliable sensors were chosen to maximise the extent of the monitoring network. The large memory capacities and battery life of the sensors reduces the number of site visits required for downloading data. Long periods between downloading data can result in delays in detecting data loss, however only one sensor has failed during the current study. Downloading sensors requires resources for staff to visit each site thus large memory capacities reduces the amount of staff resource required to maintain the geo-observatory, however, manually downloaded sensors do not provide real-time data.

Telemetered sensors allow real-time data to be streamed to open access web viewers reducing the need to regularly visit the sites and rapidly highlighting when sensors fail, thus potentially reducing data loss. Telemetry can reduce health and safety concerns where access is difficult or in boreholes where groundwater may be contaminated. Telemetry systems also offer e-mail or SMS alerts of system failures or exceeded pre-defined values which is useful in dynamic situations such as near ground source heat recovery operations. However, telemetry can be expensive to install and has ongoing maintenance costs and may not be required where there is less dynamic change in groundwater temperatures. Data hosted or stored by third parties could be potentially at risk in the event that the external company cease to provide this service, or in cases of cyber threats, and data should be backed up securely on separate servers.

In areas with good access to the boreholes, manually downloaded sensors may prove to be sufficient and financially efficient. In urban areas where security issues may arise, the low cost of these sensors and their lack of external infrastructure needed to support them may make them more suitable. However, for remote or dynamic sites where access may be limited or real time data more crucial, telemetry may be preferable. We found that a mixture of both telemetry and manually downloaded sensors provided the best method of data capture and recommend that when establishing a new network consideration is given to the costs and requirements before deciding which method to employ.

Open access data

To increase the impact of the temperature data, the majority of which has been funded from public resources, it is appropriate for the data to be available via an online, open access data portal. Open access data encourages and enables technical and non-technical stakeholders, including local authorities, planners, developers, policy makers and regulators to better plan and de-risk subsurface development including ground source heat recovery and storage. It is hoped that research and development will also be supported by the open access data.

Positive societal and environmental impacts will be realised if low-carbon ground source heat and recovery becomes part of the renewable energy mix, and open access data can raise the profile of this type of work. Open access data allows informed decisions to be taken about the subsurface reducing the risks of delays and overspend and increasing investor confidence that systems will be financially viable and technologically reliable. We recommend that particularly where geo-observatories are publically funded data should be made available via open-access portals as this increases the likelihood of data being utilised to its full potential and allows for greater collaboration with a host of other interested organisations.

Integrating evidence into decision making

Data from urban geo-observatories could be used to support early-stage integration of low-carbon heat networks into new development areas. Evidence has been shared with partners and stakeholders including the City of Cardiff Council and the National Assembly for Wales in order to support policy planning and decision making that is based on scientific evidence. Positive outcomes of this approach have included the addition of shallow geothermal energy into the Heat Network Delivery Unit (HNDU) master plan for Cardiff, and inclusion of the demonstrator ground source heat pump in a national briefing paper (National Assembly for Wales 2018). However, challenges such as how to integrate this evidence to support new policy, urban planning and heat regulation decisions remain. Development of geo-observatories in partnership with local authorities can help ensure scientific data is engaged with by planners at an early stage and thus increase the likelihood of sustainable development based on evidence. Similarly, case studies of successful geo-observatories that provide baseline data on which areas such as Cardiff have been able to make strategic decisions can prove useful in illustrating the need for similar investment elsewhere. Baseline data prove resource availability prior to system installation, reducing the risk of unsuitable sites being selected at feasibility stage. Furthermore, these data can be used to characterise change from background conditions thus identifying the long-term effects. Through integration into planning and regulation, this can enable better management of subsurface heat thus making its exploitation a more reliable and sustainable prospect.

Thermal management and ownership of heat

One of the main challenges in the UK is the absence of a regulatory framework that enables management and governance of heat in the subsurface. If not managed properly, issues surrounding ownership of heat resources may lead to conflict between users and interference between systems, reducing the effectiveness of installations and undermining investor and public confidence. Disparities between the regulatory approach applied to closed loop (no regulation) and open-loop systems (abstraction licence and permit to discharge) results in fewer open-loop systems and more, unregulated closed-loop systems. The need for better management of subsurface heat in the UK has been highlighted previously (Fry 2009; Herbert *et al*. 2013; Abesser *et al.*; 2018) however little has been done at government level to address these concerns. The Common Vision for the Renewable Heating and Cooling sector in Europe recommends that authorisation procedures associated with this type of technology be streamlined, with the cost of permits reduced to encourage uptake, whilst at the same time not compromising the environment (Sanner, *et al*. 2011). With heat recovery becoming ever more topical it is time for policy makers to work closely with scientists and engineers from industry to address these challenges. Whilst they do not address the ownership of heat directly, urban geo-observatories can provide evidence, required to support decision making on the ownership and governance of heat in the subsurface. We propose there is an urgent need to update licencing, permitting and policy to reflect the challenges of a low-carbon economy, and that scientists, industry, policy makers and regulators need to work together to address this challenge.

Limitations

Re-purposing an existing groundwater monitoring network has several logistical and cost advantages however this approach has led to data being limited to the locations of a network not originally designed for this purpose. Ideally, boreholes should be drilled where they will be of most use to the purpose of the geo-observatory to yield the best data coverage, however, due to the extensive network in Cardiff the data covers the key lithologies, land use and spatial cover. The total number of sensors was governed by the available funding, however the amount deployed in Cardiff is considered sufficient. We recommend that where possible multiple sensors are installed in boreholes to characterise the depth to the Zone of Seasonal Fluctuation which is variable within urban areas. Finally, it is noted that in order to produce hydrogeological and heat transport models, and enable long-term temperature forecasting, other datasets need to obtained in addition to the groundwater temperature and levels, geotechnical data and the 3D geological model. These data include sewer and water mains, land use and land cover maps, details about recharge potential, and thermal properties data.

Conclusion

Establishment of a geo-observatory can provide evidence of subsurface conditions required by policy makers, regulators, planners and developers to implement ground source heat recovery and storage schemes. We conclude that;

- A city-wide monitoring approach is favoured to be applicable across an aquifer to allow for the characterisation of the available resource and the long-term implications of its use. The accompaniment of 3D geological models provides a conceptual framework for planning and development of subsurface heat recovery and storage schemes.

- Re-purposing existing groundwater monitoring boreholes is a cost effective way to establish a geo-observatory.

- Partnership with local authorities can highlight the potential of ground source heating in urban areas and increases the likelihood that data will be used to make strategic decisions.

- Temperature sensors should be placed across a range of depth, land use and land cover to characterise temperatures throughout target aquifer. Low-cost, reliable sensors allow more boreholes to be instrumented, however consideration should be given to required resources. Telemetry is not essential for all monitoring points and can be concentrated in boreholes where dynamic or rapid changes may occur, for example at active ground source heat pumps. Manual sensors are a cost effective alternative to telemetry in accessible sites or where security may be an issue.

- Open access portals allow planners, developers, researchers and heat pump installers to better design shallow heat recovery and storage systems, increasing investor confidence. Baseline data could benefit regulators and policy makers, allowing evidence-based decisions ensuring sustainable use of subsurface resources. Data is needed for long-term temperature forecasting and can form a basis for hydrogeological and heat transport models.

- Thermal management and ownership of heat in the subsurface are still key challenges that need to be addressed in the UK if sustainable subsurface heat recovery and storage is to be achieved. Scientists, policy makers and regulators need to work in partnership to develop a fit-for-purpose regulatory approach to subsurface heat.

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Figures

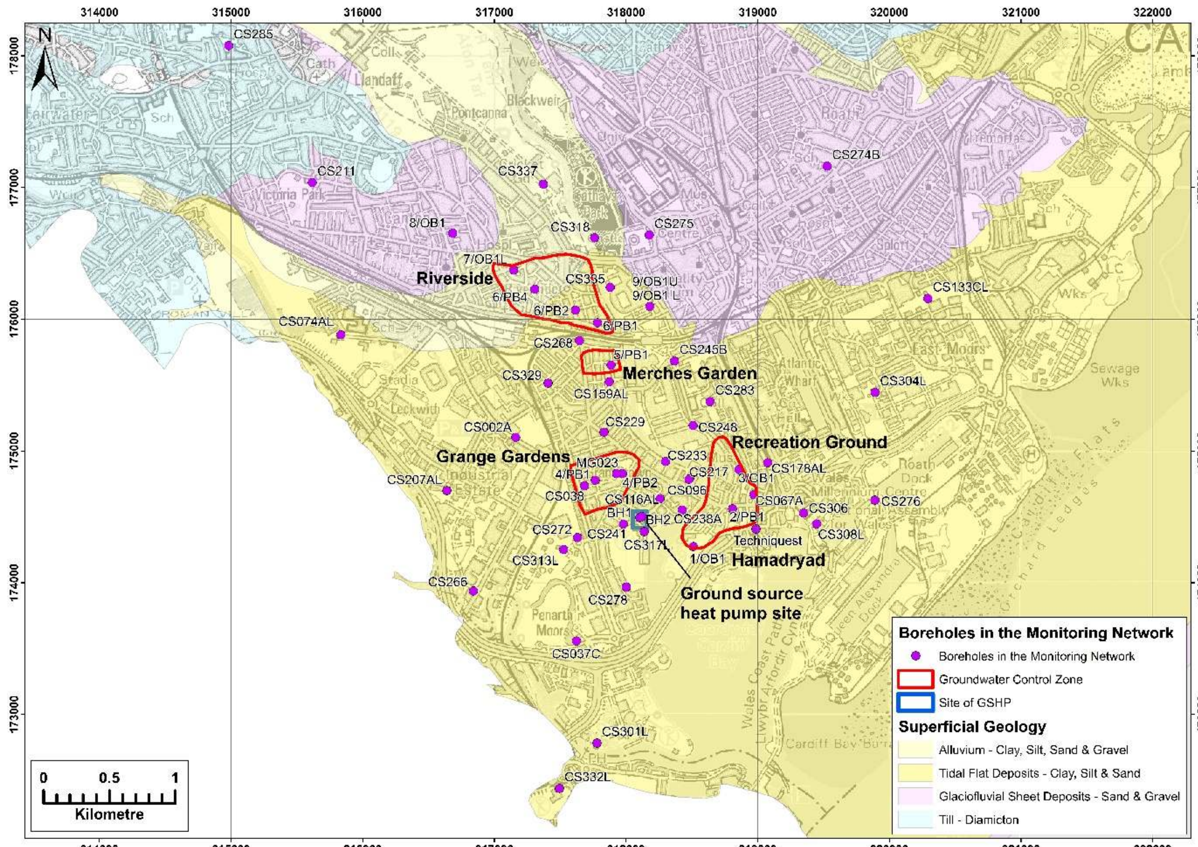


Fig. 1. Quaternary geological map of the Cardiff Urban Geo-Observatory showing monitoring boreholes, demonstrator ground source heat pump site and dewatering operations in the target sand and gravel aquifer. Contains 1:50,000 BGS DiGMap and OS data © Crown Copyright and database rights 2019.

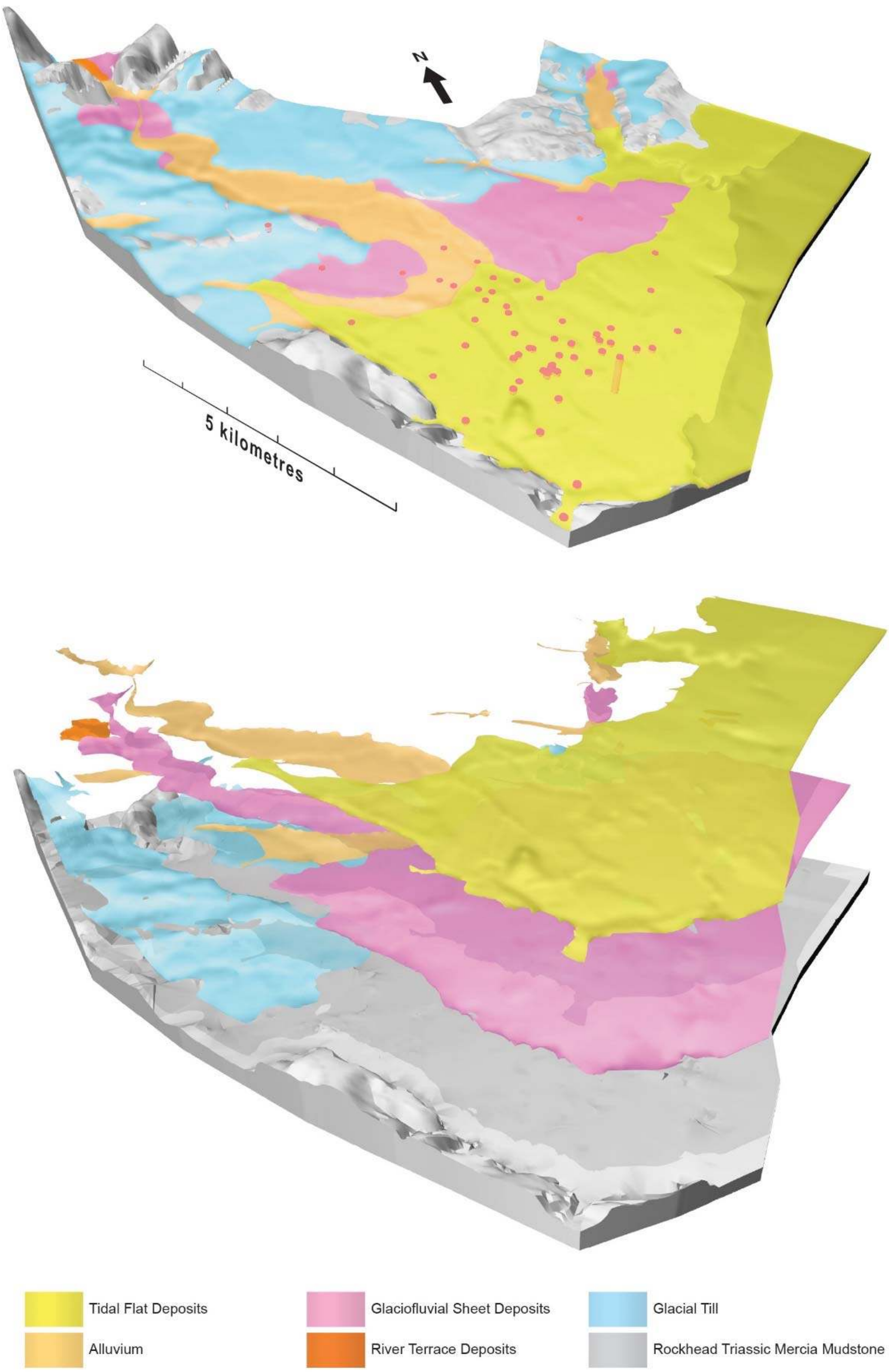


Fig. 2. Above: Initial image from the developing 3D geological model of Cardiff (Kendall et al. 2018) with monitoring borehole locations shows as pink dots, 5 x vertical exaggeration. **Below:** an exploded version of the same model but without the borehole locations ©British Geological Survey

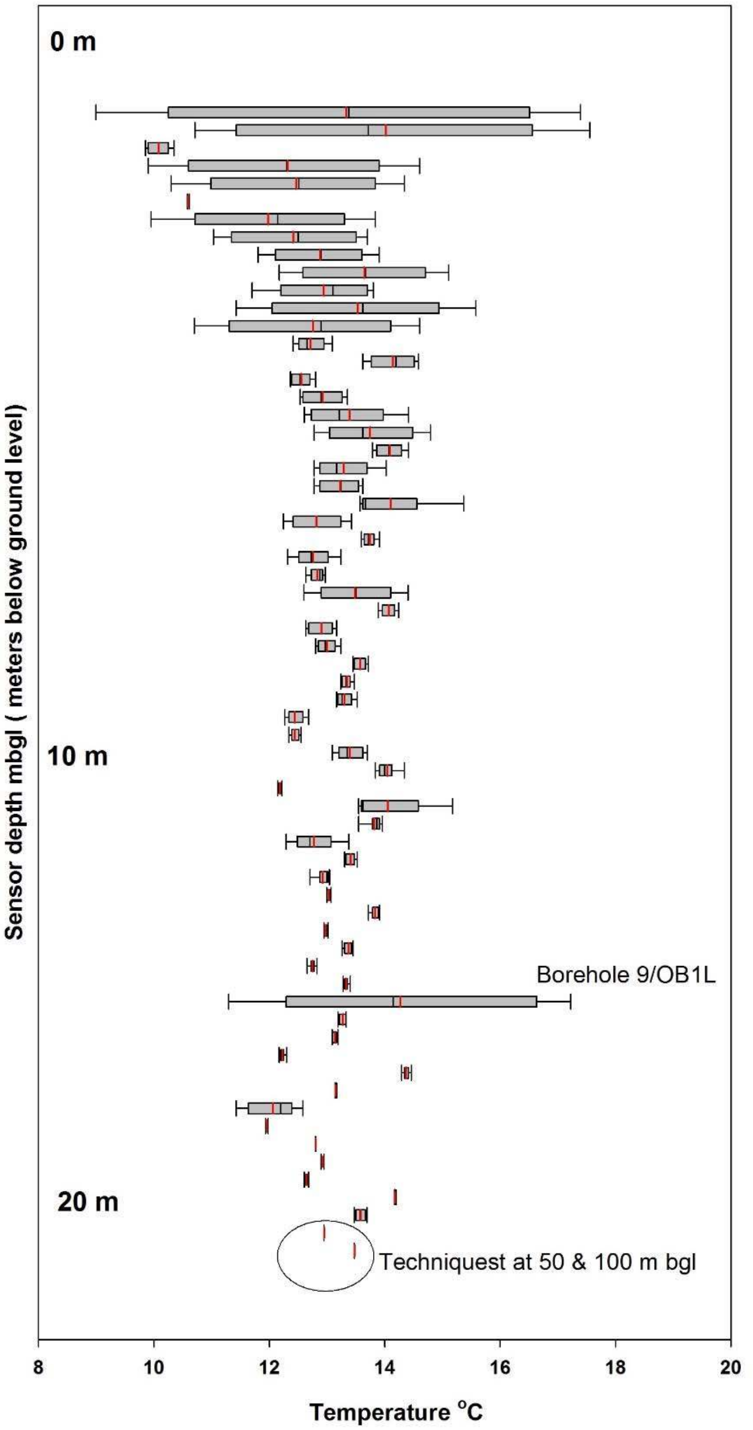


Fig. 3. Groundwater temperatures, comprising of 3.75 million measurements between 2014 and 2017. Box Plots show 25th and 75th percentile, and within the box the black line is the median and the red

line is the mean. The stalks represent the 5^{th} and 95^{th} percentile, outliers are not shown in this dataset. Location of temperature sensors (Table. 2).

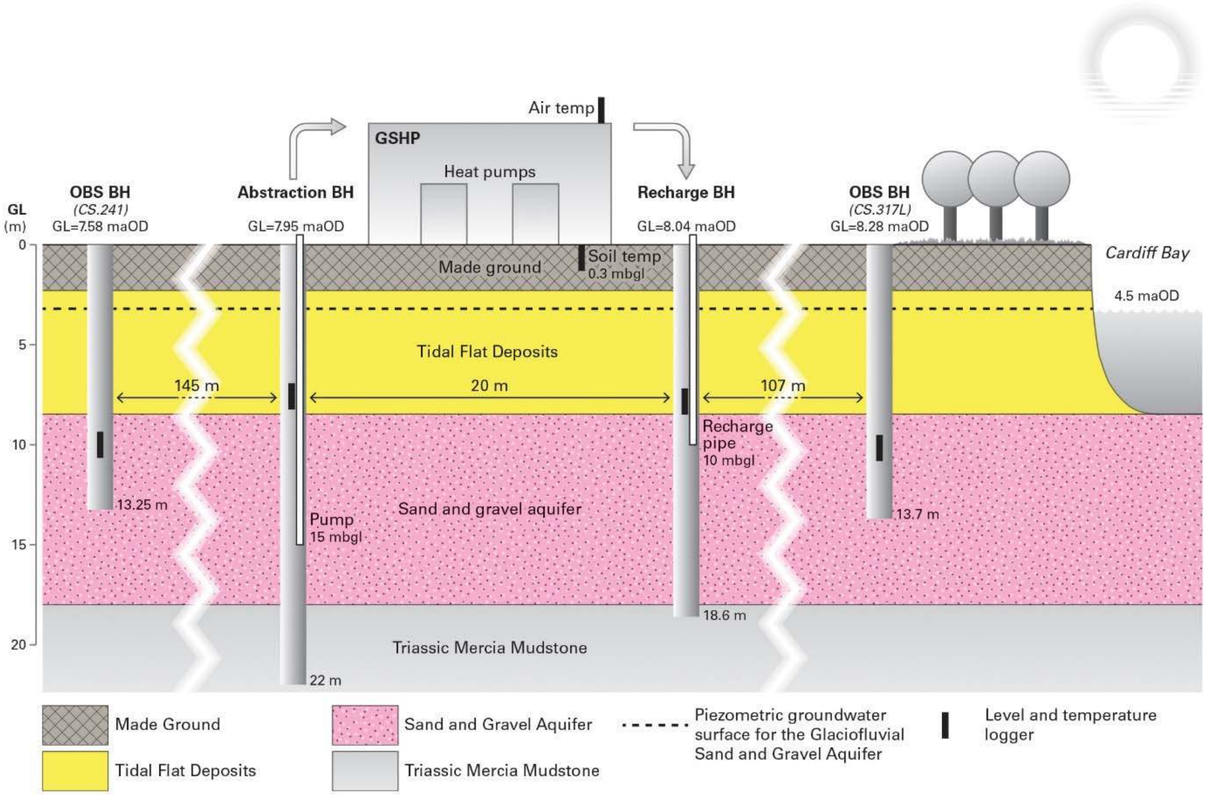
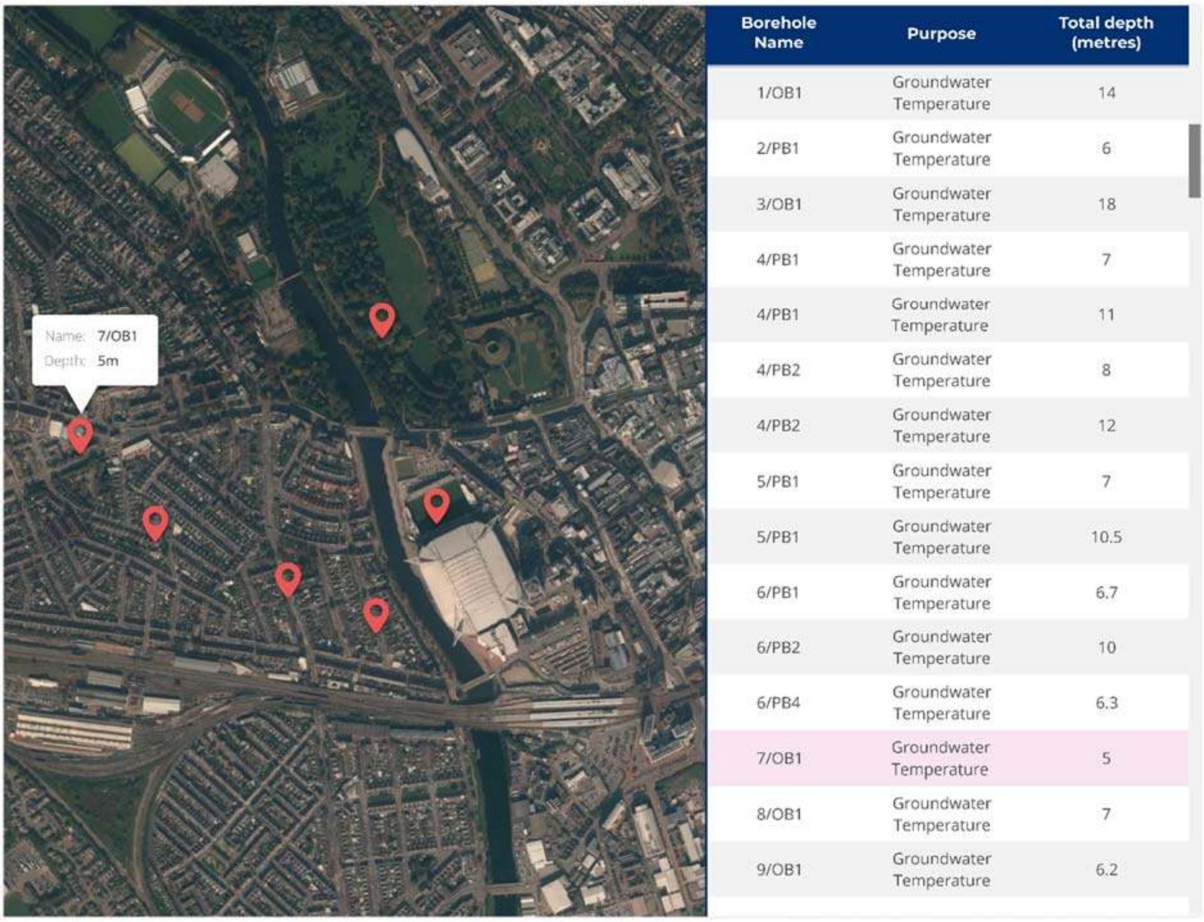


Fig. 4. Schematic diagram of the demonstrator open loop ground source heat system at Grangetown Nursery ©British Geological Survey.



Borehole Name	Purpose	Total depth (metres)
1/OB1	Groundwater Temperature	14
2/PB1	Groundwater Temperature	6
3/OB1	Groundwater Temperature	18
4/PB1	Groundwater Temperature	7
4/PB1	Groundwater Temperature	11
4/PB2	Groundwater Temperature	8
4/PB2	Groundwater Temperature	12
5/PB1	Groundwater Temperature	7
5/PB1	Groundwater Temperature	10.5
6/PB1	Groundwater Temperature	6.7
6/PB2	Groundwater Temperature	10
6/PB4	Groundwater Temperature	6.3
7/OB1	Groundwater Temperature	5
8/OB1	Groundwater Temperature	7
9/OB1	Groundwater Temperature	6.2

Fig. 5. The Cardiff Urban Geo-Observatory open-access data portal where groundwater temperature data from the manually downloaded and telemetered sensors is archived (www.ukgeos.ac.uk/observatories/cardiff). Contains NERC materials ©NERC 2019.

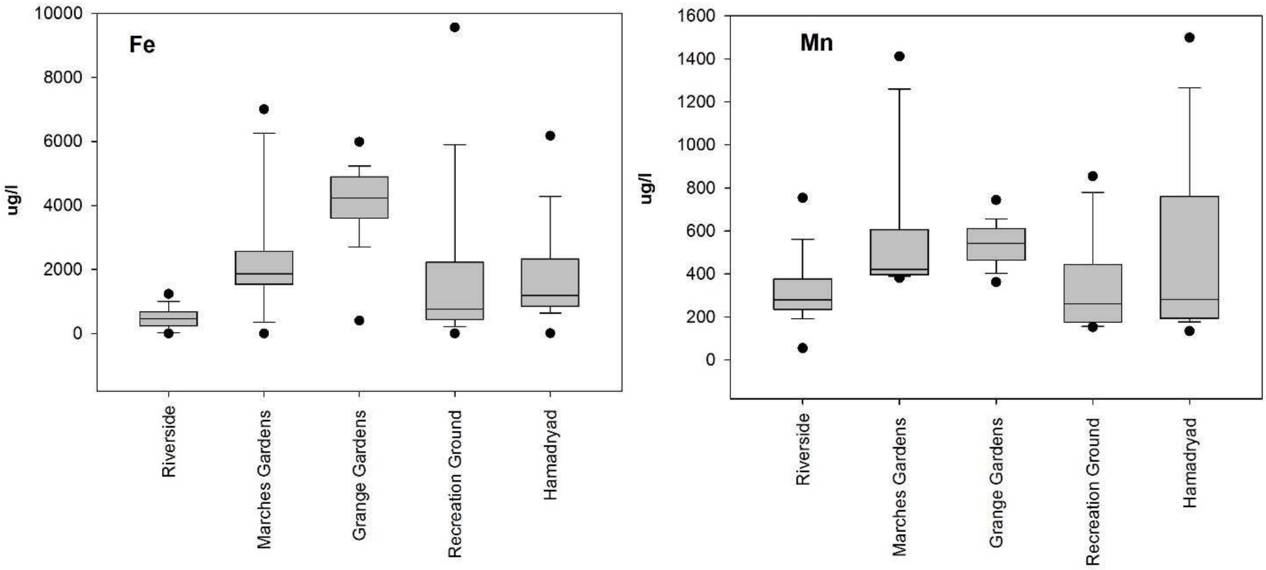


Fig. 6. Box plots showing the range of Fe and Mn (ųg/l) in groundwater samples collected between 2000 – 2012 from the 'groundwater control zones' which are dewatering operations in the sand and gravel aquifer. The box part of the Box Plots show 25th and 75th percentile, the line through the middle is the mean and stalks show the 5th and 95th percentile with the black dots marking the extent of the outliers. Data reproduced with kind permission of Cardiff Harbour Authority.

Tables

Country	City / Region	Description	Reference
UK	Cardiff	Mapping groundwater temperatures in a glaciofluvial sand & gravel aquifer. Depth 0-30 m.	Farr *et al.* 2017
	London	Interaction of open loop ground source heat pumps, thermal modelling of multiple open loop schemes.	Fry, 2009; Headon *et al.* 2009; Herbert *et al.* 2013
Republic of Ireland	Cork	Characterising groundwater temperatures in a sand & gravel aquifer. 0-50 m depth.	Allen *et al.* 2003
Germany	Berlin Munich Cologne Karlsruhe Hamburg	Groundwater temperature monitoring networks in sand and gravel aquifers, heat potential, groundwater modelling, evolution of temperatures and anthropogenic heat fluxes	Benz *et al.* 2016; Zhu *et al.* 2010; 2015; Menberg *et al.* 2013a; b
	Ludwigsburg	Modelling of geothermal potential	Schiel *et al.* 2016
Netherlands	Amsterdam, The Hague and Herleen	Web based viewer for groundwater temperatures	Bonsor *et al.* 2017
Finland	Turku, Lohja & Lahti	Characterising geothermal potential i glacial sand and gravel aquifers. Depth 0-60m. Country wide geothermal potential mapping	Arola & Korkka-Niemi 2014; Arola *et al.* 2014
Spain	Barcelona & Zaragoza	Characterising, monitoring & modelling of quaternary aquifer impacted by ground source heat pumps, management of thermal resources.	García-Gill *et al*. 2014; 2015a; 2015b; Epting *et al.* 2017
Slovenia	Ljubljana	Thermal conductivity & groundwater temperature monitoring	Janža *et al.* 2017
Italy	Cuneo province	Assessment and mapping of groundwater temperature	Casasso *et al.* 2017
Austria	Vienna	Trends in groundwater temperature	Benz *et al.* 2018a
	Leibnitz	Modelling of fulvioglacial aquifer	Händel *et al.* 2013
Switzerland	Zurich & Basel	Characterising, monitoring and modelling of urban aquifers. Sustainable management of thermal resources.	Benz *et al.* 2016; Epting *et al.* 2013; Epting & Huggenberger 2013; Epting, 2017; Mueller *et al.* 2018; Epting 2017; Epting *et al.* 2018
Japan	Tokyo & Osaka	Groundwater temperature monitoring network, with repeat temperature profiling of boreholes and assessment of urban heat island	Taniguchi *et al*. 2007; Hayashi *et al*. 2009; Arimoto *et al*. 2015; Benz *et al.* 2018b.
Korea	Seoul	National groundwater temperature monitoring network	Lee 2006; Taniguchi *et al*. 2007
Canada	Winnipeg	Groundwater temperature measurements in 40 wells	Ferguson *et al.* 2007; Zhu *et al*. 2010

Table 1. Global examples groundwater characterisation, monitoring and modelling of shallow groundwater aquifers and the subsurface Urban Heat Island

Borehole ID	Easting	Northing	Geology	Sensor Type	Sensor depth mbgl
1/OB1	318511	174275	S&G	1	14.0
2/PB1	318809	174561	S&G	1	6.0
2/PB2	318851	174749	S&G	3	15.0
3/OB1	318857	174859	S&G	1	18.0
4/PB1	317766	174778	S&G	1	7.0 & 11.0
4/PB2	317973	174828	S&G	1, 1, 3	8.0, 10.0 & 12.0
5/PB1	317886	175652	S&G	1,1	7.0 & 10.5
5/PB2	317886	175652	S&G	3	10.0
6/PB1	317783	175973	S&G	1	6.7
6/PB2	317616	176069	S&G	1	10.0
6/PB4	317307	176228	S&G	1	6.3
7/OB1L	317147	176374	S&G	1	5.0
8/OB1	316683	176653	S&G	4	7.0
9/OB1U	318181	176098	S&G	1	6.2
9/OB1L	318181	176098	S&G	1	13.0
CS002A	317162	175103	S&G	1	7.9
CS037C	317624	173558	S&G	1	14.5
CS038	317685	174736	S&G	1	6.0
CS067A	318972	174669	S&G	1	13.2
CS074AL	315834	175882	S&G	1	6.0
CS096	318483	174789	S&G	4	6.5
CS116AL	318258	174638	S&G	1	12.5
CS133CL	320293	176158	S&G	1	10.3
CS159AL	317873	175526	S&G	1	1.5
CS178AL	319076	174911	S&G	1	8.8
CS207AL	316639	174699	S&G	1	8.0
CS211	315617	177038	S&G	1	3.9
CS217	318478	174785	S&G	1,1	7.5 & 11.5
CS229	317833	175143	S&G	1	7.0
CS233	318300	174920	S&G		7.0 &11.0
CS238A	318427	174553	S&G	1	15.5
CS241	317980	174445	S&G	1	11.5
CS245B	318368	175683	S&G	1	8.0
CS248	318510	175193	S&G	1	7.8
CS266	316841	173938	S&G	1	11.4
CS268	317646	175838	S&G	1	7.0
CS272	317632	174343	S&G	1,1	7.0 & 11.0
CS274B	319528	177162	S&G	1	5.2
CS275	318177	176639	S&G	4	5.0
CS276	319891	174627	S&G	4	4.7
CS278	318002	173967	S&G	1	18.9
CS283	318639	175375	S&G	1	7.7
CS285	314982	178077	S&G	1	3.0
CS301L	317779	172783	S&G	1	15.5
CS304L	319892	175445	S&G	1	13.7
CS306	319349	174529	S&G	1	10.2
CS307L	319251	174489	S&G	1	14.2
CS308L	319448	174447	S&G	1	18.1
CS313L	317526	174252	S&G	1	11.0
CS317L	318139	174388	S&G	1	12.4
CS318	317761	176618	S&G	4	3.0
CS329	317408	175515	S&G	1	6.5

Borehole ID	Easting	Northing	Geology	Sensor Type	Sensor depth mbgl
CS332L	317494	172439	S&G	1	6.0
CS335	317880	176242	S&G	4	4.0
CS337	317372	177025	S&G	4	5.5
MG023	317928	174829	MG	1	1.50
Ground Source Heat Pump Demonstrator Site					
Abstraction	318104	174495	S&G	3	10.0
Recharge	318120	174502	S&G	3	8.0
OBS1	318066	174436	S&G	2	10.0
OBS2	318008	174384	S&G	2	10.0
Techniquest	318987	174408	MM	1,3	10.0, 15.0, 50.0 &120.0

Geology: MG = Made Ground, S&G = Quaternary Glaciofluvial Sand and Gravel, MM = Triassic Mercia Mudstone Group (bedrock)

Sensor Type:

1 = Hobo Temp Pro V2® (Range 0 to + 50 °C, resolution 0.02°C, accuracy ±0.21°C)

2 = Solinst Levellogger® (Range 0 to +50 °C, resolution 0.003°C, accuracy ±0.05°C)

3 = OTT® Hydrometry® Orpheus Mini (Range (Range 0-70°C, resolution 0.1°C, accuracy ±0.5°C) via telemetry

4 = OTT® Hydrometry® Orpheus Mini (Range (Range 0-70°C, resolution 0.1°C, accuracy ±0.5°C)

Table 2. Locations of groundwater temperature sensors (all borehole logs are open access and can be viewed on the British Geological Survey ‘Onshore GeoIndex’ viewers (www.bgs.ac.uk))