The first city-wide map of shallow groundwater temperatures in the UK to support the development of ground source heat systems

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Abstract: Low enthalpy ground source heating systems can help to reduce our dependency on fossil fuels, in turn reducing greenhouse gas emissions and increasing energy security. In order to de-risk and support the sustainable development, regulation and management of ground source heating systems in urban areas, detailed baseline mapping of groundwater temperatures is required. Groundwater temperatures were measured in 168 monitoring boreholes primarily within a Quaternary sand and gravel aquifer in the city of Cardiff, UK. The data has been used to create the first city-wide map of shallow groundwater temperatures in the UK. This map can be used both to support development of ground source heating but also to act as a detailed baseline from which to measure change. Shallow groundwater temperatures under the city were found to be 2°C warmer than the UK average groundwater temperature and this additional heat is attributed to the Urban Heat Island. The Zone of Seasonal Fluctuation varies from 7.1 and 15.5 mbgl within the shallow Quaternary aquifer, averaging 9.5 mbgl. Deeper groundwater

temperature profiles incorporating both the Quaternary and bedrock aquifers, suggest a 'Zone of Anthropogenic Influence' exists down to about 70 mbgl.

Introduction

Around a third of the UK's greenhouse gas emissions are produced by space heating, and the UK Government recognises the need to change the way heat is produced and consumed in order to reduce the impacts of climate change and improve energy security (DECC, 2013). In response to this driver the UK Government has established targets in the legally binding Climate Change Act, 2008, to reduce greenhouse gas emissions by 80% from the 1990 baseline by 2050. In Wales the 'Well-being of Future Generations Act Wales (2015)' requires Public Bodies to take action to undertake sustainable development to drive social, economic and environmental benefits, both now and into the future. Low enthalpy ground source heating systems, when deployed in a sustainable manner, can provide a low cost, low carbon, and secure form of heating (e.g. Allen *et al*., 2003). Ground source heat pumps can broadly be classified as either 'open loop' or 'closed loop' systems. Open loop systems require the abstraction of groundwater which is passed through a heat exchanger before being returned to the aquifer. Open loop systems can have a higher coefficient of performance (COP) and require less boreholes where shallow groundwater is available. Open loop systems may not be suitable if water cannot be successfully recharged to the same aquifer and there are also requirements for abstraction licences and discharge permits or exemptions. The closed loop system uses a sealed pipe that can be either laid flat or installed vertically into a borehole, however these systems often require a greater number of boreholes, increasing cost, however in the UK they do not require licensing and this can reduce costs. Sustainable development of ground source heat pump (GSHP) systems for both heating and cooling requires characterisation of baseline groundwater temperatures. Knowledge of baseline conditions is important to support the design and regulation of GSHP. Baseline temperature data is required to assess the potential impacts of multiple ground source heating and cooling systems in order to avoid interactions between neighbouring systems (Fry 2009; Banks 2009; Headon *et al*., 2009). It is anticipated that if negative interactions between ground source heating and cooling systems continue that some aquifers, mainly in densely populated cities, will need to be managed in terms of heat as well as groundwater resources (Banks, 2009). Regulators need legal, policy and scientific tools to support risk based management of the subsurface, and one such tool is baseline temperature data and mapping of groundwater heat resources.

The shallow gravel aquifer in Cardiff is a favourable geological setting in which to develop open loop ground source heating systems. To support the sustainable development of this technology we have produced the first city-wide baseline map of groundwater temperatures and better defined the depth of the Zone of Seasonal Fluctuation. The data and supporting map outputs will provide an independent source of information for system designers and installers, housing developers, space planners, and regulators that is intended to help inform planning decisions and optimise design of GSHP schemes. Additionally, we describe observed seasonal groundwater temperature variation and define the base of the 'Zone of Seasonal Fluctuation', which will enable developers to locate abstraction boreholes at depths unaffected by seasonal temperature changes. An initial estimate of available thermal energy that could be transferred from existing dewatering abstractions is made as an illustration of the city-wide potential.

Study area

The City of Cardiff is located on a flat, low-lying, south-facing, coastal flood plain adjacent to the Bristol Channel (Fig. 1). It covers an area of 140 km^2 and has a population of approximately 346,000 (Office for National Statistics, 2012). The city lies at the mouth of three rivers; the Taff, Ely and Rhymney. Two of these, the Taff and the Ely, discharge into Cardiff Bay, an artificially impounded freshwater body, while the Rhymney drains directly into the Bristol Channel. Much of Cardiff is underlain by bedrock geology comprising Triassic age mudstone with subordinate siltstone, sandstone and conglomerate of the Mercia Mudstone Group. The bedrock is overlain by Quaternary superficial deposits, up to 30 m in thickness, that include Alluvium and Tidal Flat deposits (clay, silt, sand and gravel), Glaciofluvial Sheet Deposits (sand and cobbly gravel), and Till (cobbly and clayey gravel) (Fig. 1 & Fig. 2).

The groundwater regime in the city has been extensively monitored and modelled to quantify possible impacts, such as flooded basements, resulting from the construction and impoundment of the Cardiff Bay barrage in 1999 (Edwards, 1997; Heathcote *et al*., 1997; Heathcote *et al*., 2003). The target aquifer for the study is the glaciofluvial sand and gravel (Fig. 2) which is underlain by the lower permeability Triassic Mercia Mudstone, which defines the base of the sand and gravel aquifer. The sand and gravel is overlain by alluvium of intermediate to low permeability (Edwards, 1997). Groundwater is generally encountered within a few metres of the surface, however perched groundwater can occur closer to the surface within the extensive made ground deposits, especially in the southern part of the city. Recharge to the glaciofluvial sand and gravel aquifer occurs both where it is unconfined, mainly to the north of the city, but also via downwards leakage through the alluvium within the city centre and south towards the coast. Heathcote *et al*., (2003) describe how recharge can be impeded in areas where low permeability surface cover redirects precipitation to rivers or sewers. Conversely the potential impact of proposed sustainable urban drainage systems (SuDS) schemes should be considered as these could either further reduce (in the case of non-infiltration SuDS) or increase (e.g. borehole soakaways) recharge to the glaciofluvial sand and gravel aquifer. The impact on groundwater temperatures from SuDS within the aquifer are unknown. Artificial recharge can also occur via leakage from drinking water mains and sewers (Heathcote et al., 2003). Groundwater flow generally occurs towards the rivers and southwards towards the coast, although man-made structures such as sewers can act to locally depress the peizometric surface (Heathcote *et al*., 2003). Groundwater in the glaciofluvial sand and gravel aquifer can discharge into the base of the rivers and the bay (Edwards, 1997). Construction of the Cardiff Bay barrage, and creation of a permanent body of water (Cardiff Bay) has introduced a fixed head of water at 4.5 maOD, a stark contrast to the pre barrage natural estuary setting where mean spring tides ranging between +6.0 maOD to – 5.1 maOD (Heathcote & Crompton, 1997).

History of groundwater monitoring in Cardiff

It was possible to undertake high density mapping of groundwater temperatures at a city-wide scale due to an existing network of monitoring boreholes. This network was installed in response to construction of the Cardiff Bay Barrage which extends between Cardiff Docks and Penarth Head. The purpose of the Barrage was to create a freshwater lake and a new transport link that would provide a catalyst for urban regeneration in the derelict parts of Cardiff Docks (Hunter & Gander, 2002).

Before construction, the Cardiff Bay Barrage Act, 1993, was approved by Parliament placing a legal requirement for long-term groundwater monitoring by the Cardiff Bay Development Corporation and its successor, Cardiff Harbour Authority, to assess the impacts of the barrage. Groundwater monitoring was based on model predictions of likely increases in groundwater levels that could result in the flooding of basements in the South Cardiff area (Cardiff Bay Barrage Act, 1993). The groundwater monitoring network was established between 1995 and 1999, comprising 236 boreholes extending down into made ground, superficial and bedrock deposits. Many of these sites have a dual installation with deep and shallow boreholes and piezometers. Today 194 boreholes remain in the monitoring system covering an area of approximately 15km^2 (Williams, 2008), with 42 boreholes removed after a review in 2011.

Pre-impoundment groundwater monitoring and subsequent modelling (Heathcote *et al.,* 2003) predicted a general rise in groundwater levels to +4.5 maOD within the gravel aquifer. Six areas were identified as being at particular risk from raised groundwater levels (Heathcote et al., 2003) within the gravel aquifer impacting on the made ground.

In these areas ‘groundwater control zones’ (GCZ) were established, with observation wells and abstraction wells monitoring and maintaining groundwater levels within the pre-impoundment range (Fig. 1). The GCZs are characterised by an absence or disturbance of the estuarine alluvium that usually separates the gravels from the made ground. Three types of control measures were installed prior to impoundment; surface drilled horizontal collectors, single wells and field drains. This high density groundwater level monitoring network in south Cardiff has been utilised to characterise baseline urban groundwater temperatures.

Materials and Methods

To create the heat map and develop a city-wide groundwater temperature profiling campaign this study has made use of the pre-existing groundwater monitoring boreholes and data. The data used, and steps involved in the creation of the heat map, are described below in the order they were undertaken.

The borehole monitoring network

The majority of the boreholes utilised in this study were designed and installed between 1995 and 1997 (Ove Arup & Partners, 2000). In total, 225 boreholes were drilled, primarily within the Protected Property Area (Fig. 1) and are instrumented to monitor groundwater levels within the superficial deposits and the underlying bedrock. The majority of these boreholes are within the boundary line of the Protected Property Area that approximately equates with the 10 maOD contour and covers an area of 15 km^2 however there are 11 boreholes located outside of the boundary (Fig. 1). The boreholes range in depth from 1.1 to 19.3 m and are gravel packed along a slotted section and sealed with bentonite clay. Construction is of plain uPVC (50-200 mm diameter) with a slotted section wrapped in a fine gauze geotextile membrane (Ove Arup & Partners, 2000).

Data collection

In situ fixed depth temperature data

A variety of pressure transducers were deployed by Cardiff Harbour Authority (CHA) in the existing Cardiff Bay Barrage monitoring boreholes to record water levels in the network. Seven boreholes (CS248, CS268, CS318, CS274, CS276, CS328B, CS333A) were instrumented with OTT

Hydrometry$^{®}$ Orpheus Mini loggers that record in situ groundwater temperature to a resolution of 0.1°C and accuracy of ± 0.5 °C. The loggers were installed at fixed depths between 4 and 7 mbgl, within the zone of seasonal fluctuation, recording temperature every 30 minutes between March 2012 and February 2014. The time series data from theses boreholes were used to identify annual maximum and minimum temperatures, enabling the profiling of boreholes to take place during April-May, when groundwater was coolest, and September-October when it was warmest.

Depth temperature profile survey

Downhole temperature profile data were collected in order to measure spatial variation in groundwater temperatures within the Quaternary aquifer. It was not possible to measure groundwater temperatures other than via groundwater boreholes, thus it is not known if, for instance, grouted thermistors would provide different results. Temperature profiles were recorded at 168 boreholes (Fig. 1) between 28th March and 15th April, 2014; the expected coolest time of the year for shallow groundwater. An 'In-Situ® Rugged Temperature, Level and Conductivity (TLC) meter was used. The manufacturers report that the meter is able to record between -20 to 85 °C, has a resolution of 0.06 °C and is accurate to ±0.5 °C. Of the 168 profiled boreholes, 164 were observation wells and 4 were licensed groundwater abstractions. Two deep boreholes were profiled including 'Borehole B', 78 m, and 'Techniquest' borehole, 130 m. At each borehole a rest water level relative to a known datum was measured and observations on the daily weather, air temperature and immediate land use were recorded on a site proforma. The TLC metre was calibrated at the start of the day, and allowed to settle in the hole until the temperature was stable. The TLC meter was then lowered by increments of 1m, the probe being allowed time to settle at each meter interval before temperature data were collected. Finally a plumbed depth was measured to confirm the base of the borehole, as ingress of fine sediments, collapse and inconsistent drilling records can often result in shortening and blocking of the slotted section.

This process was repeated six months later on a subset of 35 boreholes during September 2014, when groundwater temperatures are generally at their warmest. The boreholes selected for resurvey represent a range of depth, geology and temperature conditions. Groundwater temperature profiles from the Spring and Autumn were compared to characterise the 'Zone of Seasonal Fluctuation'.

Surface water and air temperature monitoring

Surface water temperature in the River Taff was recorded using a YSI®600XLM data logger suspended from a buoy 1m below the surface. The YSI® loggers are reported to have a range of -5 to 60 °C, resolution of 0.01 °C and accuracy of ±0.15 °C, and record temperatures every 15 minutes. The average air temperature between March 2012 and February 2014 was 10.8 °C (Table 1) however the long-term average annual air temperature of 10.9 °C, calculated by averaging UK Met Office monthly average temperature data from Bute Park collected between 1981 and 2000, was used to infer the predicted geothermal gradient.

Data analysis and baseline groundwater temperature map

To create the baseline groundwater temperature map, data from the 168 borehole temperature profiles, collected in Spring 2014, were considered. Of these data the first (upper most) result from each profile was not considered in order to eliminate atmospheric effects. Data from a further 30 boreholes were excluded from the analysis as they were either dry or terminated less than 2 m below the rest water level, and therefore had only one temperature reading. A further 15 boreholes all <4 m deep were excluded where only made ground was encountered as they can become seasonally dry. Finally, 2 other boreholes were discounted due to poor headworks or compromised casing suspected of allowing ingress of non-representative surface water into the borehole. Data from the repeat profiles measured at a subset of 35 boreholes in September 2014 were not used for the production of the heat map as these were only collected to understand temporal changes and to better define the Zone of Seasonal Fluctuation.

For the remaining 121 boreholes the mean average temperature of the entire water column, excluding the first measurement of each profile, was calculated (Table 1). We acknowledge the potential effect of borehole construction (screened versus plain cased sections) on measured groundwater temperatures within a borehole column. In light of this we compared average groundwater temperatures within the slotted section of each borehole with those derived from the entire water column, including the slotted and plain cased sections of the borehole. There was <0.12 °C difference between the values, justifying the use of average whole borehole temperature values for creation of a baseline groundwater temperature map.

The baseline groundwater temperature map was created using the average temperature data from these 121 boreholes (Table 1). Contouring was done using Surfer® 10 (Golden Software, Inc). The grid file was created using the point Kriging method with no drifts and a linear variogram model. The extent of the grid was defined by the locations of the boreholes and the boundary of the Protected Property Area. The temperatures were contoured with a 0.5 °C contour interval, reflecting the probe manufacture's stated accuracy. The filled contours were displayed with a colour ramp, where darker shades of red represent warmer temperatures and pale colours cooler temperatures. The contour plot was exported as a georeferenced TIFF and imported into ArcMap™ (Environmental Systems Research Institute, Inc) where it was clipped to fit the boundary of the Protected Property Area within which the majority of the monitoring boreholes are located (Fig. 1).

The boreholes are mostly concentrated within the central part of the city, with the largest clusters located within the city centre, Riverside, Butetown and Grangetown areas. The density of boreholes in the east and west of the city is lower resulting in reduced level of confidence in the contour map here compared with the city centre, however the variation in borehole density was allowed for in the contouring. Kriging was chosen as the gridding method for its accuracy and for its ability to compensate for clustered data with a lesser weighting given to the cluster in the overall forecast. However, as the contours are derived from an interpolated grid it is possible that some of the original data points are not honoured using the Kriging method. One drawback of this method is that the contour plot is estimated around its edge but the lower confidence data is removed in this case by clipping the map to the Protected Property Area.

Results and discussion

Annual trends (2012-2014)

In situ hourly groundwater temperature data recorded at discrete depths from seven boreholes (OTT Hydrometry® Orpheus Mini loggers), one river (YSI®600XLM) and one weather station (MetOffice, Bute Park) were compared for a two year period between March 2012 and February 2014, prior to the Spring 2014 baseline survey (Table 2). Data loggers in the boreholes are all installed between 3 and 7 mbgl and thus are within the zone of seasonal fluctuation and will respond, with varying time lags to changes in seasonal atmospheric temperatures**.** Maximum air temperatures of 30.1°C were observed during July and minimum air temperatures of -4.3°C during March, averaging 10.8 °C during the study period. The latter is very similar to the 1981-2000 MetOffice average air temperature of 10.9 °C for Cardiff. The shallow in-situ river temperatures closely reflect the changes in atmospheric conditions, with maximum river temperatures of 24.9 °C recorded in July and minimum river temperatures of 2.3 °C during March. The maximum recorded in situ groundwater temperature between 2012 and 2014 was 16.1 °C, which was recorded in the unconfined sand and gravel aquifer at a depth of 4.7 m, within the Zone of Seasonal Fluctuation. The minimum groundwater temperature recorded prior to the study was 9.1 °C during April and May. Annual temperature variability recorded on in situ loggers can range from 1.1 to 6.6 °C (Table 2). During the study period, maximum groundwater temperatures are achieved 2-5 months after the peak in summer air temperature. This ‘lag effect’ is generally shorter where recharge occurs to the unconfined parts of the aquifer. Land cover and material properties such as thermal conductivity and diffusivity will also influence the time taken for groundwater within the Zone of Seasonal Fluctuation to respond to patterns in seasonal atmospheric temperature.

Baseline groundwater temperature map

Groundwater temperatures within the shallow aquifer are coolest during spring time (April-May). During this period the average temperature within the shallow aquifer is 12.4 °C, which is > 1 °C above the average groundwater temperature reported for England and Wales of 11.3°C (Stuart *et al.* 2010). More than 90 % of the data in the study exceed this value. Groundwater temperatures can be predicted by applying the average UK geothermal gradient of 28 °C km^{-1} (Busby et al., 2011) to the local annual average air temperature of 10.9 °C (MetOffice); a line representing this predicted geothermal gradient is shown in Figure 3. However, the data clearly lie to the right of the predicted geothermal gradient and are thus warmer than predicted.

The heat map (Fig. 4), which illustrates the average spring-time groundwater temperatures, illustrates that the highest groundwater temperatures are found within the city centre and surrounding high-density residential areas of Riverside, Canton, Cardiff Bay, Grangetown, and industrial parts of East Moors and Leckwith. The Marl, a former landfill site located outside of the city centre, also registered above-average groundwater temperatures. Cooler temperatures are found both on the outskirts of the city and in areas of open ground such as Cogan, Victoria Park and Cardiff Rugby Football Club (adjacent to the Millennium Stadium) suggesting land cover and land use may provide a major control on shallow groundwater temperature.

Delineation of temperature zones

The temperature profiles for all 168 boreholes are plotted in Figure 3. The majority of boreholes are less than 20 mbgl, and are installed within the Quaternary aquifer. There was no pre urbanised or modern geothermal gradient available for Cardiff so the UK average geothermal gradient, of 28 °C km^{-1} (Busby *et al.,* 2011), was applied. The majority of the groundwater temperature profiles show temperatures up to 4 °C warmer than the predicted geothermal gradient. Elevated groundwater temperatures are reported in other urban aquifers and are considered to be associated with heat loss from the wider urban heat island (UHI) (e.g. Benz *et al.*, 2015). The near subsurface has been divided into two zones the upper ‘surficial zone’ or ‘Zone of Seasonal Fluctuation’, and the lower ‘Geothermal Zone’ (e.g. Parsons 1970; Anderson 2005; Banks 2008). The Zone of Seasonal Fluctuation is delineated by the area where groundwater temperatures experience annual variations.

Zone of Seasonal Fluctuation

It is useful to define the depth of the Zone of Seasonal Fluctuation as heat pump installers may want to locate abstraction pumps within groundwater that has year-round stable temperatures. To delineate the Zone of Seasonal Fluctuation we compared data from 15 boreholes where the Spring and Autumn profiles converge (Fig. 5). The average depth to the base of the Zone of Seasonal Fluctuation is 9.5 mbgl, however this varied across the city and ranged between 7.1 and 15.5 mbgl. Developers can benefit from this information and pumping from open loop systems should, where possible be undertaken from below 15.5 mbgl to avoid temperature fluctuations associated within the Zone of Seasonal Fluctuation. The controls on the variation of the depth of the Zone of Seasonal Fluctuation are not currently defined for the city of Cardiff, however thermal diffusivity, land use, heterogeneity within the subsurface and hydrogeological heterogeneity could all contribute.

Zone of Anthropogenic Influence

Below the Zone of Seasonal Fluctuation ground temperature increases with depth following the UK average geothermal gradient (Busby *et al.* 2011). In Cardiff groundwater at 100mbgl would hence be expected to be approximately 13.7 °C. However, the shallow and deep profiles (Fig. 3) show these temperatures are encountered at much shallow depths, between 10 and 20 mbgl, offering and alternative to deeper, more costly boreholes.

It is useful to consider the maximum depth to which anthropogenic heat loss can be observed on groundwater below an urban area as this may affect the thermal recharge rate. This zone is defined by groundwater that occurs at temperatures above that of the predicted geothermal gradient (see Banks *et al.* 2009). This zone could be termed the ‘Zone of Anthropogenic Influence’ (Fig. 3). In Cardiff the two deep borehole profiles (Borehole B and Techniquest) both converge with the predicted UK average geothermal gradient at a depth of about 70 mbgl, suggesting that anthropogenic heat loss may extend to this depth, however we cannot rule out the possibility of the ingress and mixing of shallow water via compromised borehole casing. These profiles have similarities to a site in Gateshead, Tyne and Wear, UK (Banks *et al.*, 2009), where a geothermal anomaly is observed to a depth of 55 m, attributed to historical downward heat leakage from the urban environment.

Heat Sources

Seasonal variation in groundwater temperature can be influenced by heating and cooling of the land surface (Anderson 2005), local confinement, hydraulic conductivity (Parsons 1970), specific heat capacity of the geological deposits (Banks 2008), climate change (Taylor & Stefan 2009) and proximity to potential heat sources such as sewage systems and heat loss from basements (Menberg *et al.* 2013). Benz *et al.,* (2015) have shown a correlation between long term averaged land surface temperatures and cities with shallow groundwater tables. This study was not able to quantify the relative importance of the multiple factors that could result in elevated urban groundwater temperatures. Multiple factors may interact to influence groundwater temperatures in Cardiff, these are illustrated on a simple conceptual model (Fig. 6). Variation of land cover (e.g. buildings, green spaces) and geology (including variations in made ground) may be the dominant control on shallow groundwater temperatures below the city. The conceptual model also illustrates other potential heat sources including; sewers and underground infrastructure, landfill, interaction with surface water bodies, canals, docks or rivers. Other factors not illustrated include; existing ground source heat systems; sustainable urban drainage systems (SuDS), exothermic microbial processes, and water-rock interactions. The contribution of deeper upwelling groundwater has also been proposed as a possible source of elevated temperatures in Cardiff (Buckley *et al.,* 1998) due to its relative proximity to the Taffs Well thermal spring (Farr & Bottrell 2013) however there is no evidence to support this theory. Only two deep boreholes were temperature profiled; Borehole B and Techniquest (Fig. 3), and neither indicated that groundwater at depths of over 70 mbgl within the bedrock is warmer than would be predicted by the UK average geothermal gradient. This however does not rule out the possibility of contribution for deeper groundwater but rather reflects the paucity of information on deep groundwater temperatures in the Cardiff area.

Geothermal potential of existing dewatering abstractions

Groundwater and its potential to support low enthalpy ground source heating has been characterised in cities including Cologne, Berlin and Munich in Germany (Menberg *et al.* 2013); Basel, Switzerland (Epting & Huggenberger 2013); Cork, Republic of Ireland (Allen *et al.* 2003); Winnipeg, Canada (Ferguson & Woodbury 2007) and Tokyo, Japan (Hayashi *et al.* 2009). Cardiff, like Cork and many other cities on coastal floodplains, benefits from a thermally enhanced shallow aquifer system, reducing the depth of drilling and head of water, thus increasing the efficiency of the system whilst also decreasing the overall costs of abstracting and recharging groundwater. In these settings shallow geothermal may offer cost and operational benefits over more conventional deeper systems.

To produce an initial estimate of thermal capacity (G) from existing dewatering boreholes, we have used values from long-term pumping at six dewatering abstractions (Table 3), part of the Cardiff Bay Barrage groundwater control scheme. Long term groundwater pumping data (Cardiff Harbour Authority, 1999-2016) provides evidence that abstractions at these volumes are achievable. The existing dewatering boreholes all discharge groundwater to surface water, thus information on recharge potential into the shallow aquifers is limited, and presents a knowledge gap for development of open loop systems in Cardiff. The thermal capacity, G (W), of an open -loop borehole depends upon the volume of water, Z (l/s), that can be sustainably abstracted, the volumetric heat capacity of water, S_{vc} (4180 $J/(K^{-1}l^{-1})$), the starting groundwater temperature (°C), and the heat removed by a heat pump (Δt); in this case we assume a conservative value of $\Delta t = 3$ °C, presented in this equation:

$$\mathbf{G = Z \times S_{vc} \times} \Delta t \qquad (1)$$

Assuming a heating demand of 15,000 kW/year for a typical three bedroom terraced house, the existing dewatering scheme operated by Cardiff Harbour Authority could supply approximately 1GW/year of energy per year, heating about 74 homes. This estimate is based only upon data from six existing dewatering abstractions, and an updated hydrogeological model and better understanding of sustainable pumping rates will be required to fully realise the available resource for open loop groundwater source energy schemes, which we estimate will be several orders of magnitude greater.

Conclusions

This study has produced the first city-wide map of shallow groundwater temperatures in the UK, illustrating the distribution of groundwater temperatures across the city. The resulting map is of use to planners who could use this to de-risk open loop ground source heating schemes and influence developers to consider installing systems for existing buildings or new developments. Natural Resources Wales, the environmental regulator in Wales, will also benefit from the data and map to support risk based regulation, licensing and permitting of future GSHP systems. The baseline data will enable changes in groundwater temperatures to be measured against a high resolution baseline.

Utilising existing monitoring borehole networks installed to monitor impoundment effects of the Cardiff Bay Barrage, temperature profiles were recorded at 1m intervals primarily within a shallow (0-20 mbgl) superficial gravel aquifer, made ground, and the upper part of the bedrock formations. The upper 20 m of the subsurface environment in Cardiff is typically 2 °C warmer than the average air temperature, suggesting localised anthropogenic enhancement of shallow groundwater temperatures. Shallow aquifers are convenient for open loop GSHP systems as this reduces both the depth required for drilling and head of water to pump, thus cost savings can be transferred to the customer via reduced installation costs and improved whole system efficiency.

Maximum groundwater temperatures of 16.1 °C are observed between September and December with time lags of 2-5 months from maximum recorded air temperatures in July. Minimum groundwater temperatures of 9.1 °C occur over a shorter period between April and May, with time lags of 1-3 months from minimum air temperatures. If the predicted geothermal gradient of 28 °C km^{-1} (Busby *et al.* 2011) is applied to the average annual air temperature of 10.9 °C the predicted temperature at 15m depth would be 11.2 °C. During the spring of 2014 groundwater temperature at 15 mbgl ranged from 12.1 to 14.9 °C, several degrees warmer than expected. Repeat profiling of a subset of these boreholes during the warmest period of the year shows that the ‘Zone of Seasonal Fluctuation’ occurs between 0 and 9.5 mbgl. Two deep boreholes profiled during the study had temperatures above the average geothermal gradient, suggesting anthropogenic heat transfer may occur to 70 mbgl slightly deeper than previously reported.

The shallow groundwater system offers potential efficiencies, as groundwater warmed by the Urban Heat Island effect is stored within shallow superficial deposits and only limited drilling depths and pumping heads are required to operate a ground source heat pump. Open loop systems should abstract water below 15.5 mbgl to avoid seasonal temperature changes within the zone of seasonal fluctuation, which in Cardiff occurs in groundwater from ground level to 15.5 mbgl. The thermal capacity of six existing dewatering abstractions is enough to heat over 74 homes and the full potential is likely to be several orders of magnitude larger.

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References

Allen, A., Milenic, D. & Sikora, P. 2003. Shallow gravel aquifers and the urban ‘heat island’ effect: a source of low enthalpy geothermal energy. *Geothermatics* 32, 569-578.

Anderson, M.P. 2005. Heat as a groundwater tracer. *Groundwater,* 43. No 6, 951-968.

Ascott, M. 2014. Physical Processes Governing Groundwater Temperature Measurements in England and Wales. *British Geological Survey Internal Report*, IR/14/023. 24pp.

Banks, D. 2008. *An introduction to thermogeology*. Ground Source Heating and Cooling. Blackwell Publishing. pp339

Banks, D. Gandy, C.J. Younger, P.L. Withers, J. and Underwood, C. 2009 Anthropogenic Thermogeological 'Anomaly' in Gateshead, Tyne and Wear, UK *Quarterly Journal of Engineering Geology and Hydrogeology* 2009, v.42; p307-312.

Benz, S.A., Bayer, P., Goettsche, F.M., Olesen, F.O and Blum, P. 2015. Linking surface urban heat islands with groundwater temperatures. *Environ. Sci. Technol.*, **2015**, *50* (1), pp 70–78. **DOI:** 10.1021/acs.est.5b03672

Buckley, D.K., Perkins, M.A. & Cripps, A.C. 1988. *Groundwater Temperatures in the Cardiff area: report on a short visit*. British Geological Survey. WK/88/005.

Busby, J., Kingdom, A & Williams, J. 2011. The measured shallow temperature field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44, 373-387.

Cardiff Bay Barrage Act 1993: Elizabeth II. Chapter 42. (1993) [Online]. Available at: http://www.legislation.gov.uk/ukpga/1993/42/contents (Accessed: 10th July 2014).

Department of Energy and Climate Change. 2013. The future of heating: meeting the challenge.

Edwards, R.J.G, 1997. A review of the hydrogeological studies for the Cardiff Bay Barrage. Quarterly Journal of Engineering Geology and Hydrogeology V30, pg49-61.

Epting, J. & Huggenberger. P. 2013. Unraveling the heat island effect observed in urban groundwater bodies – Definition of a potential natural state. *Journal of Hydrology* 501, 193-204.

Farr, G & Bottrell, S. 2013 The hydrogeology and hydrochemistry of the thermal waters at Taffs Well, South Wales, UK. *Cave and Karst Science Transactions of the British Cave Research Association*, 40 (1). 5-12.

Ferguson, G.*, and* A. D. Woodbury 2007. Urban heat island in the subsurface*, Geophys. Res. Lett.*, 34, L23713

Fry, V.A. 2009. Lessons from London: regulation of open-loop ground source heat pumps in central London. *Quarterly Journal of Engineering Geology and Hydrogeology*, 42, 325-334.

Headon, J., Banks, D., Waters, A. & Robinson, V.K. 2009. Regional Distribution of ground temperature in the Chalk aquifer of London, UK. *Quarterly Journal of Engineering Geology and Hydrogeology*, 42, 313-323.

Hayashi, T., Tokunagam, T., Aichi, M., Shimada, J & Taniguchi, M. 2009. Effects of human activities and urbanization on groundwater environments: an example from the aquifer system of Tokyo and the surrounding area. *Science of the Total Environment*, 407, Issue 9, 3165-3172.

Heathcote, J.A & Crompton, D.M. 1997. Managing the impact of urban groundwater rise. In Chilton, J (ed) Groundwater in the urban environment. Proceedings of the XXVII IAH Congress on Groundwater in the Urban Environment, Nottingham, UK. 21-27th September 1997 pp597-602.

Heathcote, J.A., Lewis, R.T., Russell, D.I & Soley, R.W.N.S. 1997. Cardiff Bay Barrage: groundwater control in a thin tidal aquifer. Quarterly Journal of Engineering Geology, 30, 63-77.

Heathcote, J.A., Lewis, R.T. & Sutton, J.S. 2003. Groundwater modelling for the Cardiff Bay Barrage, UK – prediction, implementation of engineering works and validation of modelling. *Quarterly Journal of Engineering Geology and Hydrogleology*. 36, 156-172.

Hunter, P.D., & Gander, H.C.W. 2002. Cardiff Bay Barrage: Planning and design. *Proceedings of the Institution of Civil Engineers – Water and Maritime Engineering,* 154, No. 2, 117-128.

Office for National Statistics (ONS). 2012. *2011 Census*. Available online:http://www.ons.gov.uk/ons/publications/re-reference-tables.html?edition=tcm%3A77-294277. Last accessed 10th July 2014.

Menberg, K., Bayer, P, Zosseder, K., Rumohr, S. & Blum, P. 2013. Subsurface urban heat islands in German cities. *Science of the Total Environment*, 442, 123-133.

Ove Aurp & Partners. 2000. Cardiff Bay Development Corporation. Cardiff Bay Barrage – Groundwater monitoring Pre Impoundment review of monitoring data. Report No 99/4153.

Parsons, M.L. 1970. Groundwater thermal regime in a glacial complex. Water Resources Research 6, 1701–1720.

Stuart, M.E., Jackson, C.R. & Bloomfield, J.P. 2010. Preliminary analysis of trends in UK groundwater temperature measurements from England and Wales. *British Geological Survey Internal Report*, IR/10/033.60pp.

Sutton, J.S., Coulton, R. & Williams, B. 2004.*Hydrogeology and groundwater control, Cardiff Bay Barrage*. In Urban Geology in Wales. National Museum and Galleries of Wales.

Taylor C.A. & Stefan H.G. 2009. Shallow groundwater temperature response to climate change and urbanization. Journal of Hydrology. 12, 375:601.

Waters, R.A & Lawrence, D.J.D. 1987. Geology of the South Wales coalfield, part III, the country around Cardiff. Memoir for the 1:50 000 geological sheet 263, England and Wales. 3rd Edition. HMSO, 114pp.

Williams, B. 2008. Cardiff Bay Barrage: Management of Groundwater Issues. Water Management. *Proceedings of the Institution of Civil Engineers*. 161(WM6), 313-321.

Captions for Figures

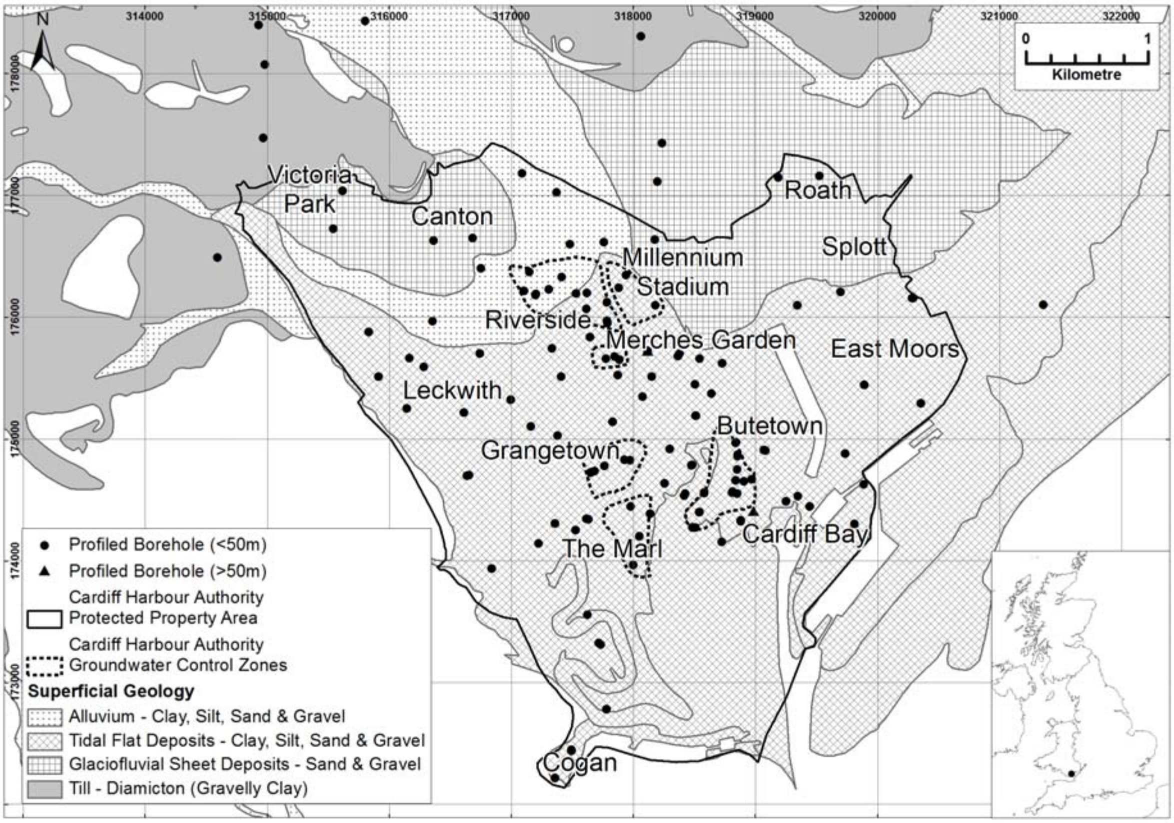

Fig. 1. Location map showing superficial geology, profiled boreholes, and the Cardiff Harbour Authority groundwater control zones and protected property area. DiGMap 1:50,000 British Geological Survey © NERC. Contains Ordnance Survey data © Crown Copyright and database rights 2015.

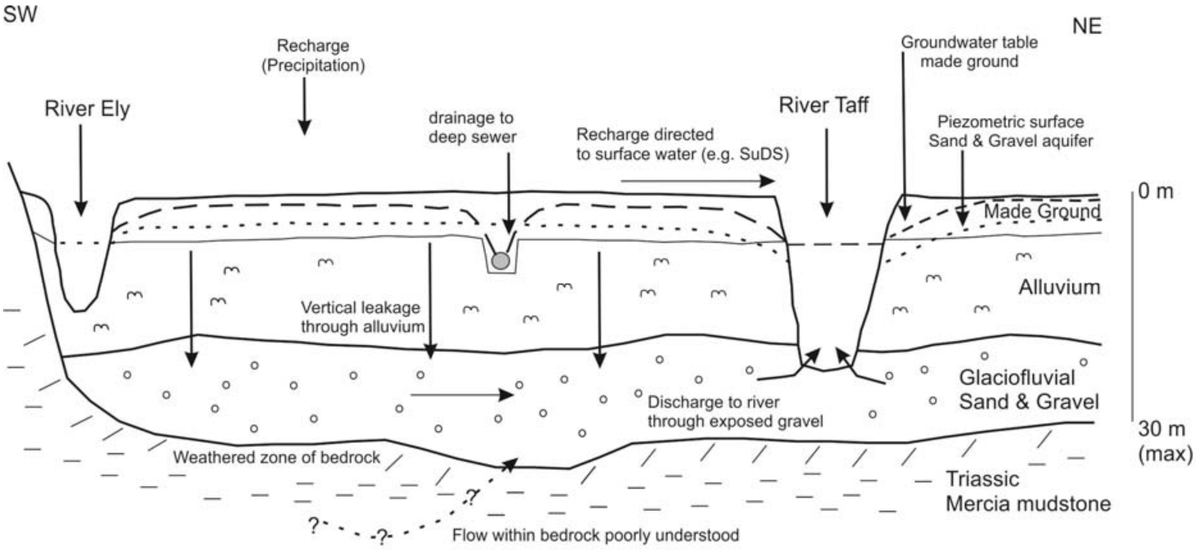

Fig. 2. Schematic conceptual model for groundwater in the southern part of the city (after Edwards, 1997).

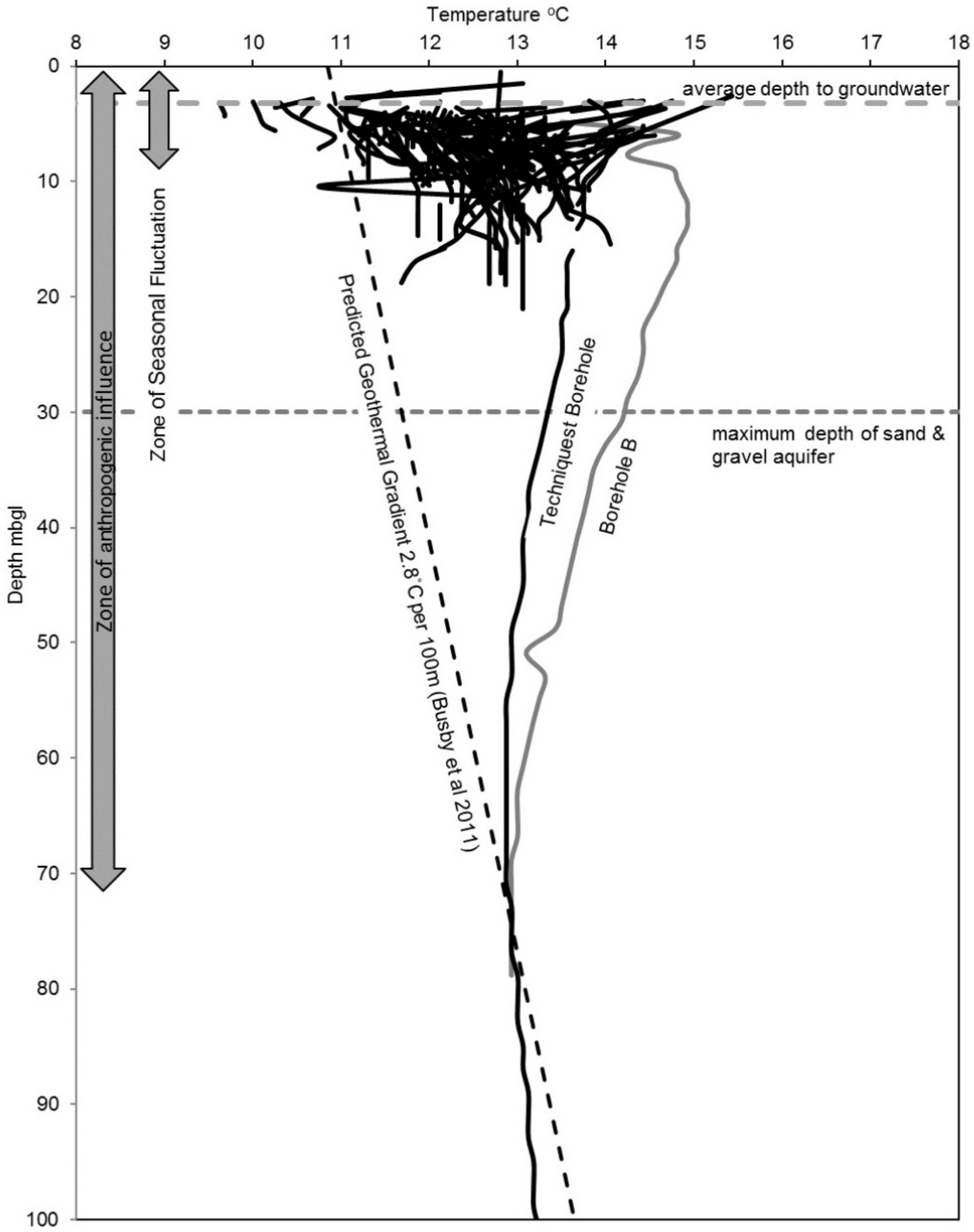

Fig. 3. Temperature profiles of boreholes, the zone of anthropogenic influence and the zone of seasonal fluctuation compared to the UK average geothermal gradient.

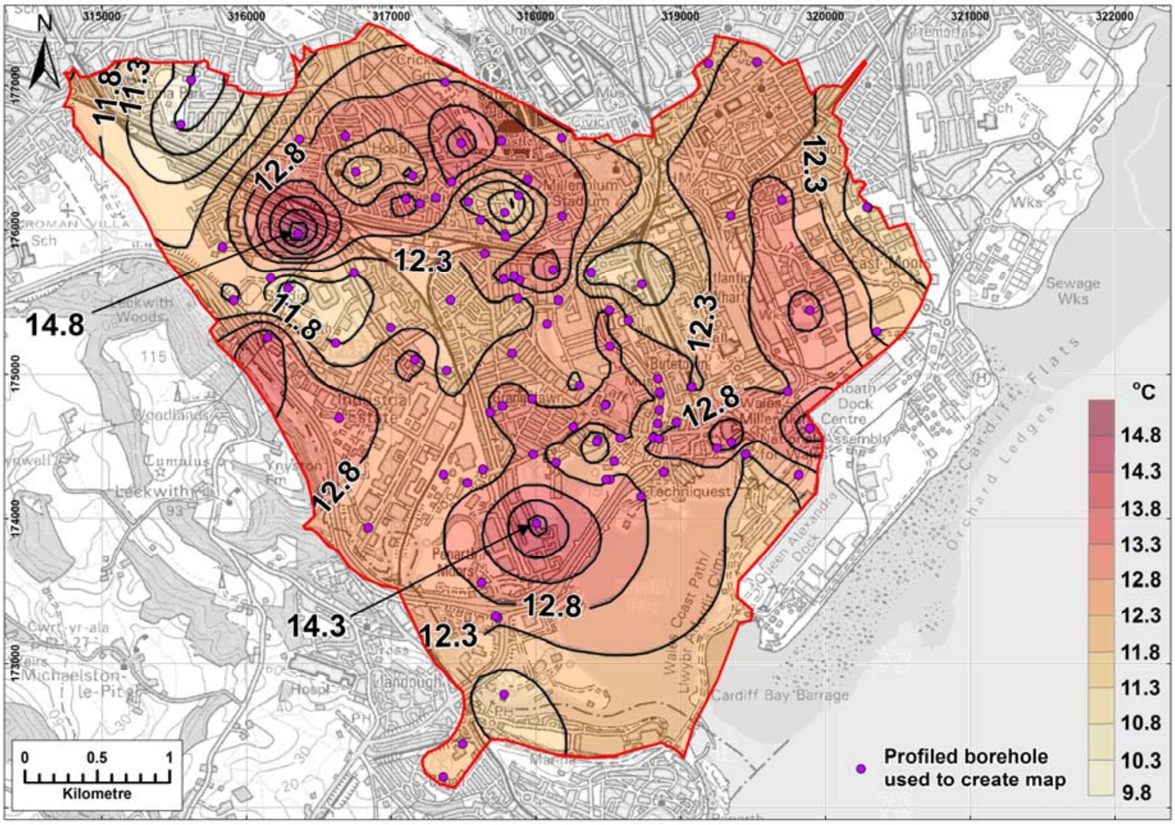

Fig. 4. Baseline groundwater temperature map for the City of Cardiff. Contains Ordnance Survey data © Crown Copyright and database rights 2015.

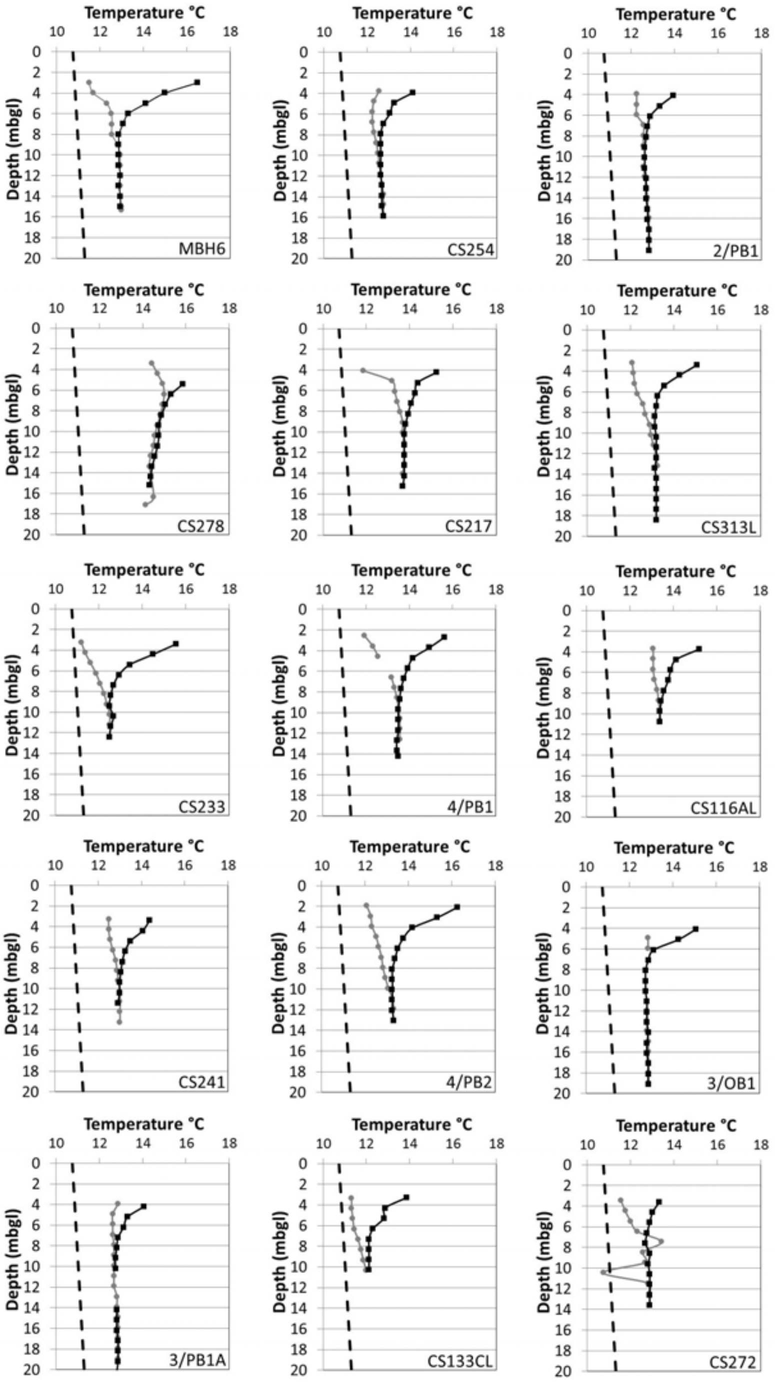

Fig. 5. Spring (grey circle) and Autumn (black square) temperature profiles for 15 boreholes that are part of the Cardiff Harbour Authority groundwater monitoring scheme. The depth of the Zone of Seasonal Fluctuation is inferred where the profiles join. Black dashed line is the average UK geothermal gradient.

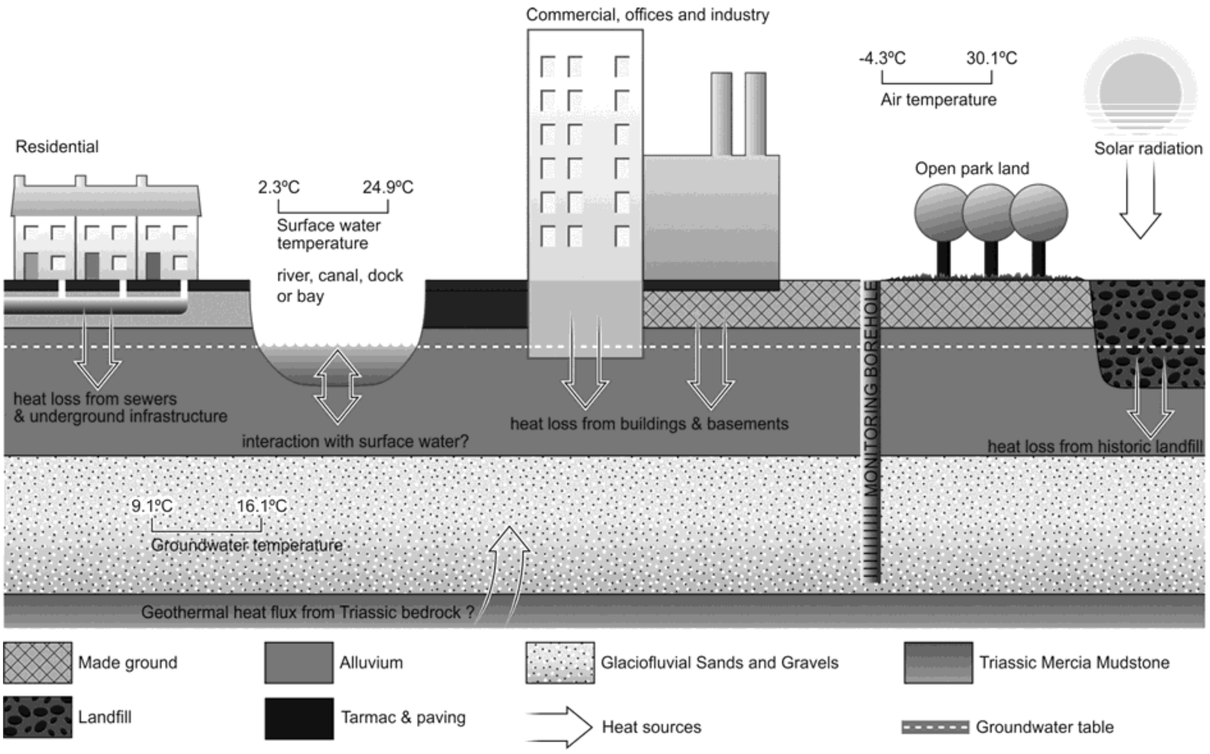

Fig. 6. Conceptual model showing potential heat sources to groundwater in the city of Cardiff.

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the ‘Zone of Seasonal Fluctuation’ °C*
1/OB1	318511	174275	12.91	12.91
1/PB1A	318484	174275	12.67	12.41
10/OB1	318050	174202	11.37	
2/OB1	318812	174570	12.27	12.48
2/PB1	318809	174561	12.61	12.72
2/PB2	318851	174749	12.68	12.66
3/OB1	318857	174859	12.85	12.85
3/PB1A	318854	174874	12.75	12.8
4/PB1	317766	174778	13.23	13.55
4/PB2	317973	174828	12.78	13.21
5/PB1	317886	175652	13.08	13.22
5/PB2	317848	175679	12.79	
5/PB3	317776	175662	13.15	13.56
6/OB1	317204	176190	Dry	
6/PB1	317783	175973	12.43	12.62
6/PB2	317616	176069	12.81	13.25
6/PB3	317415	176332	13.39	13.47
6/PB4	317307	176228	13.61	13.15
6/PB5	317198	176184	13.05	
7/OB1L	317147	176374	12.04	
8/OB1	316683	176653	13.37	
9/OB1L	318181	176098	13.25	
CS002	317162	175103	13.13	
CS003	317382	175027	11.91	
CS014	314592	176492	12.67	
CS018	317101	176217	13.94	
CS019A	317532	176197	11.72	
CS021	319700	176210	13.02	13.47
CS037C	317624	173558	12.87	13.04
CS038	317685	174736	12.75	

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the ‘Zone of Seasonal Fluctuation’ °C*
CS040A	318507	175448	13.01	
CS059B	316166	175666	12.07	12.18
CS067A	318972	174669	12.63	12.95
CS073	316354	175970	15.49	
CS074AL	315834	175882	11.97	
CS074AU	315834	175882	14.62	
CS075A	316366	176630	12.62	
CS085B	318725	174155	12.87	12.75
CS089	317790	175951	12.33	
CS093A	317784	176123	11.03	
CS096	318483	174789	13.3	
CS107A	317483	176602	14.29	
CS108	317332	175744	12.15	
CS113	316840	173935	Dry	
CS116AL	318258	174638	13.22	13.37
CS116AU	318258	174638	12	
CS132BU	318843	174974	<2m**	
CS133BL	320293	176158	11.34	
CS133BU	320293	176158	11.75	
CS133CL	320293	176158	11.62	12
CS133CU	320287	176160	11.26	
CS134A	315616	177038	10.64	
CS138	318062	178307	No Result***	
CS140	318235	177432	10.56	
CS149	315803	178435	11.25	
CS159AL	317873	175526	12	
CS159AU	317873	175526	<2m**	
CS169A	318841	174971	12.66	12.92
CS171	317226	174145	Dry	
CS177AL	319071	174911	12.47	12.47

CS177BU	319085	174905	10.31	
CS178AL	319076	174911	12.07	12.25
CS178AU	319076	174911	<2m**	
CS207AL	316639	174699	13.1	
CS207AU	316639	174699	12.06	
CS208	316656	174705	14.03	
CS210	316285	175594	10.47	
CS211	315617	177038	9.66	
CS215	317651	174723	<2m**	
CS216	317106	176217	Dry	
CS217	318478	174785	13.58	13.72
CS224	317495	172447	15.12	
CS225	317619	176202	Dry	
CS229	317833	175143	12.58	
CS231	317833	175142	<2m**	
CS233	318300	174920	12.07	12.5
CS235	318299	174920	<2m**	
CS238A	318427	174553	11.82	11.86
CS240	318419	174533	11.48	
CS241	317980	174445	12.79	12.89
CS243A	318368	175683	11	
CS245A	318380	175704	11.34	
CS245B	318368	175683	<2m**	
CS246A	318730	175623	11.31	
CS247A	318730	175623	11.35	
CS248	318510	175193	12.94	12.81
CS250	318513	175191	Dry	
CS251L	318581	174558	12.91	12.5
CS253	318584	174561	<2m**	
CS254	318839	174660	12.51	12.66
CS256	318839	174661	<2m**	
CS258A	318906	174653	<2m**	

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the ‘Zone of Seasonal Fluctuation’ °C*
CS259	318541	174398	12.62	
CS261	318542	174398	Dry	
CS262	318883	174325	12.11	12.54
CS264	318882	174331	<2m**	
CS266	316841	173938	12.47	12.79
CS268	317646	175838	12.36	
CS269	317645	175838	<2m**	
CS272	317632	174343	12.35	12.28
CS274	319528	177162	12.62	
CS275	318177	176639	12.56	
CS276	319891	174627	14.37	
CS278	318002	173967	14.62	14.4
CS280	318002	173965	14.18	
CS283	318639	175375	12.19	12.44
CS284	318197	177117	10.75	
CS285	314982	178077	10.12	
CS286	314970	177473	12.53	
CS287	317616	174346	<2m**	
CS292	318973	174671	Dry	
CS301L	317779	172783	11.5	
CS301U	317779	172783	13.02	12.56
CS303L	319345	176099	12.62	12.62
CS303U	319345	176099	Dry	
CS304L	319892	175445	13.62	13.36
CS304U	319892	175445	13.47	
CS305L	320356	175296	12.2	12.23
CS305U	320356	175296	12.93	
CS306	319349	174529	14.06	13.81
CS307L	319251	174489	13.32	13.73
CS307U	319251	174489	14.18	

CS308L	319448	174447	12.16	12.44
CS308U	319448	174447	<2m**	
CS309L	319739	174879	12.66	12.83
CS309U	319739	174879	<2m**	
CS310	319815	174305	12.4	
CS311CL	317360	174307	12.4	12.56
CS311CU	317360	174307	10.62	
CS313L	317526	174252	12.71	13.11
CS313U	317526	174252	11.56	
CS315L	316742	175703	11.78	12.06
CS317L	318139	174388	12.68	12.71
CS317U	318139	174388	<2m**	
CS318	317761	176618	13.24	
CS319L	316996	175324	12.14	11.93
CS319U	316996	175324	Dry	
CS320	316754	176402	11.63	
CS321AL	315912	175514	11.69	
CS321AU	315912	175514	10.62	
CS322L	316614	175217	11.67	11.97
CS322U	316614	175217	11.12	
CS325	319191	177151	12.18	
CS326	315544	176727	10.11	
CS327L	318850	174553	13.53	13.46
CS327U	318850	174553	13.02	
CS328	318076	175350	12.41	
CS329	317408	175515	11.83	
CS331AL	316144	175253	13.96	
CS331AU	316144	175253	Dry	
CS332L	317494	172439	12	
CS332U	317494	172439	12.56	
CS333L	317358	172215	<2m**	
CS333U	317358	172215	12.06	

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the ‘Zone of Seasonal Fluctuation’ °C*
CS334L	317942	176348	13.41	
CS335	317880	176242	11.36	11.31
CS337	317372	177025	12.84	
CS339	317657	174731	<2m**	
CS340L	318154	175514	12.41	
CS340U	318154	175514	11.68	
MG023	317928	174829	11.5	
Non Cardiff Harbour Authority boreholes				
Techniquest (Dec 2014)	318987	174408	13.27	13.18
Borehole A	312384	180264	11.87	11.87
Borehole B	318118	175722	13.9	13.85
Borehole C	318544	175662	12.37	
Borehole D	321360	176103	Poor headworks	Poor headworks
Borehole E	314930	178400	13.06	13.06
Borehole F	317735	173313	12.35	
Borehole G	317719	173325	12.7	12.95

Table 1. Average borehole temperature data for March 2015.

Site	Type	Easting, Northing	Depth (mbgl)	T (°C) max		T (°C) min		T (°C) average	T (°C) variation
Bute Park	Air	317609, 177204	Above ground	30.1	Jul	-4.3	Mar	10.8	34.4
	Soil		0.1	22.2	Aug	0.6	Mar & Nov	9.9	21.6
	Soil		0.3	21.5	Aug	4.3	Mar	11.4	17.2
	Soil		1.0	18.0	Jul-Aug	5.7	Mar	11.3	5.6
River Taff ,	River	317743, 176489	1.0	24.9	Jul	2.3	Mar	11.0	22.6
Dumballs Road CS248	Groundwater, Confined Gravel	318510, 175193	7.0	13.5	Dec	12.4	May	12.8	1.1
Clare Road CS268	Groundwater, Confined Gravel	317646, 175838	5.5	13.7	Oct	11.8	May	12.8	1.9
Blackfriars CS318	Groundwater, Unconfined Gravel	317761, 176618	4.0	14.3	Sept	9.1	Apr	11.9	5.2
Elm Street CS274	Groundwater, Unconfined Gravel	319528, 177162	4.7	16.1	Sept	9.5	Apr	12.8	6.6
Mission to seafarers CS276	Groundwater, Unconfined Made Ground	319891, 174627	3.0	15.6	Oct	10.8	Apr	13.4	4.8
Curran Embankment CS328B	Groundwater, Unconfined Made Ground	318076, 175350	6.5	14.9	Oct	10.3	May	12.7	4.6
Cogan Leisure Centre CS333U	Groundwater, Unconfined Bedrock	317358, 172215	4.0	13.4	Oct	10.2	May	11.8	3.2

Table 2. Summary of temperature variations in air, soil, surface water and groundwater during a two year monitoring period from March 2012 to February 2014.

Groundwater Control Zone	Pumping Rate Z (l/s^{-1})	Specific heat capacity (S_{vc}) by volume of water ($J/K^{-1}l^{-1}$)	Drop in temperature (Δt) across heat pump (°C)	Kilowatts per year (kWa^{-1})	No. of average 3-bedroom homes
Riverside	1.1	4180	6	27588	2
Millennium Stadium	10	4180	6	250800	17
Merches Garden	6.5	4180	6	163020	11
Central Grangetown	5.5	4180	6	137940	9
South Butetown	11	4180	6	275880	18
The Marl	10	4180	6	250800	17
Total				1106028	74

Table 3. Estimate of shallow geothermal heat potential from existing groundwater dewatering abstractions within the City of Cardiff.