

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

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11

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

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

25 **Introduction**

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

49 that some aquifers, mainly in densely populated cities, will need to be managed in terms of heat as well
50 as groundwater resources (Banks, 2009). Regulators need legal, policy and scientific tools to support
51 risk based management of the subsurface, and one such tool is baseline temperature data and mapping
52 of groundwater heat resources.

53

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

65 **Study area**

66 The City of Cardiff is located on a flat, low-lying, south-facing, coastal flood plain adjacent to the
67 Bristol Channel (Fig. 1). It covers an area of 140 km² and has a population of approximately 346,000
68 (Office for National Statistics, 2012). The city lies at the mouth of three rivers; the Taff, Ely and
69 Rhymney. Two of these, the Taff and the Ely, discharge into Cardiff Bay, an artificially impounded
70 freshwater body, while the Rhymney drains directly into the Bristol Channel. Much of Cardiff is
71 underlain by bedrock geology comprising Triassic age mudstone with subordinate siltstone, sandstone
72 and conglomerate of the Mercia Mudstone Group. The bedrock is overlain by Quaternary superficial
73 deposits, up to 30 m in thickness, that include Alluvium and Tidal Flat deposits (clay, silt, sand and

74 gravel), Glaciofluvial Sheet Deposits (sand and cobbly gravel), and Till (cobbly and clayey gravel)
75 (Fig. 1 & Fig. 2).

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

99

History of groundwater monitoring in Cardiff

100

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

106 Before construction, the Cardiff Bay Barrage Act, 1993, was approved by Parliament placing a legal
107 requirement for long-term groundwater monitoring by the Cardiff Bay Development Corporation and
108 its successor, Cardiff Harbour Authority, to assess the impacts of the barrage. Groundwater monitoring
109 was based on model predictions of likely increases in groundwater levels that could result in the
110 flooding of basements in the South Cardiff area (Cardiff Bay Barrage Act, 1993). The groundwater
111 monitoring network was established between 1995 and 1999, comprising 236 boreholes extending
112 down into made ground, superficial and bedrock deposits. Many of these sites have a dual installation
113 with deep and shallow boreholes and piezometers. Today 194 boreholes remain in the monitoring
114 system covering an area of approximately 15km² (Williams, 2008), with 42 boreholes removed after a
115 review in 2011.

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

120

121 In these areas 'groundwater control zones' (GCZ) were established, with observation wells and
122 abstraction wells monitoring and maintaining groundwater levels within the pre-impoundment range
123 (Fig. 1). The GCZs are characterised by an absence or disturbance of the estuarine alluvium that usually
124 separates the gravels from the made ground. Three types of control measures were installed prior to

125 impoundment; surface drilled horizontal collectors, single wells and field drains. This high density
126 groundwater level monitoring network in south Cardiff has been utilised to characterise baseline urban
127 groundwater temperatures.

128 **Materials and Methods**

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

133 **The borehole monitoring network**

134 The majority of the boreholes utilised in this study were designed and installed between 1995 and
135 1997 (Ove Arup & Partners, 2000). In total, 225 boreholes were drilled, primarily within the Protected
136 Property Area (Fig. 1) and are instrumented to monitor groundwater levels within the superficial
137 deposits and the underlying bedrock. The majority of these boreholes are within the boundary line of
138 the Protected Property Area that approximately equates with the 10 maOD contour and covers an area
139 of 15 km² however there are 11 boreholes located outside of the boundary (Fig. 1). The boreholes
140 range in depth from 1.1 to 19.3 m and are gravel packed along a slotted section and sealed with
141 bentonite clay. Construction is of plain uPVC (50-200 mm diameter) with a slotted section wrapped in
142 a fine gauze geotextile membrane (Ove Arup & Partners, 2000).

143 **Data collection**

144 **In situ fixed depth temperature data**

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

148 Hydrometry® Orpheus Mini loggers that record in situ groundwater temperature to a resolution of
149 0.1°C and accuracy of ± 0.5 °C. The loggers were installed at fixed depths between 4 and 7 mbgl,
150 within the zone of seasonal fluctuation, recording temperature every 30 minutes between March 2012
151 and February 2014. The time series data from these boreholes were used to identify annual maximum
152 and minimum temperatures, enabling the profiling of boreholes to take place during April-May, when
153 groundwater was coolest, and September-October when it was warmest.

154 **Depth temperature profile survey**

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

172 This process was repeated six months later on a subset of 35 boreholes during September 2014, when
173 groundwater temperatures are generally at their warmest. The boreholes selected for resurvey

174 represent a range of depth, geology and temperature conditions. Groundwater temperature profiles
175 from the Spring and Autumn were compared to characterise the 'Zone of Seasonal Fluctuation'.

176 **Surface water and air temperature monitoring**

177 Surface water temperature in the River Taff was recorded using a YSI®600XLM data logger
178 suspended from a buoy 1m below the surface. The YSI® loggers are reported to have a range of -5 to
179 60 °C, resolution of 0.01 °C and accuracy of ± 0.15 °C, and record temperatures every 15 minutes. The
180 average air temperature between March 2012 and February 2014 was 10.8 °C (Table 1) however the
181 long-term average annual air temperature of 10.9 °C, calculated by averaging UK Met Office monthly
182 average temperature data from Bute Park collected between 1981 and 2000, was used to infer the
183 predicted geothermal gradient.

184 **Data analysis and baseline groundwater temperature map**

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

196 For the remaining 121 boreholes the mean average temperature of the entire water column, excluding
197 the first measurement of each profile, was calculated (Table 1). We acknowledge the potential effect
198 of borehole construction (screened versus plain cased sections) on measured groundwater

199 temperatures within a borehole column. In light of this we compared average groundwater
200 temperatures within the slotted section of each borehole with those derived from the entire water
201 column, including the slotted and plain cased sections of the borehole. There was <0.12 °C difference
202 between the values, justifying the use of average whole borehole temperature values for creation of a
203 baseline groundwater temperature map.

204 The baseline groundwater temperature map was created using the average temperature data from these
205 121 boreholes (Table 1). Contouring was done using Surfer[®] 10 (Golden Software, Inc). The grid file
206 was created using the point Kriging method with no drifts and a linear variogram model. The extent of
207 the grid was defined by the locations of the boreholes and the boundary of the Protected Property
208 Area. The temperatures were contoured with a 0.5 °C contour interval, reflecting the probe
209 manufacture's stated accuracy. The filled contours were displayed with a colour ramp, where darker
210 shades of red represent warmer temperatures and pale colours cooler temperatures. The contour plot
211 was exported as a georeferenced TIFF and imported into ArcMap[™] (Environmental Systems
212 Research Institute, Inc) where it was clipped to fit the boundary of the Protected Property Area within
213 which the majority of the monitoring boreholes are located (Fig. 1).

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

224 **Results and discussion**

225 **Annual trends (2012-2014)**

226 In situ hourly groundwater temperature data recorded at discrete depths from seven boreholes (OTT
227 Hydrometry® Orpheus Mini loggers), one river (YSI®600XLM) and one weather station (MetOffice,
228 Bute Park) were compared for a two year period between March 2012 and February 2014, prior to the
229 Spring 2014 baseline survey (Table 2). Data loggers in the boreholes are all installed between 3 and
230 7 mbgl and thus are within the zone of seasonal fluctuation and will respond, with varying time lags to
231 changes in seasonal atmospheric temperatures. Maximum air temperatures of 30.1°C were observed
232 during July and minimum air temperatures of -4.3°C during March, averaging 10.8 °C during the
233 study period. The latter is very similar to the 1981-2000 MetOffice average air temperature of 10.9 °C
234 for Cardiff. The shallow in-situ river temperatures closely reflect the changes in atmospheric
235 conditions, with maximum river temperatures of 24.9 °C recorded in July and minimum river
236 temperatures of 2.3 °C during March. The maximum recorded in situ groundwater temperature
237 between 2012 and 2014 was 16.1 °C, which was recorded in the unconfined sand and gravel aquifer at
238 a depth of 4.7 m, within the Zone of Seasonal Fluctuation. The minimum groundwater temperature
239 recorded prior to the study was 9.1 °C during April and May. Annual temperature variability recorded
240 on in situ loggers can range from 1.1 to 6.6 °C (Table 2). During the study period, maximum
241 groundwater temperatures are achieved 2-5 months after the peak in summer air temperature. This
242 ‘lag effect’ is generally shorter where recharge occurs to the unconfined parts of the aquifer. Land
243 cover and material properties such as thermal conductivity and diffusivity will also influence the time
244 taken for groundwater within the Zone of Seasonal Fluctuation to respond to patterns in seasonal
245 atmospheric temperature.

246 **Baseline groundwater temperature map**

247 Groundwater temperatures within the shallow aquifer are coolest during spring time (April-May).
248 During this period the average temperature within the shallow aquifer is 12.4 °C, which is > 1 °C
249 above the average groundwater temperature reported for England and Wales of 11.3°C (Stuart *et al.*
250 2010). More than 90 % of the data in the study exceed this value. Groundwater temperatures can be

251 predicted by applying the average UK geothermal gradient of 28 °C km⁻¹ (Busby et al., 2011) to the
252 local annual average air temperature of 10.9 °C (MetOffice); a line representing this predicted
253 geothermal gradient is shown in Figure 3. However, the data clearly lie to the right of the predicted
254 geothermal gradient and are thus warmer than predicted.

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

263 **Delineation of temperature zones**

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

274 **Zone of Seasonal Fluctuation**

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

285 **Zone of Anthropogenic Influence**

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

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

301 **Heat Sources**

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

324 **Geothermal potential of existing dewatering abstractions**

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

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

$$343 \quad \mathbf{G} = \mathbf{Z} \times \mathbf{S}_{vc} \times \Delta t \quad (1)$$

344 Assuming a heating demand of 15,000 kW/year for a typical three bedroom terraced house, the
345 existing dewatering scheme operated by Cardiff Harbour Authority could supply approximately
346 1GW/year of energy per year, heating about 74 homes. This estimate is based only upon data from six
347 existing dewatering abstractions, and an updated hydrogeological model and better understanding of
348 sustainable pumping rates will be required to fully realise the available resource for open loop
349 groundwater source energy schemes, which we estimate will be several orders of magnitude greater.

350 **Conclusions**

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

358

359 Utilising existing monitoring borehole networks installed to monitor impoundment effects of the
360 Cardiff Bay Barrage, temperature profiles were recorded at 1m intervals primarily within a shallow
361 (0-20 mbgl) superficial gravel aquifer, made ground, and the upper part of the bedrock formations.
362 The upper 20 m of the subsurface environment in Cardiff is typically 2 °C warmer than the average
363 air temperature, suggesting localised anthropogenic enhancement of shallow groundwater
364 temperatures. Shallow aquifers are convenient for open loop GSHP systems as this reduces both the
365 depth required for drilling and head of water to pump, thus cost savings can be transferred to the
366 customer via reduced installation costs and improved whole system efficiency.

367 Maximum groundwater temperatures of 16.1 °C are observed between September and December with
368 time lags of 2-5 months from maximum recorded air temperatures in July. Minimum groundwater
369 temperatures of 9.1 °C occur over a shorter period between April and May, with time lags of 1-3
370 months from minimum air temperatures. If the predicted geothermal gradient of 28 °C km⁻¹ (Busby *et*
371 *al.* 2011) is applied to the average annual air temperature of 10.9 °C the predicted temperature at 15m
372 depth would be 11.2 °C. During the spring of 2014 groundwater temperature at 15 mbgl ranged from
373 12.1 to 14.9 °C, several degrees warmer than expected. Repeat profiling of a subset of these boreholes
374 during the warmest period of the year shows that the ‘Zone of Seasonal Fluctuation’ occurs between 0
375 and 9.5 mbgl. Two deep boreholes profiled during the study had temperatures above the average

376 geothermal gradient, suggesting anthropogenic heat transfer may occur to 70 mbgl slightly deeper
377 than previously reported.

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

385

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389 Ellery, Cardiff Harbour Authority; Keith Gorf, Brains Ltd Cardiff; David Tucker, WDS Green Energy
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391 Schofield publish with the permission of the executive director, British Geological Survey (NERC).

392

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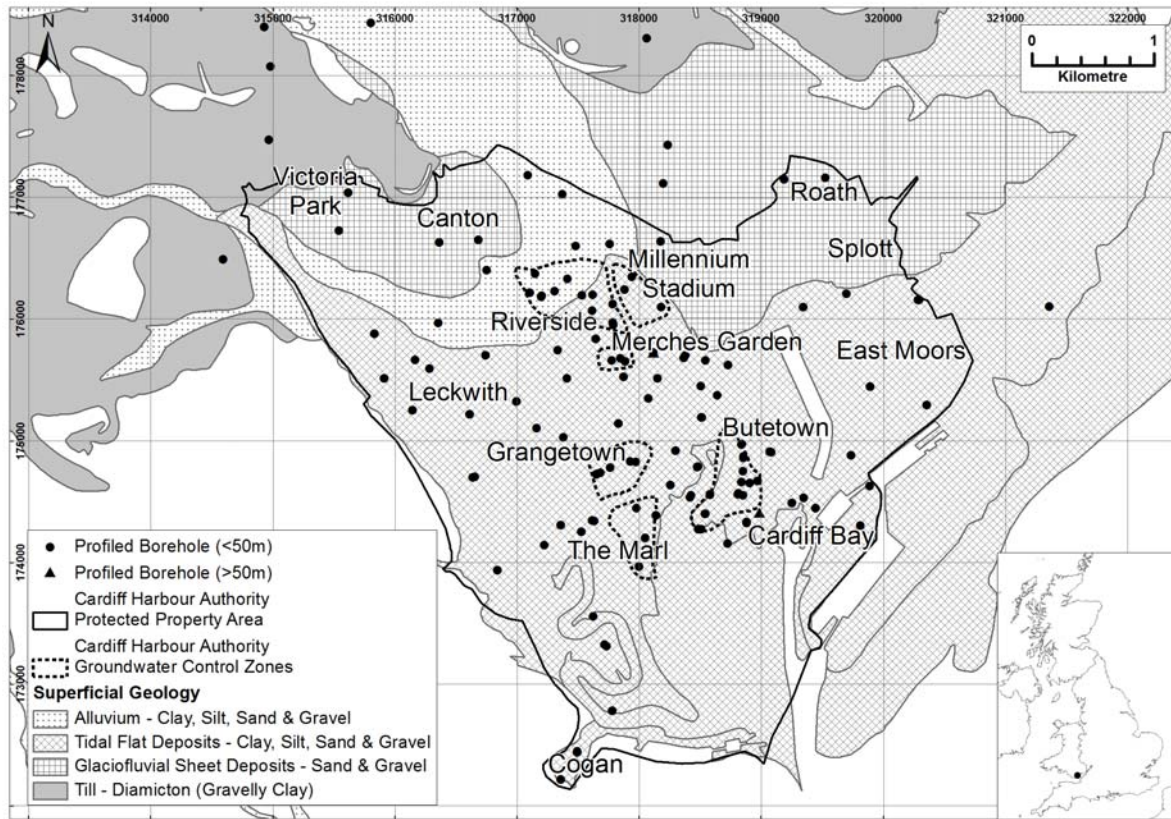
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491 Captions for Figures



492

493 Fig. 1. Location map showing superficial geology, profiled boreholes, and the Cardiff Harbour
494 Authority groundwater control zones and protected property area. DiGMap 1:50,000 British
495 Geological Survey © NERC. Contains Ordnance Survey data © Crown Copyright and database rights
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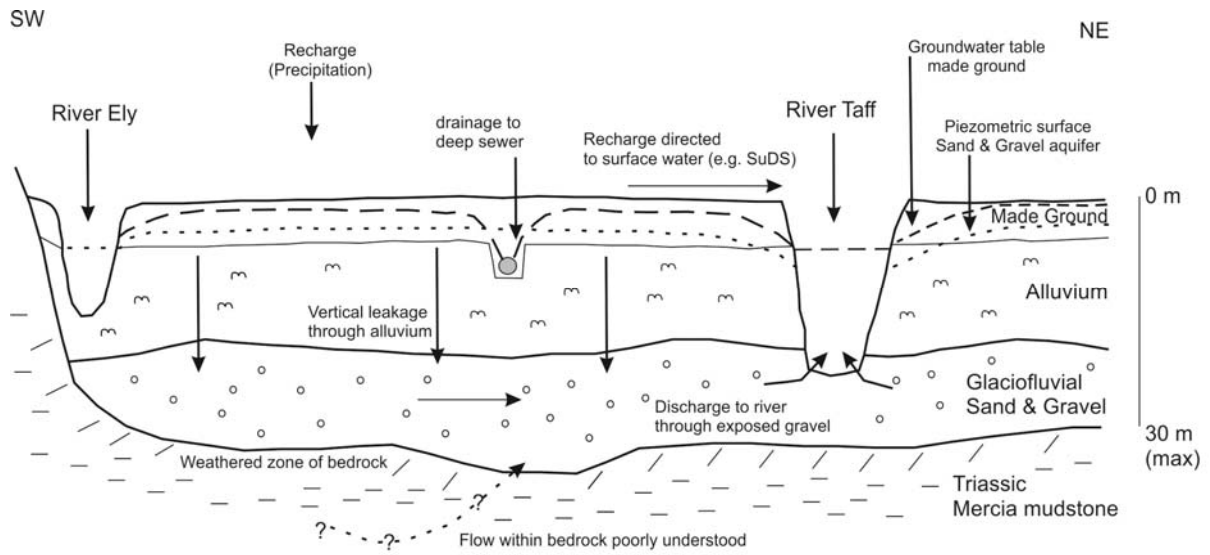
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504 Fig. 2. Schematic conceptual model for groundwater in the southern part of the city (after Edwards,
 505 1997).

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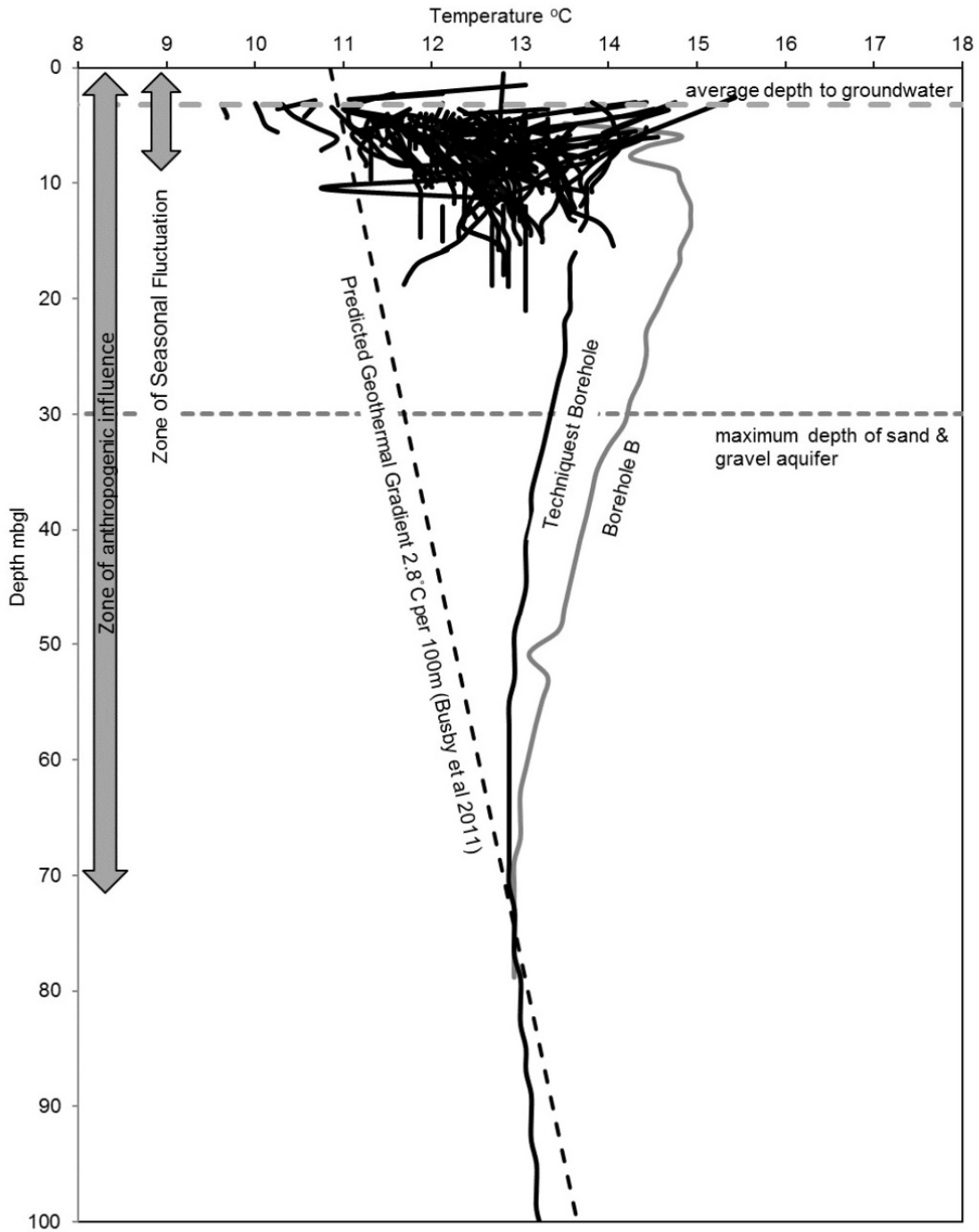
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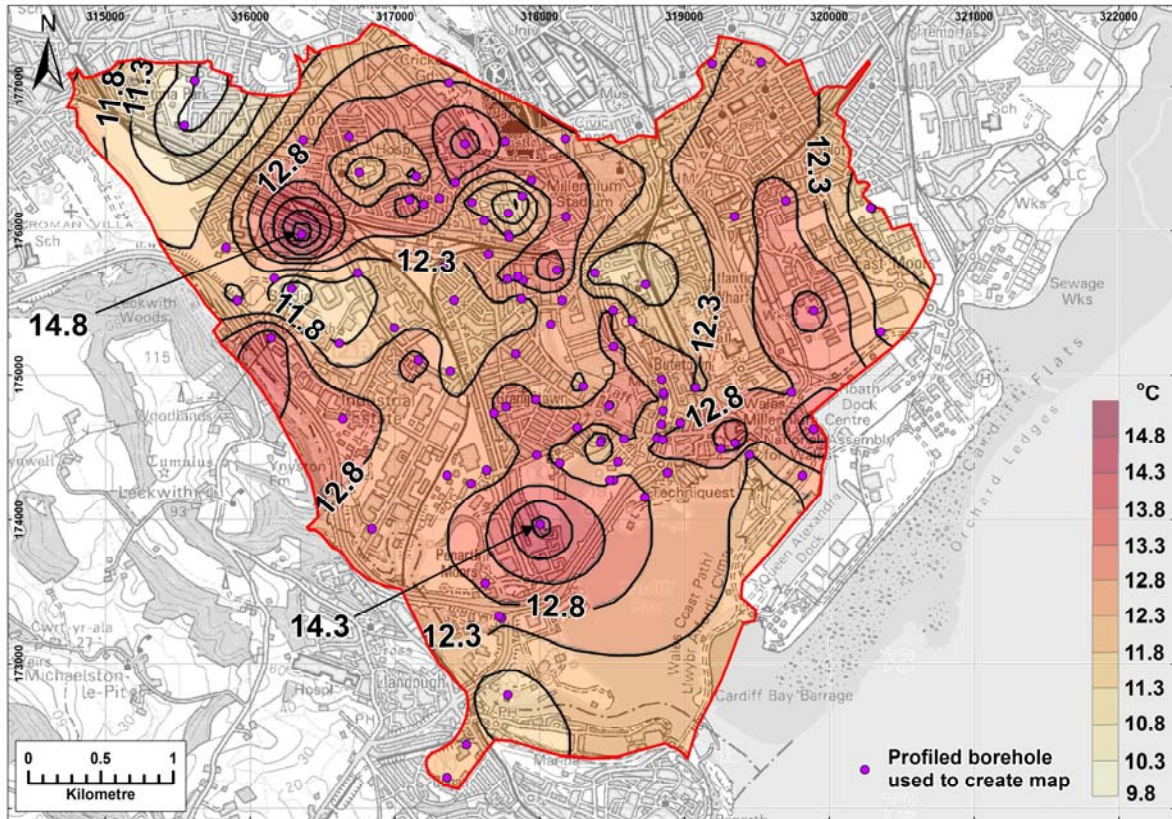


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519 Fig. 3. Temperature profiles of boreholes, the zone of anthropogenic influence and the zone of
 520 seasonal fluctuation compared to the UK average geothermal gradient.

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524 Fig. 4. Baseline groundwater temperature map for the City of Cardiff. Contains Ordnance Survey data

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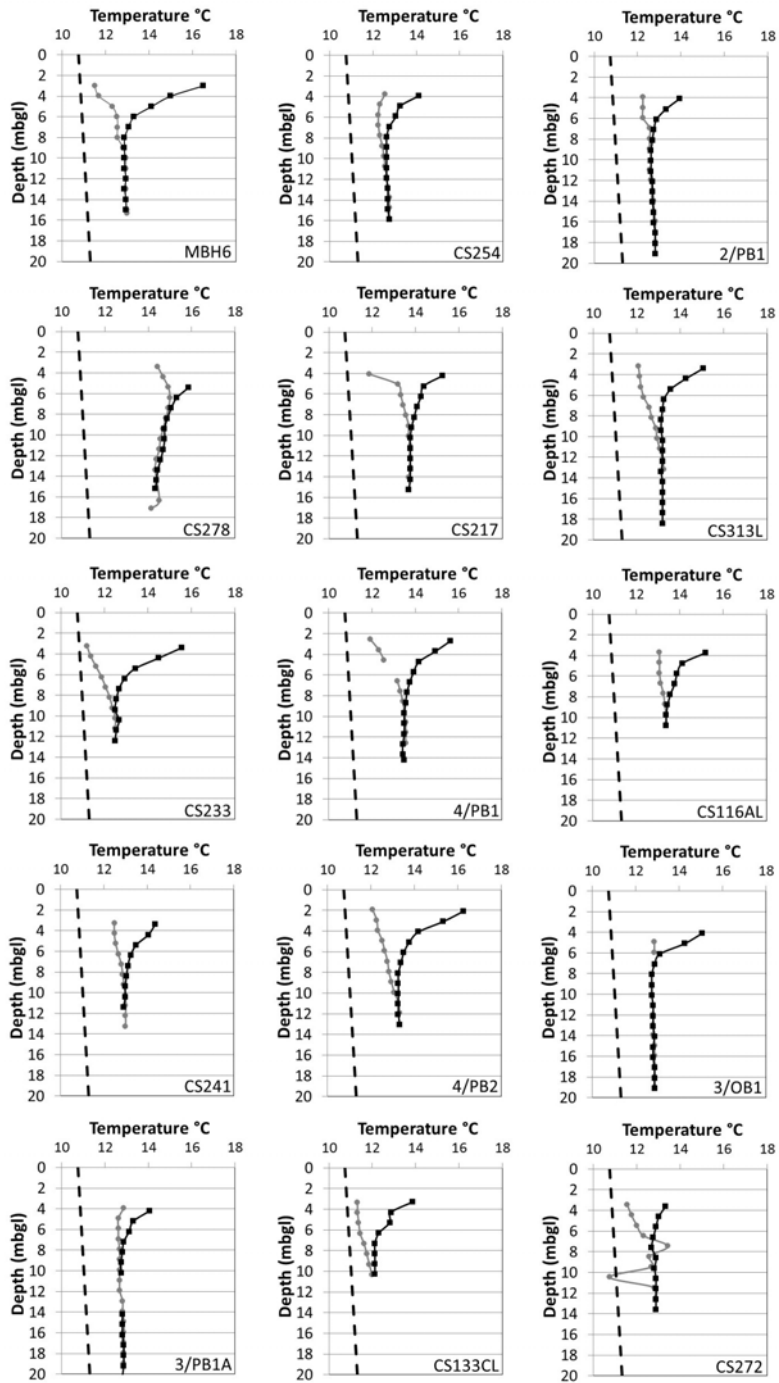
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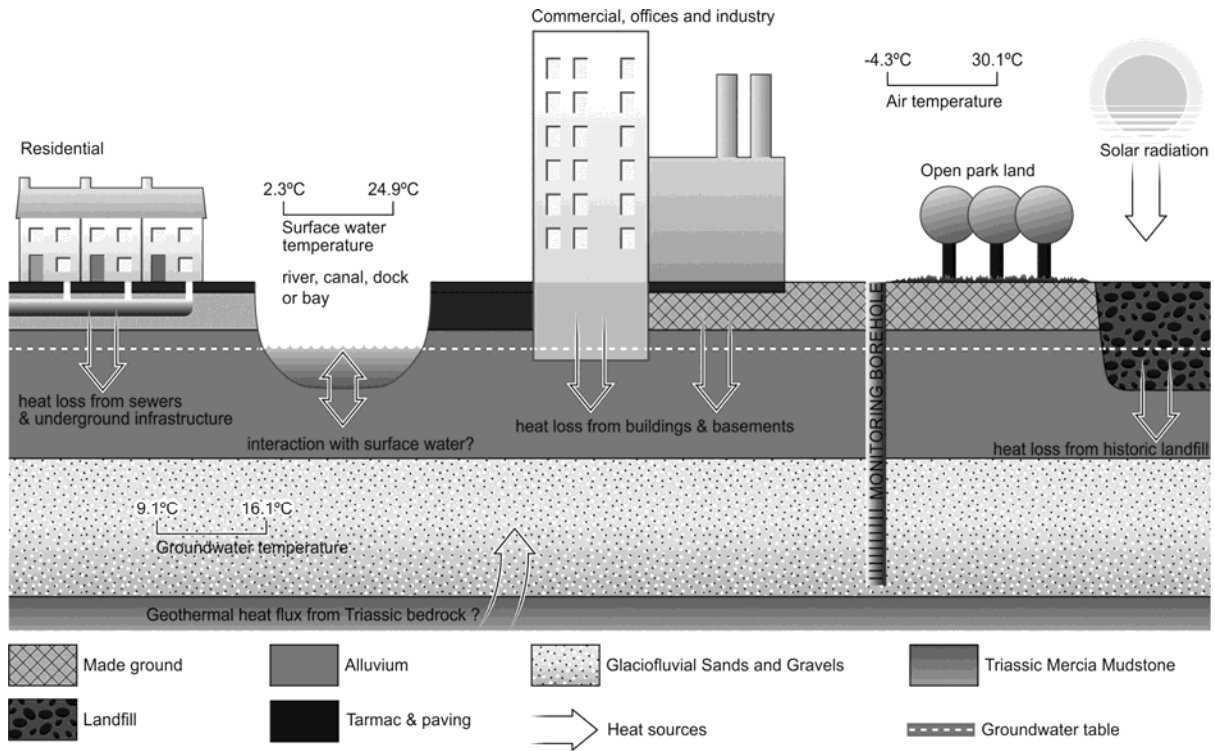


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536 Fig. 5. Spring (grey circle) and Autumn (black square) temperature profiles for 15 boreholes that are
 537 part of the Cardiff Harbour Authority groundwater monitoring scheme. The depth of the Zone of
 538 Seasonal Fluctuation is inferred where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

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

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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	

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	

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the 'Zone of Seasonal Fluctuation' °C*
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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**	

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	

Borehole ID	Easting (m)	Northing (m)	Average Temperature °C	Average Temperature below the 'Zone of Seasonal Fluctuation' °C*
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				
Techniquet (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

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555 Table 1. Average borehole temperature data for March 2015.

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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

566 Table 2. Summary of temperature variations in air, soil, surface water and groundwater during a two

567 year monitoring period from March 2012 to February 2014.

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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 (kW a ⁻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

571

572 Table 3. Estimate of shallow geothermal heat potential from existing groundwater dewatering

573 abstractions within the City of Cardiff.