Hydrogeology Journal
https://doi.org/10.1007/s10040-025-02930-2

PAPER

Using groundwater temperature time-series to reveal subsurface thermal and hydraulic processes

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Received: 4 December 2024 / Accepted: 18 June 2025

Abstract

Understanding subsurface heat transport processes is important for geothermal energy development and heat-flow modelling applications, and for resolving hydrogeological, biogeochemical and microbiological processes. Studies of subsurface thermal regimes have predominantly focussed on repeat temperature-depth profile analysis. The application of groundwater temperature time-series data to characterise thermal and hydraulic processes is relatively under-exploited. Here, an unusually rich set of half-hourly groundwater level and temperature time-series data from 48 boreholes in the Cardiff Geo-observatory (UK) between 2014 and 2018 is used to explore the interrelationships between subsurface hydraulic and thermal processes. Characteristic time-series curve shape categories were identified in annual-scale temperature changes and shown to be indicative of distinct flow and heat transport mechanisms. Sinusoidal curves are found in conduction-dominant settings, while 'right-leaning' time-series indicate faster cooling than warming and are associated with the influence of advection of heat due to recharge. Short-lived temperature events found on the cooling limbs of right-leaning curves correlate with sharp groundwater level rises, indicating recharge. Temperatures rebound quickly following these events but do not return to pre-event levels, having the effect of cooling groundwater faster in winter than it is warmed in summer. More complex behaviours observed in boreholes located close to rivers indicate recharge responses coupled with the influence of changes in stream–aquifer interactions which co-occur with heavy rainfall. The results demonstrate that groundwater temperature time-series interpretation may be a cost-effective way of providing new insights into the characteristics of subsurface hydraulic and thermal processes with implications for geothermal exploration and a range of other hydrogeological applications.

Keywords Subsurface thermal regime · Groundwater temperatures · Aquifer properties · Cardiff · United Kingdom

Introduction

Understanding subsurface thermal and hydraulic regimes is crucial for a variety of purposes, including contamination pathway assessment, water resource management and geothermal exploration. Heat has been shown to be a useful groundwater tracer (Anderson 2005) and can provide insights into groundwater flow patterns, hydraulic conductivity and groundwater–surface water interactions. Understanding how heat propagates within aquifers is key to modelling thermal regimes, the sustainable use of shallow geothermal resources (Mueller et al. 2018) and ground source heat pump (GSHP) efficiency (Li et al. 2018), but it may also be useful for other applications such as aquifer characterisation, contaminant pathway modelling, water resource management and the assessment of geological suitability for nuclear waste repositories.

Insights from previous studies on groundwater temperature data have proven the effectiveness of using heat signals to gain insights into hydraulic processes (e.g. Taniguchi 1987; Anderson 2005; Bense et al. 2017; Rau et al. 2017). A proliferation of studies in recent decades demonstrated the use of groundwater temperature measurements in the analytical solutions of the one-dimensional heat transport equation to determine groundwater velocity (e.g. early pioneer papers by Suzuki 1960; Bredehoeft and Papaopulos 1965; Stallman 1965), while Lapham (1989) showed that annual variation in

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Published online: 17 July 2025

subsurface temperature profiles beneath streams are useful in estimating vertical groundwater velocities.

While there has been a recent increase in research related to groundwater temperatures, the use of temperature time-series data is generally limited to streambed temperatures in studies of groundwater–surface water interactions (e.g. Rau et al. 2017), deep groundwater studies below the depth of seasonal temperature variability (e.g. Smith and Elmore 2019) or time-series data generated from repeat temperature-depth profile (e.g. Benz et al. 2018). Existing studies into groundwater temperatures generally focus on single point in time measurements, sometimes repeated years apart, or repeat temperature-depth profiling (e.g. Bense et al. 2017; Benz et al. 2018; Casillas-Trasvina et al. 2022; Dentzer et al. 2017; Kurylyk et al. 2018; Taniguchi 1987; Taniguchi et al. 1999). For example, Anderson (2005) notes the potential for temperature profiles to provide insight into seasonal recharge and discharge events caused by precipitation and groundwater–surface water interactions, and highlights previous work on the use of heat to detect induced infiltration from streams (e.g. Rorabaugh 1956; Salem et al. 2004). Taniguchi (1993) and Taniguchi (1994) observed that the shapes of temperature-depth profiles could be used to identify recharge (characterised by profile elongation caused by downward groundwater movement) and discharge (characterised by compression of the profile caused by upward groundwater movement). This is consistent with later findings by Kurylyk et al. (2018) that under steady-state conditions temperature-depth profiles are concave-upward in shape in recharge zones, with recharge events bringing cooler water to depth. Temperature-depth profiles have also been used to estimate groundwater recharge and discharge rates by Cartwright (1970) and Ferguson et al. (2003), and to quantify groundwater–surface water interactions (e.g. Lapham 1989; Stonestrom and Constantz 2003).

There has also been a recent increase in the use of fibre-optic distributed temperature sensing (FO-DTS) to reveal subsurface thermal regimes (e.g. Furlanetto et al. 2024; Read et al. 2013) and in 3D modelling of groundwater temperatures (e.g. Casillas-Trasvina et al. 2022; Dentzer et al. 2017). However, Casillas-Transvina et al. (2022) found that when comparing modelled temperature-depth profiles to real data, whilst there was good agreement in temperature gradients, temperatures themselves showed discrepancies. The authors theorized that these differences may be due to seasonal and diurnal temperature changes in the near surface affecting heat propagation. They also highlight that uncertainty in the temperature curve at the water table is a limiting factor to simulated models. This curve is difficult to model due to imperfectness of the top boundary and/or local heterogeneity, and also advection (forced convection) in the near surface may have a significant effect on temperatures. Dentzer et al. (2017), however, believe 3D models could be used to model cases of thermal flux anomaly in the near surface resulting from the thermal role of recharge and Sippel et al. (2013) states that the difference in thermal regimes resulting from conduction-only conditions versus the combination of conduction and advection on 3D modelled temperatures shows a need for investigation of the impacts of advective processes to enable forecasting of aquifer temperatures. Benz et al. (2018) observed that a significant percentage of anthropogenic heat flux was not stored in the aquifer subsurface urban heat island (SUHI) effect but is transported elsewhere. Therefore, small scale, detailed analysis of near surface groundwater temperatures in urban aquifers is needed to understand conductive and advective heat fluxes. Without this, 3D models ability, over 1D models, to replicate temperature variation will not show improvement.

This study aimed to investigate whether characteristic patterns in groundwater temperature time-series data could be used to reveal subsurface processes. Here, half-hourly data recorded between 2014 and 2018 from 48 groundwater temperature sensors installed in boreholes across the city of Cardiff, UK, (Farr et al. 2019; Patton et al. 2020), and one borehole over a 1-month period in October/November 2023 at 5-min intervals from three loggers and 1-h frequency from one logger, have been used to demonstrate the usefulness of groundwater temperature time-series in identifying hydraulic and thermal subsurface processes. The objectives of this work were to 1. assess whether profile curve shapes produced by plotting groundwater temperature time-series data and comparing these to fitted sine waves are indicative of heat transport mechanisms. This is based on an approach that sinusoidal curves indicate a conduction-dominant environment where groundwater temperatures reflect a damped and attenuated land surface temperature sine wave. 2. Evaluate the presence of short-lived temperature events within time-series data in conjunction with groundwater level time-series data to establish whether these are simply noise or if they reveal hydraulic and heat transport mechanisms. 3. Assess the use of groundwater temperature time-series in identifying hydraulic and thermal processes such as recharge and groundwater–surface water interaction. 4. Describe the effects of these processes on annual temperature variability. 5. Characterise recharge patterns across Cardiff to understand local confinement conditions and identify preferential flow paths.

Materials and methods

Study area

Location

Cardiff is a coastal city located at 51.4816° N, 3.1791° W (WGS84), immediately adjacent to the Bristol Channel, UK (Fig. 1). It has a mean annual daytime temperature of 14.7 °C and a total annual rainfall of 1203 mm (Met Office, UK 2024). The city is low-lying, built on a former coastal floodplain. In 1999 the Cardiff Bay Barrage was constructed, impounding two of the city's three rivers (the Taff and the Ely) to form a freshwater lake along the former coastline, effectively isolating the city from the coast, preventing seawater ingress. A pressure effect from ocean tides is still observed in boreholes close to the former coastline (Patton et al. 2021).

Geology and hydrogeology

Cardiff's bedrock comprises folded Silurian, Devonian and Carboniferous strata unconformably overlain by the Triassic Mercia Mudstone Group. The bedrock is overlain by Devensian glacial till and glaciofluvial sand and gravels, in turn overlain by Holocene tidal flat deposits and river alluvium (Waters and Lawrence 1987; Kendall 2015).

The glaciofluvial sand and gravel deposits comprise dense, poorly sorted sandy gravel with cobbles (Heathcote et al. 2003) and forms a shallow aquifer. In the south of the study area, the glaciofluvial deposits are confined by low to intermediate permeability tidal flat deposits (Edwards 1997; Patton et al. 2021); however, these may be absent in some areas across the city known as groundwater control zones (GCZs). GCZs are areas where excavations or other disturbances of the clays is thought to have taken place historically. In these areas there is thought to be a hydraulic connection with the overlying made ground (Williams 2008). As a result, these areas were initially dewatered by the local authority due to concerns over post-impoundment groundwater flooding; however, pumping has since ceased in all but one of the GCZs.

Groundwater levels across the study area are typically 2.5–4.5 mbgl and, since the Cardiff Bay impoundment, are no longer subject to large ocean tidal fluctuations. A network of Victorian, brick-lined sewers is found across the city and

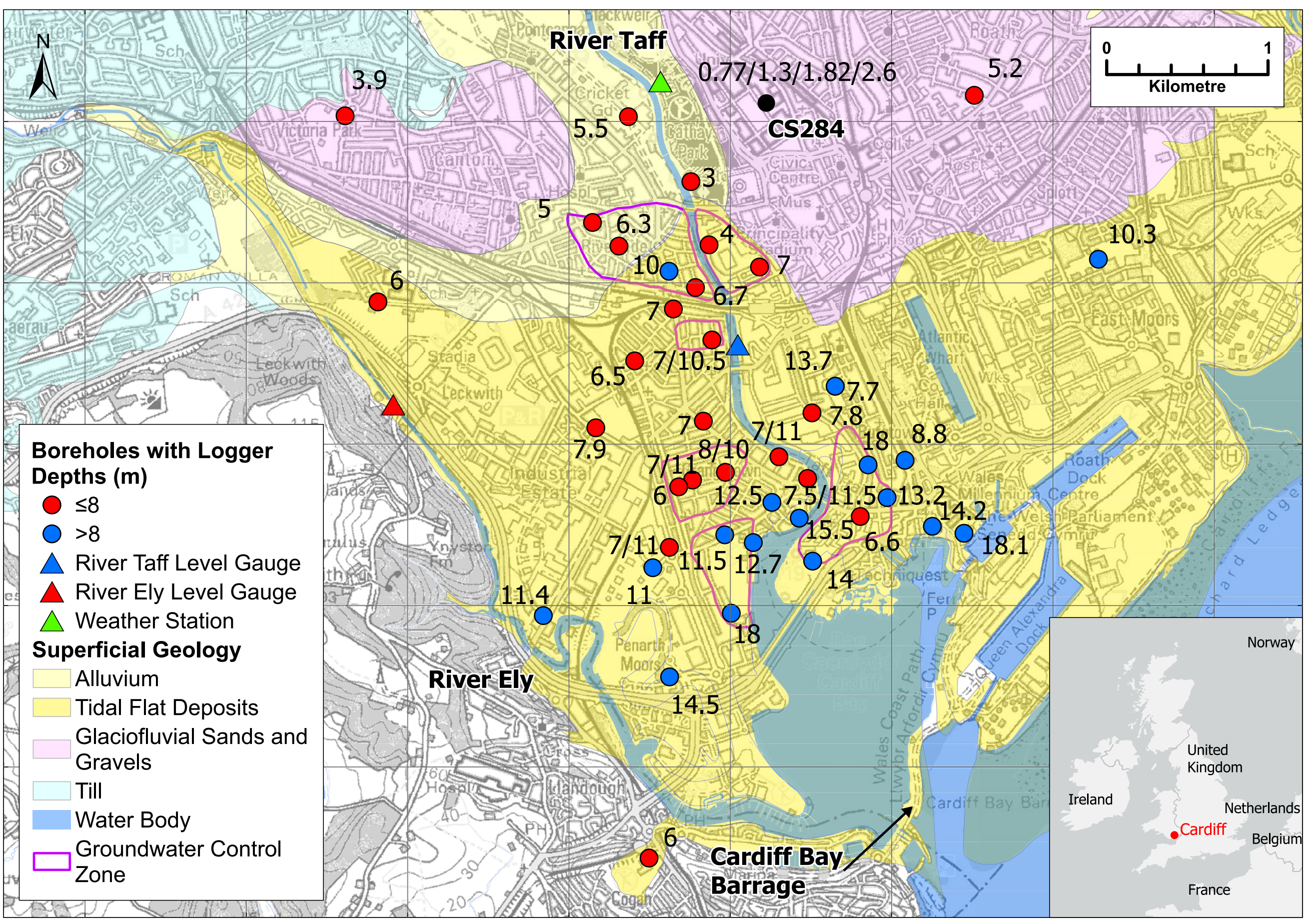

Fig. 1 Map of the Cardiff study area showing the locations of the boreholes containing groundwater temperature loggers, shown with logger depths. Weather stations, mapped superficial geology, principal water bodies and areas identified by Cardiff Harbour Authority as having discontinuous or absent clay deposits (groundwater control zones) are also shown. Coordinate system: British National Grid. Contains DiGMapGB 1:50 000 British Geological Survey © UKRI & Ordnance Survey data © Crown Copyright & database rights (2024) OS AC0000824781. Contains data from OS Zoomstack

are estimated to remove two thirds of the rainfall entering the Made Ground, leaving the remaining third as effective precipitation available for recharge (Hydrotechnica 1991).

Borehole network

As a condition of the development of the Cardiff Bay Barrage, a groundwater monitoring network comprising 234 boreholes was installed across the city (Heathcote et al. 1997), owned by Cardiff Harbour Authority. Across the network, groundwater levels were recorded at half-hourly intervals between 1996 and 2019. The 20 km^2 covered by this network makes up the study area for this research. Borehole logs were made available by Cardiff Harbour Authority and have been reviewed as part of this study.

Subsurface urban heat island effect

Farr et al. (2017) found groundwater in Cardiff to be up to 4 °C warmer than predicted by the UK average geothermal gradient of 28 °C/km^{-1} (Busby et al. 2011) as a result of the SUHI effect. The mean groundwater temperature for the city was found to be 12.4 °C; however, annual temperature variance in Cardiff's subsurface was revealed to be somewhat heterogeneous by Patton et al. (2020).

Data collection

Groundwater temperature data

This study makes use of time-series temperature data collected between 2014 and 2018 from 48 Hobo Pro V2 water temperature loggers (resolution = 0.02 °C, accuracy = ± 0.21 °C) installed within 42 of the Cardiff Harbour Authority boreholes (Patton et al. 2020) (Fig. 1). The loggers were installed at a variety of depths within the boreholes, ranging between 3.0 and 18.1 mbgl, and record temperature at half-hourly intervals. The data are used as recorded and are not subject to further processing. Six of the boreholes had two loggers installed at different depths. At one location (CS284), at Cardiff University, shown on Fig. 1, data was also collected at four depths over a 1-month period in October/November 2023 to identify changes in temperature signal with depth in response to short-lived events. In this case, time-series temperature and water pressure data were logged at 5-min intervals at three of the depths (0.77, 1.30 and 1.82 mbgl) using Schlumberger Water Services Divers (resolution = 0.01 °C, accuracy = ± 0.10 °C) and at 1-h frequency at the remaining depth of 2.60 mbgl using an in situ rugged troll (resolution = 0.01 °C, accuracy = ± 0.30 °C). Repeat temperature-depth profiles (RTDPs) were also obtained for two boreholes, surveyed at 1-m depth intervals each month over the course of 1 year to depths of 9.5 m and 7.6 m (termination depths of the boreholes). The RTDP were conducted by lowering a Solinst temperature level and conductivity (TLC) meter (resolution = 0.1 °C, accuracy = ± 0.2 °C) down the borehole to the rest water level. The TLC meter was allowed to equilibrate at this depth before a temperature reading was taken. The probe was then lowered by 1 m and allowed to equilibrate again before a further measurement was taken. The probe was lowered each metre, pausing to take a reading each time, to the base of the borehole. A downward direction of measurement was chosen to limit disturbance of the water column. Temperatures in the boreholes are thought to be representative of the surrounding aquifer as the boreholes are of small diameter and in quick conductive thermal equilibrium with the surrounding aquifer, except during short-lived recharge events.

Additional datasets

Half-hourly groundwater level data were supplied by Cardiff Harbour Authority for all boreholes except CS284 for the period 2014–2018. These data were processed by Cardiff Harbour Authority using manual dips and correcting for barometric pressure. Half-hourly river stage data from the Rivers Taff and Ely were also provided, together with precipitation data collected at the Bute Park weather station in the centre of the city. The locations of these monitoring stations can be found in Fig. 1.

Data analysis

To visually assess how groundwater temperatures fluctuate throughout the seasons and years, the groundwater temperature data were plotted for each borehole individually alongside the air temperature and precipitation data, groundwater levels and river stage data for those boreholes close to one of the city's rivers. A summary of the borehole log is provided in Table S1 of the electronic supplementary material (ESM) was added to the plot, together with the logger(s) depths to aid interpretation.

Data quality control

Six of the curves created by plotting the time-series data did not follow a typical seasonal wave pattern (depicted as 'other' in Fig. 2). In each case the loggers were found to be entangled with other equipment within the borehole casing and not located at the depth at which they were initially thought to be installed. Thus, it is considered that these loggers may have been disturbed during the monitoring period and the data have been discounted. One borehole (CS274) was also removed from the study as it was found to be predominantly dry.

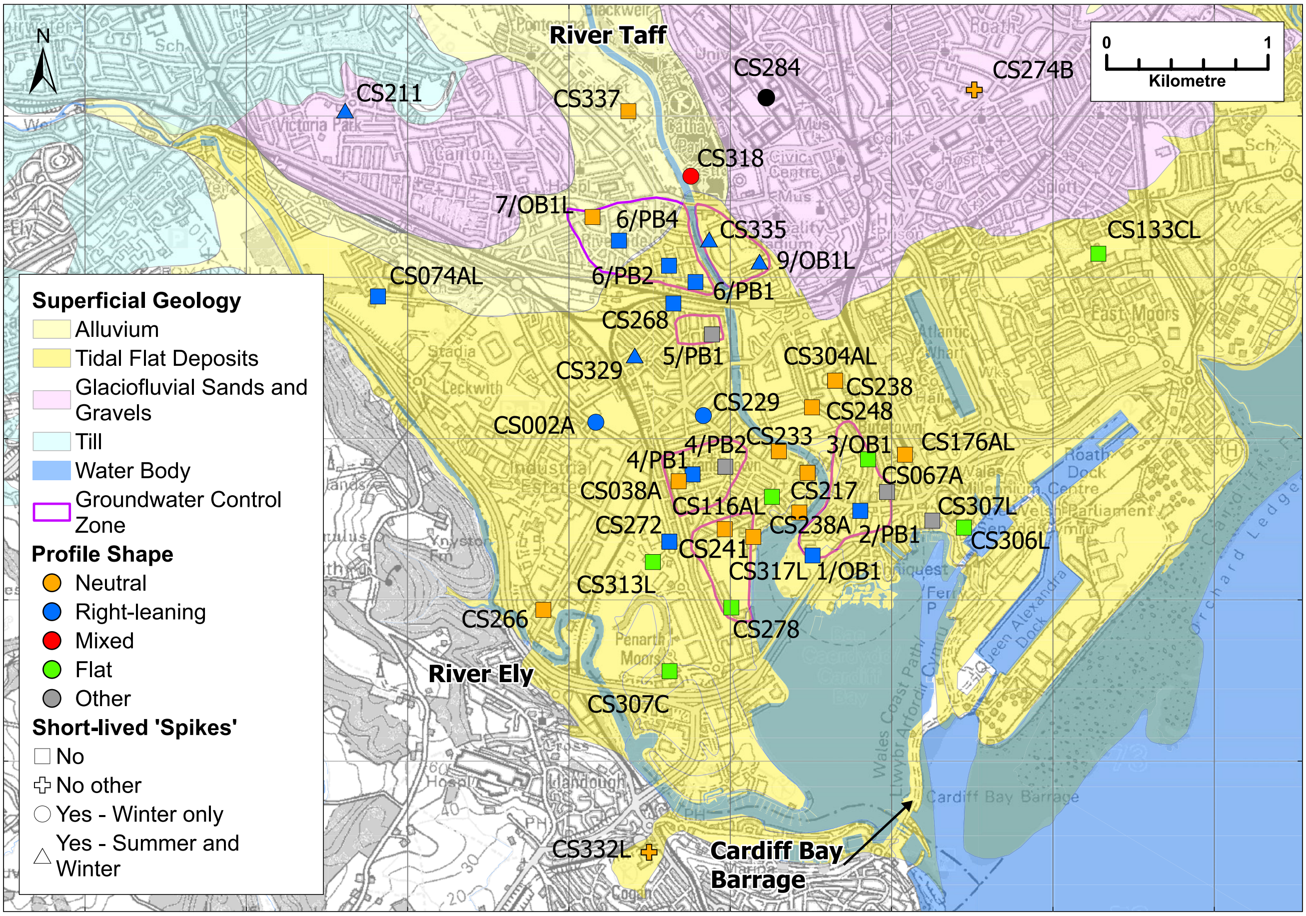

Fig. 2 Map showing the spatial distribution of the groundwater temperature curve shapes and boreholes with spikes, with borehole IDs. Symbol colours denote the overall curve shape, while symbol shapes identify short-lived events. Spikes are identified as occurring in winter only (cooling spikes) or summer and winter (a combination of warming and cooling spikes). The two 'no other' boreholes are either dry or show ocean tides. Coordinate system: British National Grid. Contains DiGMapGB 1:50 000 British Geological Survey © UKRI & Ordnance Survey data © Crown Copyright & database rights (2024) OS AC0000824781

Time-series curve shapes

A sine wave model with a period of 1 year was compared to the groundwater temperature data for each borehole location to initially assess and classify the temperature record. A sinusoidal record would be expected in a conduction-dominated heat transport setting, where groundwater temperatures would reflect seasonal surface temperature oscillations with the amplitudes being damped and attenuated with depth (Boyle and Saleem 1979). Monthly mean land surface temperatures were obtained from MODIS products MOD11A1 and MYD11A1 from NASA's TERRA and AQUA satellites, accessed via Google Earth Engine. These showed the mean annual land surface temperatures for the study area to be sinusoidal. Where significant deviations from a sine wave are observed the implication is, therefore, that processes other than conduction alone may be substantially controlling the observed temperature signal, and/or that there are significant heat sources other than the sinusoidal air temperature force acting at or within the subsurface.

A year-on-year warming trend was noted at some boreholes, so a linear trend was also added to the model before fitting by optimisation to minimise the root mean square error (RMSE) normalised by the amplitude of the modelled sine curve component. The time-series curve shapes were categorised into four groups: neutral, flat, right-leaning and mixed. Where the normalised root mean square error (NRMSE) was less than a threshold of 10% the plotted curve of the groundwater temperature data was deemed to be conduction dominated and categorised as 'neutral'. The modelled data at this threshold correlate very strongly with the observed data. The mean R^2 for those boreholes with an RMSE of ≤ 0.1 is 0.98. Those with an RMSE of > 0.1 have a mean R^2 of 0.52. Where the NRMSE exceeded 0.1, the shape of the curve was categorised as 'flat' – where there was no seasonality to the temperature data or seasonality fell below the resolution of the data logger, 'right-leaning' – where the seasonal wave was skewed towards the right (i.e. a shallower warming limb and steeper cooling limb), and 'mixed' – where the seasonal variation contained a mixture of years that behaved as sine waves with others that did not and in some years had a slight left-leaning skew (i.e. the curve had a steeper warming limb and shallower cooling limb). Typical examples of boreholes from each of these categories is shown in Fig. 3. Once the boreholes were assigned one of the four curve shapes these were mapped to see how their distribution plotted spatially (Fig. 2).

Short-lived events

Analysis was also carried out on sub-seasonal short-lived temperature events seen within the time-series data. These events can be as short as 1 h in duration. The events are most commonly drops in temperature occurring on the cooling limb of the temperature curve with a temperature recovery close to, but slightly lower than, the groundwater temperature preceding the event. They are here termed 'cooling spikes'. Similar short-lived rises in temperature appear on the warming limbs of temperature curves, termed 'warming spikes', but occur less frequently than cooling winter spikes within these locations. The spikes occur immediately following sudden increases in groundwater levels. The magnitudes of these events were statistically compared to size and timing, and visually to the steepness of concurrent changes in groundwater levels. To determine how localised the processes are which generate these spikes, the heat conduction diffusive length scales and groundwater flow characteristic diffusive length scales were calculated. The heat conduction diffusive length scales for these events were determined using Eq. 1 (Carslaw and Jaeger 1959):

$$L_T = \sqrt{\tau_T . D} \tag{1}$$

where L_T is the characteristic conduction length scale (m), τ_T is the characteristic heat conduction timescale and D is the thermal diffusivity (m^2/d).

The groundwater flow characteristic diffusive length scales for these events were determined using Eq. 2, derived by analogy to heat flow as per Eq. 1 (after Cuthbert et al. (2019) and references contained within):

$$L_F = \sqrt{\frac{\tau_F . T}{S}} \tag{2}$$

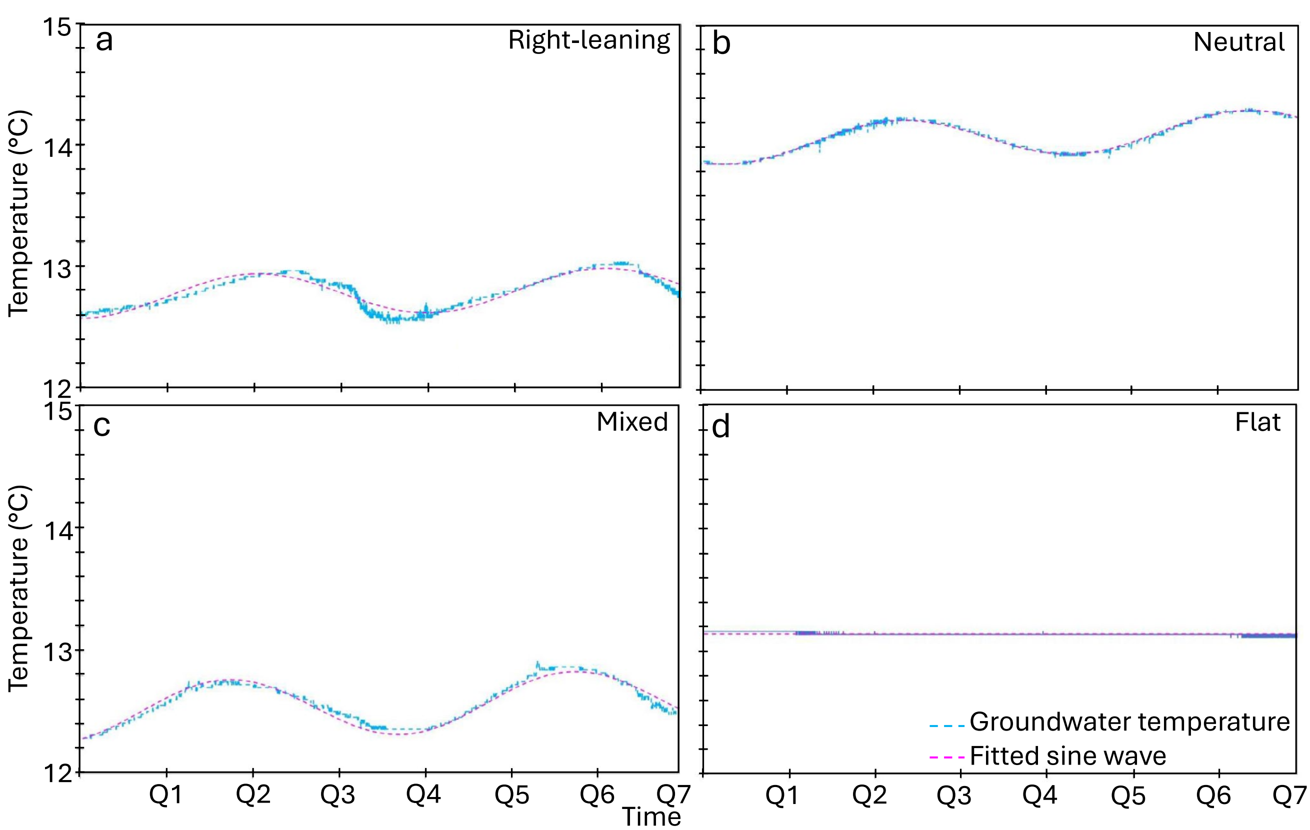

Fig. 3 a–d. Typical examples of the main shapes of groundwater temperature curves together with sine curves fitted to the data over a nearly 2-year period. Divisions on the x-axis marks year quarters

where L_F is the characteristic length of the flow path (m), τ_F is the characteristic groundwater flow timescale, T is the transmissivity (m^2/d) and S is the storativity (-).

Tabulation of data

To identify patterns between the borehole sites, the heat conduction and groundwater flow length scales were added to a table of all the boreholes, cataloguing the geological succession, depth of the piezometric head, logger depth, curve shapes, presence of short-lived events, and groundwater level patterns at each location (Table S1 of the ESM) and characteristic patterns of behaviour were grouped based on these results.

Results

Seasonal time-series curve shapes and their spatial distribution

Of the boreholes which remained after quality control, 14 curves were found to have neutral shapes, 16 were right-leaning, one was mixed, and 10 were flat.

The spatial distribution of these curve shapes is shown in Fig. 2. The majority of boreholes with right-leaning curves (termed right-leaning boreholes) are found to the northwest of the study area, and boreholes with neutral curves (neutral boreholes) more commonly found to the southeast. The exception to this general pattern is a neutral borehole (CS337) found in the northwest of the city, the mixed borehole located near the river Taff (CS318) and four right-leaning boreholes (1/OB1, 2/PB1, 4/PB1 and CS272) found in the southeast. One borehole (CS332L) has a neutral curve shape but also shows temperature fluctuations at two cycles per day coincident with the ocean tide oscillations seen in the groundwater levels.

Short-lived temperature events

Eight of the borehole time-series temperature curves, including the multi-depth data collected from CS284, show short-lived cooling spikes in groundwater temperature (Fig. 4). However, four boreholes show both cooling spikes and warming spikes. Despite temperatures rebounding following an event, temperatures post-event do not always return to the expected seasonal trend, with a step in temperature seen between pre- and post-event levels. Hence, it is inferred that the cumulative effect of numerous cooling temperature spikes is to cool groundwater temperatures faster in winter than they are warmed in summer.

The spikes are only seen in boreholes where the loggers are installed to depths of < 8 m suggesting this effect is damped with depth and is not seen below 8 m. The boreholes displaying spikes are only found in the northwest of the study area (where the tidal flat deposits are absent, thin or locally discontinuous), and always coincide with right-leaning or mixed curve shapes. The other boreholes in the southeast of the study area, where loggers are installed below 8 m, show no spikes (Fig. 2). Boreholes 6/PB1, 6/PB4, 7/OB1L, CS074AL, CS268 and CS337 in the north of the city show no appreciable spikes despite the loggers being at depths of < 8 m suggesting the process by which these spikes form is very localised and variation in geology and/or surface properties may impact whether these events occur. The size of the spikes is not correlated with logger depth ($r(14) = 0.05$, $p = 0.865$) nor seasonal temperature amplitude ($r(14) = 0.02$, $p = 0.949$), but do always correspond to steep rises in groundwater level, often following large rainfall events.

Monthly RTDPs were available for two of the boreholes (CS229 and CS335) exhibiting temperature spikes. It is noted that in these boreholes, the cooling spikes coincide with times of the year where the RTDPs show warming with depth, while the warming spikes occur at times of cooling with depth. In CS229 an average temperature drop in the time-series data from pre-event to post-event recovery of 0.024 °C corresponds with a groundwater level rise of 0.14 m. The RTDP gradient shows that groundwater 0.14 m above the depth of the logger corresponds to such a temperature difference. A similar result is seen in CS335 where a 0.1 °C temperature change corresponds to the 0.35 m groundwater level rise which is again plausible at the temperature gradient observed within this borehole.

Cooling spikes were also observed at multiple depths in CS284. These events quickly follow rises in groundwater levels and can be seen at all depths (Fig. 4). The temperature changes occur in depth order from shallowest to deepest logger, albeit only minutes apart. The groundwater flow characteristic length scales calculated for these temperature events are a few tens of metres.

Groundwater level fluctuations

Groundwater levels within the glaciofluvial sand and gravel aquifer vary between 2.5 and 4.5 mbgl across Cardiff, with a hydraulic gradient of approximately 0.0007 (Mitchell 1996) towards the rivers and coast. Groundwater levels are no longer affected by seawater ingress and regress due to ocean tides due the construction of Cardiff Bay Barrage, but 21 of the boreholes in this study are still subject to pressure effects caused by ocean tides (Patton et al. 2021).

Groundwater levels also appear to be impacted by river levels in the Taff and Ely, with borehole hydrograph responses closely resembling river stage responses at six sites (five of which are located between 15 and 100 m from a river with the sixth located 180 m from a river). A further ten boreholes located further from the rivers show

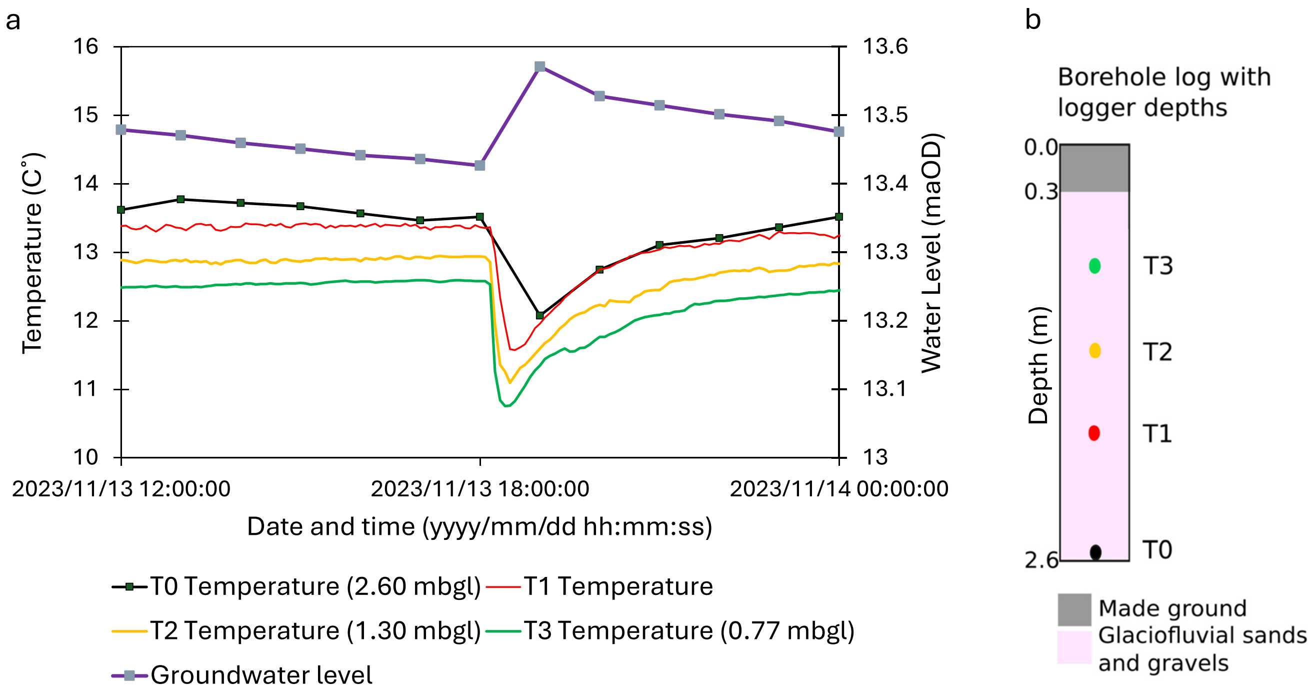

Fig. 4 **a** An example of a recharge event at CS284, **b** the borehole log showing the logger depths. Groundwater level rises temporarily from 0.72 mbgl to 0.58 mbgl during the recharge event quickly followed by cooling spikes in groundwater temperatures at all depths in quick succession. Following the event temperatures rebound near to, but not exactly at, their pre-event levels. Groundwater level and T0 temperature are hourly measurements, while T1-T3 temperature measurements are taken at five-minute intervals. The borehole is screened throughout the glaciofluvial sands and gravel

a similar pattern of level fluctuations to the rivers, albeit lagged behind the river responses. These rivers are flashy, in that their levels respond very quickly to rainfall. Hence the resemblance between the river and borehole levels may indicate that both are subject to rainfall influence, with the rivers responding first, followed by groundwater levels as a result of recharge. At CS318, a mixed curve shape borehole, river levels occasionally rise above groundwater levels, with groundwater level rises following shortly afterwards (Fig. 5).

Groundwater levels at several boreholes respond with immediate or delayed level rises following precipitation events recorded by the Cardiff weather station, indicating recharge. Patton et al. (2021) showed that the sand and gravel aquifer is often confined in areas where it is overlain by tidal flat deposits, except for a narrow region adjacent to the city's main rivers. However, these results show that groundwater levels do fluctuate in response to rainfall at some boreholes in the presence of tidal flat deposits, and recharge is able to have an impact on groundwater levels and temperatures. This recharge is likely to be localised as evidenced by the short groundwater flow characteristic length scales associated with the temperature spike events (Cuthbert 2014). At these boreholes, groundwater temperatures respond to these fluctuations with cooling spikes in winter and, to a lesser extent, warming spikes in summer. Elsewhere, in areas of the city that are overlain by thick confining tidal flat deposits, the pressure effect of recharge occurring further from the borehole can be detected in groundwater levels but these do not correspond to changes in groundwater temperatures.

Discussion

Processes controlling the seasonal curve shapes

Groundwater in Cardiff flows towards the rivers under a low hydraulic gradient. Heat propagation within the aquifer is therefore likely to be predominately via conduction. This is evidenced by the time-series curve shapes which in many areas strongly reflect seasonal air temperature oscillations. However, during and after large local rainfall events, recharge and concurrent river stage increases result in temporarily increased dominance of advective heat transport in some areas. This is evidenced by the deviation of seasonal curve shapes seen in time-series groundwater temperature data, away from the conduction-only sinusoidal response.

The majority of temperature curve shapes fell within two categories: neutral, which follow the seasonal air temperature

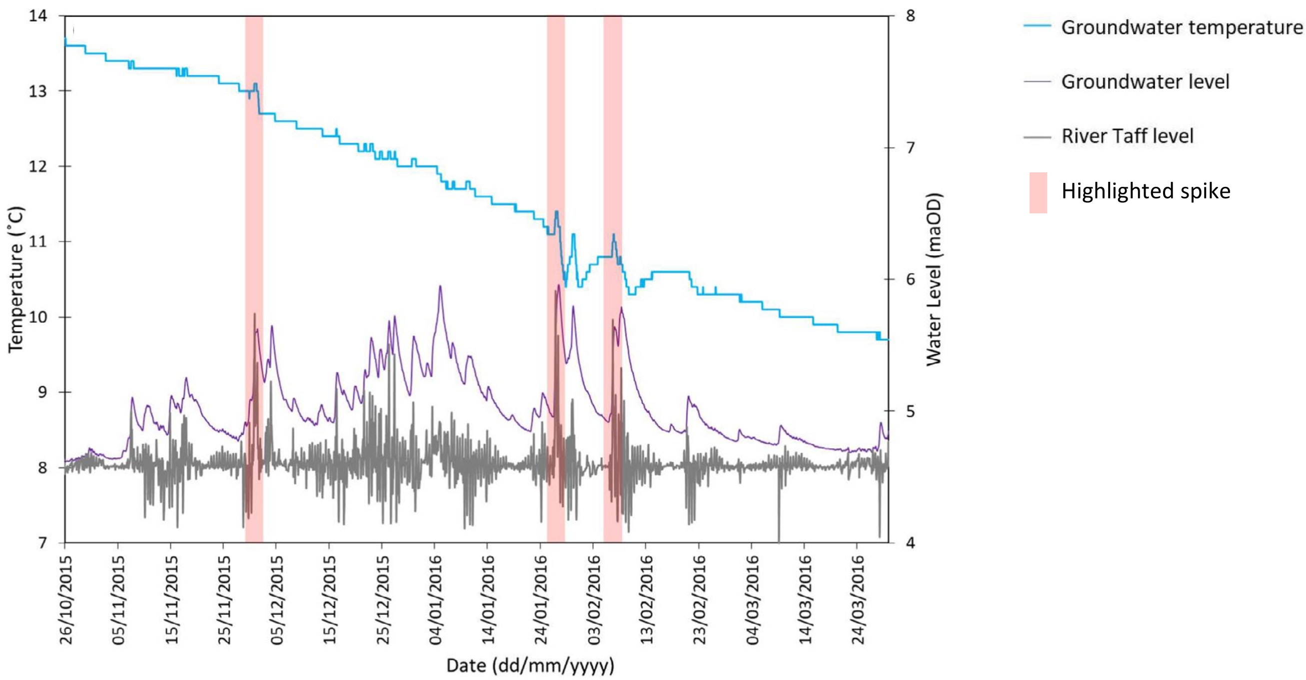

Fig. 5 A river-influenced mixed borehole (CS318) curve showing groundwater level temporarily rising above groundwater level during storm events impacting on groundwater temperatures (highlighted in red) with an initial rise in temperature followed by a drop and recovery. Detailed responses are shown in the third panel of Fig. 6 for the second red events highlighted

cycles, and right-leaning, which follow a seasonal trend but have over-steepened cooling limbs. The right-leaning boreholes where the loggers are installed < 8 mbgl tend to exhibit temperature spikes and all but one of the spikey time-series had right-leaning curve shapes. As the spikes were predominantly greatest in the winter, injections of cooler water appear to have the effect of cooling the groundwater by advection more quickly than it is warmed in summer, thus producing a time-series temperature curve where the cooling limbs are steeper than the warming limbs, giving them a right-leaning appearance.

Kurylyk et al. (2018) note that in the deep aquifers and offshore groundwater environments studied under steady state conditions, temperature-depth profiles of boreholes in recharge zones are concave-upward in shape as recharge events bring cooler water to depth from above. The effect of this on time-series data would be to skew the curve shape away from a lag and attenuated response to air temperature variations. The reverse would be true in discharge areas. Therefore, right-leaning curves seen in Cardiff are considered to occur where recharge takes place, and neutral curves are hypothesised to represent locations where recharge is absent or minimal and heat transport is predominantly by conduction. Table 1 shows the interpreted processes at each location across the study area.

The spatial distribution (Fig. 2) of these curves suggests that recharge is confined to the areas to the north of the city, where the tidal flat deposits are absent or thin, and to the GCZs where it is likely to be discontinuous, while elsewhere the low hydraulic conductivity of these thick deposits prevents event-based aquifer recharge. There are two exceptions to this pattern. Firstly, 7/OB1, a neutral curve borehole in the north of Cardiff outside of the mapped tidal flat deposits. This site may experience minor recharge but not enough to skew the curve, or may not be subject to recharge due to the sealed surfaces present at this location. This site was undergoing major construction works and land cover changed during the data collection period which may have impacted drainage conditions. The second exception is CS337 which behaves as a conduction-only borehole despite being located outside the limits of the mapped tidal flat deposits. This borehole is located within the grounds of a major sports stadium with its own irrigation and drainage systems to control the water level on the pitch. It is not known what impact this may have on groundwater in this area.

Processes occurring during short-lived temperature 'spikes'

Appearance and locations of temperature spikes

Temperature spikes are only seen in those boreholes with loggers installed at depth of < 8 m. This may be due to a damping effect on the advective pulse with depth. It may also be in these boreholes small spikes are observed that

Table 1 Summary of features identified at each borehole with process interpretation. Y denotes presence of spikes

Borehole ID	Cooling spikes	Warming spikes	Curve shape	Process	Comments
1/OB1	-	-	Right-leaning	Recharge	Located within a groundwater control zone. Right-lean may be the result of heat transport related to dewatering or ocean tide influence. 120 mm diameter
2/PB1	-	-	Right-leaning	Recharge	Located within a groundwater control zone. Right-lean may be the result of heat transport related to dewatering or ocean tide influence. 120 mm diameter
3/OB1	-	-	Flat	Undetermined	120 mm diameter
4/PB1 Shallow	-	-	Right-leaning	Recharge	Located within a groundwater control zone. Right-lean may be the result of heat transport related to dewatering. 120 mm diameter
4/PB1 Deep	-	-	Flat	Undetermined	120 mm diameter
4/PB2 Shallow	-	-	Undetermined	Undetermined	Logger entangled and thought to have been recording at different depths during the monitoring period. 120 mm diameter
4/PB2 Deep	-	-	Flat	Undetermined	120 mm diameter
5/PB1 Shallow	-	-	Undetermined	Undetermined	Temperature curve shows non-seasonal variation thought to related to undetermined processes such as pumping. 120 mm diameter
5/PB1 Deep	-	-	Undetermined	Undetermined	Temperature curve shows non-seasonal variation thought to related to undetermined processes such as pumping. 120 mm diameter
6/PB1	-	-	Right-leaning	Recharge	120 mm diameter
6/PB2	-	-	Right-leaning	Recharge	120 mm diameter
6/PB4	-	-	Right-leaning	Recharge	120 mm diameter
7/OB1L	-	-	Neutral	Conduction-only	120 mm diameter
9/OB1L	Y	Y	Right-leaning	Recharge	120 mm diameter
CS002A	Y	-	Right-leaning	Recharge	50 mm diameter
CS037C	-	-	Flat	Undetermined	50 mm diameter
CS038A	-	-	Neutral	Conduction-only	35 mm diameter
CS067A	-	-	Undetermined	Undetermined	Logger entangled and thought to have been recording at different depths during the monitoring period. 50 mm diameter
CS074AL	-	-	Right-leaning	Recharge	50 mm diameter
CS116AL	-	-	Flat	Undetermined	50 mm diameter
CS133CL	-	-	Flat	Undetermined	50 mm diameter
CS178AL	-	-	Neutral	Conduction-only	50 mm diameter
CS211	Y	Y	Right-leaning	Recharge	50 mm diameter
CS217 Shallow	-	-	Neutral	Conduction-only	50 mm diameter
CS217 Deep	-	-	Neutral	Conduction-only	50 mm diameter
CS229	Y	-	Right-leaning	Recharge	50 mm diameter
CS233 Shallow	-	-	Neutral	Conduction-only	50 mm diameter
CS233 Deep	-	-	Undetermined	Undetermined	Logger entangled and thought to have been recording at different depths during the monitoring period. 50 mm diameter
CS238A	-	-	Neutral	Conduction-only	50 mm diameter
CS241	-	-	Neutral	Conduction-only	50 mm diameter
CS248	-	-	Neutral	Conduction-only	50 mm diameter
CS266	-	-	Neutral	Conduction-only	50 mm diameter
CS268	-	-	Right-leaning	Recharge	50 mm diameter
CS272 Shallow	-	-	Right-leaning	Recharge	Major construction works (likely involving dewatering) immediately adjacent to the borehole during the monitoring period may have influenced groundwater flow and heat transport. Borehole located close to former river meander on post-industrial land both of which may produce unknown impacts on groundwater. 50 mm diameter

Table 1 (continued)

Borehole ID	Cooling spikes	Warming spikes	Curve shape	Process	Comments
CS272 Deep	-	-	Right-leaning	Recharge	Major construction works (likely involving dewatering) immediately adjacent to the borehole during the monitoring period may have influenced groundwater flow and heat transport. Borehole located close to former river meander on post-industrial land both of which may produce unknown impacts on groundwater. 50 mm diameter
CS274B	-	-	Neutral	Undetermined	Dry during the monitoring period. 50 mm diameter
CS278	-	-	Flat	Undetermined	50 mm diameter
CS283	-	-	Neutral	Conduction-only	50 mm diameter
CS304AL	-	-	Flat	Undetermined	50 mm diameter
CS307L	-	-	Undetermined	Undetermined	Logger entangled and thought to have been recording at different depths during the monitoring period. 50 mm diameter
CS308L	-	-	Flat	Undetermined	50 mm diameter
CS313L	-	-	Flat	Undetermined	50 mm diameter
CS317L	-	-	Neutral	Conduction-only	50 mm diameter
CS318	Y	-	Mixed	River	50 mm diameter
CS329	Y	Y	Right-leaning	Recharge	Borehole chamber found to be flooded frequently with water overtopping the borehole casing. 50 mm diameter
CS332L	-	-	Neutral	Tidal	Two cycle per day groundwater temperature fluctuations coincide with ocean tide driven groundwater level oscillations. 50 mm diameter
CS335	Y	Y	Right-leaning	Recharge	50 mm diameter
CS337	-	-	Neutral	Conduction-only	Located within the grounds of a cricket stadium with an irrigated pitch. 50 mm diameter

are below the accuracy of the sensor (< 0.2 °C) and thus not apparent at these locations. The absence of spike in these boreholes may also be due to the conditions in which they form not being present at these boreholes.

Temperature spikes observed in groundwater temperature time series are always coincident with sudden rises in groundwater level (Fig. 6) which are generally concurrent with local rainfall events. However, they may also be the result of responses to changes in the levels of the rivers Taff and Ely due to rainfall upstream of the study area when no precipitation is recorded within the study area. It is also noted that not all large rainfall events produce steep groundwater level rises. However, as rainfall data is collected only at a single location in the city, the exact timings of rainfall events that generate recharge at specific sites may vary.

The size of the groundwater temperature spikes is not directly related to the size of the groundwater level rise nor amount of rainfall that occurs immediately before the event (as can be clearly seen from the variation in groundwater level rises and rainfall data when plotted against the temperature record) but rather the steepness of the groundwater level rise. Figure 7 illustrates a series of groundwater level rises where steep rises result in temperature spikes while a gradual one does not.

Temperatures rebound quickly following an event (Fig. 6), but do not return exactly to pre-event temperatures of the expected seasonal trend, with the net result being a moderate overall cooling effect caused by these events in winter. Not all rises in groundwater levels produce changes in groundwater temperatures. This may be due to the localised confinement of the aquifer which allows recharge further afield to be detected as a pressure response in the borehole, but no localised recharge to cause vertical flow displacement and hence temperature anomalies.

The high-resolution logging interval at CS284 (Fig. 4) illustrates how responsive groundwater temperatures are to level rises and how quickly (0.35–0.83 days) they resolve after an event (Table S1 of the ESM). Hence, in some cases, the choice of temperature logging interval may result in very rapid responses being missed.

The groundwater temperature spikes occur in boreholes to the north of the city, and within Cardiff Harbour Authority's GCZs, where the tidal flat deposits are absent, thin or anthropogenically disturbed. As the temperature spikes follow rainfall-induced groundwater levels rises (as indicated by precipitation data from the weather station shown in Fig. 1) and occur in areas of the city known to have discontinuous tidal flat deposits, it is evident that spikes are the result of recharge and the movement of water through the system. Figure 8 conceptually illustrates mechanisms of altered flow patterns which are described below. Panel A shows the baseline conditions for loggers installed within parts of the system that are

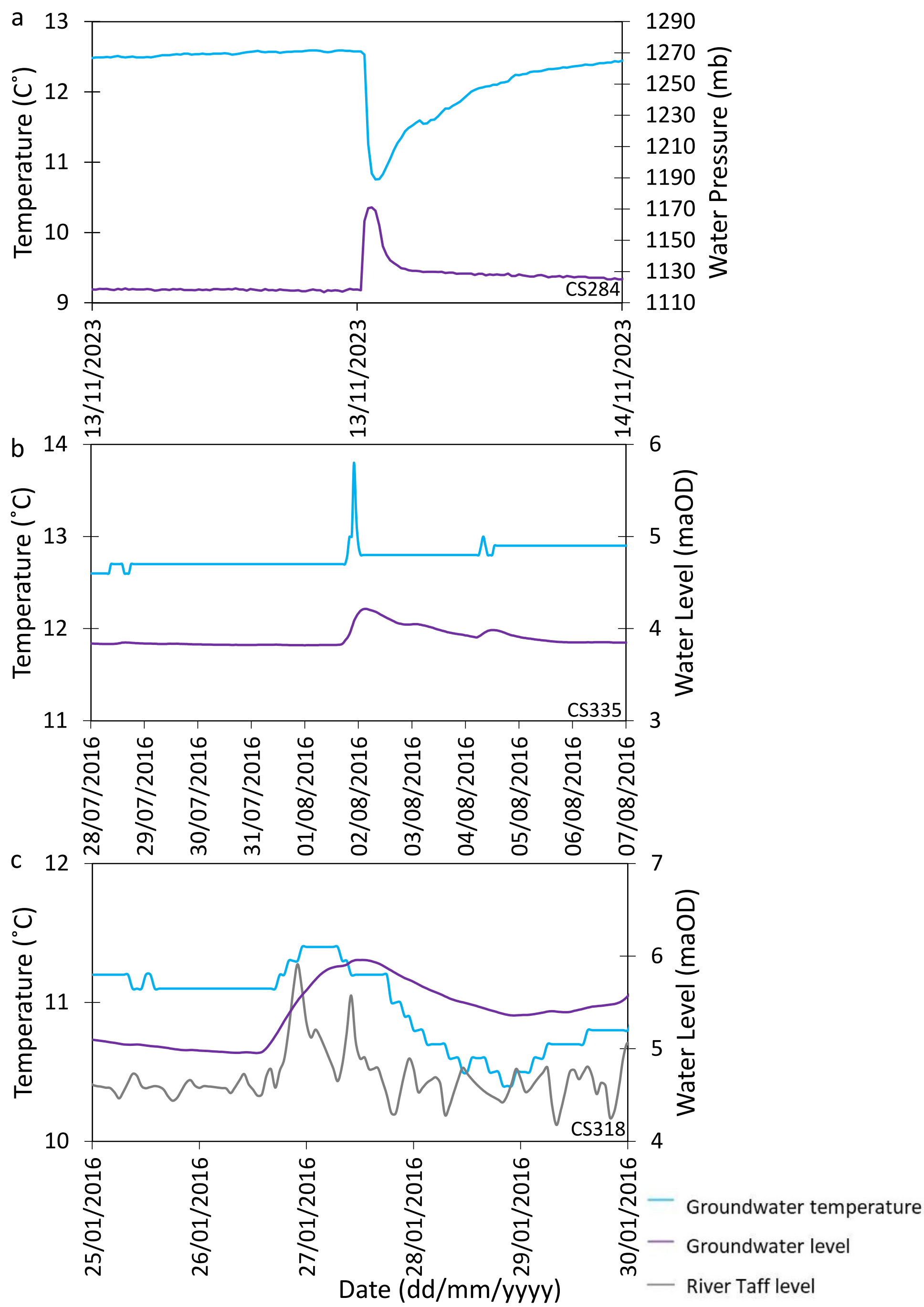

Fig. 6 Examples of groundwater temperature 'spikes' as a response to rapid rises in groundwater levels. **a** has a logging interval of 5 min and shows a typical cooling spike where temporary rises in groundwater level following rainfall cause cooler water to move down to the depth of the logger resulting in a drop in temperature. This event occurs during the cooling period and results in a step down in temperatures following the event which is greater than baseline seasonal decline in temperature. **b** (half-hour logging interval) shows a rise in groundwater level in summer bringing warming water to depth generating a warming temperature spike. This event occurs during the warming period but the step up in temperatures following the event exceeds the background warming trend. **c** (half-hour logging interval) shows the temperature response of a river influenced borehole, where rises in river level temporarily change the flow paths in areas adjacent to the river

conduction-dominant, and where loggers are installed too deep to detect seasonal temperature fluctuations. The other panels illustrate the processes occurring elsewhere in the study area.

Compromised boreholes (Fig. 8b)

One local pathway for the conveyance of cooler water to the location of the logger is the borehole itself. For example, this could be due to borehole overtopping enabling rapid movement of cold meteoric water directly into the borehole as illustrated by Borehole B in Fig. 8.

During the monitoring period the borehole chamber of CS329 was observed on several occasions to have flooded with water overtopping the standpipe. The data for this borehole look different from those of other boreholes where spikes are observed (Fig. 9) with very large drops in temperature (4.0–9.5 °C) well above those expected due to recharge at these temperature gradients. Furthermore, the spikes in CS329 do not correspond to groundwater level rises and

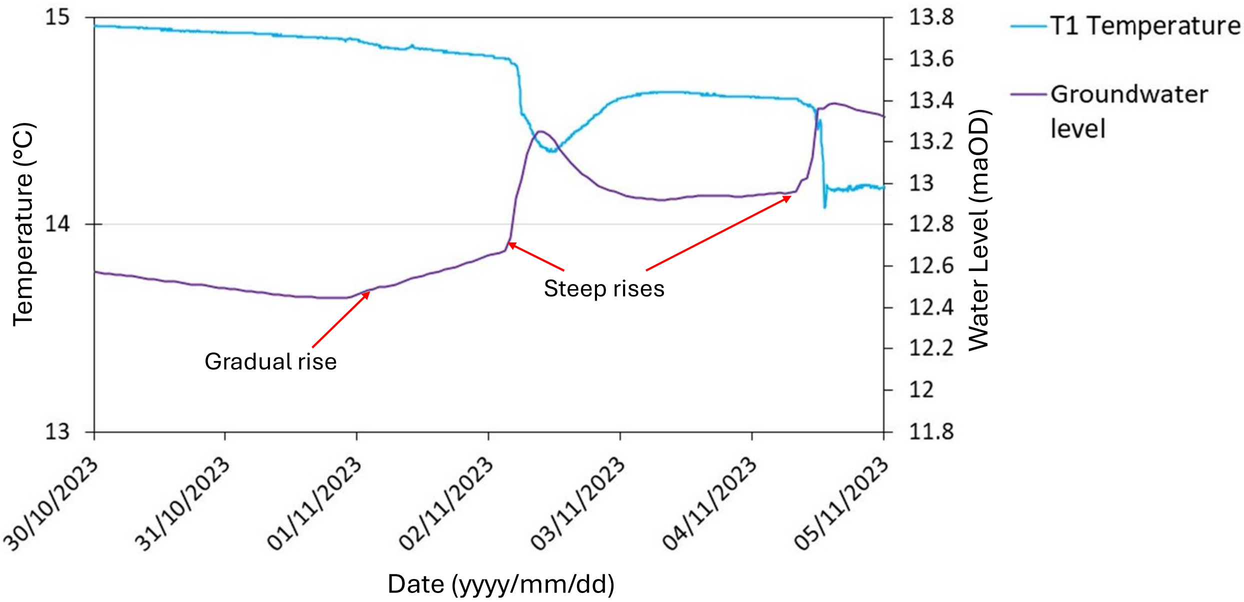

Fig. 7 Examples groundwater level rises and their impacts on groundwater temperatures. Steep rises in groundwater level result in temperature spikes, whereas gradual increases do not

temperatures rebound to the expected seasonal trend temperature level rapidly afterwards as heat is conducted back into the borehole from the aquifer. It has also been observed on several occasions that the manhole chamber of CS329 periodically floods above the level of the borehole casing.

Poor borehole construction may, theoretically, also bring water preferentially from the surface to the screened section of the borehole. However, this is not thought to be a significant problem here as the boreholes are known to have been constructed to a high standard, cased with a screened section at the monitoring depths and backfilled with bentonite. Other than at CS329, the temperature change of the spikes is also far smaller (0.06–1.30 °C) and is realistic for the observed temperature gradients within the conceptual model proposed below.

Groundwater recharge, mounding and piston flow (Fig. 8C)

With the exception of CS329, temperatures in boreholes with spikey temperature records recover following events but they do not fully return to the expected seasonal temperature trend (as illustrated by Borehole C in Fig. 8). Groundwater temperatures following a winter recharge event are lower than before the event leading to a right-leaning temperature curve; therefore, it is considered that whilst the presence of the borehole may serve as a flow path for water from above to be brought to depth, the lasting impact of these cooling events show that, unlike at CS329, the effect is caused by more than just the presence of the borehole. The failure of groundwater temperatures to return to the expected seasonal trend following an event implies that a similar process also occurs within the aquifer in proximity to the borehole. Where boreholes are not simply overtopping, it is implausible that rainfall itself is conveyed to a deep enough depth to be the cooler water detected by the loggers during a spike event. However, the introduction of precipitation to the system results in groundwater level rises which impact flow paths moving cooler groundwater from above to the depth of the logger (Borehole C in Fig. 8).

Since the spikes coincide with steep rises in groundwater levels, the absence of the phenomenon in areas of thick, low permeability clays suggests the rapid, short-lived temperature events are caused by local recharge, either directly in areas where tidal flat deposits are absent, or through preferential flow paths in areas where the deposits are thin or discontinuous. The short groundwater flow characteristic diffusive length scales (10 s of metres) of these events (Table S1 of the ESM) suggest either this recharge is very localised or that there are closely spaced pathways that quickly drain the additional water, while the longer-term groundwater recessions are seasonal and controlled by drainage to the rivers (Cuthbert 2014; Cuthbert et al. 2016). Rather than meteoric water being carried to depth via these pathways, it is more likely that recharge events cause a temporary mounding of groundwater locally and change flow paths around the observation points as a result of piston flow. In this case, mounding refers to localised, short-term rises in groundwater level as a result of recharge which is more rapid than the speed with which the water can laterally flow away. Piston flow refers to groundwater being displaced by meteoric water during a recharge event.

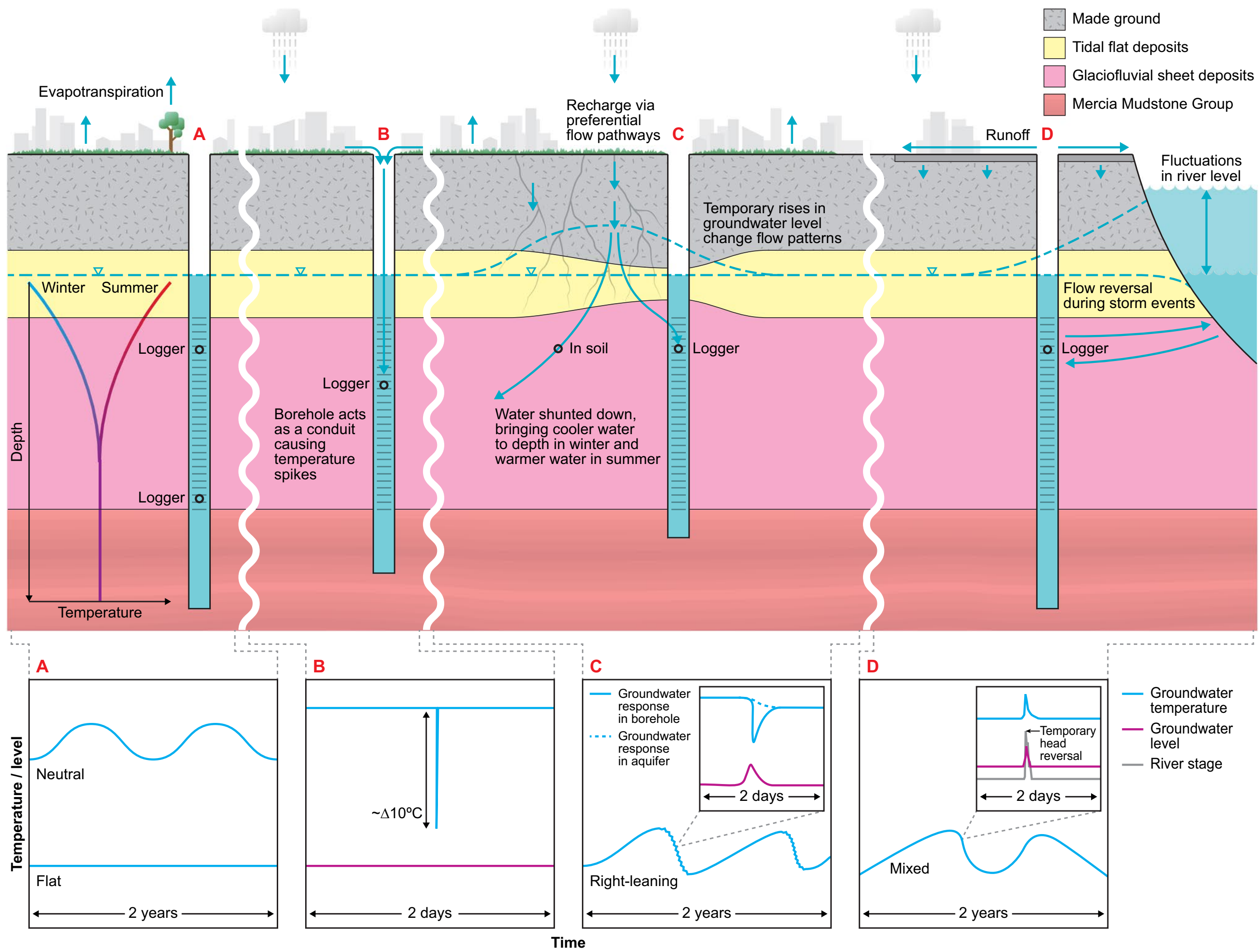

Fig. 8 Conceptual model showing the effects of localised recharge on groundwater temperatures. During a recharge event, groundwater mounds with meteoric water displacing groundwater bringing cooler water to depth in winter and warmer water to depth in summer by piston flow. The temperature gradients with depth in winter (blue) and summer (red) are shown to the left of the figure. **a** shows typical groundwater temperature curves for conduction-dominant boreholes and for those boreholes with deep loggers. **b** shows the effect on groundwater temperatures where cold meteoric water is overtopping the borehole during rainfall events and reaching the logger. **c** shows the effects on groundwater temperatures where preferential flow paths convey recharge to the aquifer. The solid line shows the temperature response in a borehole where the screened section alters flow paths. The dashed line shows the inferred step-down in temperatures seen in the aquifer without the presence of a borehole. **d** shows the combined effects of rainfall induced recharge with river influence on groundwater temperatures associated with a temporary reversal in flow direction from the river to the aquifer during storm events

This is evidenced by those boreholes with spikes where RTDPs are available. These show that cooling spikes occur during the part of the year when the groundwater above the logger is cooler than it is at the depth of the logger, and that warming spikes occur when groundwater above the logger is warmer. Calculations based on the temperature gradients in the boreholes with both time-series and RTDP data indicate that the average degree of post-event temperature change compared to pre-event is approximately consistent with the average amount of groundwater level change at the time of the recharge events.

During these events, local flow paths are altered and cooler (or warmer in summer) water from above is then pushed downwards as localised recharge mounds redistribute themselves laterally. One preferential flow path for this displaced water is the observation borehole itself. Evidence for this is seen in the data from CS284 where a cooling effect of a similar magnitude is seen to sequentially propagate downwards through the water column. As recharge occurs above, the displaced water reaches the screened section of the borehole and a rapid change in temperature is detected by the logger. Once the recharge event has ended the pulse of displaced water ceases and temperatures within the borehole equilibrate as heat is transferred back to the borehole by conduction. However, as the advective pulse occurs in the surrounding aquifer as well as in the borehole

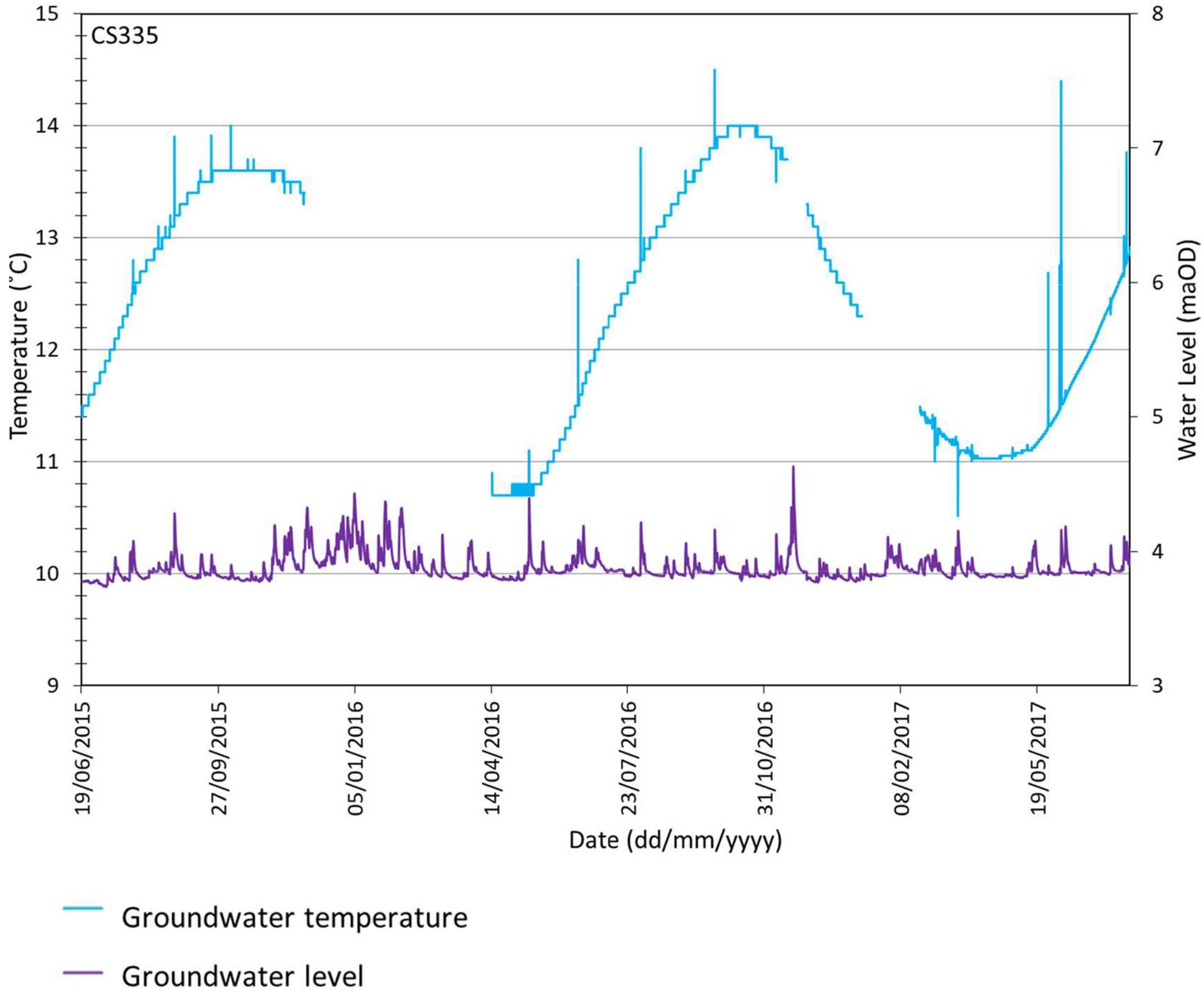

Fig. 9 Temperature spikes at CS329 show an order of magnitude greater temperature change than at other sites, rebound to expected levels based on the background trend, pre-event levels and do not correspond to steep rises in groundwater levels. These large temperature spikes are due to flooding of the borehole chamber with water regularly overtopping the borehole following heavy rain

itself, there is an overall step change in temperatures caused by recharge events (as illustrated in Fig. 8C) and temperatures do not fully recover to the seasonal trend. As recharge is more commonplace during winter, these rapid cooling events lead to right-leaning temperature curves. Therefore, while the spikes observed are artefacts of the presence of the borehole taking part in the redistribution of flow during a recharge event, it is proposed that the overall change in temperature from the start and end of such an event is indicative of the temperature of the surrounding aquifer. Were the borehole not present and temperatures were measured directly within the soil, there would be a step down in temperatures following a recharge event rather than a spike and recovery (Fig. 8).

In areas where the tidal flat deposits are absent, direct recharge has the effect of cooling groundwater faster in winter than it is warmed in summer. Within the area of thin tidal flat deposits, preferential flow paths in the unit would have the effect of locally increasing hydraulic conductivity and allowing aquifer recharge. Several studies were conducted ahead of the construction of Cardiff Bay Barrage which concluded that the tidal flat deposits are of low hydraulic conductivity and confine the aquifer where present (e.g. Hydrotechnica 1991; Mitchell 1996; Edwards 1997). Six GCZs were identified as areas where the tidal flat deposits may be discontinuous, having been removed or disturbed by activities such as the infilling of a former canal or clay excavations for the manufacture of bricks. The remainder of the south of the city was considered confined. Patton et al. (2021) confirmed that this area is confined for the most part but the tidal flat deposits vary considerably and the evidence of recharge in boreholes in the northern part of the mapped tidal flat deposits, where borehole logs show the deposits to be thinner, suggest that either the tidal flat deposits are missing in some localised areas or that preferential flow paths are allowing the downward movement of water through the unit, which could also explain the speed (Table S1 of the ESM) with which groundwater levels and temperature respond to rainfall events. Such preferential flow paths are well documented elsewhere (e.g. Beven 2018), and several potential pathways are suggested for Cardiff in the existing literature and include relict root systems (Mitchell 1996), gravel channels (which have similar hydraulic properties to the glaciofluvial sand and gravel aquifer (Mitchell et al. 1996) or service trenches (Hydrotechnica 1991). It is also noted that tidal flat deposits once formed the land surface and relict root structures from historic surface vegetation cover may also provide preferential flow paths allowing the movement of water through the clays. Those boreholes with neutral temperature curve shapes identify areas where the aquifer is confined, as no right-lean denotes no recharge, or where recharge is by slow drainage through the tidal flat deposits rather than as rapid pulses, but groundwater levels may still fluctuate in these areas due to the propagation of pressure responses caused by recharge occurring further from the borehole. Heathcote et al. (2003) note that characterisation of the vertical hydraulic conductivity within the tidal flat deposits is hard to constrain, with laboratory results and falling head test values varying between 4.2×10^{-6} and 1.2×10^{-1} m/d, and are unlikely to be representative of field-scale values. Thus, it is plausible that localised parts of the area identified by this research are more hydraulically conductive than established by Mitchell (1996) and incorporated into the existing Cardiff groundwater model, or that the tidal flat deposits may be absent in places.

River–aquifer interactions (Fig. 8D)

One borehole, CS318, produced a mixed temperature curve shape suggesting multiple hydraulic processes affecting heat transport (like Borehole D in Fig. 8). CS318 has a curve which appears as neutral in some years and slightly left-leaning in others as may be expected with discharge when compared with Kurylyk et al.'s (2018) findings. This mixed type of signal is suggestive of more than one process in action at the site. Although CS318 shows winter cooling spikes indicative of recharge, it does not have a right-leaning curve shape. The mixed curve is evidence that rapid warming in summer is offsetting the winter cooling. CS318 experiences warming spikes in the summer. Figure 5 shows that warming spikes in groundwater temperature occur when there is a rapid rise in groundwater levels that appear to be caused by sudden rises in the River Taff level. The river level can be seen to exceed the groundwater level at these times. This suggests that during storm events the river level temporarily rises above the groundwater level causing a reversal in flow direction from the river to the aquifer, changing the direction of the groundwater flow paths (particularly the vertical components) and altering the temperature recorded by the logger. This is then followed by a more typical drop in groundwater temperatures with a recovery similar to those seen during a recharge event. This potential river-influence may, when combined with the cooling effect of winter recharge events, explain the mixed style of temperature signal seen at this location.

Local thermal nonequilibrium

It is noted that whilst temperatures do not return to pre-event levels, they do approach baseline temperatures rapidly following an event. The large grain size of the glaciofluvial sand and gravel aquifer (50–90% of grains are 2–200 mm) in combination with high flow rates could result in a Peclet number high enough to allow for local thermal nonequilibrium (LTNE), as illustrated experimentally by Baek et al. (2022). LTNE occurs where there is a local heat exchange and temperature difference between groundwater and the surrounding solid material. The temperature rebounds at some locations in Cardiff may be suggestive of LTNE whereby heat from Cardiff's gravels may be able to warm the groundwater back up again by conduction after a cooling advective pulse has moved through. This would be difficult to identify with certainty but the lowest estimate of the Peclet number for the gravel aquifer is > 2 (based on the lower end of the grain size range for which the majority of the material is comprised), well above the threshold of 1.00 defined by Baek et al. (2022) as required to assume LTNE. Therefore, LTNE cannot be ruled out and should be investigated further. Detailed site-specific modelling of the Cardiff data is needed to investigate LTNE, but it is possible that groundwater temperature time-series data may aid identification of this phenomena in the field, which could improve heat transport models at such sites.

Conclusions

This work has demonstrated that groundwater temperature time-series can reveal subsurface thermal and hydraulic processes. Seasonal and sub-seasonal variability in groundwater temperature time-series data can provide insights into heat transport processes which in turn uncover hydraulic processes, including localised recharge, degree of confinement, and groundwater–surface water interactions. As a result of this work, it is possible to draw the following conclusions:

Groundwater temperature time-series patterns

1. Spikes in groundwater temperature time-series data should not be assumed to be noise or erroneous data. Recurrent spikes or spikes at multiple locations should be investigated as real events that can reveal insights into hydraulic processes. (Objective 2.)
2. Groundwater temperature time-series curve shapes can be used to identify hydraulic processes including localised recharge, or lack thereof, river influence, ocean tides and localised confinement. (Objectives 1 and 3.)

Short-lived events and their significance

3. Boreholes may display short-lived rapid temperature fluctuations concurrent with steep rises in groundwater level. In winter, when the temperature gradient with depth is from cooler to warmer groundwater, this results in cooling spikes observed in the time series. These are caused by downward flow of cooler water due to recharge. Preferential flow through the borehole screen causes a temporary 'spiked' decrease in temperature which only partially recovers following the event due to conductive re-equilibration with cooler water in the surrounding aquifer which has also been displaced downwards to a lesser extent. In summer, warmer water is transferred downwards resulting in warming spikes, although this is less commonly seen than the more pronounced winter recharge events. (Objectives 2, 3 and 4.)
4. Temperature spikes cause more rapid cooling of groundwater during winter than warming in summer, therefore producing a right-leaning annual curve indicative of localised recharge of the aquifer. The size and length of the temperature spike and recovery is controlled by a complex set of interactions between the borehole construction, aquifer properties and recharge mechanisms. (Objectives 1, 2, 3 and 4.)

Groundwater–surface water interaction

5. In those areas close to rivers where the base of the river is in direct contact with the aquifer, the usual hydraulic flow regime is one of discharge from the aquifer to the river. However, during storm events, river levels may temporarily rise above groundwater levels causing a reversal of flow direction from the river to the groundwater altering flow patterns and impacting on groundwater temperatures. When this effect combines with recharge from above, the result is a nonuniform groundwater temperature curve shape that may have a slight left-lean in some years, depending on which effect is dominant. (Objectives 1, 3 and 4.)

Practical application

6. Understanding if recharge or river-influence is occurring at a site is crucial to unravelling how heat is transported through the subsurface. Recharge increases the amplitude of seasonal temperature variation at depth by introducing more seasonal water from higher up in the system to greater depths. An appreciation of this is necessary for modelling heat transport prior to the design of shallow geothermal energy systems that are to make use of the SUHI effect.
7. In Cardiff, recharge controlled advective heat transport is found to be the most common process in the north of the city in the area where the tidal flat deposits are absent or very thin, while the south of the study area is underlain by thicker tidal flat deposits and is dominated by conduction-only heat transport. The exceptions to these are those boreholes situated within an area of low recharge to the north which may be the result of anthropogenic activity or local heterogeneity within the subsurface. Recharge within the area of mapped tidal flat deposits may be via preferential flow paths (such as relict root structures, gravel channels or services trenches), with short groundwater flow characteristic length scales indicating recharge is localised, while at broader scales the deposits are generally confining (e.g. Hydrotechnica 1991; Mitchell 1996; Edwards 1997; Patton et al. 2021). Potentially river-influenced sites are found in the north, immediately adjacent to the River Taff, as evidenced by CS318. This may be explained by a reversal of head gradient during storm events where the river is in hydraulic connection with the aquifer. (Objectives 2 and 5.)
8. Time-series temperature data are an underused resource in identifying subsurface hydraulic processes and can be useful in understanding how these processes affect thermal regimes. This type of analysis has value to a range of disciplines with uses not limited to developing shallow geothermal energy, environmental monitoring and contamination assessment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10040-025-02930-2.

Acknowledgements The authors would like to thank the following: C. Abesser and C. Woodward from the British Geological Survey, and D. James formerly of the County Council of the City and County of Cardiff. Groundwater and river level, and meteorological data has been used in this research with the kind permission of Cardiff Harbour Authority, County Council of the City and County of Cardiff, UK.

Author contributions AMP – data collection, data analysis, interpretation, writing.

PJC – guidance with interpretation and writing, reviewing.

MOC – guidance with interpretation and writing, reviewing.

Funding Funding from the British Geological Survey, Natural Environment Research Council. This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 835852.

Data availability Groundwater temperature data available at Farr G, Patton A, Boon D, James D, Coppell L, James L (2019) Cardiff Urban Geo-Observatory, Groundwater Temperature Data 2014–2018. In *British Geological Survey. (Dataset).* https://www.data.gov.uk/dataset/a609a496-1f29-498f-9ac4-2ffbd6832af4/cardiff-urban-geo-observatory-groundwater-temperature-data-2014-2018. Groundwater level data available on request from Cardiff Harbour Authority.

Declarations

Competing interests On behalf of all the authors, the corresponding author states that there is no conflict of interest.

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