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Heat as a natural, low-cost tracer in mine water systems: The attenuation and retardation of thermal signals in a Reducing and Alkalinity Producing Treatment System (RAPS)

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ABSTRACT

A combined chemical and thermal tracer test has been attempted, using iced water and sodium chloride, in the compost and limestone Tan-y-Garn Reducing and Alkalinity Producing System (RAPS), designed to treat iron-rich net acidic mine water in South Wales, UK. The applied thermal signal was, however, inadequate to produce a temperature anomaly in the output water, being overwhelmed by the summer solar/atmospheric daytime heat input to the lagoon. Nevertheless, natural diurnal temperature signals could be discerned in the outlet water, being retarded relative to the input signal. Thermal retardation could be calculated as approximately 2.3 to 2.9, and various estimates of the RAPS bulk volumetric heat capacity tend to fall between 2 and 3 MJ m^{-3} K^{-1}. The natural diurnal thermal signal potentially provides a low cost substitute for artificial tracers in estimating RAPS retention times.

1. Introduction

1.1. The Tan-y-Garn site

Tan-y-Garn was a small drift colliery at Garnswllt, Ammanford, Carmarthenshire, South Wales, UK (51.7696°N 3.9849°W; OSGB36 Grid reference SN 6313 0973). The mine complex underlies a total area of less than 0.3 km^2 and worked the "Ynysarwed" coal seam from 1876 to 1990. This "Ynysarwed seam" is often taken to be synonymous with what is currently referred to as the Rhondda No. 2 seam (Strahan et al., 1907), although the naming of seams has historically been somewhat arbitrary and problematic to relate to current accepted nomenclature. In the specific case of Tan-y-Garn, it seems more likely that the seam worked was the stratigraphically slightly higher Rhondda No. 1 (or Duke) seam (see the published geological map by BGS, 1977 and the report by SRK, 1994). Both the Rhondda No. 1 and No. 2 seams lie in the Rhondda Beds member of the Lower Pennant Measures of the Westphalian Upper Coal Measures. The seams are associated with a relatively thick sandstone unit with subordinate silts and shales. The worked seam was recorded as 2 ft. 11 in. (89 cm) thick at "Old Garn Swllt" colliery by Strahan et al. (1907). The local dip of strata is between 10° and 17°S to SW according to BGS (1977).

Following abandonment in around 1990, the Tan-y-Garn workings (c. 0.12 km^2) flooded, and eventually overflowed via a mine entrance as a polluting ferruginous discharge on the south side of the local stream, the Afon Cathan. The workings of Tan-y-Garn underlie the area south of this main minewater discharge point and are thus below the discharge level, reaching down to elevations of −30 m below sea level. The mine was connected to the adjacent Garnswllt colliery (SRK, 1994) to the west of the discharge point The Garnswllt workings, of very limited areal extent (0.017 km^2), being largely above the discharge level, are assumed to be unflooded. The discharging mine water at the site has a typical flow rate of 2 L s^{-1}, although this can vary significantly with rainfall from 0.5 to 5 L s^{-1}. The overflowing mine water is now collected in a pipe and directed to a passive mine water treatment system. The annual average air temperature at Ammanford is estimated as around 10 °C, and was 10.3 °C for the year March 2007–March 2008, while the mine water has typically has a relatively constant temperature of approx. 11 °C. After intense rainfall episodes, however, sharp deviations ('spikes') in both temperature and electrical conductivity can be observed in the mine water. These are believed by the UK Coal Authority (who manage the scheme) to represent occasional entry of surface run-off, during rainfall events, to the otherwise groundwater-dominated mine water discharge. The system is described in full in the accompanying paper by Taylor et al. (in press).

The iron-rich (pH 6.2, 40–50 mg L^{-1} iron) water flowing from the mine is treated before it is allowed to discharge to the Afon Cathan. This is achieved by means of a Reducing and Alkalinity-Producing

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System (RAPS), which passively adds bicarbonate alkalinity to the water via dissolution of limestone clasts in a reducing organic matrix. It is intended that the reducing environment should maintain iron in its dissolved ferrous (Fe^{II}) state and prevent armouring of the clasts by ferric oxyhydroxides (in reality, in the Tan-y-Garn system, iron and sulphate concentrations decrease through the RAPS, suggesting removal of iron as an oxyhydroxide and/or sulphide precipitate - Taylor et al., in press). On exiting the RAPS, the water flows down a sequence of aeration cascades and settlement ponds, where ferrous iron is allowed to oxidise, hydrolyse and precipitate as ferric oxyhydroxide ('ochre'). The principles of such a scheme are described by (Kepler and McCleary, 1994; Watzlaf et al., 2000; Younger et al., 2002; Amos and Younger, 2003; PIRAMID Consortium, 2003; Fabian et al., 2005). The specific Tan-y-Garn system is described by Atkins, 2006; Watson et al., 2009; Geroni, 2011; Geroni et al., 2011; Geroni et al., 2012; Taylor et al., in press).

1.2. The RAPS

As described by Taylor et al. (in press), the water exits the coal mine at a relatively constant temperature of around 11 °C (mean 10.89 °C with a standard deviation of 0.27 °C for the period 9th June–30th July 2008). The water flows via a short pipe and a manhole chamber into the surface pond of the RAPS system, which commenced operating in January 2006 (Fig. 1). The RAPS comprises (Fig. 2):

- Up to a maximum freeboard 30 cm of standing supernatant water, derived from mine drainage. The flow from the mine varies somewhat seasonally.
- 10 cm upper layer of municipal (peat-free) compost.
- 60 cm mixed layer of 50:50 vol.% municipal compost and limestone gravel, with a maximum limestone clast size of 40 mm.
- Lower layer of 10 cm of limestone gravel.
- An underdrain, comprising silica gravel and embedded drainage pipes, of design thickness of 22.5 cm to the base of the embedded pipes. The drainage pipes feed the water into an outflow pipe.

The RAPS is thus around 1 m thick. It has a top surface area of around 280 m^2 as an oval shape approx. 30 m by 10 m. The liquid surface area is

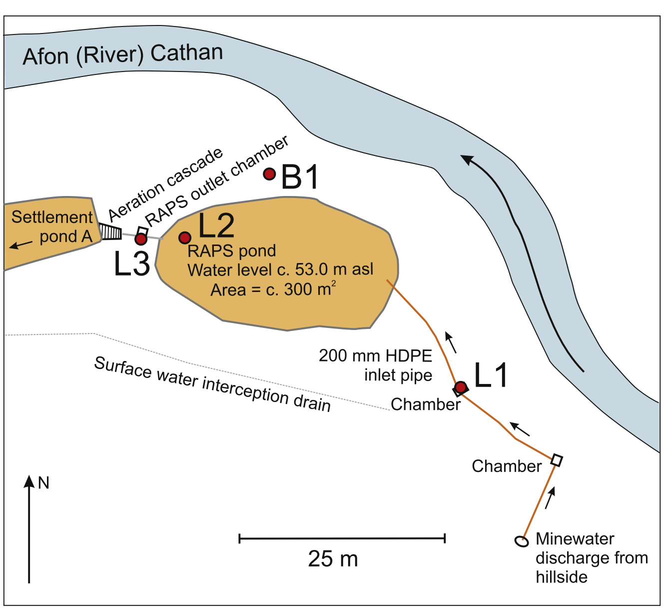

Fig. 1. Outline map of Tan-y-Garn mine water treatment system showing logger locations L1–L3 and B1. Tracer injection at L1. HDPE = high density polyethylene. Based on maps in Atkins (2006).

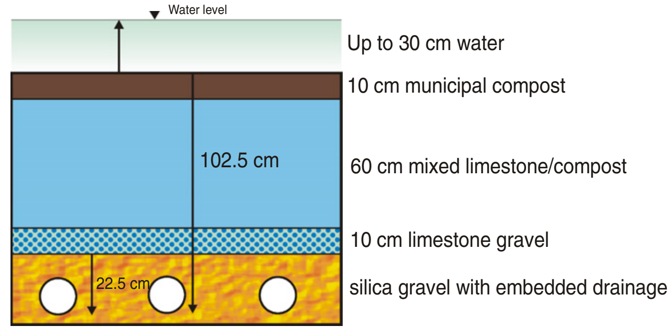

Fig. 2. Schematic cross-section through the Tan-y-Garn RAPS system.

dependent on flow rate, however: low flows can cause portions of the lagoon surface to dry out.

The outflow pipe is flexible and the level of its mouth can be adjusted. Thus, the head difference across the RAPS can be manipulated. The supernatant water level in the RAPS depends on the head gradient (the controlled level of the outflow pipe), the hydraulic permeability of the RAPS media and the flow entering the system.

2. Methods and materials

2.1. Objective

Tracer tests have previously been successfully used to elucidate hydraulic conditions and modal and mean residence times in mine systems and RAPS (Aldous and Smart, 1988; Diaz-Goebes and Younger, 2004; Wolkersdorfer, 2002, 2008; Wolkersdorfer et al. 2005, in press; Watson et al., 2009). With these aims in mind, a combined thermal and chemical (NaCl) tracer test was carried out on the 25th of June 2008 (Taylor, 2008; Taylor et al., in press) at Tan-y-Garn. The thermal component of the tracer test was intended to demonstrate the retention and thermal retardation of the heat signal (chilled water) in a geological medium (similar to an artificial wetland) under controlled conditions, and to compare the breakthrough of the heat signal with that of a conservative tracer (common salt, NaCl). The retardation of heat in geological media is a widely recognised phenomenon (Banks, 2012), but is not frequently documented in large-scale empirical experiments (but see Luhmann et al., 2012; Vandenbohede and Van Houtte, 2012, for example). A further by-product of the research was an evaluation of whether monitoring the temperature of RAPS effluent water might provide a low cost substitute for chemical tracer tests, in the context of assessing RAPS performance.

2.2. Combined tracer test: June 2008

The combined sodium chloride and thermal tracer test started at 13:10 on the 25th of June 2008,

Prior to the test, the untreated influent mine water had a temperature of 10.8 to 10.9 °C and an electrical conductivity of 460 µS/cm. The coal mine system and overlying rocks have a huge thermal inertia which evens out any diurnal or seasonal temperature fluctuations. Thus, the mine water temperature reflects a constant deep subsurface temperature (which in turn is largely controlled by annual average air temperature). The effluent water from the RAPS had, prior to the test, an electrical conductivity of 650 µS/cm and a temperature of 14.1 to 14.2 °C. The RAPS is only 1 m thick, but it still has a substantial thermal inertia and exhibits effluent temperatures that reflect the average air and RAPS supernatant water temperatures (Fig. 3) during the previous few days and weeks (warm in summer). In Wales as a whole, the average air temperature in June and July 2008 was 12.8 °C and 15.1 °C, respectively (Meteorological Office, 2016).

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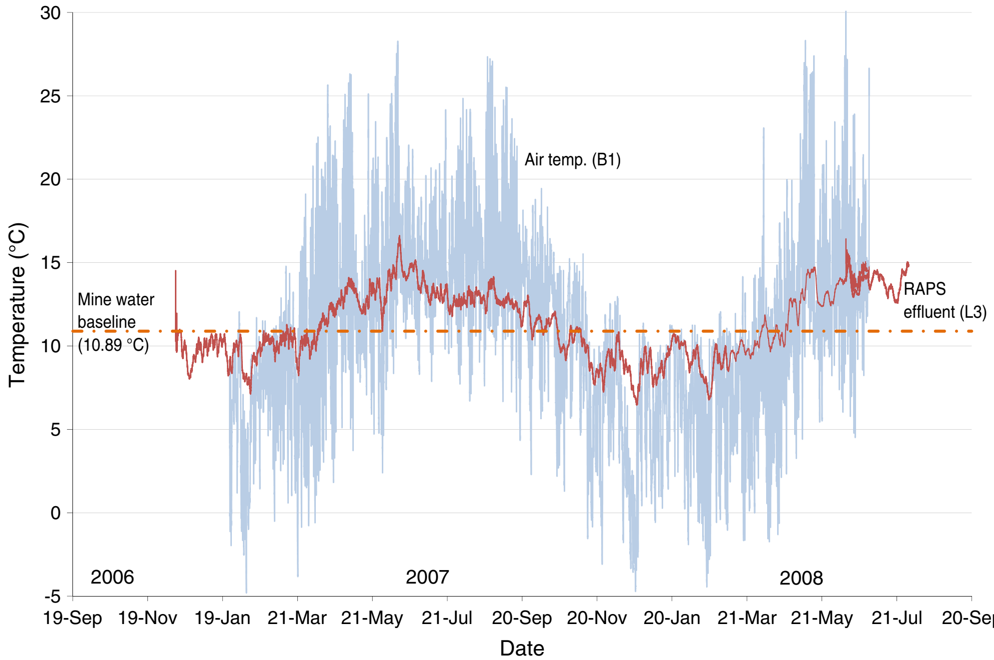

Fig. 3. Plot of long term air temperature (pale trace) and RAPS effluent water temperature (bold trace) corresponding to location L3 on Fig. 1) at the Tan-y-Garn site. Data provided by UK Coal Authority.

At the time of the test, the flow rate through the RAPS was lower than the typical flow rate (cited above as around 2 L s^{-1}), reflecting the low recharge to the mine system during summer. During the 72 h period following the commencement of the tracer test, the flow varied between extremes of 0.62 and 1.13 L s^{-1}, with an arithmetic mean of 0.87 L s^{-1}, a standard deviation of 0.09 L s^{-1}, but with no systematic increasing or decreasing trend.

For the test, an empty 200 L drum was placed adjacent to the access chamber L1 (Fig. 1) down-gradient from the mine entrance from which the water emerges. 15 kg of sodium chloride (common salt) and 100 kg of crushed water ice were initially placed in the drum. From upstream of a temporary impoundment in the chamber, around 0.65 L s^{-1} of the mine water flow were pumped into the drum, which was stirred manually, dissolving the NaCl rapidly and gradually melting the ice (Fig. 4).

When the drum was full, after some 300 s, the cold saline water from the drum was allowed to overflow via a hose back to the access chamber, downstream of the impoundment, re-joining the total mine water flux (to result in the narrow spike in electrical conductivity at L1 — Fig. 5b). Over the course of the next 35 min, a further 100 kg ice was added to the drum and melted into the mine water flux, with the drum continuously overflowing through the discharge hose back to the mine water flux in the access chamber. The thermal tracer input pulse ceased at 14:20 (by which time all the ice had melted and been discharged), implying a discharge of 70 min (4200 s) duration. The temperature of the ice, having been delivered by an ice wholesaler as sacks of ice fragments, could not be representatively measured with the resources available during the experiment. Fortunately, as will be seen in Eq. (1) below, the magnitude of the heat sink that the ice represents is dominated by the latent heat of fusion of the ice, rather than its sensible heat, and is thus not highly sensitive to the ice temperature. If it is assumed that the mass of the ice is negligible, relative to the mine water volume to which it is added, the ice can be regarded as a heat sink (source of cooling) of magnitude H, relative to a baseline temperature of 10.89 °C (the ambient mine water temperature), where.

$$H = M_{\text{ice}} \times ([T_{\text{melt}} - T_{\text{ice}}] \times c_{\text{ice}} + [T_{\text{basline}} - T_{melt}] \times c_{\text{water}} + L) \qquad (1)$$

where

- c_{ice} specific heat capacity of ice = 2.05 kJ kg^{-1} K^{-1} (Rauf, 2012);
- c_{water} specific heat capacity of water = 4.2 kJ kg^{-1} K^{-1} (Incropera et al., 2007);
- M_{ice} mass of ice added = 200 kg;
- L latent heat of fusion of water = 334 kJ kg^{-1} (Rauf, 2012);
- T_{baseline} baseline temperature = ambient mine water temperature = 10.89 °C;
- T_{ice} the initial temperature of the ice, which is unknown (°C);
- T_{melt} melting temperature of ice (0 °C).

If it is assumed that $T_{\text{ice}} = -5\ (\pm 2)$ °C (the result is not highly sensitive to this assumption), then the ice addition represents $200 \times (2.05 \times 5 + 379.7)$ kJ = c. 78 (±1) MJ of "coolth". Over the 70 minute course of the tracer injection, this 78 MJ represents an average thermal cooling power of 78 MJ/4200 s = 18.6 kW.

The test was monitored by four electronic loggers (Schlumberger Water Services Diver® type) installed at the site (Fig. 1) at the following locations:

- B1 in the open air adjacent to the RAPS, measuring ambient air temperature and barometric pressure (Baro-Diver®). The readings from diver B1 were used to compensate divers L1 to L3 for atmospheric pressure.
- L1 in the "inflow chamber" receiving mine water from the mine entrance, recording water level and influent water temperature and electrical conductivity (CTD-Diver®).
- L2 in the RAPS supernatant water, measuring water level and water temperature (Mini-Diver®), located near the downstream end for reasons of access).
- L3 in the RAPS effluent chamber, measuring water level, water temperature and electrical conductivity (CTD-Diver®). A c.30° v-notch weir was installed in the chamber, allowing flows to be calculated from water levels at L3, using a conversion algorithm provided by the Coal Authority. Manual readings were taken at the weir board at regular intervals to confirm logged data.

No density compensation was made to divers L1 to L3 as the electrical conductivity at the NaCl tracer peak in the RAPS effluent only

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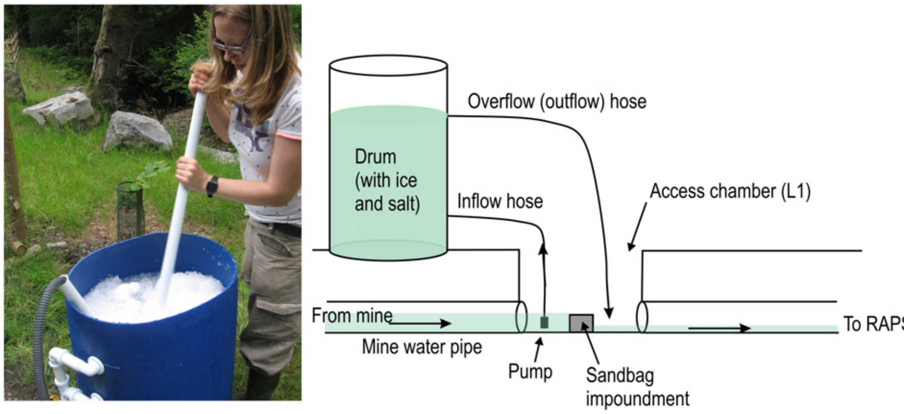

Fig. 4. Schematic diagram and photograph of the drum in which ice was melted and salt dissolved before being added to the mine water flow.

reached 750 μS cm^{-1} and the total variation over the course of the test was only 100 μS cm^{-1} (Fig. 5b).

3. Results

3.1. Thermal tracer test

Fig. 5a shows the temperature spike in the influent water at L1 during the introduction of the cold water to the access chamber. The average influent water temperature (T_{inf}) during the tracer injection was 7.06 °C. Given a flow rate (Q) of 0.87 L s^{-1}, a tracer pulse duration (t_{pulse}) of 70 min. (4200 s) and a baseline ($T_{baseline}$) of 10.89 °C, this equates to a thermal pulse (H) of:

$$H = (T_{\text{baseline}} - T_{\text{inf}}) \times Q \times t_{\text{pulse}} \times C_{\text{water}} \\ = 3.83\ ^\circ\text{C} \times 0.87\ \text{L s}^{-1} \times 4200\ \text{s} \times 4.2\ \text{kJ L}^{-1}\ \text{K}^{-1} = 59\ \text{MJ} \tag{2}$$

where C_{water} is the volumetric heat capacity of water = 4.2 kJ L^{-1} K^{-1} (Incropera et al., 2007).

This value of H is 24% less than that calculated from the volume of ice in Eq. (1), but may reflect heat gains between the mixing drum and the monitoring chamber, or uncertainties in the added mass of ice or in the flow rate (which was logged at a weir at the RAPS outflow at L3, not at the inflow; the Coal Authority estimate an uncertainty in flow determination of 10–20% — Taylor, 2008).

Otherwise, the temperature of the mine water inflow (L1) is typically constant at between 10.8 and 10.9 °C, with only a few discrete upward deviations, corresponding to downward deviations in electrical conductivity (Fig. 5b), presumed to represent short rainfall episodes (marked "R" on the figures), resulting in entry of surface run-off to the mine water. Indeed, the UK Coal Authority report that Chamber L1 receives some input of rainfall runoff draining from a small area of hard standing; and there is no substantial delay between the onset of rain at site, and the observed temperature and conductivity deviations.

The air temperature (Logger B1) displays the expected diurnal variation, typically dipping below 13 °C at night (and down to 8.4 °C on one occasion) and reaching over 21 °C during the day. This variation is reflected in Logger L2, installed in the supernatant water of the RAPS, albeit with a time lag of typically approximately 3 h. The L2 temperature typically exceeds air temperature during the day, presumably due to direct absorbance of solar radiation in the lagoon.

The effluent water temperature from the RAPS was relatively constant during the tracer test (Fig. 5a) at around 14 °C, albeit with some low amplitude fluctuations (range 13.4 to 14.5 °C), implying that the bulk of the RAPS is thermally buffered from diurnal variations in atmospheric temperature (indeed, it has long been recognised that diurnal temperature fluctuations only penetrate a few tens of cm by pure conduction into most geological media, as compared to seasonal fluctuations in temperature, which typically penetrate several m - Forbes, 1846; Thomson, 1859; Banks, 2012). The RAPS acts as a thermal "accumulator" or "capacitor" - it stores heat from the atmosphere and the downward seepage of warmed lagoon water during summer days and releases it to the slightly cooler influent water (see record for L2 in Fig. 5a) at night. The overall effect is that the effluent is largely buffered from diurnal temperature variations (Fig. 3) and that the effluent is some 3 °C warmer than the original mine water temperature (L1), reflecting the average influent water and atmospheric temperatures to which the RAPS has been exposed over the previous few days.

While the attempted ice-water tracer test can be seen in the inflow water (L1 on Fig. 5a), its signal coincides with the midday solar input of heat to the RAPS supernatant water pond. The solar input thus overwhelms the applied temperature signal and it cannot be distinguished in logger L2 (supernatant water), let alone the RAPS effluent at L3. The thermal portion of the tracer test itself was unsuccessful, but is documented here, so that subsequent researchers will recognise the need to apply far larger thermal signals to such systems. Additionally, it might be wise to carry out such tests during periods of more stable temperature (e.g. cloudy conditions, evening-time).

The saline tracer signal emerged from the base of the RAPS with an injection-to-peak concentration travel time of 23 h. The chemical tracer test has been interpreted by Taylor et al. (in press), who found that a simple 1-D advection-dispersion model was adequate to simulate the initial tracer breakthrough, but not the long "tail" of the signal. They found that the addition of two further components were necessary for a good match between real and modelled concentrations: (i) matrix diffusion processes, according to a model by Diaz-Goebes and Younger (2004); (ii) a mixing-tank model to simulate the progressive dilution and exponential decay of the salt concentration in the supernatant water entering the top surface of the RAPS. Taylor et al. (in press) found that mixing processes in the supernatant water would tend to result in an apparent delay in the emergent salt concentrations, and that the mean RAPS vertical transit time of the mobile pore water and associated conservative tracer, is likely to be somewhat less, at 17 h.

3.2. Diurnal temperature signals

In contrast to the first day of the tracer test, the 2nd and 3rd days after the tracer test (t = 18 to 66 h) are rather cool, with daytime temperatures not exceeding 15 °C (Fig. 5a — Logger B1). This results in a low temperature signal (t = 12 to 70 h) in the supernatant water entering the top of the RAPS. It is noted that a very subdued low temperature output signal emerges from the RAPS at in the period t = 55 to 120 h. If the output signal is related to the low-temperature surface signal this might suggest a thermal travel time or signal "time lag" of some 40 to 50 h through the RAPS. Additionally, the temperature data from L2 and L3 were compared for the period 20th June to 30th June 2008, and the

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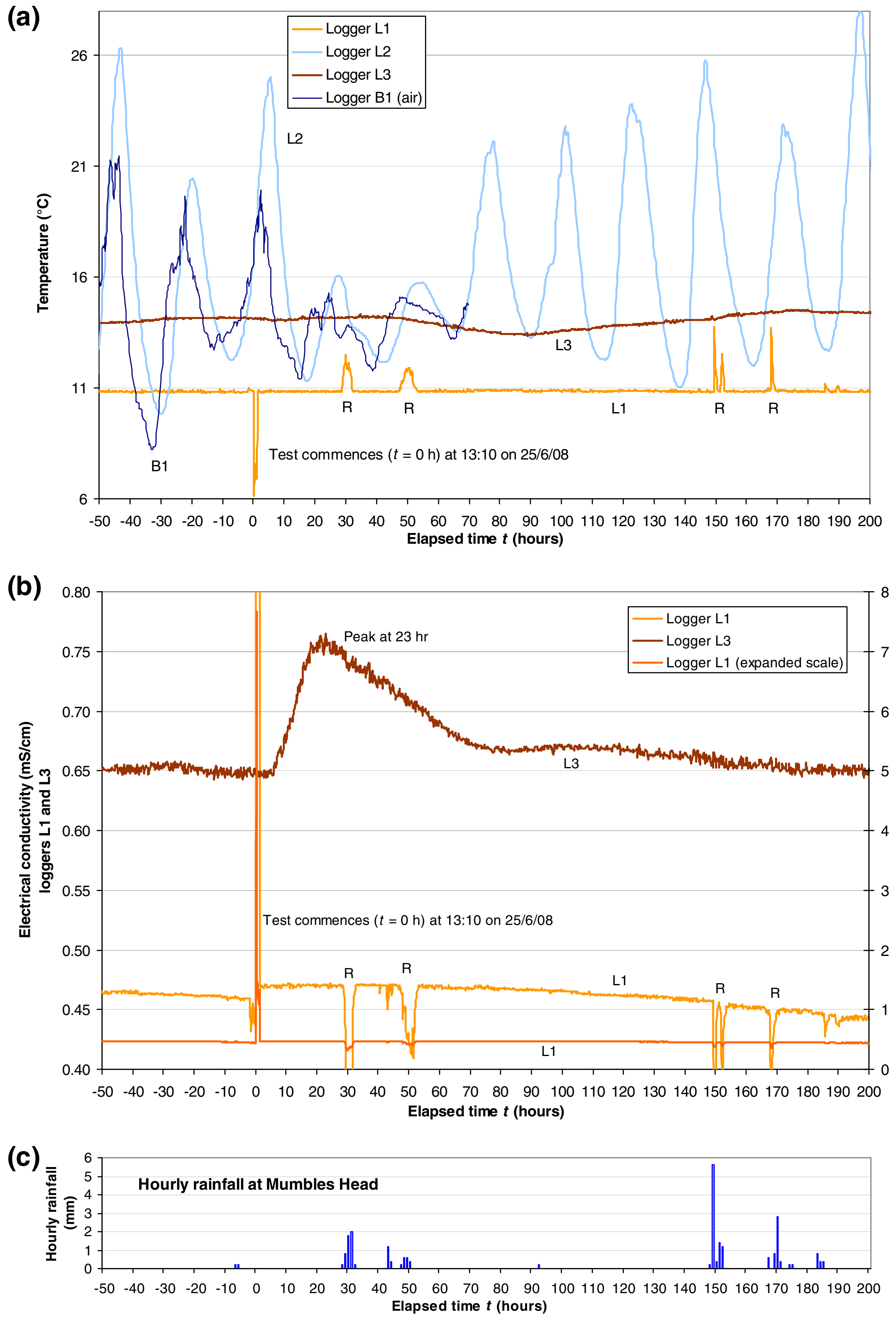
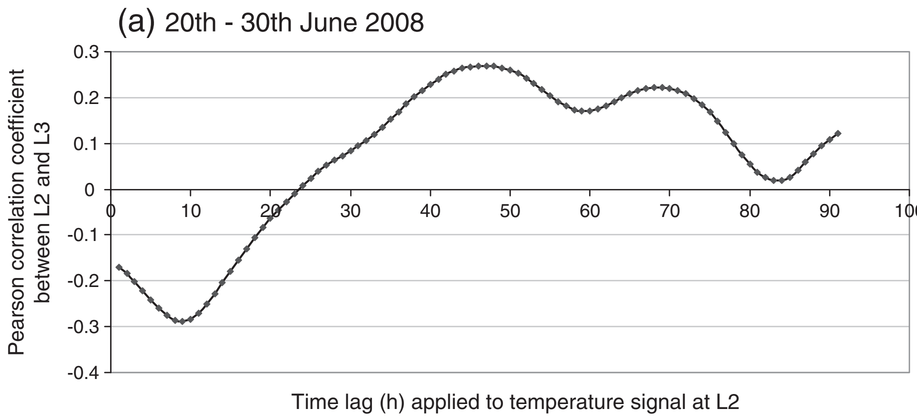


Fig. 5. (a) Temperature and (b) electrical conductivity measurements during tracer test of June 2008 (conductivity uncorrected for temperature). Tracer injection at $t = 0$ h. R denotes rainfall events diluting the mine water. (c) Hourly rainfall measurements for Mumbles Head meteorological station (OSGB36 Grid reference SS 627870, approximately 23 km due south of Tan-y-Garn).

Pearson correlation coefficient calculated for different applied time delays to L2 (Fig. 6). The maximum correlation occurred at a time lag of 47 h, confirming the visual evaluation.

To further confirm this hypothesis, historic monitoring data were re-examined, in order to identify air temperature signals that were clearly reflected, with a time delay, in the RAPS effluent water. As can be seen, diurnal temperature signals were being transmitted, via water advection, through the RAPS (Fig. 7).

For more detailed analysis, the period of February 2007 is presented, as flow data were also available for this period (Fig. 8). Individual



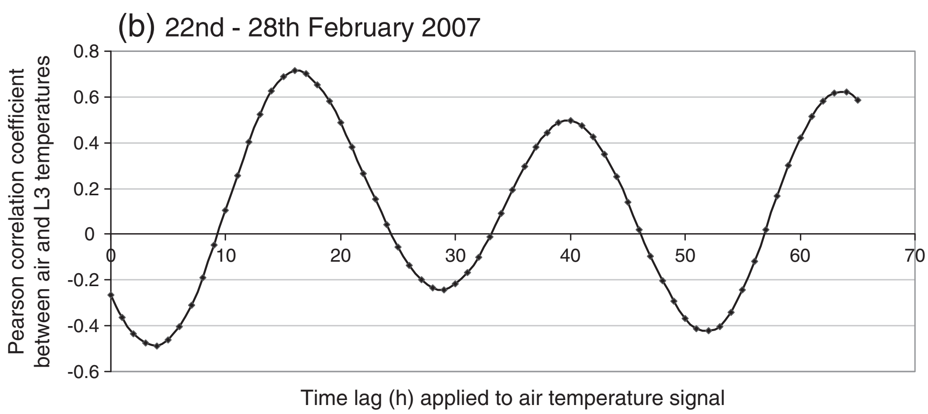


Fig. 6. Pearson correlation coefficient between RAPS effluent temperature and air (Feb. 2007) or RAPS supernatant (L2 — June 2008) temperature, with varying time delays applied to L2/air temperature. For the period 20th–30th June 2008, a time lag of 47 h applied to L2 gave the best correlation. For data from the last week in February 2007, the correlations were much improved, with the maximum correlation occurring at 16 h.

characteristic peaks and troughs were selected visually and lag times identified. This visual analysis was verified by correlation analysis of the time lags for each week of the month (e.g., Fig. 6b — which indicates a typical time lag of around 16 h in the last week of February 2007).

In the February 2007 data, the RAPS effluent temperature was in the range 7 to 11 °C (cooler than the original mine water discharge).

Eight characteristic diurnal temperature maxima or minima (a–h) were identified in both the air and RAPS effluent temperatures (Fig. 8), where the thermal time lag varied from 14 to 21 h. Additionally, using statistic correlation of the time series, the average time lags resulting in optimal statistical correlation were also calculated for each week of February 2007 (Fig. 6b and Table 1), and these ranged from 16 to 22 h.

Fourier analysis has been applied to the apparently diurnal signals in the RAPS effluent to verify that no cyclical fluctuations at other frequencies are apparent. The results simply demonstrated that the diurnal signal was the only identifiable signal in the data.

3.3. Transmission of diurnal temperature signals — advection or conduction?

It is reasonable to query whether we can be sure that the diurnal temperature signals are being transmitted primarily by advection, or whether they can be explained purely by conductive heat transfer through the RAPS medium.

If the transport of heat is dominated by advection, one should observe that the apparent thermal velocity is related to water throughflow rate in the RAPS. Indeed, from Table 1, the shorter time lags were observed towards the end of February 2007, when flows were higher, than at the start of the month. Furthermore, the time lags in February 2007 were much shorter than that observed for the June 2008 data (47 h), and this relates to a much larger winter mine water throughflow in February.

Secondly, one can apply Eq. (3), cited by Williams and Gold (1976), for cyclical diffusion of a temperature signal by thermal conduction only:

$$T(z,t) = \overline{T} + A.\exp\left(-z\sqrt{\frac{\pi}{\alpha t_o}}\right)\cos\left(\frac{2\pi t}{t_o} - z\sqrt{\frac{\pi}{\alpha t_o}}\right) \tag{3}$$

where

t	time (s)
t_0	period for one complete cycle (s)
z	depth (m)
α	thermal diffusivity of medium ($m^2\ s^{-1}$)
A	amplitude of temperature signal at surface ($z = 0$) (K)
$\overline{T}$	mean temperature at surface ($z = 0$) (K)
$T(z,t)$	temperature at depth z at time t (K).

Application of this equation demonstrates that a diurnal input signal of peak-to-peak amplitude 12 °C (which is typical of the examples in Figs. 5, 7 and 8), in a medium of thermal diffusivity $7.8 \times 10^{-7}\ m^2\ s^{-1}$ (representing a typical, water-saturated geological medium of thermal conductivity 1.8 W m^{-1} K^{-1} and volumetric heat capacity 2.3 MJ m^{-3} K^{-1} — see Banks, 2012), would result in a peak-to-peak temperature amplitude of only 0.05 °C at 0.8 m depth and 0.01 °C at 1 m depth. In the RAPS effluent, amplitudes of at least 0.5 °C are common, which is therefore too large to be accounted for purely by conduction.

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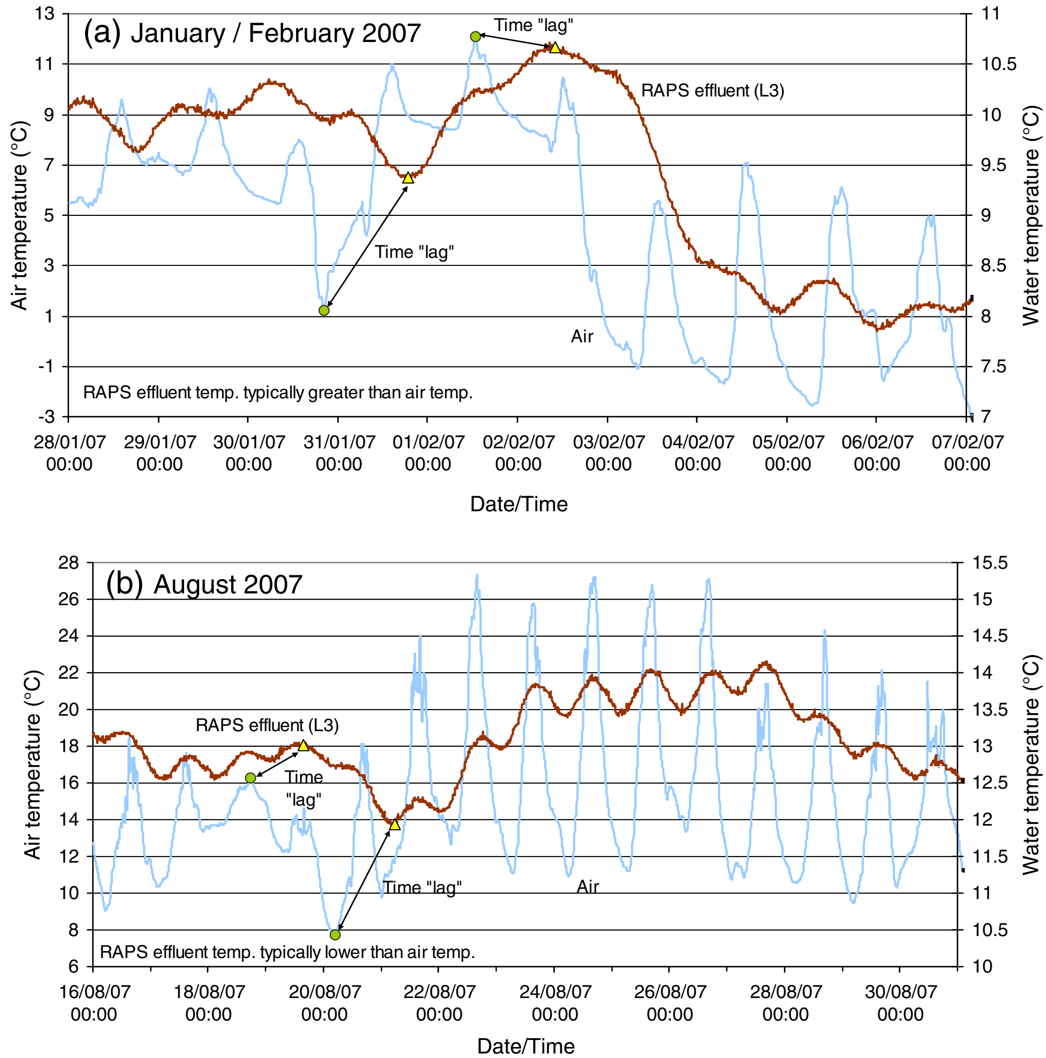

Fig. 7. Selected air (pale trace) and RAPS effluent water (dark trace) temperature data from Tan-y-Garn RAPS. "Time lag" refers to the delay between a characteristic peak or trough in the air temperature signal, and the same feature in the RAPS effluent water (L3).

It is thus concluded that advection is the primary mechanism responsible for transmitting the diurnal temperature signals to the RAPS effluent water.

3.4. Analysis of thermal retardation

Thermal signals are retarded in porous media (De Marsily, 1986; Banks, 2012), relative to hydraulic transport or transport of conservative solutes. This retardation is expressed by a dimensionless *thermal retardation factor* R_{th}, (defined as the ratio between the linear travel time (t_{th}) for a heat signal relative to the mean linear hydraulic travel time (t_{hyd}) for a representative water molecule or conservative tracer — see Bodvarsson, 1972; Banks, 2012) where.

$$R_{th} = \frac{t_{th}}{t_{hyd}} = \frac{v}{v_{th}} = \frac{v_D}{n_e v_{th}} = \frac{C_{vaq}}{n_e C_{vwat}} \quad \text{thus} \quad C_{vaq} = R_{th} n_e C_{vwat} \tag{4}$$

or

$$C_{vaq} = \frac{C_{vwat} v_D}{v_{th}} \tag{5}$$

and where

- v_D = mean Darcy (filtration) flux of water (m s^{-1})
- v = mean intergranular flow velocity of water (m s^{-1})
- v_{th} = apparent thermal velocity (m s^{-1})
- C_{vwat} = volumetric heat capacity of water = 4.2×10^6 J m^{-3} K^{-1}
- C_{vaq} = volumetric heat capacity of saturated aquifer (RAPS) material (J m^{-3} K^{-1}) (common values for heat capacity are shown in Table 2)
- n_e = effective porosity of saturated aquifer (RAPS) = c. 0.25 to 0.32 (derived from this and previous tracer tests, as documented by Taylor et al., in press).

If the thermal retardation result from June 2008 is used (i.e. $t_{\mathrm{th}} = 40$ to 50 h), and the RAPS thickness is assumed to be 1 m, then:

- v_{th} = 1 m/40 or 50 h = 0.48 to 0.60 m d^{-1};
- v_D = 0.87 L s^{-1}/280 m^2 = 75.2 m^3 d^{-1}/280 m^2 = 0.269 m d^{-1};

then R_{th} can be estimated (Eq. (4)) as the ratio between thermal and hydraulic travel time ($t_{\mathrm{th}}/t_{\mathrm{hyd}}$). If we use the uncorrected dominant (modal) hydraulic travel time (t_{hyd}) of 23 h as a first approximation of the mean travel time, we can calculate that R_{th} = 1.74 to 2.17. If the mean travel time of t_{hyd} = 17 h, corrected for lagoon mixing effects (Taylor et al., in press) is applied, then R_{th} = 2.35 to 2.94. These values of R_{th} allow us to relate the travel time for a thermal signal to a hydraulic travel time,

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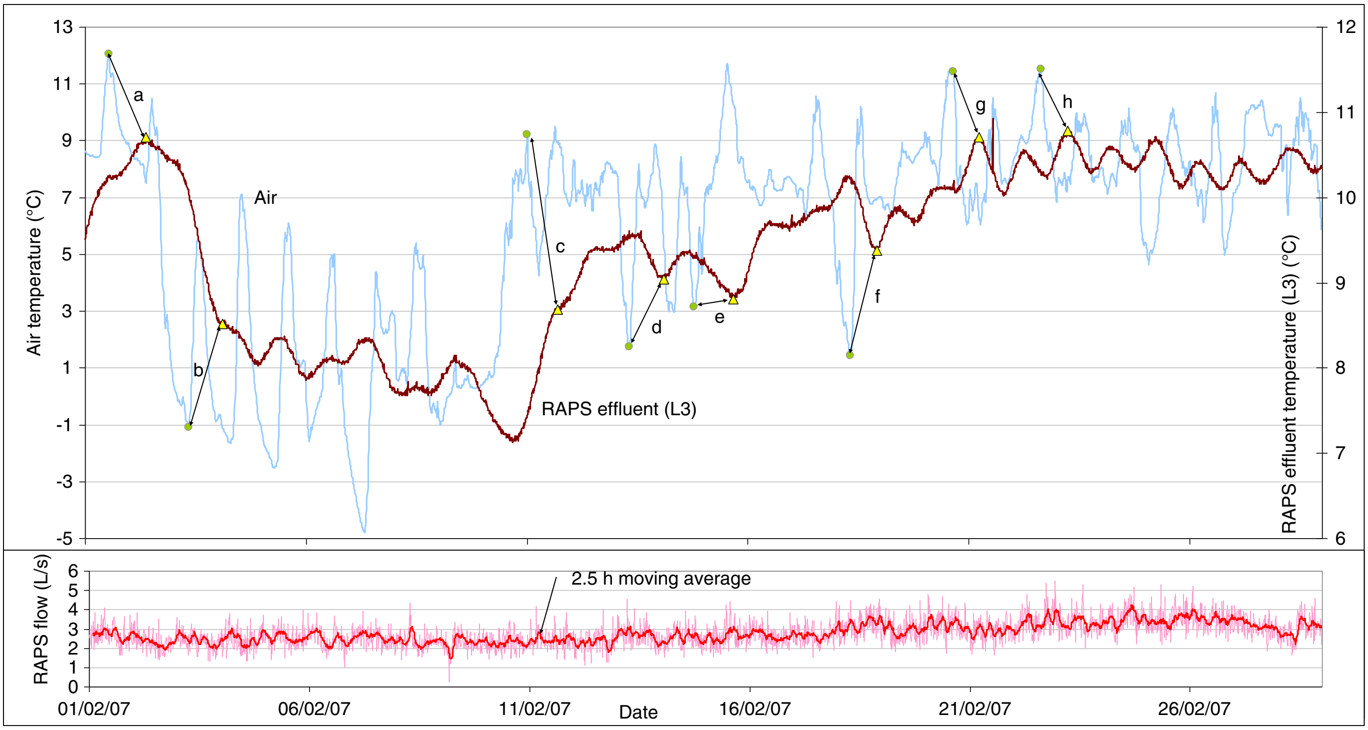

Fig. 8. (top) Air temperature and RAPS effluent temperature in February 2007; (bottom) RAPS effluent flow rate in L s^{-1} every 0.25 h, with a 2.5 h moving average (darker trace). RAPS effluent rate and temperature measured at location L3. "a" to "h" represent identified delayed characteristic temperature features listed in Table 1. Modified after Taylor (2008).

which has practical implications for managers of RAPS systems. Eq. (5) allows us to estimate the C_{vaq} of the RAPS (without needing to know v, the intergranular flow velocity) as 1.8 to 2.4 MJ m^{-3} K^{-1}.

Similar calculations can be applied to the thermal retardations from February 2007 (Fig. 8). Table 1 shows the calculated volumetric heat capacity of the RAPS medium, from Eq. (5). There is a large variation in the calculated values, from 2.2 to 3.1 MJ m^{-3} K^{-1}, but the averages of approximately 2.5 to 2.9 MJ m^{-3} K^{-1} coincide well with expected values (Table 1) for a medium with a high saturated porosity (water content).

One could argue that as, for February 2007, the correlation is between air temperature with RAPS effluent temperature (i.e. B1 with L3), rather than between supernatant water with RAPS effluent temperature (i.e. L2 with L3), the thermal travel time should be reduced by c. 3 h to account for the lag between B1 and L2 observed in June 2008 (Fig. 5). Regrettably, as L2 was only installed for the duration of the tracer test in June 2008, it is not possible to know whether this 3 h lag is observed throughout the year. If t_{th} is reduced by 3 h, however, the range in calculated C_{vaq} reduces to 1.8 to 2.6 MJ m^{-3} K^{-1} with averages (from the visual and statistical analysis methods) of 2.1 to 2.4 MJ m^{-3} K^{-1} (Table 1).

4. Discussion — implications for RAPS design

It is important to understand the modal and mean residence times of water being treated in a RAPS unit in order to assess the system's performance against design criteria. This would allow the improvement of future designs, e.g. by optimising the design residence time (Kusin et al., 2012; Kusin, 2013). RAPS operators need to understand how residence

Table 1
Thermal time lag (t_{th}) through the RAPS system in February 2007 with corresponding calculated bulk volumetric heat capacities C_{vaq} of the saturated RAPS material. The top half of the table shows the time-lags derived from visually recognisable characteristic peaks and troughs in Fig. 8 (labelled a–h). The lower half of the table shows the time lags resulting in maximum statistical correlation for each week of data in February (as illustrated in Fig. 6). The final column marked C^*_{vaq} shows volumetric heat capacities where the thermal travel time has been reduced by 3 h to account for a temperature response lag between the atmospheric temperature and the supernatant water.

Characteristic signal (Fig. 8)	t_{th} hrs	RAPS flow L s^{-1}	v_D m d^{-1}	v_{th} m d^{-1}	C_{vaq} MJ m^{-3} K^{-1}	C^*_{vaq} MJ m^{-3} K^{-1}
a	19.75	2.56	0.79	1.22	2.73	2.32
b	18.25	2.33	0.72	1.32	2.30	1.92
c	16.5	2.43	0.75	1.45	2.16	1.77
d	18.75	2.54	0.78	1.28	2.57	2.16
e	21	2.56	0.79	1.14	2.90	2.48
f	14.25	3.24	1.00	1.68	2.50	1.97
g	14	3.01	0.93	1.71	2.27	1.79
h	14.25	3.46	1.07	1.68	2.66	2.10
Average	17.09	2.77	0.85	1.44	2.51	2.06
1st–7th Feb	20	2.49	0.77	1.20	2.69	2.29
8th–14th Feb	22	2.41	0.74	1.09	2.86	2.47
15th–21st Feb	20	2.88	0.89	1.20	3.11	2.64
22nd–28th Feb	16	3.32	1.02	1.50	2.87	2.33
Average	19.5	2.78	0.86	1.25	2.88	2.43

Table 2
Volumetric heat capacities of common geological materials, modified from Banks (2012).

Medium	Volumetric heat capacity MJ m^{-3} K^{-1}
Saturated silica gravel	2.2 to 2.9
Limestone	1.9 to 2.4
Peat	0.5 (presumed dry) to 3.8
Pure calcite	2.24
Water	4.18

time varies with varying flow rates. Taylor et al. (in press) have shown that the Tan-y-Garn RAPS exhibits a predictable pattern, with modal residence times decreasing proportionately to increasing flows. During the operational lifetime of the RAPS, there is a possibility that preferential flow pathways through the RAPS matrix could develop. One way of monitoring for this could be to repeat chemical tracer tests, and compare against the early-life correlation of residence time versus flow rate. This would provide a means of gaining confidence that residence times, and therefore treatment performance, are not decreasing to an undesirable extent. However, the work done in this study suggests that an even more straightforward method to monitor the ongoing residence time could be to record influent and effluent temperatures. Monitoring of diurnal temperature changes has been shown here to allow the identification of peaks passing through the system, or to allow correlation of influent and effluent signals, and the lag time can then provide an approximate estimation of the residence time. For example, in practice, a thermal retardation factor of approximately 2.5 could be assumed, in which case the estimated residence time would be somewhat less than half the observed lag time between temperature peaks across the system being evaluated.

Using the method of collecting and analysing time series of temperature data would quickly result in a large database of residence times for a full range of flow rates experienced. In turn, this could give designers confidence to propose designs with shorter residence times (currently it is commonly assumed that a hydraulic residence time of approximately 14 h is needed in a RAPS (PIRAMID Consortium, 2003)).

Wider applications include similar compost-based throughflow systems (e.g. anaerobic compost wetlands) where sulphate reduction is encouraged in order to precipitate and immobilise metals as sulphides. Thermal tracing methods might also be applied in other passive water treatment systems, which rely on water having a certain residence time, in any type of treatment media, and where such systems are exposed to diurnal temperature changes.

5. Conclusion

A thermal tracing test has been attempted in a RAPS at Tan-y-Garn, Wales, by the application of iced water as a thermal signal. This test failed as the applied signal was too small in comparison with the temperature variations due to heat influx from solar radiation at the time of the test. However, natural diurnal temperature signals were detected in the effluent water from the RAPS, with an apparent time lag relative to the supernatant water entering the top of the RAPS. The travel time for the thermal signal was at least twice as long as the mean hydraulic residence time, and the various estimates of the volumetric heat capacity of the RAPS medium fall between 2 and 3 MJ m^{-3} K^{-1}. These estimates are in line with what might be expected for a water saturated geological medium of high porosity (Table 2).

Further research on this and other RAPS should attempt to confirm the existence of a clear relationship between the travel time for natural temperature signals and the dominant (modal) and/or mean hydraulic travel times deduced from tracer tests. The observation of the temperature of RAPS effluent water might provide a low cost substitute for chemical tracer tests, in the context of monitoring RAPS performance.

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