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ORIGINAL ARTICLE

A combined pumping test and heat extraction/recirculation trial in an abandoned haematite ore mine shaft, Egremont, Cumbria, UK

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Abstract A pumping test at rates of up to 50 L s^{-1} was carried out in the 256 m-deep Florence Shaft of the Beckermet–Winscales–Florence haematite ore mine in Cumbria, UK, between 8th January and 25th March 2015. Drawdowns in mine water level did not exceed 4 m and the entire interconnected mine complex behaved as a single reservoir. Pumping did, however, induce drawdowns of around 1 m in the St. Bees Sandstone aquifer overlying the Carboniferous Limestone host rock. During a second phase of the pumping test, a proportion of the 11.3–12 °C mine water was directed through a heat pump, which extracted up to 103 kW heat from the water and recirculated it back to the top of the shaft. Provided that an issue with elevated arsenic concentrations (20–30 μg L^{-1}) can be resolved, the Florence mine could provide not only a valuable resource of high-quality water for industrial or even potable uses, it could also provide several hundred to several thousand kW of ground sourced heating and/or cooling, if a suitable demand can be identified. The ultimate constraint would be potential hydraulic impacts on the overlying St Bees Sandstone aquifer. The practice of recirculating thermally spent water in the Florence Shaft produced only a rather modest additional thermal benefit.

Keywords Haematite iron ore · Heat pump · Geothermal energy · Mine shaft · Mine water · Arsenic

Introduction

It is well established that heat (for space heating or cooling, domestic hot water, or industrial processes) can be extracted from or rejected to a flow of groundwater via the use of a heat pump. The use of groundwater for this purpose is advantageous, because its temperature is usually constant throughout the year, at a level slightly above the annual average air temperature (for shallow groundwater), and typically increasing at a rate of 1–3 °C per 100 m depth (Kavanaugh and Rafferty 1997; Banks 2012). Groundwater is thus usually significantly warmer than outdoor air in winter and significantly cooler in summer (making it an ideal source of winter heating and summer cooling). The water contained in abandoned, flooded mines is usually, in origin, groundwater. However, the use of such mine water for heating and cooling offers a number of additional advantages:

- The workings and void space of the abandoned mine represent an enormous storage of water and heat. This can be seasonally manipulated to store warm water or cold water (Minewater Project 2008).
- The tunnels and workings of the mine represent high transmissivity flow pathways, which, if intercepted by a borehole or shaft, can sometimes yield many tens or hundreds of L s^{-1} of water.

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- The workings may already be accessible for pumping via the existing abandoned shafts (no drilling costs).
- Mine water is often regarded as a potentially costly environmental liability (Banks and Banks 2001; Bailey et al. 2016). Its use for low-carbon heating and cooling allows it to be transmuted into an environmental and economic asset.
- Many abandoned mine sites are ripe for redevelopment for commercial or residential purposes, with heating and cooling demands.

Mine water has been used for several decades for heating and cooling; reviews have been provided by Banks et al. (2003, 2004), Watzlaf and Ackman (2006), Hall et al. (2011), Preene and Younger (2014), Ramos et al. (2015), Bracke and Bussmann (2015) and Banks et al. (2017). Among a number of mine water, heat pump systems operating worldwide can be listed: Park Hills, Missouri, USA (Watzlaf and Ackman 2006; DOE 2015), Springhill, Nova Scotia, Canada (Jessop 1995; Jessop et al. 1995; Raymond et al. 2008), Marywood University, Pennsylvania, USA (Korb 2012), several in Saxony, Germany (Ramos et al. 2015), Henderson molybdenum mine, Empire, Colorado, USA (Watzlaf and Ackman 2006), Saturn coal mine, Czeladz, Poland (Malolepszy et al. 2005; Tokarz and Mucha 2013), and Novoshakhtinsk, Russia (Rostov Regional Government 2011; Ramos et al. 2015). At a MW (megawatt) scale, one can mention the hospital and university heating/cooling system sourced from Barredo coal mine shaft at Mieres, Asturias, northern Spain (Loredo et al. 2011; Ordóñez et al. 2012; Jardón et al. 2013; Banks 2017) and the Heerlen scheme, The Netherlands (Minewater Project 2008; Ferket et al. 2011; Verhoeven et al. 2014; Banks 2017).

In the UK, however, the few operational mine water heat pump schemes are either at a pilot stage or at a very modest scale (not exceeding several tens of kW thermal output): Shettleston, Glasgow, and Lumphinnans, Fife (Banks et al. 2009), Dawdon, County Durham (Watson 2012; Bailey et al. 2013), Caphouse mining museum, near Wakefield (Athresh et al. 2016; Burnside et al. 2016a; Banks et al. 2017) Markham, near Bolsover (Athresh et al. 2015; Burnside et al. 2016b; Banks et al. 2017), and Cefn Coed, Crynant, South Wales (Farr et al. 2016).

Modes of operation for mine water heat pump/exchange schemes

There are a number of modes in which heat can be exchanged with mine water. In a closed loop system, which will not be discussed further in this paper, a heat exchanger is submerged in the mine water. A heat transfer fluid is circulated between the heat pump and the submerged heat exchanger, which thus extracts heat from or rejects heat to the mine water.

In an open loop system, the mine water is abstracted (often pumped from a borehole or shaft) and is passed through a heat exchanger (which may, in turn, be thermally coupled to a heat pump). The amount of heat extracted ($\dot{H}$) is governed by the mine water yield (Q) and the temperature change at the heat exchanger (ΔT_{he}), as described by the following equation:

$$\dot{H} = Q \cdot \Delta T_{\mathrm{he}} \cdot \rho_{\mathrm{w}} \cdot c_{\mathrm{w}} \tag{1}$$

where $\dot{H}$ is the heat power available (J s^{-1} or W), ρ_{w} is the water's density (kg L^{-1}), c_{w} is the water's specific heat capacity (J kg^{-1} K^{-1}), Q is the water flow rate (L s^{-1}), and $\rho_{\mathrm{w}} \cdot c_{\mathrm{w}}$ is the water's volumetric heat capacity (= c. 4190 J L^{-1} K^{-1}).

Having passed through the heat pump/exchanger, the thermally spent water (i.e., cool water, if heat has been extracted) needs to be disposed of legally and sustainably. The water may simply be rejected to a surface water recipient (river or sea) if the quality is good enough (e.g., at Barredo coal mine shaft, Northern Spain—Loredo et al. 2011; Ordóñez et al. 2012; Jardón et al. 2013). Often, however, the water will require treatment (e.g., to remove iron, manganese, or acidity) prior to disposal to surface water, as at the pilot heat pump scheme at Caphouse colliery in Yorkshire, UK (Athresh et al. 2016; Burnside et al. 2016a). Alternatively, the treatment costs can be avoided by reinjecting the thermally spent water back to the mine system via another (sufficiently distant) shaft or borehole, or to a superjacent or subjacent aquifer unit. Examples of this type of scheme include Lumphinnans, Fife, and Shettleston, eastern Glasgow, Scotland (Banks et al. 2009). Reinjection is also practiced at Heerlen, The Netherlands (Minewater Project 2008; Ferket et al. 2011; Verhoeven et al. 2014). For reinjection to be sustainable, dissolved iron and manganese should remain in solution (in practice, this means avoiding exposure to oxygen); otherwise, reinjection wells can rapidly become clogged (Banks et al. 2009).

A final option is to reinject all or part of the thermally spent water back to the shaft from which it was abstracted. For example, if mine water is abstracted from near the base of the shaft, reinjected water can be returned to the top of the shaft. If sufficiently deep, the reinjected (cool) water will gradually reacquire heat from the warmer rocks in the walls of the shaft as it travels down the shaft to the pump. For a cool fluid circulating down a borehole or shaft of diameter r_{b}, a "thermal version" of the hydrogeologists' Thiem equation approximately applies (assuming that thermal resistance of heat transfer from the shaft walls to the shaft fluid is negligible):

$$\dot{q} = \frac{2\pi\lambda(\Delta T_{\text{fluid-rock}})}{\ln(r_0/r_b)}, \qquad (2)$$

where λ is the thermal conductivity of surrounding rock (W m^{-1} K^{-1}); $\dot{q}$ is the heat replenishment rate from the shaft walls (W m^{-1}); $\Delta T_{\text{fluid-rock}}$ is the mean temperature difference between water in shaft and ambient rock; r_0 is a somewhat hypothetical radius of thermal influence (i.e., the radial distance from the centre of the shaft at which the cooling of the rock is negligible). Loredo et al. (2017) suggest that r_0 may be of the order of a few tens of m after several decades.

Thus, for a host rock of $\lambda = 3$ W m^{-1} K^{-1}, where $r_0 =$ 10–50 m and a shaft where $r_b = 2$ m, the long-term heat replenishment rate from the shaft walls might be 6–11 W per vertical m per K temperature differential. Thus, for a 100 m shaft, the long-term thermal replenishment may be not more than 1 kW per K for a system operating continuously. For a short-term period of operation, the heat yield will be somewhat higher (if we assume $r_0 = 4$ m, the heat yield may be 27 W m^{-1} K^{-1}), but for typical temperature differentials of 3–5 K, the heat yield is unlikely to exceed several tens or maybe 100 W m^{-1}.

This type of arrangement is called a "standing column" system and has been described by Mikler (1993), Deng (2004), Deng et al. (2005), Orio et al. (2005), O'Neill et al. (2006), and Banks (2012). If all the abstracted water is returned to the shaft or borehole, the "bleed percentage" is said to be zero. This is the type of system operated at Markham Colliery No. 3 shaft near Bolsover, Derbyshire, UK (Athresh et al. 2015; Burnside et al. 2016b; Banks et al. 2017). If there is no natural advection of water up or down the shaft, the heat transfer rate will ultimately be constrained by the thermal conductivity of the rocks in the shaft walls (Eq. 2). If none of the abstracted water is returned to the shaft (i.e., it is disposed of elsewhere), the bleed percentage is 100% and the system is a fully open loop system whose heat yield is governed by the water yield (Eq. 1). In many standing column systems, it is common for a proportion of the water to be bled away (the bleed percentage *B*) and the remainder to be returned to the borehole or shaft. Heat is thus replenished by a combination of mine water advection and conduction through the host rocks.

Bleeding water from a standing column system effectively "forces" advection of fresh mine water (which also represents thermal replenishment) into the shaft. However, if there is natural water advection along the shaft, this also represents thermal replenishment, increasing the heat yield. In extreme cases, if the natural advection along the shaft is very large, the reinjected water may flow away from the shaft before returning to the pump, effectively becoming decoupled from the pumping horizon (Fig. 1b).

Florence and Beckermet mines

A combined pumping test and heat production/recirculation test was carried out on the water from Florence iron ore (haematite-Fe_2O_3) mine in Cumbria, Northern England (Fig. 2; see Smith 1924). The system was run both in "open loop" mode, with disposal of spent water to the nearby Little Mill stream, and also in "standing column" mode (Fig. 1), where a proportion of the pumped water was recirculated down the shaft.

Mining history

Beckermet mine's No. 1 shaft (Fig. 2; known as "Mildred pit") was sunk in 1903–06 and deepened to 419 m in 1915. Shaft No. 2 ("Winscales pit") was sunk in 1916–1918, reaching 380 m depth (M&QE 1954a, b; Steetley Minerals 2016). Production from the Beckermet shafts peaked in 1929 at 307,000 tons (312,000 tonnes) haematite per year.

Florence shaft is believed to have originally been a part of Ullbank mine. Ullbank No. 1 (sometimes later also referred to as Florence No. 1) shaft was sunk in 1914, while Ullbank No. 2, which subsequently became known as "Florence" (or Florence No. 2) shaft (Fig. 3), was sunk in 1945. To avoid confusion, the term "Florence shaft" as used in this paper refers to the second (1945) shaft. The two shafts were joined underground during the 1950s (Steetley Minerals 2016). The mines were also connected underground to the Ullcoats complex of mines to the northeast. Between 1968 and 1970, Florence mine was acquired by British Steel and was linked underground to Beckermet mine, several km to the south. Thereafter, ore was extracted via Beckermet shaft. British Steel closed the entire mine complex in 1980, but Florence mine was repurchased by a number of employees and run as the Egremont Mining Company until 2007–2008, when mining finally ceased (Shropshire Caving and Mining Club 2016).

Florence mine shaft is 13 ft (3.96 m) in diameter, is concrete-lined, is believed to be 842 ft (256 m) deep, and was worked from two different levels. The shallower "Lonely Hearts Level", at around sea level, accessed workings up–dip to the east–northeast and interconnected with Ullcoats No. 7 mine. At the base of the shaft, the "pit bottom haulage level" interconnected with Ullcoats No. 1 mine to the ENE and with the Beckermet mine complex (this being the connection made in 1969–1970) to the SSW (Fig. 3).

Geology and hydrogeology

The palaeozoic bedrock geological sequence dips to the south west. The haematite ore is predominantly hosted by

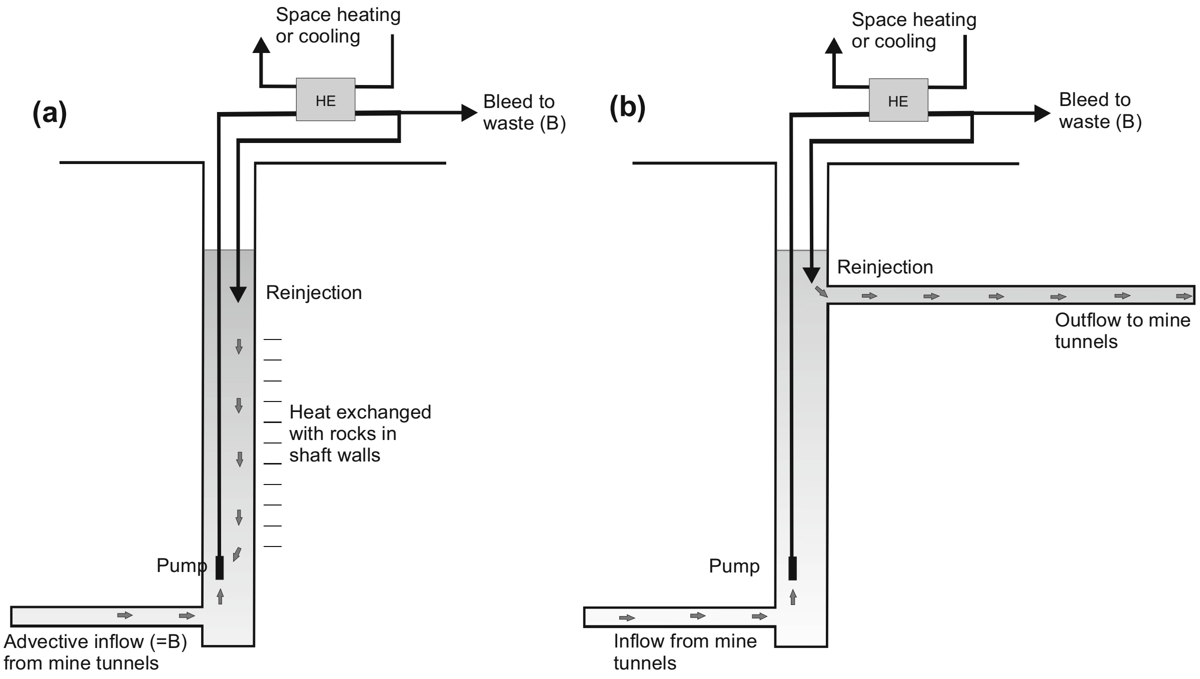

Fig. 1 **a** Standing column heat pump system in mine shaft with bleed (*B*) and recirculation in shaft, **b** standing column configuration, with large natural flow up shaft. *HE* heat exchanger or heat pump. Reproduced with permission of © David Banks

the Lower Carboniferous (Dinantian) Frizington Limestone Formation (a division of the Great Scar Limestone Group). The limestone unconformably overlies Lower Palaeozoic slates of the Skiddaw Group (at Florence and Ullcoats) or volcanics of the Borrowdale Volcanic Group (at Beckermet—M&QE 1954a). The limestone is unconformably overlain by the Permian-early Triassic Brockram Breccia (part of the Appleby Group), which is in turn overlain by the early Triassic St. Bees Sandstone (Fig. 3). The Brockram and St. Bees Sandstone are designated by the Environment Agency as regionally important Principal Aquifers (loosely referred to hereafter as the Sherwood Sandstone). The Carboniferous Limestone is designated a "Secondary A" aquifer (i.e., "capable of supporting water supplies at a local rather than strategic scale, and in some cases forming an important source of base flow to rivers"—EA 2016). The entire sequence is blanketed by Quaternary (Devensian) glacial tills, with some glaciofluvial sands and gravels. The geological section at Florence is shown in Fig. 3. In the extreme northeast of the mine complex, at Ullcoats, the St Bees Sandstone and Brockram wedge out and the ore body is directly overlain by till deposits. The rest water level in Florence mine shaft is only a few metres below ground level: prior to the pumping test (26/12/14 to 8/1/15), it varied between 6.16 and 5.99 m below ground level (bgl).

Smith (2014) reckoned the total floodable void space in the Beckermet–Florence complex to be some 2–4 million m^3. He also noted, based on anecdotal information from the mine owner (G. Finlinson, *pers. comm.*), that (1) pumping at 630 tons (640 tonnes) per hour (178 L s^{-1}) from Beckermet No. 1 was adequate to maintain the entire mine complex dry to below −335 m asl, when working, (2) pumping at 440 tons (447 tonnes) per hour (124 L s^{-1}) from Florence shaft was adequate to maintain water levels just below 0 m asl and allow working of the Lonely Hearts Level of Florence shaft. This observation suggests that the majority of water ingress to the mine was either derived from high level inflows or from vertical leakage from the overlying Brockram/St. Bees Sandstone aquifer.

Ore body

The ore body itself is dominated by haematite (Fe_2O_3) formed by metasomatic replacement of limestone. Accessory minerals include quartz, up to c. 5% barite, limonite, siderite, calcite, dolomite, and traces of pyrite (M&QE 1954a; Goldring and Greenwood 1990; Smith 2014). The Winscales–Mildred ore deposit at Beckermet mine was narrow but up to 91 m tall (G. Finlinson, *pers. comm.*), whereas the ore at Florence was broader but not so thick. The method of working was by upwards room-and-pillar

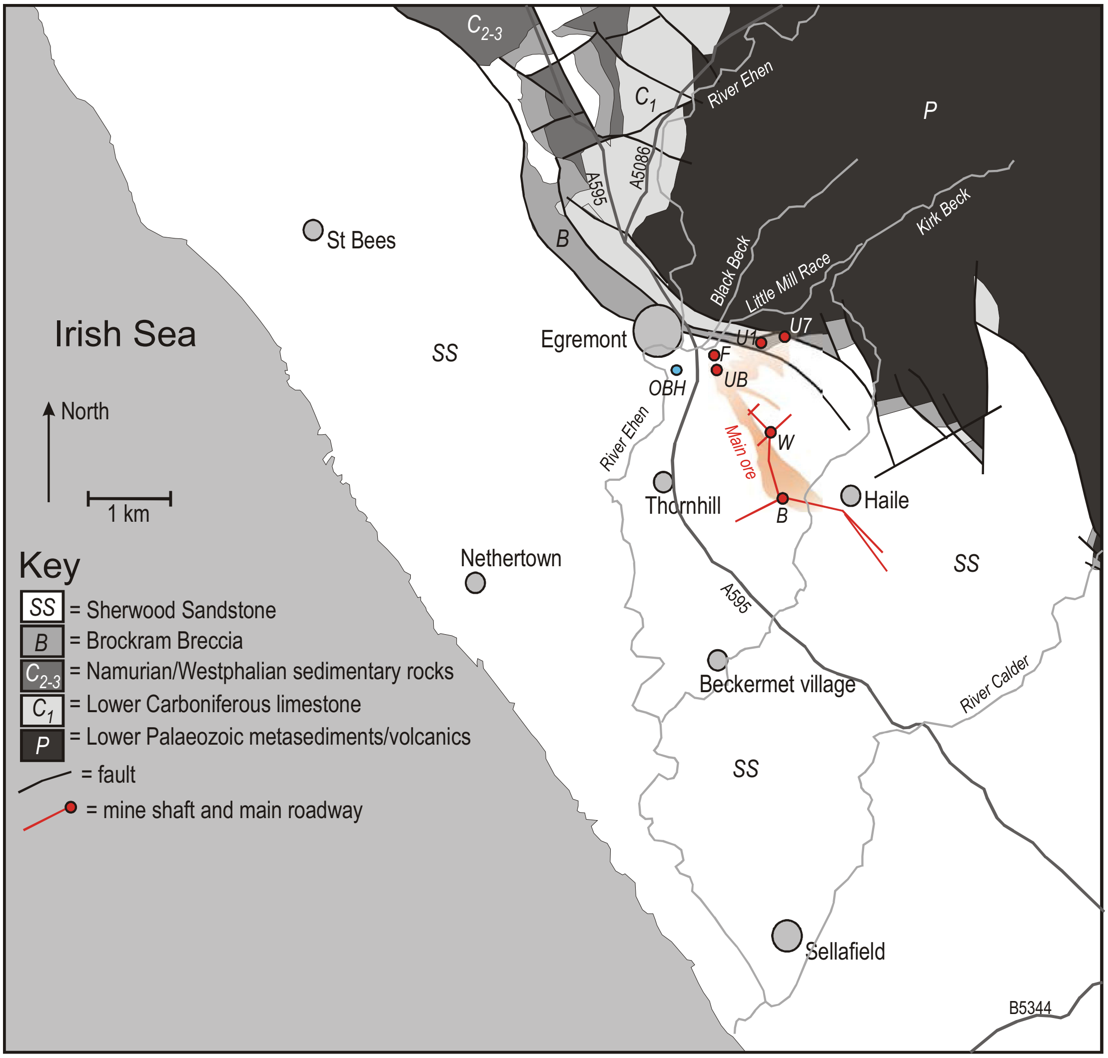

Fig. 2 Schematic geological map based on British Geological Survey OpenGeoscience mapping (http://www.bgs.ac.uk/geoindex/). *B* Beckermet No. 1 (Mildred) shaft, *W* Winscales (Beckermet No. 2) shaft, *UB* Ullbank No. 1 shaft, *F* = Florence shaft, *U1 and U7* Ullcoats No. 1 and 7 shafts. *OBH* Bridge End Sherwood Sandstone artesian observation borehole. Contains British Geological Survey materials ©NERC (2016)

stoping, following by downwards robbing, and is described in detail by M&QE (1954a). The consequence of this is believed to be that rubble filled voids replaced the ore body, and provided for good vertical and horizontal hydraulic connectivity throughout the mined system.

Source of water supply

Following the employee take-over of Florence mine, the mine was allowed to partially flood, with dewatering still taking place to allow working via the upper Lonely Hearts Level. As the pumped water quality was generally excellent (with the exception of slightly elevated arsenic levels), it formed the basis for a water transfer scheme. A system of licences was acquired allowing the pumped water from Florence mine to be discharged to streams tributary to the River Ehen and abstracted further downstream for industrial purposes.

Pumping and tracer tests: methods

Equipment installed

In 2015, a steel-shrouded submersible pump was set at 37 m bgl in Florence shaft. A 200 mm diameter PVC eductor pipe was attached to the base of this, extending to 235.4 m bgl. (Fig. 3). Thus, water was effectively extracted from 235.4 m depth, without the need for a long rising main or electric cabling. Water pumped from the shaft was discharged to the adjacent Little Mill stream. The Little Mill stream is believed to be a former mill race, taking

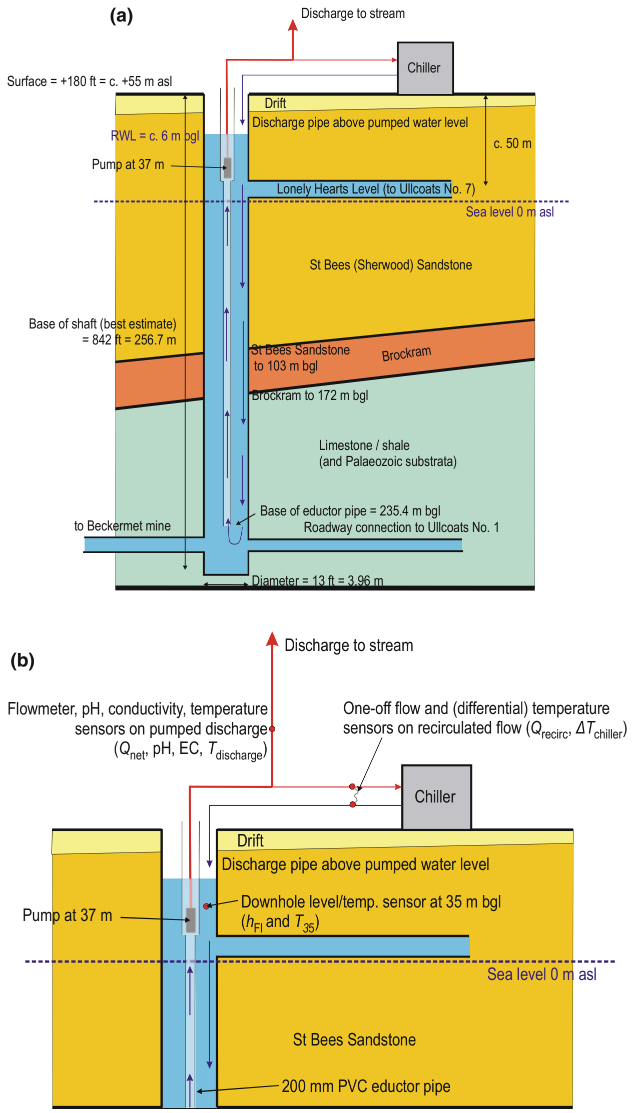

Fig. 3 **a** Schematic cross section of Florence shaft, showing pumping test installation, **b** detail of upper portion of shaft. *m bgl* metres below ground level. *m asl* metres above sea level

water from the Kirk Beck, draining from the Lake District Massif to the northeast (WA Archaeology 2012). The Little Mill Race flows down through Egremont town to the River Ehen. During "standing column" episodes of the pumping test, a proportion of the pumped water (typically c. 7.2–7.5 L s^{-1}) was passed through the evaporator of a heat pump (an industrial "chiller") and recirculated back into the shaft at a point above the shaft water level (Fig. 3).

The monitoring installed at Florence mine comprised:

- An OTT PLS relative pressure sensor installed at 35 m bgl in Florence Shaft (outside the eductor pipe) to continuously monitor in situ Florence shaft water level (h_{Fl}) and temperature (T_{35}).
- Sensors installed on the discharge pipe to the stream to continuously monitor pH, dissolved oxygen (DO), electrical conductivity (EC), temperature ($T_{discharge}$), and net discharge rate (Q_{net}) of the non-recirculated water.
- Differential temperature sensors and an electromagnetic flow meter could be temporarily installed on a straight section of pipe in the recirculation loop near the chiller, to allow individual readings to be made of the differential temperature ($\Delta T_{chiller}$) across the chiller and the recirculated flow rate (Q_{recirc}).

The total (gross) pumping rate of the submersible pump is termed Q_{sub} and thus:

$$Q_{sub} = Q_{net} + Q_{recirc}. \tag{3}$$

Other monitoring points

In addition to monitoring at Florence shaft, Solinst "Leveloggers$^{®}$" were installed at (Fig. 2):

- The Environment Agency's pre-existing Bridge End Observation Borehole (OBH), which is an artesian borehole in the St Bees sandstone. The logger thus monitored the artesian water pressure.
- Beckermet No. 1 shaft to measure water level and temperature, at 63.2 m depth.
- Ullcoats No. 1 shaft to measure water level and temperature, at 44.1 m depth.

These sensors were compensated for fluctuations in atmospheric pressure (using a barometric logger located at Egremont), and were also calibrated against manual water-level measurements.

Heat pump

The heat pump connected to the recirculation loop was an industrial "chiller": an MTA TAE EvoTech 402 model with a nominal cooling capacity at the water-cooled evaporator of 123 kW. The condenser was cooled by two top-mounted air fans. The chiller contains four compressor circuits, which can operate independently, effectively providing four "steps" of heat pump power. Due to technical problems with the refrigerant circuit pressures, at various stages during the test, either 2, 3, or 4 compressors were operating. Monitoring of $\Delta T_{chiller}$ across the chiller and the recirculated flow rate (Q_{recirc}) allowed quantification of the cooling effect as 53, 81, and 103 kW (for 2, 3, and 4 compressors, respectively). The highest power corresponds to a temperature differential of c 3.3 K at around 7.4 L s^{-1}.

Chemical and stable isotope analyses

In addition to the in-line or downhole monitoring of temperature, dissolved oxygen, pH, and electrical conductivity, regular samples (every c. 3 days) of the pumped water were taken into flasks pre-filled with appropriate preservative agents, and dispatched by courier for analysis at the UKAS/MCERTS accredited Alcontrol Ltd. laboratory. At the time of sampling, a field pH determination (calibrated hand-held meter) and alkalinity titration (Hach digital titrator) were made.

Samples for $\delta^{18}O$ and $\delta^{2}H$ isotopic analysis were taken on three occasions during test pumping on 6th February, 3rd March, and 23rd March 2015; on each occasion in triplicate using clean 10 mL glass screw-cap vials, it was sealed with paraffin film to hinder sample evaporation. Samples were also taken from the adjacent stream (Little Mill Race). Isotopic analyses were completed at the SUERC laboratories, East Kilbride; the full analytical procedure is detailed in Burnside et al. (2016a).

Geophysical logging and saline tracer test

On 28th August 2014, European Geophysical Services Ltd. was commissioned to run CCTV, fluid temperature, and fluid conductivity logs of the shaft in its static condition prior to the pumping test. On that date, a heat pulse flowmeter was also employed to estimate the axial water flow rate up or down the shaft at various locations. The logging exercise was repeated on 12th March 2015, during the pumping test, while the chiller was operating at full power (EGS 2015). On this latter occasion, a CCTV log and four separate fluid temperature/conductivity runs (Runs 1–4) were made. Run 1 was made at c. 10:30 a.m. (Fig. 4).

On 12th March 2015, a tracer test was also attempted by introducing a saline solution to the recirculated water. Around 13:30, saline tracer fluid injection commenced (Run 2). From around 15:00 to 17:00, the pumping rate was increased (Runs 3 and 4) temporarily to around 50 L s^{-1}. The saline tracer introduction had to be aborted after only 50 L had been introduced, due to technical problems. On 20th–21st March 2015, the salt solution tracer test was repeated, with 2000 L being introduced to the recirculated water over a 26 h period. The results of the saline tracer test were not easy to interpret and will not be discussed in detail in this paper.

Pumping test schedule

Following a brief functionality test of the submersible pump on 8th January 2015, the main pumping test commenced, with pumping rates (Q_{sub}) gradually increasing to 50 L s^{-1}. The period of testing continued until 25th March 2015, according to the following schedule (shown schematically in Fig. 5):

- 8th January to 17th February 2015. Pumping test at 40 - 50 L s^{-1}, without recirculation or chiller
- 17th–28th February 2015. First episode of chiller operation, with recirculation of 7.2 to 7.4 L s^{-1} chilled water.
- 28th February to 10th March 2015. Partial recirculation (7.4–7.5 L s^{-1}) without chiller.
- 10th–16th March 2015. Second episode of chiller operation (4 compressors), with recirculation of c. 7.5 L s^{-1} chilled water.
- 12th March 2015, 10:30–16:30. Shaft geophysically logged while pumping during chiller operation. Aborted salt solution tracer test.
- 16th–21st March 2015. Partial recirculation (c. 7.0–7.5 L s^{-1}) without chiller.
- 20th and 21st March 2015. Repeated salt solution tracer test.
- 21st–25th March 2015. Pumping test at 50 L s^{-1}, without recirculation or chiller
- 25th March 2015. Pumping terminated.

Results

Due to the many strands of investigation during the course of the test pumping, some degree of basic interpretation of individual strands of data is included in the relevant 'Results' sections below. A greater degree of interpretation and discussion is found in the following 'Synthesis' section.

Pre-test geophysical logging

Figure 4 shows the pre-test (non-pumping) fluid logs run on 28th August 2014. It will be seen that the electrical conductivity is relatively constant throughout the shaft at 780–800 µS cm^{-1}, with a slight tendency to increasing conductivity towards the base. Above the Lonely Hearts Level, however, the conductivity is somewhat lower, suggesting an immobile layer of more recent hydrochemically immature water, above a zone of more actively circulating groundwater (driven by ambient vertical head gradients) between the Lonely Hearts Level and the base of the shaft.

The temperature log shows a very static fluid column of c. 10.9 °C from the rest water level down to c. 170 m bgl. Below 170 m bgl, the temperature creeps up to around 11.4 °C near the base of the shaft. In a 250 m static water column, a geothermal gradient of c. 2 °C per 100 m (which is broadly typical for onshore Britain—Banks 2012) would have produced a temperature increase of 5 °C along the length of the shaft. The fact that this is not observed that

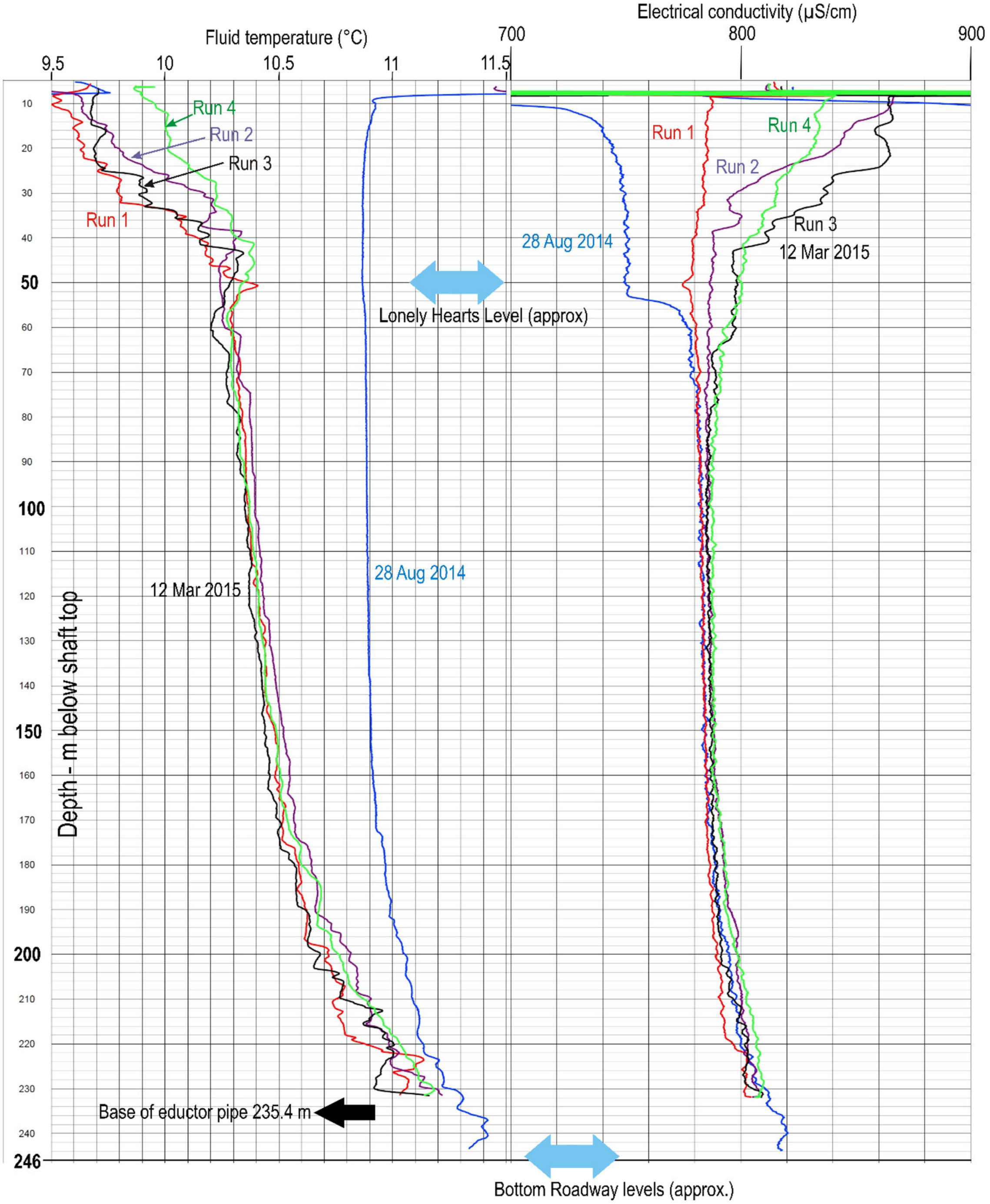

Fig. 4 Geophysical fluid temperature and electrical conductivity logs run prior to the pumping test (28th August 2014) and during a "standing column" phase of the pumping test (12th March 2015—runs 1 to 4)

argues strongly for an advective flow, driven by vertical head gradients along the shaft, presumably in a downward direction, given the rather low temperature found at the base. The increasing temperature below 170 m might suggest flow horizons within this depth interval, despite the absence of known mine roadways.

Heat pulse flowmeter readings at 9, 15, 35, 50, 65, 150, 165, 179, and 245 m bgl all suggested a consistent upwards-directed low flow of around 2 mm s^{-1}. The apparent discrepancy with the other fluid logs and the fact that an upward flow was detected in a supposedly static section of shaft at 9–35 m bgl suggest that the heat pulse

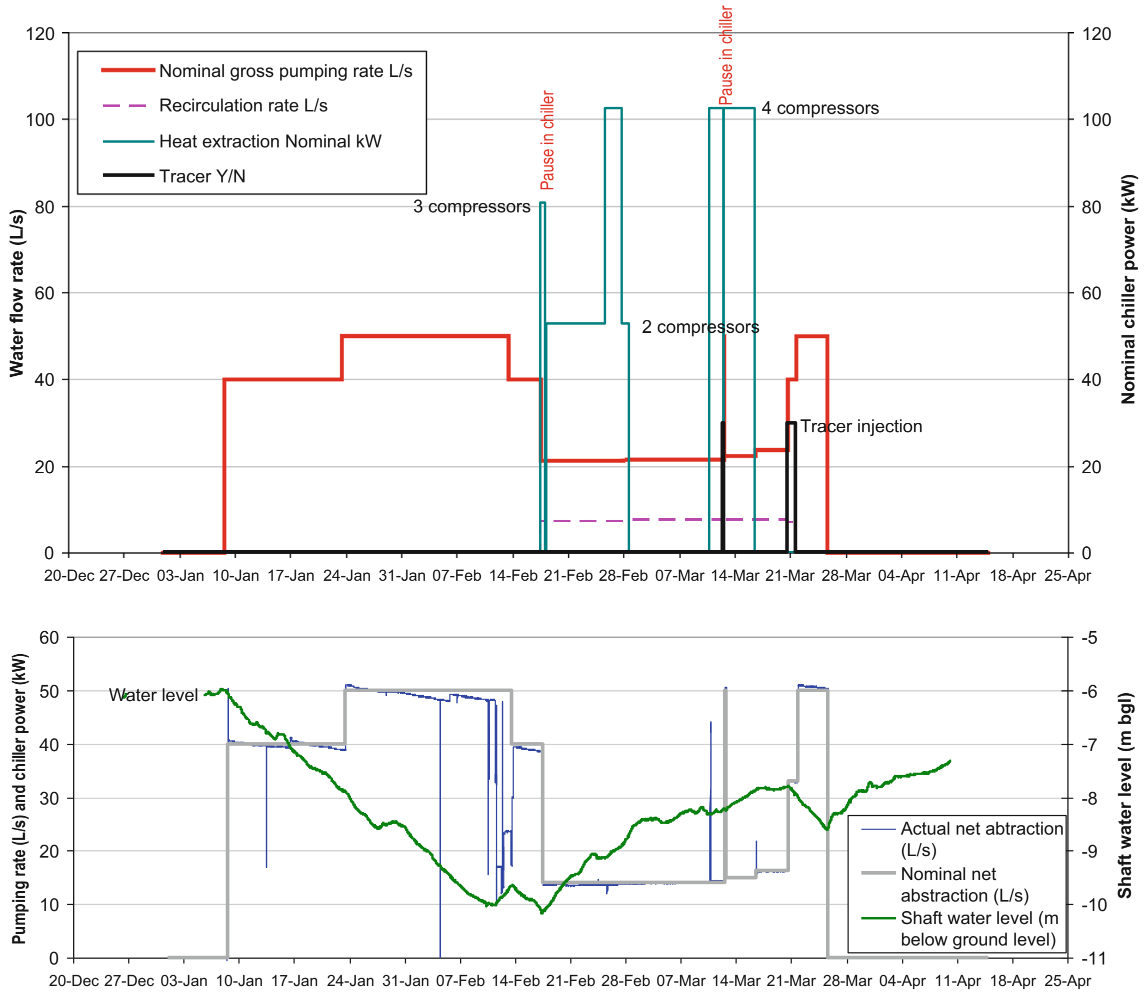

Fig. 5 Schematic of nominal gross, net, and recirculation pumping rates, actual (measured) net discharge rate, chiller effect (kW), and Florence shaft water level during Florence pumping test

flow readings may be erroneous and might be affected by convection. In fact, given a shaft of diameter c. 4 m, the development of free convection cells (at least in the absence of head-driven advection) is almost inevitable (Gretener 1967; Eppelbaum and Kutasov 2011).

Groundwater chemistry

The hydrochemistry of the water pumped from Florence shaft during the test was relatively constant for almost all parameters (Table 1). The water is consistently of a Ca–(Na–Mg)–HCO_3^- type of slightly alkaline (7.4–7.6) pH (Fig. 6). Slightly elevated concentrations of Na, K, HCO_3^-, Mg, and Cl^- were noted at times of the highest pumping rate. In addition, the Ca/Sr mass ratio decreases at times of high pumping rate, while Ba and Mn concentrations, and Mg/Ca and Na/Cl ratios all increase slightly (Fig. 7). These observations suggest that high pumping rates induce an increased proportion of long-residence groundwater with elevated Ba, Sr, Mg, and lithogenic Na concentrations. The elevated Ba and Mn suggest that this “mature” groundwater is also somewhat reducing in nature.

The initial pumped water from Florence shaft contains a relatively low dissolved oxygen content of c. 0.5 ppm. As recirculation commences, dissolved oxygen is introduced to the shaft water column (via cool water cascading back into the shaft from the chiller) and concentrations in the pumped water rise to 4 ppm (Fig. 8).

Dissolved iron (with three exceptions) remains below the analytical detection limit of <19 µg L^{-1} throughout the pumping test. Total iron varies widely in concentration (but is typically several tens of µg L^{-1}), with high concentrations noted immediately after the start of the test and after the commencement of recirculation. This suggests that particles of ferric oxide iron are mobilised in the water at commencement of pumping—it is not known whether these are derived from the mine or from rusting metalwork in the shaft. During the course of the test, no obvious iron

Table 1 Pumped water chemistry variation from Florence shaft during pumping test (19 analyses during period 8/1/15 to 16/3/15)

Parameter	Value 3/2/15	Interquartile range
pH	7.58	7.44 to 7.58
Major anions		
Alkalinity (meq L^{-1})	4.08	4.03 to 4.08
Cl^- (mg L^{-1})	42.6	35.9 to 39.0
F^- (mg L^{-1})	1.37	1.09 to 1.28
NO_3^- (mg L^{-1} as NO_3^-)	2.63	2.38 to 3.39
$SO_4^{=}$ (mg L^{-1})	18.9	17.5 to 18.0
Major cations		
Ca (mg L^{-1})	53.8	51.7 to 55.3
Na (mg L^{-1})	38.4	29.7 to 36.1
Mg (mg L^{-1})	13.6	12.7 to 13.4
K (mg L^{-1})	7.8	6.5 to 7.7
Ion balance error (%)	−1.0	−4.2 to −0.9
Trace elements (dissolved)		
Fe (μg L^{-1})	<19	<19 to <19
Mn (μg L^{-1})	54	22 to 44
As (μg L^{-1})	27	21 to 27
Ba (μg L^{-1})	177	168 to 183
Br^- (μg L^{-1})	118	119 to 130
Sr (μg L^{-1})	1710	1160 to 1535
Zn (μg L^{-1})	11	5 to 22
Key ratios		
Mg/Ca (molar)	0.42	0.40 to 0.42
Na/Cl (molar)	1.39	1.28 to 1.38
Cl^-/Br^- (mass)	361	281 to 340
Ca/Sr (mass)	31.5	33.9 to 44.4

pH and alkalinity determined in field, other parameters in laboratory. The table shows data for 3/2/15 and interquartile range for entire data set (*N* = 19)

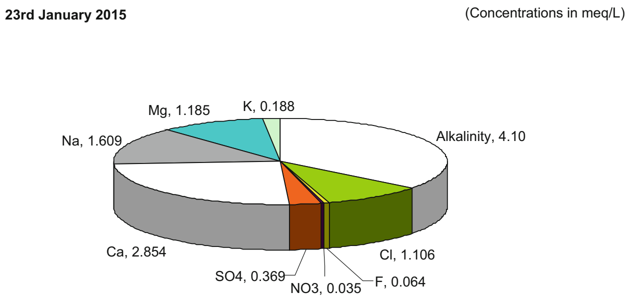

Fig. 6 Pie diagram illustrating the major ion content of the Florence mine water as meq L^{-1} percentages of the total ion content. Numbers show ion concentrations in meq L^{-1}

scaling or ochre formation was noted in the pipework or heat exchangers.

Dissolved arsenic concentrations are rather elevated at around 20–30 μg L^{-1}. Like manganese, dissolved arsenic increases somewhat during high pumping rates. Total arsenic is typically a little higher than dissolved arsenic, and may suggest that a small proportion of arsenic is associated with particulate iron oxides (either as a component of primary haematite, or as a sorbed element on secondary iron oxyhydroxide flocs). Like iron and manganese, a spike in total arsenic coincides with commencement of recirculation (mobilisation of particles).

Stable isotopes

The isotopic signature of the pumped waters from Florence shaft does not vary significantly throughout the pumping period and exhibits mean $\delta^{18}O$ and $\delta^{2}H$ values of −6.5 ± 0.1 and −40 ± 0.3‰, respectively (very close to the analytical method's limits of reproducibility). These are almost identical to the mean stream water composition of −6.7 ± 0.2 and −39 ± 1‰ from Little Mill Race (Table 2). This suggests that the origin of the stream water and mine water within Florence mine may be similar (i.e., runoff from the Lake District massif to the NE, which, having left the Lower Palaeozoic rock complex, encounters the more permeable or karstified Carboniferous limestone and Brockram strata, and enters the groundwater system).

There is no nearby long-term isotopic precipitation monitoring station, but long-term weighted mean values from UK and Irish sites are plotted in Fig. 9 for comparison. Also included in Fig. 9 are short-term (6 month) averages from pumped coal mine waters 150 km to the SE at Caphouse, Yorkshire (Burnside et al. 2016a) and 200 km to the SE from Markham, Derbyshire (Burnside et al. 2016b). The UK long-term monitoring points are all within c. 20 m elevation of the Florence mine (+55 m asl), with the exceptions of Altnabreac (+155 m asl) and Fleam Dyke (+30 m asl). The Valentia monitoring station in SW Ireland is at +9 m asl. The Florence mine water and stream water isotopic signatures are significantly heavier than short-term values from the colliery sites and long-term averages from the UK monitoring stations. This is particularly puzzling as it cannot be explained by seasonal factors: monitoring stations typically demonstrate relatively light isotopic signals during the winter months (Lawler 1987). Neither can the signature be explained by the stream water and mine water being ultimately derived from upland catchments, as these also typically yield isotopically light signatures (Fig. 9).

Hydraulic response in Florence shaft

Figure 5 shows the actual measured net discharge rates and the hydraulic response of the water level in the Florence shaft. It will be seen that there was a slight tendency for the pumping rate to decline with time as water levels fell (and increase as they rose, a typical response of a submersible

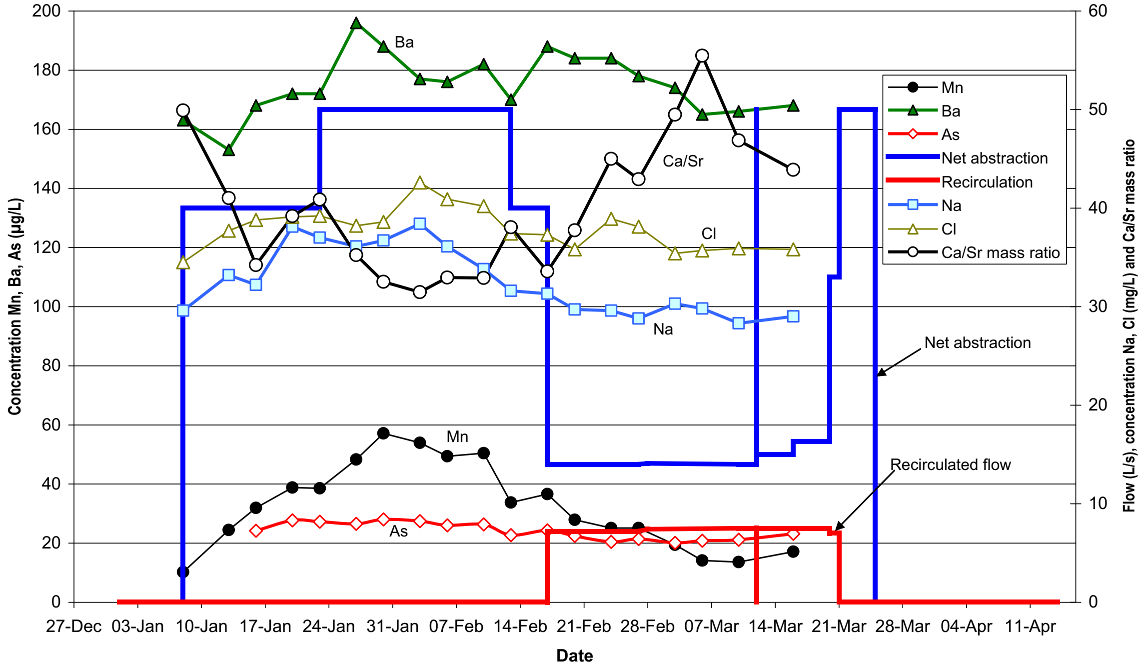

Fig. 7 Trends of key hydrochemical parameters (concentrations of chloride, sodium, dissolved manganese, arsenic, and barium) and the Ca/Sr mass ratio in the pumped mine water during the course of the Florence shaft pumping test

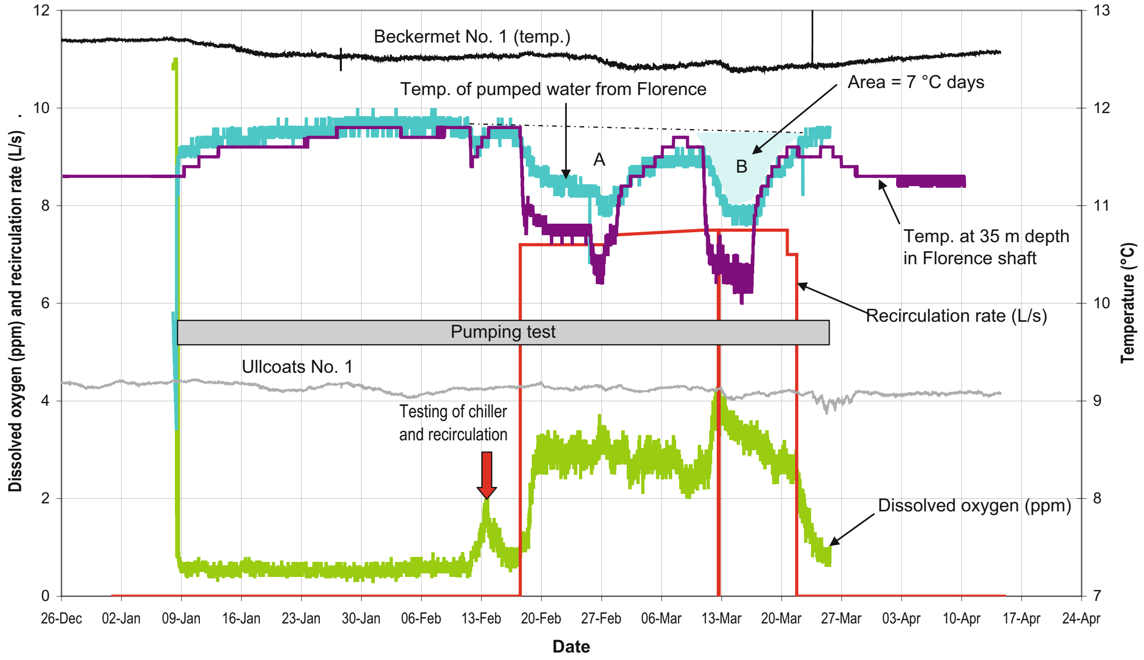

Fig. 8 Temperature in shaft water column at 35 m bgl, temperature of pumped water, and dissolved oxygen content of pumped water, Florence shaft pumping test. *A* and *B* refer to the two periods of chiller operation. The area represented by episode *B* in the pumped water represents 7 °C days

pump). The response of the water level was surprisingly small; the drawdown reached only some 4 m at a nominal pumping rate of 50 L s^{-1}, although it was still falling and did not stabilise. Even when the pumping rate was reduced to 40 L s^{-1} on 13th February 2015, the decline in water level continued. Only when the net pumping rate was reduced to c. 14 L s^{-1} on 17th February 2015, did water level rise.

The rate of drawdown (and recovery) appeared to be approximately linear with respect to time and also to be

Table 2 ^{18}O and ^{2}H isotope determinations for H_2O pumped from Florence mine shaft

Sample site	Date	$\delta^{18}O$ (VSMOW)	$\delta^{2}H$ (VSMOW)
Florence shaft pumped water	06/02/15	−6.5	−40
	03/03/15	−6.6	−40
	23/03/15	−6.4	−41
Little Mill race	06/02/15	−6.8	−39
	03/03/15	−6.5	−38
	23/03/15	−6.7	−41

All δ-values ‰ against Vienna Standard Mean Ocean Water (VSMOW) standard. Average values of triplicate analyses are cited for each of the three sampling dates

related to the net discharge. This suggests that, when pumped, within a very modest range of water-level fluctuation (maximum drawdown = c. 4 m), the mine is simply acting as a large reservoir of effective cross section A, with a limited constant net influx or recharge of groundwater:

$$Q_{\mathrm{net}} = Q_{\mathrm{inf}} - A \times \Delta h_{\mathrm{Fl}}/\Delta t, \tag{4}$$

where Q_{inf} is the net influx of groundwater to the mine (m^3 day^{-1}); Q_{net} is the net discharge rate from mine (m^3 day^{-1}); A is the effective cross-sectional area of mine (m^2); $\Delta h_{\mathrm{Fl}}/\Delta t$ is the rate of change of water level in Florence mine (m day^{-1})

Figure 10 shows the rates of drawdown observed for differing net discharge rates. A similar exercise can be performed for the recovery sections. It will be noted that

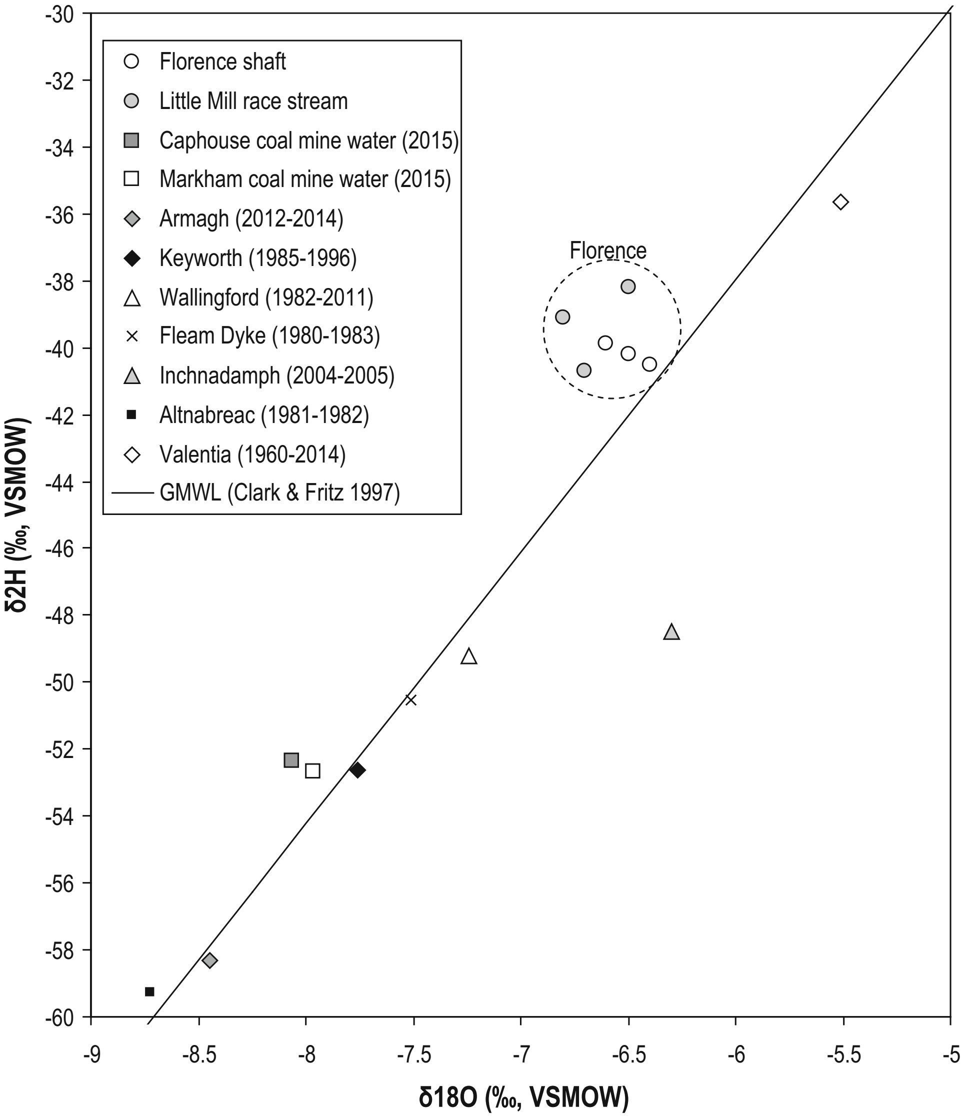

Fig. 9 Plot of $\delta^{18}O$ and $\delta^{2}H$ for Florence mine waters, as compared to local stream (Little Mill Race), short-term (6 month) pumped minewater from Caphouse (150 km SE) and Markham (200 km SE) coal mines, and long-term weighted mean values for meteoric water recorded at Armagh (200 km west), Keyworth (240 km SE), Fleam Dyke (350 km SE), Wallingford (360 km SSE), Inchnadamph (420 km N), Altnabreac (450 km N), and Valentia (530 km SW) (IAEA/WMO, 2016). *Solid trend line* represents the Global Mean Meteoric Water Line (GMWL)

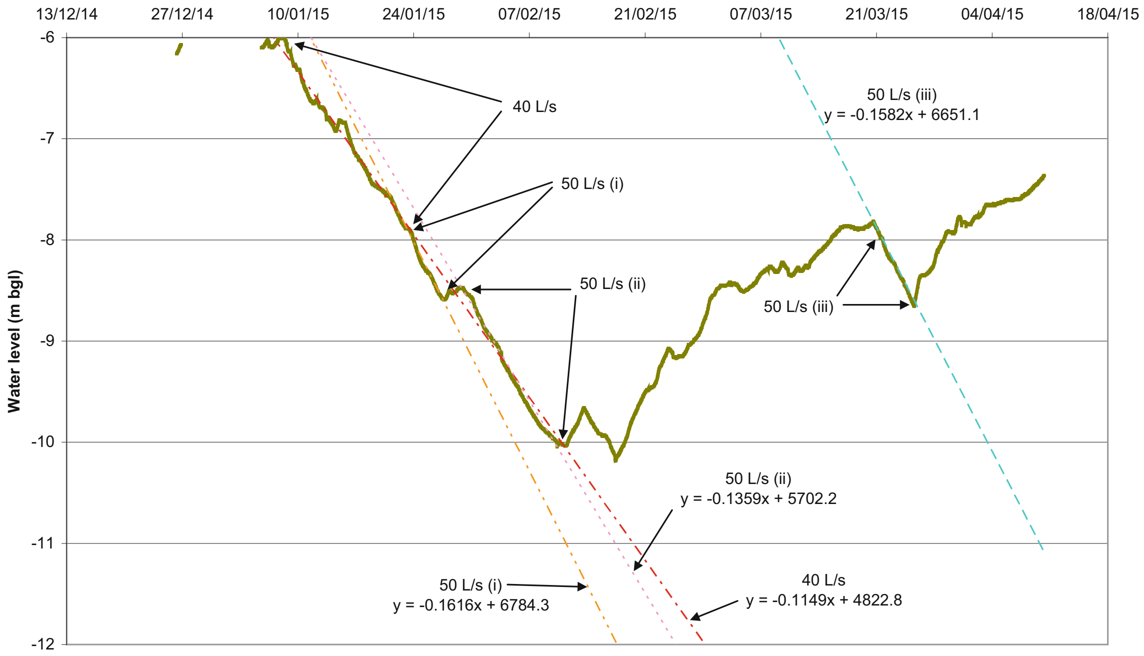

Fig. 10 Detail of water-level response to pumping in Florence shaft. *Trend lines* show best fit linear drawdown response to different episodes of constant rate net pumping at 40 or 50 L s^{-1}

Eq. (4) represents a linear relationship between Q_{net} and $\Delta h_{Fl}/\Delta t$, with Q_{inf} representing an intercept and A representing a gradient. A combined analysis of the slopes for pumping sections (at different rates) and recovery sections suggests that, for a drawdown of c. 4 m, there is an inflow to the mine of some 2000 m^3 day^{-1} (23 L s^{-1}). In other words, at a net pumping rate of 23 L s^{-1}, an approximate steady state should be achieved, while at higher pumping rates, continued drawdown should be observed.

Hydraulic response in other observation points

The water-level response in Beckermet shaft was essentially identical to that in Florence shaft, confirming that the shafts intercept a single hydraulically interconnected underground reservoir. The water-level response in Ullcoats No. 1 shaft was also identical to Florence and Beckermet, but, apparently, several tens of cm higher with respect to sea level. This could simply represent uncertainty in the elevations of the shaft tops, or it could represent a hydraulic impedance between the Ullcoats and Florence–Beckermet complexes.

The water level in the Bridge End St Bees Sandstone OBH is artesian, but lower in absolute elevation than the mine complex. This implies that, in both a static and a pumping condition, there is an upwards head gradient from the mine complex to the St Bees Sandstone. During the pumping test of the mine, the upward regional head gradient was not reversed, but it was reduced (Fig. 11) and the groundwater head in the Sandstone OBH apparently declined by just over 1 m. This strongly implies that the water abstracted from the mine is derived at the expense of captured upwards discharge (in the sense of Theis 1940; Bredehoeft et al. 1982) from the mine to the Sandstone.

Temperature and temperature response

Prior to, after and at the start of the pumping test, the water temperature at 35 m depth in Florence shaft (and of the initial pumped water) was c. 11.3 °C. As pumping progressed, the water temperature from Florence shaft increased to almost 12 °C (Fig. 8), presumably due to a greater component of deep water being induced to flow into the shaft (supporting the hydrochemical findings), possibly from the adjacent deep workings of Beckermet mine. The water temperature in Beckermet shaft, the deepest of the shafts and the furthest hydraulically down-gradient, was around 12.5 °C. The water temperature in the Ullcoats No. 1 shaft was the lowest at just over 9 °C. This is unsurprising as it is the shallowest of the shafts and also the furthest up-gradient, essentially receiving surface water recharge and groundwater inflow from the foothills of the Lake District to the northeast.

The two periods of chiller operation (A and B in Fig. 8) produced two clear downward inflections in shaft water temperature. Remembering that cold water from the chillers was returned at the top of the shaft at a rate of just over 7 L s^{-1}, the earliest and clearest temperature response was

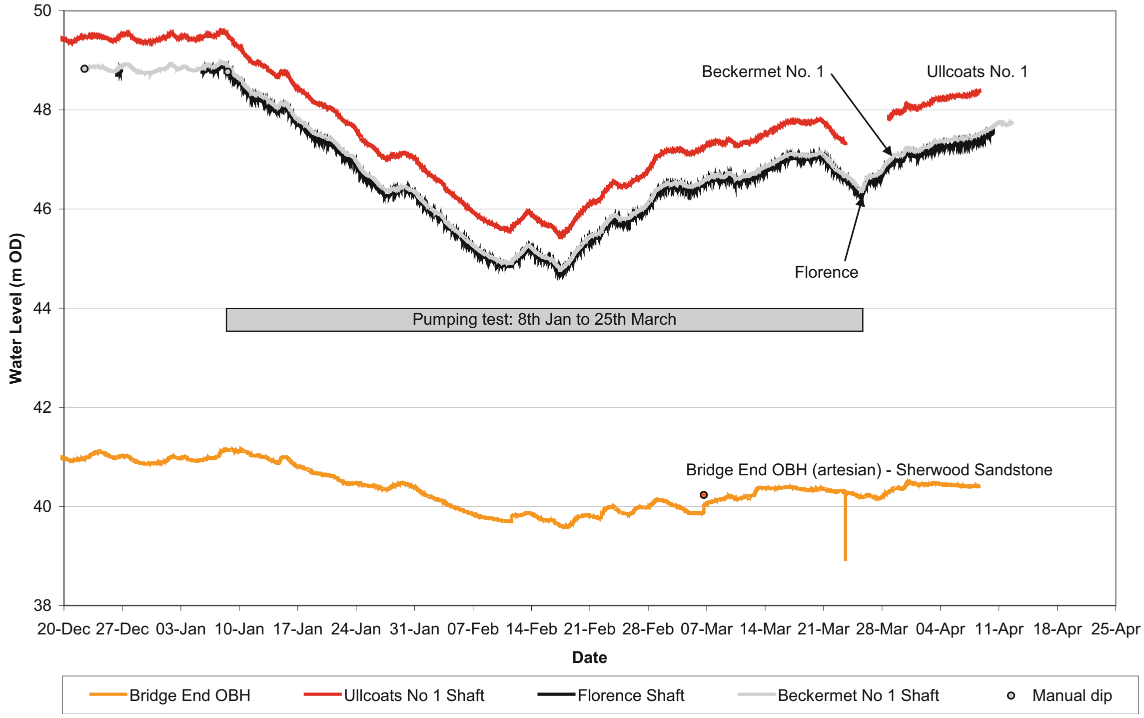

Fig. 11 Groundwater head response in various observation points in m above sea level (m OD) in various observation points during Florence shaft pumping test

seen in the shaft sensor at 35 m depth. This was followed by a delayed (as the cool signal had to travel to the base of the shaft and then up the eductor pipe and rising main) and more subdued response in the pumped water.

Interpretation of chiller recirculation test and geophysical logging

The cool water thermal signal during the 2 periods of chiller operation (A and B in Fig. 8) can be estimated by dividing the peak chiller output (c. 103 kW) by the recirculated flow rate of (c. 7.4 L s^{-1}), yielding a value of 13,920 J L^{-1}. This translates to a negative temperature pulse of 3.3 °C (assuming a volumetric heat capacity of water of 4190 J L^{-1} K^{-1}) travelling down the shaft. In reality, the temperature drop at the 35 m bgl sensor did not exceed 1.8 °C. If the thermal signal is divided by the total pumped flow of 22 L s^{-1}, one would expect a thermal pulse of around 1.1 °C in the abstracted water. In the actual data set, a temperature drop of up to 1 °C was noted in the pumped water. The slight discrepancies might be due to:

- The thermal signal at 35 m being affected by incomplete mixing and dispersion in the wide shaft, or by turbulent mixing processes near the mouth of the Lonely Hearts roadway.
- General hydromechanical dispersion (to produce a broader, shallower signal).
- Heat being released to the cool pulse by the shaft walls.
- Some of the thermal pulse disappearing down side adits (possibly by water flow to Beckermet mine).

The second phase of geophysical logging commenced at 10.30 am on 12th March 2015, 39.25 h after the chillers were switched on at 19:15 p.m. on 10th March 2015. With a gross pumping rate of 22 L s^{-1}, this should have just allowed enough time for the cool signal to have traversed the length of the shaft, if the entire 22 L s^{-1} was derived from the top of the shaft. If the down-shaft flow was 7 L s^{-1} (the recirculation rate), with the remainder derived from the base of the shaft, the cool signal would only have travelled some 80 m down the shaft. It will be seen from Fig. 4, that the logs from 12th March are cooler than the pre-test log all the way along the shaft, with a pronounced change in gradient at the Lonely Hearts level and a lesser change in gradient below 170 m. This suggests that the Lonely Hearts level is contributing a significant quantity of water, diluting the recirculated cold water signal, and that there may also be additional inflows below 170 m. The fluid conductivity logs (Runs 1–4) show the progress of the saline tracer down the shaft, but have proved difficult to interpret quantitatively with any confidence and will not be discussed further in this paper.

The area of the negative temperature anomaly corresponding to chiller episode B (Fig. 8) in the pumped water is estimated as 7 °C days. At an average net abstraction rate over this chiller operation period of 15.2 L s^{-1}, this equates to 9.2×10^6 K L. Given a volumetric heat capacity of 4190 J $°C^{-1}$ L^{-1}, this represents a negative heat signal of 38 GJ. The total cooling signal applied by the chillers is estimated as 103 kW x 5.61 days of chiller operation = 50 GJ. Thus, one can estimate that 11–12 GJ of heat has been recovered from the shaft over the course of the recirculation test. Given a nominal duration of the test of 5.70 days (allowing for 2 h of chiller shutdown, mid-test), this represents a rate of heat replenishment of some 23 kW or c. 100 W m^{-1} (assuming a 228 m standing column). For a temperature differential of 3.3 °C at the highest chiller power, this corresponds to 30 W m^{-1} per °C temperature differential.

From the fluid temperature logs of 12th March 2015 (Fig. 4), one can also estimate a temperature gradient of 0.2 °C per 100 m between 80 and 180 m bgl during chiller operation. For a downhole flow rate in this section of 15 L s^{-1} (which is an educated guess, as this is not exactly known), this would represent a heat replenishment rate of 0.2 °C × 4190 J L^{-1} $°C^{-1}$ × 15 L s^{-1} = 12.6 kW per 100 m = 126 W m^{-1}, which approximately corresponds to the figure derived above.

It will be recalled that the long-term heat extraction from a large diameter standing column shaft was predicted to be several tens of W m^{-1}. The more complex Rodríguez and Díaz (2009) model (Loredo et al. 2017) has been applied to a scenario where 7 L s^{-1} of water at 8 °C is introduced into a 228 m mine shaft of 3.96 m diameter, where the rock initial temperature, thermal conductivity, and volumetric heat capacity are 11.3 °C, 3 W m^{-1} K^{-1} (which seems a reasonable figure given the typical conductivities in Table 3) and 2.1 MJ m^{-3} K^{-1}, respectively, with a Nusselt number of 10.59. The model predicts a heat replenishment from the rock walls to the flowing water of some 10–13 kW (c. 50 W m^{-1}) for the first 6 days of operation of a scheme. A simulation with 15 L s^{-1} water being introduced to the same shaft with an initial temperature of 9.7 °C and a turbulent Nusselt number of 39.4, results in similar heat yields of 7–14 kW. It is not wholly clear why the analytical models predict heat yields from conduction from the shaft walls of around half of our best estimate of the actual figure, although it may be that the thermal conductivity is significantly greater than 3 W m^{-1} K^{-1} owing to the haematite content of the rock (Table 3).

Synthesis

The interconnected Florence–Beckermet mine complex includes the Ullcoats mines (which lie furthest to the northeast and whose shaft tops lie close to the subcrops of the Carboniferous Limestone and Lower Palaeozoic rocks), the Florence–Ullbank shafts and the deepest Winscales–Beckermet shafts (where the mineralised zone occurs beneath a cover of Brockram and Sherwood Sandstone).

The Carboniferous limestone (which contains the bulk of the ore body and the mined voids), and the Brockram and the Sherwood Sandstone are lithologically distinct aquifer units, but are believed to be hydraulically connected. The mine complex forms a hydraulic short circuit through these aquifer strata, connecting recharge areas (of high groundwater head) close to the Lower Palaeozoic Lake District massif with potential discharge areas (of lower groundwater head) in the Sherwood Sandstone of the Ehen Valley. We hypothesise that the Carboniferous limestone and Brockram are partially recharged by surface water running off the low permeability lower Palaeozoic metasediments and metavolcanics in the northeast. Indeed swallow holes (sinks) are mapped on the Little Mill Race upstream of Florence mine. Stable isotopes indicate almost identical ^{18}O and ^{2}H signatures in surface water and mine water at Florence. The interconnected system of mine voids largely behaves as a continuous underground "tank" with almost identical water levels throughout the mine system. Fluid logs from August 2014 suggest a downwards flow of water under non-pumping conditions in Florence shaft from the Lonely Hearts Level towards the shaft base, suggesting a slow throughflow in the mine system from Ullcoats–Florence–Beckermet. The groundwater heads in the St Bees (Sherwood) Sandstone of the Ehen Valley (Bridge End OBH), although artesian, are lower than in the mine system. It thus appears that the mined voids lose water via upwards discharge to the St Bees (Sherwood) Sandstone (and presumably thence to superficial deposits or surface water).

Table 3 Commonly cited values of thermal conductivity of relevant geological materials

Material	Thermal conductivity (W m^{-1} K^{-1})	Source
Haematite	6.5	Mølgaard and Smeltzer (1971)
Sherwood sandstone	>3	Banks et al. (2013)
Sherwood sandstone	2.37–3.41	Rollin (1987)
Carboniferous limestone	3.14 (mean, *N* = 14)	Rollin (1987)

When Florence mine is pumped, the water levels in Ullcoats, Florence, and Beckemet mine shafts decline simultaneously and identically. At the highest net abstraction rates of 50 L s^{-1}, drawdowns of c. 4 m were achieved during this pumping test. Water chemistry was relatively constant throughout the test, though at the highest pumping rate, there appeared to be increased contributions of deeper, slightly warmer, more hydrochemically mature (higher Na/Cl, Sr/Ca) and more reducing (elevated Mn, Ba) water. For a given pumping rate, rates of decline and recovery were approximately linear and allowed an estimate of a net replenishment of water to the mine of 2000 m^3 day^{-1} (23 L s^{-1}) for a drawdown of c. 4 m. This net replenishment is presumed to represent captured discharge to the overlying Sherwood Sandstone aquifer, as the head gradient remained upwards throughout the course of the test. The pumping test response also implies an effective mine void "tank" area of some 12,000–15,000 m^2, which is entirely consistent with the estimated mine void volume of 2–4 million m^3 and the approximate depth of the workings of 140–300 m (Smith 2014).

The entire area underlain by mine workings can be estimated from mine plans to not exceed some 6–7 km^2, thus, the average captured discharge of 2000 m^3 day^{-1} works out at 0.28–0.33 mm day^{-1} = 102–120 mm $year^{-1}$. This is a quantity that is of a comparable magnitude to the potential rainfall recharge to groundwater systems in northern Britain and one would thus expect the pumping of the Florence–Beckermet mine system to have a significant effect on the water balance of the Sherwood Sandstone aquifer (unless the thermally spent water abstracted at Florence could be reintroduced to the mine system at another, sufficiently distant, location, such as Beckermet or Winscales). Indeed, the test was shown to affect groundwater heads in the St Bees Sandstone, causing a decline of almost 1 m at the Bridge End observation borehole.

It is possible to construct a yield–drawdown relationship for Florence mine shaft:

- When drawdown is 0 m, net recharge to the mine is 0 L s^{-1} (any inflow to the mine is balanced by upward leakage to the Sherwood Sandstone).
- When drawdown is c. 4 m, captured discharge is c. 23 L s^{-1} and an equilibrium drawdown should be attained at such a pumping rate.
- Pumping at 440 tons h^{-1} water = 447 m^3 h^{-1} = 124 L s^{-1} was adequate to keep the workings dewatered to below the Lonely Hearts level (drawdown c. 49 m).
- Pumping at 630 tons h^{-1} = 640 m^3 h^{-1} = 178 L s^{-1} from Beckermet No. 1 mine was adequate to keep the mine entirely dewatered to −335 m asl (drawdown c. 384 m).

The pumped water itself is of very good quality, with rather low dissolved iron concentrations, minimising the risk of ochre clogging of heat exchangers etc. The water is almost suitable for use as potable water, with the main exception of its rather elevated arsenic concentrations (typically 21–27 μg L^{-1}), which are not unheard for the Sherwood Sandstone aquifers of north-western England and which are most likely derived from reductive dissolution of arsenic-containing iron oxides (Shand et al. 2007).

It is estimated that, with a drawdown of 4 m, around 23 L s^{-1} could be continuously abstracted from Florence Shaft and discharged to surface water (an "open loop" scheme). The heating or cooling yield of this discharge depends on the temperature change that could be effected in a heat exchanger or the evaporator of a heat pump. If we assume a temperature change of 4 °C (see Eq. 1):

$$\text{Heat yield} = \dot{H} = 4\,^{\circ}\mathrm{C} \times 23\,\mathrm{L\,s^{-1}} \times 4190\,\mathrm{J\,L^{-1}\,K^{-1}} = 385\,\mathrm{kW}, \tag{5}$$

which is adequate to heat several tens of modern domestic properties. If the shaft was dewatered to the Lonely Hearts Level, the projected discharge of 124 L s^{-1} would potentially yield over 2 MW of heat. The water quality is such that, provided that arsenic issues could be mitigated, it could potentially be used for industrial or even potable supply, or could be used in a water transfer scheme for a point of use further down the River Ehen catchment. Effectively, this would represent a reinstatement of the hydraulic conditions when the mine was being worked, although it should be noted that the regulatory environment has evolved significantly since that time.

The recirculation of 7 L s^{-1} of cool water down the shaft resulted in a heat replenishment of around 23 kW. This is around double that predicted by theoretical models, for reasons which are not fully understood. While technically feasible, the additional heat likely to be acquired by recirculation of a proportion of the pumped water in a standing column arrangement is rather modest (<10% of heat yield of open loop scheme).

Conclusion

The interconnected Ullcoats–Florence–Beckermet mine complex worked a haematite ore within the Lower Carboniferous limestone aquifer, underlain by Lower Palaeozoic rocks and overlain by the Brockram Breccia and the St Bees Sandstone (Sherwood Sandstone aquifer). The interconnected mine complex is believed to behave as a single hydraulic "tank" or "pond", speculatively with slow throughflow from a recharge area near the Lower Palaeozoic/Carboniferous outcrop (near Ullcoats), down the Florence shaft to Beckermet, followed by upwards discharge to the Sherwood Sandstone of the River Ehen valley.

A pumping test was carried out at rates of up to 50 L s^{-1} in Florence shaft, producing water of 11.3–12 °C and drawdowns up no more than 4 m. At such a drawdown, analysis of the slope of pumping and recovery curves suggested a net capture of some 23 L s^{-1} of discharge. The pumping test affected heads in the Sherwood Sandstone aquifer with drawdowns of c. 1 m in nearby Bridge End OBH.

An open loop heat exchange scheme based on the pumping of Florence Shaft and discharge to surface water could produce heating and cooling effects of several hundred kW to a few MW, depending on pumping rate (although, at present, demand for heating/cooling in this sparsely populated, rural area is limited). The heat yield would ultimately be constrained by the discharge and this would be limited by what are deemed to be acceptable drawdown effects on the overlying Sherwood Sandstone aquifer. Thermally spent water could conceivably be used for industrial purposes, for a water transfer scheme or, provided that elevated arsenic concentrations can be mitigated, for potable water supply. Alternatively, the thermally spent water could be reintroduced to the mine system at another, sufficiently distant, location (Winscales or Beckermet), which would preserve the mine's hydraulic resource, but would require the construction of a substantial surface pipeline and still run some risk of thermal breakthrough within the mine system. Recirculation of a proportion of the water down the Florence shaft (a "standing column" arrangement) has been estimated to result in up to 23 kW additional heat replenishment, but this is a rather modest gain in the context of the overall potential "open loop" yield.

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