LOw Carbon After Life: sustainable use of flooded coal mine voids as a thermal energy source - a baseline activity for minimising post-closure enviromental risks

LOCAL

Research Fund for Coal & Steel

LoCAL Deliverable D4.3

Interim report on the findings of the study of field trials for the evaluation of dissolved gas partial pressures.

WP number	WP.4
Partner responsible	Alkane Energy

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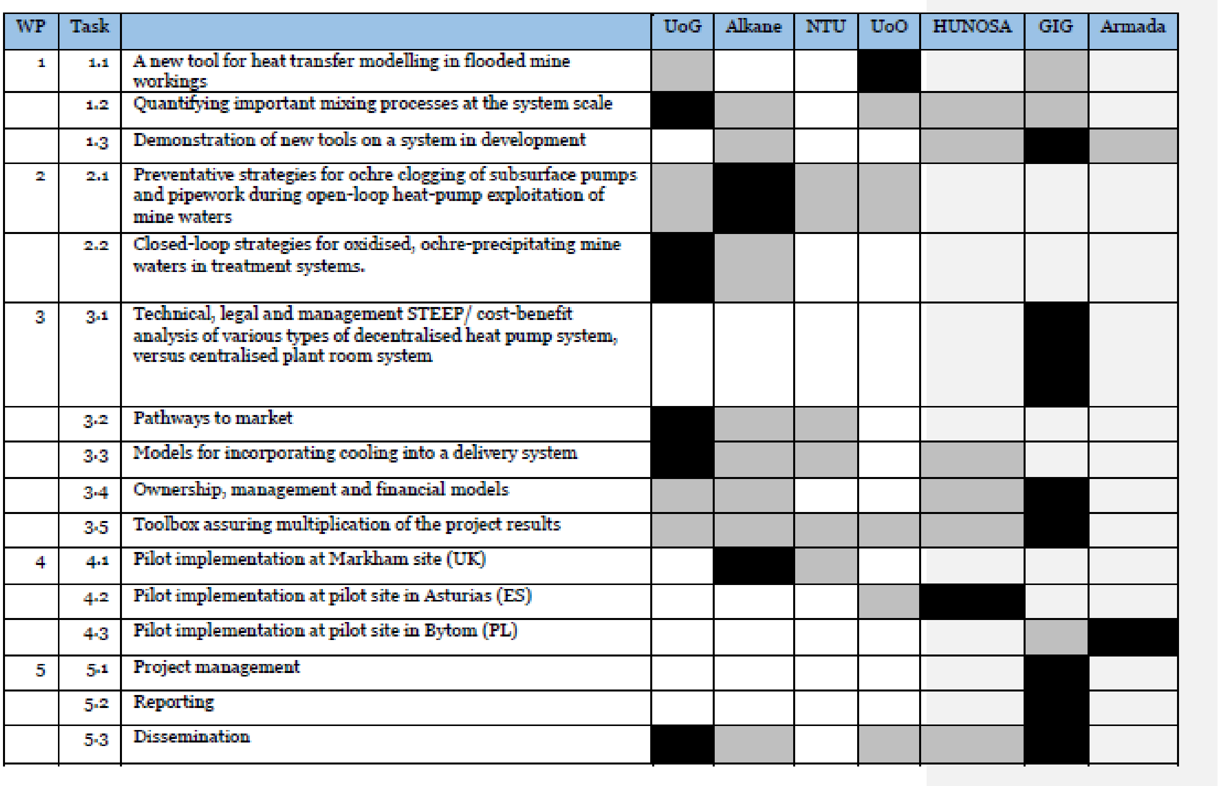
LoCAL background

This report forms part of the output from the LoCAL (*Low Carbon AfterLife: Sustainable Use of Flooded Coal Mine Voids as a Thermal Energy Source- a Baseline Activity for Minimising Post-Closure Environmental Risks*) project, funded by the European Commission Research Fund for Coal and Steel, grant number RFCR-CT-2014-00001.

The fundamental objective of LoCAL is to provide a number of technical, economic and management tools, aimed at overcoming barriers to the uptake of mine water in abandoned flooded coal mines as a source for heating and cooling (passively, or via the use of heat pumps). The project is divided into five Work Packages (WP) and a number of Tasks.



WP	Task		UoG	Alkane	NTU	UoO	HUNOSA	GIG	Armada
1	1.1	A new tool for heat transfer modelling in flooded mine workings	▒			■		▒	
	1.2	Quantifying important mixing processes at the system scale	■	▒		▒	▒	▒	
	1.3	Demonstration of new tools on a system in development		▒			▒	■	▒
2	2.1	Preventative strategies for ochre clogging of subsurface pumps and pipework during open-loop heat-pump exploitation of mine waters	▒	■	▒	▒			
	2.2	Closed-loop strategies for oxidised, ochre-precipitating mine waters in treatment systems.	■	▒					
3	3.1	Technical, legal and management STEEP/ cost-benefit analysis of various types of decentralised heat pump system, versus centralised plant room system						■	
	3.2	Pathways to market	■	▒	▒				
	3.3	Models for incorporating cooling into a delivery system	■	▒	▒		▒		
	3.4	Ownership, management and financial models	▒	▒			▒	■	
	3.5	Toolbox assuring multiplication of the project results	▒	▒	▒	▒	▒	■	
4	4.1	Pilot implementation at Markham site (UK)		■	▒				
	4.2	Pilot implementation at pilot site in Asturias (ES)				▒	■		
	4.3	Pilot implementation at pilot site in Bytom (PL)						▒	■
5	5.1	Project management						■	
	5.2	Reporting						■	
	5.3	Dissemination	■	▒		▒	▒	■	

UoG = University of Glasgow (UK), Alkane = Alkane Energy Ltd. (UK), NTU = Nottingham Trent University (UK), a subcontractor to Alkane; UoO = University of Oviedo (Spain), GIG = Central Mining Institute (Poland). Black boxes indicate Task Manager, grey indicate Task Participant.

The LoCAL Project aims at providing bespoke tools for investigating flow and heat transfer in flooded mine workings. New tools for quantifying and modelling heat transfer in networks of flooded mine workings are under development Another aim of the LoCAL project is to overcome the hydrochemical barriers to effective heat transfer from raw and treated mine waters. Ochre clogging is a well-known phenomenon which affects many mine water heating and cooling systems. The LoCAL project covers technical and engineering issues, and provides economic, legal and management models for efficient energy extraction and distribution of various types of decentralised and centralised heat pump.

Project activities are being undertaken in mining areas of the UK by research organizations in partnership with industrial enterprises (University of Glasgow in partnership with Alkane Energy Ltd.), Spain (University of Oviedo, with HUNOSA as the industrial partner) as well as in Poland (Central Mining Institute, in partnership with Armada Development).

This report aims to throw more light on the benefit/cost and energy efficiency from the mixing process. This task links to the Task 1.2 of the WP1.

Main objectives of WP 4:

- To find out how the COP of a system differs with a water level at different heights below the ground surface attending to a flooding process.
- To quantify the mixing process and the effect on the efficiency (COP) in a system with the reinjection of used mine water,
- To find out how the COP of large-scale system differs by the use of different heat exchanger and the economic impact of the WP2, advanced methods for preventing corrosion and incrustation affecting heat transfer.
- To support with real data models for efficiency of energy extraction and distribution analysed on WP3.

The objective of this Report is to fulfil the requirements of Deliverable 4.3 of LoCAL – Report on the findings of the study of field trials for the evaluation of dissolved gas partial pressures.

Summary of the deliverable

Periodic sampling of mine water was carried and the equipment was inspected at frequent intervals to look for any signs of ochre acclamation. At Markham, the water is pumped and injected back into the same shaft, but at different level. Care has been take to see that mine water does not come in contact with the air. With the iron content being very low, even with a high dissolved oxygen content and low methane and carbon-di-oxide content, no clogging has been observed. At Caphouse, the mine water has higher amount of iron concentration than the Markham site and it is partially oxygenated in the shaft (even though the methane and carbon-di-oxide are present in higher concentration), causing ochre precipitation. The analysis of the samples collected from the two site indicate it.

Markham

Markham Colliery History and Configuration

Markham Colliery, located just north of Bolsover, Derbyshire, UK, comprises four main shafts. The site (1.3285°W 53.2424°N) ('Burnside, et al., 2016). Three of those shafts were filled and capped. Two shafts (shafts No. 2 and 3) is now on the land occupied Alkane Energy. Since 1904, Markham colliery worked coal from several seams of the Westphalian Lower and Middle Coal Measures strata (Sheppard, 2005). Markham No. 3 shaft is the only one of the shafts that has not been backfilled, following abandonment in 1993. The shaft was brick-lined at 15 feet (4.6 m) diameter and was reportedly c. 490 m deep (HealeyHero, 2016). Shaft no. 1 and 4, with which shaft no. 3 interconnected, reached the Blackshale coal at c. 630 m deep ('Burnside, et al., 2016). Markham colliery is part of a wider network of hydraulically interlinked abandoned collieries, including those at Arkwright (53.2296°N 1.3633°W), Bolsover (53.2350°N 1.3116°W), Duckmanton (53.2447°N 1.3521°W) and Ireland, Staveley (53.2626°N 1.3456°W). Markham No 3 Shaft was left largely open, following abandonment, with a hydraulically open plug at the level of the Ell seam (-357 m asl), to allow venting of mine gas, see Figure 1

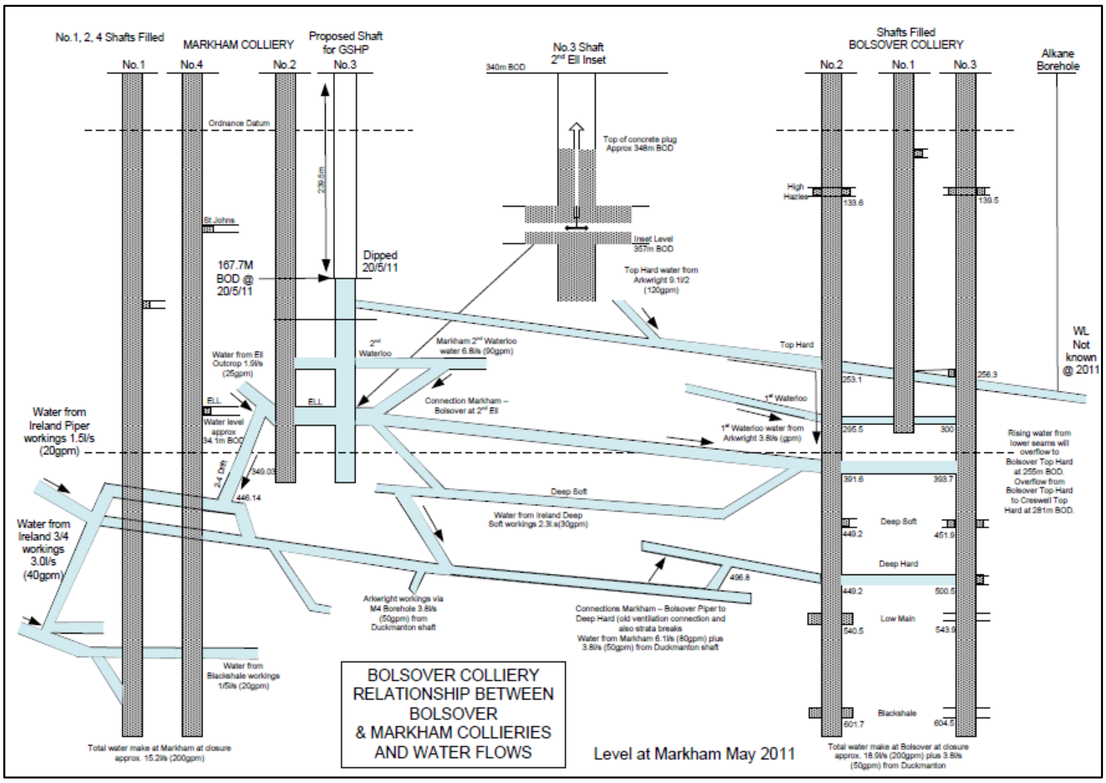


Figure 1: Schematic of the Markham colliery complex

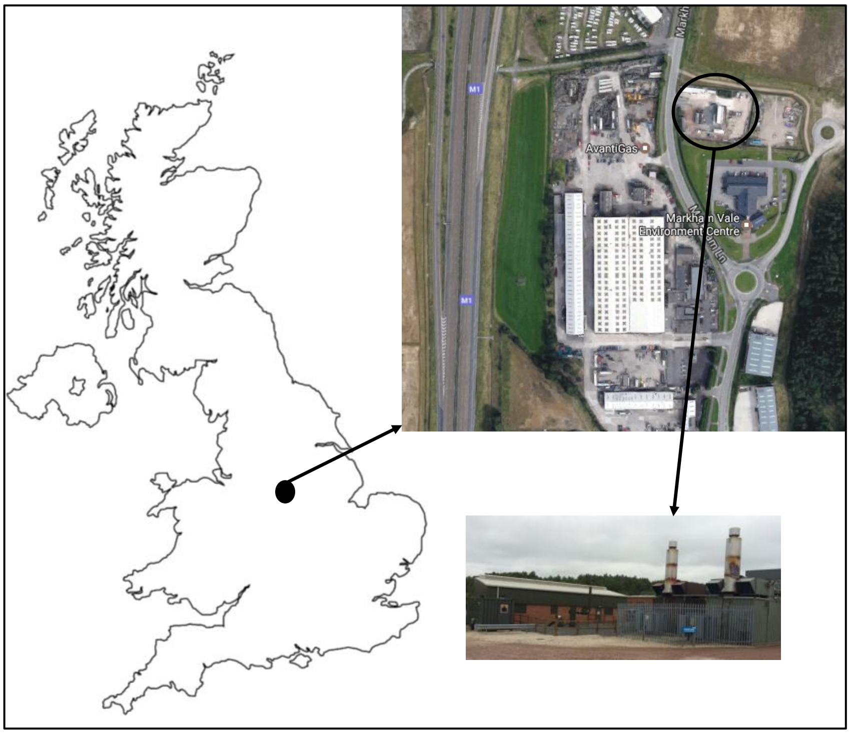


Figure 2: Google map image of Markham, Alkane energy

Mine water pumping regime from shaft number 3, Markham.

From 2012, water was pumped from 235 m below ground level (bgl) in the shaft at c. 15°C and 2-3 L/s, through shell and tube heat exchangers coupled to a 20 kW heat pump, to supply space heating to Alkane's commercial offices. The thermally spent (cool) water was returned to the same shaft at c. 250 m bgl at around 12°C. In January 2015, taking advantage of rising water levels, the pump was repositioned at 170 m bgl, and the reinjection diffuser at 153 m bgl. See Figure 3

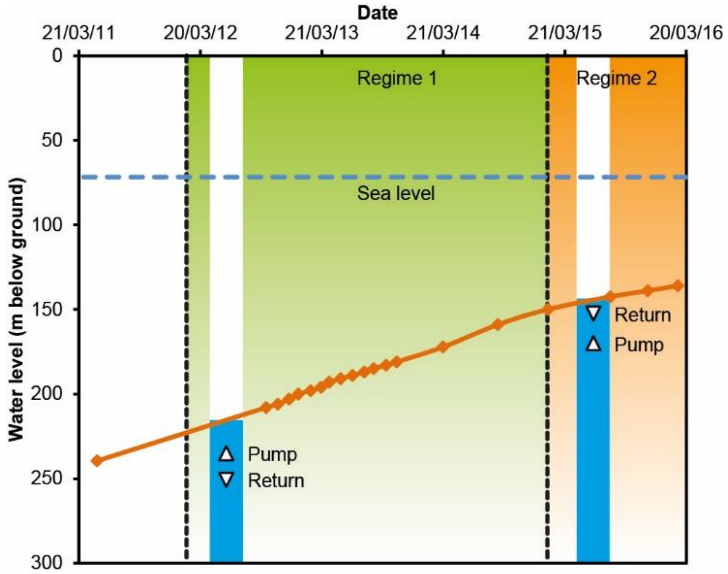
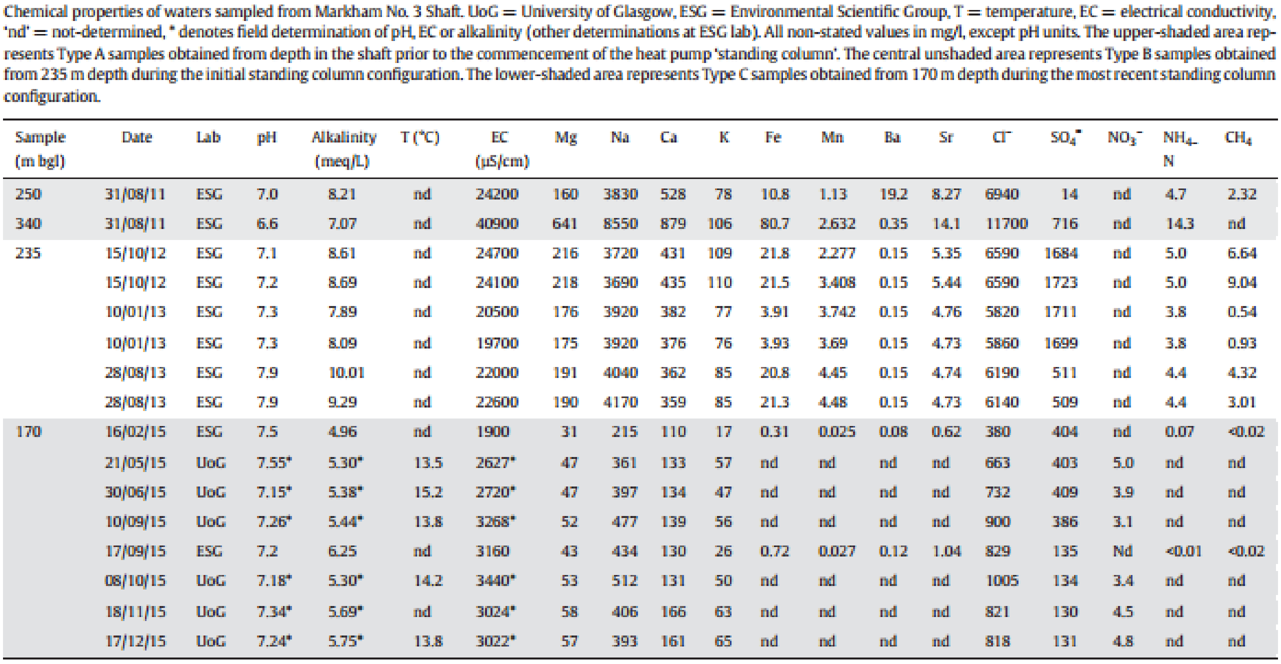


Figure 3: Schematic of the Markham No. 3 Shaft 'standing column' heat extraction arrangement, with rise in water level plotted ('Burnside, et al., 2016)

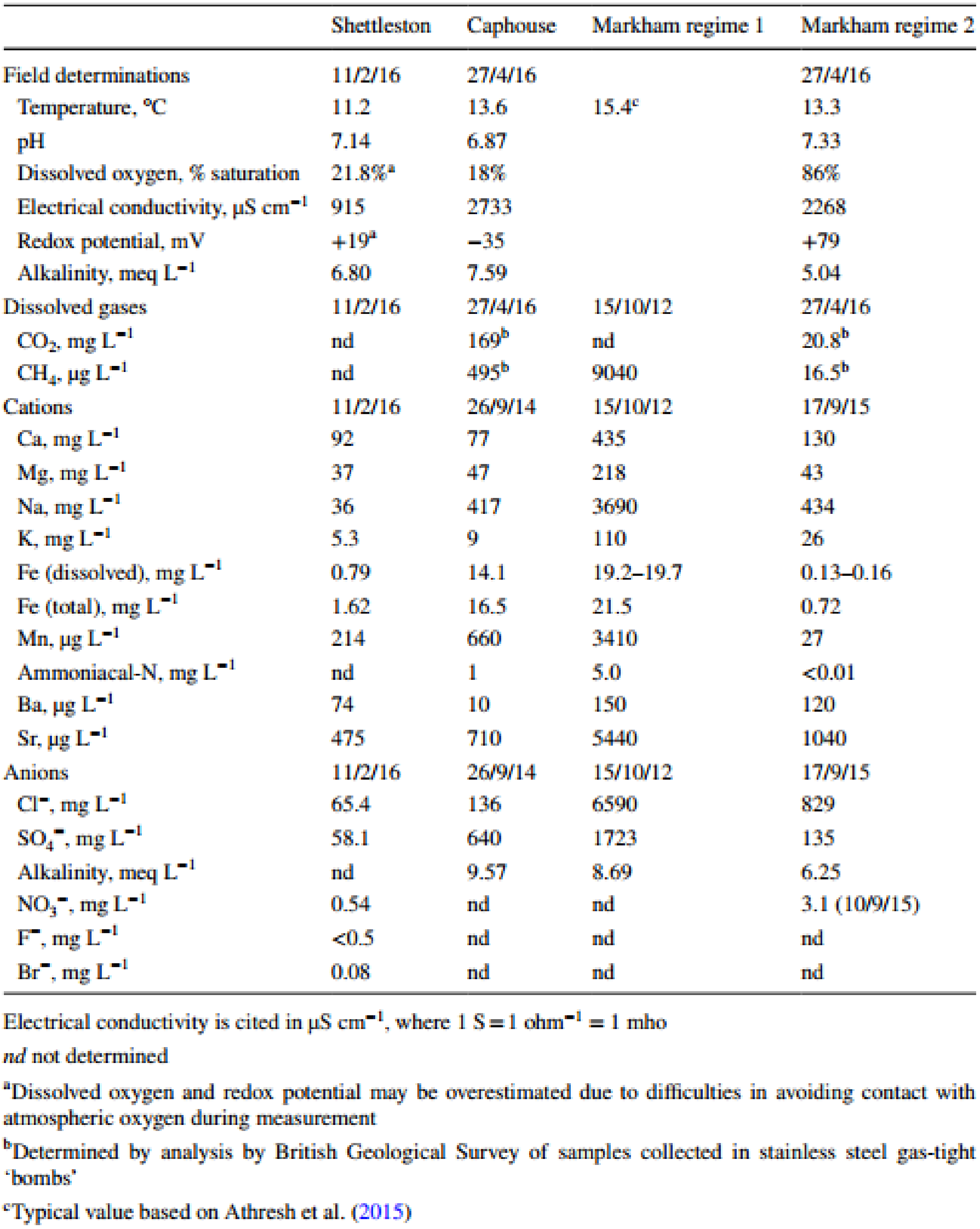
Table 1: Details of the water samples collected at Markham (Burnside, Banks and Boyce, 2016; 'Burnside, et al., 2016)



Chemical properties of waters sampled from Markham No. 3 Shaft. UoG = University of Glasgow, ESG = Environmental Scientific Group, T = temperature, EC = electrical conductivity, 'nd' = not-determined, * denotes field determination of pH, EC or alkalinity (other determinations at ESG lab). All non-stated values in mg/l, except pH units. The upper-shaded area represents Type A samples obtained from depth in the shaft prior to the commencement of the heat pump 'standing column'. The central unshaded area represents Type B samples obtained from 235 m depth during the initial standing column configuration. The lower-shaded area represents Type C samples obtained from 170 m depth during the most recent standing column configuration.

Sample (m bgl)	Date	Lab	pH	Alkalinity (meq/L)	T (°C)	EC (µS/cm)	Mg	Na	Ca	K	Fe	Mn	Ba	Sr	Cl^-	$SO_4^{=}$	NO_3^-	NH_4-N	CH_4
250	31/08/11	ESG	7.0	8.21	nd	24200	160	3830	528	78	10.8	1.13	19.2	8.27	6940	14	nd	4.7	2.32
340	31/08/11	ESG	6.6	7.07	nd	40900	641	8550	879	106	80.7	2.632	0.35	14.1	11700	716	nd	14.3	nd
235	15/10/12	ESG	7.1	8.61	nd	24700	216	3720	431	109	21.8	2.277	0.15	5.35	6590	1684	nd	5.0	6.64
	15/10/12	ESG	7.2	8.69	nd	24100	218	3690	435	110	21.5	3.408	0.15	5.44	6590	1723	nd	5.0	9.04
	10/01/13	ESG	7.3	7.89	nd	20500	176	3920	382	77	3.91	3.742	0.15	4.76	5820	1711	nd	3.8	0.54
	10/01/13	ESG	7.3	8.09	nd	19700	175	3920	376	76	3.93	3.69	0.15	4.73	5860	1699	nd	3.8	0.93
	28/08/13	ESG	7.9	10.01	nd	22000	191	4040	362	85	20.8	4.45	0.15	4.74	6190	511	nd	4.4	4.32
	28/08/13	ESG	7.9	9.29	nd	22600	190	4170	359	85	21.3	4.48	0.15	4.73	6140	509	nd	4.4	3.01
170	16/02/15	ESG	7.5	4.96	nd	1900	31	215	110	17	0.31	0.025	0.08	0.62	380	404	nd	0.07	<0.02
	21/05/15	UoG	7.55*	5.30*	13.5	2627*	47	361	133	57	nd	nd	nd	nd	663	403	5.0	nd	nd
	30/06/15	UoG	7.15*	5.38*	15.2	2720*	47	397	134	47	nd	nd	nd	nd	732	409	3.9	nd	nd
	10/09/15	UoG	7.26*	5.44*	13.8	3268*	52	477	139	56	nd	nd	nd	nd	900	386	3.1	nd	nd
	17/09/15	ESG	7.2	6.25	nd	3160	43	434	130	26	0.72	0.027	0.12	1.04	829	135	Nd	<0.01	<0.02
	08/10/15	UoG	7.18*	5.30*	14.2	3440*	53	512	131	50	nd	nd	nd	nd	1005	134	3.4	nd	nd
	18/11/15	UoG	7.34*	5.69*	nd	3024*	58	406	166	63	nd	nd	nd	nd	821	130	4.5	nd	nd
	17/12/15	UoG	7.24*	5.75*	13.8	3022*	57	393	161	65	nd	nd	nd	nd	818	131	4.8	nd	nd

Table 2: Details of the water samples from different sites in UK (Banks, et al., 2017)



	Shettleston	Caphouse	Markham regime 1	Markham regime 2
Field determinations	11/2/16	27/4/16		27/4/16
Temperature, °C	11.2	13.6	15.4[c]	13.3
pH	7.14	6.87		7.33
Dissolved oxygen, % saturation	21.8%[a]	18%		86%
Electrical conductivity, µS cm^{-1}	915	2733		2268
Redox potential, mV	+19[a]	−35		+79
Alkalinity, meq L^{-1}	6.80	7.59		5.04
Dissolved gases	11/2/16	27/4/16	15/10/12	27/4/16
CO_2, mg L^{-1}	nd	169[b]	nd	20.8[b]
CH_4, µg L^{-1}	nd	495[b]	9040	16.5[b]
Cations	11/2/16	26/9/14	15/10/12	17/9/15
Ca, mg L^{-1}	92	77	435	130
Mg, mg L^{-1}	37	47	218	43
Na, mg L^{-1}	36	417	3690	434
K, mg L^{-1}	5.3	9	110	26
Fe (dissolved), mg L^{-1}	0.79	14.1	19.2–19.7	0.13–0.16
Fe (total), mg L^{-1}	1.62	16.5	21.5	0.72
Mn, µg L^{-1}	214	660	3410	27
Ammoniacal-N, mg L^{-1}	nd	1	5.0	<0.01
Ba, µg L^{-1}	74	10	150	120
Sr, µg L^{-1}	475	710	5440	1040
Anions	11/2/16	26/9/14	15/10/12	17/9/15
Cl^-, mg L^{-1}	65.4	136	6590	829
$SO_4^=$, mg L^{-1}	58.1	640	1723	135
Alkalinity, meq L^{-1}	nd	9.57	8.69	6.25
NO_3^-, mg L^{-1}	0.54	nd	nd	3.1 (10/9/15)
F^-, mg L^{-1}	<0.5	nd	nd	nd
Br^-, mg L^{-1}	0.08	nd	nd	nd

Electrical conductivity is cited in µS cm^{-1}, where 1 S = 1 ohm^{-1} = 1 mho

nd not determined

[a] Dissolved oxygen and redox potential may be overestimated due to difficulties in avoiding contact with atmospheric oxygen during measurement

[b] Determined by analysis by British Geological Survey of samples collected in stainless steel gas-tight 'bombs'

[c] Typical value based on Athresh et al. (2015)

Caphouse

Caphouse colliery, where the system has been implemented, is now a part of the National Coal mining museum for England, where part of the underground galleries have now been converted into a museum and is open to the public. The underground galleries has to be kept dry and safe for the visiting public and for this reason dewatering pumps are employed to pump out the water. Unfortunately, the energy from this relatively warm water was not utilised efficiently despite the need for significant heating demands for the buildings of the museum. The mine water in that location has an iron content of circa 15 mg/l and is partially oxidised in the pumping shaft. The pumped water is ochre rich and undergoes passive treatment using several settling tanks and reed beds to remove the ochre before discharging it into a water stream. See Figure 4 Google satellite image of the water treatment tanks where the orange colour due to ochre is clearly visible.

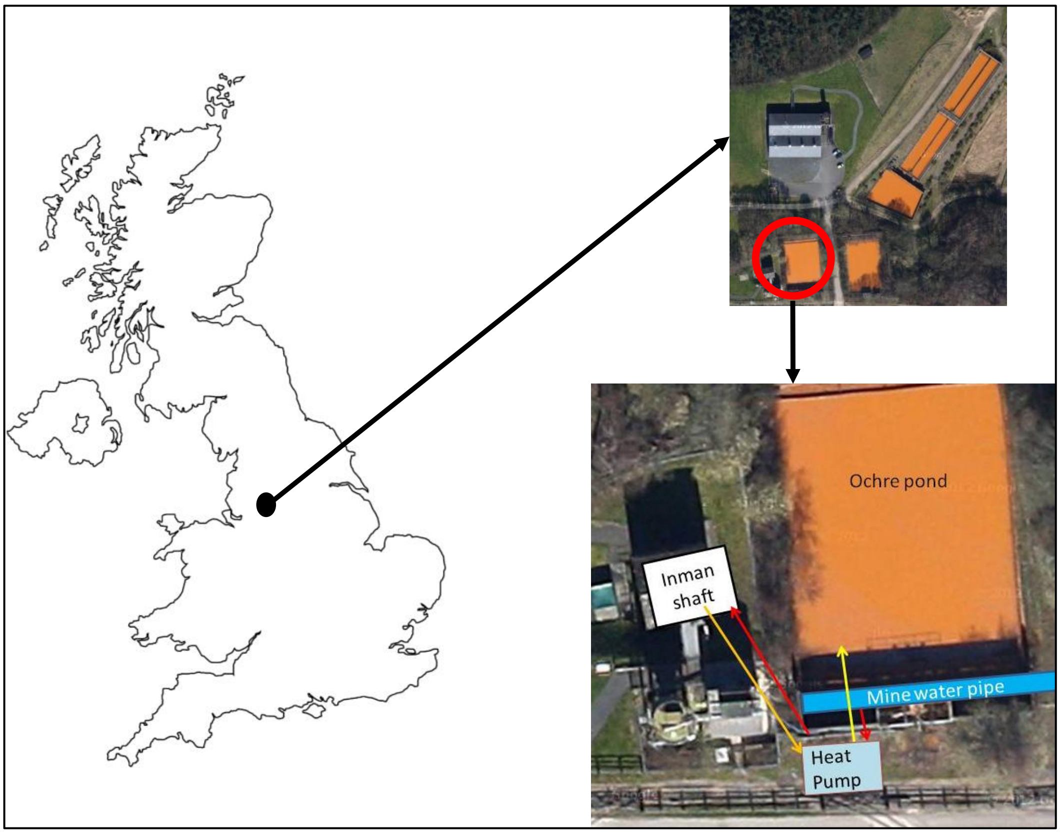


Figure 4: Google map image of the Caphouse site.

Main results

In Markham the mine water quality is fairly good and the total iron content in the water is less than 0.5 mg/l. The water quality has actually improved ever since the borehole pump was raised, previously the total iron content was circa 3.2 mg/l. The filters, pipelines and heat exchangers were removed and checked for any ochre deposition and very little deposition was noticed, during past 1.5 years. Thus by preventing the mine water from coming in contact with the oxygen the ochre clogging can be minimised to a great extent. Ever since the pump was raised, the water quality has significantly improved, see Table 1 and Table 2. The salinity has reduced considerably, see figure Figure 5 and Figure 6. The dissolved oxygen content in the water is on the higher side with 86 %, the carbon-di-oxide is 20.8 mg/l and methane is 16.5 mg/l.

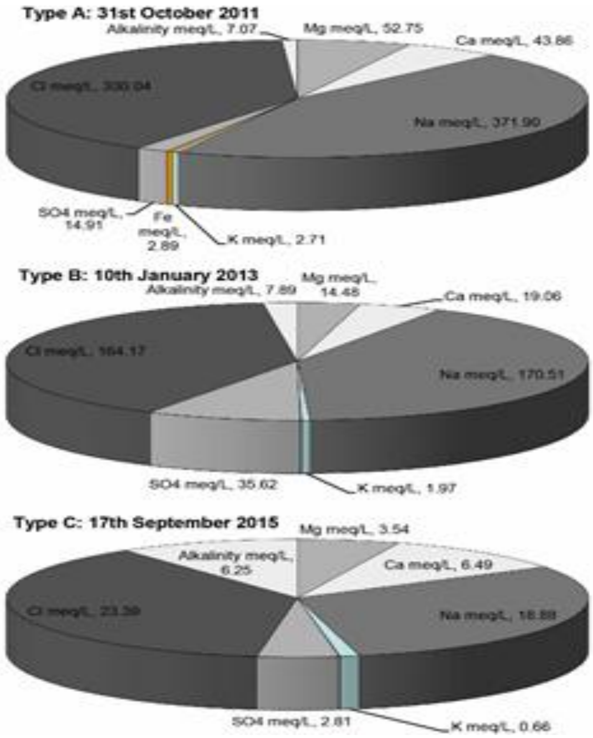


Figure 5: Pie diagrams comparing the major ion (meq/L) composition of the Markham No. 3 Shaft mine water in October 2011 (Type A), January 2013 (Type B) and September 2015 (Type C) (Burnside et al. 2016).

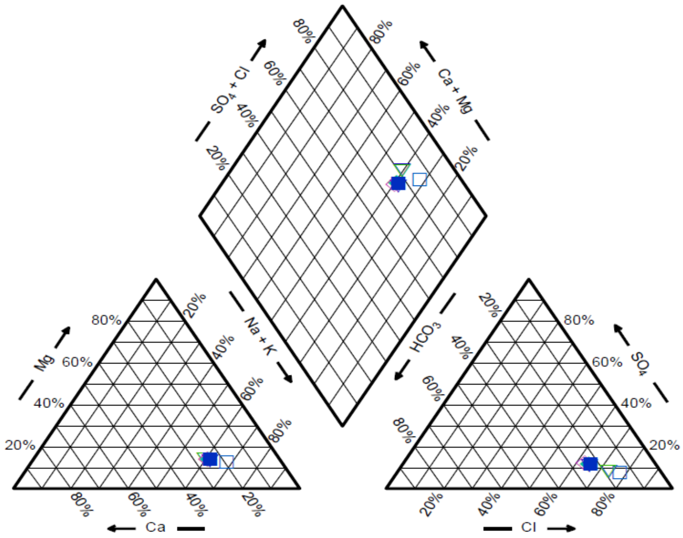


Figure 6: Piper diagram representation of cation and anion sample distribution for Type C waters (Burnside et al. 2016).

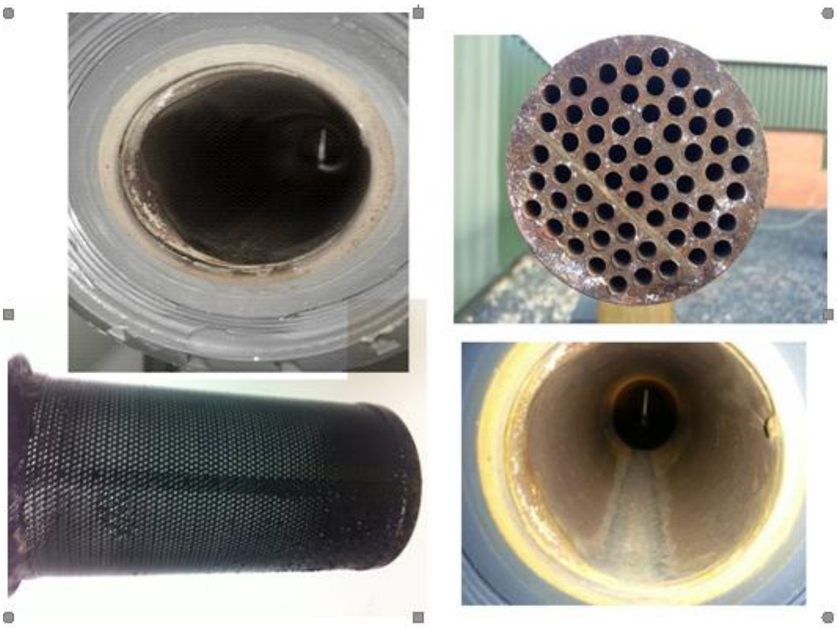


Figure 7: Inspection of pipelines at Markham

At Caphouse as expected there is a lot of clogging of the heat exchanger and the filter requires frequent cleaning, see Figure 10. It can be seen from

Figure 8 and Figure 9, the water quality is improving with most of the parameters except chlorine decreasing. The iron content in the water is circa 15 mg/l. The dissolved oxygen, methane and carbon-di-oxide contents in water are 18%, 495 mg/l and 169 mg/l respectively. See Table 2.

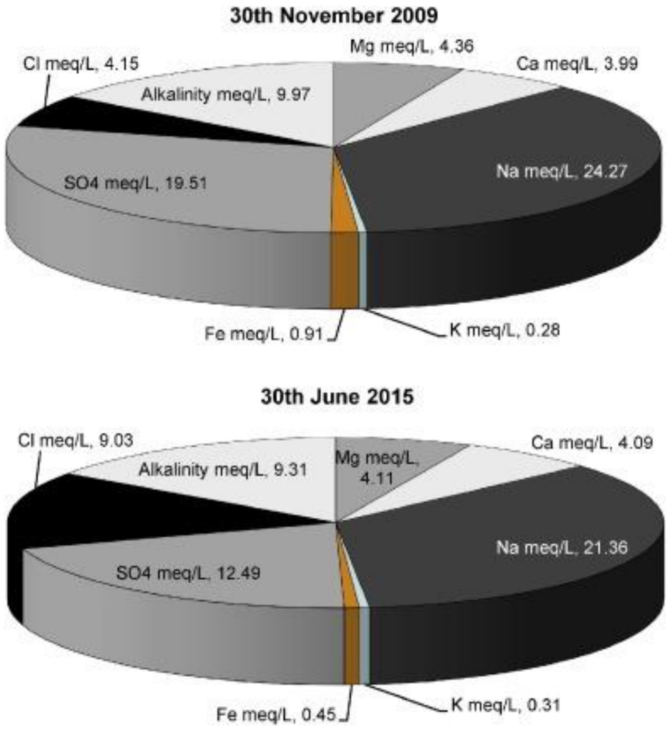


Figure 8: **Pie diagrams comparing major ion (meq/l) composition of Hop Shaft mine water in November 2009 and June 2015** (Burnside, Banks and Boyce, 2016)

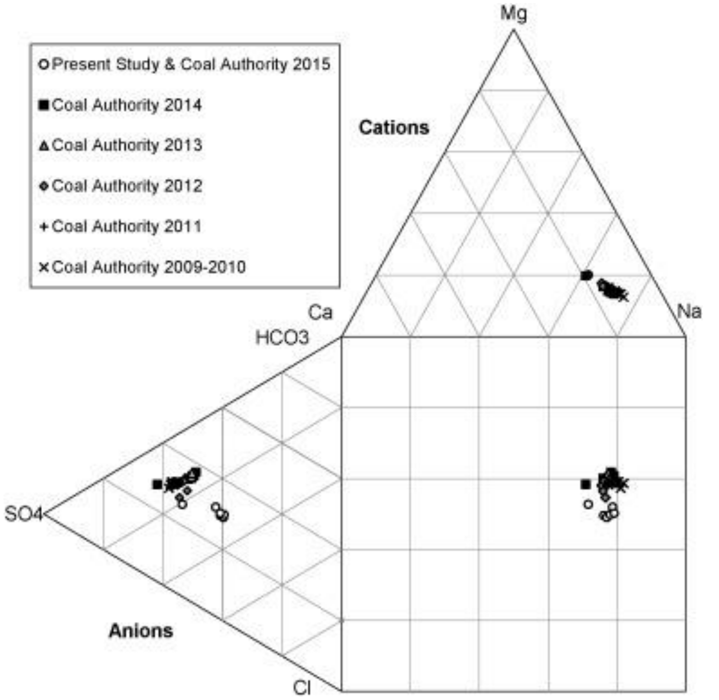


Figure 9: Durov plot for present study and Coal Authority data for May–October from 2009 to 2015 (Burnside, Banks and Boyce, 2016)

Figure 10: The ochre accumaltaion in the filter basket, at Caphouse.

Conclusions

Iron content dissolved oxygen, methane and carbon-di-oxide play a very important role in ochre precipitation and hence corrosion. By analysing the mine water quality and using suitable materials for the equipment; it is possible to minimise if not eliminate the effects of ochre clogging, incrustation and corrosion.

It is clear from the inspection and analysis of the water samples, that if the total iron content in water is low, there will be no clogging problems, even if the dissolved oxygen content is on the higher side and carbon-di-oxide and methane are degassed. By using marine grade material for heat exchangers, filters and pipeline the corrosion impact can almost be eliminated.

At Caphouse, the total iron content is on a higher side and the carbon-di-oxide and methane are not degassed, even small amount of dissolved oxygen can cause ochre precipitation. By using marine grade or corrosion resistant materials the problems of corrosion can be minimised.

Publications

- ATHRESH, A.P., AL-HABAIBEH, A. and PARKER, K., 2015. Innovative Approach for Heating of Buildings Using Water from a Flooded Coal Mine Through an Open Loop Based Single Shaft GSHP System. Energy Procedia, 75, pp. 1221-1228.
- Burnside, N. M., David Banks, and A. J. Boyce. "Sustainability of thermal energy production at the flooded mine workings of the former Caphouse Colliery, Yorkshire, United Kingdom." International Journal of Coal Geology 164 (2016): 85-91.
- Burnside, N.M., Banks, D., Boyce, A.J & Athresh, A. (2016). Hydrochemistry and stable isotopes as tools for understanding the sustainability of minewater geothermal energy production from a ‘standing column’ heat pump system: Markham Colliery, Bolsover, Derbyshire, UK. International Journal of Coal Geology
- Banks D, Athresh A, Al-Habaibeh A and Burnside N (in prep) Water from abandoned mines as a heat source: practical experiences of open- and closed-loop strategies, United Kingdom. Provisionally accepted for publication in *Journal of Sustainable Water Resources Management.*