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 1.5

Synthetic report on field site tracer tests

WP number	**WP 1**
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Deliverable 1.5

Synthetic report on field site tracer tests

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Introduction

Hydrological tracers can be used to gather data on water movement in flooded mine workings and provide key insights into subsurface hydrodynamics and mixing behavior. Natural (*in situ*) and artificial (injected during testing) mine water tracer tests studies have both been employed to assess hydrological flow paths, surface connectivity, and breakdown of water column stratification upon pumped extraction (Table 1).

Table 1. Reported tracers utilized in mine water studies, after Burnside 2010; Elliot and Younger 2013; Sánchez-España et al. 2014; and Wolkersdorfer 2002.

Artificial Tracers	Natural tracers
Salts	**Physicochemistry**
Chloride	Temperature
Bromide	Conductivity
Sulphur hexafluoride	**Hydrochemistry**
Lithium	Major ions
Iodide	CFC
Borate	REE
Dyes	Zinc
Fluorescein	**Dissolved gases**
Uranine	Carbon Dioxide
Rhodamine B	**Stable Isotopes**
Rhodamine WT	Oxygen
Solid tracers	Hydrogen
Lycopodium	Sulphur
Club Moss Spores	Lead
Microspheres	**Radioisotopes**
Radioactive tracers	Tritium
Krypton	Carbon
Neutron activation analysis	Uranium
Halogens	
REE (chelated)	

The usefulness of both tracer types, in the context of flooded mine workings, is highly dependent on the chemical composition and pH of the resident mine waters. Natural, or environmental, tracers occur naturally in water without being added, or injected on purpose, to conduct a tracer test. Unlike artificial tracers, they can be used over large areas and long timescales (Wolkersdorfer 2008). Physical measurements, such water temperature, are comparatively easy to measure/monitor and therefore can play a major role in mine water investigations.

Artificial, or applied, tracers can be roughly divided into insoluble (dyes, solid particles) and soluble (salts and radioactive substances). Natural tracers can be repurposed as artificial tracers if injected on purpose for mine water investigations. Artificial tracers require comparatively intense monitoring programs to ensure success of any targeted investigation. In addition, their usefulness is highly dependent on appropriate test design (including determination of injection and sampling locations), the nature of the tracer, the ability to detect the tracer at low concentrations, and correct interpretation of recovery data (Cowie et al. 2014). Some varieties require regulatory permits before use, and can cause public perception issues due to their 'scary' sounding names (Wolkersdorfer 2008). Dyes, especially fluorescent varieties, are the most frequently user tracer types, and typically require appropriate environmental permits before use. Salts are also common, but can be prohibitively expensive in mine water studies as large quantities (up to several tons) may be required to ensure detection.

LoCAL site specific studies

Two specific sites where originally intended to be investigated for application of tracers, Manvers and Markham, both in the UK. Unfortunately, due to development challenges, the Manvers site could not be completed within the timeframe of the LoCAL project, and so no investigation could be carried out there. Markham is operational and is discussed in more detail below. There are three other active LoCAL study sites across Poland (Bytom), Spain (Barredo-Figaredo), and the UK (Caphouse). Due to excellent long-term monitoring work carried out by our Spanish partners, University of Oviedo and HUNOSA (Loredo 2017), we are able to include tracer studies of the Barredo-Figaredo hydrological system within this report. Due to logistical and access issues, artificial tracers could not be used in either study. Therefore, natural tracers will be the focus of site specific investigations.

Markham

The abandoned workings of the former Markham Colliery are still in the process of flooding. They are being exploited, via a ‘standing column’ heat pump arrangement in Markham No. 3 shaft, to produce thermal energy. 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 (Figure 1).

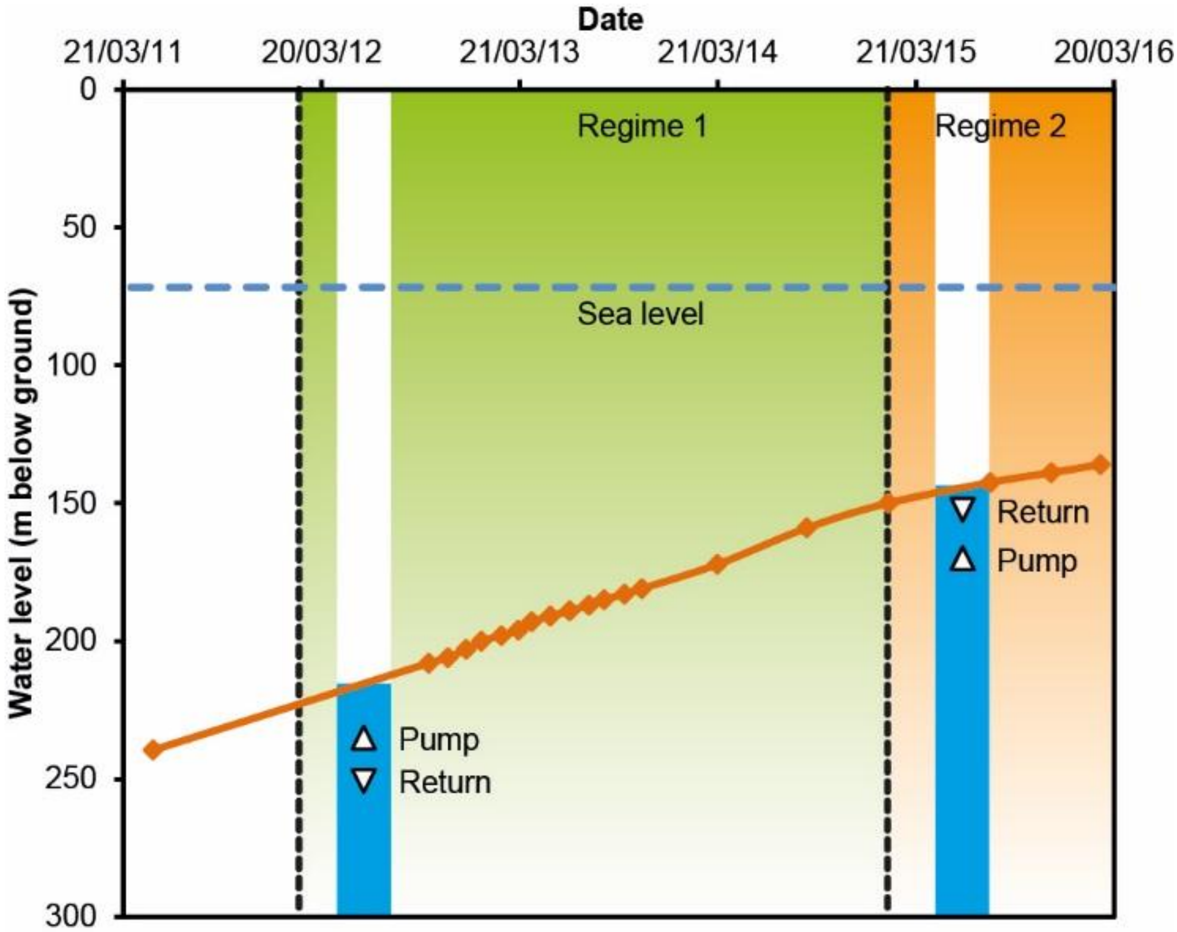


Figure 1. Schematic of the Markham No. 3 Shaft ‘standing column’ heat extraction arrangement, with rise in water level plotted (Burnside et al. 2016).

As part of Alkane Energy’s ongoing monitoring activities, suites of chemical samples had been collected from the pumped water supply. These results allow for comparison with the samples collected throughout the LoCAL project and provide useful insight into variations in water chemistry as shaft water levels have continued to rise and as the pump location has changed.

The water analysis obtained from Markham fall into three broad categories (Figure 2):

- Type A. Samples obtained during the investigative phase in 2011, prior to the installation of the heat pump system, from 250 and 340 m depth.
- Type B. Samples obtained from 2012 up to 28th January 2015, during the trialing and operation of the 'standing column' arrangement at 235-250 m depth (Regime 1 - Figure 1).
- Type C. Samples obtained following 28th January 2015, during the trialing and operation of the 'standing column' arrangement at 153-170 m depth (Regime 2 - Figure 1).

A clear difference is found between samples from

- Types A & B, which typically represent very saline, ammonium-, methane- and iron-rich water.
- Type C, which represents much less saline, methane- and iron-poor water.

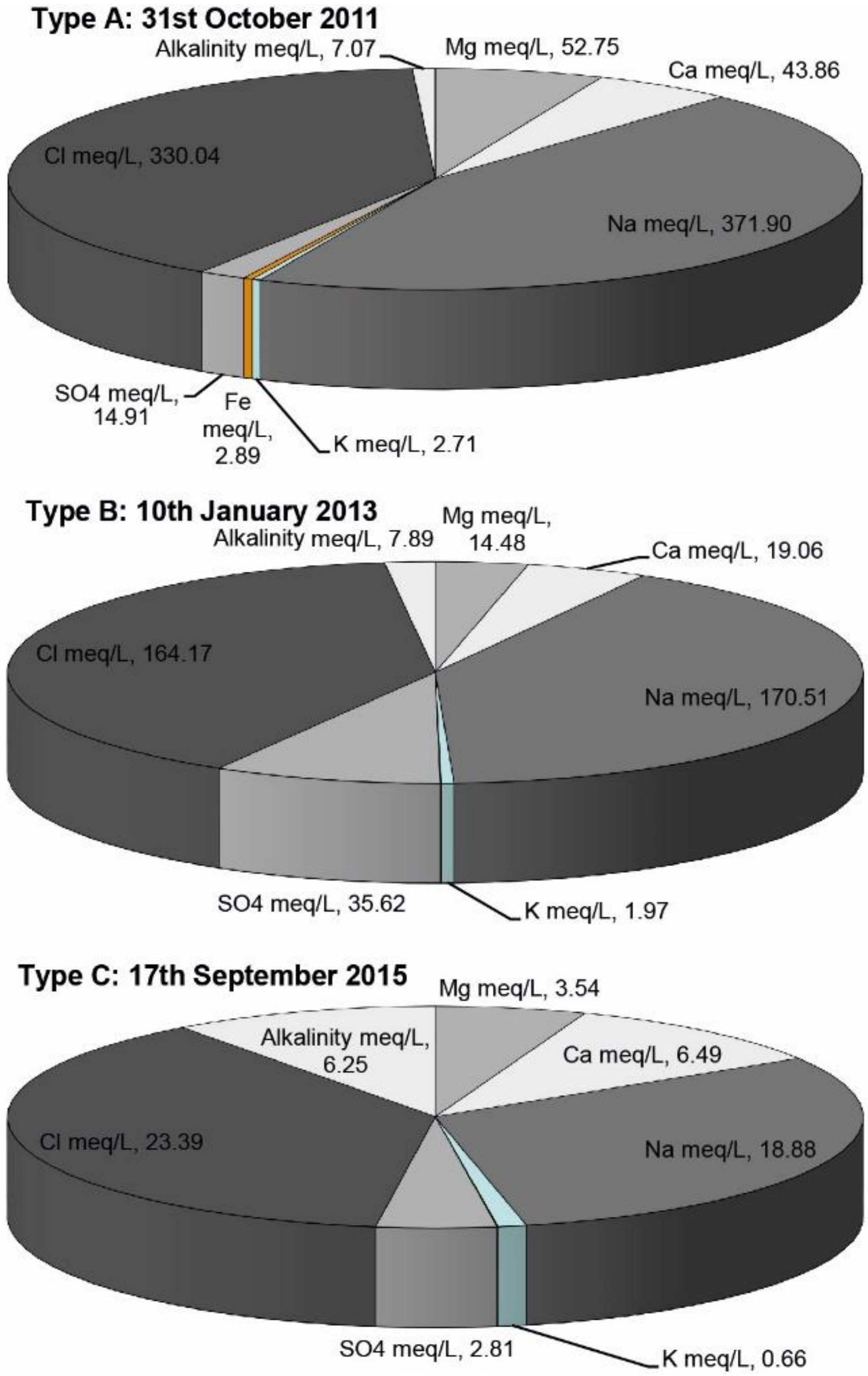


Figure 2. Pie diagrams comparing the major ion (meq/L) composition of the Markham No. 3 Shaft mine water in October 2011 (Type A), January 2013 (Type B) and September 2015 (Type C) (Burnside et al. 2016).

In the case of Markham, water salinity is clearly distinct across each of the three recorded pumping depths (Figure 3), and so represents an important tracer for determination of stratification and flow boundaries within the shaft's water column. Any increase in salinity in during the present LoCAL sampling regime would indicate breakdown of stratification within the water column and upwelling of deeper, saline waters. As this has not been observed we can conclude that the current pumping set-up does not encourage any breakdown of stratification. This observation is supported by stability in water chemistry composition throughout the LoCAL sampling regime at Markham (Figure 4).

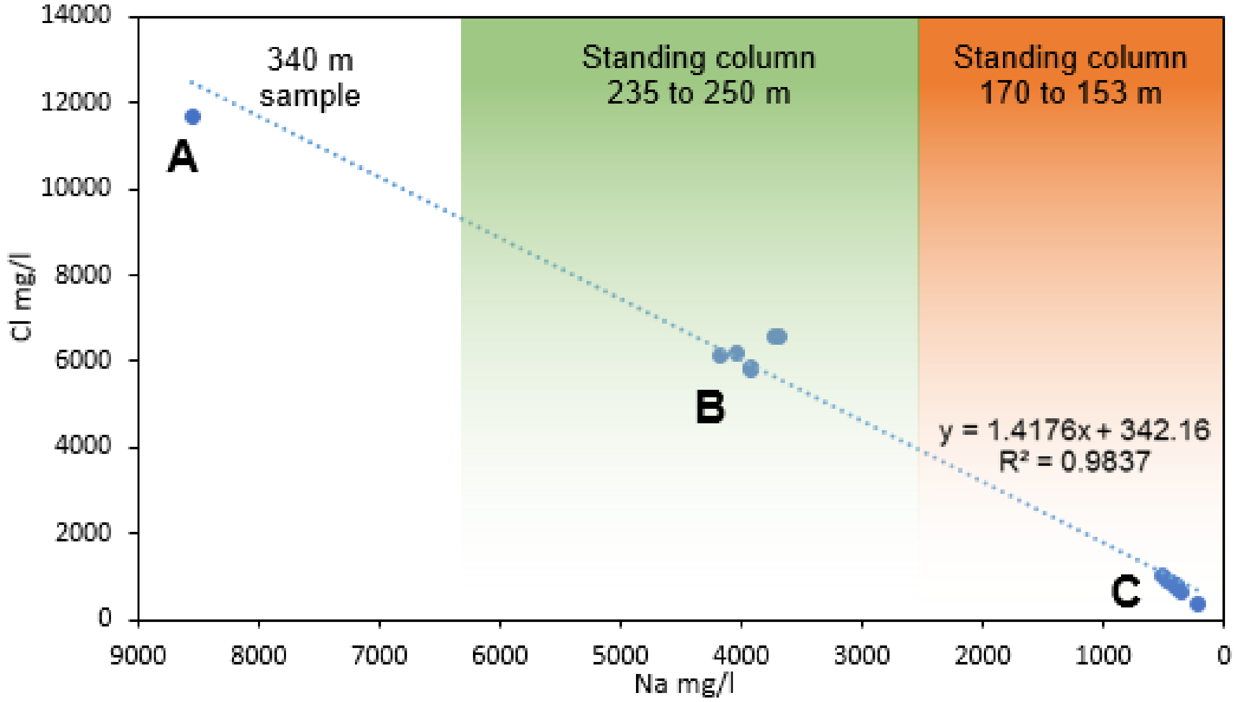


Figure 3. Plot of salinity (Na vs. Cl) evolution throughout alteration of pump depth. Water types labelled as in Fig. 2.

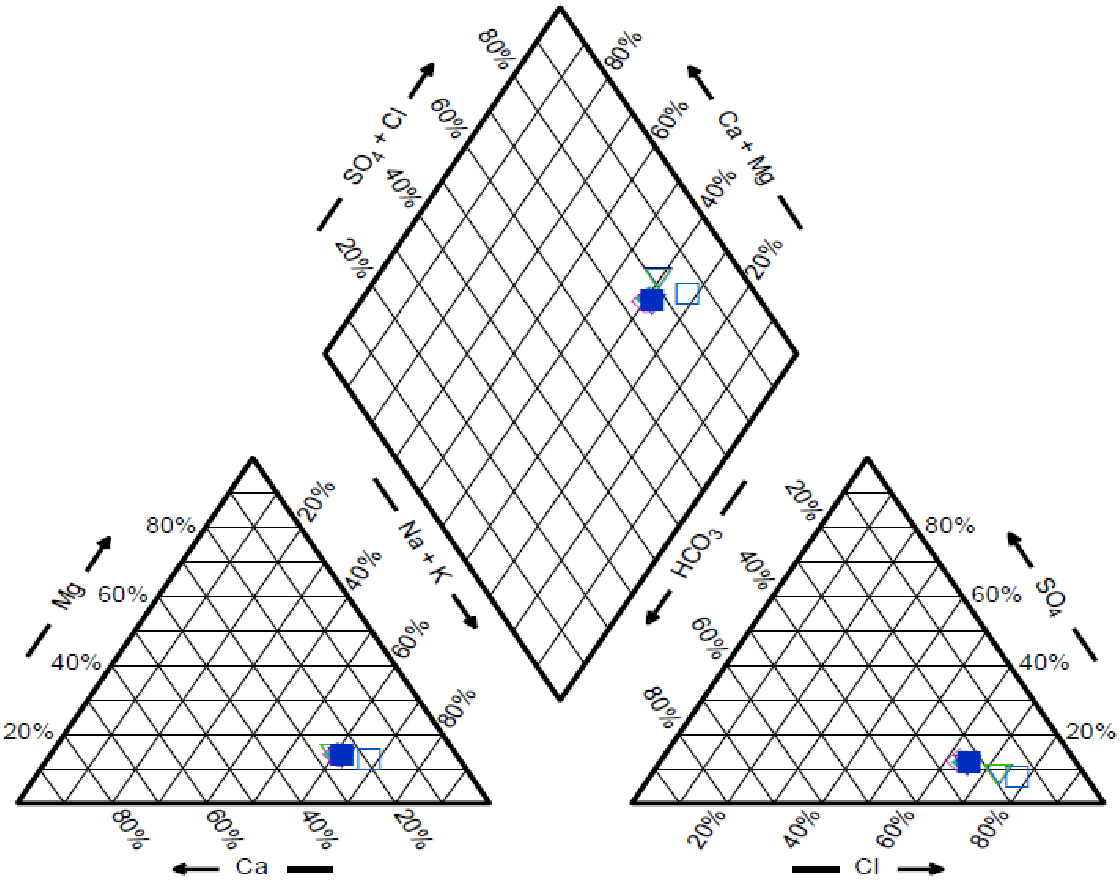


Figure 4. Piper diagram representation of cation and anion sample distribution for Type C waters.

The consistency in temperature, 14.1 ± 0.7°C, of pumped waters (170 mbgl) further suggests that the thermally spent cool water (153 mbgl) has minimal influence on extracted waters and may indicate further stratification boundary, or boundaries, between the extraction pump and reinjection diffusor.

Barredo-Figaredo

The following section was supplied by the University of Oviedo and includes information and figures from Loredo 2017. All data was supplied by HUNOSA. The Barredo underground mine was active from 1926 to 1993. It has 5 levels and a total depth of 360 m. Extractive activity at the Figaredo underground mine (formed by San Vicente and San Inocencio shafts) finished in 2007 and reached a maximum depth of 650 m. Both mines are clearly connected through faces and galleries, with the most important connection at 360 m, and they constitute a hydrogeologically isolated system (Figure 5). Extensive monitoring of temperature profiles from the extracted waters has allowed for valuable insights into water movement throughout this system.

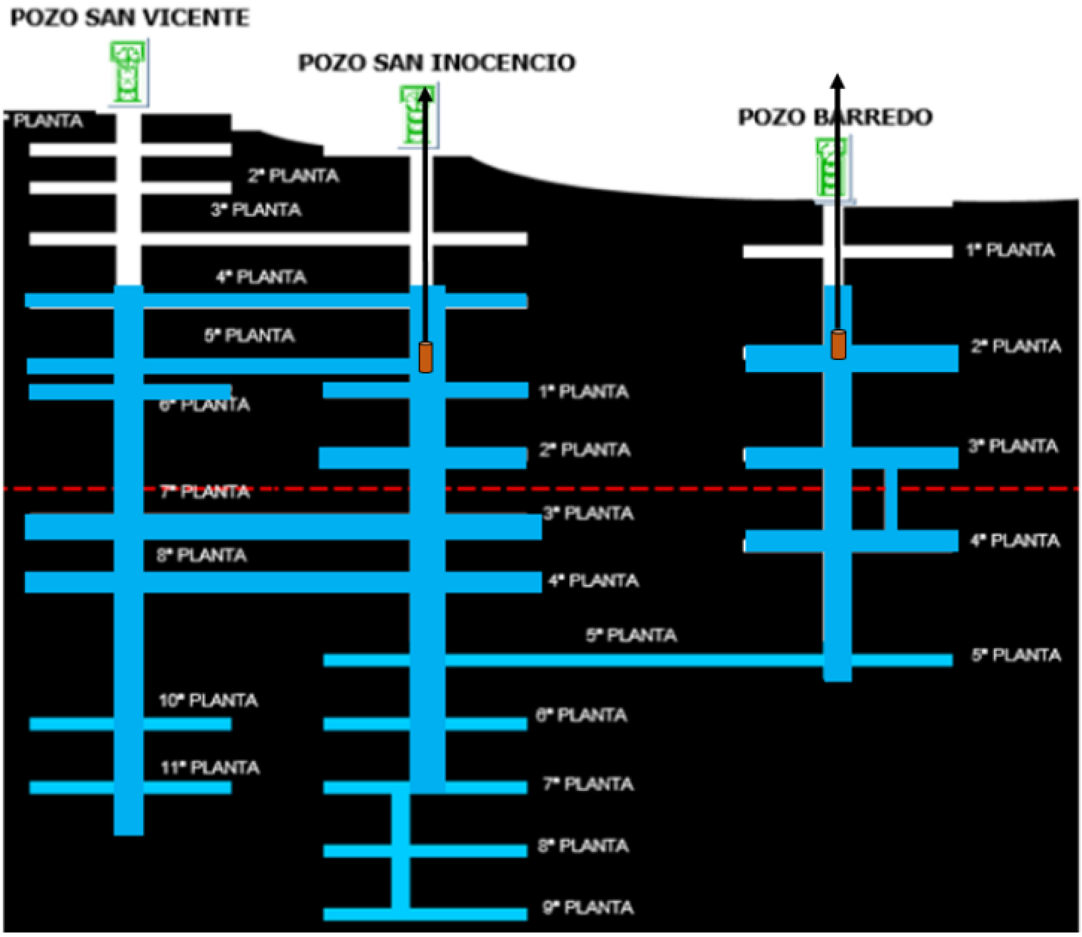


Figure 5. Barredo-Figaredo diagram

Several campaigns for measuring the temperature profiles of Barredo and Figaredo (San Inocencio) shafts were conducted by HUNOSA, the results can be observed in Figure 6.

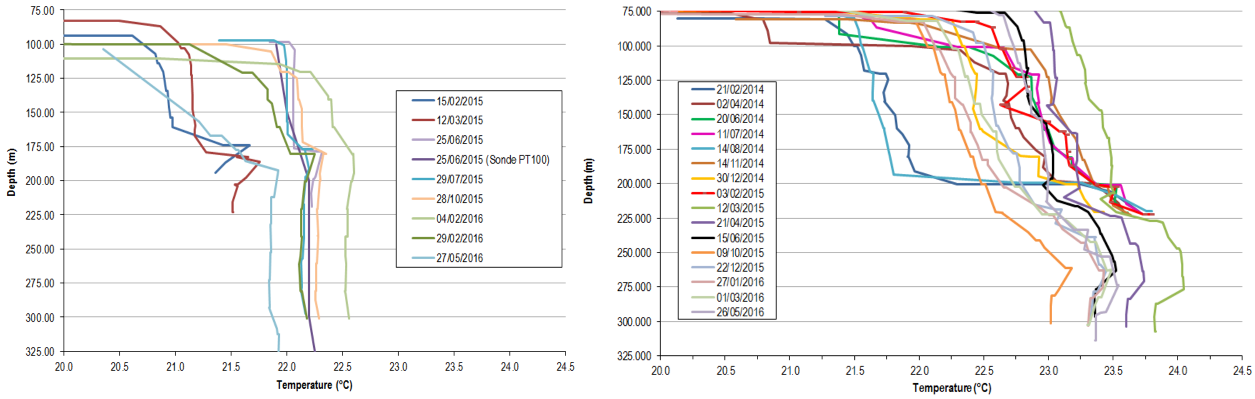


Figure 6. Figaredo (left) and Barredo (right) thermal profiles (2014-2016)

As the Barredo and Figaredo shafts differ in their wellhead altitude (220 m asl Barredo, 250 m asl Figaredo), hereinafter we will work with altitudes instead of depths. Following this strategy, the average, minimum and maximum values of both shafts have been plotted together (Figure 7). The shafts are geographically close (ca. 5 km apart), so it would be reasonable to expect the measurement of similar temperatures at similar altitudes, but surprisingly, it can be observed that water at Barredo is warmer than at Figaredo.

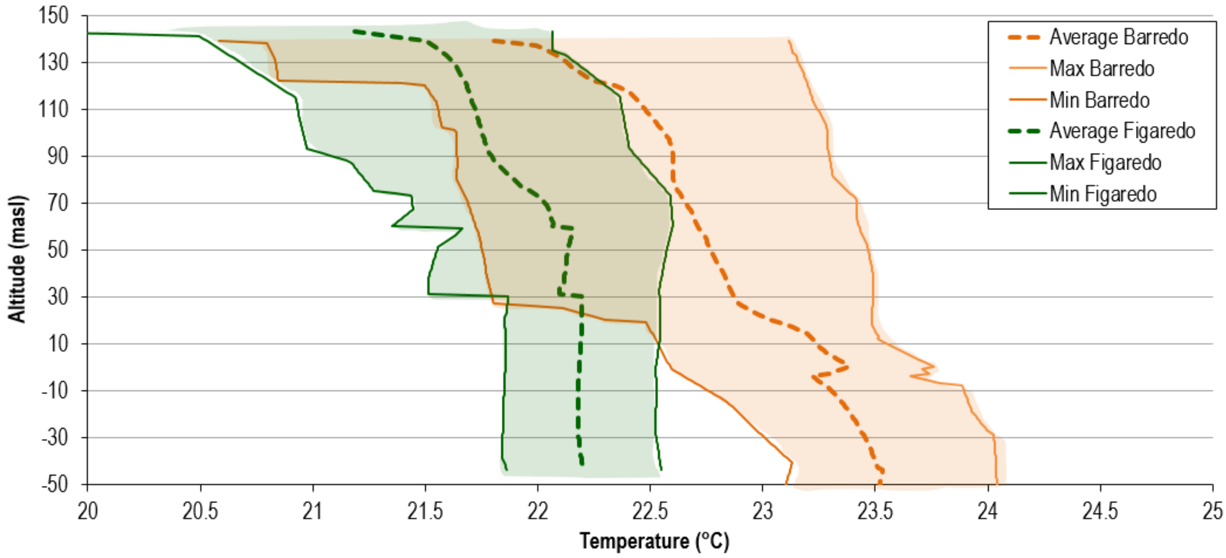


Figure 7. Barredo and Figaredo average, minimum and maximum thermal profiles (Feb14-Jun16).

It is likely that this is due to the influence and infiltration of cold Turón river waters at Figaredo and a heat transfer at the connection between Figaredo and Barredo (the main connection is 365 m bgl and about 5 km long). But, as can be seen in Figure 7, the thermal profile of each shaft evolves within the time (in a non-linear way) so further investigations into flowrate influences were carried out.

During active mining exploitation, all the water coming into the mine workings was pumped to ensure worker safety. The average percentage of pumped water from each shaft for the total water inflow in the Barredo-Figaredo system from 2002 to 2007 was calculated as 65% for Figaredo and as 35% for Barredo. These values are unsurprising as the Figaredo mine is bigger and receives infiltration from the Turón River.

After mine abandonment and flooding, the pumping strategy was changed. Now that both shafts are flooded, and in hydrological communication, the precise pumping location no longer maters so long as a regionally secure piezometric level is maintained. Thus, the pumping has been mainly centered at the Barredo shaft, which is now responsible for ca. 82.5% of the total flow (Figure 8). Data from the pre-flooded mining period suggests that half of the water currently pumped from Barredo comes from the Figaredo shaft.

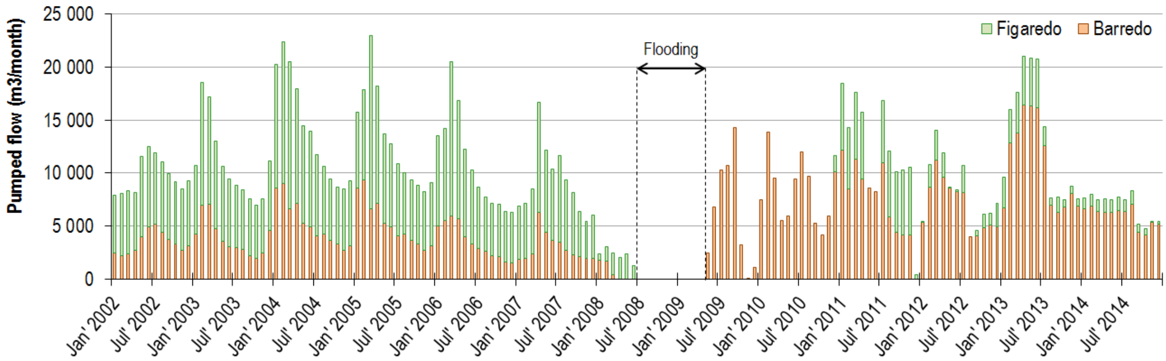


Figure 8. Temporary register of pumping rates at Barredo-Figaredo from 2002 to 2014

During the period of active mining, a fixed temperature sensor was placed in each of the two shafts, at 250 m bgl. These sensors have remained in place throughout abandonment and flooding of the Barredo-Figaredo system, and provide a continuous data set through to the present day. However, as access to them is no longer possible, a lack of maintenance has led to accuracy drift in their performance. Using the information provided by the thermal profiles (Figure 6) for the same depth, the offset of the sensors was corrected, and an eleven-day moving average was applied in order to reduce the signal noise. This type of convolution is widely used in signal filtration to reduce the effects of random noise (Smith, 2013).

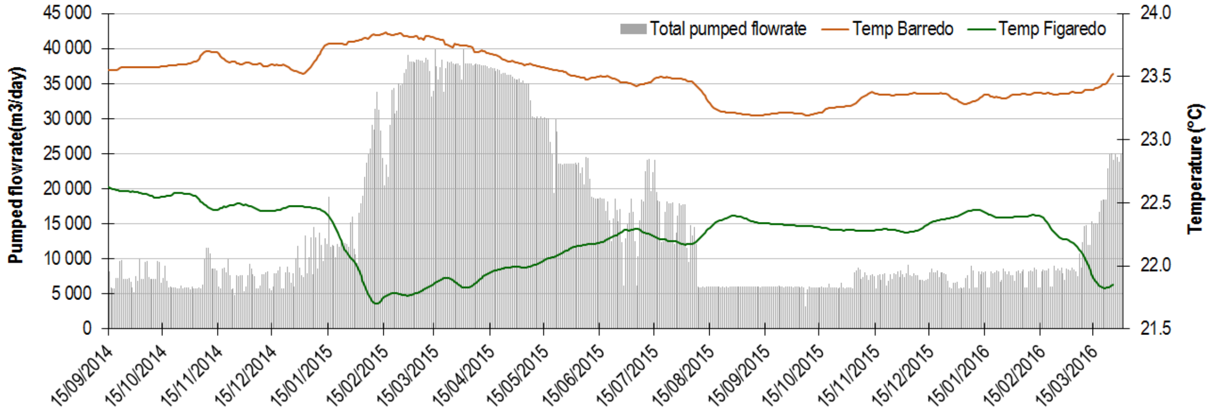


Figure 9. Corrected and averaged temperature and pumped flowrate for Barredo-Figaredo.

The corrected and averaged temperature data is presented along with the total pumped flowrate in Figure 9. Here, the distinctive behavior of the Barredo and Figaredo shafts is exposed: when the flowrate increases, Barredo temperature (plotted in orange) increases, whilst Figaredo temperature (plotted in green) decreases.

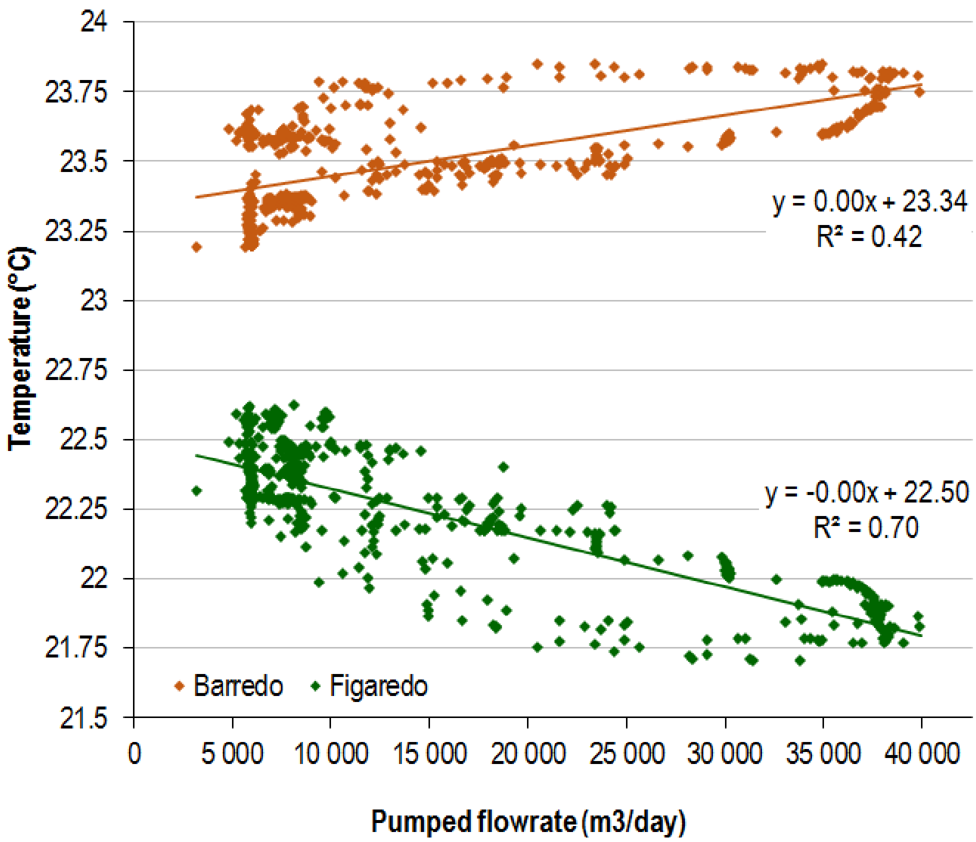


Figure 10. Direct (Barredo) and Inversed (Figaredo) correlation between pumped rate and temperature at the shaft

Figure 10 demonstrates the correlation between the pumped flowrate and the mine water temperature. Barredo water temperature is correlated with the flowrate (R^2=0.42) meanwhile Figaredo is strongly anti-correlated (R^2=0.70).

When analyzing the influence of the daily pumped flowrate in the daily temperature difference between Barredo and Figaredo a correlation of R^2=0.78 was obtained (Figure 11). So, the greater the pumped flow rate, the bigger the temperature difference between Barredo and Figaredo waters.

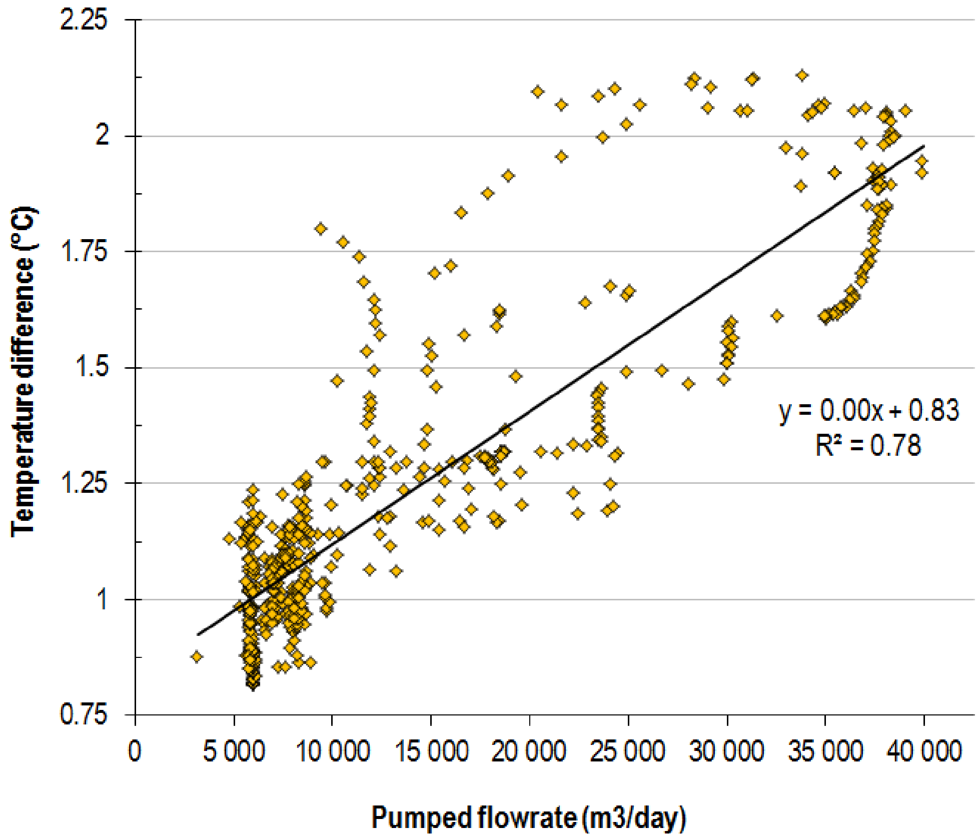


Figure 11. Temperature difference at Barredo-Figaredo with the pumped flowrate

Throughout the recorded data, there is only one day (12th of March 2015) where information is available on the thermal profiles for both the Barredo and Figaredo shafts. This allows for a direct, high-resolution comparison of pumping-rate influence on the temperature profiles of the two shafts.

As can be observed in Figure 12, there is an average difference of ca. 2°C between the shaft's water temperatures. This is one of the greatest thermal differences observed between all the studied curves, and interestingly, the pumped flowrate for this day was also one of the greatest on record. The correlation (Barredo) and anti-correlation (Figaredo) between the temperature and pumped flowrate variables observed for the data at 250 m depth, can therefore be extrapolated to the whole thermal profile of each shaft.

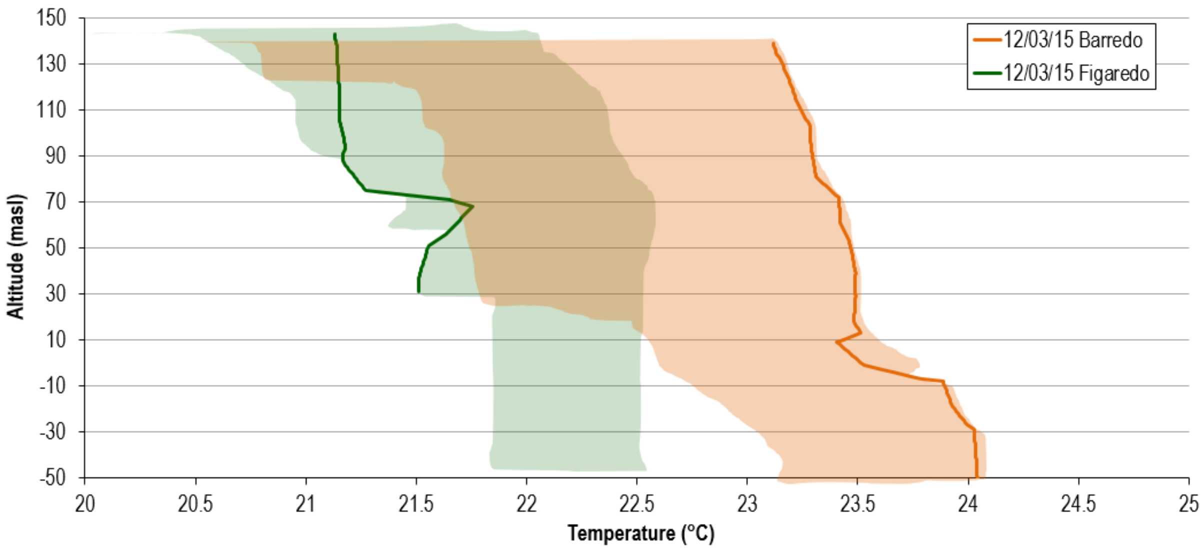
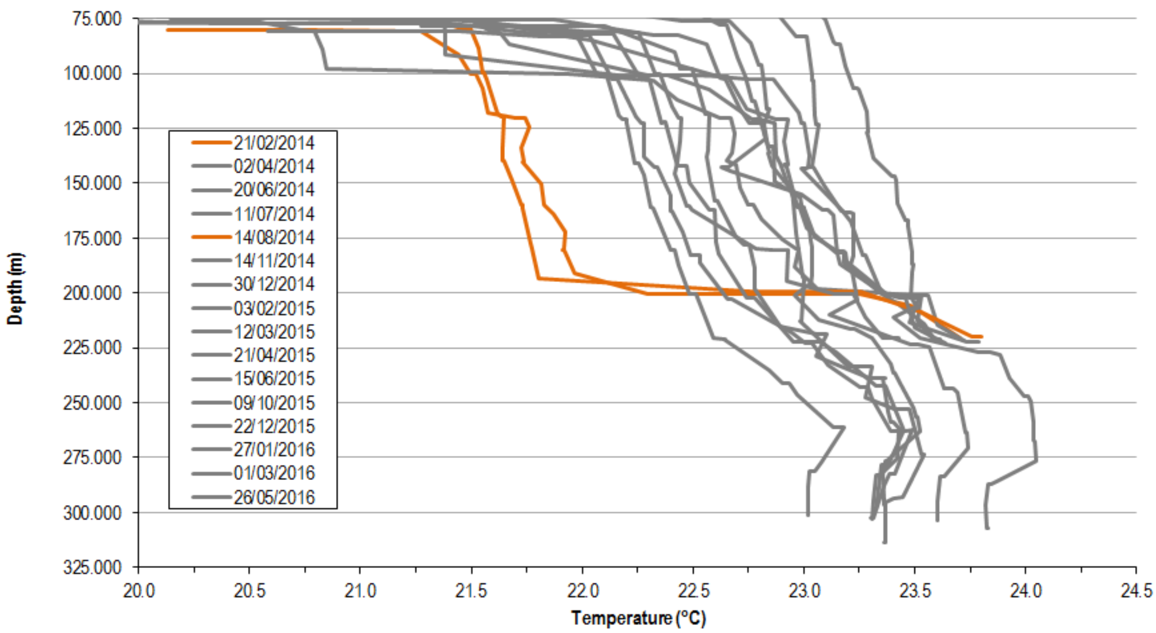


Figure 12. Comparison of Barredo and Figaredo thermal profiles 12/03/2015

Barredo is dewatered by four hydraulic pumps, three of them are placed at 100 m bgl (120 m asl) and one (the so-called 'Pump 3') is placed at 200 m bgl (20 m asl). When measuring the thermal profiles, the number of activate pumps was noted, so a study comparing the influence of each pump on measured mine water temperatures was carried out (Figure 13).



	21/02/2014	02/04/2014	20/06/2014	11/07/2014	14/08/2014	14/11/2014	30/12/2014	03/02/2015	12/03/2015	21/04/2015	15/06/2015	09/10/2015	22/12/2015	27/01/2016	01/03/2016	26/05/2016
Pump 1	0	0	0	0	0	0	0	1	1	1	1	0	1	1	1	0
Pump 2	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	1
Pump 3	1	0	0	0	1	0	0	0	1	1	1	0	1	1	0	0
Pump 4	0	1	1	1	0	1	1	1	1	1	0	1	0	0	1	1

Figure 13. Barredo thermal profile alterations due to the solely use of the deepest pump

It is remarkable how some thermal alterations can be observed on the profiles corresponding to the sole use of Pump 3 (the deepest one), marked in orange in Figure 13 above. This is likely due to the flow from Figaredo to Barredo which leads to an increase of mine water temperature around the connection area at the bottom of Barredo shaft.

Summary of site tracer studies

Both Markham and Barredo-Figaredo provide valuable insights into the use of natural tracers. The salinity of waters sampled at Markham have fallen significantly as the extraction pump has risen up the water column, suggesting stratification in the shaft. This is an important observation as it demonstrates the value in salinity tracers for determining stratification maintenance and the extent of hydrological mixing in proximity to the extraction pump interface.

The Barredo-Figaredo study shows that mine water temperature in that system is directly, and heavily, influenced governed by the pumping rate, i.e. the more water that is extracted from the system, the warmer Barredo’s water and the cooler Figaredo’s water. This demonstrates that minewater temperature can play a key role in tracing water origin and flow direction.

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