Tracer Test in the Bowden Close Passive Treatment System (UK) – Preliminary Results

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A mine water tracer test with bromide, Na-fluorescein, and NaCl was conducted at the Bowden Close passive treatment system in County Durham, UK. This passive treatment system comprises two RAPS units and one polishing wetland with surface areas of 1511 m², 1124 m², and 990 m², respectively. Mean residence times of 4—5 days and mean effective velocities of 0.01 m h^{-1} through the active RAPS layer were deduced for the two RAPS units. The maximum mine water flow rates differs between the two RAPS (30—50 L min^{-1} in RAPS 1 (mainly fed by adit drainage), and 90—110 L min^{-1} in RAPS II (fed by spoil leachate). With the exception of the NaCl tracer, which was too heavily diluted due to intense rainfall, all tracers where applied successfully in the test.

1 Introduction

Situated between Crook and Willington in County Durham, UK, the former Bowden Close Colliery and Cokeworks were abandoned in the 1960s (Fig. 1). In the mid 1970s the mine site was remediated by Durham County Council (restoration consisted mainly of demolishing decayed buildings, reshaping spoil heaps, emplacing top soil and re-vegetation (YOUNGER 2000; Brown et al. 2002). At that time no investigations of the mine spoil and underground were conducted and no measures were taken to minimise infiltration and through-flow of water through the spoil heaps. Hence, acidic metalliferous mine water began emanating from a number of points, causing degradation in the quality of the nearby stream (Willington Burn). Investigations by the Newcastle University HERO Group identified at least two highly polluted discharges of mine water from the mine site: acidic leachate from the land drains on the site causing pollution of the Willington Burn with iron, aluminium, and manganese and subsurface flow containing mobile tar compounds seeped to the surface near the southern boundary of the site (YOUNGER 1995; YOUNGER 2000).

Subsequently, with funding from the County Durham Environmental Trust (YOUNGER 2000) a pilot scale RAPS-system (reducing and alkalinity producing system) was constructed at the site. The purpose of that pilot plant was to investigation the feasibility of treating the mine water by using such a passive treatment system. First results showed that the pilot-scale system functioned well for the short time it was operational (YOUNGER 2000). GOEBES & YOUNGER 2004 conducted a tracer test in this pilot scale wetland, of which the results will be discussed later.

After the pilot tests, two RAPS-units, fol-

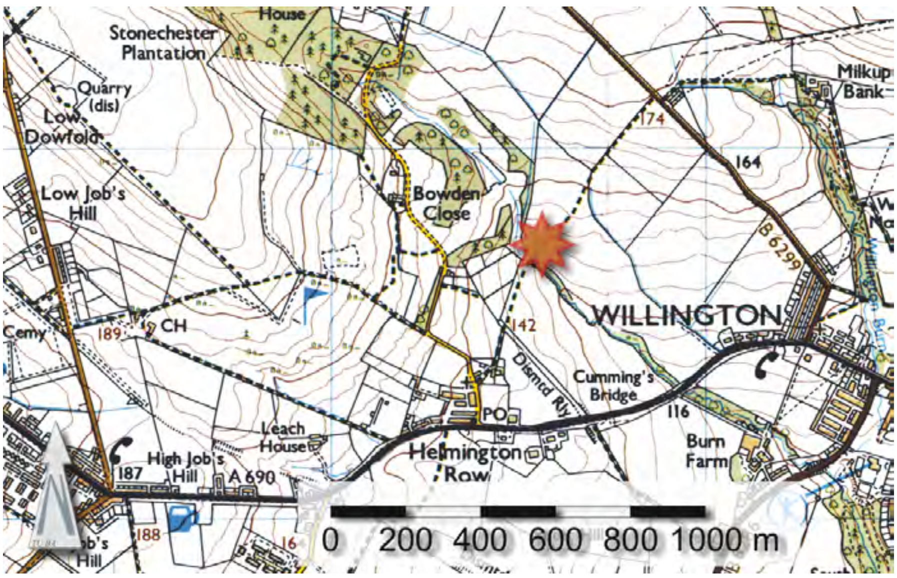

Figure 1: Location of the Bowden Close mine water treatment system (National Grid coordinates NZ 185 357).

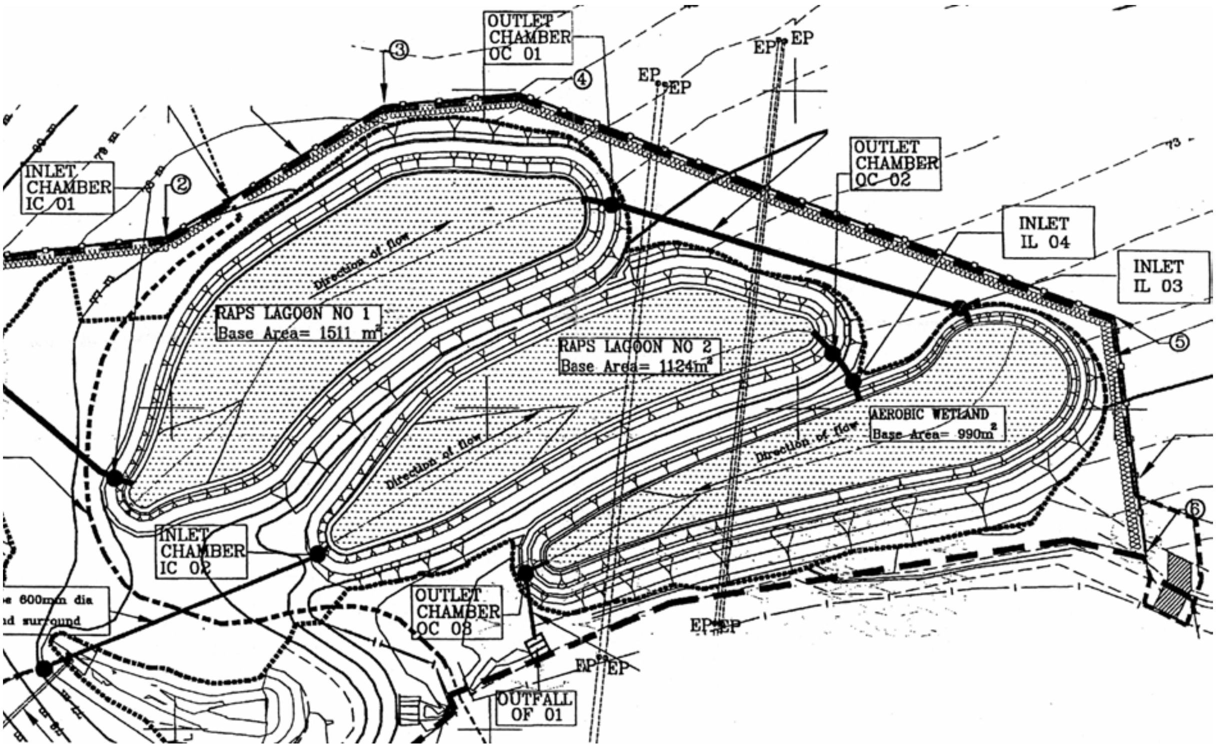

Figure 2: Map of the Bowden Close mine water treatment scheme. With the two RAPS in the upper pat and the wetland in the lower part.

lowed by an aeration cascade and an aerobic wetland were installed at the site. For investigation of the mean resistance time in the RAPS units and the wetland – aiding interpretation of system performance – different tracer tests were conducted by the research group of the TU Bergakademie Freiberg in autumn of 2004 with FP6 funding (CoSTaR Access to Research Infrastructure grant).

Tracer tests in wetlands for wastewater treatment by using bromides have already been conducted by MACHATE et al. (1998); MACHATE et al. (1998); LIN et al. (2003); KEEFE et al. (2004); WHITMER et al. (2000); WACHNIEW et al. (2003). Although Na-fluorescein is often assumed to be an unsuitable tracer for wetlands and under the conditions in the RAPS systems (MACHATE et al. 1998; KÄSS 1998) it was used

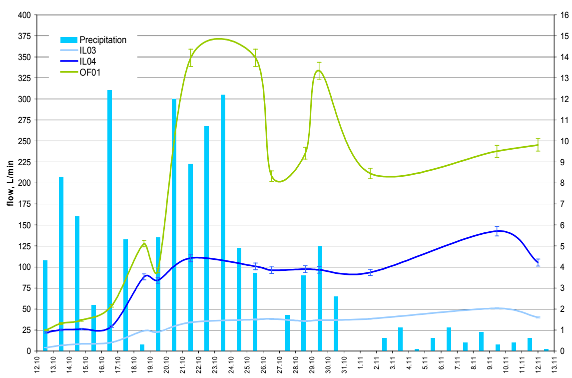

Figure 3: Flow through the two RAPS systems and the wetland and the daily precipitation for Bowden Close during the duration of the tracer test. Error bars show the mean errors for each measuring point based on 3—5 flow measurements at each measuring occasion. RAPS I: 1.5%; RAPS II 3%, wetland: 4%.

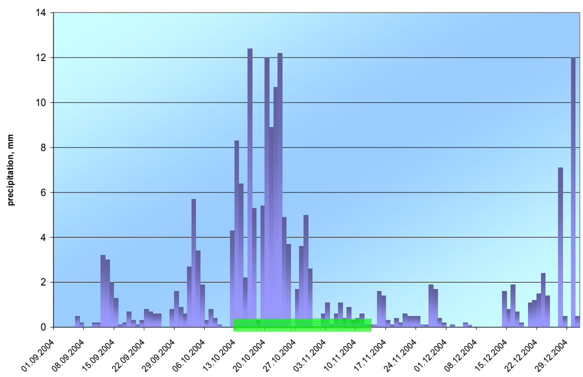

Figure 4: Precipitation at the Bowden Close Mine Water Treatment scheme between September and December 2004. The tracer test was conducted between October 12 and November 11 (data calculated from Esh Village, Dryderdale Farm, and Redworth rain gauging.

Figure 5: Injection of the Na-fluorescein tracer into RAPS II.

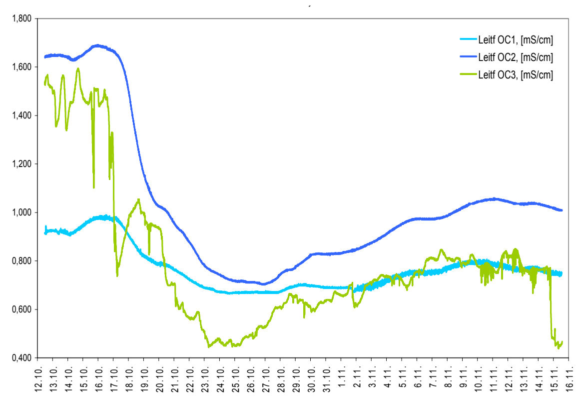

Figure 6: Continuous conductivity measurements in the RAPS 1 (upper line), wetland (middle line), and RAPS 2 (lower line). No correction for loadings. The drop in the wetland curve at the end of the measuring period is due to the flooding of the outfall chamber 3 with non treated rain water.

in this investigation, because our preliminary results in the Gernrode experimental lab showed positive results (HASCHE & WOLKERSDORFER 2004). The volumes of the RAPS and the wetland where estimated to be $363 \cdot 10^3$ m³, $270 \cdot 10^3$ m³, and $792 \cdot 10^3$ m³ (Figure 2).

2 Methods

Three different tracers for each of the two RAPS where used: Na-fluorescein, NaBr and LiBr and in addition NaCl for the wetland. The Na-fluorescein was detected with two on-line fluorometers Seapoint SFF adapted to a Dataron Data Bank data logger in the field and with a Cary Eclipse Fluorescence spectrophotometer in the laboratory. Furthermore, three auto samplers where installed at the outlet chambers OC 01, OC 02, and OC 03. Those auto samplers collected a water sample every 11 minutes and 9 samples where collected in one 1 L bottle. In the laboratory, all samples where analysed for Br with an ion sensitive probe ELIT 8271Br-57461 on a pH-meter Jenway 3310 and a reference electrode ELIT 002n KNO_3 57810 and Li with a flame photometer. At every measuring day 3 calibrations for the bromide IOS were conducted to make sure that any sensor drift was eliminated.

Detection limits for Na-fluorescein in the field were 4 μgL^{-1} and 2 μgL^{-1} in the laboratory. For Br the detection limit was 0.2 mg L^{-1} and Li had a detection limit of 0.1 mg L^{-1}. In addition, a Van Essen CTD Diver DI 218 was installed in every outlet chamber for continuous measuring of the pressure, temperature, and electrical conductivity at 5 minute intervals.

In addition to the tracers the flow in the system was measured at the Inlets IL 03, IL 04, and the Outfall OF 01 by using multiple measurements with bucket and stopwatch. Furthermore, the on-site parameters pH, redox potential, electric conductivity, and temperature were measured with a Myron P6 (Myron L Company, Karlsbad, USA)

Based on the flow before the tracer test the following tracer amounts where calculated and used: RAPS I: 69.96 g Na fluorescein, 1710 g LiBr, 2860 g NaBr; RAPS II: 50,41 g Na fluorescein, 1270 g LiBr, 2130 g NaBr; wetland: 25.8 kg NaCl.

3 Investigations

All tracer amounts where calculated on the flow data of the fully constructed RAPS system which was around 70 L min^{-1}. However, the weeks of the tracer test where some of the wettest in the second half of 2004 (Figure 4) and as such the maximum flow during the tracer test reached as much as 375 L min^{-1} (Figure 3). Because the amount of the wetland tracer was calculated in such a way that it could be detected with a conductivity probe and the flow was more than 5 times higher than expected, it was not possible to detect the NaCl over the natural conductivity fluctuation (Fig. 6).

Each of the two RAPS, in addition to the normal drainage pipes, have overflow pipes which guarantee, that the systems won't overflow during high rainfall events (to prevent possible erosion).To drive the entire tracer and the water through both of the RAPS, the two overflow pipes were closed for the duration of the tracer test.

Table 1: Some parameters for the tracer test. Physico-chemical parameters are arithmetic means for December 2003—September 2004 for in/out.

System	RAPS I	RAPS II	Wetland
№ Samples	266	264	216
Volume, 10^3 m³	363	270	792
NaBr, g	2,860	2,130	–
LiBr, g	1,710	1,270	–
Na-fluorescein, g	69.96	50.41	–
NaCl, g	–	–	25,800
pH	5.1 / 7.5	5.1 / 7.1	– / 7.2
cond, mS cm^{-1}	0.9 / 1.1	1.4 / 1.6	– / 1.3
alkal., mmol L^{-1}	0.1 / 2.3	0.1 / 2.2	– / 1.4
Fe_{tot}, mg L^{-1}	17 / 2	48 / 4	– / 6
SO_4^{2-}, 10 mg L^{-1}	45 / 24	92 / 67	– / 54

On October 12th 2004 the data loggers and auto samplers were installed at the Bowden Close treatment system. Furthermore the on-site parameters of the system where measured at the inlets, outlets and the outfall (Figure 2) and the NaCl-tracer into the wetland injected. One day later, after enough blind samples had been collected, the Na-fluorescein, NaBr and LiBr tracers were injected into RAPS I and RAPS II (Fig. 5).

Every 2—3 days the flow in the RAPS and the wetland was measured and the samples removed from the auto samplers for further investigation in the laboratory. As a result of the extreme rainfalls, RAPS I and RAPS II started to overflow across the dividing banks. While RAPS I began to overflow at a total inflow of about 30—40 L min^{-1}, RAPS II began to overflow at 100—110 L min^{-1}, providing useful information on maximum capacities.

Na fluorescein was detected with both methods, in the field and in the laboratory, at background levels of 1—3 µgL^{-1}. The source for the contamination of the system with Na-fluorescein could not be found, but it is well known that many waters are contaminated with Na-fluorescein (KÄSS 1998).

Due to failures of the auto samplers, RAPS II yielded data only from October 12th to November 9th and the wetland from October 12th to November 1st. Data for RAPS I is available for the whole period of the tracer test from October 12th to November 12th with only a few missing samples (table 1).

All three Van Essen CTD Diver conductivity probes in outlets 1 to 3 worked without any failure and the data are complete for the whole sampling period. Even when the Diver in the outlet chamber OC 03 was flooded it worked perfectly well. The temperature in the RAPS systems showed small daily fluctuations in the range of

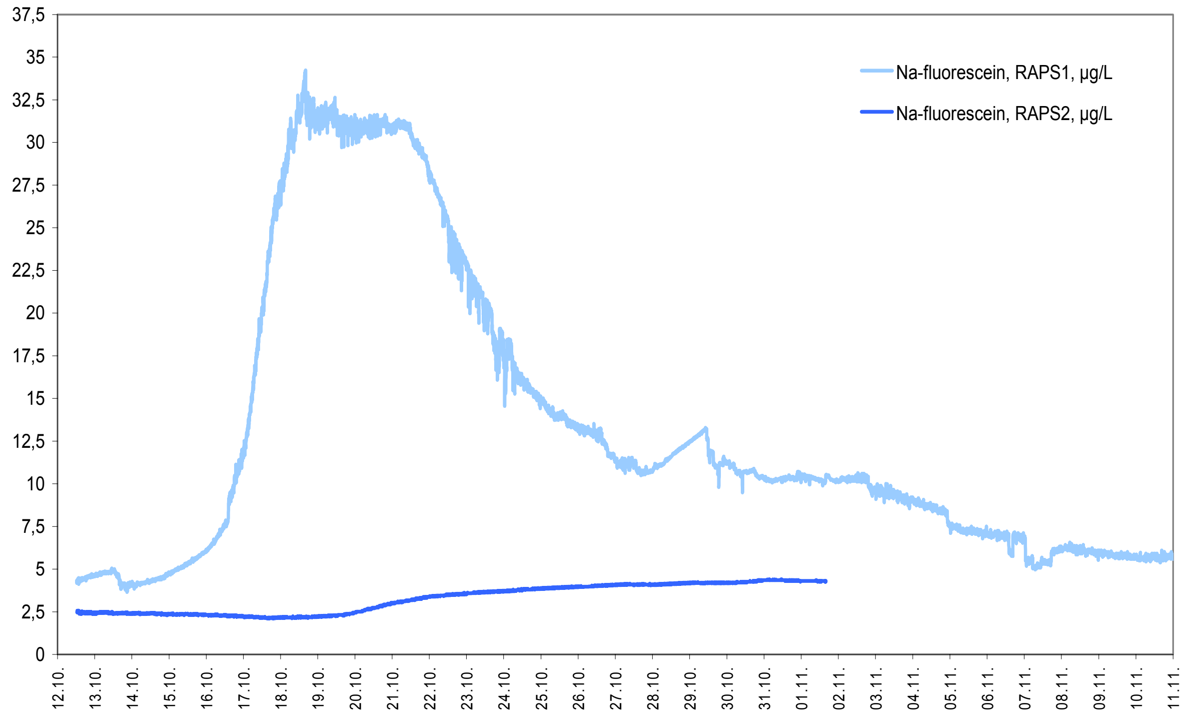

Figure 7: Na-fluorescein breakthrough curves for RAPS I (upper line) and RAPS II (lower line). Due to a data logger failure, data for RAPS II ends at October 1st. No correction for loadings.

1—2 K, while a temperature decrease from around 11 °C to 7 °C was found in the wetland system, which is more open to the air and reacts quickly to rainfall events. Its daily temperature fluctuations reached up to 5 K at November 12th and also decreased from 9—10 °C to 5—7 °C at the end of the test.

Unexpectedly, the conductivity showed fluctuations which made it impossible to use that data for a quick interpretation of the NaCl-tracer in the wetland (Fig. 6). At the beginning of the tracer test the conductivities in RAPS I, RAPS II, and the wetland were 1.65, 0.92, and 1.52 mS cm^{-1}, respectively. At the end of the test, the conductivities had decreased to 1.00, 0.75, and 0.74 mS cm^{-1}, showing a good correlation with the total flow through the system (dilution). There is no indication that the NaCl tracer which theoretically should have increased the conductivity by about 100 µS cm^{-1} was detected by the conductivity probes.

4 Results and Conclusions

Here we will give first results of the tracer test. A full evaluation of all the data will follow at a later stage.

Of the tracers used (Na-fluorescein, bromide, lithium, and conductivity) only the first three gained positive results. No valuable data is available from the NaCl, though 25 kg should have been enough for the water volume in the wetland. Also the results for lithium where not as good as expected, because the Li-concentration added to the systems was rather low and the good correlation with the conductivity proved that much of the detected Li came from the mine water, not the tracer. Excellent results came from both the bromide and the Na-fluorescein.

The first Br-tracer from RAPS I arrived at the same day it was injected into the system with a peak 4 days later. This is a clear indication for a shortcut between the inlet and the outflow used by the Br-tracer. Another situation was observed for the Na-fluorescein. It arrived 2 days after its injection and peaked 5—6 days in the tracer test. A similar, if less simple, relation could be observed for RAPS II. While the bromide arrived a day later, the Na-fluorescein needed 7—8 days for its first appearance. Our explanation is that the highly concentrated Li/NaBr solution, due to its high density, penetrated through the organic and inorganic layers to the drainage pipelines while the Na-fluorescein solution with a lower density first flowed on the RAPS' surface and slowly penetrated through the system at different locations. As such, the Br gives the quick reaction time of the system and the Na-fluorescein the mean reaction time of the system. In any case, the mean residence time in RAPS I is about 4—8 days and in RAPS II about 4—6 days.

The breakthrough curve for the Na-fluorescein does not show a clear peak (Fig. 7). This can be easily explained, because the breakthrough curve is a summation of many tracer paths through the RAPS I. As has been described earlier, the Na-fluorescein could be seen over nearly the whole surface of RAPS I for approximately 2 days. It can therefore be concluded that the tracer penetrated through the whole system at points close to and far from the outflow point. Therefore, the visual flattening of the discharge curve might be used as a measure of the retention time of the tracer in the RAPS, which corresponds nicely with the 4 days calculated earlier.

An unexpected and interesting result was gained for the wetland system, as the Br- and the Na-fluorescein injected in the RAPS systems could still be found in the wetland system. Both tracers from RAPS I where found at the wetland's outlet chamber 1 day after it entered the system. This is true for the first appearance as well as the peaks. Though a mean resistance time can't be calculated at the current stage it seems to be around 2—3 days.

In RAPS I the distance between the injection and the outflow is about 175 m, in RAPS II 167 m and in the wetland 113—156 m. Though it is not possible to calculate "real" effective velocities for the three systems, the mean effective velocities in the systems are about 1.4—1.5 m h^{-1} in both RAPS, and 6—7 m h^{-1} in the wetland. Those data are 10 times faster than the results obtained by GOEBES & YOUNGER (2004) for the Bowden Close pilot scale RAPS, which were 0.1 m h^{-1}. GOEBES & YOUNGER (2004) used the thickness of the substrate as the characteristic length instead of the length of the RAPS system. If we use the RAPS thickness as well, we get velocities of 0.01 m h^{-1}, which fits exactly into the results of the Pelenna III RAPS. It can therefore be concluded that the effective velocity through a 0.7—0.8 m thick RAPS with manure and limestone is in the range of about 1 cm h^{-1}.

These data cannot sufficiently explain the efficiency of the RAPS systems, as both systems work fine. Yet, the treatment efficiency of RAPS II is usually better than RAPS I, which can now be explained from the difference in mean residence time (which is longer in RAPS II).

As a by-product of this tracer it is possible to give data for the potential flow capacity of the two systems. As described earlier, the two overflow pipelines were closed for the duration of the tracer test, so that the entire mine water had to flow through the RAPS systems. By measuring the flow through the normal drainage pipes, it was possible to give flow data for the RAPS efficiencies. Interestingly, the efficiency, in the view of the total flow, of the two systems is rather different. While RAPS I treats 30—50 L min^{-1}, RAPS II can treat up to 90—110 L min^{-1}.

5 Acknowledgements

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