Final Report to CDENT and Durham County Council

Pilot-Scale Passive Treatment of Acidic Mine Drainage Using a Downward-Flow, Reducing and Alkalinity Producing System (RAPS) at Bowden Close, County Durham, UK.

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(One of two reports produced in fulfilment of contract conditions; the other report covers research into tar remediation)

Contents

Executive Summary

This report is one of two produced to document research funded by CDENT and DCC at the Bowden Close site in County Durham. This report considers remediation of acidic drainage, while the other considers remediation of tar contamination. Acidic drainage, heavily polluted with iron, aluminium and manganese has been flowing from the site of the former Bowden Close colliery since at least the 1960s. Following several months of monitoring of flow and hydrochemical parameters to obtain design parameters, a pilot passive treatment system was constructed at the site in the summer of 1999, with the purpose of investigating the feasibility of treating such waters using simple, gravity-fed biogeochemical reactors. Of particular interest was the scope for removing aluminium from such waters, as this has hitherto proved problematic in similar systems. The Bowden Close pilot system comprised a downward-flow RAPS (reducing and alkalinity producing system) unit, followed by an aeration cascade and a shallow, aerobic pond. Monitoring of waters entering and leaving the system showed dramatic improvements in quality, with major increases in alkalinity and pH, and major decreases in dissolved aluminium, iron and manganese. The results are sufficiently encouraging to support construction of a similar, full-scale passive system at the site, and give grounds for optimism for the implementation of similar technology at other sites with similar problems.

1. Introduction

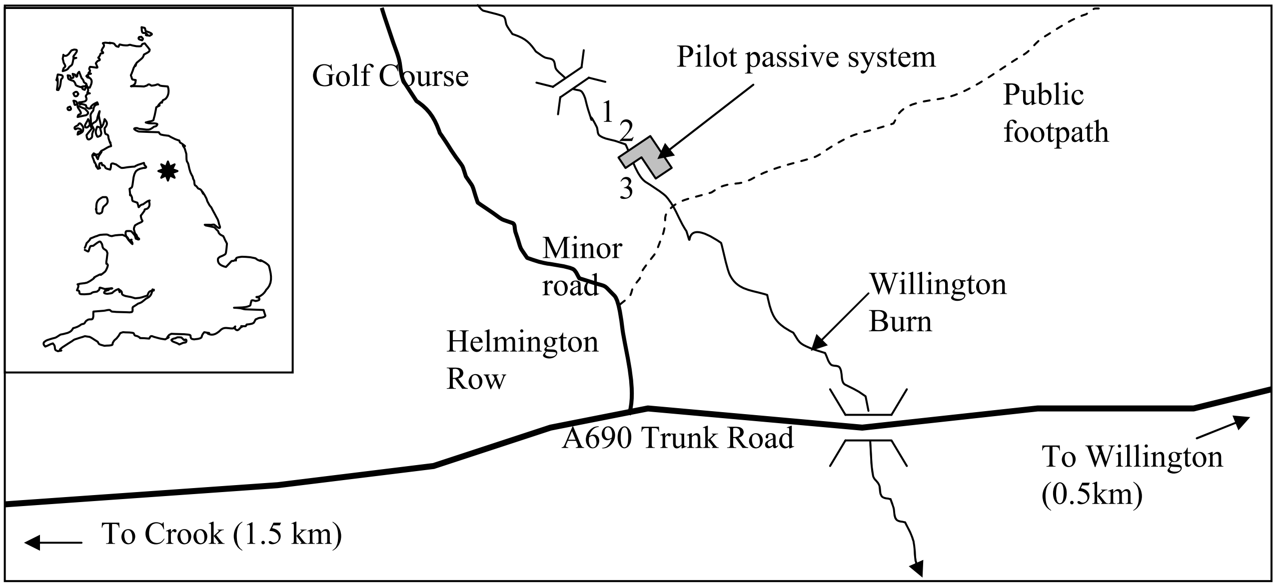
The former Bowden Close Colliery and Cokeworks, near Crook, County Durham (Figure 1) were abandoned in the 1960s. The derelict mine site was largely restored by Durham County Council in the mid 1970s. In line with contemporary standards, restoration consisted mainly of demolishing derelict buildings, reshaping spoil heaps, emplacing top soil, re-vegetating, and turning the site over to new uses as a golf course and open countryside. Although the surface drainage of the site was reconfigured in sympathy with the new landforms, no measures were taken to minimise subsurface flow through the mine spoil and made ground. In the fullness of time, the existence of subsurface hydrological pathways within the Bowden Close site manifested itself in at least two fairly dramatic ways:

(i) Acidic leachate began to emanate from land drains on the site, badly polluting the local stream with iron, aluminium and manganese (Younger, 1995).

(ii) Mobile tar compounds seeped to the surface near the southern boundary of the site, at times flowing with sufficient vigour that they too entered the local stream.

In 1998, Durham County Council (DCC) obtained funding from the County Durham Environmental Trust (CDENT), an environmental body authorised to disburse monies obtained from landfill tax credits, to undertake investigations relating to both of these phenomena. This report details work carried out in relation to the first of the two, i.e. the acidic drainage. A companion report (Jones, 2000) details work carried out in relation to tar pollution and its remediation.

Figure 1 - Location of the Bowden Close Site (1, 2 and 3 are major acid drainage discharges).



In the funding agreement between CDENT and DCC, the following terms of reference are identified with regard to the acid drainage problems at Bowden Close:

"Design a method for treating the acidic stream water so that contaminants and dissolved heavy metals are reduced to acceptable levels .. a reduced scale prototype (SAPS) system would be constructed on the site as part of the project. The project would use results from the prototype system to produce a design for a full-scale system".

The above terms of reference have been fulfilled in accordance with the agreement, and this report documents the outcomes.

2. System design, construction and modifications

2.1. Gathering design data.

The design of a prototype or "pilot" system for treatment of the acidic drainage at Bowden Close demanded the definition of design flows and hydrochemical parameters. Accordingly, a programme of monitoring was undertaken following the award of the CDENT funding to determine:

(i) The discharge rates of the major acidic drainage inputs to the Willington Burn at Bowden Close

(ii) The hydrochemistry of the Bowden Close discharges.

The acidic drainage at Bowden Close had been previously studied by Younger and Bradley (1994) and Younger (1995) (who referred to the site as "Crook"), and Jarvis and Younger (1997) (who called the site "Helmington Row"). The latter study is of particular relevance to the present activities at the site, as it demonstrated the severe ecological damage being caused by the acidic and metalliferous drainage from the site, which was shown to have pH values around 4 and total iron as high as 80 mg/l. Until the present study was undertaken , the precise means by which the acidic discharges enter the Willington Burn remained obscure. In 1996 the Coal Authority made a reconnaissance evaluation of the site as part of a national survey of polluted mine waters. Their report recorded two discharges within 30m of each other, both on the western bank of the Willington Burn. The two discharges are located in the vicinity of the site marked as "3" on Figure 1. Confusingly, one of these so-called discharges is noted to have been dry at the time of the site visit; it seems to the present author that this second "discharge" is actually a surface water drain, which enters the Burn some 30m upstream of point "3". This drain only flows during storms and does not carry acidic drainage. In view of the lack of clarity in previous accounts, it was necessary in this study to clarify the number, positions and nature of point sources of acidic drainage entering the Willington Burn before any meaningful sampling and flow gauging could be undertaken.

Site visits in the winter of 1998/99 and the spring and summer of 1999 revealed that there are actually three distinct, perennial discharges of acidic mine drainage into the Willington Burn at Bowden Close (Figures 1 and 2):

- Bowden Close No 1 is the furthest upstream of the perennial discharges. (Although minor ferruginous seepages do sometimes occur further upstream, these are not quantitatively significant). The No 1 discharge emerges from a 0.5m diameter concrete drainage pipe on the true left bank of the Willington Burn, some 50m downstream of the grassy "bridge" over the Burn within the golf freeway. The measured characteristics of the No 1 discharge in spring / summer 1999 were as follows:

Table 1 - Bowden Close No 1 Discharge - Summary of pre-design measurements 1999

Parameter	Typical value	Range
Flow (l/min)	15	2 - 20
pH	5.5	5.2 - 7.0
Alkalinity (mg/l as $CaCO_3$ equivalent)	0	0 - 24
Fe (mg/l)	30	25 - 42
Mn (mg/l)	1.4	1.3 - 1.5
Al (mg/l)	10	5 - 20
Zn (mg/l)	0.3	0.3 - 0.4

- Bowden Close No 2 enters the Willington Burn from its left bank some 23m downstream of the No 1 discharge. The No 2 discharge arises in a strange hollow amidst the stand of conifers which line the eastern flank of the Burn in this vicinity. This hollow is suspected to be the collapsed remains of an old drift mine entrance. (Coal Authority records show an old surface drift into the Harvey Seam in this vicinity). After seeping out of the ground in the hollow, the No 2 discharge gathers in a small stream channel which flows some 15m to its confluence with the Willington Burn. Table 2 below summarises the characteristics of the No 2 discharge as measured in the spring and summer of 1999.
- Bowden Close No 3 is the largest and furthest downstream of the three main discharges. Unlike the other two discharges, No 3 arises on the right bank of the Willington Burn. It is the point

source previously sampled by Younger and Bradley (1994) and Younger (1995), and it corresponds to the "Helmington Row A" discharge described in the Coal Authority's survey of 1996. It is usually conspicuously aluminium rich, depositing much white froth in and on the banks of the Willington Burn. The flow rate of this discharge is difficult to measure as it emerges from a pipe at the bed level of the Burn. However, visual inspection suggests that the

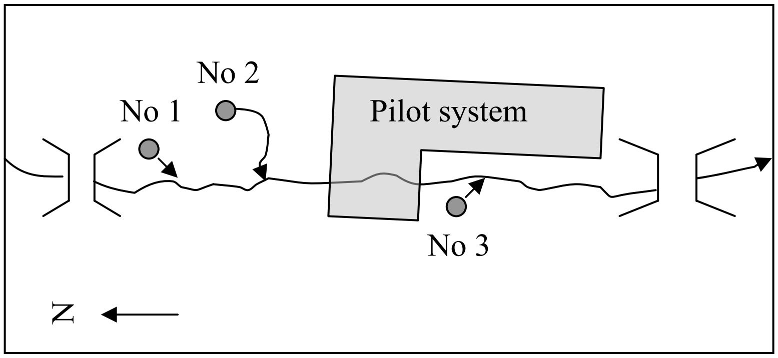
Table 2 - Bowden Close No 2 Discharge - Summary of pre-design measurements 1999

Parameter	Typical value	Range
Flow (l/min)	12	5 - 21
pH	6.7	6.4 - 7.0
Alkalinity (mg/l as $CaCO_3$ equivalent)	50	48 - 76
Fe (mg/l)	8	4 - 10
Mn (mg/l)	0.8	0.7 - 0.9
Al (mg/l)	2	0.8 - 2.7
Zn (mg/l)	0.1	0.10 - 0.11

Table 3 - Bowden Close No 3 Discharge - Summary of pre-design measurements 1999

Parameter	Typical value	Range
Flow (l/min)	200	100 - 300
pH	4.5	3.3 - 5.2
Alkalinity (mg/l as $CaCO_3$ equivalent)	0	0 - 24
Fe (mg/l)	80	35 - 140
Mn (mg/l)	7	1.3 - 20
Al (mg/l)	50	20 - 84
Zn (mg/l)	3	0.4 - 4.3

Figure 2 - Sketch map showing the positions of the three main discharges at Bowden Close



flow does not vary very markedly over the year. Table 3 summarises the characteristics of this discharge as measured in and before the spring and summer of 1999.

2.2. Design considerations.

Armed with the data given in Tables 1 - 3, it was possible to proceed to a design for a pilot passive treatment system for the site. As the purpose of the CDENT project was to undertake a pilot study using a reduced-scale prototype passive system, it was necessary to decide which of the three discharges would be treated. The decision was relatively easy to make in practice, since the largest of the three discharges (No 3) is also the most low-lying, and would have been difficult to feed into a pilot system constructed on land currently in the ownership of DCC without the use of a pump. As there is no source of electricity on site, and a generator could not be left in place to run for long periods of time, it was clear that the pilot system would have to treat No1 and/or No 2, which are both conveniently located to feed by gravity into the site available for passive system construction. As both of these discharges proved to be irregular in their flow patterns during dry summer weather it was considered necessary to feed both of them into the pilot system. Designs were concluded accordingly.

The present state-of-the-art in the passive treatment of acidic, metalliferous discharges is to use flooded beds of organic material which promote reducing conditions conducive to bacterial sulphate reduction (Hedin *et al.*, 1994; Younger *et al.*, 1997; Walton-Day, 1999; Jarvis and Younger, 2000; Younger, *in press*). In such systems the sulphate which is always present in acidic mine drainage (as it arises from the same process of pyrite oxidation which releases the acidity into solution) is used as a source of energy by anaerobic bacteria which digest organic carbon (such as is found in decaying plant debris). The reactions of relevance to mine water treatment may be summarised as follows:

$$\underset{\substack{\text{organic}\\ \text{matter}}}{2CH_2O} \underset{+}{+} \underset{\text{sulphate}}{SO_4^{2-}} \rightarrow \underset{\substack{\text{hydrogen}\\ \text{sulphide}}}{H_2S} \underset{+}{+} \underset{\substack{\text{bicarbonate}\\ \text{alkalinity}}}{2HCO_3^-} \qquad (1)$$

and

$$\underset{\substack{\text{dissolved}\\ \text{iron}}}{Fe^{2+}} \underset{+}{+} \underset{\substack{\text{hydrogen}\\ \text{sulphide}}}{H_2S} \underset{+}{+} \underset{\text{bicarbonate}}{2HCO_3^-} \rightarrow \underset{\substack{\text{iron}\\ \text{sulphide}}}{FeS} + 2H_2O + 2CO_2 \qquad (2)$$

In this scheme of reactions, the iron is removed from solution by precipitation of iron sulphide, which accumulates in the substrate. Bicarbonate generated in reaction (1) serves to neutralise acidity according to:

$$HCO_3^- + H^+ \rightarrow H_2O + CO_2 \qquad (3)$$

Although in these stoichiometric equations more HCO_3^- is consumed than is produced, this sequence of reactions tends in practice to result in a net rise in pH and an overall increase in bicarbonate alkalinity in solution. This is because there is usually far more sulphate available for reduction (reaction 1) than there are iron ions and protons available to consume the resultant bicarbonate.

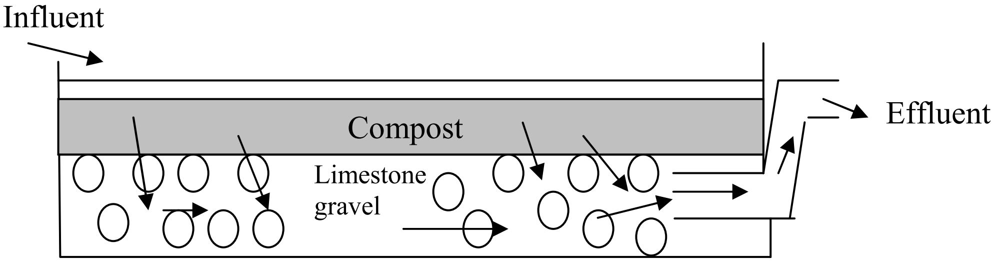
The conditions which favour the above reactions (and similar, sympathetic reactions) can be established by two means:

(i) At its simplest, and wherever the total head (i.e. relief) across a site is limited, a bed of compost can be flooded with mine water, which then effectively flows over it, exchanging solutes as it goes (Hedin *et al.*, 1994; Younger *et al.*, 1997; Jarvis and Younger, 1999).

(ii) More satisfactorily, wherever there is sufficient head, it is preferable to make the mine water flow vertically downwards or upwards through the compost, thereby maximising the potential for the maintenance of reducing conditions. In down-flow systems, it is common practice to install a limestone gravel under-drain layer below the compost, which gradually dissolves in the water, adding valuable alkalinity in the process. Such systems were originally developed in the USA by Kepler and McCleary (1994), and have since been successfully implemented in the UK (Younger, 1998) and Spain (Laine, 1998; Ordoñez *et al.*, 1999). Originally termed "SAPS" (successive alkalinity producing systems), they have recently been more accurately re-christened RAPS (reducing and alkalinity producing systems) by G Watzlaf and co-workers at the US Department of Energy.

As Bowden Close is a reasonably hilly site, there is sufficient head for a RAPS-type system, and the design was therefore based on this concept. Figure 3 illustrates the basic layout of a RAPS unit in cross-section. It is usual practice to construct an aerobic pond or wetland downstream of a RAPS unit to allow removal of any metals which were not trapped as sulphides (Younger, 1998). Provision for this was also made for this at Bowden Close.

Figure 3 - Diagrammatic cross-section illustrating the layout of a typical RAPS unit (after Younger, *in press*).



Despite their increasing uptake, RAPS-type systems are subject to a number of uncertainties, in relation to their hydraulic performance, their ability to remove non-reducible ecotoxic metals such as Al, and the suitability of a range of carbon sources as substrates. The Bowden Close system was designed to allow evaluation of all of these issues, in particular:

(i) The system was designed with access to all major points in the system to facilitate hydraulic tracer tests and flow measurements.

(ii) The selected discharges (No 1 and No 2) contained sufficient aluminium (see Tables 1 and 2) to allow its removal to be monitored.

(iii) The carbon substrate used here was horse manure and straw, a waste material which is in plentiful supply locally and can be obtained essentially free of charge. This substrate has not previously been used in RAPS systems (although it formed part of the carbon fill in the surface-flow wetland at Quaking Houses; Jarvis and Younger, 1999); the US systems have used mushroom compost, and the South Wales system used composted bark mulch.

In order to accommodate a large enough pilot system on the site at Bowden Close, it proved necessary to culvert a short section of the Willington Burn and construct part of the system over the culvert. This necessitated a 90^o bend in the system, which was probably beneficial from the point of view of limiting hydraulic short-circuiting. The layout of the Bowden Close pilot system is shown in Figure 4, and Figure 5 is a photograph shows the completed pilot reactor immediately prior to the diversion of the No 1 and No 2 discharges into the system. Viscreen liner covers the colliery spoil used to form the beds and banks of the two bunded structures. The RAPS unit has a surface area of 128 m^2, and contains a 0.5m thick lowermost layer of 13mm diameter single-size limestone gravel, overlain by a nominal 0.5m of horse manure and straw (actual thickness varies from 0.6m to 0.2m), and standing water is typically a few centimetres deep.

Figure 4 - Sketch plan of the Bowden Close Pilot Passive Treatment System.

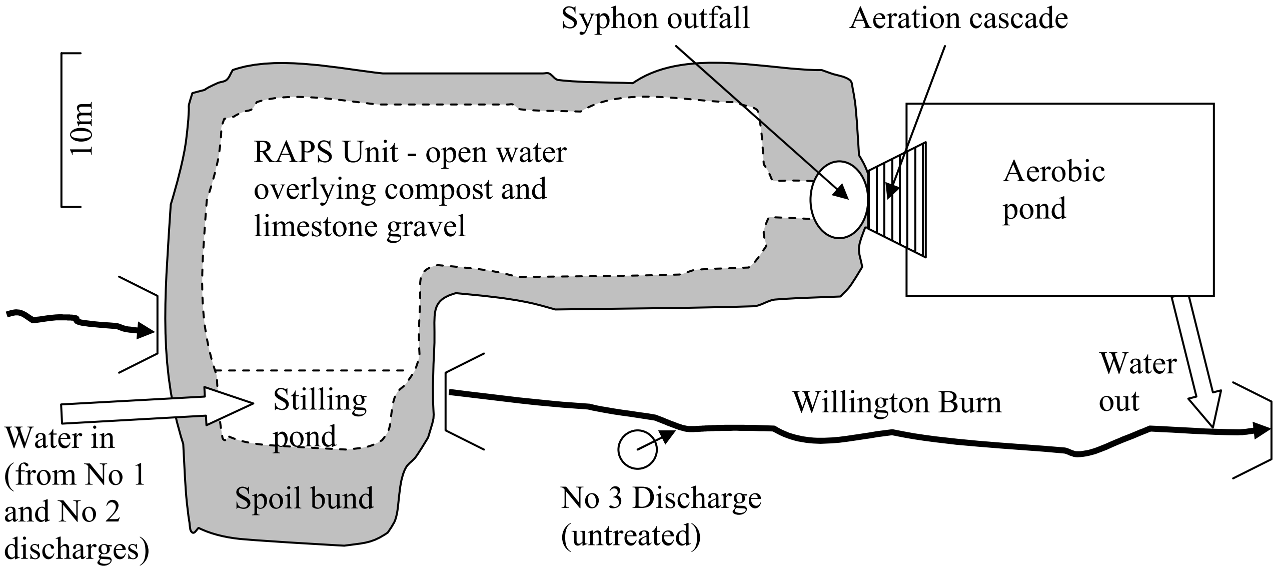
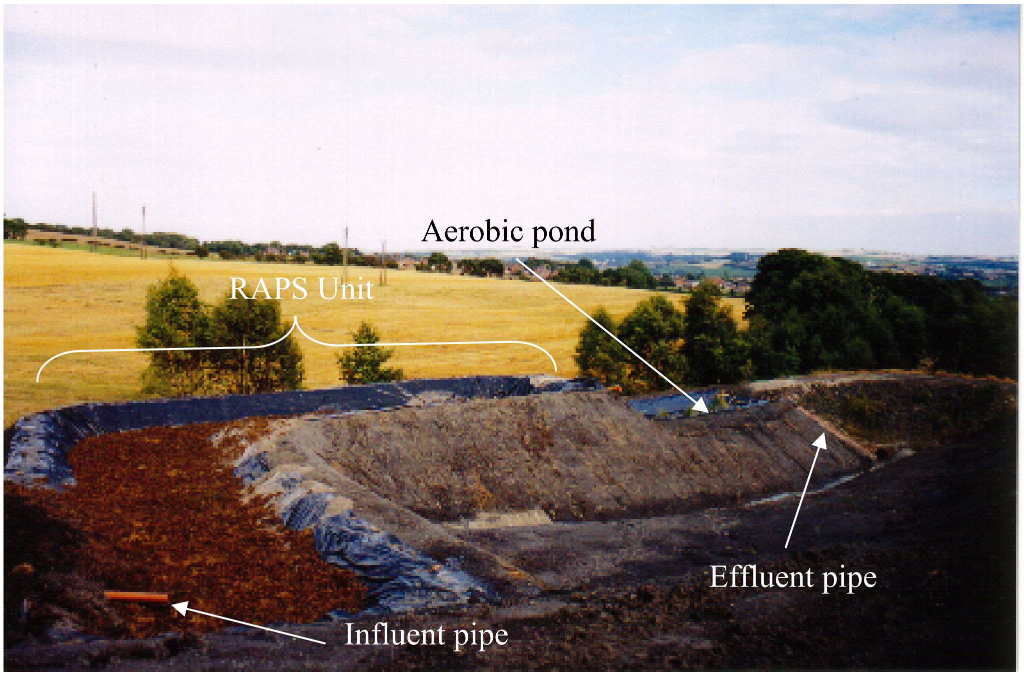


Figure 5 - Bowden Close Pilot Passive Treatment System in September 1999, immediately prior to the introduction of water into the RAPS.



2.3. System Modifications.

After test-running the system for a few weeks in the Autumn of 1999, it was soon discovered that the design flows (based on measured values during the previous year) were considerably less than the true winter flows of the No1 and No 2 discharges. During one storm in December 1999, flows were estimated to exceed 1000 l/min, and the system was temporarily drained down until some modifications could be introduced. These included the stilling pond in the first part of the RAPS unit (Figure 4) and overflows on the intakes at the No 1 and No 2 discharge locations. Wet winter weather prevented plant access until late February, and the system was finally fully operational by mid-March 2000.

3. Performance of the Bowden Close Pilot System.

3.1. Performance during initial test-running.

Table 4 summarises system performance prior to the installation of the overflow devices and stilling pond dyke. The performance is impressive in terms of all indicators (pH adjustment, alkalinity generation and removal of Fe, Zn and Al). Given the objectives of the Bowden Close system, the removal of Al is particularly encouraging. Nevertheless, in interpreting early pollutant removal rates in compost wetlands, it is important to realise that initial behaviour is very often more impressive than in the longer-term, since processes such as sorption can temporarily remove large amounts of Al, Fe etc from solution without fixing them permanently as mineral phases. Nevertheless, these results are encouraging and certainly vindicated the late, more detailed sampling campaigns.

Table 4 - Performance of the Bowden Close Pilot System in October 1999, prior to system modifications.

Date		Fe (mg/l)	Zn (µg/l)	Al (µg/l)	Alkalinity (mg/l as $CaCO_3$)	pH
5-10-99	Influent	7.688	360	2586	53	6.44
	Effluent	2.635	< 300	< 200	140	6.75
15-10-99	Influent	10.14	406	1499	10	6.5
	Effluent	3.12	340	< 200	230	7.26

3.2. Performance after modifications.

The general performance of the Bowden Close system after the modifications to the system were made is summarised in Table 5 below. During this period, measured flows passing through the system ranged from 50 to 120 l/min, about an average of 70 l/min. The data in Table 5 confirm the impression gained during the test-run period, i.e. that the system is performing very well in relation to the design objectives, with impressive removal rates for aluminium and iron, and remarkable increases in alkalinity, even when influent pH was not especially low.

Sampling at monthly or weekly intervals, which was the basis for most data shown in Table 5, is always open to the charge that the results are fortuitous; i.e. does the system really perform as efficiently in between sampling events? To address this issue, intensive sampling was undertaken at two temporal resolutions. Firstly, a period of daily sampling was undertaken during May 2000. Figures 6 to 8 show the daily variations in system performance with respect to iron, aluminium and alkalinity respectively. The overall impression is very similar to that gleaned from the weekly / monthly data in Table 5. Secondly, over a period of three days, samples were collected every hour. Figures 9 and 10 show the variations in iron and aluminium removal rates on an hourly basis during this period. Although removal rates are generally steady, brief event occur when efficiency briefly drops off for an hour or so. The precise reasons for this are not obvious, save that the greatest drops in efficiency occurred during the hours of darkness. It is possible that some photolytic oxidation processes which occur during the day are not operative at night. Temperature-dependent reactions might also be important. These are interesting possibilities, which will be worthy of further investigation in any full-scale system.

The data from this campaign of intensive sampling at Bowden Close have been pooled with data collected from the Pelenna III RAPS in South Wales to support some fundamental scientific work on the processes of solute transport through subsurface flow systems. This work was independently funded by the Fulbright Commission, and has borne fruit in a new method for modelling pollutant movement through such systems, which is currently being prepared for submission as a full paper (Goebes and Younger, *in preparation*) to *Environmental Science and Technology*, the leading journal in the field. While the subject matter of that paper is somewhat outwith the terms of reference of this study it is undoubtedly a major benefit of the existence of the CDENT-funded pilot system, and will be acknowledged as such in the paper.

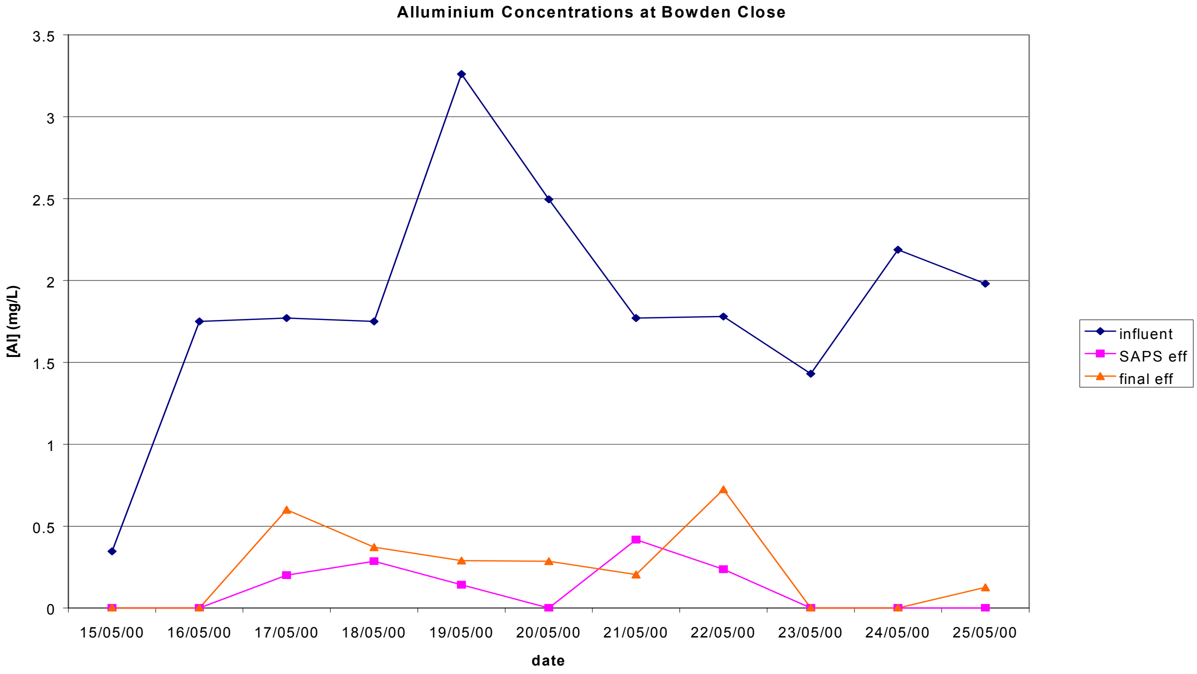
Table 5 - Performance of the Bowden Close Pilot System, Spring to Autumn 2000, after system modifications.

Date		Fe (mg/l)	Mn (μg/l)	Zn (μg/l)	Al (μg/l)	Alkalinity (mg/l as $CaCO_3$)	pH
28-3-2000	Influent	19.6	1291	63	2591	16	6.3
	Effluent	0.2	281	< 10	< 10	83	8.7
15-5-2000	Influent	11.0	1102	--	346	0	5.1
	Effluent	0.8	300	--	< 10	180	7.5
19-5-2000	Influent	12.1	2011	--	3261	8	6.5
	Effluent	0.9	446	--	290	120	7.7
25-5-2000	Influent	16.0	1100	--	6843	12	6.0
	Effluent	0.9	247	--	126	106	7.4
18-7-200	Influent	--	--	--	--	78	7.2
	Effluent	--	--	--	--	142	7.1
4-8-2000	Influent	--	--	--	--	28	7.1
	Effluent	--	--	--	--	142	7.2
17-8-2000	Influent	32.0	1830	< 10	10680	--	--
	Effluent	1.4	1041	< 10	3836	--	--
6-9-2000	Influent	4.7	462	< 10	7991	--	--
	Effluent	1.6	638	< 10	4207	--	--

Figure 6 - Daily variations in Iron removal, Bowden Close Pilot System.

Influent samples were taken at the weir leading into the SAPS. Concentrations of influent from the pipe may be higher.

Figure 7 - Daily variations in aluminium removal, Bowden Close Pilot System.



Influent samples were taken at the weir leading into the SAPS. Concentrations of influent from the pipe may be higher.
Alluminium concentrations never actually measured as 0 mg/L, but those represented as such were below detection limits.

Figure 8 - Daily variations in alkalinity generation, Bowden Close Pilot System.

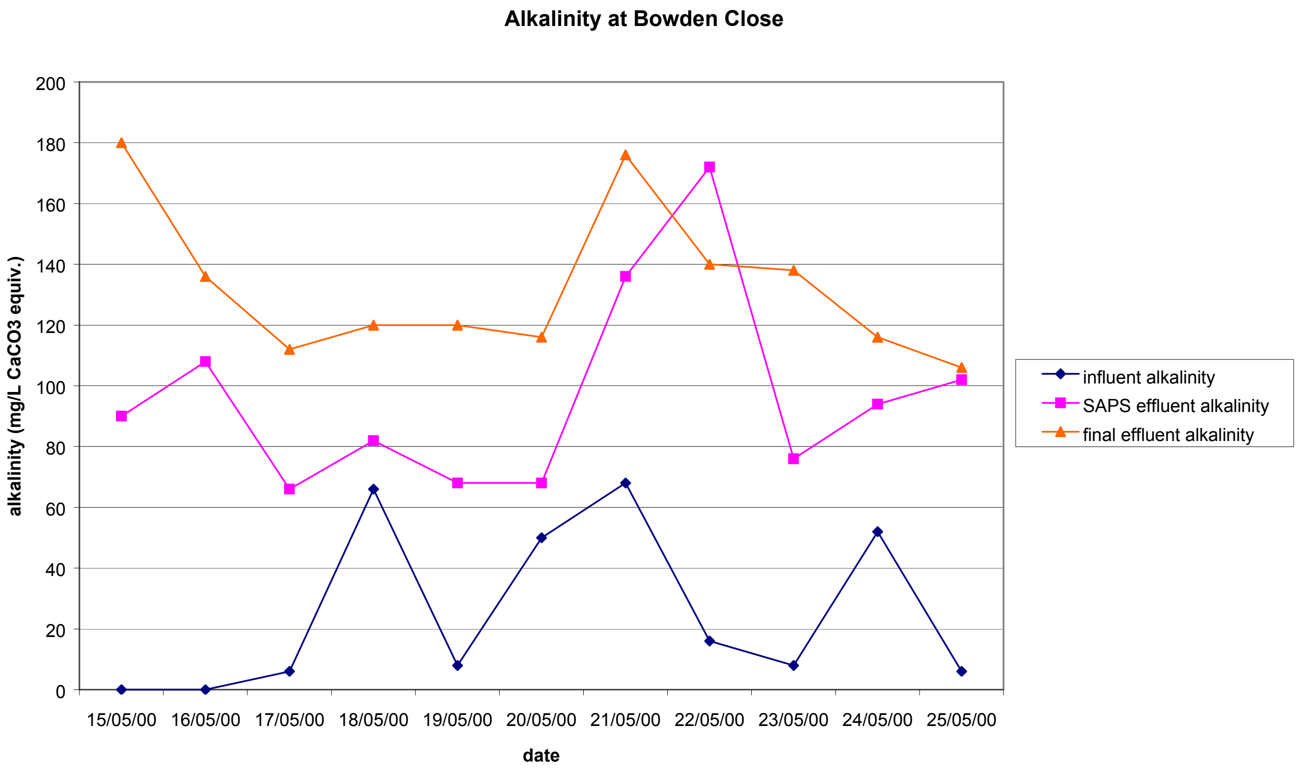
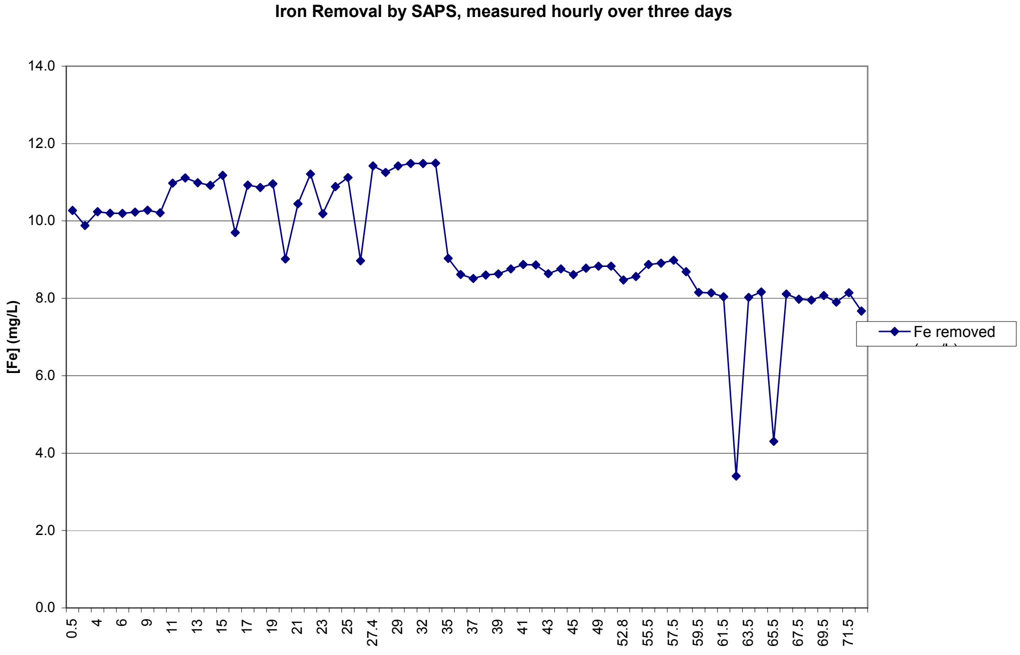
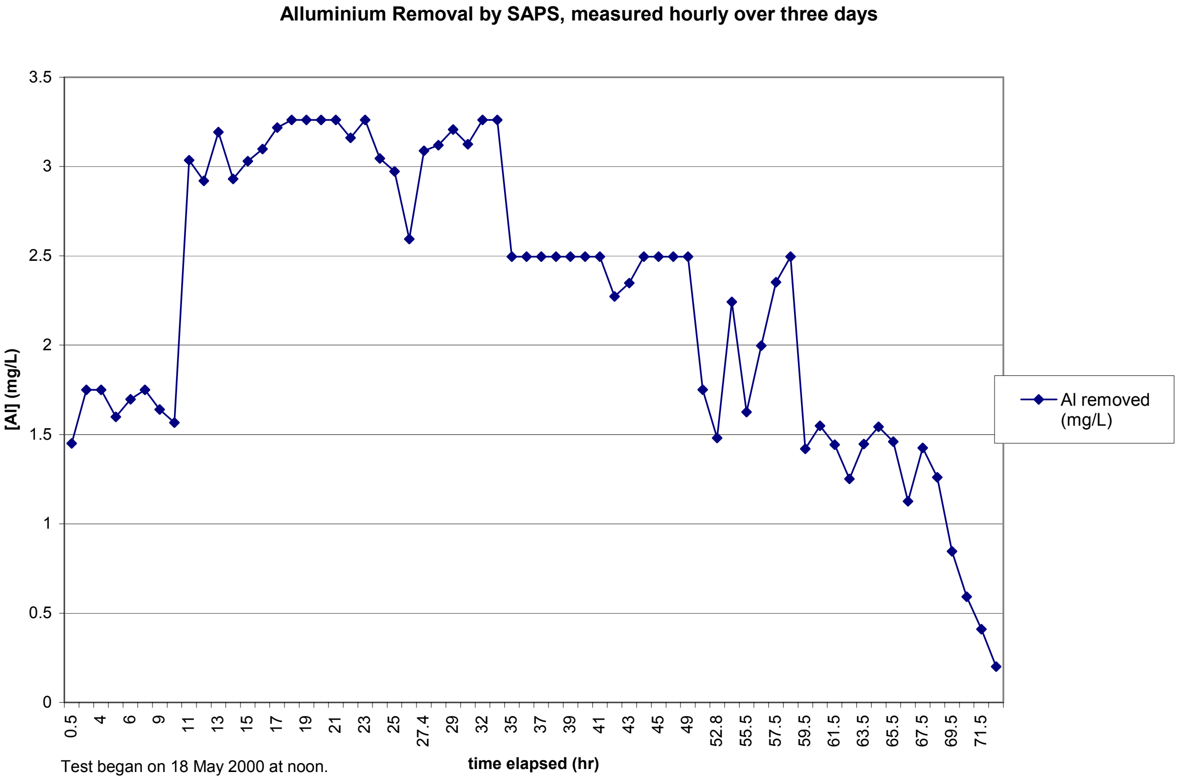


Figure 9 - Hourly variations in iron removal efficiency over a three-day period for the Bowden Close Pilot System.



Test began on 18 May 2000 at noon.

Figure 10 - Hourly variations in aluminium removal in the Bowden Close pilot system.



Test began on 18 May 2000 at noon.

In order to compare the Bowden Close system with other systems, it is necessary to express the pollutant removal rates in a standardised manner. Specifically, an acidity removal rate in terms of g/d/m^2 of wetland is the most commonly used convention (albeit it is not entirely satisfactory as a metric for vertical-flow systems). Expressed in these units[1], the Bowden Close Pilot System exhibits a mean acidity removal rate on the order of 25 g/d/m^2. This compares very favourably with mean values quoted from analogous systems in the USA (7 g/d/m^2; Hedin *et al.*, 1994) and for the surface-flow compost wetland at Quaking Houses, County Durham (6 - 11 g/d/m^2; Jarvis and Younger, 1999). It is therefore reasonable to conclude that the specific substrates and geometry used at Bowden Close are as efficient as could reasonably be expected, and that a full-scale system constructed on the same principles should serve to effectively treat the entire acidic drainage of the site (i.e. including the presently untreated discharge No 3) provided the system is adequately sized and constructed.

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[1] For design purposes, it is more helpful to deal in volumes rather than areas; since the substrate in the pilot system totalled 1m thick, the removal rate in volumetric terms is numerically identical, i.e. 25 g/d/m^3 of substrate.

4. Suggestions for full-scale implementation

Taking the removal rate of 25 g/d/m^3 as a guide, it is possible to calculate the size of a full-scale system suitable for treating the entire flow at Bowden Close (except during times of extreme runoff, when the water is in any case dilute and requires no treatment). The calculation assumes a design flow for the No 3 discharge of 200 l/min, and a total acidity of 420 mg/l as $CaCO_3$ (derived from the data given in Table 3 using the method described by Younger, 1995). This is equivalent to a loading of 120960 g/d of acidity. Add to this some 3400 g/d of acidity from the No 1 and No 2 discharges, and the total loading requiring passive treatment amounts to 124,360 g/d of acidity. Assuming a RAPS unit behaving in accordance with the pilot system performance, a total volume of compost and limestone substrate on the order of 5000m^3 will be necessary to neutralise all of this acidity.

The latest survey information provided by DCC suggests that a total area of around 2250m^2 is available for creating a full-scale system. Assuming that 250m^2 of this total will be occupied by peripheral earthworks and a small aerobic reed-bed downstream of the RAPS unit, the implication is that total treatment of the acidic drainage from this site will require the RAPS substrate to be emplaced 2.5m deep in a unit with a surface area of 2000m^2. For safety reasons, it will be necessary to include sufficient bulking material in the substrate to ensure that it can bear the weight of humans when wet. This will probably best be achieved by the inclusion of fibrous bark material with the horse manure and straw.

Critical to the development of these plans is further characterisation of the No 3 discharge, to determine whether it can be captured sufficiently far up-slope to allow it to be fed easily into the proposed RAPS unit. It is understood from DCC that this characterisation will be undertaken in the near future.

5. Summary

Acidic drainage, heavily polluted with Fe, Al and Mn, has been flowing from the site of the former Bowden Close colliery since at least the 1960s. Following several months of monitoring of flow and hydrochemical parameters to obtain design parameters, a pilot passive treatment system was constructed at the site in the summer of 1999, with the purpose of investigating the feasibility of treating such waters using simple, gravity-fed biogeochemical reactors. Of particular interest was the scope for removing aluminium from such waters, as this has hitherto proved problematic in similar systems. The Bowden Close pilot system comprises a downward-flow RAPS (reducing and alkalinity producing system) unit, followed by an aeration cascade and a shallow, aerobic pond. Monitoring of waters entering and leaving the system showed dramatic improvements in quality, with major increases in alkalinity and pH, and major decreases in dissolved aluminium, iron and manganese. The results are sufficiently encouraging to support construction of a similar, full-scale passive system at the site, and give grounds for optimism for the implementation of similar technology at other sites with similar problems.

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Neal McCay – Environment and Technical 'services Department, DCC
David Meldrum – Managing Director, Concrete Force Ltd
James Coulson – Resident Engineer for University of Newcastle
Paula Canteli, José Ivan Fanjul Alvarez and Maria del Campo Uña – LEONARDO industrial placement students from the University of Oviedo, School of Mines, Spain (on placement with NUWATER Consulting Services Ltd)
Marian Goebes – Fulbright Scholar on placement at University of Newcastle
Karen Johnson – PhD student, University of Newcastle
Dr Lesley Batty and Dr Adam Jarvis - Research Associates at the University of Newcastle.
Any errors or opinions in this report are the responsibility of the author alone, and do not necessarily represent the policy of DCC or CDENT.

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