Paper presented to the CL:AIRE Annual Project Conference, London, April 2004

A full-scale reducing and alkalinity-producing system (RAPS) for the passive treatment of acidic, aluminium-rich mine site drainage at Bowden Close, County Durham.

Paul L Younger[1], Ananda Jayaweera[2] and Richard Wood[2]

[1]School of Civil Engineering and Geosciences, University of Newcastle Upon Tyne
[2] Environment and Technical Services Directorate, Durham County Council, County Hall, Durham.

Abstract

Leachates generated by old colliery spoil heaps can pose significant risks to ecosystems, drinking water supplies and agricultural / commercial uses of surface waters. At Bowden Close in County Durham, investigations have been underway since 1999 into low-cost, environmentally-integrated methods for neutralising the acidity of, and removing ecotoxic metals from, such spoil leachates and similar drift mine drainage waters. Successful pilot-scale field tests (undertaken by the University of Newcastle and Durham County Council in 1999-2001) showed that it is feasible to passively treat Al-rich acidic leachates using subsurface flow biogeochemical reactors containing a mixture of compost and limestone. These so-called 'Reducing and Alkalinity-Producing System' (RAPS) improve water quality by the combined action of bacterial sulphate reduction and calcite dissolution. A full-scale passive treatment system based on this approach was constructed in the autumn of 2003, and full commissioning will be completed in the summer of 2004. The full-scale system incorporates two RAPS units, specifically designed to optimise Al^{3+} removal, and a polishing aerobic wetland (reedbed). Significant logistical and financial support from CL:AIRE, the BOC Foundation and the University of Newcastle's SRIF2 Earth Systems Laboratories initiative is facilitating the inclusion in this new system of unparalleled monitoring facilities. Early performance data from the new system, even before commissioning is finished, are very encouraging: pH rises from as low as 3.6 to as high as 7.6 as the polluted waters pass through the system. Net acidity removal (i.e. acidity removed plus alkalinity added) reaches nearly 250 mg/l as $CaCO_3$. Al concentrations fall from ≤ 22 to <0.5 mg/l. Fe drops from around 40 mg/l to < 10 mg/l; after the aerobic wetland is planted with *Typha latifolia* later this year, significantly lower final Fe concentrations (perhaps below 2 mg/l) are anticipated.

1. Introduction

The site of the former Bowden Close Colliery lies in the vicinity of the village of Helmington Row, in southwestern County Durham (Figure 1). After the colliery closed in the 1960s, the site was taken into the possession of Durham County Council, who proceeded to restore it according to the best practice of the period. Mine entrances were sealed and buried, derelict buildings were demolished and the voluminous spoil heaps which dominated the site were re-profiled and vegetated. The end result was a popular golf course in a pleasant rural setting.

As in many other reclamation schemes implemented prior to 1990, subsurface contamination issues were not a key driver in the original restoration scheme. However, by the end of the 1990s, Durham County Council were re-evaluating the Bowden Close site on account of two separate issues of ground contamination and associated pollutant seepages to the surface environment:

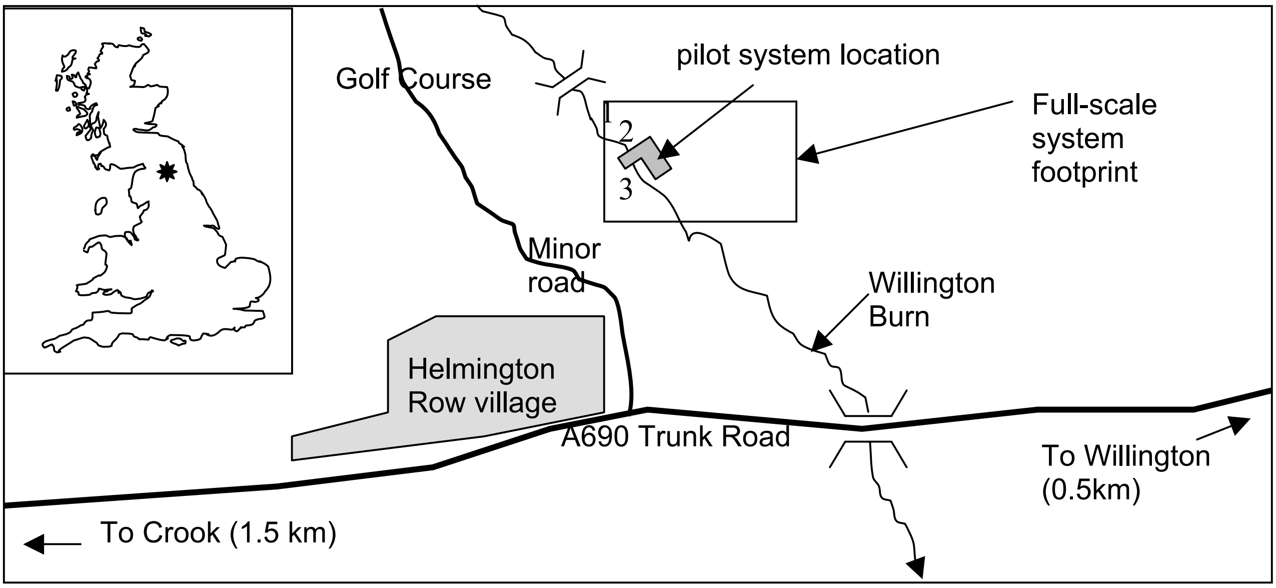
(i) Tar pollution arising from two large buried tanks, associated with the coke works which formerly occupied the southern portion of the Bowden Close site, and

(ii) Acidic, metalliferous waters, arising from spring-like features and land drains within the site, which severely polluted the adjoining Willington Burn.

A large-scale dig-and-dump operation implemented in 1999 effectively dealt with the tar pollution issue. During this operation, research was undertaken which established the feasibility of using biodiesel as a reagent to render recalcitrant tars amenable to bioremediation (Taylor and Jones, 2001).

The present paper concerns the steps taken to provide a long-term passive solution to the problems arising from the acidic metalliferous drainage on this site. Although this programme was initiated in 1999, it is only in 2004 that final completion of all of the required actions is finally within sight. This aspect of the Bowden Close remediation scheme was adopted by CL:AIRE as Technology Demonstration Project No 5 (TDP5), on account of a number of aspects of the scheme which are novel (Younger 2002). These include the specific targeting of passive technologies at aluminium removal, and the use of wholly mixed substrates in a subsurface flow bioreactor.

Figure 1 - Location of the Bowden Close (TDP5) passive mine water treatment site. The numbered points 1 - 3 are the three polluted discharges discussed in the text.



2. Acidic drainage at Bowden Close

The first published study of the acidic drainage at Bowden Close (Younger, 1995) revealed the waters to be very acidic (pH 3 - 4), with high concentrations of Fe and Al. Subsequent biological surveys of the receiving watercourse showed these polluted waters to be causing severe ecological damage (Jarvis and Younger, 1997). Site characterisation studies in 1998/99 revealed that there are actually three distinct, perennial discharges of acidic mine drainage at this site (as summarised in Table 1).

Discharge No 1 is the furthest upstream of the three perennial discharges. (Although minor ferruginous seepages do sometimes occur further upstream, these are not quantitatively significant). The No 1 discharge originally emerged 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. Although this discharge is perennial, in the height of summer and into the mid-autumn the flow can drop to a very low rate (around 0.03 l/s). During the construction of the full-scale passive system in the autumn of 2003, it was discovered that this discharge actually originates from an old mine access drift driven in the Harvey Seam, which lies only a few feet below ground at this point. A new connection into this drift was constructed, and the entire discharge captured and carried in a pipeline to the full-scale passive system.

Discharge No 2 originally entered the Willington Burn from its left bank some 25m downstream of the No 1 discharge. The source of this discharge has been observed to vary seasonally. At times it has dried up completely. At times when it is flowing at a low rate (< 0.1 l/s), the source of polluted water appears to be in a hollow amidst the stand of conifers which line the eastern flank of the Burn. This hollow is now known to be the collapsed remains of the portal of the same drift which gives rise to the No 1 discharge. During the laying of the No1 discharge pipeline a "water gate" (i.e. a small tunnel constructed to lead water out of the access drift) was unearthed, leading south-westwards from the location of the old drift portal towards the Burn. This carried a small seepage of polluted water, which was therefore diverted into the No 1 discharge pipeline. It is believed that all water formerly the seeping through the drift portal will now be captured in this manner, so that the hollow at the former portal will likely not flow at all in future. During wetter periods, the water entering the Willington Burn at the 'Discharge No 2' location commences rather higher up the site, as spoil leachate flowing from a small rill cutting spoil which underlies the eastern golf course greens. This is so acidic (pH < 2.5) that it is not visibly polluted until it mixes with less polluted water a short distance downstream, where pH rise to > 4 and both ochre and aluminium foam become apparent in the channel. The diversion of this water into the full-scale passive treatment system was being finalised at the time of writing. Table 1 summarises the characteristics of the No 2 discharge as measured in the spring and summer of 1999.

Discharge No 3 is the largest and most heavily polluted of the three main discharges, and it lies at the most downstream position of the three. 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 (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. It is believed to be spoil toe drainage from a perched water table within the spoil on the western bank of the Burn.

Table 1. Mean flow and selected hydrochemical parameters (total concentrations) for the three mine site drainage discharges at the abandoned Bowden Close Colliery, Co Durham.

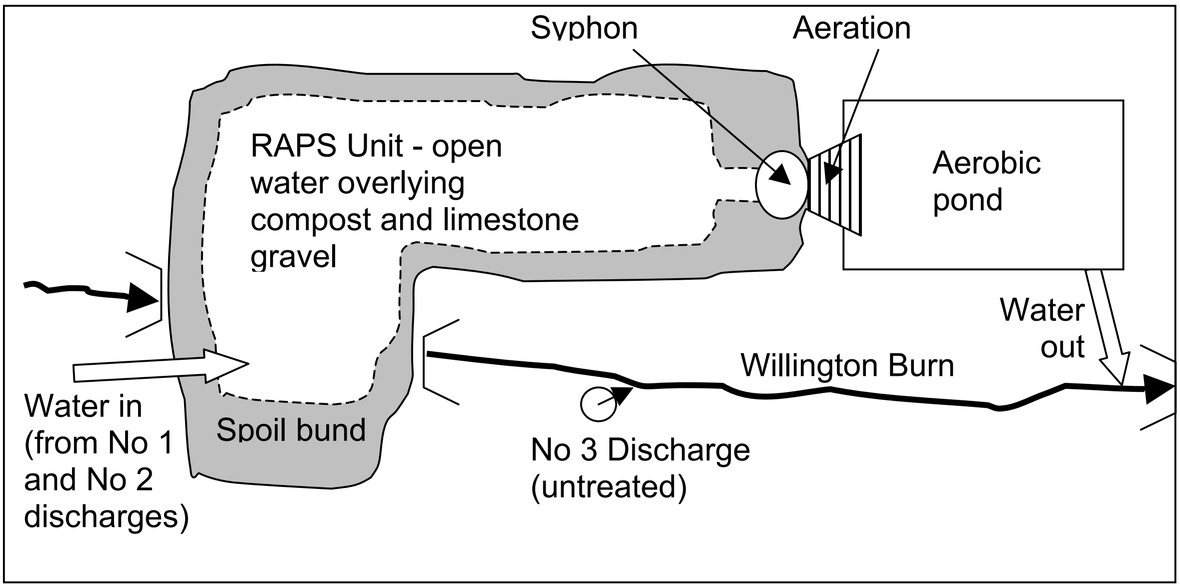
Discharge No.	*Mean flow rate (l/s)*	*Fe (mg/l)*	*Al (mg/l)*	*Zn (mg/l)*	*Alkalinity (mg/l as $CaCO_3$)*	*SO_4 (mg/l)*	*pH*
1	0.25	30	10	0.3	10	300	5.5
2	0.2	8	2	0.1	50	140	6.7
3	3.3	80	50	3	0	1530	4.0

3. Bowden Close Pilot Scheme

This system has been described in detail by Younger (2000, 2002) and Younger *et al.* (2003), so only a short summary is presented here. The Bowden Close pilot passive treatment system was constructed in the late summer and autumn of 1999 (Figure 2), and was operated until February 2001 (when further site work became impossible due to the Foot-and-Mouth Disease countryside access restrictions). The pilot system comprised a single RAPS unit followed by a small aerobic pond. (See Section 5 for definitions and explanations of these two unit passive treatment processes). Due to the late date of construction, which rendered the planting of reeds impractical, the small aerobic pond was vegetated with transplanted common rush (*Juncus effusus*). Discharges 1 and 2 were both fed into this system, which thus received a mean inflow of some 0.45 l/s of water with mean concentrations of 10 mg/l Fe and 2 mg/l Al. Influent alkalinity varied from zero to 68 mg/l.

System performance was impressive, with Fe concentrations being lowered to between 1 and 0.1 mg/l and Al concentrations to less than 0.3 mg/l (and often less than 0.01 mg/l), with effluent pH being consistently in excess of 7, and usually in the range 7.5 to 8.7. Alkalinity generation in the RAPS was particularly striking, with as much as 180 mg/l (as $CaCO_3$ equivalent) being imparted to the waters as they passed through the system (average alkalinity generated: 107 mg/l as $CaCO_3$). Overall the system proved capable of removing 25 grammes of acidity (as $CaCO_3$ equivalent) per m^2 of RAPS surface area per day, which is comparable with rates reported from systems in warmer climate settings in the eastern USA (Watzlaf *et al*. 2000).

Figure 2 - Sketch plan of the Bowden Close pilot passive treatment system, which operated from 1999 to 2001.



4. Moving to full-scale

Following on from the success of the pilot project, Durham County Council were keen to move onto installation of a full-scale passive system at Bowden Close. Funding for the system was obtained by the Council by means of the Supplementary Credit Approval mechanism, sanctioned by DEFRA. Although SCA funding was originally approved for spending in financial year 2000-2001, scheduling of other work planned by the Council meant that construction had to be held over to FY 2001-2002. In the event, the Foot and Mouth Disease outbreak prevented construction of the system in that year. By the time the plans came to be revisited, changes had occurred in the mode of implementation of Part IIA of the Environmental Protection Act 1990 and in the manner in which the Council had to deal with delivery of capital works. These changes occasioned further delays in getting approval for a final design which could be constructed on behalf of the Council by the framework partnering company, Balfour Beatty.

One of the most significant challenges to be overcome was the location of the full-scale passive system. Whereas the pilot passive system captured only the No 1 and No 2 discharges, it was always essential that the full-scale system capture all three discharges. Given the locations of the three discharges, achieving this goal was a significant challenge. For a passive system to be successfully constructed, it was essential that it be located on a site which:

a. is sufficiently spacious to allow full passive treatment of the water to preferred discharge consent standards.
b. lies topographically lower than the three discharge points, but not so far from the discharges as to demand piping untreated water over large distances.
c. is not so steep that cut-and-fill activities would be too difficult to achieve.
d. has soil conditions consistent with minimal geotechnical stabilisation requirements (which favoured building on native glacial till rather than on the rather treacherous colliery spoil which underlay the pilot plant site).
e. does not already have high landscape value (e.g. mature woodland).

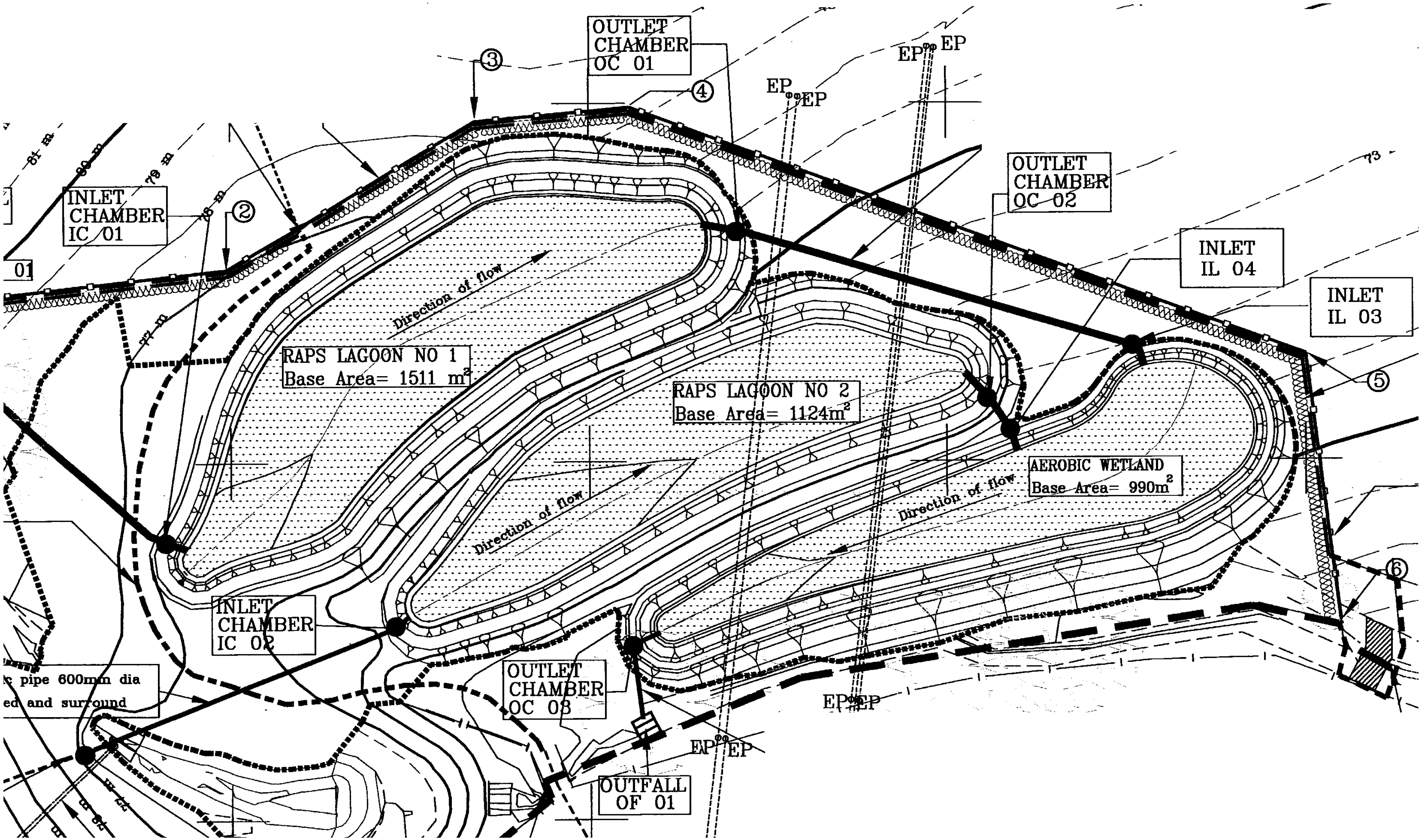
No parcel of land could be identified which met all of the above criteria. However, to the east of the Willington Burn a parcel of low-lying arable farmland was identified which complied with all of the above criteria with the exception of (a). This land was rather prone to water-logging, and hence was often unproductive agriculturally. Negotiations to purchase this land were successful. To attempt to compensate for its lack of full compliance with criterion (a) above, it was simply resolved that system design would be tailored so as to achieve as high a degree of treatment as possible in the space available. The design which was developed to achieve this is described in the following section.

It was not until mid-summer 2003 that the construction of the system at Bowden Close finally received a green light. Knowing from experiences of the pilot scheme just how difficult this site can be to work in wet weather, all concerned were anxious about the potential difficulties of completing the scheme before the end of the financial year. However, fortunes were favourable as one of the driest autumns on record ensued, allowing completion of the earthworks before the rains finally began to fall in earnest in November 2003. Nevertheless, with construction occurring in the second half of the year, it was not possible to plant up the final wetland in 2003, and this task is now scheduled for completion in late May / early June 2004.

5. Form and function of the full-scale passive system

The conceptual design of the full-scale system was undertaken by the author, and it was worked up into a detailed design by staff of Durham County Council. The layout of the system is summarised in Figure 3. The basic logic of the system is to use anaerobic processes to neutralise the mineral acidity of the waters, followed by aerobic processes to 'polish' the concentrations of key contaminants (Fe, Al, Mn and Zn) prior to final discharge to the Willington Burn. The anaerobic

Figure 3 - Layout of the full-scale passive treatment system constructed in the autumn of 2003 at Bowden Close, Co Durham.



processes are deployed within subsurface flow systems known as 'RAPS units', in which anoxic conditions are achieved by the oxygen-stripping action of organic compost (based on horse manure and straw in this case). Calcite dissolution is also effected under these anaerobic conditions, which ensures that all dissolved iron is converted to the ferrous form (Fe^{2+}), avoiding the problems of blinding of limestone clasts which occurs when iron is in the oxidised ferric form (Fe^{3+}). As is evident from Figure 3, the system is designed such that Discharge Nos 1 and 2 are directed into 'RAPS Lagoon No 1' via inlet chamber IC 01, with Discharge No 3 being passed into a RAPS of its own ('RAPS Lagoon No 2') via inlet chamber IC 02. The effluents from both RAPS units are subsequently mixed in a shared aerobic wetland (reed-bed) prior to final discharge to the Willington Burn via outlet chamber OC 03. Mine water leaving the RAPS units is expected to have a circum-neutral pH, which favours extremely rapid abiotic oxidation of Fe^{2+} to Fe^{3+}. The latter then hydrolyses rapidly to form ferric hydroxide (ochre). Any residual aluminium in the RAPS effluent will similarly hydrolyse at a very rapid rate. Mn^{2+} will also oxidise to Mn^{4+}, and precipitate as MnO_2 (pyrolusite) within the aerobic wetland. While some removal of Zn can be expected to occur within the RAPS units, further Zn removal can be anticipated in the reedbed, principally by means of sorption onto freshly precipitated ochre.

The design of the RAPS units at Bowden Close incorporates two novel features. The first is manifest in the nature of the reactive substrate in the Bowden Close RAPS (Figure 4), which is a thorough mixture of limestone clasts and compost. This differs markedly from the original RAPS design of Kepler and McCleary (1994), in which a discrete layer of limestone gravel underlies a layer of compost. Replacing this two-layer design with a mixed limestone / compost bed overcomes the following two drawbacks of the original design:

(i) throttling of the flow through the system by the limited permeability of the compost layer (which is typically some orders of magnitude lower than that of the limestone gravel layer), and

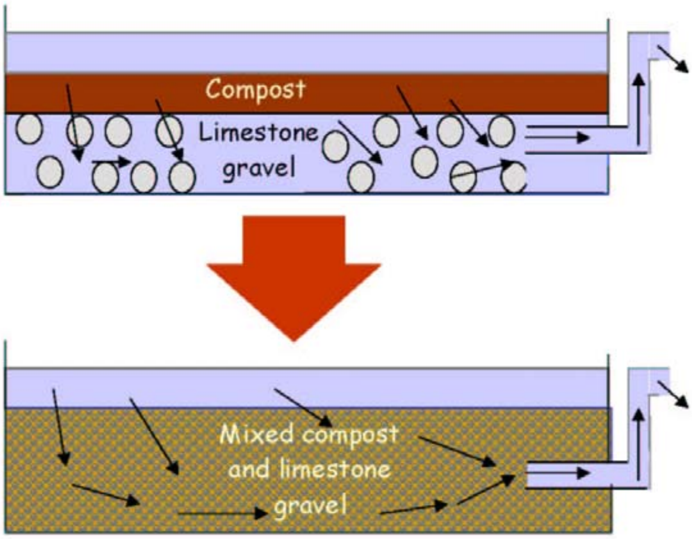
(ii) the public safety hazard represented by the presence of more than 0.5m of saturated organic matter as the surface layer.

This design development has been analysed in further detail in recent publications, which point to evidence in its favour obtained during both lab trials (Amos and Younger 2003) and during the operation of the Bowden Close pilot system (Younger 2002).

The second novelty of the Bowden Close system lies in the design of the hydraulic control at the ends of each of the RAPS units. These have been designed such that all of the water leaving the base of the compost/limestone bed is collected in fixed pipework which ends in a flexible hose suspended on chains (within a locked chamber). Not only does this make the system far easier to adjust in response to changing flows and RAPS substrate permeabilities, but it also allows for periodic dropping of the pipes to the base level of the RAPS, facilitating occasional 'scouring' of the substrate by imposing a very steep hydraulic gradient across the RAPS. This in turn should allow mobilisation of aluminium from within the pore space of the RAPS, helping to prolong the life of the reactive substrate (cf Kepler and McCleary 1997). This is especially useful in relation to RAPS 2, which receives very aluminous water.

It is also worth noting that, while RAPS 1 is fitted with an artificial liner (a HDPE membrane), RAPS 2 is unlined. The reason for this contrast was that RAPS 1 is partly dug into *in situ* clay, and partly built-up from backfilled clay removed from the RAPS 2 basin. As compaction of backfill to an uniformly low permeability is difficult to quality control on such a large structure, and as repairs would be difficult after substrate had been emplaced, it was decided that an artificial liner was justified. For RAPS 2, however, the basin is *only* excavated, not built-up. The low permeability of the undisturbed glacial till into which the RAPS 2 basin was excavated is sufficient to retain all water without further lining. Given that this RAPS receives the worst of the three discharges, and is therefore likely to need maintenance (substrate renewal) more regularly than RAPS 1, the absence of an artificial liner is a great benefit, as this means that substrate can be removed by straightforward digging without any need for costly precautions to avoid puncturing an artificial liner.

Figure 4 - Schematic cross-sections illustrating the shift in design concept from the layered RAPS design, as originated by Kepler and McCleary (1994) (top) to a fully mixed substrate, as used in the full-scale passive system at Bowden Close (bottom).

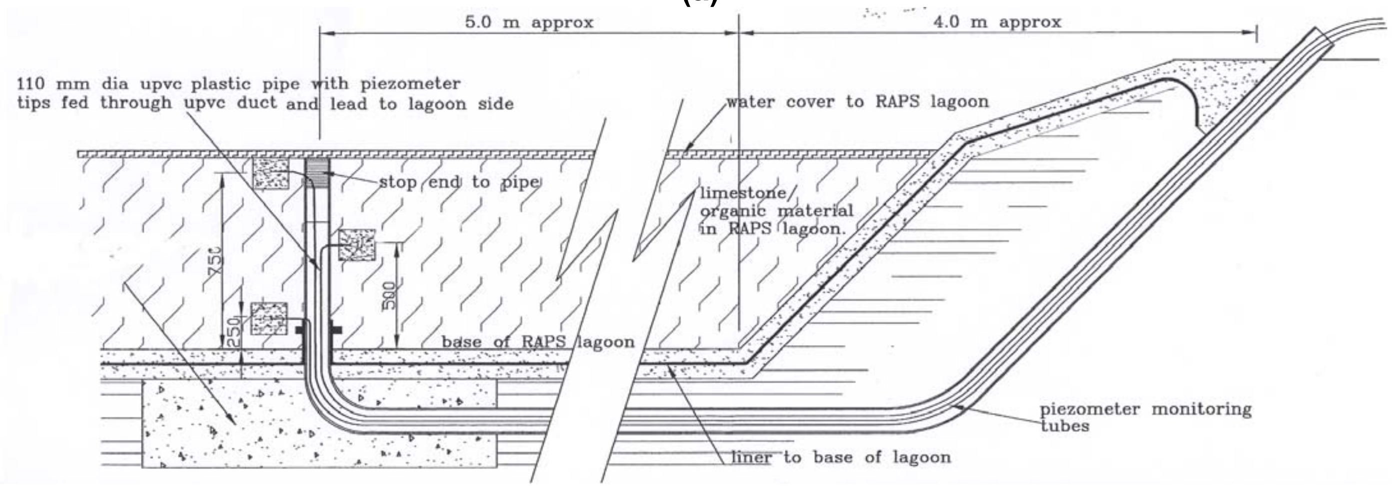


Just as significant as these process design innovations are the high-quality monitoring facilities which were incorporated in the system design. These features were made possible through significant financial support from CL:AIRE and the BOC Foundation. Secure, locked access chambers have been installed at the inlet and outlet of each of the RAPS units and of the aerobic wetland. These chambers have been designed to accommodate auto-samplers, multi-parameter water quality sondes and flow monitoring equipment. In addition, within the reactive substrates of both RAPS units triple-level piezometer clusters have been installed in accordance with an unique, novel design (Figure 5). Four such clusters have been incorporated into each of the two RAPS units (Figure 5b), giving eight positions in all at which it is possible to determine changes in hydraulic head and water quality over depth, as the water flows through the RAPS substrate.

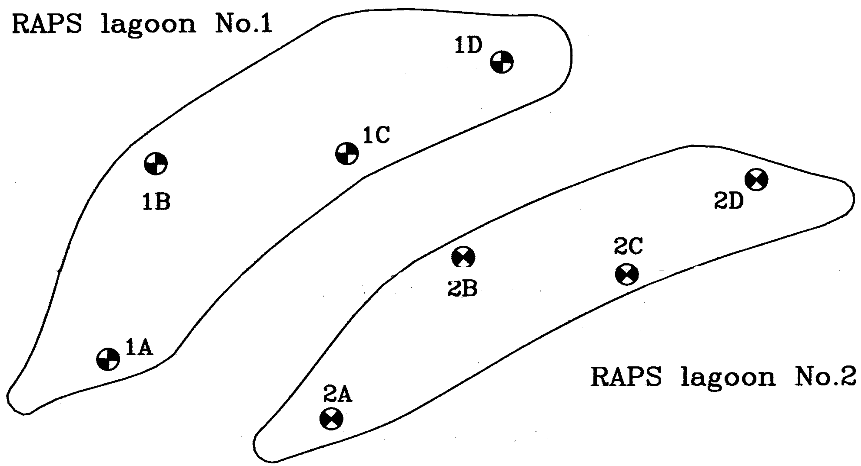
With these unique monitoring facilities in place, the scope for data capture and transmission is now planned to be further augmented by substantial additional investment in FY 2004-2005 from the University of Newcastle's SRIF2 spend, under the auspices of their new "Earth Systems Laboratories" initiative. This will provide the means for real-time transmission of flow and chemistry measurements to the University of Newcastle campus, enabling far greater observation of this system than has yet been achieved at any similar passive system anywhere in the world. At the time of writing, equipment to be installed in these monitoring chambers is under procurement, and is expected to be deployed during the summer of 2004.

Figure 5 - Triple-level piezometers in the Bowden Close RAPS units. (a) cross-section through the centre and bund of a RAPS unit showing the mode of construction (b) plan showing locations of triple-level piezo clusters within the RAPS units.

(a)



(b)



6. Early performance of full-scale system

As the Bowden Close system is not yet fully commissioned (adjustment of the head gradient across RAPS 2 is still in progress, and the aerobic wetland will not be planted with reeds until June 2004), it is still rather early to be discussing the performance of the system. Furthermore, in any discussion of system performance now or in future it is important to note that the limited availability of land at the site inevitably led to under-sizing of the RAPS and the aerobic wetland. The contrast between the ideal areas of the system components and their actual areas is highlighted in Table 2 below. While the disparity is modest for RAPS 1, the actual area of RAPS 2 is only about a quarter of the size that would have ideally been preferred.

Table 2 - Ideal versus actual areas of component passive treatment units in the Bowden Close passive treatment system

Element of system …	Ideal area[a] (m^2)	Actual area[b] (m^2)
RAPS 1	1728	1511
RAPS 2	4350	1124
Aerobic wetland	1300[c]	990

[a] as suggested by loading-based design calculations following the recommendations of Younger *et al.* (2002)
[b] see Figure 3. [c]Assumes a flow-weighted average of 15 mg/l Fe coming from RAPS 1 and RAPS 2.

Given the grounds for caution indicated by Table 2, the early performance data from the new system (in advance of final commissioning) are extremely encouraging. Table 3 summarises changes in key quality parameters as the water flows through the system. It should be noted that the fact that some parameters appear to <u>increase</u> in the aerobic wetland above the values leaving the RAPS (e.g. for aluminium) is simply due to the fact that, with commissioning as yet incomplete, some overflow of untreated water from RAPS 2 to the wetland is still occurring. (Initially, both RAPS 1 and RAPS 2 were overflowing, but increasing the hydraulic head across RAPS 1 solved this problem by mid-February 2004). Gradual adjustments of the RAPS 2 head control is progressively decreasing the overflow from this unit too, though at the time of writing about 50% of the influent to RAPS 2 is still overflowing. We anticipate eliminating overflow from RAPS 2 altogether by May 2004.

Even with some overflow still occurring from RAPS 2, overall system performance is extremely encouraging. Effluent pH never drops below 6.6, even though influent pH falls as low as 3.6. On no occasion has their been more acidity than alkalinity in the final discharge. Aluminium is always lowered below detection limits during flow through the RAPS units. Never less than 90 mg/l (as $CaCO_3$) of alkalinity is added to the waters by the RAPS units, and as much as 270 mg/l can be added on occasion. When acidity removal and alkalinity generation are taken into account the net acidity removal rates of both RAPS units average 247 mg/l as $CaCO_3$. In terms of area-adjusted acidity removal rates, RAPS 1 is effectively load-limited as it regularly lowers acidity to low single figures; this results in an under-stressed acidity removal rate of 5 - 9 g/d/m^2. RAPS 2 receives more acidic waters and is small in comparison to its ideal size (Table 2). It is thus very far from being load-limited, and it exhibits very high acidity removal rates, ranging from 20 to 40 g/d/m^2. It is noteworthy that these impressive performance figures relate to the winter months, when influent water temperatures within the system have fallen as low as 3.8^{o}C, so that reaction rates can be expected to have been at their most sluggish. The overall picture is therefore highly encouraging, and the prospects for even greater performance after the final completion of commissioning are certainly favourable.

Table 3 - Water quality determined at various points in the Bowden Close System from the start of the commissioning process (still incomplete) in December 2003. All sampling and analysis undertaken by Patrick H A Orme.

Date	Sample	pH	Cond uS/cm	Alkalinity mg/l as CaCO3	Acidity mg/l as CaCO3	Sulphate mg/l	Calcium mg/l	Iron mg/l	Manganese mg/l	Aluminium mg/l
10-Dec-03	RAPS 1 inf	6.46	980	37	40	433	113	5.9	1.4	4.9
	RAPS 1 eff	7.43	1272	130	8	354	111	1.3	0.3	1
	RAPS 2 inf	5.17	1258	10	198	730	118	37.8	5.3	21.6
	RAPS 2 eff	7.26	1890	280	10	490	155	1.5	1.7	0.7
	Wetland eff	7.03	1219	70	36	421	132	10.9	2.8	2
06-Jan-04	RAPS 1 inf	6.02	911	20	47	432	118	7.6	1.2	5.6
	RAPS 1 eff	7.29	1070	108	2	309	117	0.5	0.6	<0.5
	RAPS 2 inf	6.18	641	50	57	212	62.3	12.1	1.2	5.9
	RAPS 2 eff	7.13	978	182	5	248	127	0.7	2.1	<0.5
	Wetland eff	7.02	717	71	13	176	82.5	3.9	1.0	0.7
22-Jan-04	RAPS 1 inf	4.2	980	0	101	542	116	16.2	2.1	11.8
	RAPS 1 eff	7.3	1088	115	3	344	117	0.7	1.0	<0.5
	RAPS 2 inf	5.49	950	16	130	478	102	20.8	2.7	15.8
	RAPS 2 eff	7.15	1052	162	6	358	162	1.2	2.2	<0.5
	Wetland eff	6.79	919	61	36	359	120	8.8	2.1	3
05-Feb-04	RAPS 1 inf	4.3	963	0	94	510	110	19.5	1.9	9.6
	RAPS 1 eff	7.5	961	128	4	278	117	1	1.1	<0.5
	RAPS 2 inf	6.05	847	35	101	400	95	20.5	2.2	10.8
	RAPS 2 eff	7.33	926	178	7	292	141	1.7	2.4	<0.5
	Wetland eff	7.18	787	52	25	311	105	9.6	1.8	0.8
18-Feb-04	RAPS 1 inf	3.62	986	0	118	613	109	22.1	1.9	11.3
	RAPS 1 eff	6.97	1073	104	4	375	137	1.1	1.3	<0.5
	RAPS 2 inf	4.57	1185	5	203	801	119	37.1	4.4	23
	RAPS 2 eff	6.84	1354	171	15	571	204	3.4	4.7	<0.5
	Wetland eff	6.65	1180	83	48	529	161	11	3.6	3.9
03-Mar-04	RAPS 1 inf	3.9	1011	0	98	579	110	19.9	1.6	9.6
	RAPS 1 eff	7.64	1101	108	4	349	142	1	1.3	<0.5
	RAPS 2 inf	5.15	1170	10	197	779	117	39	4.5	21.3
	RAPS 2 eff	7.3	1482	182	16	653	230	3.5	5.6	<0.5
	Wetland eff	6.61	1122	67	61	472	148	12.2	3.4	5.9

7. Future plans

7.1. Finalising planting and optimising hydraulic behaviour

As has already been mentioned, the Bowden Close system is not yet fully commissioned. When the overflow on RAPS 2 has been eliminated, so that all of the water passes through the reactive substrate, and when the aerobic wetland has been fully planted up and experienced one or two seasons of growth, we expect to polish the remaining 10 mg/l Fe in the final effluent to less than 2 mg/l (cf Batty and Younger 2002).

7.2. Research initiatives: TDP5, CoSTaR, ASURE and ESLs

The Bowden Close system benefits from substantial research support. Its status as CL:AIRE TDP5 has already been mentioned; besides providing a pathway to significant research funding from BOC Foundation and some of CL:AIRE's own sponsors, this link is crucial to the dissemination of research findings. A full TDP report is planned to be produced in due course, as soon as an assessment of the performance of the system can be made following full commissioning. Also through the link with CL:AIRE, this system has been clustered with five others to form 'CoSTaR', an unique national facility for mine site remediation research. As well as making six highly-characterised full-scale systems available for UK research (which includes the current Bioremediation LINK project 'ASURE', involving both the University of Wales, Bangor, and Newcastle University), CoSTaR has recently been designated an "international access infrastructure" by the European Commission 6th Framework Programme. This means that researchers from all over Europe will be able to receive funding to spend significant periods of time at Bowden Close and the other CoSTaR sites, collecting data of their own and learning about passive mine water remediation in the process. Even more research infrastructure support is to be provided by the University of Newcastle through its approved spending of SRIF2 funding provided by HEFCE. As part of a wider initiative to create a network of outdoor research facilities (termed "Earth Systems Laboratories") across the north of England, the CoSTaR sites are scheduled to receive further infrastructure investment with a total value in excess of £400K. This will not only ensure that hydraulic structures and sampling facilities at all CoSTaR sites match those which are now being commissioned at Bowden Close, but will also facilitate real-time telemetric transmission of flow and chemistry data back to the University campus, whence they will be further available to collaborating researchers world-wide via the web.

Acknowledgements

The Bowden Close Pilot System was funded under the Entrust Landfill Tax Credit Scheme by the County Durham Environmental Trust (CDENT) and managed by Neal McCay of Durham County Council. Balfour Beatty constructed the full-scale system on behalf of Durham County Council. Research and monitoring facilities in the full-scale system have been funded by the BOC Foundation and CL:AIRE. Susie Roy of Durham University kindly made data available for the Bowden No 3 discharge. Some of the work reported was part-funded by the European Commission FP5 R&D Project 'PIRAMID' (EVK1-CT-1999-000021; www.piramid.org), and also by the Biorem 4 LINK project 'ASURE' (co-funded by Rio Tinto, Scottish Coal, Parkhill Estates Ltd and IMC Ltd). Numerous staff and students have contributed to fieldwork over the years, most notably: Mr Patrick Orme, Dr Adam Jarvis, Dr Paula Canteli, James Coulson and Marian Diaz Goebes. The views expressed are the responsibility of the author alone and cannot be construed as representing the views of any of the sponsoring organisations.

References

Amos P.W. and Younger P.L. (2003) Substrate characterisation for a subsurface reactive barrier to treat colliery spoil leachate. *Water Research* **37**: 108 - 120.

Batty L.C. and Younger P.L. (2002) Critical role of macrophytes in achieving low iron concentrations in mine water treatment wetlands. *Environmental Science & Technology* **36**: 3997 - 4002.

Beck P., Harries N., and Sweeney R. (2001) *Design, installation and performance assessment of a zero valent iron perme-able reactive barrier in Monkstown, Northern Ireland.* CL:AIRE Technology Demonstration Report TDP3. (ISBN 0-9541673-0-9). CL:AIRE, London. 120pp.

Jarvis A.P. and Younger P.L. (1997) Dominating chemical factors in mine water induced impoverishment of the invertebrate fauna of two streams in the Durham Coalfield, UK. *Chemistry and Ecology* **13**: 249 - 270.

Kepler D.A. and McCleary E.C. (1994) Successive Alkalinity Producing Systems (SAPS) for the Treatment of Acidic Mine Drainage. *Proceedings of the International Land Reclamation and Mine Drainage Conference and the 3rd International Conference on the Abatement of Acidic Drainage.* (Pittsburgh, PA; April 1994). Volume 1: Mine Drainage: 195 - 204.

Kepler, D.A. and E.C. McCleary, 1997, Passive aluminum treatment successes. In *Proceedings of the 18th Annual West Virginia Task Force Symposium*, held Morgantown, West Virginia, 15 - 16 April 1997.

Taylor L.T. and Jones D.M. (2001), Bioremediation of coal tar PAH in soils using biodiesel. *Chemosphere* **44**: 1131-1136.

Watzlaf G.R., Schroeder K.T., and Kairies C. (2000) Long-term performance of alkalinity-producing passive systems for the treatment of mine drainage. *Proceedings of the 2000 National Meeting of the American Society for Surface Mining and Reclamation*, Tampa, Florida, June 11-15, 2000.

Younger P.L. (1995) Hydrogeochemistry of minewaters flowing from abandoned coal workings in the Durham coalfield. *Quarterly Journal of Engineering Geology* **28**: S101 - S113.

Younger P.L. (2000) *Pilot-scale passive treatment of acidic mine drainage using a downward-flow,reducing and alkalinity producing system (RAPS) at Bowden Close, County Durham, UK.* Final report to Durham County Council and CDENT. University of Newcastle Upon Tyne, UK. 18pp.

Younger, P.L. (2002) A reducing and alkalinity-producing system (RAPS) for the passive treatment of acidic, aluminium-rich leachates emanating from revegetated colliery spoil materials at Bowden Close, County Durham. In Proceedings of the CL:AIRE Annual Project Conference, 11th April 2002, Imperial College, London. (ISBN 0-9541673-1-7). Paper 7, 21pp.

Younger P.L., Banwart S.A., and Hedin R.S. (2002) *Mine Water: Hydrology, Pollution, Remediation.* Kluwer Academic Publishers, Dordrecht. (ISBN 1-4020-0137-1). 464pp.

Younger, P.L., Jayaweera, A., Elliot, A., Wood, R., Amos, P. Daugherty, A.J., Martin, A., Bowden, L., Aplin, A.C., and Johnson, D.B. (2003) Passive treatment of acidic mine waters in subsurface-flow systems: exploring RAPS and permeable reactive barriers. *Land Contamination and Reclamation* **11**: 127 - 135.