TECHNOLOGY DEMONSTRATION PROJECT REPORT: TDP5

A REDUCING AND ALKALINITY PRODUCING SYSTEM (RAPS) FOR PASSIVE TREATMENT OF ACIDIC, ALUMINIUM RICH MINE WATERS

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Contaminated Land: Applications in Real Environments (CL:AIRE)

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A REDUCING AND ALKALINITY PRODUCING SYSTEM (RAPS) FOR PASSIVE TREATMENT OF ACIDIC, ALUMINIUM RICH MINE WATERS

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This is a CL:AIRE Technology Demonstration Project Report. Publication of this report fulfils CL:AIRE's objective of disseminating and reporting on remediation technology demonstrations. This report is a detailed case study of the application of a Reducing and Alkalinity Producing System (RAPS) for the passive treatment of acidic, aluminium rich mine waters. It is not a definitive guide to the application of passive treatment of mine water. CL:AIRE strongly recommends that individuals/organisations interested in using this technology retain the services of experienced environmental professionals.

EXECUTIVE SUMMARY

Leachates generated by old colliery spoil heaps can pose significant risks to ecosystems, drinking water supplies and agricultural uses of surface waters. As regulatory controls have tightened over the years, it has also become apparent that the risks posed by such sites are likely to persist for hundreds of years in most cases. Thus, remedial interventions which can be readily sustained over long time periods are increasingly required. Given that such treatment may have to be sustained for centuries, conventional 'active' treatment technologies such as lime dosing and sedimentation (which have high operating costs) are unappealing. Passive treatment options (in which most expenditure is concentrated in construction costs and operating costs are minimal) are far more attractive.

At Bowden Close in County Durham, investigations have been underway since 1999 into low-cost, environmentally-integrated methods for treating acidic, aluminium-rich spoil leachate and similar drift mine drainage waters. Successful pilot-scale field tests (undertaken by the University of Newcastle upon Tyne and Durham County Council in 1999-2001) showed that it is feasible to passively treat these leachates using subsurface flow biogeochemical reactors containing a mixture of compost and limestone. These so-called 'Reducing and Alkalinity-Producing Systems' (RAPS) improve water quality by the combined action of bacterial sulphate reduction and limestone dissolution, safeguarding the porosity of the limestone layer. A full-scale passive treatment system based on this approach was constructed in the autumn of 2003 and fully commissioned in the summer of 2004. The full-scale system incorporates two RAPS units and a polishing aerobic wetland. The RAPS units were specifically designed to optimise aluminium removal, as well as other contaminants, and consist of a mixed one-layer substrate, in contrast to the conventional dual-layer approach.

The performance data from the new system are very encouraging: pH rises to neutral values and key pollutants are almost completely removed. Based on the performance data, the pilot study and experiences with other passive treatment sites, lifetime and life-cycle costs were calculated. These estimations demonstrate the economic advantages of passive treatment, in particular over extended periods of operation.

With significant logistical and financial support from CL:AIRE and the BOC Foundation, the University of Newcastle's SRIF2 Earth Systems Laboratories initiative, the LINK sponsored ASURE project and the European Commission FP6 CoSTaR project, the Bowden Close remediation site features unparalleled monitoring facilities and has become a focus of national and international research. As such it is hoped that the experience of the Bowden Close investigations will yield insights of use to many other owners of former colliery sites in the UK and worldwide.

ACKNOWLEDGEMENTS

The site of the former Bowden Close colliery has now been under thorough investigation for more than a decade, starting with a University of Newcastle MSc investigation undertaken by Kim Bradley. Consequently, there are a considerable number of individuals and organisations who contributed to the current full-scale system.

The Bowden Close Pilot System was funded under the ENTRUST Landfill Tax Credit Scheme by the County Durham Environmental Trust (CDENT). Durham County Council commissioned the University of Newcastle to design and construct the pilot passive treatment facility, who in turn sub-contracted construction works to Concrete Force Ltd. The following individuals played key roles in the pilot project:
Neal McCay, David Meldrum, James Coulson, Paula Canteli, José Ivan Fanjul Alvarez, Maria del Campo Uña, Karen Johnson and Marian Diaz Goebes.

The detailed design of the full-scale system was developed from our basic concepts by Ananda Jayaweera and Richard Wood (Reclamation Section, Durham County Council). Balfour Beatty constructed the full-scale system on behalf of Durham County Council. Susie Roy of Durham University kindly made data available for the Bowden No 3 discharge. The Environment Agency and the Wear Valley District Council have been very constructive regulators throughout the whole project. We also wish to thank Chris Bullen and Richard Coulton from Unipure (Europe) Ltd.

Research and monitoring facilities in the full-scale system have been funded by the BOC Foundation and CL:AIRE and we are particularly grateful to Stan Redfearn (BOC), Paul Beck (formerly CL:AIRE) and Nicola Harries (CL:AIRE) for their enthusiastic support. Continuing funding for installation and operation of monitoring equipment is being made possible via Newcastle University’s SRIF2 funding stream (‘Earth Systems Laboratories’).

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The full-scale system at Bowden Close is also part of the Biorem 4 LINK project 'ASURE', supported through the EPSRC (grant # GR/S07247/01) and with support from the industrial partners White Young Green Ltd., Parkhill Estates Ltd., Rio Tinto Technology, and The Scottish Coal Company Ltd. We also acknowledge the contributions made by our colleagues Barrie Johnson and Kevin Hallberg from the University of Wales, Bangor.

Finally, numerous individuals from Newcastle University have contributed to the work at Bowden Close over the years, most notably: Patrick Orme, Jane Davis, Andy Aplin and Michelle Morrison.

CL:AIRE would like to thank Mr Mike Summersgill of SEnSe Associates and Dr Brian Bone of the Environment Agency for their review of the technical aspects of this report.

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ABBREVIATIONS

AAS	Atomic Absorption Spectrometry
ALD	Anoxic Limestone Drain
CDENT	County Durham Environmental Trust
CDM	Construction Design & Management
DEFRA	Department for Environment, Food and Rural Affairs
HDPE	High Density Polyethylene
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
PE	Polyethylene
QA/QC	Quality Assurance/Quality Control
RAPS	Reducing and Alkalinity Producing System

1. INTRODUCTION

1.1 BACKGROUND

This report concerns the steps taken to provide a long-term passive solution to the problems arising from the acidic and metalliferous drainage at the former Bowden Close colliery in County Durham. Although this programme was initiated in 1999, it was only in 2004 that all of the required actions were finally completed. 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, 2002a). These include the specific targeting of passive technologies for aluminium removal, and the use of wholly mixed substrates in a subsurface flow bioreactor.

1.1.1 COLLIERY SPOIL HEAP LEACHATE

Many old colliery spoil heaps passed into local authority ownership from the 1960s onwards, long before it was fully appreciated that the leachates generated by these heaps pose significant risks to ecosystems and drinking water supplies. At the time of local authority acquisition the reclamation of colliery spoil heaps focused on superficial beautification, often with substantial planting of trees and the cultivation of dense swards of grasses and sedges (e.g. Rimmer and Younger, 1997). The measure of success in a spoil heap reclamation scheme was the richness of the vegetation which had been induced to grow on the sites. Due to their hummocky topography, some of the spoil heap reclamation schemes actually went so far as to redevelop former mines sites into very successful golf courses, which now form long-established and lucrative components of many local economies.

Issues of sulphide mineral (e.g. pyrite) oxidation and subsequent leachate formation within the spoil became apparent in the form of acidic, metalliferous leachates flowing through the perimeter drains and out into receiving watercourses. These leachates are commonly contaminated with iron (causing vivid orange / red staining of streambeds) and various other metals, such as aluminium (causing white staining), and, less commonly, manganese and zinc. Aluminium is a particularly ecotoxic metal and is associated with a range of human ailments including neurological and bone diseases and triggering the onset of Alzheimer's Disease. Aluminium contamination of natural waters is therefore a great concern to environmental regulators. In some UK spoil heaps it is present at very high concentrations, as shown by the few examples listed in Table 1.1 below.

Table 1.1: Some examples of elevated aluminium concentrations in UK mine spoil leachates.

Site	**Al Concentration [mg/l]**	**Reference**
Quaking Houses, Co Durham	21	Younger *et al.* (1997)
Randolph Bing, Fife, Scotland	800	Younger (2001)
Baads Bing, West Lothian, Scotland	80	Younger (2001)
Shilbottle Brass Heap, Northumberland	298	Amos (2001)
Nailstone Colliery Spoil, Leicestershire	73	Jarvis and Younger (2000)
Bowden Close Colliery, Co Durham	50	Younger (2000b)
Upleatham Ironstone Mine, Cleveland	164	Younger (2002b)

1.1.2 REMEDIATION TECHNIQUES FOR SPOIL LEACHATE

Hydrogeochemical research has revealed that many spoil heaps will continue to generate leachates for hundreds of years unless remedial measures are implemented (e.g. Strömberg and Banwart, 1994). It is technically feasible to minimise leachate generation by capping the spoil with materials preventing the passage of moisture and air into the interior parts of the heap, hence minimising the oxidation of sulphide minerals (the process which releases the problematic acidity to the leachates). Such covers can be formed from clay (e.g. Gustafsson *et al*., 1999), geotextiles, or other materials such as sewage sludge mulches (e.g. Metcalfe, 1994).

However, in the many cases where the spoil already boasts a mature mantle of woodland, meadow or turf freeway, the disruption implicit in retro-fitting such covers is likely to meet with stiff opposition. In such circumstances, leachate treatment is often inevitable. Given that such treatment may have to be sustained for centuries, conventional 'active' treatment technologies such as lime dosing and sedimentation (which have high operating costs) are unappealing. Passive treatment options (in which most expenditure is concentrated in construction costs and operating costs are minimal) are almost always preferable.

1.1.3 PASSIVE TREATMENT

A number of cost-effective passive treatment options are feasible for spoil leachates which are contaminated only with iron (for a thorough review, see Younger *et al.*, 2002). However, in the presence of elevated concentrations of aluminium, fewer inexpensive treatment options are available. The solubility of aluminium is highly pH-sensitive, with little aluminium remaining soluble once pH rises above 4.5 and one might imagine that it would be easy to treat at low cost. However, significant problems beset treatment of aluminium-contaminated waters for the following reasons:

1. The low density of the aluminium hydroxide / hydroxysulphate precipitates which can commonly be induced to form at circum-neutral pH makes them difficult to settle from suspension. Indeed these aluminium compounds often form froths floating on the surface of treatment ponds and wetlands, and which are thus susceptible to being wind-blown onto adjoining land and downstream reaches of receiving watercourses.

2. The precipitation of aluminium hydroxide is itself an acid-generating process, as indicated by the appearance of three hydrogen ions (protons) in the right-hand side of the following stoichiometric equation:

   $$Al^{3+}_{(aq)} + 3H_2O = Al(OH)_{3(s)} + 3H^{+}_{(aq)} \qquad (1)$$

   One consequence of this is that, as more solid $Al(OH)_3$ precipitates, the pH drops and Al^{3+} gradually becomes more soluble.

3. The most popular proven technology for passive treatment of acidic waters involves alkalinity-generation in an anoxic limestone drain (ALD), which is a flooded bed of limestone gravel insulated from the atmosphere, followed by sedimentation in ponds and wetlands. The use of ALDs to treat aluminium-rich acidic leachates is prone to failure, however, because reactions such as (1) above (and similar reactions which result in the formation of aluminium hydroxysulphate particles) occur rapidly in the high-pH micro-environments provided by limestone clasts within ALDs, resulting in the precipitation of such abundant quantities of white "alum" that the pore spaces become clogged and the ALD can no longer transmit the design flow of water.

1.1.4 REDUCING AND ALKALINITY-PRODUCING SYSTEM (RAPS)

The key notion is to overcome the problems of clogging which beset ALDs by introducing a compost layer above the limestone gravel bed. Passive treatment systems configured in this manner are termed 'Reducing and Alkalinity-Producing System' (RAPS). The term ‘successive alkalinity producing systems’ (SAPS) was the one first coined for this technology by Kepler and McCleary (1994) but the more descriptive name of RAPS has since been introduced by Watzlaf and co-workers at the US Department of Energy.

1.2 PURPOSE AND OBJECTIVES

Successful pilot-scale field tests (undertaken by the University of Newcastle and Durham County Council in 1999-2000) indicated that it is feasible to passively treat Al-rich acidic leachates by applying a hybrid compost-limestone system (RAPS). Aluminium is presumably removed from solution by spatially diffuse processes of sorption / precipitation in the compost layer, largely safeguarding the porosity of the limestone gravel below.

A full-scale passive treatment system based on these principles has been constructed to treat drainage at the former Bowden Close colliery. The full-scale system incorporates two RAPS units, specifically designed to optimise aluminium removal, and a polishing aerobic reed wetland. With significant logistical and financial support from CL:AIRE and the BOC Foundation, and being a target of research sponsored by the LINK Bioremediation Programme and the European Commission FP-6 Programme, this new system is set to be one of the most extensively and intensively monitored examples of its type anywhere in the world. It is thus confidently expected to yield important insights into the mechanisms of pollutant removal, in particular of aluminium removal in the RAPS, and the likely long-term maintenance requirements (practical and financial) for such systems.

1.3 REPORT ORGANISATION

This report is organised in five main sections, addressing issues related to the construction and the operation of the pilot and the full-scale treatment system at Bowden Close.

The site and its remediation history is described in Section 2, followed by a brief report on support issues, such as contract agreements, health and safety, analytical methods etc. (Section 3). A detailed section on the construction of the full-scale system is linked with information on design, construction and performance of the pilot phase in Section 4. The early performance is discussed in Section 5, highlighting the success of the installed full-scale treatment system. Sections 6, 7, and 8 focus on practical and financial implications resulting from this project, in particular costs and long-term operation compared with active treatment.

2. STUDY SITE

2.1 SITE DESCRIPTION AND HISTORY

The site of the former Bowden Close colliery lies in the vicinity of the village of Helmington Row, in southwestern County Durham (Figure 2.1). 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.

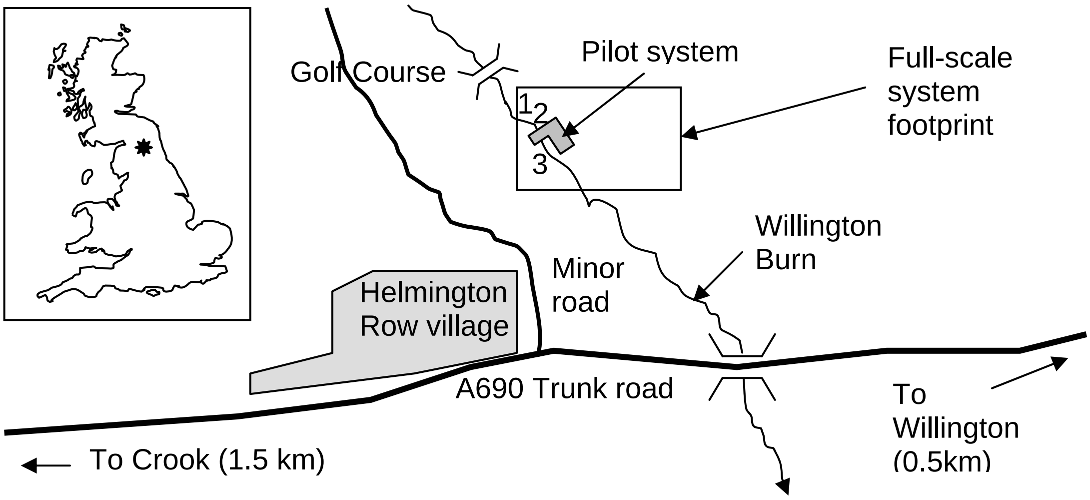

Figure 2.1: Location of the Bowden Close (TDP5) passive mine water treatment site. The numbered points 1 - 3 are the three polluted discharges discussed in the text.

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:

1. Tar pollution arising from two large buried tanks, associated with the coke works which formerly occupied the southern portion of the Bowden Close site.
2. 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).

2.2 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 2.1).

Table 2.1: 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

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 0.5 m diameter concrete drainage pipe on the true left bank of the Willington Burn, some 50 m downstream of the grassy "bridge" over the Burn within the golf fairway. 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 into the Harvey Seam, which lies only a few feet below ground at this point (Figure 2.2). 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 true left bank some 25 m 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 No 1 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 (Figure 2.3). 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 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 the 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 in the 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 rises to > 4 and both ochre (iron hydroxide/oxyhydroxide) and aluminium foam become apparent in the channel. Table 2.1 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. This discharge is usually conspicuously aluminium-rich, depositing substantial volumes of 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.

Figure 2.2: View inside Harvey Drift (representing Discharge No 1 at Bowden Close) showing roof collapse into workings.

Figure 2.3: Seepage from the water gate of Harvey Drift is captured and diverted into No 1 discharge pipeline.

3. TECHNOLOGY DEMONSTRATION SUPPORT ISSUES

3.1 CONTRACT AGREEMENTS AND REGULATORY APPROVAL

The pilot project was managed by the University of Newcastle on behalf of Durham County Council (who were in turn funded by CDENT), and constructed by Concrete Force Ltd. The construction of the full-scale system was managed directly by Durham County Council, using their Framework Contract agreement with Balfour Beatty Ltd. All necessary public and commercial insurance was managed through the Framework agreement, using standard arrangements.

As the site had been extensively restored in the past, both in terms of surface revegetation in the past and removal of large volumes of mobile tar in 2000, regulatory issues on the site were few. From liaison with the Environment Agency during the pilot-scale project, it was concluded that no licences or discharge consents would be required for the treatment system *per se*. Original plans to re-align the stream channel were discarded in the final system design as more land became available for building the system beyond the original site boundaries; hence there was no need even for a land drainage consent for the final full-scale system.

3.2 HEALTH AND SAFETY

The scale of the pilot project meant that the Construction Design & Management (CDM) regulations were not applicable, but a comparable Health and Safety regime was in any case implemented in line with the University's policies. The full-scale project was administered by Durham County Council, under full CDM regulations. The implementation was straightforward, and no problems arose during construction works. For long-term site management, minor re-alignment of a public footpath and standard public safety measures (fencing, warning notices) were implemented by the County Council. As described in Section 4.4.2.1, the change from a two-layer RAPS design to a mixed compost-gravel bed was in part motivated by public safety considerations.

3.3 DEMONSTRATION WORK AND SAMPLING PLAN

In line with the original application to CL:AIRE, the Technology Demonstration Work Plan was as follows:

- Flow measurement of influent, effluent and intermediate points, on an approximately weekly basis, with some periods of continuous data logging.
- Collection of routine hydrochemical samples of surface and subsurface waters within the system (using auto-samplers for periods of daily sampling, and manual weekly or fortnightly sampling at other times).
- Tracer testing of the entire system and its sub-components under a range of seasonal conditions. Auto-samplers were used for these exercises.
- Periodic removal and destructive analysis of cores of reactive substrate to reveal the state of compost diagenesis and forms of metals retention at different depths.

To comply with this work plan, the full-scale system at Bowden Close features various unique sampling and monitoring facilities, such as designated monitoring chambers and four clusters of triple-level piezometers in each RAPS. These facilities are described in detail in Section 4.4.2.

3.4 ANALYTICAL METHODS AND QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

Measurements of pH, redox potential, electric conductivity and temperature were taken in the field with a Myron 6P Ultrameter. Alkalinity was titrated directly with 1.6 N sulphuric acid and Bromcresol-Green Methyl-Red indicator, using a Hach AL-DT test kit. Flows were determined by multiple measurements with a bucket and stopwatch at the inlet. Continuous measurements were carried out in the field by deploying a Van Essen CTD Diver DI 218.

Water samples of the full-scale system were taken in acid-rinsed polyethylene (PE) bottles and analysed by ion chromatography, Atomic Absorption Spectrometry (AAS) and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES) at the geochemistry laboratories at the University of Newcastle, applying standard analytical protocols and standard chemicals for calibration and QA/QC.

Tracer tests were conducted at Bowden Close with Na-fluorescein (detected fluorometrically), NaBr and LiBr (analysed with a bromide sensitive probe). A detailed description of the methods used for the tracer test can be found in Wolkersdorfer *et al.* (2005).

4. REMEDIATION DESIGN AND PROCESSES

4.1 CONCEPT FOR EFFECTIVE PASSIVE TREATMENT OF ALUMINIUM-RICH ACIDIC WATERS

The treatment concept at Bowden Close is based on the principles of a reducing and alkalinity-producing system (RAPS). In a RAPS-type passive treatment system, polluted leachate is forced to flow downwards through a compost bed into a layer of limestone gravel, as shown in Figure 4.1 below.

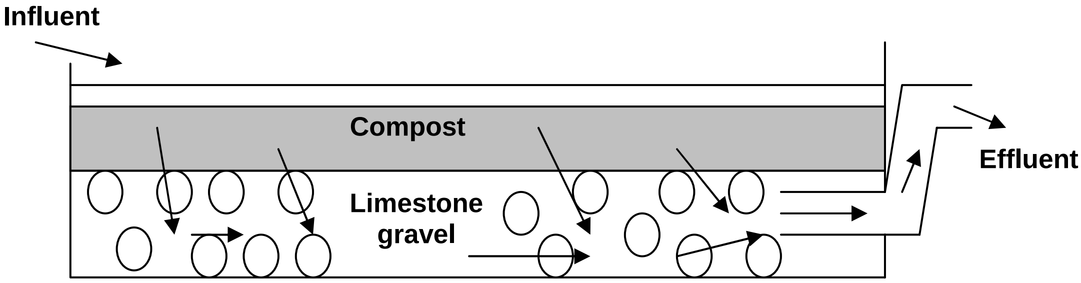

Figure 4.1: Schematic cross-section through a typical RAPS unit which is usually sized to allow 14 hours retention time. In the RAPS, there is a downward flow of polluted mine drainage through a compost layer (typically >0.5m thick) and a limestone gravel bed (adapted after Younger, 2000b).

Treatment processes occurring in a RAPS unit as shown in Figure 4.1 are thought to be primarily as follows:

1. Bacterial sulphate reduction, which generates alkalinity, raises pH and traps Fe as a sulphide within the compost layer.

2. Limestone dissolution, which further raises pH and generates alkalinity.

3. Oxidation and hydrolysis of iron, manganese and aluminium to form hydroxides (both within the RAPS unit itself, and in the small aerobic pond which is typically installed downstream of the RAPS unit).

The rise in pH within the compost layer will generally exceed the 4.5 threshold above which aluminium will readily hydrolyse according to equation (1) (Section 1.1.3). Precipitation of aluminium solids in a diffuse manner will thus largely safeguard the porosity of the limestone gravel below. Aluminium is also thought to form colloidal flocs with organic material derived from the compost. If these infiltrate the limestone gravel bed, it is thought that they can be periodically flushed out before solidifying and occluding the pore space by occasionally opening a 'scour pipe', which is designed to induce locally turbulent flows (Kepler and McCleary, 1997; Demchak *et al.*, 2001).

The concept has been tested in a large field pilot reactor, as described in the following section (Section 4.2), and will be further studied at full-scale in a newly commissioned reactor (Section 4.4).

4.2 THE PILOT-SCALE TREATMENT SYSTEM AT BOWDEN CLOSE

The Bowden Close pilot passive treatment system was constructed in the late summer and autumn of 1999 (Figure 4.2), 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 with an area of 120 m^2 followed by a small aerobic pond, as outlined in Figure 4.3.

Figure 4.2: The pilot-scale system at Bowden Close during construction in autumn 1999.

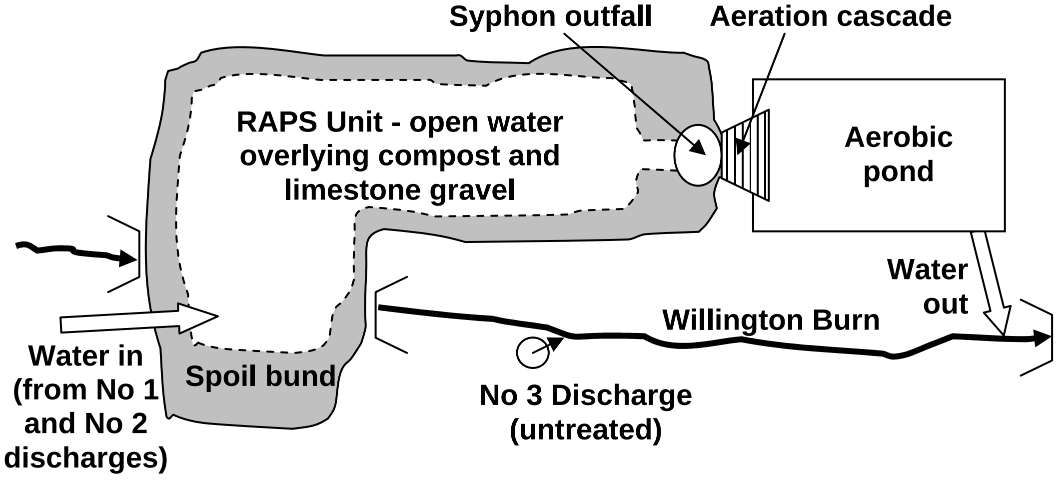

Figure 4.3: Sketch plan of the Bowden Close pilot passive treatment system, which operated from 1999 to 2001.

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 Nos 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 iron and 2 mg/l aluminium. Influent alkalinity varied from zero to 68 mg/l.

System performance was impressive, with iron concentrations being lowered to between 1 and 0.1 mg/l and aluminium concentrations to less than 0.3 mg/l. Effluent pH was 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 g of acidity (as $CaCO_3$ equivalent) per m^2 of RAPS surface area per day, which is comparable with rates reported from systems in the warmer climatic conditions of the eastern USA (Watzlaf *et al*., 2000).

4.3 MOVING TO FULL-SCALE

Following on from the success of the pilot project, Durham County Council were keen to move on to 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 Department for Environment, Food and Rural Affairs (DEFRA). Although 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 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 captured 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. was sufficiently spacious to allow full passive treatment of the water to preferred discharge consent standards.

b. lay topographically lower than the three discharge points, but not so far from the discharges as to demand piping untreated water over large distances.

c. was not so steep that cut-and-fill activities would be too difficult to achieve.

d. had 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. did 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 (Section 4.4). 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 calendar year. However, fortunes were favourable as one of the driest autumns on record ensued, allowing completion of the earthworks (Figure 4.4) 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 was completed in summer 2004 (Figure 4.5).

Figure 4.4: Earthworks for the full-scale treatment system at Bowden Close. In the background are the two RAPS lagoons. Only RAPS lagoon No 1 (to the left) has an artificial High Density Polyethylene (HDPE) liner.

Figure 4.5: The aerobic polishing wetland of the full-scale system was planted with mature reeds in summer 2004.

4.4 THE FULL-SCALE PASSIVE SYSTEM

4.4.1 LAYOUT AND FLOW PATHWAYS

The conceptual design of the full-scale system was undertaken by the authors, and it was worked up into a detailed design by staff of Durham County Council. The layout of the system is summarised in Figure 4.6. The basic logic of the system is to use anaerobic processes to neutralise the mineral acidity of the waters, followed by aerobic processes to attenuate any remaining metal contaminants (iron, aluminium, manganese and zinc) prior to final discharge to the Willington Burn.

The anaerobic processes occur within subsurface flow systems known as 'RAPS units', in which anoxic conditions are achieved by the oxygen-stripping action of organic compost (horse manure and straw in this case). Calcite dissolution is also affected 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+}). 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 directed into '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 (see Figure 4.6). 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. Reduced manganese (Mn^{2+}) will also oxidise (to Mn^{4+}) and precipitate as manganese oxides within the aerobic wetland, albeit the extent of manganese immobilisation is typically less than that of iron and aluminium. While some removal of zinc can be expected to occur within the RAPS units, further zinc removal can be anticipated in the reedbed, principally by means of sorption onto freshly precipitated ochre.

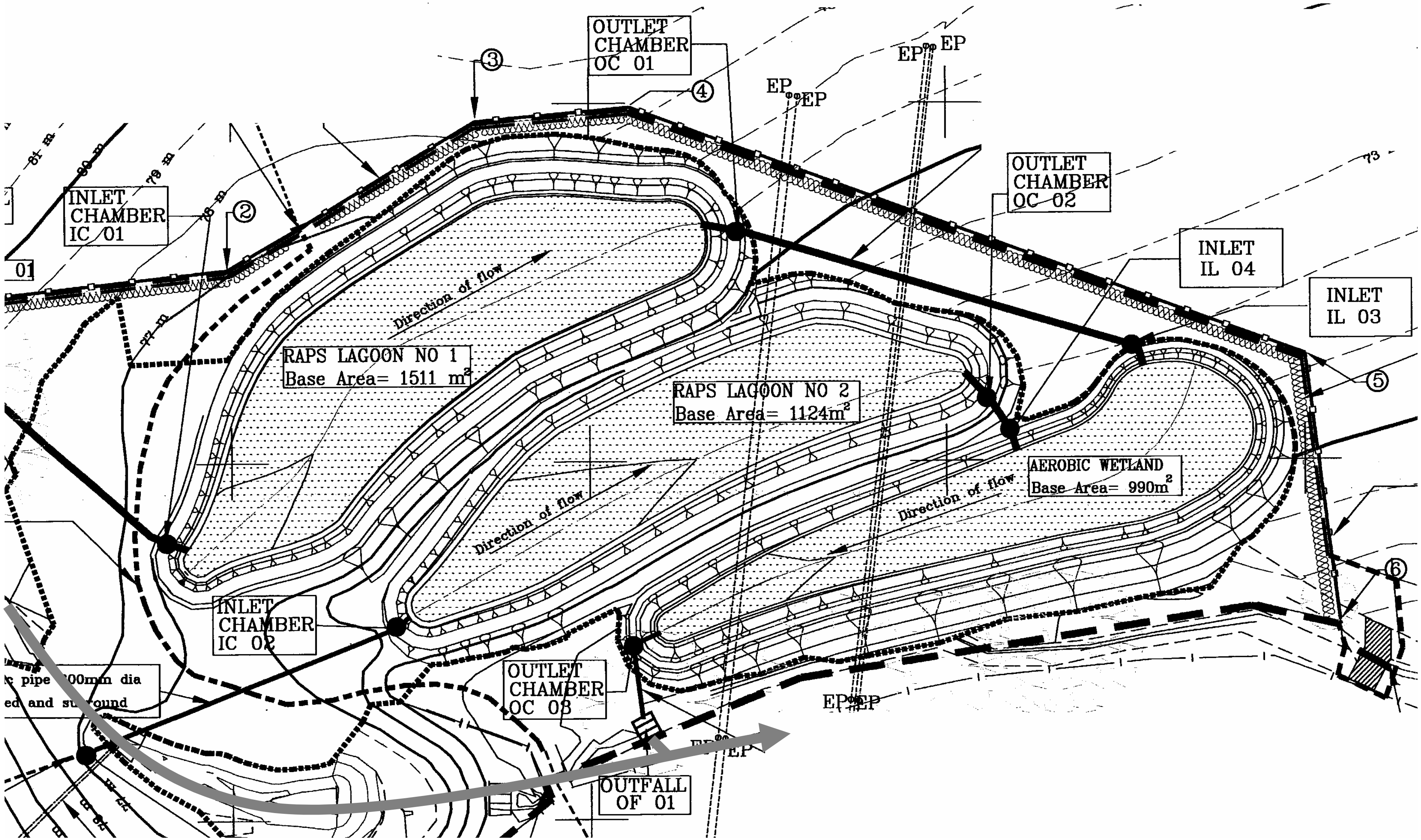

Figure 4.6: Layout of the full-scale passive treatment system constructed in the autumn of 2003 at Bowden Close, Co Durham. The grey arrow marks the direction of Willington Burn.

It is also worth noting that, while RAPS 1 is fitted with an artificial liner (a HDPE membrane), RAPS 2 is unlined (Figure 4.4). The reason for this is 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 a uniformly low permeability is difficult to achieve for such a large structure, and as repairs would be difficult after substrate had been emplaced, it was concluded that an artificial liner was justified. For RAPS 2, however, no fill material was required. 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.

4.4.2 DESIGN NOVELTIES

4.4.2.1 Mixed One-Layer Design of the Substrate

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 4.7), 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.

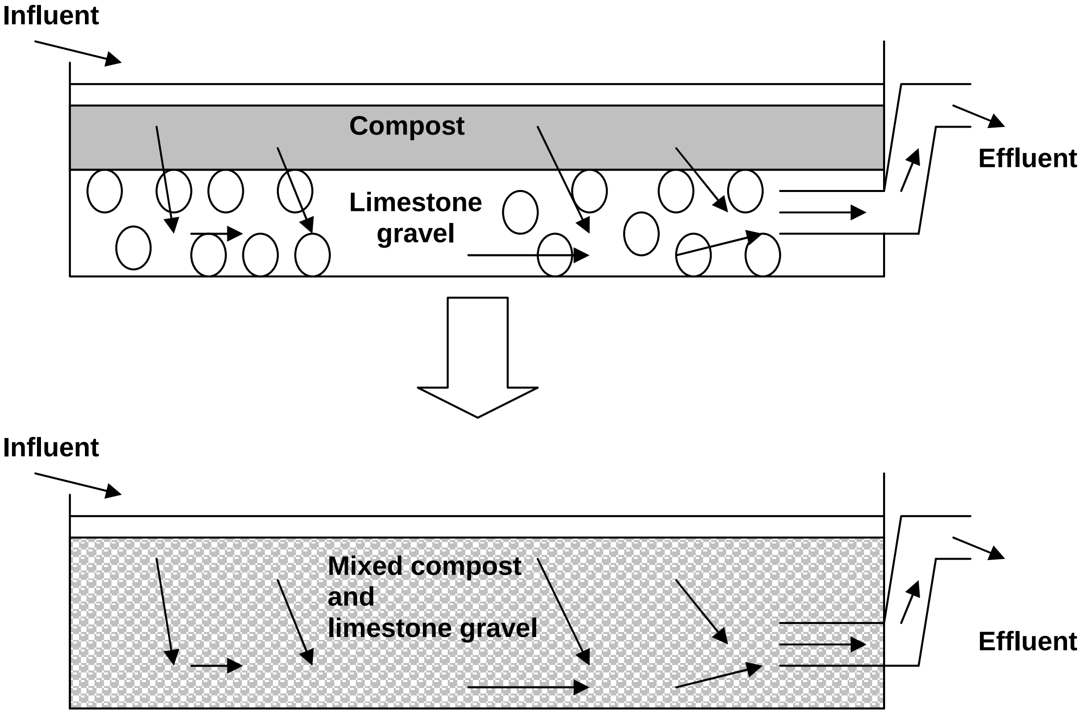

Figure 4.7: Schematic cross-sections illustrating the shift in design concept from the layered RAPS design, as originated by Kepler and McCleary (1994) (top) to a fully mixed substrate, as used in the full-scale passive system at Bowden Close (bottom).

Replacing this two-layer design with one layer of compost mixed with limestone overcomes the following two drawbacks of the original design:

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

2. the public safety hazard represented by the presence of more than 0.5 m 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, 2002a). The lab trials demonstrated that under a surcharge weight of 25 kg (to simulate overlying water and compaction under its own weight), cattle manure only had a permeability of 1.3×10^{-5} m/s, whereas a mix of 50% limestone, 25% slurry screenings and 25% compost had a permeability of 7.5×10^{-3} m/s.

4.4.2.2 Hydraulic Control

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 (Figure 4.8).

Figure 4.8: Each RAPS outlet is housed in locked chambers which can accommodate auto-samplers and monitoring sondes. The pipework ends in a flexible hose suspended on chains controlling the hydraulic gradient across the RAPS.

Not only does this make the system far easier to adjust in response to changing flow and RAPS substrate permeability, but it also allows for periodic dropping of the pipes to the base level of the RAPS, facilitating occasional 'flushing' 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 (Kepler and McCleary, 1997). This is especially useful in relation to RAPS 2, which receives very aluminium-rich water. The precipitates are flushed directly into the aerobic polishing wetland where they are retained. If they were collected in geotextile bags there would be a regular disposal issue. Due to economies of scale, it is considered better to allow long-term build up of metal precipitates in the wetland, and then address the disposal issue for a single large volume, rather than repeatedly disposing of small volumes.

4.4.2.3 Monitoring and Sampling Facilities

Just as significant as the 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 (Figure 4.8). 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 a unique, novel design (Figure 4.9). Four such clusters have been incorporated into each of the two RAPS units, 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.

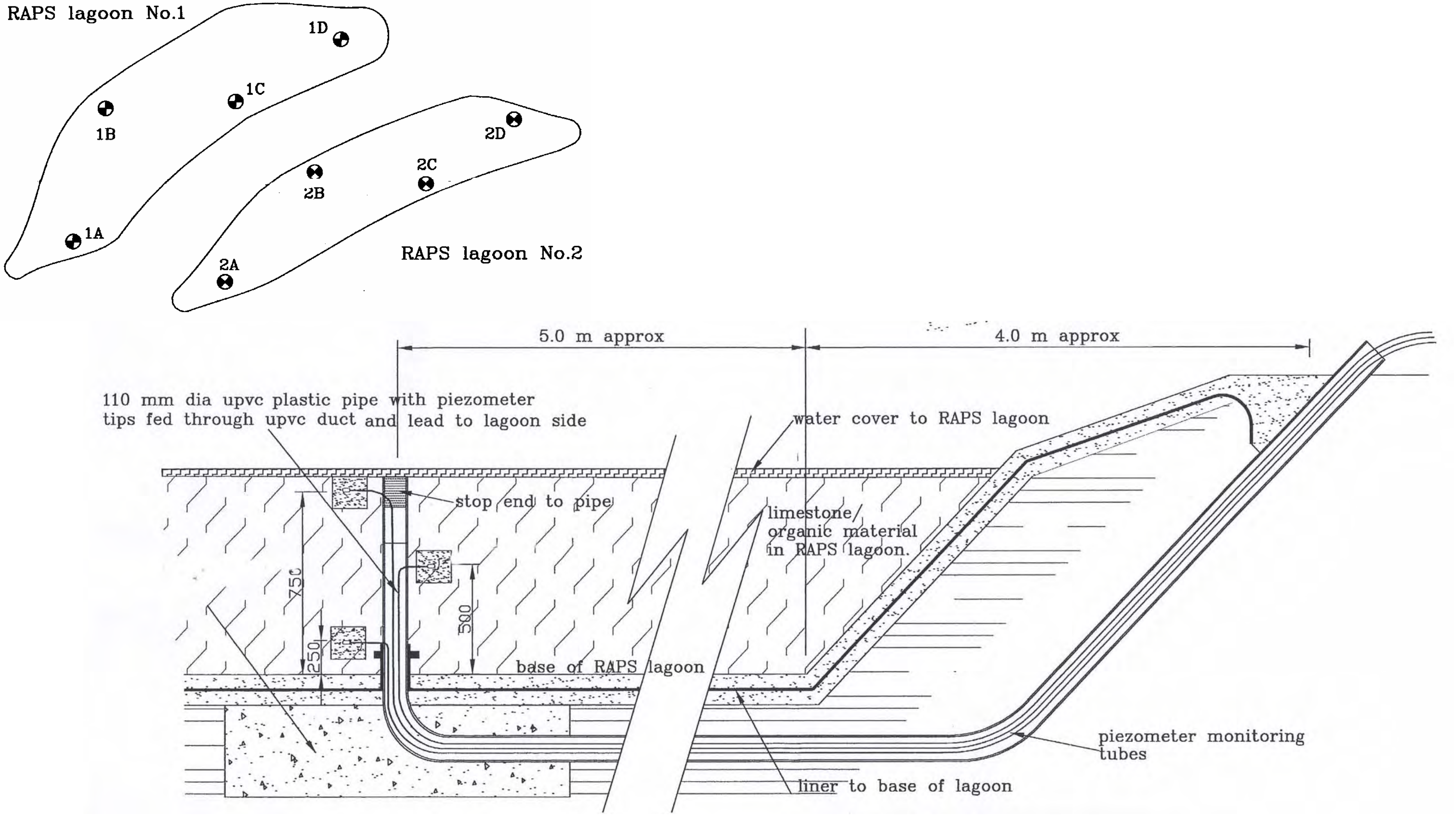

Figure 4.9: Locations of triple-level piezometer clusters within the RAPS units and a cross-section through the centre and bund of a RAPS unit showing the mode of construction of the triple-level piezometers in the Bowden Close full-scale treatment system.

5. PERFORMANCE OF THE FULL-SCALE SYSTEM

5.1 CONSTRAINTS AND HYDROLOGY

The full-scale Bowden Close treatment system has been in operation for two years now, with water sampling taking place every fortnight. The basic monitoring data can be found in the Appendix of this report. As monitoring and research on this site is still in progress, it is still rather early to be discussing the long-term performance of the system. Furthermore, in any discussion of system performance now or in the 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 5.1 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 5.1: 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 (2002a).

[b] See Figure 4.6.

[c] Assumes a flow-weighted average of 15 mg/l Fe coming from RAPS 1 and RAPS 2.

Tracer tests conducted by Wolkersdofer *et al.* (2005) revealed a difference in the maximum flow capacity for the two RAPS lagoons. RAPS 1 is estimated to be able to treat up to 30 - 50 l/min, whereas RAPS 2 is capable of 90 - 110 l/min. The tracer tests also allowed calculation of mean effective velocities. With a value of 0.01 m/h the velocities are much lower than the pilot scale system (0.1 m/h), but similar to the full-scale system at Pelenna III in Wales (Diaz-Goebes and Younger, 2004).

So far, the removal and precipitation of pollutants has not affected the overall hydraulics. Flushing of the RAPS units (see Section 4.4.2.2) has therefore not become necessary. However, it is anticipated that this situation will change with the aging of the substrate which eventually will have to be exchanged (Section 6).

5.2 ACIDITY REMOVAL AND GENERATION OF ALKALINITY

Given the grounds for caution indicated by Table 5.1, the early performance data from the new system are extremely encouraging. Effluent pH is always close to neutral and has never dropped below 6.4 (Figure 5.1). On no occasion has there been more acidity than alkalinity in the final discharge. Never less than 30 mg/l (as $CaCO_3$) of alkalinity is added to the waters by the RAPS units, and as much as 320 mg/l can be added on occasion. Table 5.2 summarises changes in key quality parameters as the water flows through the system and shows that a total of 8.5 tonnes of alkalinity (as $CaCO_3$) has been generated over the observation period.

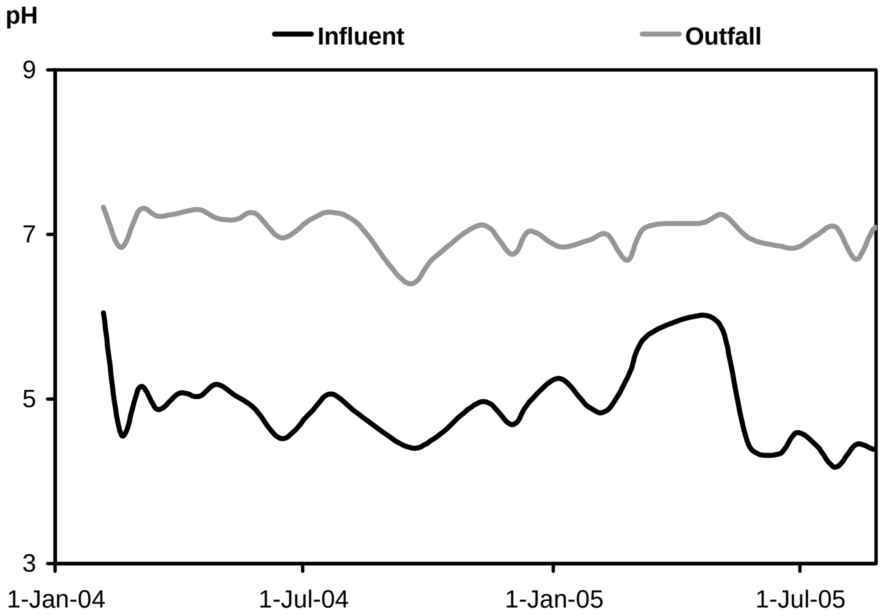

Figure 5.1: Influent and outfall pH values at RAPS 2 of the treatment system. RAPS 1 displays a very similar performance.

Table 5.2: Pollutant removal February 2004 – August 2005.

	Fe	**Al**	**Zn**	**SO_4**	**Alkalinity (as $CaCO_3$)**
Tonnes	3.0	1.5	0.05	12.1	-8.5[a]
% of Inflow	85	93	72	20	

[a] Negative values represent release of alkalinity.

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 - 10 g/m^2/d. RAPS 2 receives more acidic waters and is small in comparison to its ideal size (Table 5.1). It is thus very far from being load-limited, and it exhibits very high acidity removal rates, ranging from 20 to 40 g/m^2/d. These removal rates are similar to the rates obtained from the pilot system (see Section 4.2) and comparable with other systems in the USA (Watzlaf *et al*., 2000).

5.3 REMOVAL OF METALS AND SULPHATE

Table 5.2 shows that the removal of the target pollutants, iron and aluminium was very effective. About 85% of iron and 93% of the receiving aluminium have been removed from the mine water during its passage through the system, lowering concentrations to detection limits for aluminium (Figures 5.2 and 5.3). While aluminium is precipitated mainly as aluminium hydroxides, the dominating sinks for iron are iron sulphides.

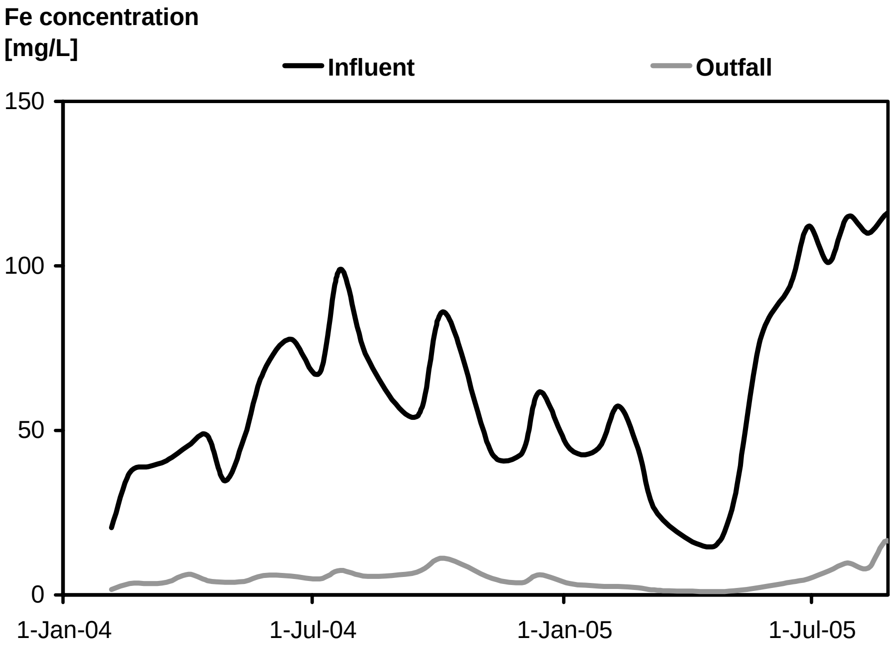

Figure 5.2: Influent and outfall iron concentrations at RAPS 2 of the treatment system. RAPS 1 receives less iron but outfall concentrations are nearly identical.

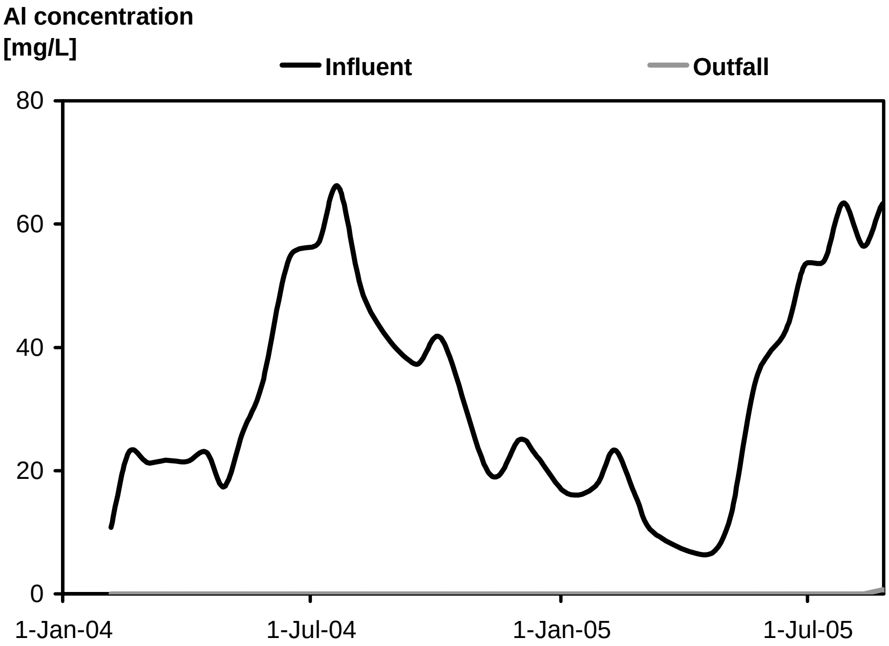

Figure 5.3: Influent and outfall aluminium concentrations at RAPS 2 of the treatment system. Note that the outfall values (grey line) appear to be zero as they are less than 0.7 mg/L. RAPS 1 receives less aluminium but outfall concentrations are nearly identical.

The removal rate of zinc is slightly less than that for iron or aluminium (at 72%). However, this value has increased to 95% after the planting of the aerobic polishing wetland, presumably due to sorption onto oxic iron precipitates in the reedbed. An impressive 12.1 tonnes of sulphate has been removed over the observation period, despite the fact that this system has not been specifically designed for sulphate attenuation. While most of the sulphate is precipitated in the form of iron sulphides, some hydrogen sulphide gas has occasionally been detected in the outfall chambers.

5.4 SUMMARY

The overall picture is highly encouraging, with the main pollutants being almost completely retained in the treatment system. A more detailed geochemical analysis can be found in Fabian *et al*. (2005). Geochemical and mineralogical studies on the precipitation of iron and sulphur phases and their distribution within the RAPS substrate are currently under way.

The results indicate that both RAPS lagoons are oversized for the average load of contaminated mine water, and so far, no decline in efficiency has been observed. It is expected that with time, exhaustion of the substrate and clogging will lead to a decline in performance, such defining the lifetime of the treatment system. At the end of the lifetime, estimated to be about 10 years, an exchange of the substrate will become necessary, which will be discussed in the following section.

6. PERSPECTIVES FOR TECHNOLOGY DEMONSTRATION CLOSE OUT

6.1 THE LIFETIME OF PASSIVE TREATMENT SYSTEMS

The main advantages of passive treatment technologies (as opposed to their active counterparts, which involve continuous inputs of energy and / or chemical additives) are their low operating costs (see Section 7 for a detailed discussion), and their overall longevity as effective treatment systems. This latter point in particular remains a key research area. Specifically, how long will a treatment system effectively remediate polluted waters, and is it possible to predict the system's lifetime?

One of the current research objectives is to answer this question, hence operation of, and research at, the RAPS at Bowden Close will not 'close out', as the title of this section might suggest; rather, it will continue as an integral part of the overall environmental improvement strategy adopted by Durham County Council (which has long-term responsibility, and ownership, of the site).

Ultimately, however, passive treatment systems such as the RAPS at Bowden Close do have a finite life. Although it is not yet possible to accurately predetermine this lifetime, there appear to be three principal mechanisms that govern overall longevity:

1. Physical clogging, due to accumulation of sediment and dead plant material within the system. The system at Bowden Close is equipped with an option to flush the substrate (Section 4.4.2.2), but roots and dead plant material will eventually take over.

2. Exhaustion of available supply of organic carbon, which is essential for the colonisation and survival of sulphate reducing bacteria (SRB), which play a central role in effective immobilisation of pollutants.

3. Exhaustion of available supply of limestone, which is essential for the removal of acidity and the generation of alkalinity.

6.2 EXPERIENCES FROM THE PASSIVE TREATMENT SYSTEM AT QUAKING HOUSES, COUNTY DURHAM

It is clearly not possible to comment on the lifetime of the RAPS at Bowden Close, or specifically how it will be addressed when the end of the lifetime is reached. However, lessons can be drawn from an analogous system at Quaking Houses, also in County Durham. This was the first compost-based passive treatment system in the UK, designed and constructed by the group at the University of Newcastle, and commissioned in November 1997. It is currently undergoing complete renovation as physical clogging by sediment, and especially dead plant material, has exhausted its capacity for effective treatment, as described above.

In this particular case, lifetime appears to have been governed principally by the rate of accumulation of dead plant material. This in itself raises an important maintenance issue at such sites, which is to ensure periodic removal of dead plant material (e.g. annually). Since reeds are not an integral part of the RAPS units, this is not such an issue at Bowden Close. The day will nevertheless arrive when total removal of the RAPS substrate will be required. At Quaking Houses (where very similar substrate has been used), the compost media has been excavated, and disposed of to landfill. Disposal to a waste handling facility is not the most preferable option in terms of environmental sustainability.

However, the experience at Quaking Houses has taught some positive lessons about close-out of such technologies:

- When removed, and therefore exposed to nominally aerobic conditions, there was no visual evidence that previously immobilised contaminants were released into the environment (e.g. no evidence of release and deposition of vivid orange hydrous ferric oxide).

- The exhausted compost material was not categorised as hazardous waste, therefore minimising disposal costs.

- The overall cost of the renovation exercise was less than £60,000 (including the costs of a civil engineering contractor). Management and consultancy costs were relatively minor, amounting to less than £5,000. Given that this renovation exercise at Quaking Houses has also included replacement of a substantial section of wooden boardwalk for access, and the installation of new concrete flumes for flow measurement and sampling purposes (which will not be required at Bowden Close), it be can concluded that renovation of the system at Quaking Houses, as an annual cost (the system has been operational for 8 years), has been in the order of £5,000 - £7,500.

In terms of the Bowden Close system, this experience at Quaking Houses suggests that technology demonstration close-out, as and when it happens, will provide further evidence that long-term costs of operation of passive mine water treatment technologies are low, and that such technologies will therefore continue to be the favoured method of treatment for abandoned mine water discharges, where liabilities are unclear, and remediation is a long-term requirement.

7. ECONOMIC CONSIDERATIONS AND A COMPARISON WITH COSTS FOR ACTIVE TREATMENT

7.1 CAPITAL COSTS

Capital cost and the acquisition of land often make passive treatment systems appear to be more expensive than active treatment. However, as outlined in the previous section, subsequent operating costs are very low. At the end of their lifetime, passive systems can be regenerated at a fraction of the initial capital cost. Typical regeneration works include removal and disposal of old substrate, any necessary repair or update of the lagoons, and filling with new substrate and subsequent planting (where applicable).

Construction costs for the pilot- and the full-scale passive treatment system at Bowden Close are given in Table 7.1, together with estimates of the construction and operation costs of an equivalent active treatment system. As expected, given the extensive earthworks requirements, the construction of the full-scale passive system was considerably more expensive than the estimate for building an active system with similar capacity. A detailed economic comparison between those two systems will follow in the next section.

Table 7.1: Comparative costings for treatment of acidic drainage at Bowden Close.

	Pilot System[a]	**Full-Scale**[b]	**Active System**[c]
Construction[d]	£20,000	£295,000	£175,000
Operation		0[e]	£22,000 / yr[e]
Land acquisition		£15,000	

[a] No land acquisition was required for the pilot plant, which treated only a fraction of the drainage at Bowden Close.

[b] Actual costs by Durham County Council.

[c] Estimates by Unipure (Europe) Ltd. based on the combined discharges treated by the full-scale system.

[d] Construction costs exclude site investigation, planning and enabling works.

[e] Operation costs exclude sludge disposal (see Section 7.2).

7.2 PROJECTED LIFE-CYCLE COSTS FOR FULL-SCALE PASSIVE AND ACTIVE TREATMENT

Although it is not possible to foresee the actual close out costs for the Bowden Close scheme with accuracy (see Section 6), estimates of the projected life-cycle costs can be made (Table 7.2). It should be stressed that the figures below are for illustrative purposes, and are not proposed as a rigorous economic analysis (as suitably accurate figures are not available).

Given the experiences from the passive treatment system at Quaking Houses (Section 6.2), a lifetime of 10 years for the RAPS at Bowden Close has been assumed (slightly longer than Quaking Houses as the RAPS have not been planted) and a figure of approximately £70,000 for replacing the substrate (there is approximately 2,500 m^3 substrate at Bowden Close, compared to just 250 m^3 at Quaking Houses, but there have been far more additional costs incurred at Quaking Houses than anticipated at Bowden Close e.g. boardwalk, concrete flumes).

Table 7.2: Estimated life-cycle costs for the existing full-scale passive treatment system and an active system designed by Unipure (Europe) Ltd.

	Passive System	**Active System**
First Life-cycle (10 years)[a]	£310,000	£395,000
Two Life-cycles (20 years)[b]	£380,000	£615,000
Each additional Cycle[b]	£70,000	£220,000

[a] excluding site investigation, planning and enabling works.

[b] excluding substrate/sludge disposal and repairs. Substrate and sludge disposal costs may be a significant proportion of overall operational costs. However, designers of active treatment systems will rarely make *a priori* judgements about the costs of disposal of treatment sludge, since even trace quantities of certain elements may increase disposal costs by an order of magnitude (lab and pilot studies would usually precede any such estimate). For comparative purposes, it is currently estimated that disposal cost of the substrate from the Bowden Close system would be in the order of £100,000 (based on the experience at Quaking Houses), which is most unlikely to be any greater than sludge disposal costs for an equivalent active treatment system (based on costs from the Coal Authority's Horden treatment system).

During the first life-cycle (10 years), the treatment costs would not be too different for passive and active treatment and would amount to £0.81 and £1.03 per kg acidity (as $CaCO_3$), respectively. Upon entering the second life-cycle, however, active treatment becomes less favourable. Over a time span of 20 years, the costs for passive treatment would decrease to £0.50 compared to £0.80 per kg acidity for the active treatment.

These numbers clearly demonstrate the advantage of passive treatment over longer time scales. However, it should be noted that they are based on rough estimations and therefore are to be used with caution. Again, it should be stressed that one of the objectives of the Bowden Close project is to learn more about long-term performance and lifetimes of passive treatment systems.

8. CONCLUSIONS

8.1 GENERAL CONCLUSIONS

The RAPS at Bowden Close is a novel passive mine water treatment technology, which is successfully remediating a series of acidic and metal-rich discharges arising from abandoned coal mining facilities near the small village of Helmington Row, County Durham. The preceding pages have illustrated not only the success of the system as a treatment unit *per se*, but also the beneficial outcomes of (ongoing) research at the site, which has been focused on establishing the precise mechanisms and rates of contaminant attenuation processes within the system.

An important side-effect of the full-scale treatment system is the creation of a valuable habitat, both for wildlife and local residents. Pheasants, herons, ducks, and various other waterfowl have been spotted and some of them even breeding within or next to the treatment lagoons. Local residents frequently stroll along the public footpath adjacent to the site and enjoy the pleasant countryside setting. Although it is difficult to express the economic value of creating such a habitat, it is apparent that a passive system is certainly preferred by local residents and wildlife than an active treatment plant.

8.2 LIMITATIONS OF THE TECHNOLOGY

Despite the successful performance of the full-scale system at Bowden Close, there are some important limitations for the application of RAPS in mine water treatment:

- An important cost factor is space. If no cheap land is available for the construction of treatment lagoons, or if very high flow rates require excessively large lagoons, the construction cost could soon become prohibitive, if indeed such a large area is available at all.
- To benefit fully from the low operating costs, the topography of the site should offer sufficient hydraulic head to avoid the need of pumping.
- The economic advantage only comes into effect after longer periods of operation. Usually mine waters are a long-lasting source of pollution, but in situations where treatment may only be needed in the short- to medium-term, active treatment may be economically favourable. It is for precisely this reason (together with issues of land availability) that active treatment is often employed at operational mines.
- In areas without a local source of limestone, the cost of delivering the limestone to the site might become considerable (such as in parts of Scotland).

An example of a mine water discharge of such high metal and acidity loads that passive treatment would simply not have been feasible is Wheal Jane (see Younger *et al.,* 2005 and CL:AIRE Case Study Bulletin CSB4, 2004). It should be noted that the RAPS at Bowden Close is in the order of 5 times smaller than an equivalent compost wetland for remediation of such a discharge. Thus, by designing more efficient systems, the limitations of space are gradually being reduced.

8.3 APPLICABILITY AND POTENTIAL FUTURE DEVELOPMENTS

There are probably far more than 100 former mining sites in the UK where acidic mine drainage could be treated by a passive system. Most of them are in local authority ownership and are yet awaiting any remediation concept. Notwithstanding the constraints outlined in the previous section, passive treatment and RAPS systems in particular may offer a low cost and sustainable solution for many of these sites.

A major uncertainty is still the longevity of passive treatment systems. By combining microbiology and geochemistry, the ongoing research at Bowden Close and at other remediation sites is expected to deliver a sound scientific answer to these questions. With several treatment systems coming into age in the course of the next few years (such as Quaking Houses), the scientific background will be complemented with practical experience, thus demonstrating the manageability of longevity issues.

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APPENDIX: BASIC MONITORING DATA

Date	Sample	pH	Alkalinity	Flow	Sulphate	Iron	Aluminium	
			mg/L as $CaCO_3$	L/min	mg/L	mg/L	mg/L	
05/02/2004	RAPS 1 inf	4.30	0	41	510	19.5	9.6	
05/02/2004	RAPS 1 eff	7.50	128	29*	278	1	<0.5	*Overflowing
05/02/2004	RAPS 2 inf	6.05	35	340	400	20.5	10.8	
05/02/2004	RAPS 2 eff	7.33	178	63*	292	1.7	<0.5	*Overflowing
05/02/2004	Wetland eff	7.18	52	>400	311	9.6	0.8	
18/02/2004	RAPS 1 inf	3.62	0	31	613	22.1	11.3	
18/02/2004	RAPS 1 eff	6.97	104	42	375	1.1	<0.5	
18/02/2004	RAPS 2 inf	4.57	5	168	801	37.1	23	
18/02/2004	RAPS 2 eff	6.84	171	86*	571	3.4	<0.5	*Overflowing
18/02/2004	Wetland eff	6.65	83	200	529	11	3.9	
03/03/2004	RAPS 1 inf	3.90	0	29	579	19.9	9.6	
03/03/2004	RAPS 1 eff	7.64	108	37	349	1	<0.5	
03/03/2004	RAPS 2 inf	5.15	10	120	779	39	21.3	
03/03/2004	RAPS 2 eff	7.30	182	49*	653	3.5	<0.5	*Overflowing
03/03/2004	Wetland eff	6.61	67	190	472	12.2	5.9	
16/03/2004	RAPS 1 inf	3.58	0	31	529	23.3	10.3	
16/03/2004	RAPS 1 eff	7.33	85	42	408	1.1	<0.5	
16/03/2004	RAPS 2 inf	4.87	0	105	875	40.8	21.7	
16/03/2004	RAPS 2 eff	7.22	162	49*	555	3.9	<0.5	*Overflowing
16/03/2004	Wetland eff	7.03	69	150	513	11.9	2.7	
01/04/2004	RAPS 1 inf	3.93	0	27	396	24.5	9.2	
01/04/2004	RAPS 1 eff	7.45	98	37	319	1.4	<0.5	
01/04/2004	RAPS 2 inf	5.07	0	105	720	45.4	21.5	
01/04/2004	RAPS 2 eff	7.26	146	76*	593	6.3	<0.5	*Overflowing
01/04/2004	Wetland eff	6.90	100	150	491	6.6	1.7	
15/04/2004	RAPS 1 inf	4.80	0	27	379	20.8	7.4	
15/04/2004	RAPS 1 eff	7.50	110	31	273	1.2	<0.5	
15/04/2004	RAPS 2 inf	5.03	10	76	791	48.5	23	
15/04/2004	RAPS 2 eff	7.30	157	75	656	4.3	<0.5	
15/04/2004	Wetland eff	7.44	135	113	551	3.2	<0.5	

Date	Sample	pH	Alkalinity mg/l as $CaCO_3$	Flow L/min	Sulphate mg/L	Iron mg/L	Aluminium mg/L	
28/04/2004	RAPS 1 inf	5.04	0	48	282	17.4	5.4	
28/04/2004	RAPS 1 eff	7.41	130	49*	202	1.4	<0.5	*Overflowing
28/04/2004	RAPS 2 inf	5.18	10	124	536	34.6	17.4	
28/04/2004	RAPS 2 eff	7.20	172	75*	446	3.9	<0.5	*Overflowing
28/04/2004	Wetland eff	7.25	110	230	388	8.3	0.9	
12/05/2004	RAPS 1 inf	5.82	10	41	346	16.3	5.2	
12/05/2004	RAPS 1 eff	7.60	161	43	277	1.3	<0.5	
12/05/2004	RAPS 2 inf	5.04	0	74	816	48	26.3	
12/05/2004	RAPS 2 eff	7.18	180	76*	637	4.1	<0.5	*Overflowing
12/05/2004	Wetland eff	7.49	160	117	469	3	0.7	
26/05/2004	RAPS 1 inf	6.05	12	10	357	19	5.2	
26/05/2004	RAPS 1 eff	7.79	242	16	217	1.3	<0.5	
26/05/2004	RAPS 2 inf	4.89	0	42	1173	67.6	33.9	
26/05/2004	RAPS 2 eff	7.26	214	41	928	5.9	<0.5	
26/05/2004	Wetland eff	7.66	208	52	663	3.4	<0.5	
15/06/2004	RAPS 1 inf	6.30	10	6	484	16.2	6.3	
15/06/2004	RAPS 1 eff	7.88	596	2.5	28	1.8	<0.5	
15/06/2004	RAPS 2 inf	4.52	0	24	1746	77.8	54.5	
15/06/2004	RAPS 2 eff	6.96	330	21	1081	5.8	<0.5	
15/06/2004	Wetland eff	6.98	320	29	821	6.5	2.1	
06/07/2004	RAPS 1 inf	5.98	20	<6	449	12.5	6.2	
06/07/2004	RAPS 1 eff	7.90	530	5	36.2	3.4	<0.5	
06/07/2004	RAPS 2 inf	4.83	0	23	1619	67.5	56.8	
06/07/2004	RAPS 2 eff	7.18	288	20	1073	4.9	<0.5	
06/07/2004	Wetland eff	7.60	260	27	828	0.8	0.5	
21/07/2004	RAPS 1 inf	5.05	0		459	15.8	9.5	
21/07/2004	RAPS 1 eff	8.15	638	2	34	4.2	<0.5	
21/07/2004	RAPS 2 inf	5.06	0	18	1686	99	66	
21/07/2004	RAPS 2 eff	7.27	324	18	1128	7.4	<0.5	
21/07/2004	Wetland eff	7.87	322	19	867	1	0.5	

Date	Sample	pH	Alkalinity	Flow	Sulphate	Iron	Aluminium	
			mg/l as $CaCO_3$	L/min	mg/L	mg/L	mg/L	
10/08/2004	RAPS 1 inf	5.85	10		419	15.9	6.1	
10/08/2004	RAPS 1 eff	7.82	433	14	118	2.3	<0.5	
10/08/2004	RAPS 2 inf	4.82	0	36	1408	71.9	47.5	
10/08/2004	RAPS 2 eff	7.13	267	33	969	5.6	<0.5	
10/08/2004	Wetland eff	7.51	254	49	730	2.8	0.8	
15/09/2004	RAPS 1 inf	5.33	17	31	385	15.1	6.1	
15/09/2004	RAPS 1 eff	6.91	278	9*	220	6.8	<0.5	*Overflowing
15/09/2004	RAPS 2 inf	4.42	0	50	1053	54.2	37.3	
15/09/2004	RAPS 2 eff	6.41	272	20*	777	6.9	<0.5	*Overflowing
15/09/2004	Wetland eff	6.71	71	66	698	0.5	0.8	
05/10/2004	RAPS 1 inf	5.60	27	10	352	14.7	4.9	
05/10/2004	RAPS 1 eff	6.76	256	14	242	5.4	<0.5	
05/10/2004	RAPS 2 inf	4.52	0	30	1314	85.9	41.3	
05/10/2004	RAPS 2 eff	6.72	216	33	1183	11.1	<0.5	
05/10/2004	Wetland eff	7.10	228	45	852	0.4	<0.5	
09/11/2004	RAPS 1 inf	5.54	3	83	330	17.6	5.7	
09/11/2004	RAPS 1 eff	7.37	202	14*	233	5.4	<0.5	*Overflowing
09/11/2004	RAPS 2 inf	4.97	0	128	651	42.8	19.5	
09/11/2004	RAPS 2 eff	7.12	245	32*	474	5	<0.5	*Overflowing
09/11/2004	Wetland eff	6.10	32	240	475	0.7	0.6	
01/12/2004	RAPS 1 inf	5.71	17	40	276	14.7	4.5	
01/12/2004	RAPS 1 eff	6.85	175	12*	218	3.3	<0.5	*Overflowing
01/12/2004	RAPS 2 inf	4.69	5	66	797	43.1	25	
01/12/2004	RAPS 2 eff	6.76	187	27*	708	3.7	<0.5	*Overflowing
01/12/2004	Wetland eff	6.39	55	107	476	1.9	0.7	
14/12/2004	RAPS 1 inf	6.54	18	35	287	16.2	3.8	
14/12/2004	RAPS 1 eff	7.65	144	30*	263	5.3	<0.5	*Overflowing
14/12/2004	RAPS 2 inf	4.97	4	62	945	61.8	22.2	
14/12/2004	RAPS 2 eff	7.04	214	49*	781	6.1	<0.5	*Overflowing
14/12/2004	Wetland eff	7.22	146	93	576	0.6	<0.5	

Date	**Sample**	**pH**	**Alkalinity**	**Flow**	**Sulphate**	**Iron**	**Aluminium**	
			mg/l as $CaCO_3$	L/min	mg/L	mg/L	mg/L	
05/01/2005	RAPS 1 inf	5.99	10	49	307	18.9	4	
05/01/2005	RAPS 1 eff	7.02	147	29*	221	4.6	<0.5	*Overflowing
05/01/2005	RAPS 2 inf	5.25	3	85	627	44.4	16.3	
05/01/2005	RAPS 2 eff	6.85	142	46*	483	3.4	<0.5	*Overflowing
05/01/2005	Wetland eff	6.67	80	146	365	0.6	<0.5	
26/01/2005	RAPS 1 inf	5.08	1	47	364	19.5	5.1	
26/01/2005	RAPS 1 eff	6.63	124	29*	306	5.1	<0.5	*Overflowing
26/01/2005	RAPS 2 inf	4.91	1	100	692	44.6	17.5	
26/01/2005	RAPS 2 eff	6.93	157	49*	609	2.7	<0.5	*Overflowing
26/01/2005	Wetland eff	6.47	50	194	517	4.9	1.2	
09/02/2005	RAPS 1 inf	5.41	3	41	363	22.2	4.0	
09/02/2005	RAPS 1 eff	7.04	128	30*	281	3.8	<0.5	*Overflowing
09/02/2005	RAPS 2 inf	4.86	0	77	840	57.4	23.3	
09/02/2005	RAPS 2 eff	7.00	174	50*	661	2.6	<0.5	*Overflowing
09/02/2005	Wetland eff	7.05	90	132	542	1.9	0.7	
24/02/2005	RAPS 1 inf	4.97	17	38	382	23.4	4.6	
24/02/2005	RAPS 1 eff	6.58	111	33*	278	4.2	<0.5	*Overflowing
24/02/2005	RAPS 2 inf	5.26	12	97	646	44.4	16	
24/02/2005	RAPS 2 eff	6.69	117	47*	672	2.2	<0.5	*Overflowing
24/02/2005	Wetland eff	6.21	52	204	390	6.1	1.2	
10/03/2005	RAPS 1 inf	4.14	0	>100	189	10.5	2.6	
10/03/2005	RAPS 1 eff	7.19	116	34*	109	3.2	<0.5	*Overflowing
10/03/2005	RAPS 2 inf	5.76	16	230	381	24.7	9.9	
10/03/2005	RAPS 2 eff	7.09	168	55*	316	1.4	<0.5	*Overflowing
10/03/2005	Wetland eff	6.61	40	>200	238	4.0	<0.5	
19/04/2005	RAPS 1 inf	5.41	21	>120	136	6.6	1.5	
19/04/2005	RAPS 1 eff	6.96	149	50*	79	1.9	<0.5	*Overflowing
19/04/2005	RAPS 2 inf	6.02	72	420	324	14.6	6.4	
19/04/2005	RAPS 2 eff	7.14	196	61*	365	1.0	<0.5	*Overflowing
19/04/2005	Wetland eff	6.98	62	>800	164	3.8	0.7	

Date	**Sample**	**pH**	**Alkalinity**	**Flow**	**Sulphate**	**Iron**	**Aluminium**	
			mg/l as $CaCO_3$	L/min	mg/L	mg/L	mg/L	
05/05/2005	RAPS 1 inf	5.80	22	78	218	13.1	2.8	
05/05/2005	RAPS 1 eff	7.65	200	53*	156	2.2	<0.5	*Overflowing
05/05/2005	RAPS 2 inf	5.83	61	135	461	28.8	12.6	
05/05/2005	RAPS 2 eff	7.24	250	57*	517	1.3	<0.5	
05/05/2005	Wetland eff	7.17	75	274	325	0.8	<0.5	*Overflowing
24/05/2005	RAPS 1 inf	6.01	17	32	295	21.9	3.9	
24/05/2005	RAPS 1 eff	7.15	200	29	226	2.2	<0.5	
24/05/2005	RAPS 2 inf	4.44	0	59	1159	77.5	34.9	
24/05/2005	RAPS 2 eff	6.96	210	57*	875	2.3	<0.5	*Overflowing
24/05/2005	Wetland eff	7.11	146	82	678	<0.1	<0.5	
15/06/2005	RAPS 1 inf	6.53	110	16	278	18.7	2.8	
15/06/2005	RAPS 1 eff	7.42	500	14	140	2.4	<0.5	
15/06/2005	RAPS 2 inf	4.33	0	36	1189	93.8	42.8	
15/06/2005	RAPS 2 eff	6.86	236	39	1139	3.8	<0.5	
15/06/2005	Wetland eff	7.20	260	51	849	0.4	<0.5	
28/06/2005	RAPS 1 inf	6.41	55	6.4	293	18.0	3.1	
28/06/2005	RAPS 1 eff	7.65	645	3.1	40	9.0	<0.5	
28/06/2005	RAPS 2 inf	4.59	0	18	1846	112	53.2	
28/06/2005	RAPS 2 eff	6.84	353	28*	1310	4.9	<0.5	*Overflowing
28/06/2005	Wetland eff	6.99	195	23	1161	7.2	4.3	
13/07/2005	RAPS 1 inf	6.54	52	3.6	320	14.2	4	
13/07/2005	RAPS 1 eff	7.97	620	3.5	50	7.1	<0.5	
13/07/2005	RAPS 2 inf	4.43	0	23.3	1783	101	54.1	
13/07/2005	RAPS 2 eff	6.99	290	18*	1222	7.3	<0.5	*Overflowing
13/07/2005	Wetland eff	7.32	216	21	1048	5.5	3.7	
27/07/2005	RAPS 1 inf	6.57	71	2.8	305	7.1	4.0	
27/07/2005	RAPS 1 eff	8.23	636	2	5.9	16.7	<0.5	
27/07/2005	RAPS 2 inf	4.17	0	17	2055	115	63.4	
27/07/2005	RAPS 2 eff	7.09	304	16*	1410	9.7	<0.5	*Overflowing
27/07/2005	Wetland eff	7.49	250	17	1280	0.2	<0.5	

Date	Sample	pH	Alkalinity	Flow	Sulphate	Iron	Aluminium	
			mg/l as $CaCO_3$	L/min	mg/L	mg/L	mg/L	
11/08/2005	RAPS 1 inf	6.16	76	2.8	318	6.2	3.7	
11/08/2005	RAPS 1 eff	7.65	652	2.6	9.5	9.2	<0.5	
11/08/2005	RAPS 2 inf	4.45	0	22	1870	110	56.4	
11/08/2005	RAPS 2 eff	6.70	250	18*	1242	8.2	<0.5	*Overflowing
11/08/2005	Wetland eff	6.97	204	18	1139	0.3	<0.5	
25/08/2005	RAPS 1 inf	6.35	76	2.2	253	2.2	3.8	
25/08/2005	RAPS 1 eff	8.10	732	1.9	4.5	9.8	<0.5	
25/08/2005	RAPS 2 inf	4.39	0	16	2117	116	63.3	
25/08/2005	RAPS 2 eff	7.08	286	16	1391	16.5	0.7	
25/08/2005	Wetland eff	7.63	262	16.5	1189	0.3	<0.5	