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# Passive treatment of acidic mine waters in subsurface-flow systems: exploring RAPS and permeable reactive barriers

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Abstract

*It is now clear that the most effective passive treatment pathways for acidic mine waters require anoxic conditions, in which carbonate dissolution can occur in the absence of $Fe^{3+}$ and/or bacterial sulphate reduction can occur, removing pollutant metals as sulphides, generating bicarbonate alkalinity and raising pH. By mimicking nature, it is most appropriate to achieve and maintain suitably anoxic conditions by designing treatment system hydraulics such that they are based on subsurface flow through porous media. Some of the challenges involved in this activity are discussed here, such as:*

- *predicting and prescribing the permeability of manure-based composts;*
- *matching sufficiently high permeability with a high enough organic matter content to ensure microbial activity;*
- *geometrical considerations in systems design.*

*The ways in which such challenges have been overcome in recent designs are discussed in relation to the Bowden Close RAPS system in County Durham and the Shilbottle PRB (permeable reactive barrier) in Northumberland. These two systems form nuclei of the new National Mine Site Remediation Research Facility (NMSRF) sponsored by CL:AIRE, and are study sites for the new DTi Bioremediation LINK project 'ASURE', which concerns bioremediation of acidic mine waters by sulphate reduction in novel, compost-based, field-scale bioreactors.*

Key words: acidic mine water, passive treatment, permeable reactive barriers, RAPS, subsurface-flow systems

## PASSIVE TREATMENT OF ACIDIC MINE WATERS

It is now clear from many studies in the UK and elsewhere that the volumetric majority of polluted mine waters are actually *not* acidic (e.g. Younger *et al.* 2002). However, those mine waters which *are* acidic generally contain a far wider range of contaminants than are found in net-alkaline mine waters. For this reason, the requirements for effective passive treatment of acidic mine waters are intrinsically more demanding than is the case for net-alkaline ferruginous mine waters. While the passive treatment of the latter can now be regarded as 'established technology' (notwithstanding residual research needs, such as the acquisition of a better understanding of processes governing the efficacy and longevity of aerobic wetland systems, etc., e.g. Batty and Younger 2002), the development of appropriate passive treatment techniques for acidic mine waters remains a challenging area for further research.

While passive treatment of acidic mine waters using compost wetland technology has been under development in the USA since the late 1980s (e.g. Hedin *et al.* 1994), and in the UK since the early 1990s (see Jarvis 2000, for a review) the relative inefficiency of this basic

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form of passive treatment continues to motivate a search for more efficacious technologies, principally based on the harnessing of bacterial sulphate reduction in subsurface flow bioreactors (see Younger *et al.* 2002, for a review). This paper describes recent and ongoing advances in this regard, drawing upon two variants of the same basic technology, both of which are being implemented at full-scale in North East England.

## CHALLENGES IN THE DESIGN OF SUBSURFACE FLOW SULPHATE-REDUCING BIOREACTORS

### System configurations

The two most common layouts currently used in passive treatment systems for acidic mine waters are the RAPS and the PRB layouts (Figure 1). Both are suitable for different circumstances. RAPS (reducing and alkalinity producing systems), also known as SAPS (successive alkalinity producing systems; Kepler and McCleary 1994) or simply 'vertical flow ponds' (Demchak *et al.* 2001) are best suited to the treatment of point surface discharges of polluted, net-acidic mine water. RAPS consist of pond structures in which a layer of compost is underlain by a layer of limestone gravel. Outflow control is arranged such that mine water is forced to flow downwards, first through the compost, then through the limestone gravel layer. The concept is that bacterial sulphate reduction in the compost layer will reduce $Fe^{3+}$ to $Fe^{2+}$, and will also strip dissolved oxygen from the water, so that risks of ferric hydroxide blinding of limestone clast surfaces is minimised, and limestone dissolution therefore maximised. A RAPS unit is typically followed by a sedimentation pond and/or an aerobic wetland, in which neutralised waters are detained while they precipitate metal hydroxides. Extensive discussions of the theory and design rationale of RAPS are available elsewhere (Kepler and McCleary 1994; Younger *et al.* 2002) and will thus not be discussed further here.

Permeable reactive barriers (PRBs) are increasingly being employed to treat a wide range of polluted groundwaters (e.g. Gavaskar *et al.* 1998; Beck *et al.* 2001). In the context of acidic mine water treatment, PRBs based on the same geochemical processes as RAPS units are applied to the *in situ* treatment of polluted groundwaters (Benner *et al.* 1997; Younger *et al.* 2002). As in RAPS, mine water treatment PRBs typically have substrates containing organic carbon sources to support sulphate reduction, sometimes coupled with limestone to provide inorganic neutralisation capacity.

### Physical properties of substrates

The key challenge in designing subsurface flow reactors to treat polluted mine waters lies in finding the best compromise between substrate permeability and reactivity. Besides considerations of the geochemical suitability of various materials which might be emplaced in such a reactor (see following section) the key physical decision variable is substrate grain size. Whatever the geochemical process, finer grained sediments react far more rapidly than coarse-grained sediments of the same chemical composition. On the other hand, fine-grained sediments are invariably less permeable than their coarser grained equivalents.

In a subsurface flow reactor, we want to find the ideal grain size which results in a sediment which is permeable enough to transmit the quantities of water which need to be treated, and yet is also reactive enough to substantially alter the chemistry of the water during its passage through the substrate. There are few better ways of identifying the best substrate than laboratory testing. In designing laboratory tests, it is important to bear in mind that the permeability of compressible organic matter is apt to decrease markedly with increasing depth of burial. Artificial loading of materials which are under test in static or flow-through lab columns can be implemented to simulate future self-loading by the saturated material in the field (Amos and Younger, in press).

### Reactive properties of substrates: the key to system performance and longevity

A range of media have been tested for incorporation in permeable reactive barriers designed to treat mine waters, including zero-valent iron, zeolites, carbonate minerals, blast furnace slags and compost or other forms of organic matter (Younger *et al.* 2002). All of these substrates are characterised by distinct reactive tendencies in relation to acidic mine waters. For instance, zero-valent iron leads to the establishment of highly reducing conditions, which can be useful in trapping redox-sensitive metals such as uranium. Zeolites trap metals by sorptive processes. Carbonates and blast furnace slag tend to raise the pH, favouring both sorption and hydrolysis of metals to form (hydr)oxide solids. Organic matter promotes bacterial sulphate reduction and thus the precipitation of metal sulphides. The kinetics of these various processes differ amongst themselves, but are all sufficiently rapid that they are amenable to deployment in passive treatment reactors in which waters are typically resident for a few hours to a few days. Clearly, the selection of a substrate for its reactive properties is also a matter of compromise, for a suitable substrate must dissolve rapidly enough to affect water quality over time-scales of hours or days, but not so rapidly that it will all dissolve after only a

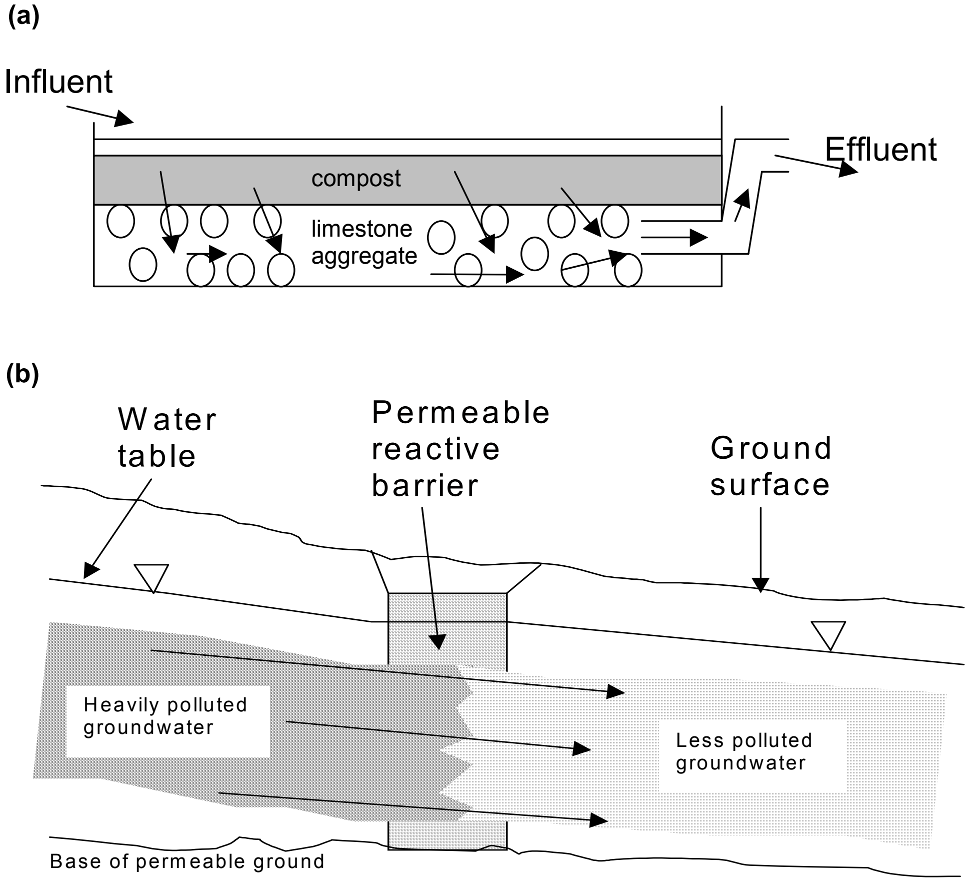

*Figure 1. Schematic cross-sections of two principal layouts for passive systems proven to be useful for the treatment of acidic mine waters using sulphate reduction processes: (a) a reducing and alkalinity producing system (RAPS); (b) a permeable reactive barrier (PRB) (after Younger 2000)*

few weeks of system use. Many geochemical reactions are sufficiently well known that they can be evaluated from documented kinetic data; for other reactions, there is still no alternative to case-specific experimental testing.

## BOWDEN CLOSE RAPS SYSTEM, COUNTY DURHAM

### Pollution problems at Bowden Close

Three polluted discharges have flowed from the site of the former Bowden Close Colliery, near the village of Helmington Row in western County Durham, ever since the mine closed in the 1960s (Younger 1995). The site was restored (to then-current national standards) in the 1970s, principally by demolishing derelict buildings, reshaping spoil, emplacing top soil and turning the site over to new uses (as a golf course and open countryside).

However, as in most other reclamation schemes implemented in that era, subsurface contamination risks were not addressed at the time. By 1999, Durham County Council (as owners of the site) were having to face up to these risks by instigating a major programme of works, with two principal foci:

(i) combat tar pollution by removing large buried tanks, which had been continuously leaking tar into the local surface water courses for at least a decade;

(ii) find long-term solutions to problems of acid mine drainage, thought to be associated with former drift mine entrances and spoil leachate.

With regard to the first of these foci, beyond physical removal of large quantities of tar, considerable progress was also made in developing the use of biodiesel as a reagent to render otherwise recalcitrant tars available for bioremediation (Taylor and Jones

**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. | 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 |

2001). No further discussion of this issue will be given here; rather, efforts made to date in relation to (ii) above are the focus of the discussion which follows.

Previous studies 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. Biological surveys of the receiving watercourse showed that these polluted waters are 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 (Table 1).

*Discharge No. 1*

This is the furthest upstream of the perennial discharges. (Although minor ferruginous seepages do sometimes occur further upstream, these are not quantitatively significant.) The No. 1 discharge emerges from a 0.5 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 a golf fairway. The measured characteristics of the No. 1 discharge in spring/summer 1999 are summarised in Table 1.

*Discharge No. 2*

Discharge No. 2 enters the Willington Burn from its left bank some 23 m downstream of the No. 1 discharge. The No. 2 discharge arises in a geomorphologically unusual hollow, amidst a stand of conifers which line the eastern flank of the burn in this vicinity. This hollow is suspected to be the collapsed remains of an old drift mine entrance. (Coal Authority records show an old surface drift into the Harvey Seam in this vicinity.) After seeping out of the ground in the hollow, the No 2 discharge gathers in a small stream channel which flows some 15 m to its confluence with the Willington Burn. Table 1 summarises the characteristics of the No. 2 discharge as measured in the spring and summer of 1999.

*Discharge No. 3*

This is the largest and most heavily polluted (Table 1) of the three main discharges, and lies at the most down-

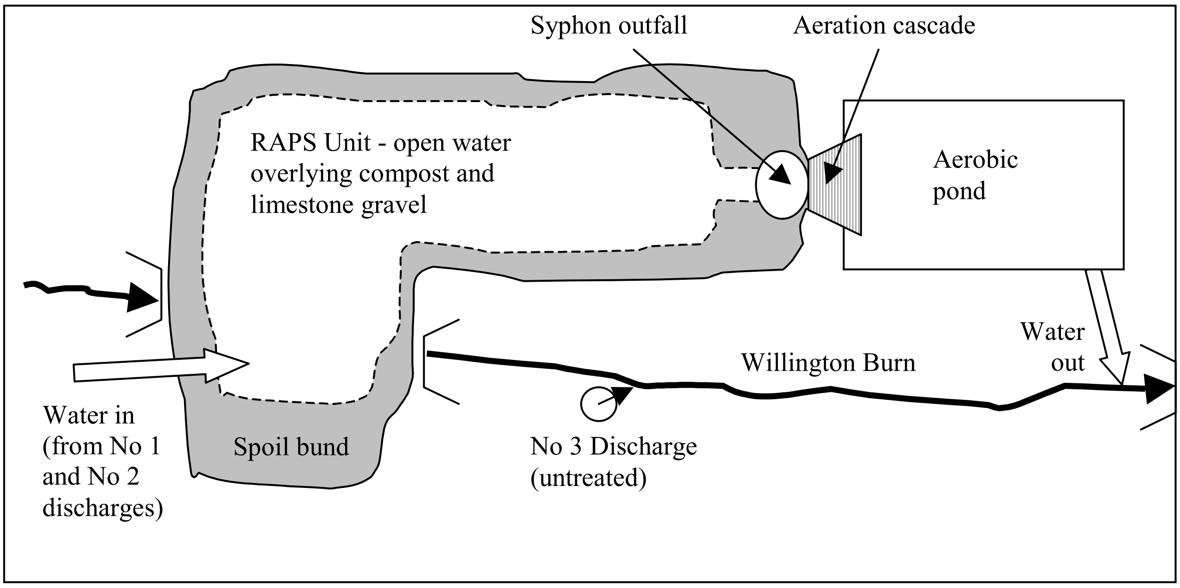

*Figure 2. Schematic plan of the Bowden Close pilot passive treatment system, which operated from 1999 to 2001*

stream 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 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.

**Bowden Close pilot scheme**

A 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 planted with the 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 effective, 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 warmer climate settings in the eastern USA.

**Full-scale design: constraints and concepts**

Based on the findings of the pilot project, and on recent experiences of colleagues in the USA (see Younger *et al.* 2002, for a review), a design has been developed for a full-scale passive treatment system at Bowden Close. The construction of this system is being financed by DEFRA via the SCA funding mechanism. This system will capture all three discharges. The full-scale system will incorporate two RAPS units: one to treat the combined flows of Nos 1 and 2, and a second to treat No. 3. The effluents from both RAPS will be combined in a final aerobic reed bed, which is intended to reaerate the waters and remove further Fe and Al prior to discharge of the site waters to the Willington Burn. Even having diverted the burn to make more room for the treatment system, the layout of the available land is probably insufficient to allow full RAPS treatment of discharge No. 3; the system has therefore been designed to over-treat Nos 1 and 2, so that the benefits of dilution by the treated equivalents of these waters will be available to counteract the inevitable shortcomings in the treatment of No. 3. (From a scientific point of view, under-treatment of No 3 is actually an advantage, as more accurate characterisation of rate processes is possible where the studied reactor is not load-limited; Hedin *et al.* 1994.)

A drawback of RAPS treatment which has come to be fully appreciated only in recent years, as the number of full-scale systems has grown, lies in the compost-over-limestone design pattern, as shown in Figure 1(a), and as implemented originally in the Bowden Close Pilot wetland. There are two drawbacks with this pattern:

(i) the entire flow through the system is throttled by the permeability of the compost layer, which is typically some orders of magnitude lower than that of the limestone gravel layer; and
(ii) from a public safety perspective, the presence of more than 0.5 m of saturated organic matter as the surface layer of the RAPS substrate is a significant hazard, for it will not bear the weight of even a small child. At the very least, this makes the compost layer a potential hazard.

A concept for overcoming these two drawbacks arose accidentally from the Bowden Close pilot study. After some by-pass leakage was discovered in the dam structure, it was necessary to switch the flow into the RAPS, drain the system down and access the dam with track-laying machinery which of necessity had to drive over the substrate. The compost layer and the limestone layer inevitably became very mixed in the process, raising fears that the RAPS would not function properly once flow was restored. In the event, this fear proved unfounded. The mixed compost–limestone layer continued to perform as before, with no signs of armouring of limestone with hydroxides, and with the advantage that the pond could now be safely entered on foot if necessary. Reflecting on this experience, and drawing also upon experimental work undertaken in relation to substrate design for the Shilbottle Permeable Reactive Barrier (see below), thoroughly mixed limestone/compost mixtures will be used in the RAPS units at Bowden, minimising hydraulic throttling and public safety concerns on this relatively remote site.

With significant logistical and financial support from CL:AIRE and the BOC Foundation (as CL:AIRE Technology Demonstration Project 5), the full-scale Bowden Close system is set to be one of the most extensively and intensively monitored examples of its type anywhere in the world. We are installing secure, locked chambers through which waters from various parts of the system will be diverted continuously to facilitate auto-sampling. These will form an invaluable part of an overall programme of characterisation and performance assessment, the key elements of which are planned to be as follows:

- flow measurement of influent, effluent and intermediate points, with data logging at hourly intervals of at least the influent and effluent points (with fortnightly manual measurements elsewhere);
- stage measurements in ponds and channels and piezometric measurements in the subsurface elements of the system (frequencies as in (a)), using innovative sub-horizontal 'tap piezometers' routed to faucets within the secure access chambers;
- collection of routine hydrochemical samples of surface and subsurface waters within the system (using auto-samplers for at least daily sampling);
- tracer testing of the entire system and its sub-components under a range of seasonal conditions. Auto-samplers will be used for these exercises. Interpretation of the tracer tests will yield robust estimates of system characteristics (hydraulic and biogeochemical reactive transport parameters);
- periodic removal and destructive analysis of pre-packaged substrate elements and dialysis tubes, installed at the time of construction in the subsurface portions of the wetland, to reveal the state of compost diagenesis at different depths over time (in terms of both mineral precipitation, and the rate of hydrolysis of ligno-cellulose materials, the characterisation of which is crucial to developing an understanding of the supply rate of those short-chain metabolites which are required by the all-important sulphate-reducing bacteria);
- rainfall and air temperature logging at or near site.

Processes other than the treatment technology which may result in contaminant 'losses' include leakage (to be minimised by using a composite liner) and dilution by incoming runoff from non-contaminated land (to be minimised by site drainage works). The flow measurements and synchronous hydrochemical sampling at several points in the system will be used to account for these 'losses'.

With this broad range of investigative activities, the Bowden Close system is confidently expected to yield important insights into (*inter alia*) the precise mechanism of $Al^{3+}$ removal in RAPS, and the likely long-term maintenance requirements (practical and financial) for such systems. 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.

## SHILBOTTLE PERMEABLE REACTIVE BARRIER, NORTHUMBERLAND

### Shilbottle Brass Heap: England's worst spoil leachate?

From the early 19th century until October 1982, Shilbottle Colliery worked a single seam of coal in the vicinity of Alnwick, Northumberland. Prior to nationalisation in 1947, Shilbottle Colliery was worked by the Cooperative Society, producing most of the household coal marketed nationally by that organisation. The Shilbottle Seam is unusual amongst major worked seams of England in that it occurs in the Carboniferous Limestone Series (Dinantian). As much of the Dinantian strata in Northumberland (as elsewhere in northern England) were either deposited or underwent diagenesis in the presence of marine waters, the Shilbottle Seam is overlain by rocks which show a strong marine influence. The immediate roof bed is a shale which underwent diagenesis in the presence of sea water and is consequently very rich in pyrite. Much of this pyritic shale was removed from the colliery during working, and deposited at the surface to form a large spoil heap (locally termed the 'Brass Heap' on account of the visible, brassy-coloured pyrite present in the shale). Overlying the shale within the stratigraphic succession is a

**Table 2. Hydrochemical parameters (total concentrations) for six monitoring boreholes (BH6 to BH1; numbering decreases west to east) and three surface seepages of groundwater (GW 9–11) at the Shilbottle Colliery site, Northumberland**

| | BH 6 | BH 5 | BH 4 | BH 3 | BH 2 | BH 1 | GW 11 | GW 10 | GW 9 |
|---|---|---|---|---|---|---|---|---|---|
| pH | 4.47 | 3.64 | 4.00 | 4.08 | 4.17 | 6.32 | 3.29 | 3.55 | 4.17 |
| Acidity (mg/L $CaCO_3$) | 742 | 2048 | 2557 | 2908 | 6342 | 78 | 1360 | 2534 | 3322 |
| Fe (mg/L) | 92 | 200 | 405 | 599 | 1136 | 26 | 278 | 452 | 688 |
| Mn (mg/L) | 68 | 108 | 180 | 205 | 299 | 22 | 165 | 181 | 238 |
| Al (mg/L) | 86 | 267 | 270 | 263 | 678 | 1.2 | 97 | 249 | 298 |
| $SO_4^{2-}$ (mg/L) | 8701 | 8162 | 8230 | 10 167 | 15 318 | 3745 | 6334 | 9288 | 11 176 |

thick limestone (the Little Limestone), which has collapsed into caved panels in the underground workings of the mine, where it is proving to be a powerful source of buffering for mine waters in the Shilbottle–Whittle deep mine complex (cf. Nuttall, this volume).

Little or no limestone was deposited in the Brass Heap, however, and the leachates which emanate from that body of spoil are devoid of alkalinity. These have been characterised by repeated sampling of a field of monitoring wells installed along the southernmost flank of the spoil heap (Table 2).

The extreme contaminant concentrations in these groundwaters qualify the Shilbottle site for the dubious distinction of being the most highly contaminated colliery spoil heap leachate yet documented in England. Discharge of this leachate to the adjoining Tyelaw Burn has long resulted in spectacular pollution of the stream, as various metals are precipitated in the form of hydroxides, such as bright orange iron ochre, white aluminium hydroxysulphate foam and (locally) black manganese 'wad' with an iridescent sheen. These precipitates are not only unsightly, they also smother the streambed and prevent photosynthesis. Furthermore, the precipitation of these hydroxides releases protons, depressing the pH even further and rendering the Burn extremely inhospitable to normal aquatic fauna and flora. Thus the Shilbottle leachate has caused severe ecological degradation for several decades, and has affected water quality to such an extent that the impacts remain significant even after major dilution downstream of the confluence of the Tyelaw Burn and the River Coquet.

### Preliminary reclamation at Shilbottle and the discovery of by-passing groundwater

After acquisition of the site from the former National Coal Board, initial reclamation of the spoil heap by Northumberland County Council included successful re-vegetation of the spoil (most recently with re-afforestation achieved by innovative use of paper-making wastes as a soil-forming material), and construction of a series of reed-beds to intercept and improve the quality of visible surface seepages of leachate. Although these measures were successful in themselves, subsequent monitoring revealed that the Tyelaw Burn remained heavily polluted. Hydrological studies undertaken by the University of Newcastle (Daugherty 1998) demonstrated on the basis of mass-balances that around two-thirds of the total loading of contaminants leaving the spoil heap as leachate were flowing via subsurface pathways directly into the Tyelaw Burn, thus completely by-passing the treatment reed-beds. Further reclamation was therefore necessary. Clearly, an alkalinity-generating process would need to be included in the system, but with heads at or below the level of water inflow to the existing reed-bed, a RAPS unit was never going to be an option. An alternative, innovative design was therefore called for, and this was developed by Northumberland County Council and the University of Newcastle over a period of two years (Amos and Younger, in press), and has now been adopted as CL:AIRE Technology Demonstration Project 13.

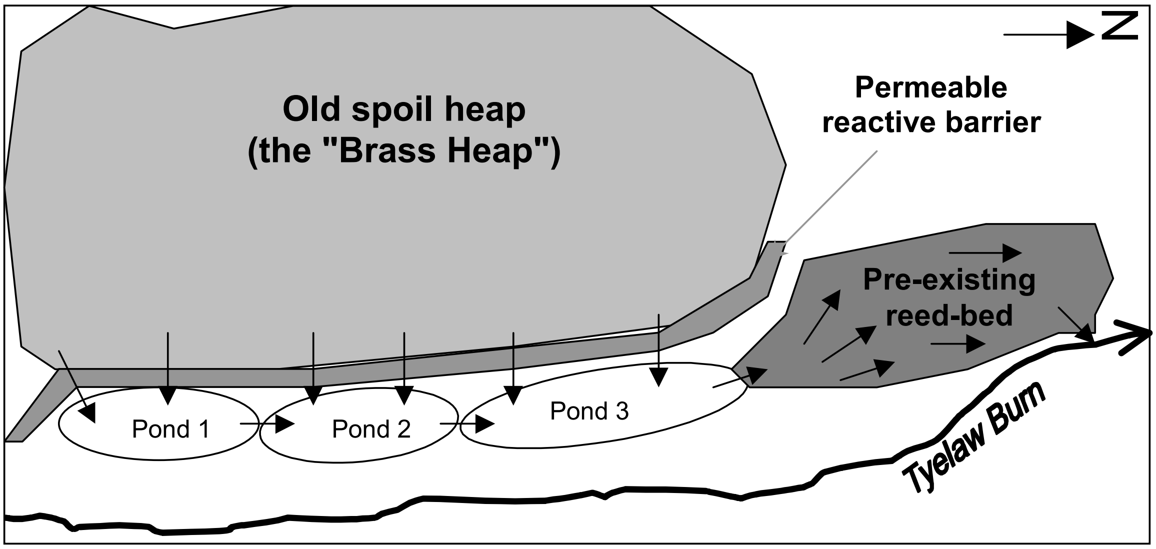

*Figure 3. Schematic layout and cross-section of the hybrid PRB–ponds–wetland system at Shilbottle, Northumberland. Black arrows show selected approximate water flow directions.*

### A hybrid remediation system: permeable reactive barrier, ponds and wetlands

The principle of using sulphate-reduction based reactors to generate alkalinity is harnessed at the Shilbottle site by installing the reducing, alkalinity-producing media in the form of a permeable reactive barrier, downstream of which the groundwater is constrained to daylight into a series of three open ponds, where further polishing of oxidisable metals occurs, prior to final polishing of the effluent in the existing reed-bed (Figure 3). To accommodate this hybrid PRB-wetlands system on the site, it was necessary to relocate the Tyelaw Burn some 12 m to the west. In the process of relocation, it was possible to ensure that the ground between the burn and the oxidation ponds is essentially impermeable, so that no further groundwater seepages enter the burn from the spoil leachate source. The Shilbottle PRB is by far the largest of its type in the world, being 180 m-long (N–S), 3 m deep by 2 m wide. It was constructed by a cut-and-fill method, in which a trench was first excavated the full length of the barrier before tipping of pre-mixed reactive media. In line with the recommendations from extensive lab-testing of possible reactive media (Amos and Younger, *in press*), the Shilbottle PRB substrate consists of 25% composted horse manure and straw, 25% green waste compost, and 50% limestone gravel (mostly 25 mm nominal single-sized, though there is one section of the barrier with 10 mm diameter limestone gravel). In one section of the PRB, the limestone clasts were substituted by blast furnace slag. These organic and inorganic components of the substrate were thoroughly mixed using a large, mobile agricultural mixer. The mix was then loose-tipped into the trench to the full depth of excavation (i.e. there is a substantial unsaturated zone of reactive media above the water table in the spoil, which both provides further reactive capacity for some future period when heads in the PRB rise in response to clogging of pores, and also provides an $O_2$ consumption blanket in the meantime). The emplaced reactive substrate is strong enough to support the passage of vehicles. Multi-level piezometers were installed in the media in two positions during emplacement, complementing the previously existing boreholes up-gradient of the PRB (which had been previously sampled to yield the data in Table 2) which continue to provide information on the native groundwater in the spoil. The downstream face of the PRB was lined with brick rubble, to provide a permeable exit filter to the oxidation ponds. In some places, an artificial liner was draped along the downstream face to divert some of the more voluminous feeders of water through larger volumes of the permeable reactive media than they would have been likely to enter had they been permitted to take the shortest flowpath across the barrier.

The Shilbottle passive treatment system is still undergoing final commissioning at the time of writing. However, early performance data suggest that the PRB and ponds are effectively treating the contaminated leachate, with water flowing from the PRB via ponds 1–3 (Figure 3) to enter the pre-existing reed-beds with a pH of 7.2, 136 mg/L of alkalinity (as $CaCO_3$), 3.8 Fe mg/L and 0.3 Al mg/L, all of which compare very favourably with the untreated waters listed in Table 2. Visual inspection of the Tyelaw Burn reveals that the previous ochre staining and benthic smothering have now been completely remedied.

## CONCLUSIONS

Some of the challenges involved in the passive treatment of acidic mine waters include:

- selecting and implementing an appropriate system geometry;
- specifying a substrate granulometry which optimises both permeability (favoured by large grain size) and reactivity (favoured by fine grain sizes);
- designing substrates which are reactive enough to affect water quality over periods of hours to days, whilst being consumed slowly enough that they will support system functioning for many years without renewal.

The ways in which such challenges have been overcome in recent designs are discussed in relation to the Bowden Close RAPS system in County Durham, and the Shilbottle permeable reactive barrier in Northumberland. These two systems form nuclei of the new National Mine Site Remediation Research Facility (NMSRF) sponsored by CL:AIRE, and are study sites for the new Bioremediation LINK project 'ASURE' (BIOREM4), which concerns bioremediation of acidic mine waters by sulphate reduction in novel, compost-based, field-scale bioreactors.

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## REFERENCES

Amos, P.W. and Younger, P.L. (in press) Substrate characterisation for a subsurface reactive barrier to treat colliery spoil leachate. *Water Research*.

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 permeable reactive barrier in Monkstown, Northern Ireland. *CL:AIRE Technology Demonstration Report TDP3*. ISBN 0-9541673-0-9. CL:AIRE, London. 120 pp.

Benner, S.G., Blowes, D.W. and Ptaceck, C.J. (1997) A full-scale porous reactive wall for prevention of acid mine drainage. *Ground Water Monitoring and Restoration*, **17** (4), 99-107.

Daugherty, A.J. (1998) Monitoring and improvement of a passive minewater remediation scheme receiving net-acidic leachate at Shilbottle Colliery, Northumberland. Unpublished MSc Thesis, Department of Civil Engineering, University of Newcastle.

Demchak, J., Morrow, T. and Skousen, J. (2001) Treatment of acid mine drainage by four vertical flow wetlands in Pennsylvania. *Geochemistry: Exploration, Environment, Analysis*, **1**, 71-80.

Gavaskar, A.R., Gupta, N., Sass, B.M., Janosy, R.J. and O'Sullivan, D. (1998) *Permeable Barriers for Groundwater Remediation: Design Construction and Monitoring*. Battelle Press, Columbus, OH.

Hedin, R.S., Nairn, R.W. and Kleinmann, R.L.P. (1994) *Passive Treatment of Polluted Coal Mine Drainage*. Bureau of Mines Information Circular 9389. United States Department of Interior, Washington DC.

Jarvis, A.P. (2000) Design, construction and performance of passive systems for the treatment of mine and spoil heap drainage. Unpublished PhD Thesis, Department of Civil Engineering, University of Newcastle, UK.

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. In: *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, pp. 195-204.

Nuttall, C.A. this volume. Testing and performance of a newly constructed full-scale passive treatment system at Whittle Colliery, Northumberland.

Taylor, L.T. and Jones, D.M. (2001) Bioremediation of coal tar PAH in soils using biodiesel. *Chemosphere*, **44** (5): 1131-1136.

Younger, P.L. (1995) Hydrogeochemistry of minewaters flowing from abandoned coal workings in the Durham coalfield. *Quarterly Journal of Engineering Geology*, **28** (4), S101-S113.

Younger, P.L. (2000) Holistic remedial strategies for short- and long-term water pollution from abandoned mines. Transactions of the Institution of Mining and Metallurgy (Section A: Mining Technology), **109**: A210-A218.

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).