Effective Passive Treatment of Aluminium-Rich, Acidic Colliery Spoil Drainage using a Compost Wetland at Quaking Houses, County Durham

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Abstract

Passive treatment of net-acidic minewaters using compost wetlands was pioneered in the USA but, so far, has had limited application in Europe. At Quaking Houses (County Durham), strongly acidic ferruginous and aluminium-rich waters discharging from the spoil heap of the abandoned Morrison Busty colliery have been obliterating aquatic life in the Stanley Burn for almost a decade. A concerted investigation involving the National Rivers Authority, the local community and a nearby University, has established the origins of the polluting discharge and assessed its impact on the receiving water. An evaluation was carried out on the possible treatment methods for the discharge, drawing upon the literature and supported by laboratory microcosm tests. A compost wetland was the favoured option, and a pilot facility was constructed with the assistance of the local community.

Plans for full-scale treatment are now well advanced, with long-term maintenance being undertaken by local volunteers at minimal cost.

Key words: **Acidity; compost; minewater; passive treatment; pollution; Quaking Houses; remediation; wetlands.**

Introduction

Since 1992, there has been an increased awareness in the UK about pollution of inland and coastal waters by ferruginous, and frequently acidic, waters draining from abandoned mines and associated features[1,2,3]. This change in perception has been prompted by at least three experiences:

(i) The Wheal Jane incident in January 1992 caused a significant pollution plume in the Fal estuary when an estimated 50 Ml of acidic, metal-laden water burst the plug of an old adit, bringing minewater pollution to the national headlines[3];

(ii) When the UK Government announced its programme of colliery closures in October 1992, anxiety was aroused over the cessation of pumping in some large coalfields which, hitherto, had been progressively dewatered for as long as 300 years[1]. While interim arrangements for continued pumping have since prevented pollution in certain abandoned coalfields, major uncontrolled minewater discharges began to flow in South Wales during 1993[4,5]; and

(iii) In areas such as central Scotland, where minewater pollution has already been established for decades[6,7], gradual remediation of other sources of pollution (especially sewage) has left the unabated minewaters as the limiting factor on any further improvement of river quality. For instance, by 1994, abandoned mines were the principal cause of freshwater pollution in the Forth catchment[8].

This raised consciousness of minewater pollution has inspired calls for national programmes to address current and future problems. However, existing legislation does not apportion responsibility for remediating pollution from long-abandoned mines to any public or private bodies (although the newly formed Coal Authority has shown considerable interest in addressing voluntarily some of these problems). Even if a national rolling programme for minewater clean-up is eventually initiated, the lack of current mining revenue, against which treatment might be off-set, will bias heavily treatment solutions towards those techniques requiring minimal long-term maintenance and no continuous inputs of treatment reagents. This paper describes the pilot implementation of one such technique.

Stanley Burn Feasibility Study

At the same time that minewater issues were receiving national prominence, the residents of Quaking Houses (County Durham) began to petition the National Rivers Authority (NRA) over the pollution of the Stanley Burn which flows past their village. Acidic metalliferous waters, emanating from the site of the abandoned Morrison Busty colliery (Fig. 1), cause extensive staining of the bed and banks of the Stanley Burn with red and orange ochre, and often turn the water white with suspended aluminium. A white/creamy aluminium precipitate ('alum') (Fig. 2) frequently aggregates into masses of froth which floats on the water surface and is blown up onto the adjoining land by the wind.

A combination of community pressure, local government concern, academic investigation and growing regulatory interest towards the end of 1993 led to the NRA funding a feasibility study to assess the possibility of remediating the polluting discharge from Morrison Busty[9]. The scope of works included:

(a) A determination of the origins of the polluting discharge at Morrison Busty;

(b) An assessment of the extent of the pollution

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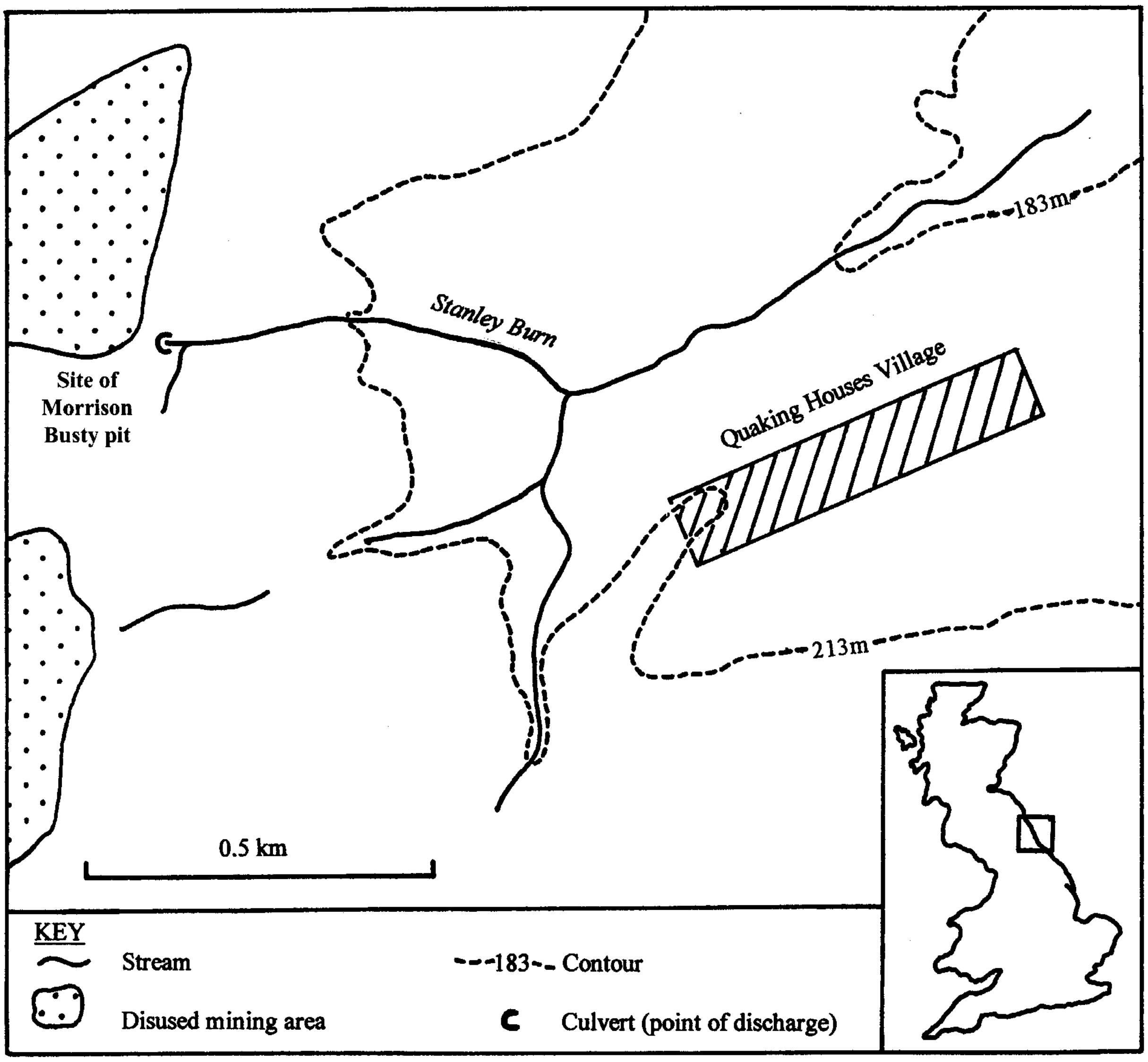

Fig. 1. Location of Morrison Busty site

problem using chemical and biological monitoring techniques;
(c) Design and testing of a pilot facility to treat the water; and
(d) Close liaison with the residents of Quaking Houses during the design, construction and maintenance of the pilot-treatment facility.

After competitive tender, the contract for the feasibility study was awarded to a team based at the University of Newcastle who had already established links with the community during earlier geochemical survey work[10].

Origin of Pollution at Morrison Busty

An appreciation of the origin of a given polluting discharge is useful not only in assessing potential liabilities for remediation, but also as a guide to the selection of appropriate management approaches for long-term pollution abatement. In this case, the assessment of possible origins for the discharge involved archival investigations (similar to those required in many contaminated land investigations), combined with interviews of local residents who worked formerly as mine officials.

Coal mining has taken place in the vicinity of the Stanley Burn for many centuries and mediaeval bell-pits are visible on surrounding scrubland. Although the earliest recorded mining company in the area was established in 1726, the first deep mine to be sunk in this area was the William pit at Quaking Houses in 1839. This pit, and adjoining collieries in the Stanley district, worked the shallower coal seams of the district. Recent open-casting of these seams adjacent to the polluting discharge has revealed that they are all dry. Deeper seams, which were only worked in this area from the Morrison Busty colliery itself, are at least partly saturated (an average of 7.85 Ml/d were pumped from Morrison Busty during working). However, when Morrison Busty was closed in 1972, steps were taken to allow water to flow eastwards through previously isolated roadways, towards the still-active dewatering pumps of Kibblesworth,

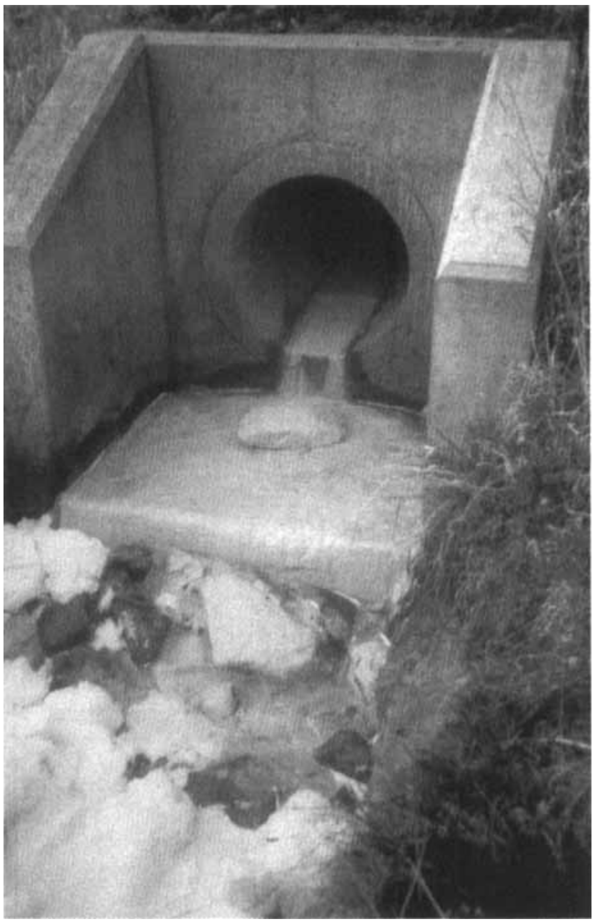

Fig. 2. Culvert at Morrison Busty colliery (before commencement of study) showing deposits of 'alum'

Chester Moor and Kimblesworth[1]. Consequently, none of the deep coal workings around the Morrison Busty site have so far flooded up to the surface, and the polluting waters entering the Stanley Burn cannot be deep mine waters. The only alternative explanation is that the acid waters are generated within the Morrison Busty spoil heap. Around 1980, the spoil heap was split by a deep road-cutting which now carries the A693. Residents in Quaking Houses recall that the minewater pollution problem arose after the road was completed. It therefore seems that the onset of the pollution was initiated by the enhanced circulation of water and air in the spoil after the cutting was made, leading to accelerated oxidation of pyrite present in the shale clasts.

Pollution Assessment of Stanley Burn

The assessment of the impacts of the Morrison Busty discharge on the Stanley Burn was undertaken by chemical and biological sampling and analysis on several occasions.

Typical analyses of the discharge water are given in Table 1. In terms of major ion chemistry, the Morrison Busty discharge was dominated consistently by Na, Cl and SO_4. The high concentration of sulphate (in association with elevated iron) is typical of acid mine drainage[11]; however, the elevated Na and Cl concentrations are unusual. Bearing in mind that the Morrison Busty discharge does not originate from deep workings, it is unreasonable to postulate a component of coalfield brine in the discharge. Similarly, while freshly deposited colliery spoil can leach small quantities of brine-rich porewaters for a few months, the spoil at Morrison Busty was deposited more than two decades ago; therefore a continued release of substantial amounts of Na and Cl is unlikely. Rather, application of brine source discrimination techniques[12] shows the source of the Na and Cl to be common road de-icing salt. Data presented in Table 1 support this inference, showing Na and Cl concentrations to be higher in the winter. The inputs of surface drainage implied by this conclusion indicate that vigilance is necessary with regard to other highway runoff pollutants, such as motor oil.

Table 1. Selected analyses of polluted water emerging from culvert at Morrison Busty, illustrating seasonal variations

Parameter	Date			
	29.11.94	25.1.95	17.5.95	14.8.95
Flow rate (l/min)	–	–	81.0	17.1
Temperature (°C)	10.4	7.6	11.5	13.6
pH	4.50	6.60	6.13	4.50
Electrical conductivity (µS/cm)	4400	844	3000	4400
Alkalinity (mg/l as $CaCO_3$)	0.0	99.0	50.0	–
Iron (mg/l)	7.5	4.6	10.9	33.5
Aluminium (mg/l)	13.4	8.1	6.4	21.3
Manganese (mg/l)	7.0	3.6	3.2	9.7
Zinc (mg/l)	–	2.0	–	–
Calcium (mg/l)	334	253	148	312
Magnesium (mg/l)	109	82	53	127
Sodium (mg/l)	642	962	425	429
Potassium (mg/l)	69	178	58	42
Sulphate (mg/l)	1308	615	486	1790
Chloride (mg/l)	750	2152	700	543

Variations in the amount of highway runoff passing through the spoil drainage system is reflected in marked changes in several other parameters. Dilution of the spoil leachate leads frequently to a short-term increase in pH value, and to the occasional presence of alkalinity in the water. Similarly, iron concentrations are higher in summer (30–35 mg/l) than in winter (around 5 mg/l). This is presumably because:

(i) Pyrite oxidation in the spoil materials (which releases iron and lowers the pH) is vigorous in the summer (when the warm air encourages bacterial activity), but sluggish in cold spells during the winter; and
(ii) There is generally more rainfall in the winter than in the summer in this area, leading to greater dilution of acidic spoil drainage .

The source of the Stanley Burn lies only a few metres from the Morrison Busty discharge and, because the flow emanating from this point is very low, the hydrochemistry of the Burn immediately downstream from the discharge corresponds closely to that of the discharge itself. However, marked changes in hydrochemistry downstream have been observed repeatedly (Fig. 3), and these can be ascribed readily to:

(a) Precipitation of ochres and alums resulting in the gradual removal of iron and aluminium from solution;
(b) Sustained depression of pH for several hundred metres due to the net proton-releasing nature of hydrolysis by ferric iron and aluminium, with a final rise in pH occurring only after high levels of alkalinity (around 100 mg/l) are restored by tributary inflow (around 400 m from the discharge);
(c) Lack of dilution by baseflow before the tributary confluence, reflected in relatively stable chloride concentrations; and
(d) A decrease in sulphate concentrations due to precipitation of aluminium hydroxy-sulphate froth.

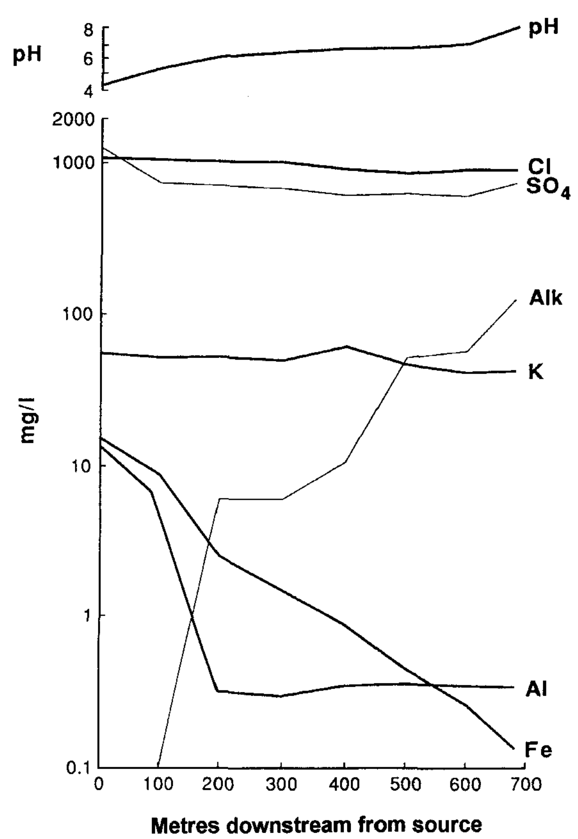

Fig. 3. Downstream changes in dissolved species on a single day in June 1993[10]

These hydrochemical characteristics are detrimental to the health and diversity of aquatic life in the Stanley Burn, although the downstream changes in chemistry result in gradually more tolerable conditions. Assessments of the invertebrate community in the Burn were made on three occasions, using kick-sampling and identification techniques advocated by the NRA. All available habitats (pool, riffle, etc.) were sampled at each of three sites (150 m, 600 m and 1000 m downstream from the discharge). Results are summarized in Table 2 as 'Biological Monitoring Working Party' (BMWP) scores, and 'average score per taxon' (ASPT), and these indicate clearly the extreme faunal impoverishment in the vicinity of the Morrison Busty discharge. Pollution-tolerant dipterans (especially members of the *Chironomidae* family) and oligochaete worms dominated the fauna at all sites. The faunal impoverishment can be ascribed to two factors:

(i) Smothering of the benthos by ochre (particularly on the riffles) and alum (where water is quiescent in pools), which precludes photosynthesis and hence removes the food source for invertebrates; and
(ii) Acute toxic effects from Fe, Al, Zn, etc. (which can be expected on the basis of their concentrations in the discharge itself (Table 1)[13]. This effect is demonstrated by the persistence of low BMWP and ASPT scores beyond 600 m, downstream from the zone where ochre smothering of the benthos dies out.

Parallel surveys of nearby unpolluted streams by the NRA helped to place these results in context, by demonstrating that much higher BMWP and ASPT scores are attained in streams of similar size which are not receiving acidic spoil drainage.

Selection of Treatment Technology

Conventional active treatment of acidic minewaters can be achieved by alkali dosing, aeration, flocculation and settlement[14]. Active treatment can also be undertaken anaerobically (in sulphidogenic reactors)[15] or electrochemically[16]. Such approaches can be cost-effective long-term solutions at sites such as Wheal Jane where loadings of metals and acidity are especially high[17]. However, where discharges from abandoned mines are less extreme in their quality, the ongoing revenue costs of active treatment can make the scheme less attractive, and passive treatment using constructed wetlands technology is favoured increasingly[18]. Furthermore, the legal framework for minewater regulation in the UK also favours low-revenue solutions, since liabilities for clean-up are usually unassignable. For these reasons the search for an appropriate solution for the Morrison Busty discharge soon focused on passive treatment methods.

In the UK, there is a tendency to equate constructed wetlands with 'reed beds' which, basically, are surface-flow aerobic systems. However, for a net-acidic discharge such as Morrison Busty, aerobic wetland treatment can be expected to lower the pH even further, because the processes of ochre and alum precipitation are proton-generating:

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad (1)$$
$$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad (2)$$

As the pH decreases metals become more soluble and removal rates decline. Consequently, the simple creation of a 'reed bed' is an inappropriate response for a net-acidic minewater. A more appropriate response for net-acidic waters is the construction of an anaerobic compost wetland[18]. In these systems, most of the flow is subsurface, or at least the depth of standing water is

Table 2. Benthic invertebrate monitoring results for Stanley Burn at different distances downstream from polluting culvert

	Sampling site (distance downstream from discharge)								
	150 m			600 m			1000 m		
Date	27.6.95	3.8.95	8.10.95	27.6.95	3.8.95	8.10.95	27.6.95	3.8.95	8.10.95
BMWP score[1]	1	6	1	7	3	11	24	17	10
ASPT[2]	1.00	3.00	1.00	2.33	1.50	2.75	4.00	3.40	3.33
Number of individuals	2	4	4	9	12	58	268	68	32

[1]Biological Monitoring Working Party score (biotic index)
[2]Average score per taxon (BMWP divided by number of taxa)

sufficiently shallow that thorough diffusional exchange of solutes with a saturated compost substrate can occur. Recently, subsurface-flow anaerobic cells have been incorporated into the Wheal Jane pilot wetland[(17)], and into minewater wetlands in the Pelenna catchment, South Wales[(3)], although reliable performance data for these newly installed systems are not yet available.

The most obvious method for producing alkalinity in a constructed wetland is by limestone dissolution. However, where significant concentrations of ferric iron are present in solution (as is the case at Morrison Busty), limestone surfaces are rapidly armoured by ochre and the rate of dissolution decreases significantly. An alternative approach to alkalinity generation is therefore preferable in these circumstances. Since sulphate is nearly always present in high concentrations in acidic minewaters, compost wetlands can generate alkalinity (as dissolved CO_2) and raise the pH (by consuming protons) through dissimilatory, microbial sulphate reduction:

$$SO_4^{2-} + 2CH_2O + 2H^+ \rightarrow H_2S + 2CO_2 + 2H_2O \quad (3)$$

where CH_2O represents an idealized carbon source.

The subsequent reaction of dissolved iron with free sulphide can lead to the precipitation of sulphides, effectively trapping the iron within the substrate:

$$Fe^{2+} + H_2S \rightarrow FeS_{(s)} + 2H^+ \quad (4)$$

The latter reaction is proton-generating, therefore the release of protons in reaction (4) would cancel out the consumption of protons in reaction (3) if all the reduced sulphate was converted to sulphide. However, in most minewaters, the molar SO_4/Fe ratio is well in excess of 2 (i.e. the S/Fe ratio for the sulphide precipitated in reaction (4)). Consequently, with more sulphate reduced than is used in precipitating sulphide, the net effect of these two reactions in a compost wetland should be an increase in alkalinity and pH. After this has been achieved, sufficient buffering capacity will exist in the water to accommodate further hydrolysis of iron and aluminium in a subsequent aerobic wetland cell ('reed bed') without allowing the pH to decrease below a critical level (around 5.5). For these reasons, passive treatment of the Morrison Busty discharge (using an anaerobic compost wetland cell and an aerobic wetland cell in series) seems desirable.

Design criteria for constructing compost wetlands were only available from the USA. It was desirable, therefore, to determine analogous criteria for UK climatic conditions. In particular, the USA sites from which design criteria have been determined[(18)] lie in an area which experiences much warmer summers than at Quaking Houses, which lies about 250 m above sea level on the edge of the North Pennine uplands. In order to determine appropriate design criteria for a full-scale wetland, a small pilot wetland was constructed and monitored adjacent to the Morrison Busty discharge.

Design, Construction and Operation of Pilot Wetland

One of the key elements in the design of a compost wetland is the identification of a suitable organic-rich substrate. In the USA (and, by mimicry, in recent developments in South Wales[(3)]) the most popular substrate for compost wetlands is spent mushroom compost[(18)]. This is available in large quantities in Appalachia (where most US constructed wetlands are situated) but is more scarce in the Pennine foothills of western County Durham. Consequently, an evaluation was made of three alternative compost materials:

(a) The existing soil adjacent to the discharge;
(b) A horse manure/straw compost from the stables in Quaking Houses village; and
(c) A cow manure/straw compost from the farm nearest to the discharge.

Each of these substrates was subjected to microcosm tests over a period of 28 days. 250 g sub-samples were placed in 1-litre Duran bottles which were filled with water from the discharge, and tightly stoppered. For each substrate, parallel exercises were run with and without the addition of crushed limestone, and with and without autoclaving. A control bottle, containing the discharge water alone, was also established. Aliquots of water were removed using sterile pipettes after 6, 14 and 28 days, and analysed for iron, aluminium and sulphate.

Fig. 4 shows the change in sulphate concentration over time for all three substrates (A, B, C) and for the discharge water on its own. For all three substrates, a gradual but monotonic removal of sulphate from solution was obvious, with substrates B and C showing the highest rates of sulphate reduction. (For all substrates, further evidence of sulphate reduction was apparent, including the emission of H_2S gas and the formation of black

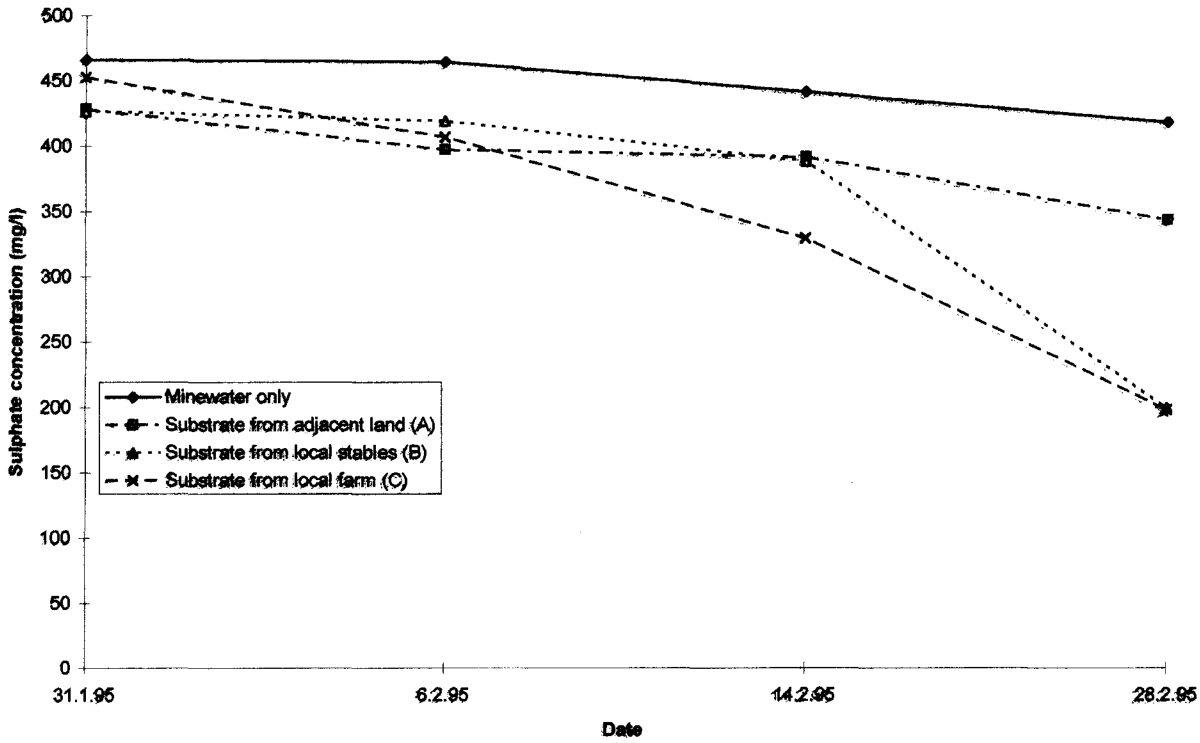

Fig. 4. Changes in concentration of dissolved sulphate for various substrates during laboratory microcosm tests

precipitates (iron mono-sulphides?) within the bottles). For the bottle containing the discharge water alone, only a minor decline in sulphate concentration was noted – presumably due to the observed precipitation of white aluminium hydroxy-sulphate salts within this jar; other results were less clear. A reduction in aluminium concentration (from about 5.0 to 1.5 mg/l) was noted for all substrates. Substrate B had the best iron-removal performance. Both B and C removed iron at a rate similar to that for aluminium, but substrate A proved to be a net contributor of iron to solution. Autoclaving of samples was expected to halt sulphate reduction (and thus metals removal), but results were erratic and ambiguous. H_2S was also detected emanating from these jars, suggesting that the sulphate-reducing bacteria either survived standard autoclaving procedures, or were inadvertently reintroduced during sampling (despite adherence to stringent microbiology laboratory protocols). Notwithstanding these complications however, the microcosm tests yielded sufficient results to favour selection of substrate B for the pilot wetland.

On 20 February 1995, volunteers from Quaking Houses arrived at the Morrison Busty site to work with the University team and NRA officers on the digging of the pilot wetland cells. The layout of the wetland comprises four cells in series (Fig. 5). The first three cells have a PVC liner (to constrain the water balance for experimental purposes) and baffles formed from compacted *in situ* soil to prevent hydraulic short-circuiting. Although this rectilinear layout outline might be expected to give rise to localized dead zones in corners, the high retention period for the water ensured that molecular diffusion could spread solutes efficiently throughout the first three cells. The fourth cell is an unlined unit, formed simply by allowing the outflow from cell 3 to flood the existing soil surface.

After the digging of the cells, compost substrate from the Quaking Houses stables was installed in the first two cells to a depth of about 300 mm, and the cells were filled with the discharge water, saturating the substrate beneath a few centimetres of standing water. Some weeks later, a sparse admixture of dolomite pebbles was added to the compost substrate to counteract an observed initial lowering of pH in these cells, ascribed to vigorous and conspicuous alum precipitation (reaction (2)). In the third cell, the compost is sparse and the dolomite pebbles are more abundant; they were later arranged to form a porous berm immediately before the outflow to the fourth cell. (While limestone would have been preferred to dolomite on account of its higher solubility, dolomite was available readily locally.)

The inflow to the pilot wetland is provided by a simple siphon from the main discharge point, using a 12.5 mm dia. plastic tube which was hidden in the streambed and undergrowth, and went undetected by vandals. The siphon yields a fairly steady 0.057 l/s to the pilot cell (which equates to 4 – 20% of the total discharge at different times). The use of narrow-bore pipes for influent feed to full-scale wetlands should be avoided because they are prone to clogging, but for the pilot study the siphon proved surprisingly reliable, only clogging completely about once every 4 – 6 months.

Wetland Performance

Monitoring of the influent and effluent hydrochemistry of cell 3 was carried out at approximately monthly intervals from May 1995 to April 1996. (The effluent from cell 4 could not be sampled as it exits the cell by

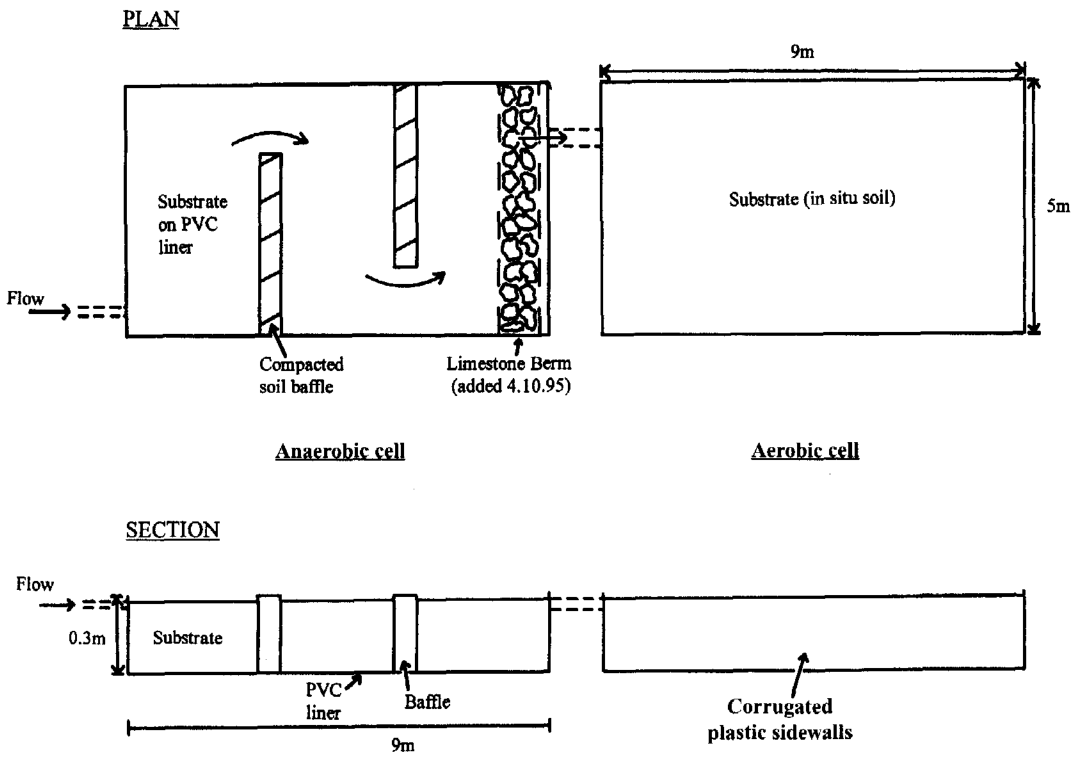

Fig. 5. Layout of pilot wetland at Morrison Busty

diffuse seepage.) The pilot wetland has a mean hydraulic retention period in excess of two days. Consequently, nominally synchronous influent and effluent samples are actually affected by a significant time lag.

Although the wetland was anticipated to require a few months' acclimation, sulphate reduction processes commenced apparently as rapidly as they had in the laboratory, and a marked improvement in water quality between influent and effluent samples was noted consistently from the first sample onwards. Fig. 6 shows the influent and effluent records for iron, aluminium and acidity. The processes which are responsible for removal of these pollutants can be inferred from observations of mineral accumulation and chemical analyses. For iron (Fig. 6(a)), there are two processes: (i) precipitation of some ferric hydroxide on the surface of the substrate in the first cell, and locally within the fourth cell; and (ii) precipitation of iron sulphides within the compost substrate (reaction (4), confirmed by coring and analysis of the substrate during the summer of 1996). Effluent iron concentrations were substantially less than influent concentrations for all but one sample (3.1.96). In this case, the influent was at an annual minimum, and the slight excess of effluent over influent can be explained by the time lag in flow across the wetland during a period when influent dilution could have been increasing.

For aluminium (Fig. 6(b)), which forms no stable sulphide phase, the only realistic sink is alum precipitation (aluminium hydroxides and hydroxy-sulphates). The precipitation of these salts was observed to occur predominantly in cells 1 and 2, and was a simple consequence of the forced increase in pH, presumably

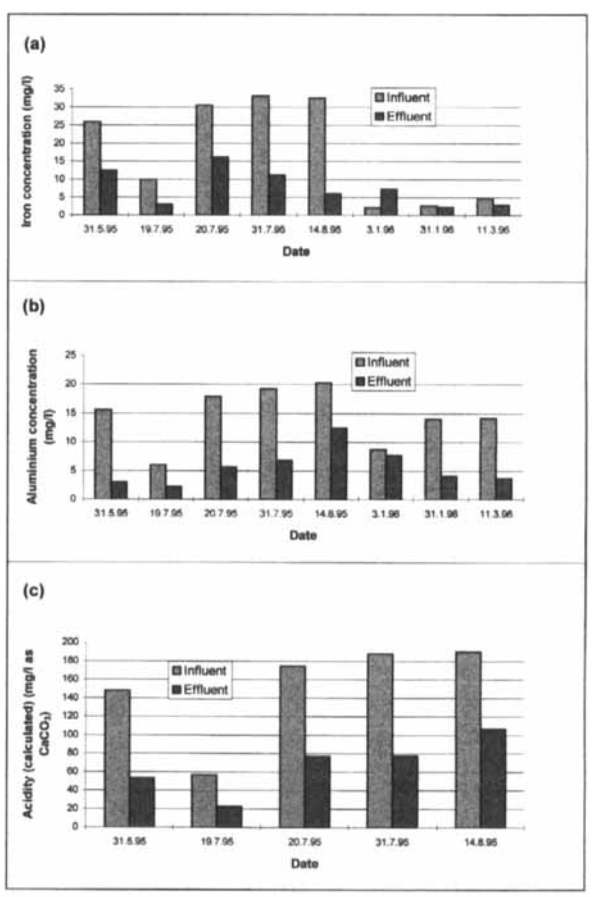

Fig. 6. Performance of pilot wetland as revealed by synchronous influent/effluent (cell 3) results

Table 3. Acidity removal rates for Morrison Busty pilot wetland

Date	Influent acidity (calculated) (mg/l as CaCO3)	Effluent acidity (calculated) (mg/l as CaCO3)	Acidity removal rate (g/m^2. d)
31.5.95	147.7	53.2	10.8
19.7.95	56.4	22.6	3.9
20.7.95	174.1	76.8	11.1
31.7.95	188.0	77.2	12.7
14.8.95	190.5	106.5	9.6

due to the postulated sulphate-reduction process (reaction (3)).

Acidity (Fig. 6(c)) encompasses 'mineral acidity' (due to the presence of 'acid' metals in solution) and 'proton acidity' (pH). Total acidity is therefore reduced by the processes of iron and aluminium removal (just described) and by consumption of protons during bacterial sulphate reduction (reaction (3)), resulting in an increase in pH and alkalinity. Table 3 summarizes acidity removal data for cells 1 to 3. On an areal basis, the average rate of acidity removal is 9.6 g/m^{2}. d, which compares well with the optimistic design value of 7.0 g/m^2. d reported from the USA; therefore this pilot wetland lends encouragement to the confident application of US design criteria in the UK situation. It should be noted further that the minimum acidity removal rate (which equated to 3.9 g/m^2. d) occurred when the influent acidity was also at a minimum, so that the effluent was still of acceptable quality.

When the pilot wetland was first commissioned, concern was expressed about the risk of the compost cells producing such a high biochemical oxygen demand (BOD) that the wetland as a whole would simply replace one pollution problem (the acid spoil drainage) with another (oxygen depletion in the receiving water). Advice from US colleagues suggested that this would be a short-lived problem. Nevertheless, the installation of the aerobic portions of the pilot wetland (i.e. cell 4, and to some extent cell 3) was intended, in part, to address this problem. Immediately after the first filling of the wetland, the effluent from cell 3 did display a high BOD (of around 800 mg/l). When the BOD was next determined, however (three months after wetland start-up) it was found to have declined to only 2 mg/l, indicating that the more mobile organic fractions were quickly flushed from the compost to leave more refractory substances behind to act as a long-term carbon source for the bacteria.

Another aspect of pilot wetland performance was the colonization of cell 3 by a diverse fauna. Invertebrates reproducing in the open waters of cell 3 include several species of water beetle and water-boatmen. Newts have also been observed in the waters of cell 3 during their breeding season, and since mid-1995 the effluent channel from cell 3 has become a regular drinking venue for wild deer.

Proposals for Full-Scale Treatment

The passive treatment strategy employed in the pilot wetland at Morrison Busty is the sequential contact of the polluting waters with:

(i) Anaerobic compost hosting sulphate reduction;
(ii) Dolomite, providing pH adjustment through carbonate dissolution; and
(iii) Aerobic surface flow over *in situ* soil.

The results vindicate the selection and ordering of these processes. Nevertheless, in a full-scale system, certain refinements of the wetland flow system are desirable to minimize the chance of any by-pass of these three key stages by the development of preferential flow pathways.

Taking a cue from recent developments in Clarion County, Pennsylvania[19], plans in preparation for full-scale passive treatment at Morrison Busty call for stacking of the compost above an under-draining bed of limestone, with head control to ensure that flow occurs vertically downwards, first through the compost and then through the limestone (Fig. 7). The vertically stacked configuration is termed 'successive alkalinity producing system' (SAPS) by its originators[19]. Polishing of the effluent from the limestone bed can then occur in a subsequent aerobic wetland. With a SAPS configuration, the compost will strip dissolved oxygen from the water and reduce ferric iron to the more soluble ferrous form, thus ensuring that the underlying anoxic limestone underdrain layer does not become armoured with ferric hydroxide precipitates, so that limestone dissolution can be sustained over many years, yielding large quantities of alkalinity and raising the pH[19]. A key constraint on use of a SAPS, however, is the availability of sufficient relief across the site to accommodate the necessary vertical head-loss. Should the topography prove limiting, treatment should still be possible using a horizontal-flow system similar to the pilot wetland, in which solutes are exchanged with the compost by diffusion.

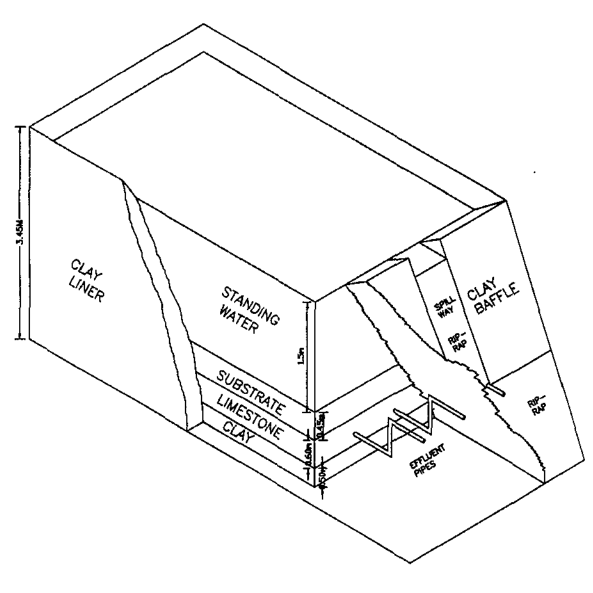

Fig. 7. Schematic cross-section illustrating SAPS configuration proposed for full-scale wetland

Conclusions

(1) At Quaking Houses (County Durham), strongly acidic ferruginous and aluminium-rich waters discharging from the spoil heap of the abandoned Morrison Busty colliery have been obliterating aquatic life in the Stanley Burn for almost a decade. An investigation involving the NRA, the local community and a nearby University, established the origins of the polluting discharge and assessed its impact on the receiving water.

(2) An evaluation was carried out of possible treatment methods for the discharge, drawing upon the literature and supported by laboratory microcosm tests. A compost wetland was the favoured option, and a pilot facility was constructed with the assistance of the local community.

(3) This pilot wetland comprises four cells in series, the first two occupied by saturated horse manure and soil, the third with open water and a limestone berm to provide pH adjustment, and the fourth an aerobic overland flow system established on *in situ* soil.

(4) During the first year of operation, the wetland has performed favourably, reducing acidity at an average rate of 9.6 $g/m^2.d$. The third cell of the wetland has now been extensively colonized by aquatic invertebrates (which are absent in the polluted stream).

(5) Plans for full-scale treatment are now well advanced. A capital cost of about £50 000 is envisaged, with long-term maintenance being undertaken by local volunteers at minimal cost.

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