CL:AIRE

CSB 2

(November2002)

case study bulletin

CL:AIRE case study bulletins provide a source of information on the characterisation and remediation of specific sites in the UK. This case study bulletin describes the design, construction and operation of a full-scale compost wetland to remediate a watercourse contaminated by colliery spoil leachates at Quaking Houses, County Durham.

Definitions of words written in bold type may be found in the Glossary of Terms within the Publications section of the CL:AIRE Web site at http://www.claire.co.uk

A Constructed Wetland to Treat Acid Mine Drainage from Colliery Spoils at Quaking Houses, County Durham

1. INTRODUCTION

This Case Study Bulletin describes the design, construction and operation of a full-scale compost wetland to remediate a watercourse contaminated by colliery spoil leachates at Quaking Houses, County Durham. Drainage from an acidic spoil heap containing elevated concentrations of iron, aluminium, manganese and zinc, was discharging into the Stanley Burn, a third order tributary of the River Wear. Based on the success of laboratory studies and a pilot-scale compost wetland, a full-scale wetland system was designed for the site and installed in 1997. The residents of Quaking Houses had significant influence over the acquisition of funding to treat the contamination, in the design of the chosen passive treatment solution and in its construction.

1.1 Background to the Problem of Acid Mine Drainage

Acid mine drainage is acidic water which is generated when rock containing sulphide minerals, most commonly pyrite, is exposed to water, oxygen weathering and microbes such as bacteria. Generally under natural rock conditions, contact between undisturbed sulphide-bearing rock and oxygen is minimal so that the rate of acid generation is slow. But activities associated with mining, such as blasting and crushing, break up the waste rock, increase its surface area and accelerate the weathering process.

The generalised chemical reactions describing pyrite oxidation are well known and are presented as Equations 1-4 below. These reactions are a simplification of the process which may include as many as 15 different reactions.

$$FeS_2(s) + 7/2\ O_2 + H_2O \longrightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \quad (1)$$

$$Fe^{2+} + 1/4\ O_2 + H^+ \longrightarrow Fe^{3+} + 1/2\ H_2O \quad (2)$$

$$Fe^{3+} + 3\ H_2O \longrightarrow Fe(OH)_3(s) + 3H^+ \quad (3)$$

$$FeS_2(s) + 14\ Fe^{3+} + 8\ H_2O \longrightarrow 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+ \quad (4)$$

Oxidation of metal sulphide to sulphate releases ferrous iron (Fe^{2+}) and acidity in the form of hydrogen ions (equation 1). This ferrous iron may itself be oxidised to ferric iron (Fe^{3+}) (equation 2). Hydrolysis of ferric iron forms ferric hydroxide and further acidity (equation 3). Additional ferrous iron may be produced via the oxidation of pyrite by ferric iron (equation 4), thus perpetuating the cycle as Fe^{2+} is fed back into equation 2.

The effects of mine water drainage on the ecology of receiving watercourses can be extremely harmful. As acidity increases, the biodiversity of algal populations in receiving watercourses decreases. Deposition of precipitates of iron hydroxide or oxyhydroxide (**ochre**) in receiving watercourses results in depletion of benthic flora and degradation of invertebrate and fish habitat. Low pH, and elevated concentrations of metals such as aluminium, may be directly toxic to fish and impact drinking water supplies.

1.2 Possible Solutions

The objective of mine water treatment is the removal of metal contaminants, especially iron, manganese and aluminium, together with sulphate and the generation of alkalinity to raise pH. Current treatment systems for mine waters can be classified as either active or passive.

Figure 1: Photo of Quaking Houses Community wetland. Source: CL:AIRE

Active treatment involves conventional engineered wastewater treatment technology, most commonly utilising oxidation, alkali dosing, and settlement lagoons. *Passive treatment* incorporates natural systems and often includes anaerobic wetlands with aerobic zones, and zones of carbonate dissolution (such as in limestone drains).

1.3 Passive Treatment Systems

Passive treatment became increasingly popular during the 1980s and 1990s, motivated by economics (a low cost, single capital investment to solve a long-term problem, with little or no operating expenditure) and ecological compatibility (adopting a 'natural' versus 'hard-engineering' approach to wastewater treatment - becoming an integral part of the wider local ecosystem). Passive treatment implies no regular inputs of artificial energy or reactive substances such as chemicals. They have the potential to deliver treatment systems to remote areas requiring low maintenance, minimal site security, no power requirements or deliveries of chemicals, and no permanent on-site staff.

Constructed wetlands are a form of passive treatment that have been used for wastewater treatment for nearly 50 years though only applied to mine water since the late 1980s. The primary aim of constructed wetlands for mine water treatment is essentially to reverse Equations 1-4 and to remove metals and sulphate from solution by forming metal sulphides and raising pH by removing acidity. Other developments in passive mine water treatment include: **Anoxic Limestone Drains** (**ALD**); **Reducing and Alkalinity Producing System** (**RAPS**); **Permeable Reactive Barriers** (**PRB**) and are emerging as potential alternatives under appropriate conditions. The prevention of mine water pollution at source by coating spoil heaps thereby isolating pyrite from weathering processes, is another potential alternative to active treatment.

2. THE PROBLEM AT QUAKING HOUSES

The village of Quaking Houses, County Durham was supported by operations at the nearby Morrison Busty Colliery which closed in 1974. In 1980, road construction through the 35 hectare colliery spoil heap, allowed infiltration of water and air into

CL:AIRE (Contaminated Land: Applications In Real Environments) wishes to thank the following organisations for their support:
Department of the Environment (Northern Ireland) Department of the Environment, Food and Rural Affairs English Partnerships Environment Agency Scottish Enterprise
Scottish Environment Protection Agency Scottish Power Shanks Soil and Groundwater Technology Association UK Coal Unilever Viridor Waste Management Welsh Development Agency

the spoil, and caused the oxidation of sulphide minerals. The iron-rich and acidic waters generated by this process, discharged directly into nearby Stanley Burn discolouring the streambed, and destroying aquatic organisms and habitat.

2.1 Aims and Approach

Following persistent lobbying by the residents of the village of Quaking Houses, the National Rivers Authority, the predecessor of the Environment Agency in England and Wales, instigated a study in 1995 to look at the feasibility of treating the source of contamination to the Stanley Burn. The work was carried out in the laboratory and at pilot scale by the residents of Quaking Houses in association with University of Newcastle upon Tyne.

A key objective of the feasibility study was to design a low cost treatment system in terms of both initial capital costs and long-term operation and maintenance with a life expectancy of 15-20 years. For this reason the investigative team adopted passive treatment technology as the preferred option, following on from recent successes in the USA. The aim was to improve understanding of the operation of passive systems in order to produce more accurate design guidelines, and to develop a new treatment design to complement existing technologies.

2.2 Pilot-Scale System - Gavinswelly

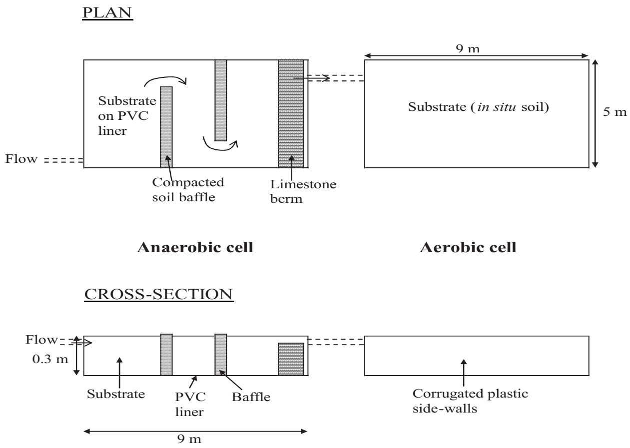
Laboratory **microcosm** studies were conducted using a variety of manure and soil substrates. The results showed that horse manure in particular was capable of promoting bacterial sulphate reduction, a key process in compost wetlands.

In order to determine whether a full-scale system would work, a small pilot-scale system was constructed. The Gavinswelly pilot-scale wetland was the first application in Europe of a passive, compost-based, sulphate-reduction technology to acidic mine water discharge (Figure 2).

Figure 2: Photo of Gavinswelly pilot-scale constructed wetland. Source: Paul Younger

The pilot wetland covering an area of 45 m^2 comprised **anaerobic** and **aerobic** components and consisted of four cells in series (Figure 3). The anaerobic component included the first two cells which contained saturated horse manure and soil and the third cell which contained open water and a bed of limestone. The fourth cell, the aerobic component, comprised an overland flow system. The system was monitored for a period of 12 months. In the first two cells, sulphate-reducing bacteria living in the compost reacted with the flowing mine water to form insoluble iron sulphide which precipitated and settled out on the bottom of the cell. As the acidity of the water decreased, aluminium present in the water formed aluminium hydroxide which precipitated and settled out of solution. This process caused an increase in acidity which was neutralised to ambient levels by directing water over a limestone bed in the third cell.

Iron and aluminium levels were reduced by approximately 80 % in the treated water. Acidity was removed in the pilot-scale wetland at a rate of 9 g/m^2/d, which compared well with the rate of 7 g/m^2/d which is often the target value adopted during design. In addition, an increase in fauna, specifically insects and newts was observed. One potential concern with the design was that the compost-rich wetland would generate a high biochemical oxygen demand (BOD) which would deplete dissolved oxygen in the effluent, thereby decreasing the ability of the discharge water from the wetland to support aquatic life. In fact the opposite was observed. When the pilot wetland was first commissioned, the effluent had a BOD of approximately 800 mg/L, but within two weeks it had declined to only 2 mg/L.



Source: Richard Pennell

Figure 3: Layout of Gavinswelly pilot-scale constructed wetland in plan and cross-section.

3. FULL-SCALE SYSTEM

Based on the success of the Gavinswelly pilot trial, a full-scale constructed wetland was designed.

3.1 Design Considerations

The design was guided wherever possible by the desires of the local community, who were central to the entire project. Consequently, whilst effective mine water treatment was always the primary objective of all parties concerned, aesthetic considerations sometimes took priority over the need for the wetland to be a dedicated scientific research resource. It is for this reason that the wetland is not rectangular, even though such a shape would have made the calculation of such variables as areal removal rates far simpler.

The objectives of the research which was carried out during and after construction included:

- evaluation of the design and engineering aspects of the wetland with a view to assisting the design and construction of future projects.
- monitoring of the wetland water quality to produce a detailed and relatively long-term set of data characterising the performance of the system.
- investigation of the most important pollutant removal mechanisms in the system.
- assessment of the performance of the wetland using a number of measures in order to ascertain which is the most appropriate measure for comparison with other wetland systems.
- development of an algorithm for predicting effluent water quality in the Quaking Houses wetland.

Design of a full-scale system at Quaking Houses began in 1996, when a suitably located area of land of approximately 500 m^2 was made available by British Coal Property. Clearance of a dense stand of willow and birch on the site enabled a thorough site survey to be undertaken. The survey revealed two critical design constraints:

i) The **hydraulic head** across the site was only 1.0 m. This low head drive eliminated a vertical flow option such as RAPS, which requires a minimum of 3 m. This confirmed that a horizontal flow compost wetland, very similar to the pilot-scale wetland, was the best option for the site.

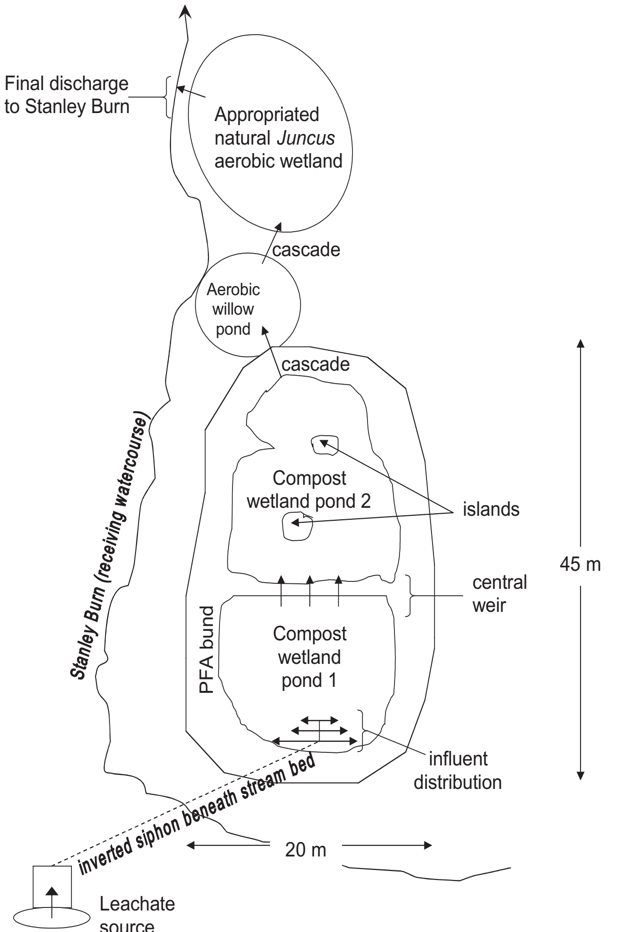
ii) Portions of on site soil proved to be contaminated with iron and aluminium resulting from an unrecorded coal washery associated with the Morrison Busty colliery. Excavation of the soil would lead to leaching of these metals. Therefore all construction works had to be located at or above ground level.

The critical design parameter and the benchmark for gauging wetland efficiency for treating acidic mine water is the effective removal of acidity in terms of areal removal rate per unit time (expressed in g/m^2/d). The effective removal of acidity of 7.0 g/m^2/d was adopted for the Quaking Houses system.

Several other key issues emerged which also shaped the design of the wetland and the manner in which it was constructed.

- To satisfy the local residents and maximise ecological integration, the wetland would be designed to be as in keeping as possible with the local countryside. This meant that angular structures and 'concrete boxes' should be avoided, and slopes should be 3:1 (length:height) or less in order to encourage pond margin wildlife.
- The wetland was to have a nominal design life of 15 - 20 years, and therefore the design had to be robust. In particular the retaining embankments had to be designed to a suitable width, and there had to be sufficient **freeboard** to allow for substantial accumulation of solids and detritus on the substrate surface.
- Exposed sections of pipe-work were to be concealed within the natural design to avoid vandalism.

A plan of the wetland is provided below (Figure 4).



Source: University of Newcastle upon Tyne

Figure 4: Plan of the Quaking Houses Community wetland.

3.2 Construction

Construction of the wetland began in late August 1997 and took 8 weeks to complete although during 2 of the weeks construction was halted due to inclement weather conditions. Figure 5 shows the wetland under construction.

To generate additional hydraulic head a concrete wall was constructed across the culvert discharging mine drainage to the wetland. Two sections of 100 mm diameter pipe were built into this wall. The first carries water underground to the influent point of the wetland, discharging into a basin from where the water is distributed across the wetland. The second section of pipe allows overflow back into the original watercourse when flow-rates exceed approximately 400 L/minute. Because contaminant concentrations are lower at higher flow-rates due to dilution, and because of further dilution of the overflow water by the effluent from the wetland, the overflow meets design criteria for the receiving watercourse.

Retaining embankments were designed to have a minimum crest width of 1.5 m, and slope angles were designed with a minimum length:height ratio of 2:1. In order to minimise expenditure on materials, **pulverised fuel ash** (PFA) was selected as the


Figure 5: Photo taken during the construction of Quaking Houses Community Wetland.
Source: Paul Nugent

material for embankment construction. Compacted PFA has a very low permeability, and is less than half the cost of clay. To avoid toe drainage, which may have affected the integrity of the structures, the base of the embankment was sunk approximately 0.2 m below existing ground elevation.

The site slopes slightly downwards away from the proposed influent point to the wetland. A central weir was incorporated in the design in order that the wetland could be constructed on two levels, the second cell being 0.4 m lower than the first cell. This led to savings in both material costs and land area used for the embankment. Baffles and islands, constructed from PFA were incorporated to minimise the potential for hydraulic short-circuiting through the wetland but they also served to improve the appearance of the wetland and diversify habitats within it.

There was insufficient local supply of manure, therefore horse manure was combined with cattle manure and municipal waste compost at an approximate ratio of 30:40:30. The system was designed such that the compost depth in the wetland would be 0.30 - 0.50 m. An additional 0.30 m of freeboard was allowed for accumulation of material on the substrate surface. The total area of substrate surface was 440 m^2. Broken limestone was deposited at the far end of the wetland, to facilitate final pH adjustment should it be required.

The water outlet structure was originally a section of 150 mm diameter plastic pipe buried into the retaining embankment. A movable 90 ° bend on the wetland-side of this pipe allowed the water level in the wetland to be adjusted. In June 1999 the effluent pipe was replaced with an open channel to avoid blockage problems.

Subsequent modification included the addition of a small willow pond and an area of surface flow through rushes to polish remaining iron concentrations.

3.3 Performance

Effective monitoring of a constructed wetland is crucial. Firstly it will establish whether the wetland effluent is meeting any performance requirements. Secondly it should enable an assessment of the efficiency of the wetland to be made, the results of which can be fed back into future designs, hence improving the efficiency and reliability of future systems. Three methods are currently in use for assessing constructed wetland performance:

i) treatment efficiency (%)
ii) area-adjusted removal rates (g/m2/d)
iii) first-order removal constants (m/d)

Ideally, a performance indicator must be independent of differences in influent contaminant concentration. By assessing the Quaking Houses wetland using all three measures it has been shown that both treatment efficiency and area-adjusted removal rate are strongly influenced by influent contaminant concentrations.

Visual inspection of the Stanley Burn alone demonstrates the significant improvement in water quality since the construction of the wetland, as old ochre deposits are being scoured from the streambed, and are not being replaced. This is complemented by the chemical results shown in Table 1.

The full-scale constructed wetland is currently maintaining a mean removal rate of acidity of 10.4 $g/m^2/d$, considerably above the design criterion of 7 $g/m^2/d$.

Table 1: Mean concentrations and values of the wetland influent and effluent water at Quaking Houses Community wetland.

Determinand	Influent	Effluent from compost wetland	Final effluent from system
pH	6.06	6.60	6.7
Acidity (calculated) (mg/L as $CaCO_3$)	51.8	24.6	15
Alkalinity (mg/L as $CaCO_3$)	49.2	66.3	70
Fe (total) (mg/L)	5.35	2.37	0.5
Al (mg/L)	5.32	2.11	0.1
Mn (mg/L)	3.78	2.67	2.2
Zn (mg/L)	1.40	1.12	1.0
SO_4 (mg/L)	801	768	760

Iron hydroxide precipitates are developing on the surface of the wetland substrate, and below the surface black deposits of iron monosulphide are increasingly evident. This is consistent with the liberation of hydrogen sulphide gas from the substrate (gas bubbles rise from pock marks in the substrate surface continually, with the identity of the gas being confirmed by occasional faint odours).

Aluminium, which will not form a sulphide, appears to be deposited predominantly as aluminium hydroxide and hydroxy-sulphate. The formation of aluminium hydroxide may be limited during higher flow-rates due to shorter residence time within the wetland, and disturbance of material on the substrate surface. Statistical analysis suggests that effluent aluminium concentrations (and acidity concentrations) are strongly controlled by ambient air temperature. Specifically, the higher the ambient air temperature the lower the effluent aluminium concentration. This is the first time such a relationship has been demonstrated for a constructed wetland system. It suggests that wetland systems operating under cold climate conditions may be less effective for aluminium removal.

Due to their higher mobility at neutral pH, the removal of manganese and zinc in the Quaking Houses wetland is less effective than for iron and aluminium.

3.4 Costs

The quantities of materials used, and the overall costs of the Quaking Houses constructed wetland are summarised in Table 2. The total capital cost of the wetland was just under £18, 000. Funding was provided primarily by Northumbrian Water Kick-Start Fund. By far the greatest costs were associated with payment of designers and engineers, and plant hire and operation.

Table 2: Construction materials quantities and costs for the Quaking Houses Community wetland.

Materials	Quantity/Duration	Cost (£)
Pulverised fuel ash (PFA)	614 t	2511
Cattle manure [a]	60 t	295
Municipal waste compost	49 t	235
Horse manure [a]	50 t	245
Limestone	31 t	258
Pea gravel	11 t	110
Broken stone	10 t	129
Pipe-work/building materials	-	955
Top soil	64 t	370
Design/engineering consultation	6 months (50% time)	4000
Plant hire and o peration	7 weeks	8880
Total		17 988

a: These costs were solely for transport

The cost of the Quaking Houses wetland on an area basis was £41/m^2 which compares favourably with a national average for other passive treatment systems of £51/m^2. Furthermore it is expected that future wetlands of this type can be constructed at a lower cost, since this was the first of its kind in the UK. Since its completion in November 1997 the maintenance costs associated with the wetland have been no greater than £250 - £500 / annum.

3.5 Legal Issues

The Quaking Houses wetland is managed by the Quaking Houses Environmental Trust and operated the University of Newcastle upon Tyne. As operators, the University is obliged by agreement to monitor the quality of the discharge, and furthermore must ensure that the discharge quality does not breach the following standards:

i) The discharge shall have a pH value of not less than 6 nor greater than 9.
ii) The discharge shall not contain more than 15 mg/L of dissolved iron.
iii) The discharge shall not contain more than 5 mg/L of total aluminium.

The wetland has consistently out-performed these requirements.

4. LESSONS LEARNED

i) Although the constructed wetland at Quaking Houses has proved a success in many respects, there are some aspects where engineering improvements may be made. In particular it is possible that hydraulic short-circuiting is limiting residence time to the detriment of the effectiveness of treatment. The baffles constructed to encourage circuitous flow paths are presently slightly submerged and should be installed to a higher level to break the water surface.

ii) The available hydraulic head and the nature of the on site soil crucially determined the final design of the wetland. A considerable period of time (and capital) was spent at the inception of the project on a variety of preliminary designs, many of which subsequently proved to be unfeasible (e.g. the RAPS).

iii) All of the materials used in the construction of the wetland were sourced locally, providing substantial savings on transportation costs. Cost savings were also made by using materials such as pulverised fuel ash in preference to more obvious (though no more effective) alternatives such as clay. Investigation of the variety of construction materials available for future projects is therefore to be encouraged.

iv) Almost 50 % of the total expenditure of this project was on plant hire and operation. Typically costs are incurred even when machinery is not operating due to inclement weather conditions.

v) By definition wetlands are suited to low-lying areas which are susceptible to flooding. It is therefore strongly advisable to undertake construction of wetlands during the driest months of the year, even if this entails delays of up to 6 months.

vi) From an ecological viewpoint extensive stands of *Typha latifolia* and other wetland plants have successfully colonised the wetland, although in some areas, especially in the lower pond, the water depth appears to be too great to allow successful early growth of plants. Ecological assessments of the receiving watercourse have not been undertaken since the wetland was commissioned. However, runoff from road salt, which is used as a winter de-icing agent will continue to cause degradation of aquatic habitat in Stanley Burn.

vii) From a social point of view the wetland continues to be a great success. The significant improvement in the visual appearance of the Stanley Burn was always a key objective of the residents of Quaking Houses village, and this has been achieved. Many of the residents of the village (of all ages) have been involved with the wetland since the inception of the project, and continue to play a vital role (voluntarily) in the routine maintenance of the system.

5. SUMMARY

- The wetland was constructed at low cost.
- The materials used during construction were local, low cost, and predominantly waste materials.
- There is no evidence at present that the retaining embankments are either eroding significantly or allowing toe drainage.
- The wetland successfully treats the contamination from the colliery spoil heap.

Acknowledgements

This Case Study Bulletin was prepared by CL:AIRE staff from the following sources:

- Jarvis, A.P., 2000. Design, Construction and Performance of Passive Systems for the Treatment of Mine and Spoil Heap Drainage. PhD Thesis, University of Newcastle upon Tyne.
- Kemp, P and Griffiths, J., 1999. Quaking Houses. Art, science and the community: a collaborative approach to water pollution. Jon Carpenter Publishing, Charlbury

This bulletin benefited from review and comments by Professor Paul Younger.

For more information contact: Professor Paul Younger, School of Civil Engineering and Geosciences, University of Newcastle upon Tyne. Email: p.l.younger@ncl.ac.uk