Construction of a novel Permeable Reactive Barrier (PRB) at Shilbottle, Northumberland, UK: engineering design considerations and preliminary performance assessment

Bowden Lawrence I.*, Jarvis Adam, Orme Patrick, Moustafa M, Younger Paul L.

Hydrogeochemical Engineering Research and Outreach group, Institute for Research on the Environment and Sustainability, University of Newcastle, Newcastle upon Tyne, UK. NE1 7RU.
E-mail: L.I.Bowden@ncl.ac.uk; Tel: +44 (0)191 246 4896
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ABSTRACT
A 170 m long PRB was installed, in two sections, for the treatment of acidic (*ca.* pH 4), metal-rich (*ca.* 700 mg/L Fe, 300 mg/L Al and 240 mg/L Mn) spoil heap leachate at Shilbottle, Northumberland, in summer 2002. The PRB is a compost-based system comprising 50% aggregate, 25% horse manure and 25% green waste compost. The barrier is 3 m deep and 2 m wide, with a nominal hydraulic retention time of 48 hours.
Since commissioning the system has consistently improved water quality, with approximate removal efficiencies of 96% for Fe, 78% for Zn, 71% for Ni, 52% for Mn, and 59% for SO_4. The extent of removal of 'problematic' metals such as Mn and Zn is particularly encouraging. The exact nature of the contaminant removal mechanisms is discussed.
After 2½ years of operation the treatment system, although still operating effectively, is in need of some maintenance. These maintenance requirements are outlined, and their implications for future PRB system design are discussed.

INTRODUCTION
Acidic mine drainage (AMD) is a much documented problem afflicting mining regions (Nordstrom & Alpers, 1999; Younger *et al.*, 2002). Sources of AMD include abandoned mine workings (Younger, 2001), tailings ponds (Younger, 1998) and waste spoil tips (Licsko *et al.*, 1999). As the target mineral is mined gangue materials are brought to the surface or exposed within the mine.
Iron pyrite is the main mineral phase in colliery spoil accountable for the creation of metalliferous and acidic leachates in mining environments. Equation 1 shows the overall process of pyrite dissolution, where reaction with oxygen and water results in the release of ferrous iron and proton acidity (Appelo & Postma, 1993).

$$2FeS_2 + 7O_2 + 2H_2O \rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \quad (1)$$

The subsequent oxidation of ferrous iron from Equation 1 results in the formation of ferric iron (Fe^{3+}), which may be responsible for the generation of eight times as much proton acidity (H^+) (Equation 2) as Equation 1 under the right conditions. Ferric iron directly oxidise iron pyrite (FeS_2) in the presence of water (Equation 2), the amount of ferric iron available is the rate limiting step to the reaction.

$$2CH_3CHOHCOO^- + 3SO_4^{2-} + 2H^+ \rightarrow 6HCO_3^- + 3H_2S \quad 2)$$

This reaction (Equation 2) is most effective at low pH where the solubility of ferric iron is greatest. Since this reaction generates huge proton acidity (H^+) the reaction is self perpetuating, as pH is further depressed.
The processes outlined in Equations 1 & 2 are particularly important in colliery spoil heaps where there are limited flows and supplies of water. Water reacts with large quantities of pyritic gangue and secondary acid generating salts (e.g. melanterite ($FeSO_4 \cdot H_2O$) and jarosite ($KFe_3(OH)_6(SO_4)_2$) (Bayless & Olyphant, 1993; Younger, 2000)). Due to the minimal flows of water typically coming from rainwater infiltration alone, the concentration of metals and acidity in these waters is greater than in systems with a higher water budget. As a result, colliery spoil heap leachate is often heavily loaded with metals and has very low pH.
The contribution of leachate from colliery spoil tips to the total pollutant load at the catchment scale can be significant. In the UK by the early 1990s there was a history of over 2000 coal mines each having one or more spoil heaps, not including the countless metal mines of which there is also a substantial legacy.
The impact of AMD on the receiving water course is not only aesthetic but often ecologically devastating, as the choking of stream beds with voluminous precipitates (Bowell, 1995) leads to the decline of benthic fauna reducing the biodiversity of the entire aquatic ecosystem where low pH waters enter the system (Byrne & Gray, 1995; Jarvis & Younger, 1997). Notably, Scullion and Edwards (1980) observed that ferric hydroxide choking of stream beds in South Wales decreased macro invertebrate biomass by 80-90% from upstream values. The deleterious effects of AMD on the quality of the receiving water course steps to remediate them may be necessary.

Acidic spoil heap leachates are sometimes treated using compost wetlands. One such system was successfully installed at Quaking Houses in County Durham UK (Jarvis & Younger, 1999), where acidic ferruginous drainage was responsible for the serious pollution of the nearby Stanley Burn (Younger *et al.*, 1997).

At many sites there is either not enough land area to accommodate the construction of a full-scale compost wetland or the cost of acquiring land may be prohibitively expensive. In these circumstances the construction of a **p**ermeable **r**eactive **b**arrier (**PRB**) is a shrewd alternative as the reactive media is cut into the aquifer intercepting the contaminant plume, remediating it *in-situ* (Gavaskar, 1999) reducing the footprint of the treatment system. PRB technology has been successfully employed for the remediation of a variety of different contaminants for example chromate (Puls *et al.*, 1999), arsenic (Lien & Wilkin, 2005) and mine drainage (Benner *et al.*, 1999; Blowes *et al.*, 2000) using a range of reactive media types.
The mechanism for treatment of AMD by PRBs is the reduction of sulphate to sulphide and the precipitation of metals as metal sulphides requires anaerobic conditions and energy for the sulphate reducing bacteria. Equation 3 shows the energy source (lactate) used for the reduction of sulphate by sulphate reducing bacteria generating alkalinity and hydrogen sulphide.

$$M^{2+} + H_2S \rightarrow MS + 2H^{+} \quad (3)$$

The hydrogen sulphide reacts with metals in solution to form insoluble precipitates as metal sulphides (Equation 4).

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

Reactive media selection for the PRB at Shilbottle in Northumberland, discussed in this paper, is outlined in Amos & Younger (2003). The media which proved most appropriate was a combination of 50% limestone chips, 25% green waste compost and 25% slurry screenings.
This paper describes the installation of the PRB at Shilbottle in the summer of 2002. The paper focuses on the engineering considerations and provides a preliminary assessment of the effectiveness of the PRB to date and modifications which may be necessary in the future. The system installed at Shilbottle is a superb example of a novel PRB in the UK.

SITE DESCRIPTION

Location
The colliery spoil heap lies in the River Coquet catchment which is in Northumberland, North-East England. The site is situated 4 km south-east of Alnwick and 2 km to the east of the village of Shilbottle (Figure 1). The southern toe (SSE ≈ 152°) of the spoil heap has the grid reference NU 220078. The spoil heap is a relict of the former Shilbottle colliery, and is a major source of pollution to the Tyelaw Burn (Figure 2).

Figure 1
The Tyelaw Burn is a tributary of the River Coquet which is a Site of Special Scientific Interest renowned for its salmon fishing. The River Coquet is also a drinking water resource and therefore its quality is constantly monitored to ensure compliance.

Site History

The spoil heap is the last remaining evidence of the Shilbottle colliery which was sunk in 1921. In its heyday the colliery employed 756 workers (1955) and produced 272,000 tons of coal, for domestic use as it contained large amounts of sulphur, which made it unsuitable for industry.

The colliery was closed in 1982 and adopted by Northumberland County Council undertaking the reclamation of the spoil heaps and the colliery yard. The reclamation of the colliery yard and the smaller eastern heap were completed by 1996. The larger western heap (15 ha) was more highly contaminated, discharging acidic and highly metalliferous (Fe, Al and Mn) leachate into the Tyelaw Burn.

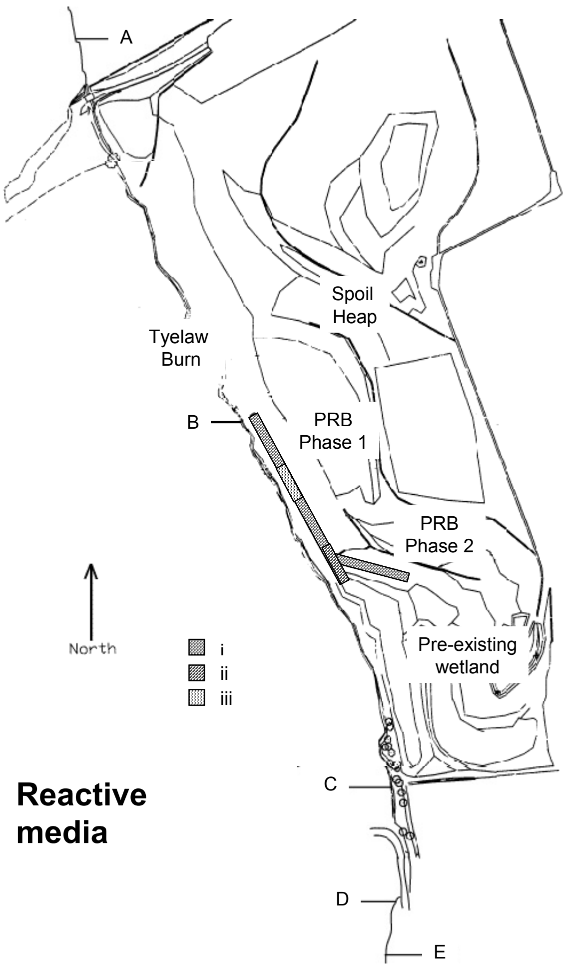

Figure 2 Plan View of spoil heap and Tyelaw Burn.

The removal of iron is important at this site due to the discolouration of the Tyelaw Burn by iron; however the removal of manganese is a particular driver in the catchment as the water is used as a drinking water source and the is element is close to consent values.

A remediation strategy was adopted by Northumberland County Council. The spoil was re-graded and landscaped with drainage channels diverting the surface waters to a series of three aerobic reed beds – however this aerobic system only served to depress the pH of the already acidic water, thus proving unsuitable. In addition much of the flow of water on the site is subsurface, 60% of the acidic water by-passing the network of gulleys directly entered the Tyelaw Burn.

Geology and Hydrogeology

The solid geology of East Northumberland consists mainly of igneous and sedimentary rocks, with superficial glacial deposits being laid upon them. The Coquet catchment lies centrally in this region. Here the geology is composed primarily of Lower Carboniferous limestone, sandstone, shales and thin coal deposits. These strata have an easterly dip and extend offshore under the North Sea. Much of the area is now covered by glacial drift deposits consisting of boulder and laminated clays.

The colliery spoil heap at Shilbottle is founded on these clays. The impermeable clays underlying the site are responsible for the perched aquifer and hydraulic gradient within the spoil heap. The ground water within the spoil tip flows along the impermeable clay and into the Tyelaw Burn.

PERMEABLE REACTIVE BARRIER

At Shilbottle there are a series of wetlands which predate the construction of the PRB by some years. The problem with this existing system was that it only received 40% of the water at the site and that there was no mechanism for alkalinity generation. These two issues had to be addressed to ensure that the water was of good quality i.e. increased pH and considerably reduced iron, was discharged into the receiving water course, Tyelaw Burn.

Design and Construction

There are two different types of PRB which may be installed in the field: continuous wall (Gavaskar, 1999) and funnel-and-gate (Gavaskar, 1999; Starr & Cherry, 1994). At Shilbottle the continuous wall style system was chosen for the interception and remediation of contaminated ground water.
PRB Trench
Once the direction of groundwater flow had been ascertained the precise position of the PRB could be decided. The barrier trench was cut through the toe of the spoil (dark shale and coal) and keyed to a depth of 500 mm into the glacial till underlying the site (Figure 3). The glacial till provides an impermeable base to retain the water in the PRB, creating a small reservoir.

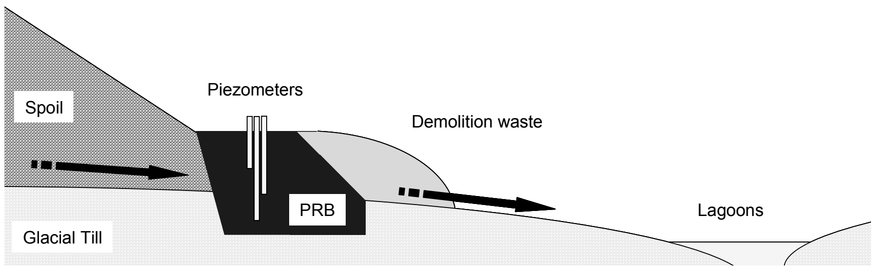

Figure 3

Figure 2 shows that the PRB was constructed in two sections along the south western side (Phase 1; 140m long) and southern toe (Phase 2; 30m long) of the spoil heap. The phase 1 of the barrier has a fall (1cm/m) draining towards the existing wetland system to the south of the site. The fall is designed to encourage the influent ground water to flow along the length of the PRB rather than flowing straight across, increasing the retention time and treatment efficiency.
Low level berms (250 mm) of glacial till were formed in the base of the trench-cut at 20 m intervals promoting the retention of water in lower level of the PRB, this action was deemed necessary as discrete inputs to the PRB were observed along the length of the trench. The construction of low level barriers within the trench decrease the effect of piping in the reactive substrate which would lessen the retention time in the PRB. Toward the middle section of the PRB the discrete inputs were observed at the highest rate (*ca.* 15m^3/day) a 10 m stretch of high density plastic was run along the downward face of the trench supported by 500 mm of glacial till sourced from the site preventing the water from short-circuiting straight through the PRB.

Reactive Fill Media

The choice of reactive media for the PRB is outlined by Amos & Younger (2003) based on site specific requirements such as hydraulic conductivity. The construction materials used were changed from those specified in Amos & Younger (2003) when up scaling the PRB for field installation. Three different trial media were used to assess their relevant capabilities for metal attenuation.
In each of the three trials 25% horse manure obtained from a local farm, 25% green waste compost (containing barks and branches to act as a long term recalcitrant carbon source to prolong the life of the PRB) and 50% aggregate was used. The type of aggregate used and its placement in the PRB was varied (Figure 2):

i – 10 mm calcite limestone (increased surface area and therefore alkalinity generation compared to 20 mm limestone);
ii – 20 mm calcite limestone;
iii – 20 mm blast furnace slag (cheaper alternative to limestone and has a high acid neutralising capacity).

The reactive media was emplaced in the trench cut from the 'open' – downward side of the PRB (Figure 4). The media overlaps the trench cut dug into the clay and has a basal width of *ca.* 3m and a height of *ca.* 2.5m (less in phase 2 *ca.* 1.5 m). Figures 3 & 4 show that the media has a gradient at the front edge of the PRB giving a maximum width at the top of approximately 2m; this narrowing of the PRB to the top is inconsequential as the water retained in the PRB never reaches this level before passing through.

Figure 4 Construction of the PRB at Shilbottle, Northumberland.

The downward side of the PRB was built up to level using locally sourced demolition waste; this material has very high hydraulic conductivity encouraging the water to flow easily from the barrier (Figure 3). The entire construction was then covered in topsoil (500mm).
The treated water flows into the lagoons which serve both to aerate and ‘polish’ the water before entering the receiving watercourse. The water exiting the lagoon flows into the pre-existing wetland for final treatment before exiting the site into the Tyelaw Burn.
Two sets of multi-level piezo-meters were installed one of which can be seen in the foreground of Figure 4. Each set comprises a cluster of three piezo-tips at various depths within the reactive substrate (30 cm, 100 cm and 190 cm) packed in 30 cm of inert gravel media. In addition two more observation boreholes were drilled into the PRB to depth. Monitoring of the spoil ground water is via a series of boreholes and the effluent from the barrier is sampled from the lagoon. The quality of the water leaving the site from the final wetland before discharge into the Tyelaw Burn is also monitored.

PRELIMINARY PERFORMANCE ASSESSMENT

The influent ground water quality supply to the PRB is consistently acidic (pH 4.11) and contains high concentrations of metals, Fe 448 mg/L, Mn 126 mg/L, Zn 2.42 mg/L, Ni 2.37 mg/L, Al 276 mg/L and SO_4 8060 mg/L.

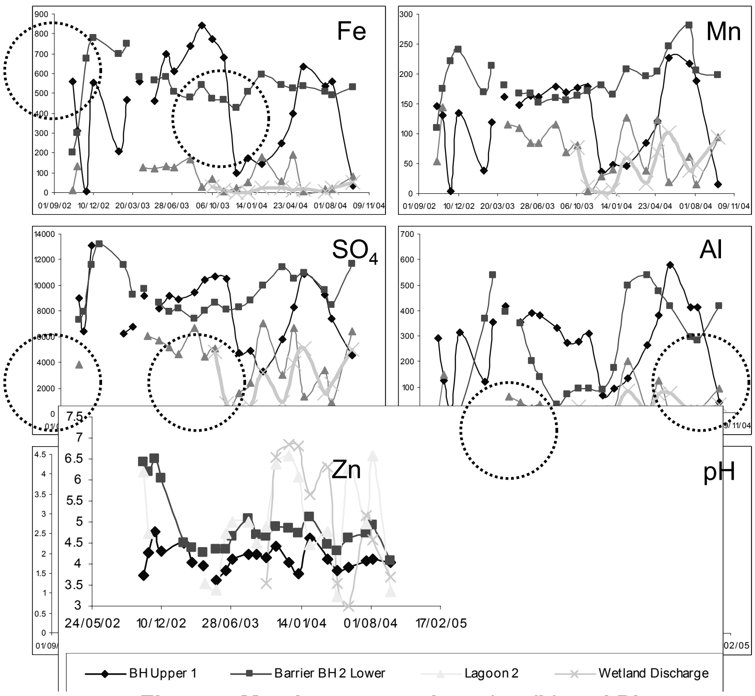

Figure 5 Metal concentrations (mg/L) and Ph

Figure 5 shows spatial and temporal metal concentrations and pH change at Shilbottle for the 2 years immediately after the PRB construction. The results show that there is a decrease in metal concentrations and a corresponding increase in pH as the water flows across the site. The change in concentration is particularly noticeable when a comparison is made with Lagoon 2. This location is directly after the PRB and indicates the successful removal of metals and increase in pH as a function of the PRB.

Table 1 shows percentage removal of metals as the water flows through the site. The greatest level of removal from the upstream borehole is observed in the lagoon directly after discharge from the PRB, with a smaller additional percentage of removal being achieved in the 'polishing' lagoons and pre-existing wetland when the leachate leaves the site at the Wetland Discharge.

	Percentage Removal	
	Lagoon 2	**Wetland Discharge**
Fe	82	96
Mn	41	52
SO4	48	59
Al	85	88
Ni	60	71
Zn	71	78

Table 1 Percentage removal rates at Lagoon 2 and Wetland Discharge compared to influent metal concentrations from BH Upper 1

The extent of removal of all metals is highly encouraging and the removal of 'problematic' metals such as Mn and Zn is particularly significant. Mn and Zn are notoriously difficult to remove from AMD in the presence of high Fe, thus these results are important when the very high concentrations of Fe present at this site are fully taken into account.

It is evident from Figure 5 that there are seasonal trends in concentration occurring in the influent ground water (circled areas) the metals being more concentrated in the summer months when there is likely less rainfall. It is noteworthy however that the average metal removal rates and ph increase is not significantly impacted by this seasonal trend.

Though most of the water on the site is now being captured by the PRB there is still some water which is by-passing the northerly extent of the PRB and deleteriously affecting the water quality. It is therefore necessary that some works be carried out extend the PRB to capture all of the contaminated ground water at the site. This work will be carried out in the coming months using the same design parameters to those outlined in this paper.

CONCLUSIONS

In conclusion the PRB construction for the treatment of acidic and metalliferous colliery spoil leachate at Shilbottle, Northumberland , UK has proven very successful with the majority of the water on the site now being treated. Since commissioning the system has consistently improved water quality, with approximate removal efficiencies of 96% for Fe, 78% for Zn, 71% for Ni, 52% for Mn, and 59% for SO_4. The extent of removal for Mn is significant as this is a driver in the River Coquet catchment where the water is used as a drinking resource and the concentration of Mn is close to the guidelines concentrations. This point is particularly important when other discharges in the area are responsible for the discharge of manganiferrous waters.

Since its inception the aesthetic quality of the receiving water course, the Tyelaw Burn, has improved dramatically with a significant improvement to the volume of ochreous deposits on its bed.

Though some water is by-passing the PRB to the North at the present time this situation will be rectified in the coming months with the extension of barrier further improving the quality of the water being discharged from the site.

The PRB is a novel example of this type of technology in the UK for the treatment of acidic spoil leachate. The PRB was constructed using mainly locally sourced materials and is environmentally sustainable method of remediating contaminated water which was having a serious impact on the receiving water courses.

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