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TECHNICAL ARTICLE

Low Footprint Passive Mine Water Treatment: Field Demonstration and Application

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Abstract This paper presents iron and manganese removal data from a novel low footprint mine water treatment system. The paper discusses possible design configurations, and demonstrates that the system could treat 1 l/s of mine water containing 7.2 mg/l of Fe to <1 mg/l with a system footprint of 66 m^2. A conventional lagoon and aerobic wetland system based on standard sizing criteria would require a minimum of 135 m^2 to achieve the same treatment. Other advantages of the system are that it polishes manganese concentrations, produces ochre that is dense (15% w/v) and free of plant detritus (and therefore amenable to recycling) and that heavy machinery will generally not be required for construction of similar scale systems.

Introduction

Passive mine water treatment schemes typically incorporate settling ponds/lagoons. These are included at various points in the treatment system for the removal by settling, of oxidised iron solids. For waters that are net-alkaline from source and of circum-neutral pH, where abiotic Fe(II) oxidation and precipitation occurs rapidly, the water is directed through settling lagoons from source before being routed through aerobic surface flow wetlands. The treatment for net-acidic waters is similar, except that the acidity is consumed and pH raised up-front, usually by routing the water either through some form of anoxic limestone drain or anaerobic compost based (or other substrate) system. Having produced a circum-neutral, net-alkaline discharge from these units, the water is then routed through settling lagoons as for the treatment of net-alkaline water. In the UK, the current best practice for the passive treatment of net-alkaline mine waters similarly involves lagoons and aerobic wetlands. The intention is to remove 30–50% of the iron in the settlement lagoons before the mine water enters the wetland. This allows for more effective sludge management and prolongs the life of the wetland. The design of lagoons is usually based on either an empirical iron removal rate derived from the performance of aerobic wetlands (Hedin et al. 1994) or by defining a nominal retention time. The tendency to use guidelines that are based on observations is explained by the difficulty in accurately formulising the effect of the lumped processes of Fe(II) oxidation, oxygen transfer and settling velocities encountered for mine waters of different pH and chemistry. Settling lagoons (and aerobic wetlands) based on these guidelines are typically large. Whilst effective treatment is often achieved by such systems, the surface area requirement is often a hindrance to their application to treat mine waters wherever, for a multiplicity of different reasons, land availability is restricted. In the case of the UK, in addition to land area being at a premium (a reflection of the population density) many mine water discharges occur in steep-sided valleys, making the application of convention large-area passive systems problematic.

Previous research (by the authors) on an existing rapid alkalinity producing system (RAPS) unit in South Wales revealed that the system, counter to designed intent, was actually removing iron (as ochre) very effectively on top of

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the RAPS unit. This led to the idea that perhaps this accidental but very effective iron removal could be engineered into a system specifically designed to achieve it. Subsequent trials at laboratory and small field scale indicated promising results (Dey et al. 2003; Sapsford et al. 2005). As a result of this initial promise a large pilot scale system was constructed at the former Taff Merthyr colliery site in South Wales where net-alkaline mine water is being treated in a conventional lagoon/wetland system. The system is hereafter referred to as the vertical flow reactor (VFR). The VFR comprises a commercially available bespoke steel panelled tank, 7.32 m long by 3.66 m wide and 2.30 m deep, with a baffle wall 1.22 m from the end of the tank. A cartoon schematic of the tank and photographs are shown in Fig. 1a. The mine water flows down through a 21.6 m^2 bed of sandstone gravel, which sits on a plenum floor. The plenum floor is made of galvanised steel mesh sheets sitting on top of 300 mm high concrete support pillars. This means that the whole gravel bed is under-drained by a large void space; the design is chiefly intended to improve the uniformity of flow through the ochre and gravel bed. Water flows through this under-drain, under the baffle wall and up through into a rise chamber. The mine water discharges into an overflow chamber where a pipe takes the water away to discharge back into the existing wetland system. Further details of the pilot scheme and typical results are available in Sapsford et al. (2005, 2006). These results revealed that the pilot system was achieving higher iron removal rates than the conventional lagoon system that runs in parallel and generally in a shorter residence time. Intensification of iron removal in the system is attributed to (1) filtration of iron hydroxide particles by the ochre bed and (2) surface-catalysed oxidation of iron (II) and subsequent accretion of iron hydroxide around pre-existing iron hydroxide particles in the accumulating bed.

However, the early pilot plant results were not as promising as some of the initial trials had indicated. The reason for this was found to be short-circuiting of flow where the edge of the tank intersected the ochre/gravel bed. The coarseness of the gravel used in the first-instance (20 mm chips) is believed to have contributed to this problem. Subsequently, the ochre that had accumulated in the system was removed and a new gravel bed installed. The new gravel bed consisting of a 100 mm thickness of 6 mm sandstone gravel chips and was laid over the original 100 mm thickness of 20 mm gravel chips. Before application of the new gravel layer, a $\approx$300 mm fillet of builder's sand was packed against the walls of the tank to curtail problems of short-circuiting flow down the tank walls. This paper presents the most recent results from the system.

Results and Discussion

Iron Removal

Table 1 gives the typical chemistry of the mine water at Taff Merthyr, all measurements and analyses were made using standard methods. Recorded pH, ORP, dissolved oxygen activity, and alkalinity values over approximately 2 years are given, metals data are for the last year of pilot operation. The chemistry is typical of mine waters associated with coal mine drainage in the UK. Although seemingly benign compared to some mine waters, the environmental damage that such discharges cause

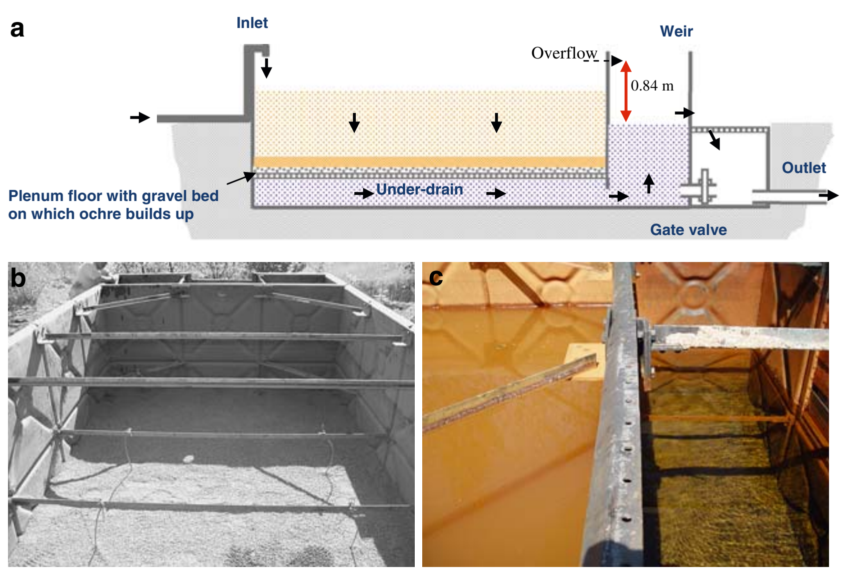

Fig. 1 The VFR. **a** schematic; **b** after installation of new gravel bed; **c** ocherous downflow (*left*), clean upflow (*right*)

Table 1 Chemistry of Taff Merthyr mine water

	Mean	# of samples	Standard deviation
pH	6.7	41	0.4
Redox potential	+7.6 mV	39	80.7
Dissolved oxygen	4.2 mg/l	37	1.1
Alkalinity (as $CaCO_3$)	233 mg/l	13	22
Total iron	7.2 mg/l	36	1.7
Dissolved Iron <0.45 µm	6.3 mg/l	17	1.3
Total manganese	0.70 mg/l	36	0.08
Filtered manganese <0.45 µm	0.70 mg/l	36	0.07

(primarily due to smothering of river benthos with iron flocs) should not be underestimated.

Table 2 shows the influent and effluent iron concentrations for the VFR tank over the period June 2006 (when the new gravel bed was installed) to May 2007. Importantly, the system was typically discharging water well below typical UK Fe discharge consent limit of 1 mg/l. Flow rates through the tank are variable through a combination of chance occurrences and design. The flow rates are inconsistent for many reasons including seasonal changes in flow rates exiting the mine workings, intermittent blockages in the VFR influent pipe (as happened in August 2006) and occasionally purposefully (e.g. 16 September 2006) to assess the effect of increased flow rates on iron removal efficiency.

Generally, iron removal efficiency was excellent in the tank over the course of the 11 months between June 2006 and May 2007. There were some notable exceptions. The influent flow rate was increased (flow is controlled by a manually operated ball-valve) to around 2.2 l/s in September. Although the system achieved high iron removal rates of 70 g/(m^2/day) at this time, a hypothetical 1 mg/l discharge consent (which is the operational target effluent concentration) was being exceeded. Also, the following week, despite flow rates being reduced, the iron removal efficiency was poor (66%, see Table 2), suggesting that the increased flow and therefore velocity through the bed had scoured the ochre.

However, iron removal efficiencies recovered thereafter. In November, the iron removal efficiencies dropped again. This was because over the course of the preceding operation, the water backed up, developing the necessary driving head in the down-flow chamber to drive the water through the ochre bed, which not only had increased in thickness but decreased in permeability due to compression. By November, the head of water developed was 0.84 m. With the current tank configuration, this resulted in some water from the down-flow side of the tank draining through the over-flow into the up-flow chamber (see Fig. 1a). This resulted in the observed decrease in iron removal efficiency. Subsequently the gate-valve was opened slightly so that water exited the tank through it, and sufficient driving head could then develop to continue tank operation; however, as the permeability in the bed decreased, further overflows occurred and the influent flow rate was reduced to remedy this.

Manganese Removal

Although Mn was present in only low concentrations in the Taff Merthyr mine water (influent containing between 0.84 and 0.54 mg/l), the VFR performed well at lowering these concentrations. Figure 2a shows that at times the VFR achieved almost 100% Mn removal. This is interesting because Mn is difficult to remove from mine waters due to slow oxidation kinetics at circumneutral pH. The pre-existing Taff Merthyr settling lagoons (which have a designed residence time of at least 24 h) typically only remove 5% of the influent Mn.

The actual rates of Mn oxidation are shown in Fig. 2b, as calculated from the data and calculated retention times (this implicitly assumes that the Mn removal is primarily through Mn oxidation and precipitation). The data shows that the rate increases from an initial low and fluctuates thereafter. The increased rate of Mn oxidation in the VFR system is possibly due to heterogeneous catalysis of manganese oxidation on ochre and manganese oxide surfaces with subsequent co-precipitation with iron hydroxide/manganous oxides. In fact, the ochre bed at the bottom of the pilot plant was shown (after decommissioning) to contain manganese enriched layers (see Fig. 3), the photograph was taken after carefully scrapping ochre back to reveal a cross-section. The manganous solids were recovered from a sample of the ochre by using 30% HCl to dissolve the iron oxides away. The filtered and washed solids were identified by XRD as hydrous manganese oxide. The occurence of these layers is intruiging; water chemistry data indicates that the influent manganese is almost all in the dissolved form, so the layers are probably authigenic rather than allogenic. Similar layers of manganous oxides are a common feature in sediments and represent a redox interface; in the VFR system, the occurence of layers may indicate the point where Fe(II) concentrations have been lowered to such a level that MnO_2 reduction is no longer thermodynamically favourable, thus allowing it to precipitate and accumulate. However, the reason for the presence of a number of such layers is unknown.

The Mn removal rate observed [g/(m^2/day)] was often higher than those used to size aerobic wetlands for Mn removal (Hedin et al. 1994) (see Fig. 2c); such removal is especially surprising considering the low concentrations of manganese (which limit the reaction rate). Further research

Table 2 Treatment data for the Cardiff University VFR

Date	Total Fe influent (mg/l)	Total Fe effluent (mg/l)	Flow rate (l/s)	Fe removal (%)	Comments
4 June 2006	8.38	0.12	0.34	99	
6 June 2006	7.84	0.11	0.34	99	
8 June 2006	9.07	0.13	0.48	99	
14 June 2006	8.65	0.06	0.46	99	
20 June 2006	7.82	0.46	0.91	94	
28 June 2006	8.51	0.50	0.94	94	
07 July 2006	7.72	0.25	0.97	97	
11 July 2006	7.64	0.21	0.99	97	
28 July 2006	7.57	0.00	0.15	100	
20 August 2006	8.12	0.00	0.01	100	
16 September 2006	9.32	1.47	2.2	84	Possible bed scour
22 September 2006	8.90	2.99	1.4	66	Possible bed scour
29 September 2006	8.48	0.01	0.73	100	
05 October 2006	7.74	0.36	0.27	95	
09 October 2006	7.26	0.45	0.24	94	
16 October 2006	7.21	0.20	0.57	97	
20 October 2006	6.49	0.08	0.34	99	
15 November 2006	6.66	1.94	0.83	71	Overflowing
17 November 2006	6.86	1.97	0.97	71	
27 November 2006	5.08	2.97	0.93	42	Overflowing
05 December 2006	4.91	2.16	1.03	56	Overflowing
07 December 2006	4.74	1.35	1.04	72	
14 December 2006	5.05	0.62	0.8	88	
05 January 2007	5.35	0.51	0.56	90	
24 January 2007	4.79	0.00	0.5	100	
15 February 2007	4.65	0.04	0.27	99	
23 February 2007	13.62	1.57	0.71	88	Overflowing
06 March 2007	5.35	0.96	0.58	82	Overflowing
23 March 2007	6.41	0.38	0.43	94	
13 April 2007	7.11	0.01	0.38	100	
24 April 2007	6.56	0.05	0.37	99	
01 May 2007	6.84	0.19	0.23	97	
04 May 2007	7.11	0.17	0.22	98	
09 May 2007	6.17	0.06	0.14	99	
10 May 2007	7.20	0.03	0.22	100	
13 May 2007	6.16	0.08	0.25	99	

is required to see how well a VFR system would treat higher concentrations of Mn. However, the pilot plant has already shown that the VFR could be used to “polish” Mn concentrations in mine waters.

Sludge Properties

Results of a strong acid digest (conc HNO_3/HCl) on the ochre recovered from the bottom of the VFR after 11 months of operation is given in Table 3. Of note are the high Mn concentrations (as discussed above), the black layers were sampled and found to contain ≈11% Mn. The Ca and C content are probably due to calcite precipitation caused by CO_2 degassing from the mine water. The sulphur content indicates that there is some sulphate adsorbed or co-precipitated with the Fe; this may be significant in terms of the reactivity and surface area of the ochre as sulphate inhibits the formations of crystalline iron oxides (Brady et al. 1986). Whereas most metals are probably associated with the iron oxide, analysis of composition with depth (data not shown) indicates that Co and Tl are distinctly associated with the manganous oxide layers.

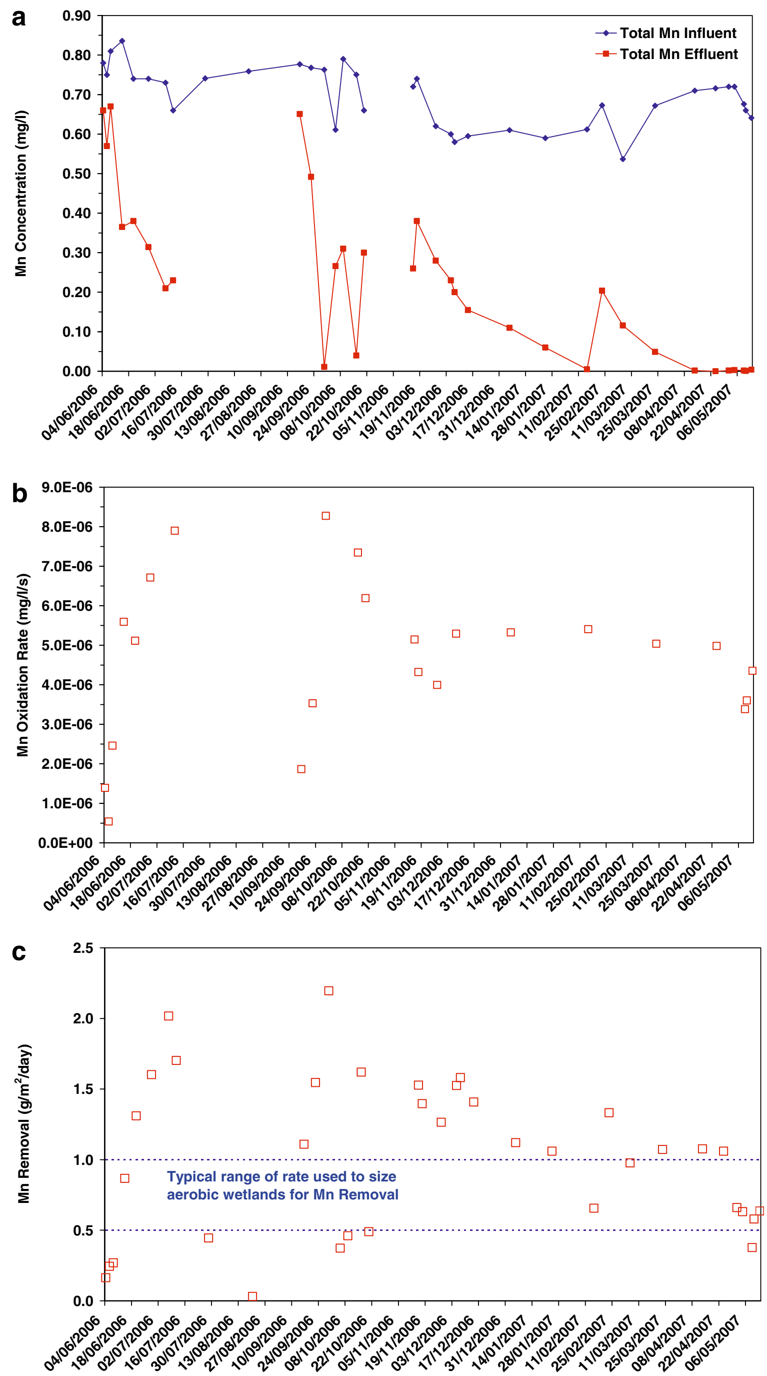

Fig. 2 Mn data for the VFR: **a** total Mn concentration in VFR influent and effluent; **b** calculated Mn oxidation rate; and **c** calculated Mn removal rate

Sludge recovered from the VFR after 11 months of operation (with the 6 mm gravel bed) exhibited a solids content of 15.0% w/v. This compares favourably with many ochre sludges that have solids contents of typically <5% (m/v). Sludge with a high solids content is favourable from the perspective of on-site storage and costs of eventual removal from site. Although no direct measurements were made, the yield strength of the in situ ochre was estimated to be high, with the sludge having the consistency of estuarine mud rather than the typical “fluffy” (with low yield strength) ochre typical of many mine water treatment systems. This high yield strength may influence the choice of de-sludging technique.

Sizing Comparison between a VFR and a Conventional System

This research project will culminate in design criteria for a treatment system based on this concept. The criteria will be

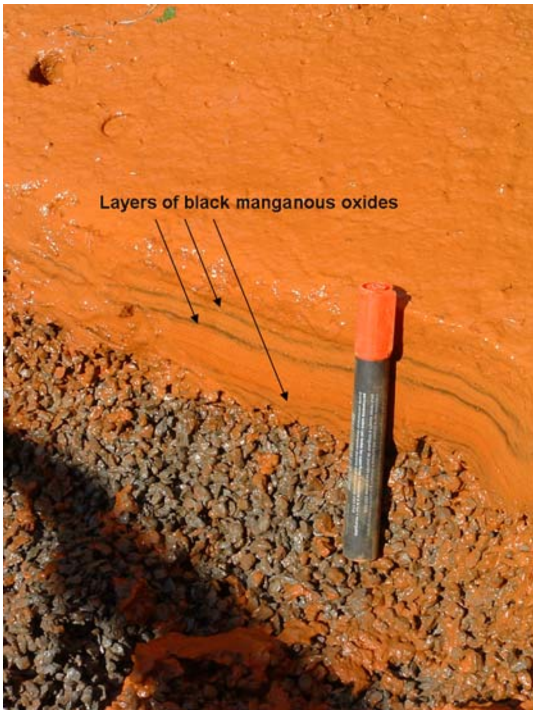

Fig. 3 Photograph of a cross-section of ochre sludge in the bottom of the VFR after decommissioning revealing layers of black manganous oxide

Table 3 Chemical Composition of Ochre Sludge after 11 months of VFR operation

Al	761	Fe	53.6%	Pb	85
As	185	K	561	Sr	362
Ba	433	Li	71	Ti	25
Ca	2.17%	Mg	1294	Tl	54
Co	60	Mn	2.17%	Zn	1,262
Cr	51	Na	3,559	C	0.83%
Cu	22	Ni	51	S	0.13%

Values are in ppm unless marked otherwise

based on the results of ongoing experiments (e.g. Barnes et al. 2006, 2007) aimed at determining homogenous and heterogeneous Fe(II) oxidation rates in the laboratory and field. These are essential for predicting the operation of the system for different mine water chemistries. This section of the paper outlines some of the basic design concepts and operational procedures that will be recommended in the final guidelines, and uses the data gathered so far to offer a simple worked example of a comparison between the footprint of a conventional lagoon/wetland system and the VFR system.

Design Calculation Information and Assumptions

1. Treating Taff Merthyr water (see Table 1): the target treatment is the reduction of Fe in the mine water from a mean of 7.2 mg/l to a target of 1 mg/l (typical UK discharge consent limit).
2. Design for the treatment of a flow of 1 l/s (86.4 m^3/day).
3. Using data from Table 2, we estimate that the VFR in its current configuration could successfully treat (i.e. discharge <1 mg/l Fe total) 0.75 l/s of Taff Merthyr water for 5 months before overtopping through the overflow (see Fig. 1).
4. We therefore assumed that if the VFR was linearly increased from the current footprint of 25–33 m^2, it could also treat 1 l/s of mine water for 5 months.
5. An iron removal rate of 5 g/(m^2/day) for Taff Merthyr lagoons was used, based on actual observation of typical iron removal rates in the existing Taff Merthyr lagoon (see Sapsford et al. 2006).
6. We assumed two parallel settling lagoons to ensure continued treatment so that one could be taken off-line and de-sludged (this is common practice in the UK).
7. The calculation uses 10 g/(m^2/day) as a typical iron removal rate for an aerobic wetland (e.g. Hedin et al. 1994).
8. The calculation is based on following the UK best practice of removing 50% of the iron up-front in a lagoon and the rest in an aerobic wetland.

Meeting the above criteria with a lagoon and wetland system would require a total area of 135 m^2. This is based on two parallel 54 m^2 lagoons and an aerobic wetland of 27 m^2. Point measurements of the iron removal rate in the Taff Merthyr aerobic wetlands revealed an iron removal rate of circa 3 g/(m^2/day) (data not shown) rather than the 10 g/(m^2/day) used in the above calculation. If these point measurements are in fact typical of the wetland performance, then the design area would need to be increased to a minimum of 197 m^2. These calculated areas would also need to be amended upwards by at least 20% because they do not take into account the additional footprint incurred by the bunds, embankments, and other landscaping features common to these schemes (Parker 2007, personal communication).

The VFR system would require a minimum of two tanks in parallel (see Fig. 4) to allow de-sludging of one tank while maintaining treatment capacity in the other. The operation sequence would then be as follows:

1. Mine water would be directed into the first VFR tank. With a suitable flow distribution system up-front, the second tank could act in this time as additional capacity for treatment of storm flow.
2. After 5 months the water level would rise in tank 1. This would then (with the appropriate positioning of the height of the overflow) overflow into tank 2 (see Fig. 4).

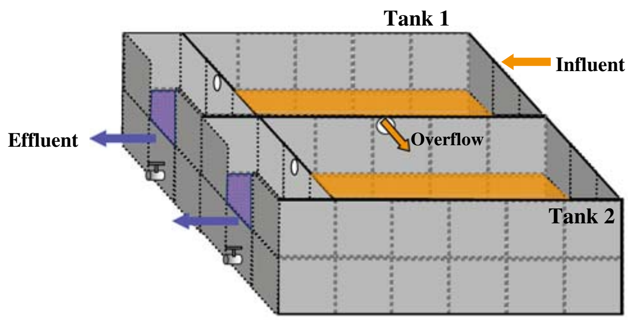

Fig. 4 Schematic of two VFRs running in parallel

3. The mine water is then treated in two locations. A portion of the flow will still be exiting the system through the ochre bed in tank 1 while the untreated overflowing portion is treated in tank 2.
4. The life-time of tank 2 (i.e. time before it overflows and the treatment system fails completely) should be at the very least 5 months (i.e. the same as the tank 1) but in reality will be a lot longer because tank 1 will still be treating a portion of the influent mine water (because the bed is still permeable) and the concentration of iron in the overflow to tank 2 will be less than the concentration of iron in the influent to tank 1.
5. Before the life-time of tank 2 is exceeded, maintenance is required. Influent is diverted from tanks 1–2 and tank 1 is de-sludged.

By operating the parallel tanks in this way, it anticipated that the VFR system would successfully treat mine water for at least 12 months without maintenance. Periodically, ochre will have to be removed from the VFR system to re-establish the permeability in the VFR. The required length of operation before de-sludging is required is of great importance. For remote sites, the key consideration may be decreasing the frequency of de-sludging operations. The development of methods of de-sludging the tank is an area for future work. The focus will be on ways to achieve de-sludging that a maintenance team could perform easily in a few hours with little or no equipment and so be suitable for remote sites. Typical practice at passive mine water drainage sites is to use mobile sludge-gulpers (PIRAMID Consortium 2003); other methods to be considered include draining the system, manual scraping, or jetting the ochre away. An adaptation of the hydraulic cleaning method that is often used for cleaning gravel roughing filters (e.g. Wegelin 1996) may be useful. Hydraulic cleaning involves opening an appropriately positioned valve (e.g. the gate valve in Fig. 2) to drain the whole system rapidly; the relatively high velocities thus induced would mobilise and remove accumulated ochre solids.

Once the sludge is removed, it is usual to transfer it to, or route it to (if washing the system out) a drying bed for on-site storage and natural dewatering. The incorporation of drying beds (or storage ponds) would give the VFR much added utility. Ochre sludge could then be periodically removed from the VFR (e.g. every 12 months) and stored until long-term removal is required. Although the need for a drying bed increases the overall area requirement for such a system, which is counter to the design philosophy of the VFR, the advantage of drying beds over the requirement for additional treatment area is that drying beds (or storage ponds) do not need to be of regular size or shape to provide effective storage and so can be easily sited. In some cases, a settling lagoon can also be used a storage pond.

Conclusions

This paper has presented 11 months of operational data from a novel mine water treatment system. The aerobic VRF has demonstrated excellent removal of iron and polishing of Mn concentrations. The results and calculations in this paper suggest that the VFR system would achieve the same treatment in a footprint that is less than half of that that would be required for a conventional settling lagoon and wetland system. The Cardiff University VFR system is a passive mine water treatment technology that can be used in areas where restricted land availability prohibits the application of conventional passive systems, the VFR system could also act as unit process in combination with other established technologies (e.g. RAPS), replacing settling ponds and/or aerobic wetlands in the treatment scheme. Additional advantages of the VFR system are that the treatment produces a relatively dense sludge (15% w/v). Also, the ochre recovered from the VFR system is "clean" i.e. not mixed with organic or other debris and therefore more amenable to recycling if/when viable recycling options arise. Many mine water discharges are so remote that access roads for heavy machinery required for the construction of conventional systems is difficult or impossible. The on-site assembly used in construction of the commercially-available bolt-together water tank used in this study is potentially very useful for treating small mine water discharges in such locations.

Further research is planned to investigate the potential for VFR system for removal of iron and manganese at lower pH and also for removal of other metals from solution where they occur with iron. The intimate contact between mine water and the accumulating ochre cake in a VFR is expected to encourage the adsorption and co-precipitation of a range of contaminant metals (e.g. Zn, Pb, As, Cd) by adsorption and/or co-precipitation in circum-neutral mine water where the adsorptive affinity of ochre for dissolved cations becomes very pronounced (e.g. Dzombak and Morel 1990).

By the time this paper is published, full design criteria for an aerobic VFR system based on modelling of the pilot plant data and measured homogeneous and heterogeneous Fe(II) oxidation rates will be available on request from the principal author.

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