Chemical and Hydraulic Characterisation of Passive Mine Water Treatment Systems in S.Wales, UK[1]

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ABSTRACT

Settling lagoons and constructed wetlands are widely used across the UK for the passive treatment of mine water. The effectiveness of these systems for iron removal is dependant upon the rates of Fe(II) oxidation, settling rates of particulate Fe(III) and the system's hydraulic residence time. This study presents the results of chemical and hydraulic characterisation of a number of Coal Authority mine water treatment sites across South Wales. Included are snapshots of iron removal performance for three passive mine water systems, two conventional lagoon and aerobic wetland systems and a RAPS system. In addition to examining changes in the concentration and speciation of iron across the systems, the paper details the results of tracer tests that were used to determine residence time distributions and also includes some noteworthy observations made at the time of data collection. Understanding how the iron removal mechanisms interact with the system's hydraulics is a necessary step towards engineering improvements in passive mine water treatment systems.

Additional Key Words: Constructed Wetlands, Settling Lagoons, Tracer Tests

[1]Paper was presented at the 2009, Securing the Future and 8[th]ICARD, June 22-26, 2009, Skellefteå, Sweden.

INTRODUCTION

The UK Coal Authority have built, and now operate, around 50 passive mine water treatment facilities across the UK for the treatment of coal mine effluent. South Wales has numerous major mine water discharges and 14 treatment systems have been constructed at the sites of former collieries across the South Wales coal field. Many of the waters are ferruginous but well buffered (net-alkaline) and are typically treated by a combination of settling lagoons /ponds and aerobic wetlands. The intention of incorporating lagoons 'up front' of the wetlands is to remove as much iron as possible before the wetland. It is practically much easier to remove accumulations of ochre sludge from a lagoon than a reedbed. Thus for improved site management, system longevity and maintenance, lagoons are incorporated ahead of the wetlands. The two principal mechanisms at work within aerobic mine water treatment systems are [1] the oxidation of Fe(II) and hydrolysis of Fe(III) as the water emerges from the mine and [2] the coagulation and settling of the particulate ferric iron consequently produced. It is through settling that the iron is actually removed. Overall iron removal will depend on the water chemistry, residence time, rates of gas (O_2 and CO_2) transfer, temperature and a range of other (less important) physico-chemical parameters.

Clearly improvements in iron removal could be achieved by the provision of greater residence time for Fe(II) oxidation and greater area for settling to occur across. But of course land comes at a premium (especially in the UK) thus it is necessary to look for ways of intensifying iron removal by making improvements on the current designs. In order to engineer a mine water treatment system it is first necessary to have an understanding of the processes occurring within that system. This paper details some of the results of a large study that examined the hydraulic performance and iron removal performance of a number of passive mine water systems. Although the literature is replete with case studies of passive mine water performance, this study aims to standout by the inclusion of not only total iron data but ferrous/ferric iron data, pH and flow rates. In addition the paper also examines the performance of a trial Reducing Alkalinity Producing System (RAPS) to elucidate iron removal mechanisms in this system as compared to conventional lagoon plus aerobic wetland systems.

STUDY SITES

Lindsay

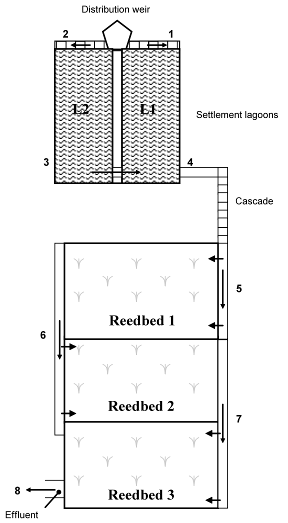
Lindsay is a passive mine water treatment facility constructed close to Capel Hendre, Camarthenshire, South Wales. The site was originally designed for treatment of mine waters with Fe(II) concentrations up to 98 mg/l. The site employs parallel oxidation lagoons used to feed a series of reedbeds. Observations at site indicate that considerable accumulations of ochre have occurred within the aeration and distribution channels and lagoons, with ochre visible just below the surface of the inlet. A schematic plan of the Lindsay site is shown in Fig 1.

Tan-y-Garn

The Tan-y-Garn mine water treatment system in Ammanford was constructed as a trial site, employing a ‘Reducing Alkalinity Producing System’ (RAPS). The design of the RAPS unit is intended to allow for passive treatment of net-acidic mine waters without continual addition of chemicals. The Tan-y-Garn RAPS unit consists of a 10 x 30 m (approx.) bed of limestone and organic substrate designed to add alkalinity to the water. Mine water passes down through the RAPS unit prior to entering the ponds and wetland. A schematic plan of the Tan-y-Garn site is shown in Fig 1

Taff Merthyr

This is a passive mine water treatment facility developed for mitigation of ferruginous mine drainage arising from the Taff Merthyr mine. This is the largest facility under study, with three hectares of wetlands for combined treatment of the contaminated water from both north and south mineshafts. The site employs a total of four settlement lagoons, which feed a series of six wetlands. Two of the lagoons run in parallel and feed three independent series of wetlands, whereas the other two unconnected lagoons feed two chains of wetlands that combine before the mine water is discharged into the river Taff. A schematic plan of the Taff Merthyr site is shown in Fig 1.



Lindsay

Flow = 20.5 l/s

Fe_{TOT} in = 26.6 mg/l

Fe_{TOT} out = 0.96 mg/l

pH = 6.7 – 7.2†

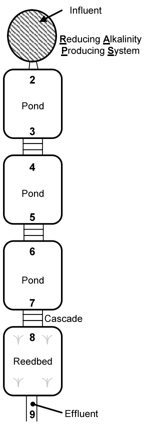
Lagoon Area = 2 x 1200 m^2

Reedbed 1 = 1374 m^2

Reedbed 2 = 1124 m^2

Reedbed 1 = 995 m^2

Total Area = 5893 m^2



Tan-y-Garn

Flow = 1.6 l/s

Fe_{TOT} in = 46.0 mg/l

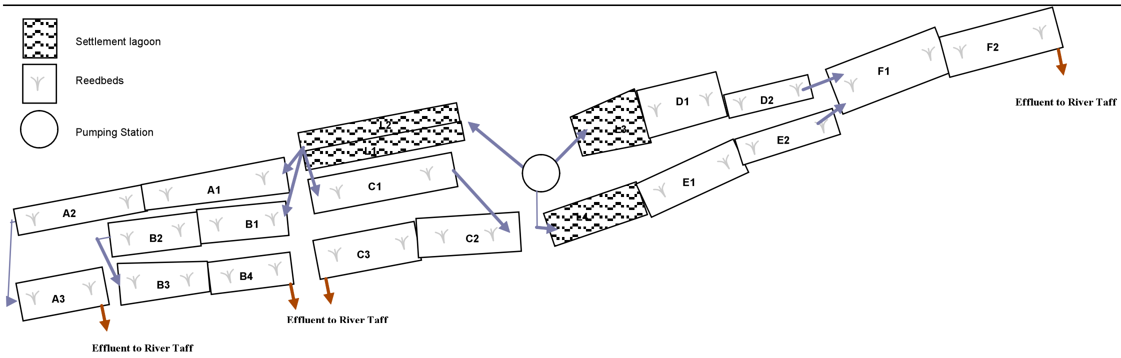
Fe_{TOT} out = 1.79 mg/l

pH = 5.7†

RAPS Area = 395 m^2

Area of ponds = 580 m^2

Reedbed = 220 m^2



Taff Merthyr Flow = 98.1† l/s, Fe_{TOT} in = 6.91† mg/l, Fe_{TOT} out = 0.21† mg/l, pH = 6.5 – 6.8†, Lagoon L1 and L2 Area = 2 x 1250 m^2, Reedbeds A1 and A2 = 2800 m^2

Figure 1 Schematics of the studied mine water treatment sites. Reported data is mean data from Coal Authority database. † data from this study (i.e. unavailable from Coal Authority database). Numerics and alphanumerics refer to sampling locations.

METHODS

Water Quality

Site surveys were conducted at the mine water treatment sites detailed above. pH, Dissolved Oxygen (DO), conductivity (EC) were initially determined using a range of field meters. After 07-08-2008 two Hanna HI-9828 multi-parameter data logging probes were used. The probes were, where possible, employed in unison, and programmed to take a reading every 5 seconds. After sampling for 10-15 minutes at each point, logging was discontinued and average values across the time period determined. Concentrations of Fe, Al, Ca, Mn, and S were determined using ICP-OES. Both total and filtered (0.45 µm) samples were taken and fixed with acid prior to analysis, the filtered iron analysis is taken to represent dissolved Fe(II). Spectrophotometric determinations (using a portable HACH DR-890 colourimeter or laboratory spectrophotometer) of Fe(II) were also made after addition of 1-10 phenanthroline as per standard methods (e.g. AWA, 1996).

Tracer Testing

Phase I (28-11-07 to 07-03-08)

The first set of tests were carried out on the wetlands and lagoon at Taff Merthyr, and at Lindsay. Salt was dissolved in mine water on site in buckets or, for larger amounts of salt (> 25 kg), a 190 L water butt. The salt solution was then released into the influent to the studied system. After using the water-filled butt to dissolve the salt, the tracer solution was then introduced into the influent stream by draining through the bottom tap. The means that the salt was injected in a 10 minute (approx) pulse rather than an instantaneous 'slug'. Although this is not ideal for tracer tests, the injection time is negligible compared to the length of the tests – typically 70 hours. The good mixing between salt and influent water was an intentional attempt to minimize the formation of density driven salt water currents that may give inaccurate results. Flow rates were calculated from measured velocities which were found using an impellor positioned at $^3/_5$ of the water depth. The number of impellor revolutions was typically taken over 15 minute intervals. After repeating these measurements, mean calculated velocities were then multiplied by channel cross-section area (using measured depths) to give calculated flows.

Phase II (18-07-08 – 20-09-08)

The second phase of tracer tests was carried out on Lindsay lagoons, Lindsay wetland, and Taff Lagoon. Salt was introduced into the systems using the water butt in the same way as detailed above. Flow rates were monitored using a factory calibrated doppler flow meter (Mainstream P2211 Flow Meter). pH, Dissolved Oxygen (DO), conductivity, and temperature were monitored in the influent and effluent using a Hanna HI-9828 multi-parameter proble. Probes were calibrated on site before installation. 24 samples of the influent and 24 effluent samples were collected at regular intervals using an Envitech Sampsys automatic sampler. The sampler took samples every 3 hours, delivering 200 ml of sample into 5 ml of 20% HNO_3. On returning to the laboratory the samples were submitted for analysis of Na, Fe, Mn, Al, S by ICP-OES and Cl by IC. A separate subsample was taken and Fe(II) analysed spectrophotometrically using 1-10 phenanthroline and a sodium bicarbonate buffer (AWWA, 1996).

RESULTS AND DISCUSSION

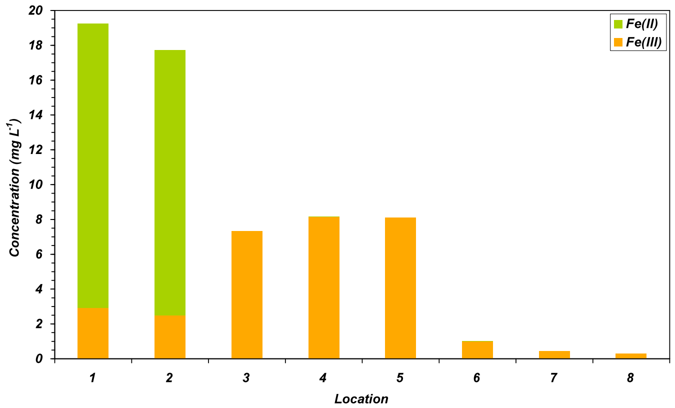
Iron Removal Data

Lindsay

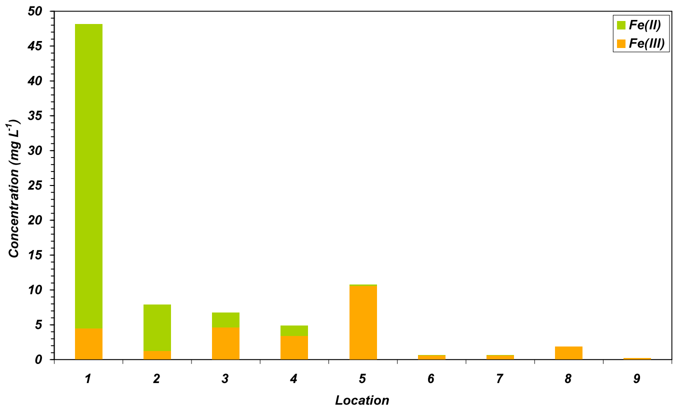
The lagoons which are designed to have a depth of approximately 1.5 m had substantial accumulations of ochre reducing the depth to between 0.7 and 0.9 m. Despite this the iron removal data demonstrate that overall the Lindsay mine water treatment system is still performing as required, removing sufficient iron to fall well below the 1 mg L^{-1} discharge consent. The mine water emerges at circum-neutral pH and was found to remains, as expected for a net-alkaline mine water. Total pH change across the entire site was an increase of 0.8 units, the biggest change in pH occurs across the settlement lagoons – probably due to CO_2 exsolution. Fig 2 (a) shows the that total Fe concentrations at the inlet to the settlement lagoons are approaching 20 mg L^{-1}, with almost all of the Fe(II) oxidised before the inlet to the first reed bed. On the sampling occasion the lagoons accounted for around 56% of total Fe removal. The Lindsay lagoons were fulfilling their design criteria of removing > 50% iron for 4 of the 5 occasions when they were monitored. The removal rates for the Lindsay Lagoon L2 range from 5.43 – 12.9 g/m^2/day.

Tan-y-Garn

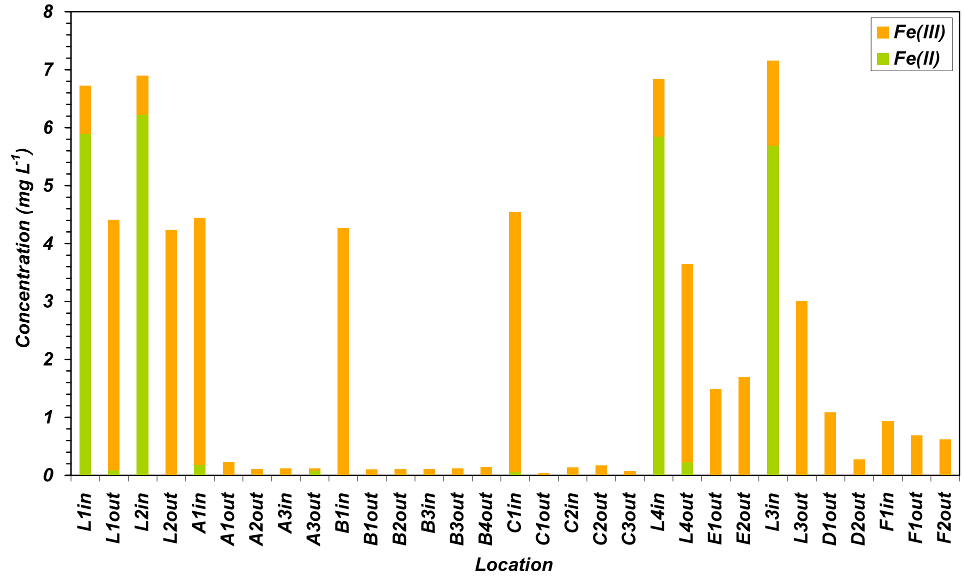
Mine water pH was found to rise across the system by 1.79 pH units. Figure 2(b) shows that the initial Fe concentrations were approaching 48.2 mg L^{-1}, with approximately 90% present at Fe(II). Interestingly, Fe(II) concentrations drop from 43.7 mg L^{-1} to 6.65 mg L^{-1} on passage through the RAPS. Visual observations suggest that significant iron is deposited as ochre on top of the RAPS system, the fact that S concentrations (data not shown) only dropped from 84 mg L^{-1} to 74 mg L^{-1} indicates that sulphide precipitation could only account for a small proportion of the iron removal. These ochre deposits almost certainly form by autocatalytic and microbial Fe(II) oxidation and precipitation. This is the same mechanism exploited in novel treatment systems described by Jarvis and Younger (2001) and Sapsford and Williams (2009). Influent pH was 5.67 indicating that iron heterogeneous iron precipitation can constitute an effective removal mechanism into the acidic pH region.



(a) Lindsay, pH 7.21, Q = 28.1 l/s

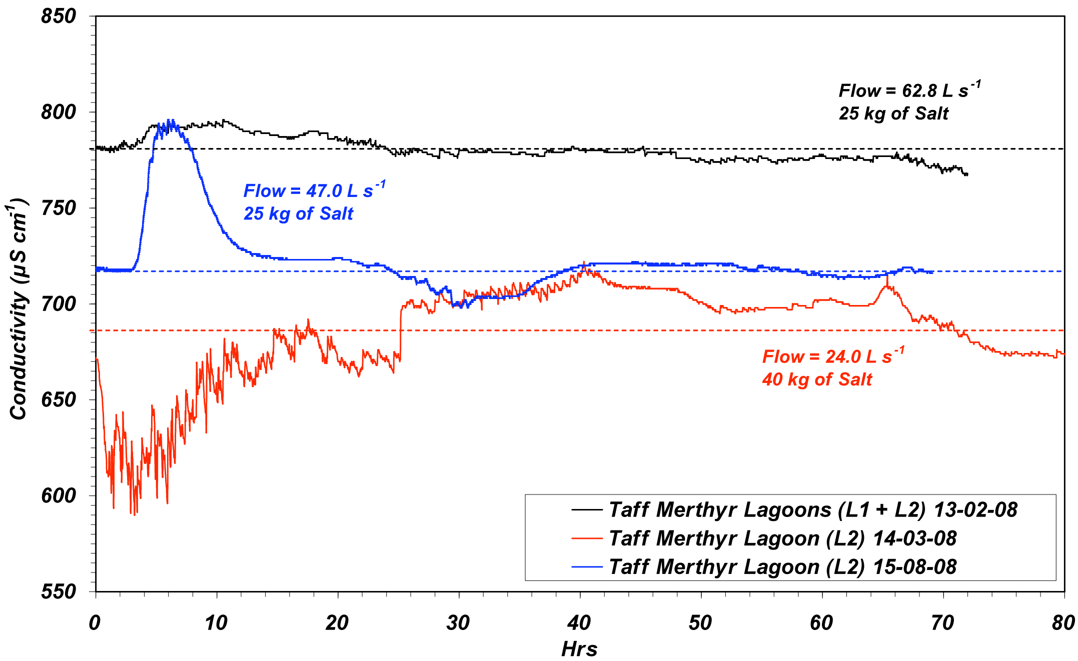


(b) Tan-y-Garn, pH 5.67, Q = 1.8 l/s

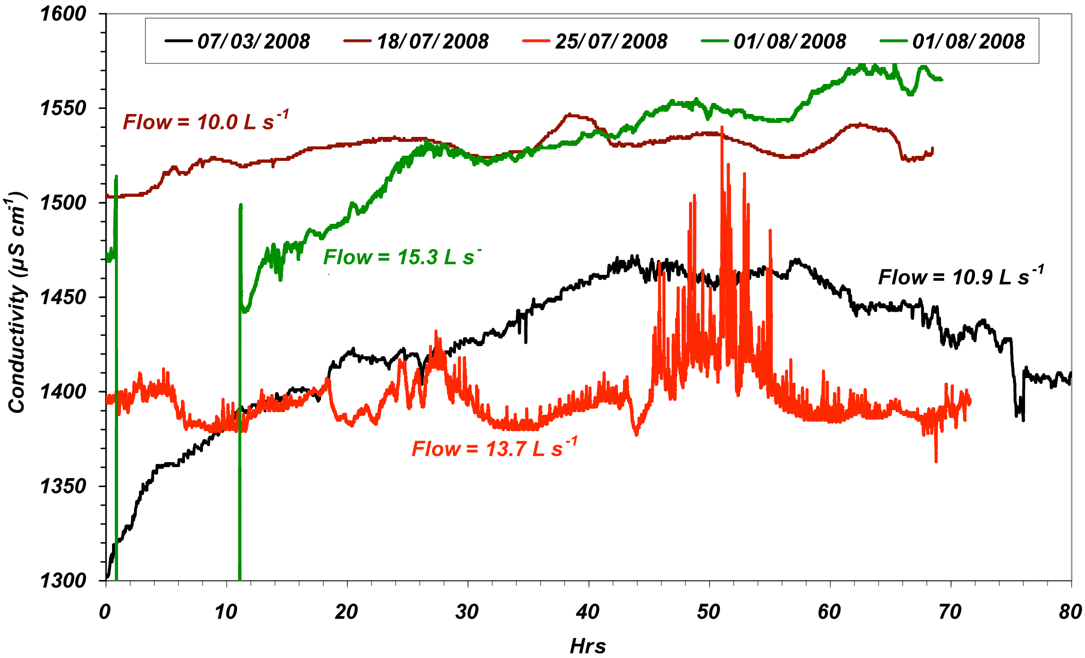


(c) Taff Merthyr, pH 6.65, Q = 69.4 l/s and 28.8 l/s

Figure 2 Iron concentrations across lagoons and wetlands (a) Lindsay mine water treatment system, 10-07-2008. (b) Tan-Y-Garn mine water treatment system, 11-07-2008. (c) Taff Merthyr mine water treatment system, 11-07-2008. Flow figures are for the left hand side and right hand side of the system respectively (see Fig 1)



(a) Taff Merthyr Lagoons



(b) Lindsay Lagoon L2

Figure 3 Conductivity responses in the lagoon effluent during tracer tests for Taff Merthyr and Lindsay systems

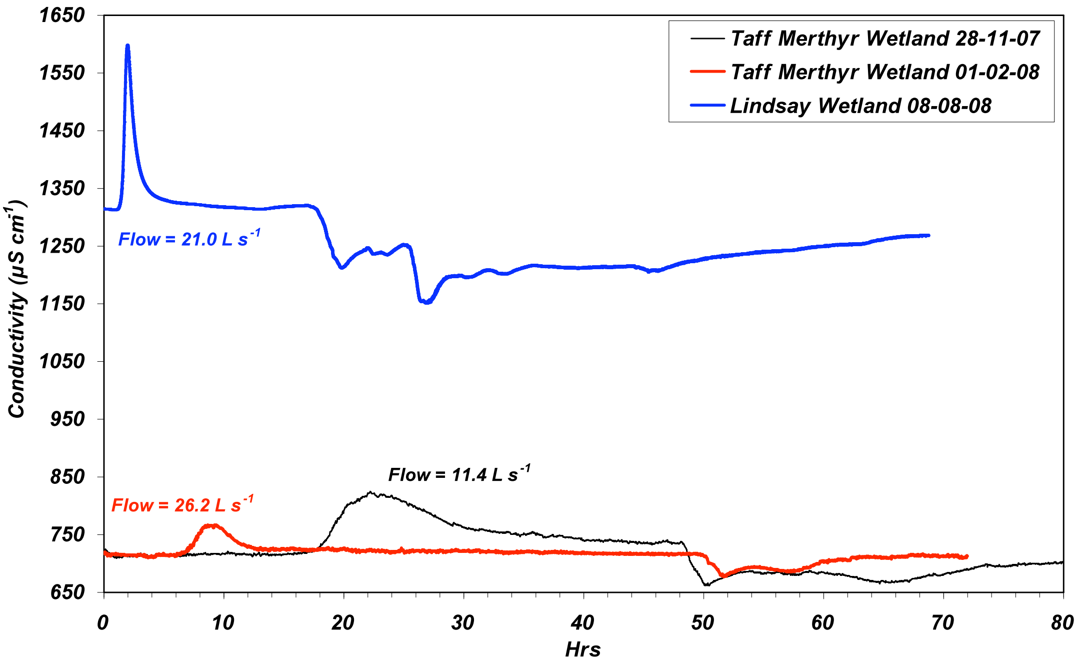


Figure 4 Conductivity responses in the wetland reedbed effluent during tracer tests for Taff Merthyr and Lindsay systems

Taff Merthyr

Influent pH was 6.5-7.2 over the sampling days. The pH increase across the entire site varies between wetlands but the maximum value reached is pH 7.7. Fe concentrations throughout the site suggest Taff Merthyr as a facility is performing very well. Across all of the lagoons between 96 and 100% of the Fe(II) is oxidised, and frequently (with the exception of the E series) the discharge target is met in the effluent from the first wetland. Figure 2 (c) shows iron removal characteristics and speciation across the Taff Merthyr site. The Taff Merthyr Lagoons were not fulfilling their design criteria of removing > 50% iron on both occasions they were assessed. Iron removal rates in the wetlands was between 2.43 g/m^2/day and 2 g/m^2/day and between 4.91 and 5.97 g/m^2/day in the lagoons. These values are all low considering the commonly used design removal rates of 10 g/m^2/day for both lagoons and wetlands. The low removal efficiencies are probably due to relatively low iron concentrations in these systems compared to many passive systems.

General Observations

In addition to the iron data and other observations and measurements were made during the study as briefly outlined here. Scoop sampling of the ochre accumulated in the Lindsay lagoons and distribution channels revealed that the samples were olive green at depth. The green colour of the lagoon ochre is indicative of the formation of reducing conditions at the base of the settlement lagoon and the possible presence of green rust. Bioreduction of Fe(III) (hydroxy)oxide minerals and the formation of green rust is well documented (O'Loughlin et al, 2007 and references therein). pH was found to decrease with depth into the sludge (attributed to higher P_{CO2}), dissolved oxygen was < 1 mg L^{-1} and conductivity significantly higher than in the water column, suggestive of microbial-driven reductive dissolution of the accumulated ochre. This may be an important mechanism for remobilization of Fe(II) (although none was seen at the time of the site survey) and also alkalinity generation. Similar observations were made at Taff Merthyr.

It was noted that solid dense ‘flecks’ of ochre precipitate can be seen in the influent at Lindsay. These flecks can be quite large (up to milimeters in size). Their morphology suggests that they have not formed in the same way as the typical oxidised, coagulated and settled ochre flocs within lagoon systems (which is much ‘fluffier’). This ochre probably precipitated out on surfaces underground or in the pipework. Flecks of this ochre have later been washed off and end up in the influent. These readily settlable solids are important as they constitute much of the ochre that sediments out and fouls the aeration channels and entry point to the lagoons (also noted, to a lesser extent, at Taff Merthyr). A sediment trap before the aeration cascades would probably extend the required maintenance period for the cascade and lagoon.

Lagoon and Wetland Hydraulic

The results of the tracer tests can be seen in Figs 3 and Fig 4. Plotted are the conductivity profiles measured at the effluent point of the unit (end of wetlands A2 for Taff Merthyr). Comparing Fig 3.1 (a) and (b) to Fig. 4 it can be seen that flow through the lagoons is much more dispersed than flow through the wetlands. The lagoon tracer tests reveal much broader and less well defined peaks whereas the residence time distribution (RTD) is much narrower for the less dispersed wetlands. Although some of the conductivity profiles are hard to interpret because of rising background conductivities, in general the lagoon traces show multiple and broad peaks, early breakthrough and long ‘tails’ all indicative of well mixed systems. Chloride effluent data (not shown) also mirror the conductivity traces observed. The exception to this apparent dominance of dispersion in lagoons is shown in the Taff Merthyr lagoon tracer test on the 15-08-08. During this test all the flow had been diverted through one lagoon (for maintenance purposes) leading to a much higher than normal flow rate through that lagoon (47 L s^{-1}). The result is a much narrower RTD indicating that, as expected, the amount of dispersion in the lagoon systems is dependant upon the relative rates of advective and dispersive flow. It is suggested that at the normal flow rates that most of these lagoons operate at, that wind driven ‘diffusion’ may be an important dispersive mechanism. This may mean that the hydraulic performance and therefore iron removal performance of lagoons may be improved by taking steps to minimise wind driven turbulent diffusion.

The shape of the RTD does not give the full account of how efficiently utilized the lagoons or wetlands volume/area is. To interpret the hydraulic efficiency not only requires appropriate measures of dispersion, but also some means of comparison to the design (‘nominal’) retention time. Such methodologies have been developed extensively by practitioners in the field of wetland treatment of wastewaters e.g. Ta and Brignal (1998); Thackston et al (1987) and Persson et al (1999).

CONCLUSIONS

The following conclusions can be drawn from this study:

[1] Site surveys give a useful snapshot of how a mine water treatment site is performing.

[2] All systems studied here are meeting discharge consents with ease at the time of monitoring.

[3] Tracer studies have indicated that flow through settling lagoons is more dispersed than wetlands, wind-driven turbulent diffusion is postulated to be an important mechanism in determining the poor hydraulic efficiency of the lagoons studied.

[4] Optimizing the hydraulic regime to optimize the residence time and effective area for Fe(II) oxidation and settling respectively will make the treatment system more efficient. The inclusion of baffles within the lagoon is one possible way to achieve this.

[5] The Tan-y-Garn results reveal that heterogeneous iron oxidation and precipitation can constitute an effective iron removal mechanism into the near-acidic pH region.

[6] If significant accumulations of ochre sediment are present in a lagoon, reductive dissolution of Fe(III) may lead to remobilisation of iron (as Fe(II) from settling lagoons but may also be a significant source of alkalinity.

Understanding how the iron removal mechanisms interact with the system's hydraulics should lead to ways of improving the design of settling lagoons. Reappraising the design of these settling lagoons for mine water treatment is a worthwhile goal. Even small incremental improvements in efficiency may have important consequences: By maximising iron removal 'up-front' where it can be easily removed, the lifetime of the subsequent wetlands can be extended and reed-bed maintenance reduced.

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