CURRENT PERFORMANCE OF PASSIVE TREATMENT SYSTEMS IN SOUTH WALES, UK

J.N. GERONI[1*], D.J. SAPSFORD[1], A. BARNES[2], I.A. WATSON[3] and K.P. WILLIAMS[1]

[1]Cardiff School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK; E-mail:geronijn@cf.ac.uk*
[2]SRK Consulting (UK), Cardiff, CF10 2HH
[3]The Coal Authority, Mansfield, NG18 4RG, UK

ABSTRACT

This study presents the results of the chemical and hydraulic characterisation of a number of passive mine water treatment sites across South Wales. Various measures of system hydraulic efficiency are presented in conjunction with influent and effluent iron chemistry to give a snapshot of system performance. The effectiveness of both settlement lagoons and wetlands are discussed with respect to rates of iron removal and the relative importance of different iron removal mechanisms. It is suggested that where significant accumulations of ochre sludge occur in settlement lagoons reductive dissolution of Fe(III) may lead to remobilisation of iron as Fe(II) into the surrounding water. The role of aeration cascade design in increasing dissolved oxygen and increasing pH via CO_2 degassing is also considered for a number of the sites investigated. The sites studied include four systems comprising settling lagoons and wetlands. Influent iron concentration, pH and alkalinity varied considerably between sites with 5.67- 48.2 mg/L Fe, pH 2.20-7.22 and 120-251 mg/L as $CaCO_3$ alkalinity. Settling lagoons were found to work more efficiently at higher influent iron concentrations though all of the systems met their targets for effluent water quality. The data collected are used to critically evaluate current international guidelines for the sizing of passive treatment systems and inform recommendations for future system design.

1. INTRODUCTION

Settling lagoons and constructed wetlands have been widely deployed in the UK for the passive treatment of net-alkaline mine waters. The UK Coal Authority has built and now operates more than 50 passive treatment sites across the country for the remediation of coal mine drainage. South Wales has historically been the site of a large number of coal mines and today has numerous major mine water discharges. 14 treatment systems are currently in operation across the South Wales coal field, mostly dealing with well buffered ferruginous waters that can be treated using a combination of settling lagoons and aerobic wetlands. The incorporation of lagoons as a first stage in the treatment process is important as it ensures that much of the iron is removed prior to the wetlands, increasing their lifespan and reducing the maintenance costs associated with the site (lagoons being much easier to “de-sludge” than reed beds).

The removal of dissolved iron from mine water discharges occurs in two stages; firstly the oxidation of Fe(II) as it emerges from below ground, followed by the rapid hydrolysis of Fe(III) and secondly the coagulation and settling of the resulting Fe(III) precipitates. The overall success of any treatment system is therefore affected not only by properties of the influent water (temperature, pH, alkalinity, dissolved O_2 and CO_2 etc) but also by the residence time and rates of gas transfer taking place, both of which can be optimized by careful system design. Many of the passive mine water treatment schemes built to date have been sized according to rules of thumb such as those listed in the PIRAMID (2003) guidelines, e.g. 48h retention time or 10 $g/m^2/d/$, though these criteria often lead to quite different estimates for system size.

The simplest way of ensuring maximum iron removal is to increase residence time for Fe(II) oxidation and provide a larger area over which the settling of precipitates can take place. This of course requires the use of a larger area of land, something that especially in the UK comes increasingly at a premium. In order to reduce the area required for treatment it is necessary to gain a greater understanding of both the chemical and physical processes taking place within it. This paper aims to provide a greater insight into the influence of system design on Fe(II) removal using data gathered during the course of a large study of a number of passive treatment facilities in South Wales. This study aims to stand out from many of those already in the literature by incorporating data for both ferrous and ferric iron, pH, flow rates and the effect of aeration cascades on dissolved O_2 and CO_2 (seen as increasing pH). It is hoped that this paper will add to the insight gained through case studies previously published by Sapsford *et al* (2009).

2. SITES STUDIED

Glyncastle

This site is situated close to the town of Resolven, South Wales. Water discharges by gravity out of two directionally drilled, sub-horizontal boreholes into the scheme (Watson, 2007). The scheme is unusual in that it features two triangular settling lagoons, instead of the usual rectangular design. Water flows out of the settling lagoons into a series of three reed beds prior to discharge. A schematic plan of the site, and the other study sites described below, is shown in Figure 1.

Morlais

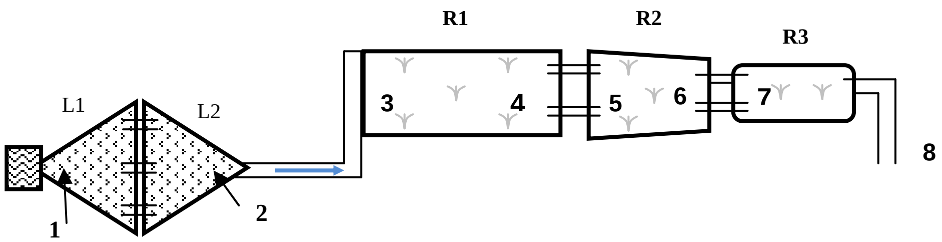
This site is situated near to the town of Llangennech in South Wales. Mine water discharges by gravity from a shaft, the collar of which was raised to enable an aeration cascade to be constructed. The cascade feeds into a 50m long channel which then feeds into two settling lagoons in series. The water flows out of the second lagoon into two parallel wetlands and finally through a third wetland before discharge to a nearby river. At the time of this study lagoon L1 was not in use. All water was directed to L2 via a diversion channel.

Taff Merthyr

Situated in the Taff Bargoed valley near Merthyr Tydfil, mine water is collected in a sump and pumped up to a distribution chamber. In total there are 4 settlement lagoons with preceding aearation cascades and 16 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 Taff Bargoed river. On the day of sampling at this site the pumps were not working and all flow was directed through lagoon L4 and onwards through wetlands E1 – F2.

Lindsay

This site is located close to Capel Hendre, Carmarthenshire, South Wales. Mine water is collected in a sump and pumped up to a distribution chamber above the aeration cascades leading to the two parallel lagoons. The site was originally designed for the treatment of mine waters with Fe(II) concentrations up to 98 mg/l. Observations at site indicate that considerable accumulations of ochre have occurred within the aeration and distribution channels as well as the lagoon. A detailed site survey and discussion of the overall performance at this site have been presented previously by Sapsford *et al* (2009). A description of the design and performance of the aeration cascades are presented here.



Glyncastle flow rate = 20.41 l/s, Fe_{TOT}in= 24.53 mg/l, Fe_{TOT}out= 1.25 mg/l, pH= 6.2-6.8†, lagoon area L1= 1766 m^2, L2 = 1005 m^2, reedbed area R1 = 1958 m^2, R2 = 532 m^2, R3 = 271 m^2, total area = 4532m^2, hydraulic loading, L1 = 1.00 m/d, L2 = 1.75m/d

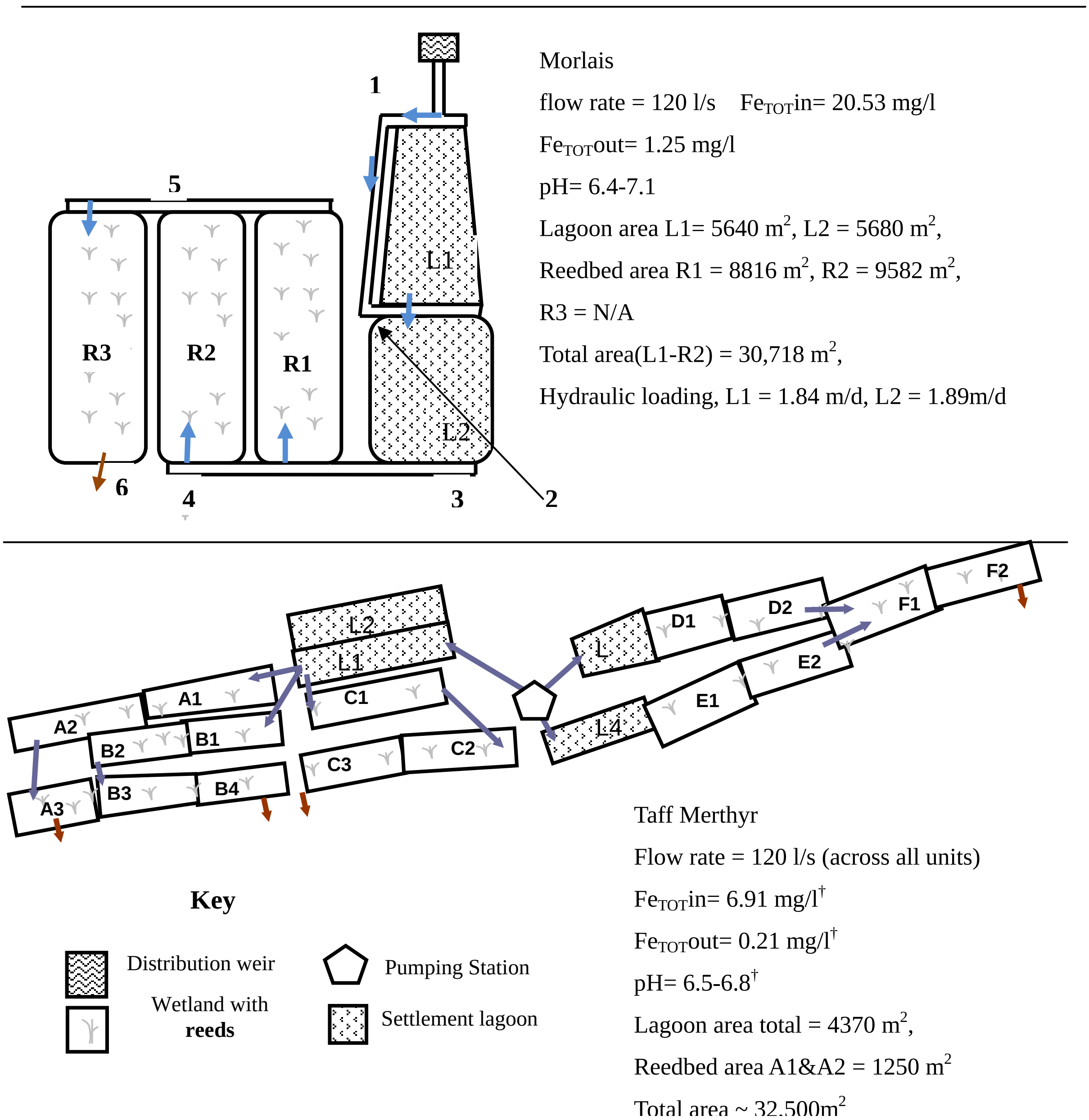


Figure 1. Schematics of the studied mine water treatment sites. Reported data are mean data from Coal Authority data base. † Data collected in study 08/2008. (Diagrams not to scale)

3. METHODS

Water Quality

Site surveys were conducted at the water treatment sites detailed above. pH, dissolved oxygen (DO), and conductivity were initially determined using a range of field meters (only selected data shown). 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 were determined using ICP-OES. Both total and filtered (0.45µm) samples were taken and fixed prior to analysis, the filtered iron analysis is taken to represent dissolved Fe(II). An alternative method was also employed to provide a comparable value of Fe(II). Spectrophotometric determinations (using a portable HACH DR-890 colorimeter or laboratory spectrophotometer) of Fe(II) were made after addition of 1-10 phenanthroline as per standard methods (e.g. APHA *et al*, 2005).

Aeration Cascades

In the case of aeration cascades initial analysis was performed using the data logging multi-parameter probes for 1 hour of sampling, logging every 5 seconds. After on site calibration, the probes were positioned at the top and bottom of the cascade and logging initiated.

4. RESULTS AND DISCUSSION

Iron Removal Data

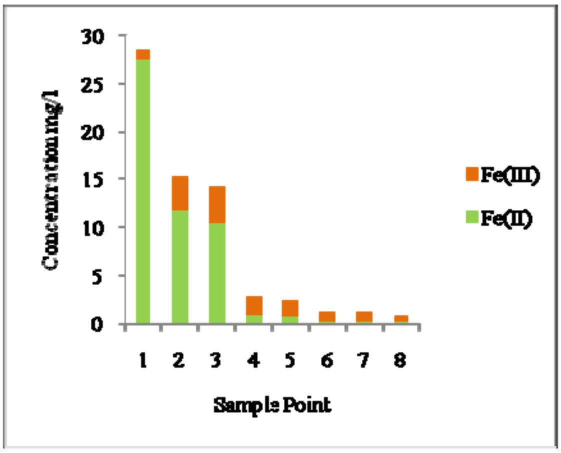
Glyncastle

At Glyncastle the pH of the influent at 6.23 is the lowest of all the sites discussed in this study. The pH is in fact closer to that at Tan y Garn (Watson *et al*, 2009, Sapsford *et al*, 2009) where a Reducing Alkalinity Producing System (RAPS) has been installed to treat the marginally net acidic water. However, Glyncastle mine water is net-alkaline, so does not require a RAPS. Only 57% of the Fe(II) is oxidised by the end of the lagoons (in comparison to almost 94% at Morlais) with an iron removal rate of around 6.61 g/m^2/day. Despite the relatively low pH there is sufficient alkalinity, 121 mg/l as $CaCO_3$ (at the inlet) in the system to ensure that the remaining iron is oxidised in the reed beds. Concentrations of Fe(II) and Fe(III) across the site are shown in Figure 2 for the sample points identified in Figure 1.

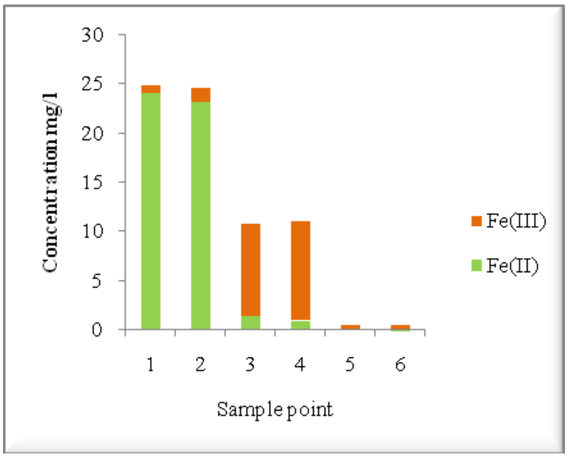
On the day this survey was undertaken the discharge consent (1 mg L^{-1}) had been met with total iron concentration of 0.82 mg L^{-1} exiting the system. However, previous studies of the site conducted during early 2008 reported a discharge total iron concentration in excess of 1 mg L^{-1}. During the early 2008 winter visits the last reed bed was very sparsely vegetated, but at the time of the survey during summer 2008 was densely vegetated.

Morlais

The flow rate through lagoon L2 is the highest flow rate through any single lagoon in a passive treatment system on the Coal Authority database. The area of the lagoon however is also one of the largest on the database and despite the closure of lagoon L1 still allows for a relatively low hydraulic loading (2.93 m/d) that on the day of testing gave a reduction in Fe(II) concentration of just less than 94% from 21.5 to 1.3mg/L with iron removal rate of approximately 22 g/m^2/d. A small portion of the iron is removed prior to the lagoon, and is observed as an ochre coating in the distribution channel. Unlike the Glyncastle site, the reed beds at Morlais serve mainly to polish the effluent prior to discharge rather than removing large quantities of iron themselves.



(a)



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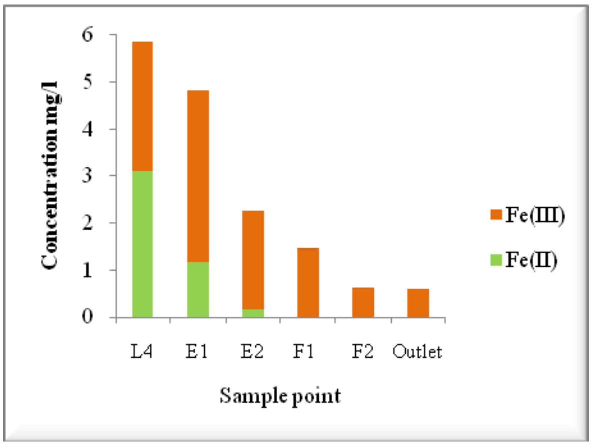

(c)

Figure 2. Concentrations of Fe(II) and Fe(III) across the sites studied (a) Glyncastle, (b) Morlais, (c) Taff Merthyr (sample locations given in Figure 1.)

Taff Merthyr

On the day of sampling the pump at the site was not operational. All flow was directed through lagoon L4 and exited the site via reed bed F2. Unsurprisingly performance of the lagoon was reduced in terms of %Fe removed as a result of the higher flow rate (hence reduced residence time) compared to times of normal operation, though the iron removal efficiency (g/m^2/d) actually increased. Overall it was observed that despite a 6 fold (approximate) increase in hydraulic loading through from L4 to F2 there was very little effect on the quality of the effluent water. It is not clear if this apparent improved performance would be sustained in the long term, or if it was a temporary effect due to the pumps having recently turned off.

Aeration Cascades

The performance of aeration cascades is a continuing area of research interest because achieving the maximum possible gas transfer (increasing dissolved O_2 and degassing of CO_2) is desirable in order to improve Fe(II) oxidation rates. Dissolved oxygen is clearly vital in the system if iron is to be removed via oxidation. It is for this reason that many aeration cascades have been designed and built as part of the overall treatment process at passive treatment schemes. Equally (if not more) important however is the degassing of CO_2 which ultimately leads to an increase in pH. An increase in dissolved O_2 from 4.0 to 8.0 mg/l (a realistic target for an aeration cascade) should double the rate of Fe(II) oxidation as shown by Equation 1 (Stumm and Lee, 1961). However, at circumneutral pH the second order dependence on OH^- means that even small changes of 0.2 or 0.3 pH points can produce large changes in Fe(II) oxidation rate. Further explanation of the pH dependence of Fe(II) oxidation is given by Morgan and Lahav (2007).

$$\frac{dFe(II)}{dt} = -k[Fe(II)][O_2][OH^-]^2$$

Equation 1. Rate equation for Fe(II) oxidation at circumneutral pH

Lindsay

Data for dissolved oxygen (DO) and pH at the top and bottom of the cascade are shown in Figure 3. A schematic of the cascade is shown in Figure 4. The DO is relatively high at the top of the cascade; this is believed to be due to entrainment of oxygen as the mine water falls into the sump. Thus the oxidation process begins in the sump, and the rising main pipes require regular jetting to prevent rapid blockage. The Coal Authority now seeks to design sumps which do not entrain oxygen, thus minimising this maintenance issue. Fluctuations in the data are an artefact of the on/off water pumping cycles at the site. Unfortunately flow rates were not measured at the same time as pH and DO so rates of gas transfer cannot be calculated, although if required estimates could be made using the site flow data. Aside from the aqueous chemistry it is worth noting the build up of ochre behind each of the steps in the cascade. This is not the fluffy ochre seen in the lagoons, but dense hard flecks of solid and is discussed further at the end of this section.

Taff Merthyr

The aeration cascade that feeds lagoon L2 was studied. A schematic of the cascade is provided in Figure 4. The change in pH between the top and bottom of the cascade is plotted in Figure 3 along with the change in DO. Like Lindsay, the mine water is partly pre-aerated at the pumping sump, with pH increasing down the cascade (though the pH increase here is somewhat greater), suggesting CO_2 degassing.

The dissolved oxygen results also show a similar trend to that observed in the Lindsay data, fluctuating with the pumping cycles. The rise in DO is much greater at Taff Merthyr, approximately 3-4 mg/l, compared to just 1-2 mg/l at Lindsay, showing this cascade to be more necessary. The final level of DO reached in both cases is very similar, as it is approaching saturation in both cases. While this shows that both cascades are successful in increasing DO their efficiency with regards to CO_2 degassing requires further study.

Morlais

The cascade at Morlais differs from those at Lindsay and Taff Merthyr in that the channel narrows over the length of the cascade as shown in Figure 4 rather than remaining of a fixed width. Observations suggest that this narrowing increases the turbulence and entrainment of air bubbles, though a more detailed study of the cascade would be required to confirm this in terms of rates of gas transfer.

It has been suggested that the use of a series of plunge pools in place of a simple cascade will increase the gas transfer (PIRAMID, 2003) over a cascade. The narrowing of the cascade at Morlais creates areas of deeper water where mixing can take place so perhaps it is not surprising that the greatest change in pH of 0.28 occurred here compared to 0.06 and 0.13 and Lindsay and Taff Merthyr respectively (average values). Due to technical difficulties at the time of monitoring no DO data are available for Morlais.

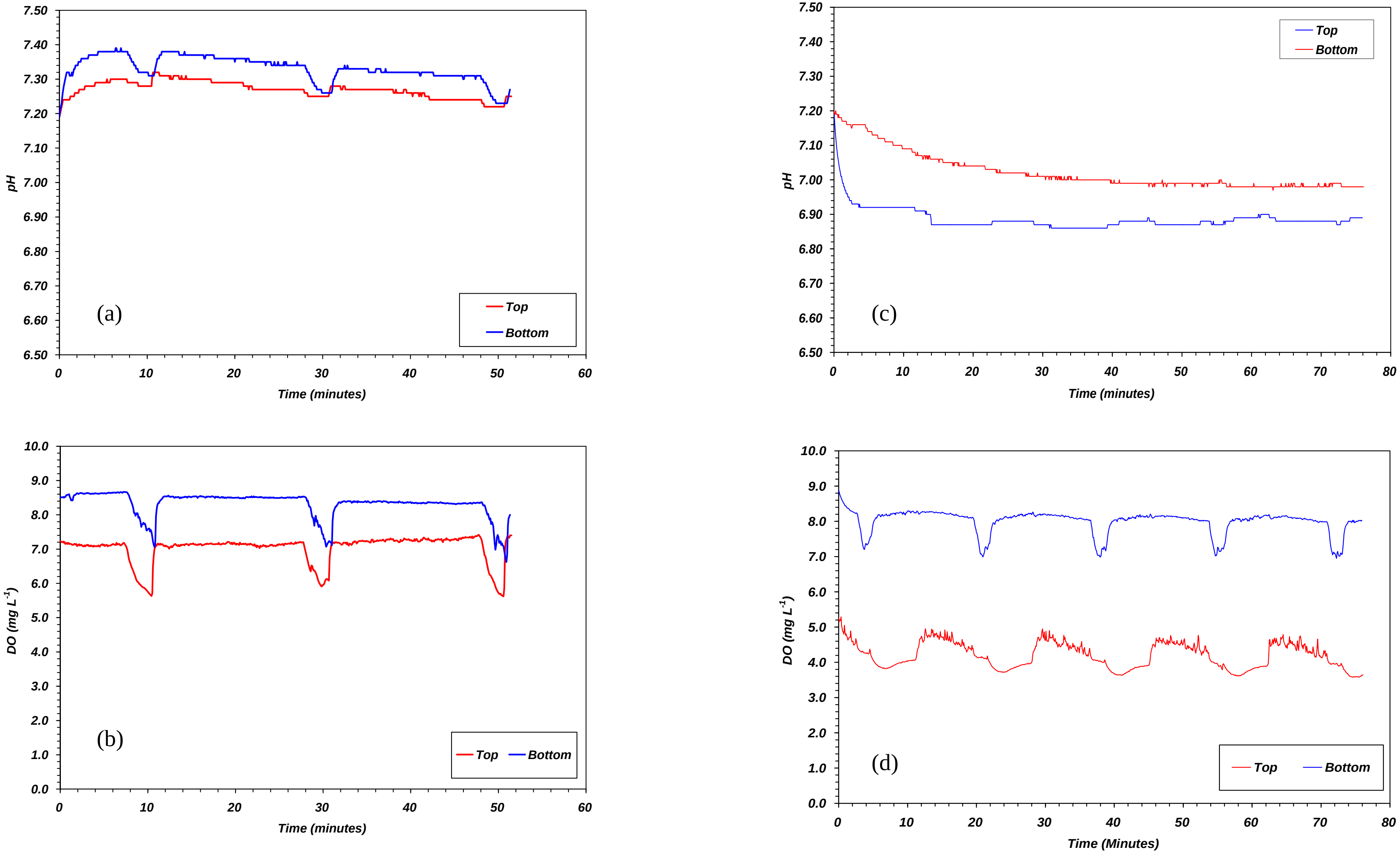

Figure 3. pH and dissolved oxygen data for aeration cascades at Lindsay (a) & (b) and Taff Merthyr (c) & (d)

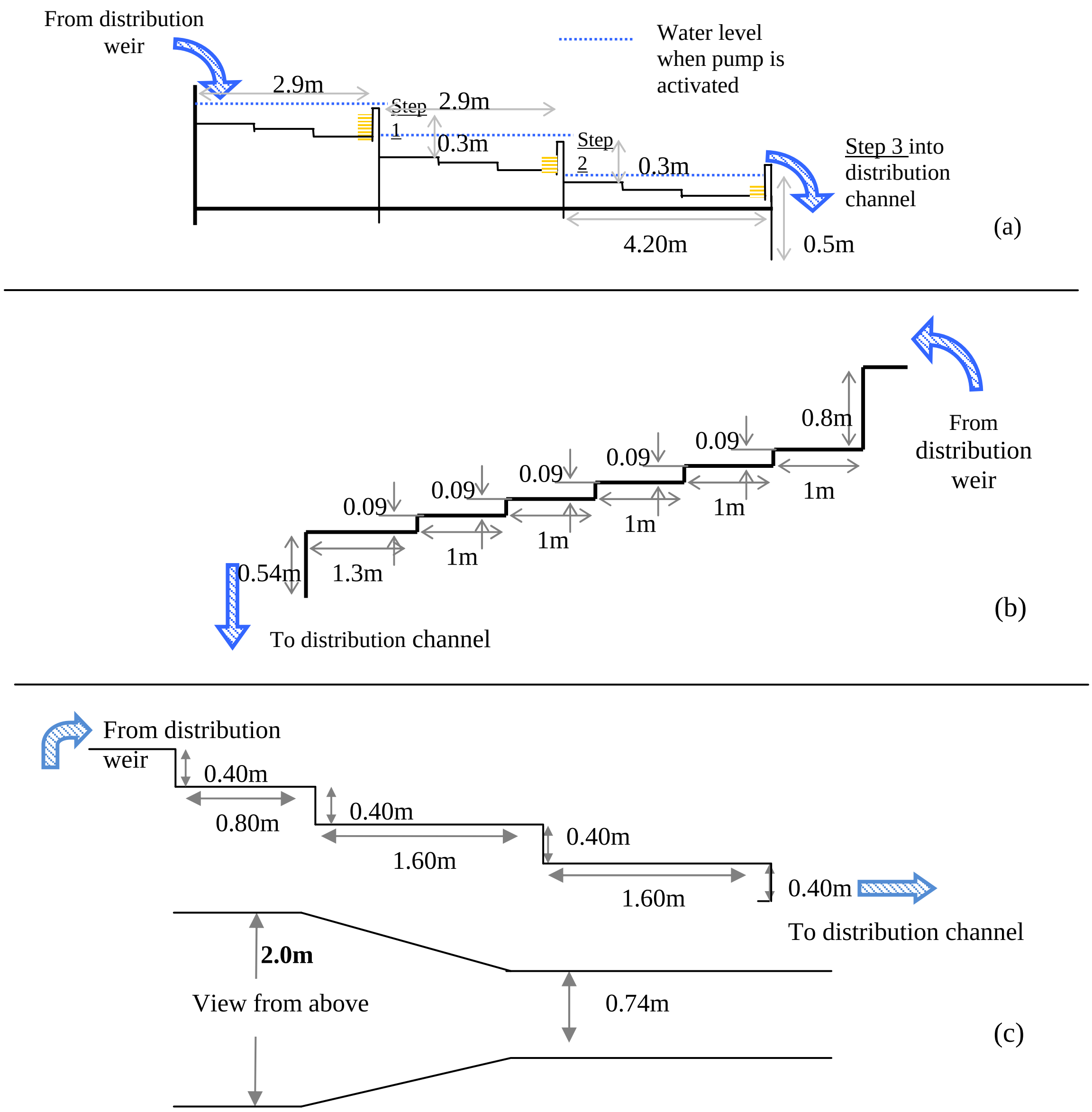

Figure 4. Schematic diagrams of aeration cascades at (a) Lindsay and (b) Taff Merthyr (c) Morlais (Not to scale)

General Observations

In addition to the data presented above other more qualitative observations and measurements were made during the study and are briefly outlined below. Scoop sampling of the sludge accumulated in the Taff Merthyr lagoons revealed that at depth the samples were olive green rather than the orange colour seen from the surface. The green colouration is indicative of Fe(II) hydroxide possibly formed by the bioreduction of Fe(III) as PO_2 decreases with depth. The bioreduction of Fe(III)(hydroxy)oxide and formation of green rust is documented in O'Loughlin et al (2007) and is a potential mechanism for the remobilisation of Fe(II) into the system.

It was noticed that ochre formations at the outlet of the distribution weir at the Lindsay site were hard, brittle and thinly layered with a black substance that was almost glassy in appearance. These deposits were formed where falling water impacted on a hard surface and so were not the result of accumulations of settled ochre flocs. Flecks of this solid had built up behind the steps in the aeration cascade and were also responsible for fouling of the aeration channel. XRD analysis of the samples showed the brittle solid to be goethite.

5. CONCLUSIONS

1. All of the sites studied were meeting their discharge consent at the time of monitoring.

2. Site surveys of existing treatment schemes provide a wealth of data that can be used to inform more effective designs for future systems.
3. Maximising gas transfer over aeration cascades is important not only in terms of increasing dissolved oxygen, but possibly more importantly raising pH by maximising CO_2 degassing.

As land for passive mine water treatment schemes becomes increasingly scarce and increasingly costly it is necessary to find ways to maximise the iron removal efficiency of such systems and hence reduce their required footprint. Increasing understanding of the mechanisms of iron removal in lagoons and maximizing their efficacy is important in ensuring that systems are no longer oversized as has happened in the past. One way to allow for a reduction in the size of lagoons is to increase the Fe(II) oxidation rate, something that can be achieved by optimising gas transfer through careful aeration cascade design.

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