Beyond Piramid: The Coal Authority's Approach to Design of Passive and Semi-Passive Treatment Schemes for Ferruginous Mine Waters in the UK

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Abstract

Since the publication of the Piramid guidelines in 2003, the Coal Authority has brought over 40 passive treatment schemes into operation that treat 72 billion litres per year of ferruginous mine waters. Over this time the organisation's approach to design has followed the recommendations of Piramid, with adaptions based on our operational experience. Key areas of development include the move away from areal removal rates for iron to the use of a combination of operationally derived rate constants and minimum residence times for design of lagoons and reed beds; the use of multiple treatment trains to accommodate high flows; and the treatment of saline and seasonably variable water qualities. The key applications for this work are to inform practitioners managing similar net-alkaline mine waters on the approach adopted by the Coal Authority that can help promote more effective adoption of passive treatment approaches internationally.

Keywords: Treatment design, coal mine water, ferruginous, net-alkaline, passive

Introduction

Since their publication, the guidelines produced by the Piramid Consortium (2003) have become a key resource in the design, construction, operation and maintenance of mine water treatment schemes (MWTS). The guidelines represent a concerted effort to collate the key scientific and technical knowledge on mine water treatment available at the time and have been used successfully in the development of MWTS across the globe.

In the UK, the Coal Authority has responsibility for the management of mine water originating from coal mining activities and currently manages a portfolio of 75 treatment schemes. This operational portfolio includes over 40 passive coal MWTS designed and built following the publication of the Piramid guidelines. These treatment schemes combined treat a total of 72 billion litres per year of ferruginous mine waters, preventing almost 1,000 tonnes of iron and 50 tonnes of manganese from entering UK watercourses each year.

Over the last 20 years the Coal Authority's approach to passive treatment design has been based on the recommendations of Piramid. However in recent years, the approach has been adapted based on our more recent operational experience. This paper will outline how our approach has moved on from the Piramid guidelines based on 20 years of design, construction and operational experience of passive mine water treatment across aeration, settlement and the use of aerobic wetlands (reed beds).

UK Coal Mine Water Chemistry

Coal mining has occurred across large parts of the island of Great Britain peaking in the deep coal mining activities in the late 19th and early to mid-20th centuries, with major coal mining areas across the Central Belt of Scotland, the North and Midlands of England and South Wales. The resultant mine water chemistry from these abandoned mines is variable, but is largely circum-neutral and net alkaline in nature due to the carboniferous limestone geology present in most UK coal mining areas.

UK coal mine waters typically contain appreciable levels of iron (present in ferrous and ferric states) as well as levels of manganese but generally very low levels of ecologically toxic metals such as zinc, cadmium or lead. The levels of anionic species can vary between mining areas with some mine waters being significantly more saline than others with salinity largely dominated by chloride and sulfate. In a small number of cases, UK coal mine waters can be marginal or net-acidic in nature or show variations in acidity related to the seasonal interaction of water with local geological and mining features.

Table 1 shows some examples mine water chemistries for a range of UK coal mine waters to demonstrate the discussion above. It is noted that mine water flow rates experienced in the UK can also be highly variable, ranging from a few L/s to several hundred L/s.

Passive treatment for net-alkaline circum-neutral ferruginous mine waters

The general approach to treatment of typical UK coal mine waters adopted by the Coal Authority remains in line with that recommended by the Piramid guidelines in that a combination of aeration units, settlement lagoons and aerobic wetlands (reed beds) are used to remove iron from mine waters. Depending on the iron levels and discharge requirements following aeration, either settlement lagoons, aerobic wetlands or a combination of both are used to reduce iron levels to typically 1-3 mg/L prior to discharge to the environment.

Mine water aeration

Aeration of mine waters is achieved through the use of stepped cascades. The Piramid guidelines state that a range of step heights/ numbers and cascade designs were possible including the use of deep plunge pools to aid in aeration. Operational experience on a range of sites constructed since 2003 have enabled the Coal Authority to develop a standard design that allows the construction to be undertaken using concrete units of standard dimensions as per Figure 1.

Standard cascade designs currently utilise five steps, each with a typical drop of 500 – 525 mm and a step length of ≈1000 mm, with a slight fall back towards the upper step to allow a very shallow pool of water to be present. Step widths are a standard 100 mm per 1 L/s of flow in line with Piramid recommendations, with a maximum width of 2.5 m (equivalent to 25 L/s) for a single cascade unit to enable safe access for inspection and maintenance. Where flows greater than 25 L/s require treatment, multiple cascade units arranged in parallel are used (usually within an overall single structure).

Such cascade designs show good aeration performance with dissolved oxygen concentrations of 70-90% saturation achieved. This enables oxidation of between 30 - 50 mg/L of ferrous iron per aeration stage without the need to use large plunge pools. For design purposes, a more conservative maximum of 30 mg/L ferrous iron is used per aeration stage, as recommended by Priamid. However, where site constraints (such as available land area and/or topography) prevent passive re-aeration over subsequent cascades then the use of a chemical oxidation (such as hydrogen peroxide) may be required.

At ferrous iron concentrations between 30–50 mg/L, it is possible that sufficient aeration may be achieved using a single cascade; the Coal Authority has a number of examples where single cascades provide sufficient oxidation of iron at these concentrations (e.g. Great Clifton, Cumbria and Horden, Country Durham). Consequently, where it is not feasible to install secondary cascades at sites when iron concentrations fall within this range, provision is made for the subsequent installation of peroxide dosing equipment if it is found to be necessary, rather than installing equipment in the initial design. A typical standard cascade construction is shown in Figure 2.

Table 1 *Examples of typical coal mine water chemistry and flows (annual averages) in the UK*

Mine water discharge	Total Iron mg/L	Dissolved Iron mg/L	pH	Alkalinity mg/L eq. $CaCO_3$	Chloride mg/L	Flow L/s
Woodside (Derbyshire)	5	3	7.7	808	1216	110
Bullhouse (South Yorkshire)	63	57	5.4	56	72	30
Deerplay (Lancashire)	30	29	7.1	238	8	25
Dawdon (Co. Durham)	54	53	6.7	465	18678	100
Sheephouse Wood (South Yorkshire)	31	22	6.1	119	82	5

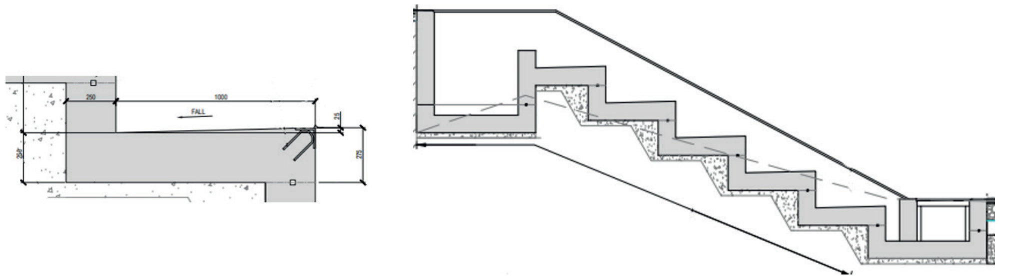

Figure 1 Aeration cascade pre-cast unit standard design cross section (left, all measurements in mm) and typical overall arrangement cross-section including inlet and outlet channels (right)

Settlement Lagoons

For mine waters where iron concentrations are >10 mg/L, settlement lagoons are deployed to allow for the completion of the oxidation and settlement of iron solids prior to further treatment in wetlands. The Coal Authority has followed the recommendations of the Piramid guidelines in terms of typical depth (3m) and side slope ratio (2:1, where ground conditions allow). Settlement lagoons are lined with an impermeable liner to prevent ingress of partially treated mine water into underlying aquifers prior to discharge. Various methodologies for sizing of such lagoons were noted in the Piramid guidelines including the use of a nominal 48 hour residence time, an allowance of 100m^2 of lagoon area per L/s of water and using areal removal rates derived from anaerobic wetlands (e.g. 10 g/m^2/day derived from the work of Hedin *et al.* (1994)). It is acknowledged that these methods lead to a wide range of treatment areas and thus run the risk of under- or over-sizing these lagoons. Initial work by the Coal Authority to derive relationships between iron removal and hydraulic retention time from our operational schemes was also mentioned (Parker 2003). A review of 15–20 years' worth of additional operational data from our 75 operational mine water treatment schemes in the UK has allowed further refinement of that approach, utilising prior research by Tarutis *et al.* (1999) with a first order relationship derived initially for wetland treatment (Eq. 1).

Figure 2 A recent cascade installation (2021) for a maximum flow rate of 80 L/s split into 4 cascades of 2 m individual width to aid in access of inspection and maintenance (Bullhouse, South Yorkshire)

Eq. 1 $$A = \frac{Q}{k_1 \ln(C_{in} - C_{out})}$$

Where A is the treatment area (m^2), Q is the mine water flow (m3/day), C_{in} and C_{out} are inlet and outlet iron concentrations (mg/L) respectively, and k_1 is the first order removal constant (m/day).

For existing schemes where treatment areas, flows and inlet and outlet concentrations are known, it is possible to calculate the removal constants, which can then be used in future designs. These constants are under continuous review but currently a removal constant of 0.8 m/day is used for the design of new settlement lagoons. In order to add some conservatism to a scheme design however, all lagoon treatment areas calculated using this approach are compared to the treatment area required for a minimum hydraulic residence time of 24 hours per lagoon, to prevent under-sizing of lagoons. This approach represents a more narrowly defined potential range of treatment areas than the previous methodologies proposed in the Piramid guidelines and ensures that performance from actual schemes forms the core basis for future designs.

In addition to absolute sizing for treatment performance, a number of other factors need to be considered to aid in the successful operation and maintenance of treatment schemes. Based on prior experience, the Coal Authority uses a maximum flow rate of 50 L/s for a single treatment train, therefore, for higher flow rates, multiple treatment trains are generally recommended. This is to ensure that individual treatment units can be taken off-line for maintenance activities with minimal impact to overall treatment performance. Furthermore, allowances in settlement lagoon design for sludge accumulation must also be considered. The Coal Authority uses an assumption that sludge accumulates as 3 wt% $Fe(OH)_3$ based on the iron removal rate with a planned de-sludge cycle of five years in normal circumstances.

Another key consideration for the successful operation of lagoons is maintaining an even distribution of flow across the treatment unit. Water inlet channels are designed to maximise the lateral distribution of water across the full width of the lagoons using crenelated weirs to reduce dead zones. Baffles have also been installed at some sites (e.g. at Clough Foot and Deerplay, Lancashire) to improve flow distribution, but the success of these has been limited to date.

The above approach has allowed the Coal Authority to reliably design settlement lagoons to achieve treatment down to 10 mg/L or less on its passive treatment schemes enabling further treatment by aerobic wetlands where required. This approach has been applied to high flow rates such as the Lynemouth MWTS (constructed 2015–2019) in Northumberland that can treat up to 240 L /s of mine water with a typical raw iron concentration between 40–50 mg/L (Figure 3). This scheme features a total of seven rectilinear treatment ponds in three treatment trains with a total treatment area of 28,000m^2 reliably treating water to <10 mg/L total iron ready for discharge into the North Sea.

Polishing – Aerobic wetlands (reed beds)

Where further iron reduction to achieve final discharge concentrations <3 mg/L is required (i.e. where discharge is to occur to an inland watercourse) then passive treatment using aerobic surface flow wetlands (or reed beds) is standard practice for the Coal Authority. In the UK, mine water treatment reed beds are typically planted with common reed (*Phragmites australis*), Bulrush (*Typha latifolia*) or a combination of the two. *Phragmites* has been found to be a generally hardy plant when exposed to a range of mine waters and UK climates. For example, reed bed wetlands have been successfully operated by the Coal Authority treating high chloride mine waters (typically approx. 10,000 mg/L) in a coastal setting (e.g. Horden, County Durham, constructed 2011), in exposed upland areas (elevation 400 m AOD, Deerplay, Lancashire,

Figure 3 *Aerial photograph of the Lynemouth mine water treatment scheme in Northumbria showing a series rectilinear ponds. In the background is the Lynemouth Power Station and in the foreground is a stocking area for dried and bagged iron ochre produced by the scheme for use in anaerobic digestion.*

constructed 2002) and at northerly latitudes (56˚N, Lathallan Mill, Fife, constructed 2004). The latter of these examples is considerably more northerly than the recommended 53˚N as stated in the Piramid guidelines, however this may due to the impacts of the North Atlantic Drift and climate change on the UK climate, as well as the feed of constant temperature mine water throughout the year. For reference the city of Stoke-on-Trent is located at a latitude of 53°N.

The Coal Authority also utilises the Tarutis first order relationship to assess and size reed beds for the treatment of coal mine waters (Eq 1). Performance of reed beds for iron removal has been found to be quite variable with first order rate constant for UK reed beds typically in the range of 0.2–3.0 m/day, equivalent to areal removal rates of between 1–14 g/m^2/day with overall average performance for the Coal Authority's reed beds yielding a removal constant of 1.2 m/day equivalent to an areal removal rate of 3.2 g/m^2/day) meaning that the standard recommended areal removal rate of 10 g/m2/day would tend to undersize a reed bed. With such large variations in performance within the Coal Authority's schemes, final decisions on reed bed areas for a new scheme are made on a risk-based approach, which considers areas derived from the range of observed rate constants alongside site specific factors such as land availability, local climate, elevation, mine water quality and impact of underperformance amongst other factors.

In the Piramid guidelines a number of recommendations were made regarding the design of reed beds to improve their habitat and amenity value as well as performance. These include discouraging the use of liners, using uneven surfaces with spits and islands, avoiding significant concrete structures and softening edges of reed beds. Coal Authority reed beds have impermeable liners to prevent potential contamination of the water table. Lined reed beds have generally performed well in our experience with liner damage being a rare occurrence. The use of uneven surfaces, islands and spits creates challenges in terms of effective maintenance (reed cutting and refurbishment) of reed beds, in addition to the creation of 'dead zones' where water flows are low; inclusion of these features is no longer part of standard Coal Authority designs. The use of rectilinear reed beds with concrete inlet and outlet structures does not appear to have the detrimental impact to amenity and habitat value feared within the Piramid guidelines. The Coal Authority has a number of such reed beds that function well, are used as amenity areas by local communities and have observed biodiversity comparable to natural wetlands (Athorn 2018) with a range of insects, flora, small mammals and birds observed at our sites.

In recent years, reed bed designs have begun to include provision for an unplanted open water zone at the front of primary reed beds where iron concentrations are highest. This helps to prevent reed fouling of inlet structures and allows further precipitation of ochre which can be easily removed during maintenance without disturbing the reed area. It is important to note that for new schemes, such areas must be considered in addition to the calculated reed bed areas.

The above principles have been applied to a range of reed beds for coal mine waters in the UK including at schemes with high flows. A key example is the Blindwells scheme, East Lothian, which is a series of three reed beds (total area 17,415 m^2, design flow rate 450 L/s) typically treating a flow of 300 L/s of mine water with an average iron concentration of 5 mg/L and an average iron removal rate of 90% (Figure 4).

Chemical dosing (semi-passive treatment) & seasonally acidic mine waters

In some cases UK coal mine waters can experience seasonal variations in chemistry changing from net-alkaline in the summer, to net-acidic in the winter. This is understood to be related to higher winter water levels interacting with weathered coal and other mineral workings that are usually not flooded in the summer months. One example of this is at Clough Foot, West Yorkshire where net-alkaline mine waters turn net acidic with increased aluminium levels in winter months. Whilst passive alkalinity provision is possible as outlined in the Piramid guidelines, sizing such units for variable water qualities is highly challenging, as is the management of such systems with relatively high iron concentrations (e.g. Clough Foot raw total iron concentrations are ≈30 mg/L).

To counter this, the Coal Authority's approach has been to use sodium hydroxide dosing as this not only has a lower land footprint, but is more flexible in providing alkalinity during seasonal water chemistry variations. Dosing rates are determined by calculating the alkalinity demand for iron and aluminium precipitation, as well as including a pH correction to a defined target value (typically pH 7.0–7.5) using data obtained from routine sampling. Based on experience a conservative assumption of 80% chemical efficiency is used to ensure reliable treatment of the mine water is achieved and to account for any chemistry variations between monitoring rounds.

Conclusions

This paper provides a high level discussion of the Coal Authority's current approach to treating ferruginous coal mine waters in the UK. The key applications for this work are to inform mine water practitioners who may be dealing with similar mine waters on the approach adopted by the Coal Authority that can help promote more effective adoption of passive treatment approaches internationally as we look towards updating the Piramid guidelines in the coming years.

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Figure 4 *Aerial photograph of the Blindwells scheme in East Lothian, showing a cascade and three reed beds in series with a conditioning zone at the front of the primary reed bed (©Vexcel imaging ©2023 Microsoft, Microsoft Bing Maps screen shot reprinted with permission from Microsoft Corporation).*