Application of the Welsh Mine Water Strategy: Cwmrheidol Case Study

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Abstract

Minewater emanating from two adits at the Cwmrheidol abandoned metal mine site is contributing significant quantities of lead and zinc to the Afon Rheidol watercourse. As part of a new strategy to deal with such waters, the Environment Agency commissioned SRK Consulting to provide remedial designs for the management of the mine site and the protection of the local watercourses. This is the first set of mine sites to be treated under the new strategy and the risk-based approach adopted to derive remedial designs is described. The minewaters have a pH of approximately 3 and contain a cocktail of elevated metals, including iron, copper, zinc, cadmium and lead. The preferred minewater treatment option is the use of limestone dissolution, ochre precipitation, and a Reducing and Alkalinity Producing System. Other remedial measures are also recommended that reduce the volume of minewater requiring treatment.

1 Introduction

The mid-Wales orefield was extensively worked during the 17th and 18th centuries, as described by Bick (1975), Lewis (1967), and Rees (2004). Much of the working had however ceased by the early part of the twentieth century, with only a limited revival for lead in the 1960’s (Lewis 1967). Today, metal mining is virtually non-existent apart from specialist gold (EA 2002). As a consequence, there are now over 1500 abandoned metal mine sites in Wales (Bevins and Mason (1997, 1998, 1999)).

In July 2002, the Environment Agency (the Agency) published its Metal Mine Strategy for Wales (as described by Johnston (2004) and EA (2002). The Strategy documented the top 50 abandoned metal mine sites the Agency wish to remediate to prevent or reduce the impact they are having on local watercourses. The Cwmrheidol Lead Mine, at NGR SN 730 783 was identified as a significant contributor of lead and zinc to the Rheidol catchment and was therefore selected for detailed evaluation.

Steffen, Robertson & Kirsten (UK) Ltd (SRK) based in Cardiff was appointed by the Agency in May 2003 to undertake a site investigation of the Cwmrheidol metal mining site. The mine is hydraulically connected to five other mines (Ystumtuen, Penrhiw, Bwlchgwyn, Llwynteify, and Temple) and the aim was to treat the complex as a whole with the aim of providing detailed remedial designs to prevent or reduce the impacts to local watercourses. This paper documents the approach and the remedial plans recommended.

1.2 Site Description

The Cwmrheidol site is located some 8 km east of Aberystwyth, in West Wales, within an area known as the Central Wales Orefield (CWO) (Bevins and Mason 1997). The Cwmrheidol mine site is located on the northern slopes of the steeply-sided Afon Rheidol valley through which the river flows westward. The other sites are located above the Cwmrheidol site, in an area referred to, in this paper, as the upper plateau (Fig. 1).

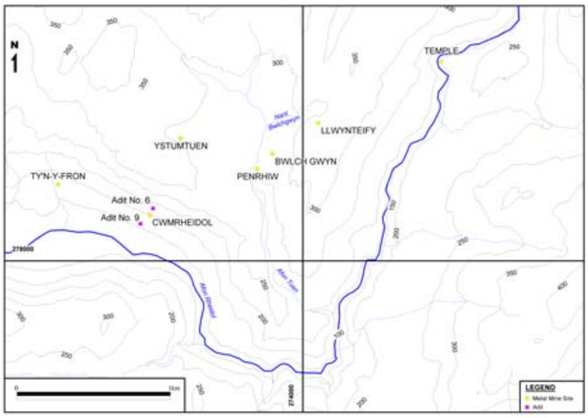


Fig. 1. Metal mine site locations and topography

The Cwmrheidol site comprises partially vegetated sulphide surface waste material deposited directly beneath two mine adits – upper adit No. 6 and lower adit No.9. Both adits are currently discharging acidic ferruginous mine water that has led to the accumulation of ochre along their channels and within the adits. Between the waste dumps and the river is a strip of relatively flat land that is split by a site access road, which is used by hill walkers and site visitors. Limited remedial works were attempted in the 1960's and comprised a limestone filter bed: a concrete lagoon containing limestone through which both adit discharges were intended to flow.

1.3 Environmental Geology

Wales plays host to a remarkably diverse range of metal deposit types considering its relatively small size (see Rees 2004). The most comprehensive and recent summary of the various styles of deposits and the mineralogy found is the MINESCAN study, commissioned by the Countryside Council for Wales (CCW) and undertaken by workers at the National Museums and Galleries of Wales (Bevins and Mason 1997, 1998, 1999).

In terms of mining activity and metal production, it was the Ordovician and Silurian polymetallic (principally lead-zinc) mineralisation hosted by clastic marine sediments of the CWO that were the most productive. The two principal ore sulphides at Cwmrheidol were galena and sphalerite. However, it is the occurrence of marcasite and pyrite that makes the discharges particularly acidic and iron rich. The acidity and metal loads found are unusually severe by Welsh (and wider UK) standards, with few discharges elsewhere containing such high levels of acidity and a diverse range of elevated dissolved metals (Rees 2004 and Younger et al. 2004b).

2 Risk Assessment

Critical to any remedial project is a thorough understanding of the plausible environmental risks and some way of ranking these risks so that resources are efficiently used to maximise environmental improvement. For each mine site, risk-based matrices were developed that highlighted the principle hazards on the basis of a desk study followed by a site walk-over. As the Agency remit is to protect the local watercourses, greatest priority was given to those issues that affected this goal. On this basis, two key issues were identified during the risk assessment:

- Inflow of water into the mine workings on the upper plateau, particularly along the stream bed of the Nant Bwlchgwyn and at a collapsed shaft at Llwynteify.
- Discharge of acidic, metal- and sulphate-bearing minewater at upper adit No.6 and lower adit No.9 at Cwmrheidol.

Monitoring undertaken by the Agency of the Afon Rheidol consistently indicates that the water quality fails to meet the anticipated River Ecosystem Classification on the basis of elevated zinc levels. This is due to the mine water discharges at Cwmrheidol as the mining complex contributes some 35% of the total Rheidol zinc loading, with the discharge from adit No.9 typically contributing 70% of this value.

2.1 Minewater flow

Understanding the mine hydrogeology was considered critical for successful remediation. The detailed site walkover identified potential stream losses on the upper plateau along the Nant Bwlchgwyn stream bed and at a partially collapsed shaft at Llwynteify. According to available mine plans, water lost in these areas would eventually emerge at the Cwmrheidol adits. Such a connection was known to exist, as the Nant Bwlchgwyn stream channel catastrophically collapsed into underlying workings in 1986 during storm conditions. This collapse resulted in a surge of water at upper adit No.6, providing evidence of a connection. To prevent this re-occurring, a steel half-pipe was placed over a short section of the Nant Bwlchgwyn stream bed at the time. To establish the current relationship between stream flow on the upper plateau and the discharges at Cwmrheidol, and the performance of the steel stream channel, detailed flow gauging and a tracer test was commissioned in September 2003.

The subsequent monitoring results confirmed that surface water was being lost along the bed of the Nant Bwlchgwyn. The volume of water lost accounted for approximately 50% of the adit No. 6 discharge on the same day.

A tracer test was conducted in October 2003. The aim was to demonstrate a connection between the collapsed shaft at Llwynteify and the adits at Cwmrheidol. Tracer detection points were set up at the adits at Cwmrheidol and also adits at Temple. The latter points were included as it was unclear from the mine plans if a connection existed between the collapsed shaft and these adits. The testwork involved introducing Rhodamine B dye into the collapsed shaft at Llwynteify and monitoring for four days.

Dye was detected at adit No. 6 but not at adit No.9, due to malfunction of the autosampler. Despite that problem, the investigations indicated that recharge of the mined system drained by the adits at Cwmrheidol was occurring on the upper plateau.

2.2 Minewater chemistry and microbiology

According to the mine plans and mine geological summaries available, the greatest occurrence of acid generating sulphides is in the lower parts of the Ystumtuen mine, which are drained by adit No.9. Further east, the amount of pyrite and marcasite decreases and these minerals are rare in the open cuts at Bwlchgwyn and Llwynteify, which are drained by adit No.6. These differences in the geology and the influence of the mine hydrogeology are apparent from the minewater chemistry.

Table 1 contains a summary of selected water quality and flow data for the two adits while Table 2 summarises calculated metal loadings. On the basis of this monitoring data, which primarily covered the winter period, several key conclusions were made:

Table 1: Summary of selected water quality and flow data

Adit No.6	Date	Flow l/s	pH su	Temp.	D0 mg/l	Cl mg/l	Al mg/l	Cd mg/l	Fe mg/l	Pb mg/l	Zn mg/l	SO_4 mg/l
EA	24-Sep-03	3	3.59	10.12	10.6	12.3	5.35	0.0469	6.05	0.346	17.3	234
EA	15-Oct-03	50	3.62	9.92	10.94	<10	3.75	0.0354	4.64	0.473	12.4	182
EA	13-Nov-03	7	3.55	10.05	11.09	-	3.67	0.0404	4.56	0.546	13.4	184
EA	20-Nov-03	17	3.58	9.98	11.34	-	2.72	0.0302	3.55	1.24	10.72	139
EA	22-Dec-03	19	3.6	8.71	10.71	18.6	2.74	0.0363	4.87	0.854	11.6	134

Adit No.9	Date	Flow l/s	pH su	Temp.	D0 mg/l	Cl mg/l	Al (f) mg/l	Cd (f) mg/l	Fe (f) mg/l	Pb (f) mg/l	Zn (f) mg/l	SO_4 mg/l
EA	24-Sep-03	2	3.08	11.09	2.48	14.9	<0.004	0.137	186	0.00445	113	1140
EA	15-Oct-03	16	3.01	10.63	2.71	10	39.2	0.131	175	0.00572	102	1130
EA	13-Nov-03	9	3.16	10.7	5.06	-	27.3	0.0928	110	0.0104	-	823
EA	20-Nov-03	5	3.12	10.53	6.61	-	21.9	0.0775	125	0.0133	-	794
EA	22-Dec-03	2	3.03	9.94	7.02	17.3	20.9	0.0761	57	0.013	51.7	564

Note: All metal values are dissolved values and account for >95% of total measured values

Table 2: Calculated loadings at Cwmrheidol adits

	Flow	Loadings kg / day						
Adit No.6	**m3/day**	**ACIDITY**	**Total Fe**	**Total Al**	**Total Zn**	**Total Pb**	**Total Cd**	**SO4**
24-Sep-03	259	22.5	2.4	1.4	4.5	0.1	0.012	60.7
15-Oct-03	4320	272.4	23.4	17.0	54.0	2.1	0.154	786.2
13-Nov-03	605	40.8	3.9	2.3	8.1	0.4	0.024	111.3
20-Nov-03	1469	78.6	6.2	4.2	15.5	2.0	0.046	204.2
22-Dec-03	2074	75.6	13.0	4.8	2.8	1.4	0.060	220.0
Adit No.9								
24-Sep-03	173	95.9	33.0	-	19.4	0.001	0.024	197.0
15-Oct-03	1382	1002.4	239.2	53.1	138.2	0.018	0.180	1562.1
13-Nov-03	778	395.7	92.5	21.1	56.1	0.009	0.071	640.0
20-Nov-03	432	213.3	53.1	10.4	28.9	0.007	0.039	343.0
22-Dec-03	259	62.2	11.0	3.7	9.1	0.004	0.013	97.5
Combined minewaters								
24-Sep-03	432	118.4	35.4	-	23.9	0.095	0.036	257.6
15-Oct-03	5702	1274.8	262.6	70.1	192.2	2.113	0.334	2348.4
13-Nov-03	1382	436.4	96.4	23.4	64.2	0.368	0.095	751.2
20-Nov-03	1901	291.9	59.3	14.6	44.4	2.005	0.085	547.2
22-Dec-03	2333	137.8	24.0	8.5	11.9	1.450	0.073	317.4
% of adit No 6 as a function of combined minewaters								
24-Sep-03	60%	19%	7%	-	19%	99%	34%	24%
15-Oct-03	76%	21%	9%	24%	28%	99%	46%	33%
13-Nov-03	44%	9%	4%	10%	13%	98%	25%	15%
20-Nov-03	77%	27%	10%	29%	35%	100%	55%	37%
22-Dec-03	89%	55%	54%	57%	23%	100%	82%	69%

- Despite adit No. 6 typically accounting for over 60% of the combined minewater flow, metal loading from adit No.6 is typically less than 30% of the total loading from both adits.
- Adit No. 6 discharge is far more responsive to changes in flow, and chloride levels significantly decrease under higher flow conditions. This suggests better connection with mine workings on the upper plateau that are being recharged by recently infiltrated surface water.
- Metal concentrations within adit No.9 discharge do not significantly decrease during high flow conditions whereas those in adit No.6 do. This suggests that under high flow conditions, adit No.6 discharge is diluted by relatively clean water from surface recharge while rises in the water level in adit No.9 results in release of significant stores of secondary products.

Some moderately acidophilic (growth from pH 6 to 3) iron-oxidising bacteria were detected in the waters, but these were outnumbered by the more extreme iron-oxidizing acidophiles (growth from pH 3 to 0) *Leptospirillum ferrooxidans* and *Acidithiobacillus ferrooxidans*.

4 Remedial Design Evaluation

Following a thorough review of available technologies, three main potential treatment options were considered for detailed evaluation:

- Passive treatment using a compost-based Reducing and Alkalinity Producing System (RAPS) based system;
- Active alkali dosing using lime; and
- Sulphide formation using liquid bioreactors.

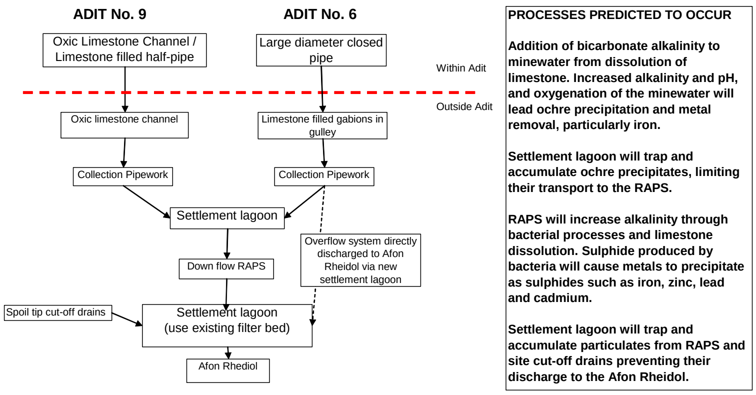
4.1 Passive Treatment Options

Within the EC, the most recent guidelines for the passive treatment of acid mine drainage are PIRAMID (2003). According to these guidelines, and experience at other mine sites, the most suitable option for the passive treatment of the acid mine water at Cwmrheidol would be a RAPS. This is because anoxic limestone drains (ALD) are unsuitable due to the waters being partially oxygenated and containing ferric iron and aluminium. Further, there is potentially suitable land available directly below the adits to take advantage of the hydraulic gradient available in the steep sided valley.

RAPS operate by passing the water vertically through a compost bed underlain by a layer of limestone as described in PIRAMID (2003). Recent designs have incorporated mixed compost/limestone beds as described by Younger et al., (2004a) for two RAPS at Bowden Close, County Durham.

To obtain maximum removal of metals such as lead, zinc, and cadmium within the RAPS, the high iron and acidity loadings would first need to be reduced as much as possible. This could be achieved by constructing limestone channels within which the mine water would flow and/or optimising bacterial iron oxidation. Precipitates formed during these processes could be captured in a settlement lagoon. Figure 2 is an outline of the conceptual system considered.

Figure 2: Outline of conceptual passive treatment system



4.2 Alkali dosing

Several reagents exist for the introduction of alkali to minewater as discussed in detail by Coulton *et al*, (2003). The most common reagent used for minewater treatment is lime. Several options exist for the application of lime but one option which is widely adopted is a High Density Sludge (HDS) process where hydroxide sludge is recirculated with the mine water prior to the addition of the lime. Sludge produced from such dosing is reduced in volume, thereby minimising the volume requiring storage and ultimately landfill. Fig. 3 outlines the conceptual process flow chart for an anticipated lime dosing plant.

Typically, such an active treatment plant would occupy an area some 40 m by 40 m. However, in addition to the requirements of the treatment plant itself, the system would also require the controlled collection of minewater at the adits, transport of the minewater to a flow attenuation lagoon and storage of the sludge produced in a lagoon.

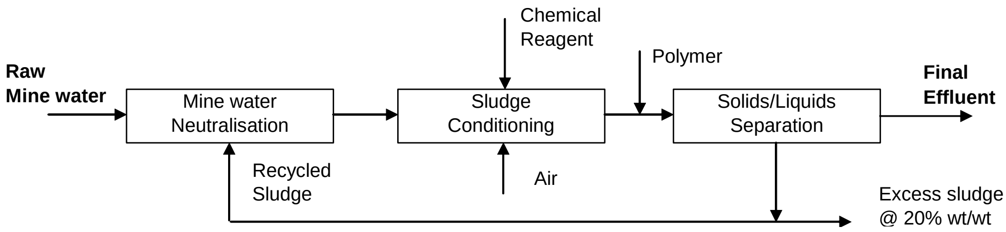


Fig. 3. Outline of a conceptual alkali doing plant

4.3 Sulphide formation using bioreactors

Within compost-based bioreactors such as RAPS, it has been found that the permeability of the substrate decreases with time unless active management occurs. As the compost is broken down into smaller particles, biofilms form and metal sulphides precipitate. As a consequence, pore space decreases and flow is potentially restricted. Also, the rate of bacterial processes and therefore metal sulphide removal can not be controlled as the substrate must be added in excess to allow for multiyear life. As several types of substrate are commonly incorporated into RAPS initially, these are utilised at different rates. As the more bioavailable material is utilized preferentially, the rates of reaction are anticipated to decrease with time unless the compost is replenished or supplemented.

In response to these potential limitations, metal sulphide formation using liquid based bioreators are being increasingly applied for the treatment of mine waters. Liquid bioreactors are based on the same principles as RAPS; bacterial sulphate reduction (BSR) causes the formation of metal sulphides. However, the matrix consists of non-reactive material such as cobbles or sand, which act as inert hosts for bacterial populations. Such systems are therefore considered to maintain a near constant permeability over time. A potential simplified process flow chart for a liquid bioreactor is shown in Fig. 4 (adapted from Younger et al. 2002).

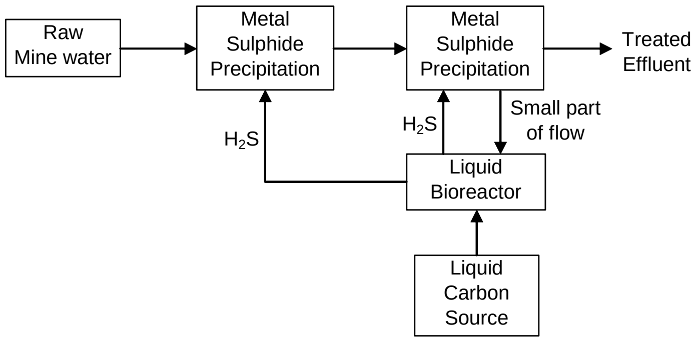


Fig. 4. Outline of a conceptual liquid bioreactor plant

The footprint of a liquid bioreactor would be similar to that of an active alkali plant. However, due to the instability of the sulphide sludge under oxidising conditions, the sludge would require sub-aqueous storage, as occurs in a RAPS.

4.4 Ranking matrix

Selection of a suitable minewater remedial design requires the consideration of several factors: technical aspects, stakeholder views, long-term sludge handling, life-cycle assessment, regulatory compliance and cost. To select the preferred minewater treatment option, a ranking matrix was developed that allows all of these factors to be scored relatively. The treatment option with the lowest total score is the preferred option on the basis of these criteria. Coupling this appraisal to budget cost estimates enables each potential treatment option to be ranked in terms of perceived cost-benefit.

The scores given to each factor reflect experience from other UK and international minewater remedial schemes, the compilation of views presented in the Agency Metal Mines Strategy, opinions of various stakeholders, and an appraisal of the long-term technical capability and practicality of each potential treatment option.

The matrix (see Table 3) indicated that there was no distinction between the three potential treatment technologies, reflecting that:

- Active treatment requires a flow attenuation pond and sludge storage area, such that the footprint between the three treatment options is not wholly distinct;
- Active treatment requires more involved routine management, including the disposal of sludge and replenishment of consumables;
- Stakeholders favour a passive treatment scheme; and
- Sludge stability from each of the treatment options being considered is similar in the long term as the only presently viable disposal mechanism is landfill.

Table 3 – Ranking Matrix Table

Treatment option	Impact on site aesthetics	Water quality control / achievement of water quality targets	Demonstrated Technology	Treatment system footprint	Stakeholder acceptance	Sludge stability	On-going maintenance requirements	**Total Score**	**Budget Capital costs (£ '000)**	**Annual operating cost costs (£ '000)**
Passive treatment using ochre accretion, alkali dissolution and RAPS	2	3	3	4	2	2	2	**18**	**510**	**91**
Active lime dosing	3	2	1	3	3	2	4	**18**	**525**	**140**
Active sulphide formation using liquid bioreactors	3	1	1	3	3	3	4	**18**	**610**	**Unknown**

Due to the similarity in ranking values between the three potential treatment technologies, cost comparison therefore becomes increasingly important in the overall selection process.

4.4 Cost Comparison

Unlike active treatment systems, the passive system does not involve the routine introduction of chemicals or sludge disposal. Consequently, passive systems are often regarded as systems requiring little maintenance. Although this is true in the short term and when compared to active treatment systems, there will at some point be a requirement to de-sludge the passive system and replace the substrate. Therefore, for the purposes of cost comparison, the RAPS was assumed to be operational for 10 years. Consequently, passive system operating costs given in Table 3 represent the total cost of sludge disposal and system replenishment averaged over 10 years at present-day rates. The other costs quoted in Table 3 for each treatment option include all ancillary and preparatory works, including site access and construction of lagoons for flow attenuation and temporary sludge storage.

4.5 Preferred Option

On the basis of the ranking matrix and the cost comparison, a passive treatment system was recommended as the preferred treatment option. This decision was based on the passive system:

- having the lowest capital and operating costs.
- being considered by several stakeholders to potentially add to the biodiversity, educational and aesthetic value of the site.
- potentially being better suited to the Agency financial funding structure, as funding would be required for the initial capital expenditure and the system replenishment, with only minimal expenditure required during the life of the system.
- not requiring the extensive use of manufactured chemicals and plant.

5 Remedial Measures Recommended

5.1 Upper Plateau

Primary works on the upper plateau are limited to:

- Simple diversionary works to stop the stream entering the collapsed shaft north of the Llwynteify reservoir.
- Investigation and stabilisation of the stream bed of the Nant Bwlchgwyn.

5.2 Cwmrheidol

Works recommended for the Cwmrheidol site include:

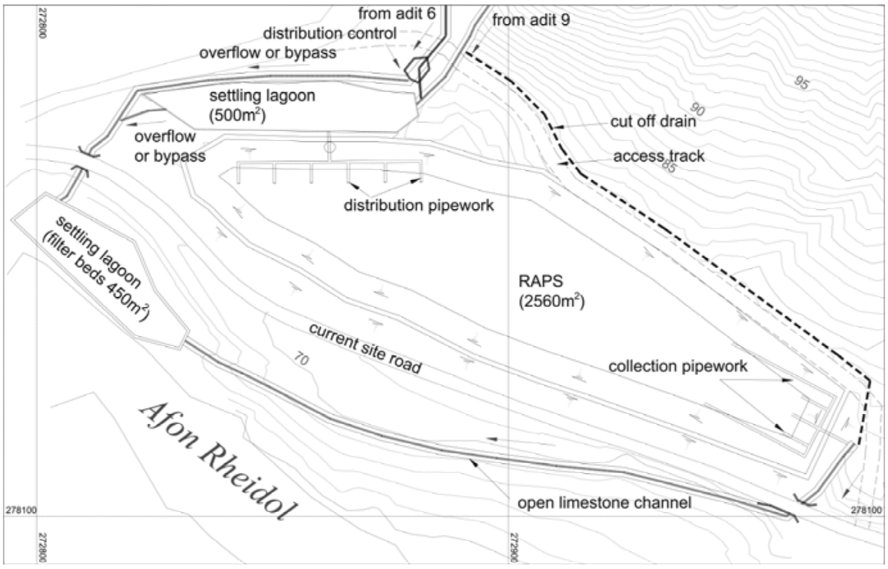
- Gaining safe access to both mine adits;
- Removal of ochre within the filter bed and adits;
- Internal geotechnical assessment of the filter bed;
- Conversion of the filter bed to a settlement lagoon; and
- Construction of the passive system north of the site road.

5.2.1 Minewater Capture

At adit No.6, mine water capture would comprise pipe work set in a granular bed to transfer the maximum flow rate observed (50 l/sec). At adit No. 9, a large diameter half-pipe filled with limestone set on a granular bed would be used for minewater capture. Both of these structures would extend as far as possible into each adit and comprise flow monitoring access and scouring capabilities to allow for the removal of accumulated precipitates.

5.2.2 Passive system outline

The main RAPS component of the passive treatment scheme is illustrated in Figure 5. Minewater from adit No. 6 would be directed using pipe work to the gulley created by the storm surge in 1986. From the top of the gulley, it would continue to flow in the closed pipe until a suitable gradient is reached where limestone gabions could be emplaced. At this point, the mine water would emerge from the pipe work and flow over and through the cobble-sized limestone clasts housed in the gabions. Mine water oxidation and limestone dissolution would occur and ochre precipitation and accretion encouraged.



Fig, 5. Plan of passive treatment system

Minewater from adit No. 9 would be collected via the open channel pipe work and directed to a settlement lagoon occupying some 500m^2 (1500m^3). This settlement lagoon would be designed to allow the precipitation and accumulation of ochre. The lagoon would also include by-pass measures to enable storm flow from adit No. 6 to by-pass the RAPS, thereby ensuring a consistent residence time and minimising the potential for inundation of the bacterial populations within the RAPS. This system would also offer the opportunity of only treating the more polluting adit No. 9 drainage should this be considered applicable, following initial operation of the system.

From the lagoon, the partially treated water would be directed via limestone filled channels to the RAPS. The RAPS embankments would be constructed using suitable material identified at site. To ensure the system is in keeping with the surroundings, the surface of the embankments would be covered by loosely tipped local waste material.

Distribution of the water to the RAPS surface would occur at several positions to minimise short circuiting. Ideally, the RAPS would consist of two cells, such that one could be taken off-line for maintenance. However, due to the limited land available, and to avoid the potential for re-oxygenation of the water and maximise the water retention time, just one unit is recommended. With an active area of 2560 m^2, 1m of limestone (either as one layer or mixed with compost), an assumed porosity of 40%, and a limestone density of 1.8, there should be sufficient limestone alkalinity present to neutralise the acidity from adit No. 9 for over 20 years. This does not include the alkalinity release along the open channels or via bacterial processes. Furthermore, with an active volume of 2560 m^3, treating only the more polluting adit No. 9 minewater would result in a residence time of some 5 days, assuming a flow of 5 l/sec.

The control of water level (and hence residence time and hydraulic gradient) is critical to the successful long-term performance of a RAPS. Consequently, the outlet structures would be constructed so that their height could be varied vertically and at least 1.5 m of free board above the static water level maintained.

6 Summary

Minewater emanating at two adits at Cwmrheidol comprises recharge from overlying workings. Upper adit No. 6 is highly responsive to rainfall due to good connection with the upper workings. Lower adit No. 9 is less responsive as it drains a less extensive, potentially poorly connected area of mine workings. To limit the volume of mine water requiring treatment at Cwmrheidol, drainage diversionary works are recommended to stop the flow of water into a collapsed shaft at Llwynteify and limit the loss of surface water along the Nant Bwlchgwyn stream bed.

Mine water at Cwmrheidol is acidic with a pH between 3 and 4, partially oxygenated and contains several elevated metals including iron, lead, zinc and aluminium.

The preferred treatment option for both adits is the use of a down-flow RAPS coupled to the use of limestone within channels and settlement lagoons to capture ochre precipitates and supplement alkalinity. Both minewaters would be captured within the respective adits and transported via separate routes to a common settlement lagoon with storm by-pass. From here, the flow would be directed at several points into the RAPS. The system is designed so that the less polluted adit No.6 discharge may be only partially treated, maximising the residence time of the more polluting adit No.9 discharge in the RAPS. Effluent discharge from the RAPS will be via an adjustable system allowing water levels and hydraulic gradients within the RAPS to be controlled.

Prior to detailed design of the system, an extensive programme of laboratory and site-based testwork is likely to be undertaken to identify cost savings while optimising the design.

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