Passive Treatment Systems for the Remediation of Acid Mine Drainage at Wheal Jane, Cornwall

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Abstract

In 1992, Knight Piésold was appointed to formulate a long-term treatment strategy for the remediation of acidic metal-rich minewater issuing from the abandoned Wheal Jane mine in Cornwall, UK. The study has investigated both passive and active treatment technologies. As part of the study, a pilot passive-treatment plant was constructed during 1994, comprising three separate systems. Each system contains the same main treatment stages which consist of five aerobic reedbeds, an anaerobic cell and an aerobic rock-filter. Two of the systems also incorporate pretreatment, one in the form of lime dosing and the other in the form of an anoxic limestone drain. This paper discusses the theory and design criteria used in the construction of the plant and examines performance data during the period June 1995 to November 1996.

Key words: **Minewater; passive treatment; reedbed; wetland.**

Background

Wheal Jane, situated in Cornwall, UK, was formally abandoned in March 1991, at which time mine dewatering ceased, resulting in groundwater rebound within the mine workings. Anticipating the release of acidic minewater into the local watercourse (Carnon River), the Department of the Environment made funds available to set up an emergency treatment facility using conventional lime dosing. The unexpected failure of an adit plug in January 1992 led to a much publicized pollution event in which, over a 24-h period, approximately 30 000 m^3 of acidic metal-rich minewater was released into the River Carnon and subsequently to the Fal Estuary(1). Environmental quality standards (EQSs) for several metals within the River Carnon were exceeded by up to three orders of magnitude(2) following the incident, although prior to this incident the river-water quality already exceeded some of the standards, reflecting the long history of mining in the area.

In 1992, Knight Piésold were appointed by the National Rivers Authority† to design and operate a temporary active-treatment facility and to formulate the most cost-effective long-term treatment strategy to meet defined water-quality objectives for the River Carnon. Because of the predicted longevity of the acid mine-drainage problem at Wheal Jane, the use of passive-treatment technology was perceived to have potential benefits in terms of reduced operating costs and lower consumption of raw materials, energy and labour. At the time of the pollution incident in 1992, the concept of passive technology was relatively new in the UK. The objectives of the operation of the plant have been to (i) confirm the original design principles and to refine the parameters used in the design, (ii) assess the applicability of passive technologies for the treatment of the Wheal Jane minewater, and (iii) evaluate passive-treatment technology for possible applications elsewhere in the Carnon valley or the UK. Whilst operation of the pilot plant is continuing, this paper addresses the design and construction of the plant, and assesses certain aspects of its performance between the period June 1995 to November 1996.

Selection of Appropriate Passive Technologies

The passive-treatment strategy at Wheal Jane was defined on the basis of the range and predicted concentrations of contaminants in the minewater, with the objective of treating the minewater from Jane's adit, which connects directly to the Wheal Jane mine workings. At the pilot-plant design stage, the best available minewater quality data were from Wheal Jane No. 2 shaft. The metal concentrations were particularly elevated at the time, as a result of the recent rebound of water levels within the mine workings. The plant design was therefore based upon conservative predictions produced from modelling of the then available data for Wheal Jane No. 2 shaft (Table 1). The wide range of metals present in the minewater at Wheal Jane resulted in the requirement for a number of treatment components, each designed to remove particular 'target' metals. These included:

(i) Aerobic reedbeds for the removal of iron by precipitation as ferric hydroxide, and arsenic by co-precipitation and/or adsorption with the ferric hydroxide;
(ii) Anaerobic cells for the removal of zinc, copper and cadmium, by the formation of insoluble metal sulphides from the reaction between the dissolved metals and hydrogen sulphide gas, produced via the bacterial reduction of sulphate; and
(iii) Aerobic rock filters for the removal of manganese by the utilization of algae to create high pH 'micro-environments' to precipitate manganese oxide.

There are a number of significant differences between the predicted and actual concentrations: in particular, the

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Table 1. Predicted minewater quality used in pilot-plant design and actual minewater quality during period June 1995 to November 1996

	pH	Al	As	Cd	Cu	Fe	Mn	Pb	Zn	DO	SO_4
No. 2 Shaft predicted (in 1992)	3.0	40	15	0.1	5	250	20	0.3	250	3–5	1000
Jane's adit (actual)†	3.8	50	2.5	0.15	0.4	136	23	0.3	77	1.6	1756

Note: All units (except pH) are expressed in mg/l. All metal concentrations as 'total' metal.
†Median values 1 June 1995 to 30 November 1996 from weekly samples taken at the influent point to the lime-dosed system.

lower than predicted iron, arsenic and zinc concentrations. These have implications for the performance assessment, as described later.

Because of the limited availability of land for any subsequent full-scale treatment plant at Wheal Jane, there was a need to investigate the possibility of enhancing reedbed performance by the incorporation of a pH-adjusting pretreatment stage into the systems. The final construction therefore comprised three systems, which are identical in their main methods of treatment (aerobic reedbeds followed by anaerobic cell and finally, aerobic rock filter) but which differ in their form of pretreatment:

(a) The 'lime-free system', with no pretreatment;
(b) The 'lime-dosed system', with a lime-dosing plant prior to the aerobic reedbeds; and
(c) The 'anoxic limestone drain' (ALD), with an ALD prior to the aerobic reedbeds.

A schematic of the pilot passive-treatment plant at Wheal Jane is shown in Fig. 1.

Design and Sizing of Treatment Components

The sizing of the pilot-plant systems was based upon empirical design parameters derived from passive systems operating in the USA. The purpose of the pilot plant is to allow assessment of the validity of those empirical parameters under site-specific operating conditions. The mechanisms operating in each treatment component, and the associated design, are outlined below.

Aerobic Reedbeds

The 'target' metals are iron and arsenic, although only iron was used in the system design. The principal mechanisms for the removal of iron comprise the oxidation and subsequent hydrolysis of iron:

$$\begin{aligned} Fe^{2+}_{(aq)} + H^{+}_{(aq)} + \tfrac{1}{4}O_{2(aq)} &\rightarrow Fe^{3+}_{(aq)} + \tfrac{1}{2}H_2O_{(\ell)} \\ Fe^{3+}_{(aq)} + 3H_2O_{(\ell)} &\rightarrow Fe(OH)_{3(s)} + 3H^{+}_{(aq)} \end{aligned} \qquad (1)$$

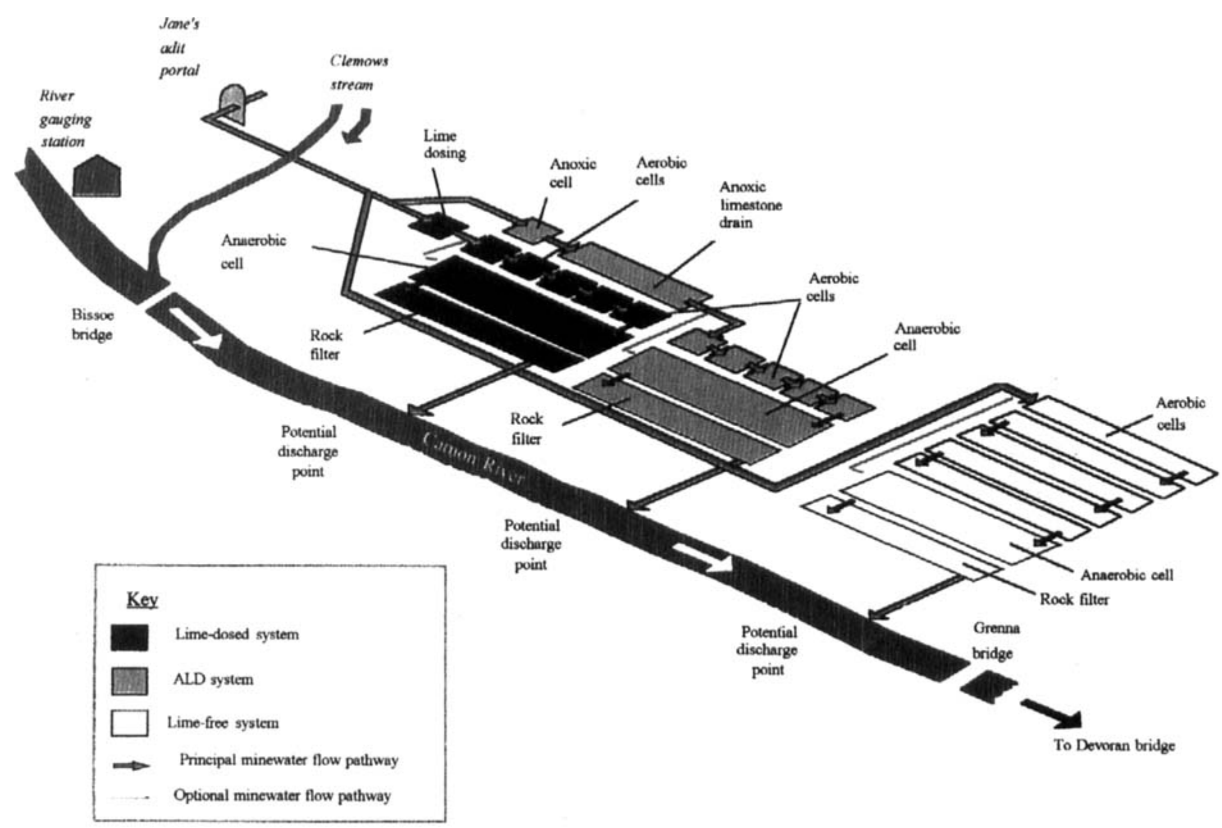

Fig. 1. Schematic of pilot passive-treatment plant

Maintenance of pH plays an important part within the aerobic cells, due to the need to counteract acidity generated by the precipitation of ferric hydroxide, particularly at Wheal Jane where there is no alkalinity in the influent minewater. The design of the aerobic reedbeds takes account of the influent pH in addition to the iron loading, because this determines the efficiency of the bicarbonate pH buffering system, which functions poorly below about pH 5.5[3].

The following loading factors were used to calculate the surface area of the reedbeds constructed at Wheal Jane[3]:

(i) Where influent pH < about 5.5, load at 2–4 g Fe/m^2. d; and
(ii) Where influent pH > about 5.5, load at 5–11 g Fe/m^2. d.

In accordance with the above relationship between pH and influent load, it is apparent that the reedbeds can be loaded at higher rates (therefore require a smaller surface area) if the minewater undergoes initial pH adjustment. Two forms of pH elevating pretreatment were incorporated at Wheal Jane:

(a) Lime dosing to pH 4.6, to achieve some initial pH adjustment without precipitating excessive amounts of ferric and aluminium hydroxides; and
(b) Increasing the alkalinity by limestone dissolution in an anoxic limestone drain (ALD). This is preceded by an anoxic cell (pre-ALD) which reduces the dissolved oxygen (DO) concentration in the influent minewater and minimizes ferric hydroxide precipitation on the limestone.

Anaerobic Cell

The 'target' metals are zinc, copper and cadmium, plus any iron remaining after aerobic treatment. The simplified reactions occurring are:

$$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^- \quad (2)$$
$$M^{2+} + H_2S + 2HCO_3^- \rightarrow MS + 2H_2O + 2CO_2$$

Where CH_2O denotes organic matter
M represents the metal ion

The sulphate-reducing bacteria (*Desulphovibrio* family) thrive in an anaerobic environment and are capable of adjusting the pH of their environment to within the range pH 6–8. Indicators of successful sulphate-reducing bacterial activity are an anaerobic cell effluent with a pH in the range pH 6–8 and a redox potential (Eh) less than 100 mV. The size of the anaerobic cells at Wheal Jane was based upon two principal factors[3]:

(i) *A volumetric-loading factor*, where experience suggests that 1 m^3 of substrate is capable of producing about 0.3 moles of hydrogen sulphide gas per day[3] via sulphate reduction. This hydrogen sulphide then potentially reacts with 0.3 moles of metal to form insoluble sulphides;
(ii) *A surface-loading factor*, related to both the permeability of the substrate and the ability of the sulphate-reducing bacteria to adequately buffer the pH of their environment to between pH 6 and 8. At Wheal Jane (with an influent pH of less than about 5.0), a surface loading factor of 20 m^2/l. min was used, based on pilot-scale studies carried out in the USA[4].

Rock Filters

The 'target' metal is manganese, which requires a pH of about 9.5 to precipitate as an oxide. Algae can increase the pH of the water in their immediate vicinity, thereby creating a high pH 'micro-environment', even though the pH of the surrounding water may be much lower[5]. This is sufficient to allow precipitation of manganese as the oxide in an autocatalytic reaction. Sizing of the rock filters at Wheal Jane was based upon experimental evidence that manganese removal is typically about 2 g Mn/m^2. d[5] in the presence of a sufficiently dense algal mat.

Pilot Passive-Treatment Plant Construction

Minewater Flow and Discharge Control

The minewater passes by gravity from Jane's Adit, via a buried pipe, into a constant-head holding tank at the influent point to each system. Flow control into the systems is achieved using a master valve, and flow control within each system is achieved using a number of shut-off valves. After passing through the systems, minewater reaches the discharge point from where it can be returned to the former Wheal Jane mine site for discharge into the active-tailings facility, or discharged directly to the River Carnon.

Pretreatment Components

Lime-Dosed System

A variable-control peristaltic pump was used to add lime slurry to the influent minewater. The dosed minewater then enters a sludge channel which is designed to settle out any precipitated metals.

ALD System

The ALD pretreatment system consists of two components:

(a) The anoxic cell which comprises a high-density polyethylene (HDPE) lined cell containing a substrate of sawdust and hay, with a cattle slurry bacterial inoculum; and
(b) The ALD which comprises a seam-welded 'closed' HDPE-lined cell, containing pure limestone of grade 20–40 mm. The engineering design took account of the need to minimize the potential for aluminium hydroxide precipitate to block flowpaths within the ALD.

Aerobic Reedbeds

The principal factors determining efficiency of an aerobic system are an adequate oxygen supply and the capability of the system to maintain a suitable pH, to allow precipitation of the target metals. The diffusion of oxygen into the minewater has been enhanced at Wheal Jane by:

(i) Landscaping the substrate into ridges at 90 degrees to the flow to increase the retention time;
(ii) Restricting the water depth to 300 mm or less; and
(iii) Dividing each aerobic system into five discrete cells separated by weirs.

The depth of the aerobic cells was determined by the reed-rooting depth and water-depth requirements, plus a suitable operational freeboard. The cells were isolated from the surrounding ground by lining with HDPE, upon which was placed a coarse-granite tailings substrate. *Phragmites australis* (common reed) and *Typha latifolia* (common cattail) were planted in equal proportions, along with some specimens of *Seirpus* (Bullrush).

Anaerobic Cells

Certain fundamental criteria were considered in the construction of the anaerobic cells. These were (a) restriction of oxygen ingress, (b) provision of a suitable carbon source (both short-term and long-term) for use by sulphate-reducing bacteria, (c) provision of a source of sulphate-reducing bacteria, and (d) engineering design to achieve sufficient permeability to give required retention time.

The 1-m depth of substrate used at Wheal Jane consisted of a 95% softwood sawdust and 5% hay mixture with cattle slurry bacterial inoculum. The anaerobic cells of all three systems were lined with an HDPE impermeable membrane, and the cells of the lime-free and ALD systems were covered with a polythene cap, overlain by a 400-mm earth-capping layer. The lime-dosed system anaerobic cell did not have a polythene capping layer in order to allow an assessment of any effects of oxygen ingress upon anaerobic cell performance.

Rock Filters

In order to promote algal growth and maximize manganese removal at Wheal Jane, two aspects of the construction were given particular attention, i.e. shallow water to allow sufficient light penetration, and sufficient surface area to maximize algal coverage. The rock filters were lined with HDPE, and a substrate of 75-mm granite cobbles was added. Rock berms were constructed at approximately 10-m intervals along the length of the cell to prevent short-circuiting of flow. Filamentous algae were transplanted from the nearby River Carnon, into the rock filter ponds.

Pilot-Plant Operation and Performance

Since June 1995, the different components of the three systems have been operated at various influent flow-rates, depending upon the operational objectives at the time. The range of operational flows is given in Table 2.

Table 2. Pilot-plant operation: influent flow-rates between June 1995 and November 1996

System	Treatment component	Range of influent flow-rates (l/s)
Lime-free system	Aerobic	0.2–0.5
	Anaerobic	0.2
Lime-dosed system	Aerobic	0.1–0.6
	Anaerobic	0.1
ALD system	Aerobic	0.1–0.5
	Anaerobic	0.1–0.3

Note: Rock-filter influent flow-rates were restricted by, and thus identical to, anaerobic cell flow rates.

A comprehensive programme of water-quality monitoring has been undertaken at up to 46 key points throughout each system. Water samples for laboratory analysis were taken before and after each treatment stage and *in-situ* monitoring using portable equipment was performed throughout each system on a weekly basis. In the interpretation of analytical results, an allowance was made for dilution and evaporation occurring in the aerobic cells. The allowance was made using influent and effluent concentrations of 'non-reactive' chloride ions, to calculate flow changes across the aerobic cells due to dilution/evaporation; therefore all metal-removal values quoted are due to 'treatment' alone.

At the design flow, the retention time of the minewater in each system is about two weeks. In interpreting the performance data, periods have been selected where the systems were operating at a stable influent flow-rate, where flow remained unchanged for a period of at least two months. An allowance for a time lag in the interpretation of the results has not been made, because under stable influent flow-rates this lag time should have minimal effect. All quoted values are median for the period of stable flow.

The performance of the pilot plant has been assessed in terms of the main treatment processes and their target metals, i.e. iron and arsenic for the aerobic systems; zinc, cadmium, copper and residual iron in the anaerobic cells; and manganese in the rock filter.

pH and Redox Potential

The pH and, to a lesser extent, the redox potential (Eh) provide an indication of the chemical driving force behind the removal of metals in the passive-treatment processes occurring in the aerobic and anaerobic systems. The relationship between pH and Eh across the components in each system is illustrated in Fig. 2.

The median influent pH for the systems was 3.8–3.9, and this pH value was increased during the lime-dosed system and ALD system pretreatment. The effect of ferric hydroxide precipitation on pH is clearly demonstrated across the aerobic cells of all three systems. The decline in pH observed across the lime-free system aerobic cells was less pronounced than in the other two systems; this is likely to be due to a lower rate of hydroxide precipitation per unit area – even though percentage removal was higher (Fig. 3). The extent to which pH buffering by the reeds was contributing has not been proven. The Eh increased across all aerobic cells, with oxygenation of the minewater. The pronounced increase in pH and decrease in Eh in the ALD system anaerobic cell indicates the occurrence of sulphate-reducing bacterial (SRB) activity. The increase in pH was less pronounced in the other two systems – indicating less successful SRB activity, although the decrease in Eh was similar for all systems. The differences between the

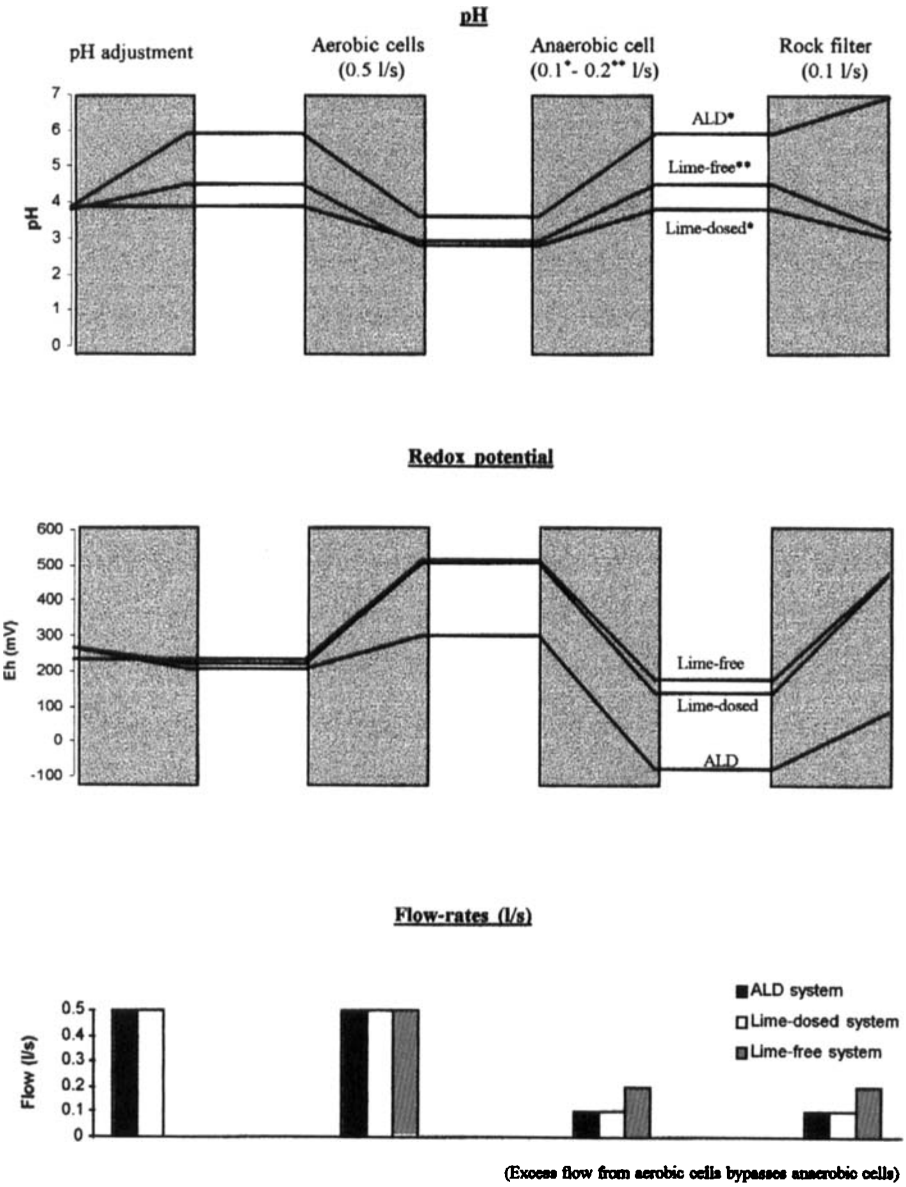

Fig. 2. Passive treatment pilot-plant performance (median values) at stable flow-rates: June 1995–November 1996

systems most likely reflect the higher influent pH into the ALD system, which is more suitable for SRB activity.

Only in the ALD system rock filter was there an increase in pH (over a three-month period in the summer of 1996), attributed to algal activity. The pH decline across the lime-free and lime-dosed system rock filters was due to the precipitation of residual iron as ferric hydroxide. As in the aerobic cells, Eh increased across all rock filters.

Aerobic Systems

Because the influent iron concentration at the pilot plant has been at a median of 136 mg/l, as opposed to the predicted 250 mg/l (see Table 1), the aerobic systems have been loaded at a lower rate per unit area than originally anticipated by the 'sizing' parameters. Therefore it is most appropriate, in performance evaluation, to compare the effluent load per unit area with the actual influent load per unit area.

An inspection of Fig. 3 reveals that, for the selected stable flow periods, the lime-dosed and ALD systems have received a higher iron loading per unit area than the lime-free system (note the scale differences on the figure), resulting from similar influent concentrations and flow-rates for all three systems, but a larger surface area for the latter. In the lime-free system, a median influent load of 1.7 g Fe/m^2. d was reduced to 0.5 g Fe/m^2. d at the effluent point, whilst in the lime-dosed and ALD systems median influent loads were reduced from 5.4 g Fe/m^2. d to 1.7 g Fe/m^2. d and 5.5 g Fe/m^2. d to 2.0 g Fe/m^2. d, respectively. Thus, enhanced removal is observed in the systems receiving pretreatment. However, the load per unit area on the lime-free system has not been as high as on the other two systems, and therefore it is not known whether comparable removal rates might be achieved with a similar influent load per unit area.

Between 63 and 74% of the influent iron load was

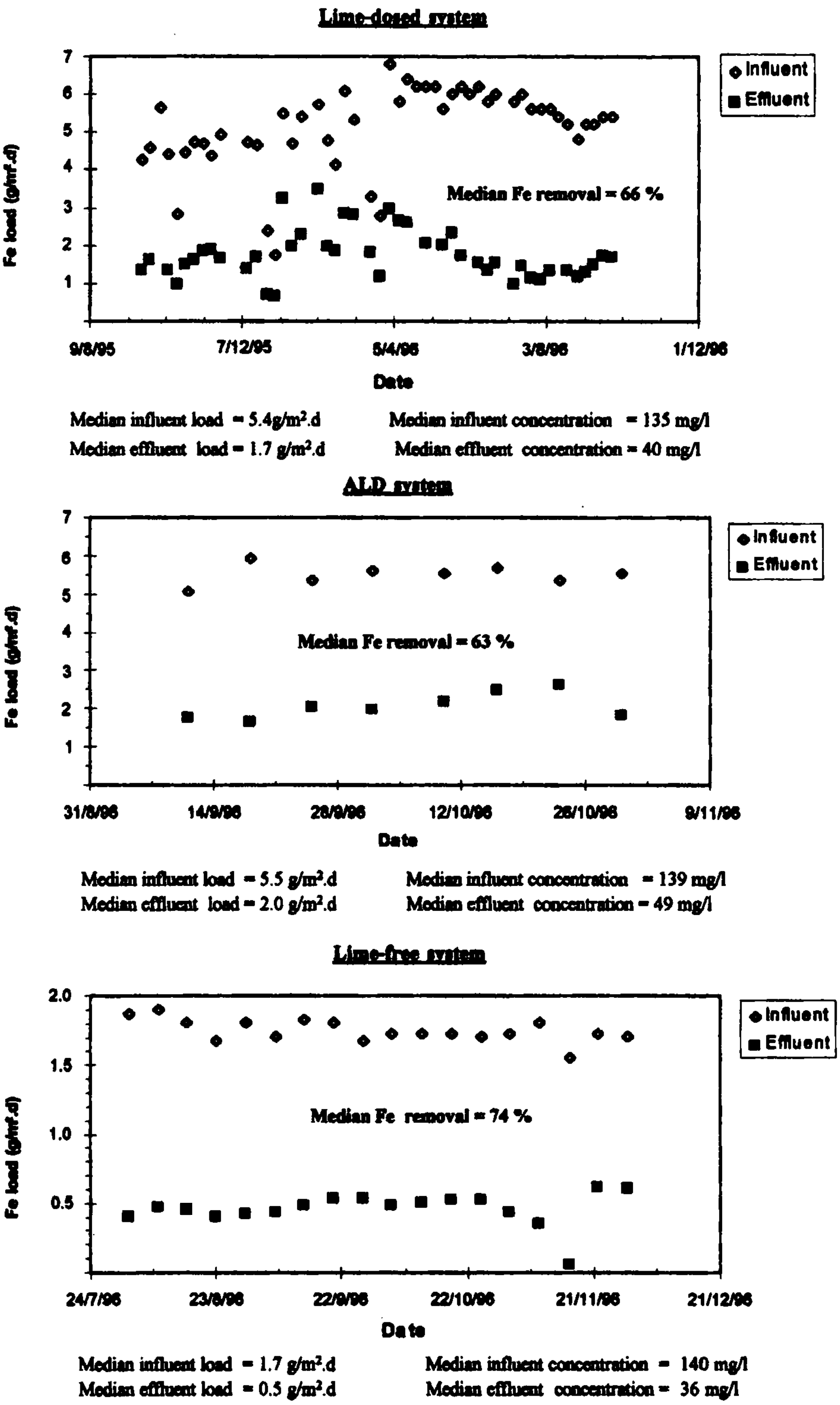

Fig. 3. Fe removal in aerobic cells (0.5 l/s influent flow)

removed in the aerobic cells of the three systems (Fig. 3). It would appear that the potential for higher percentage iron removal was limited by insufficient pH buffering to counteract the acidity generated during the ferric iron hydrolysis reaction. Figs. 4, 5 and 6 (the Eh/pH diagrams for the Fe - S - H_2O system) are presented for concentrations of 1000 mg/l SO_4 and 100 mg/l Fe. For clarity, only the main stable iron compounds are considered in these diagrams, and the field of water stability is defined by the dotted lines. The arrows portray the changes in pH and Eh (median values) between the influent and effluent points for the aerobic systems. In the ALD system (Fig. 5), the condition of the influent minewater to the aerobic cells already satisfies the requirements for the precipitation of ferric hydroxide due to the elevated pH. In the case of the lime-dosed and lime-free systems (Figs. 4 and 6), the Eh and pH conditions appear to closely follow the iron (II) and iron (III) hydroxide equilibrium,

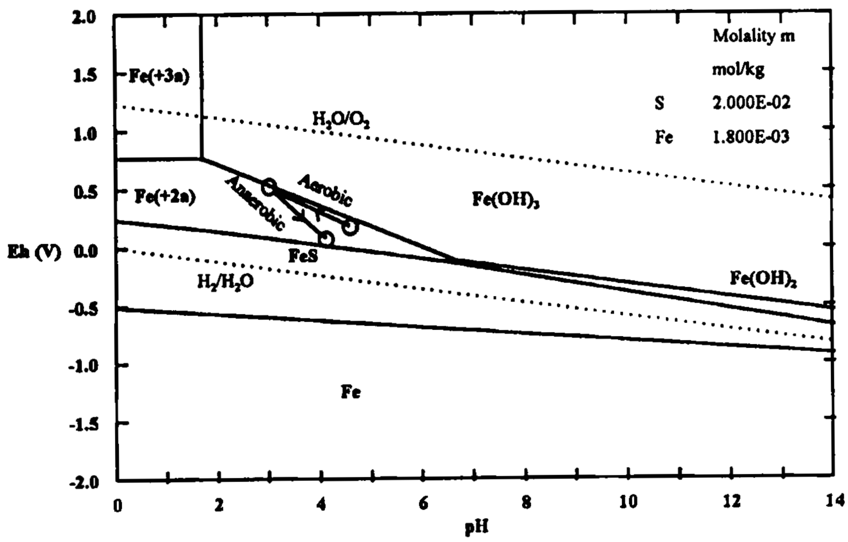

Fig. 4. Lime-dosed system: Eh and pH diagram for Fe - S - H_2O system at 25°C

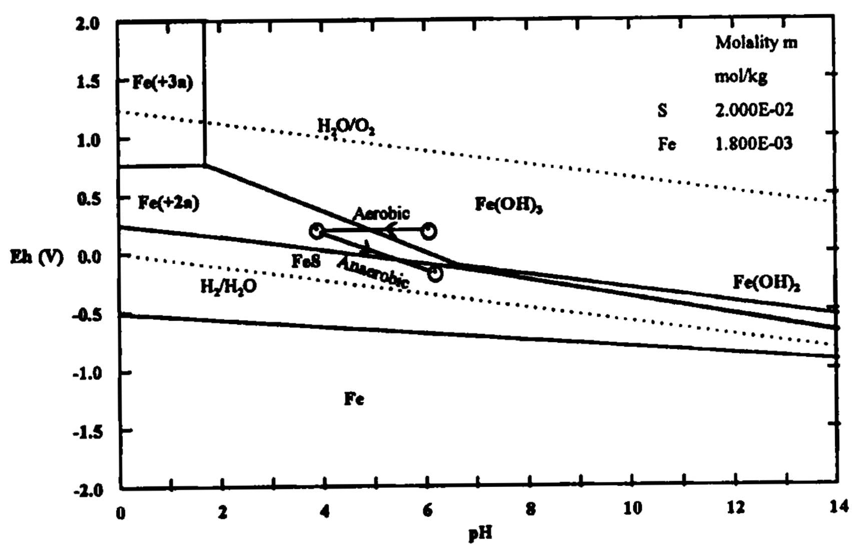

Fig. 5. ALD system: Eh and pH diagram for Fe - S - H_2O system at 25°C

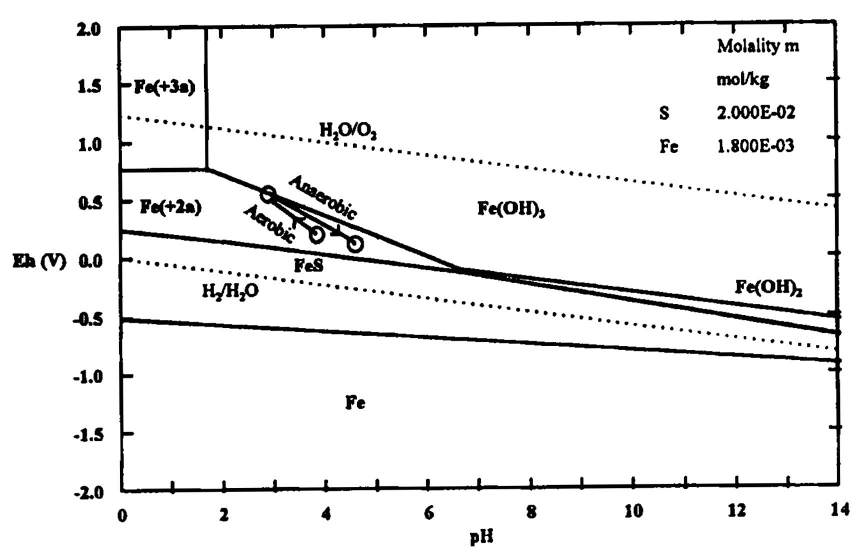

Fig. 6. Lime-free system: Eh and pH diagram for Fe - S - H_2O system at 25°C

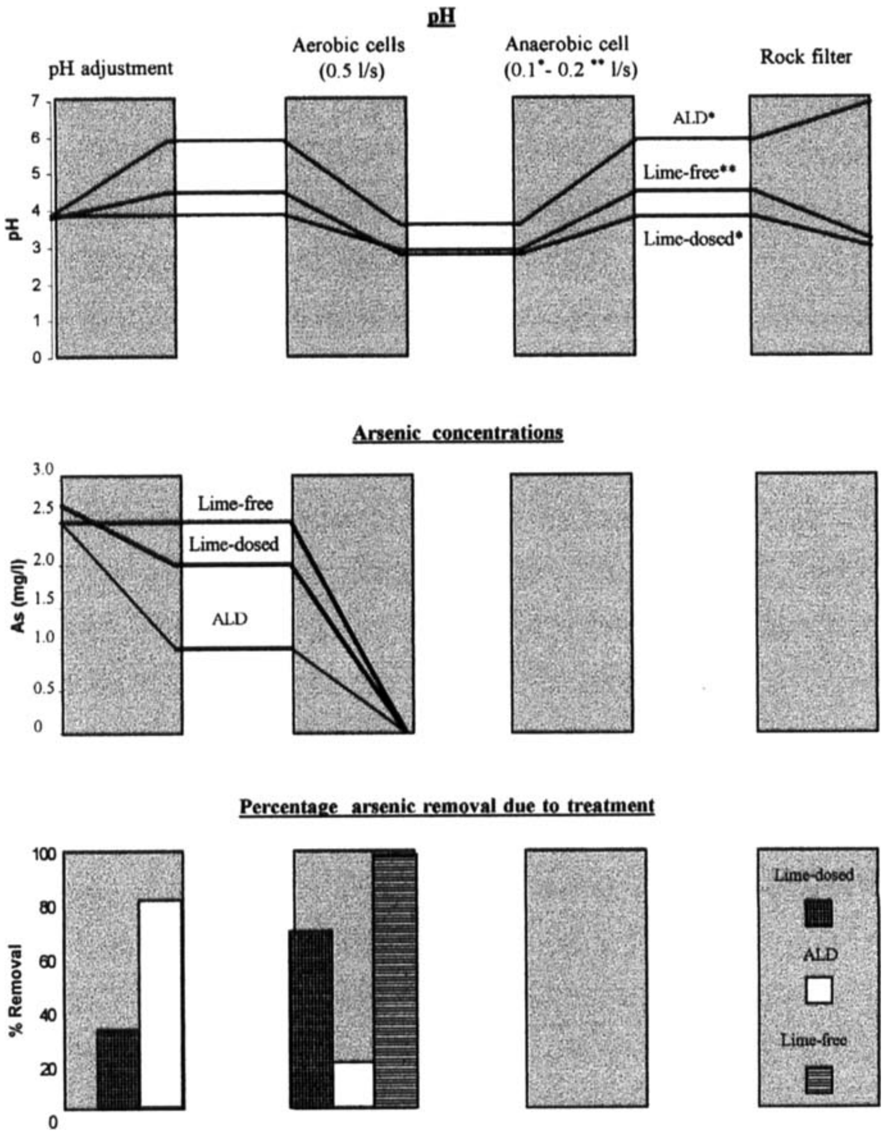

Fig. 7. pH, redox potential, arsenic concentration and arsenic removal

with a decrease in pH matched by an increase in Eh along the equilibrium line.

Arsenic removal (Fig. 7) was close to a median of 100% (i.e. below the detection limit) in all three systems, albeit with some removal occurring in the pretreatment stages.

Anaerobic System

Fig. 8 refers to sulphate and total 'target' metal (Zn, Cu, Cd, Fe) removal in the anaerobic cells. Sulphate removal has been variable in the lime-dosed and lime-free systems, and more consistent over the shorter time period illustrated for the ALD system. Sulphate removal was typically less than 0.1 mol/m^3. d, associated with target metal removal of 0.01–0.02 mol/m^3. d in all three systems; this reflects the challenge involved in the operation of anaerobic cells with an influent minewater having a pH of less than 4.0. The rate of target metal removal would be expected to be close to the rate of sulphate removal/sulphide generation, based upon the stoichiometry of the metal-hydrogen sulphide reaction; Fig. 8 indicates relatively good correlation between sulphate removal and metal removal for the lime-dosed and ALD systems, but less so for the lime-free system. This might be accounted for by physical factors, e.g. sulphide generation could be occurring in discrete 'pockets' within the cell, leaving other 'sulphide-free' areas, where the minewater does not come into contact with the sulphide during its passage through the cell; alternatively the minewater may be short-circuiting through preferential flow pathways within the cell.

The range of median effluent pH values for the anaerobic cells was 3.8–5.9, as shown in Fig. 9. Effluent redox potential and zinc concentrations ranged from −77 mV to 178 mV, and 9 to 43 mg/l respectively. The ALD system anaerobic cell has the highest zinc removal efficiency with a median of 86% over the period, while the lime-dosed and lime-free systems cells show a comparable removal efficiency of 54 and 45% respectively. Influent copper and cadmium concentrations were consistently removed to below detection limits in all three anaerobic cells.

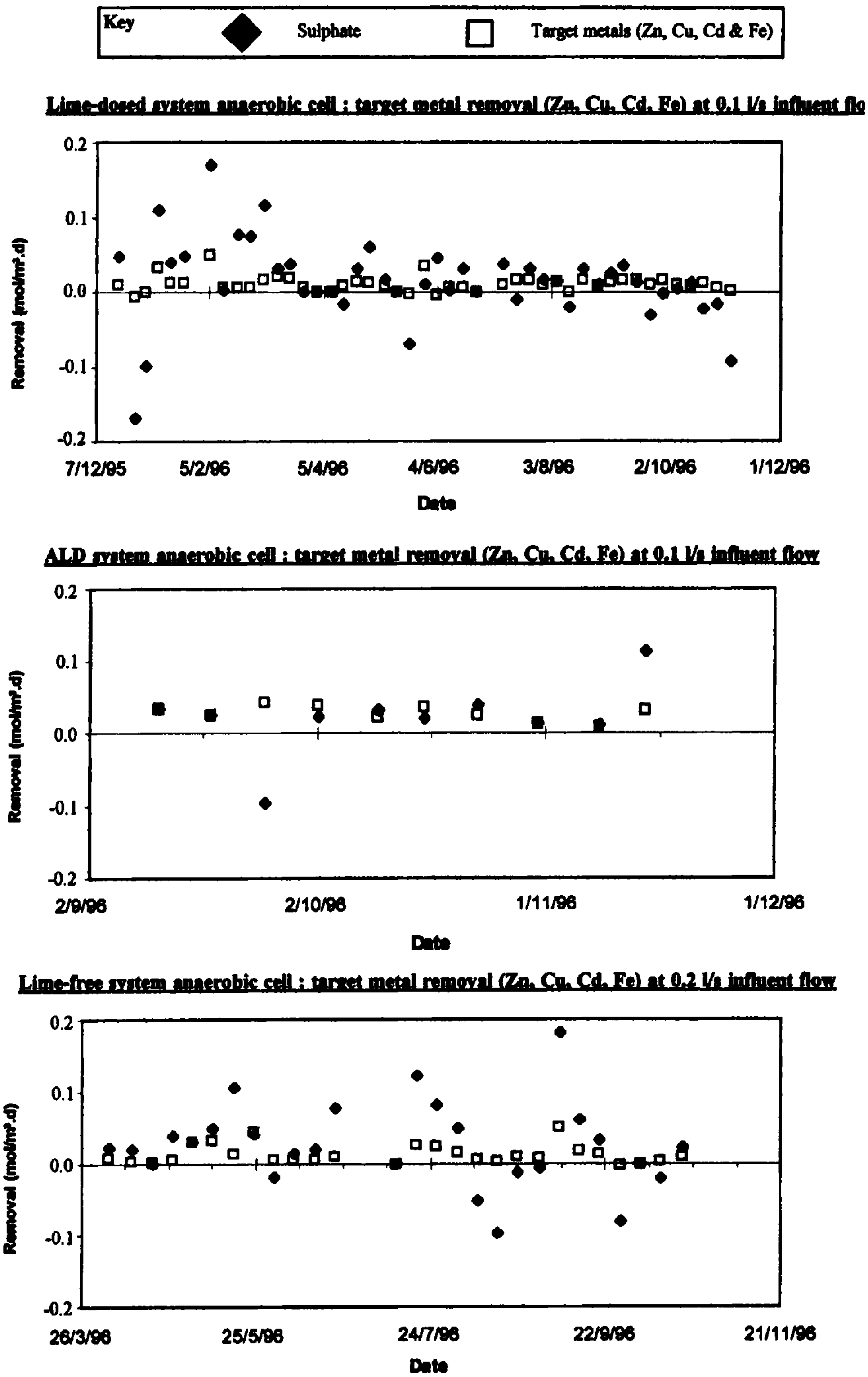

Fig. 8. Anaerobic metal removal: comparison with design parameters

Rock Filters

The operation and performance of the rock filters for the removal of manganese have been restricted by the performance of the preceding anaerobic cells, being particularly hindered by:

(a) Low influent pH;
(b) Residual influent iron precipitating and further lowering pH; and
(c) Poor water clarity (and thus hindrance to algal growth) in the early part of the rock filter due to anaerobic cell-derived dissolved and particulate organic matter.

In addition, there has been a lack of 'sustained' algal presence through all seasons. However, during a three-month period in the summer of 1996, a dense algal mat formed in the ALD system rock filter, and the median

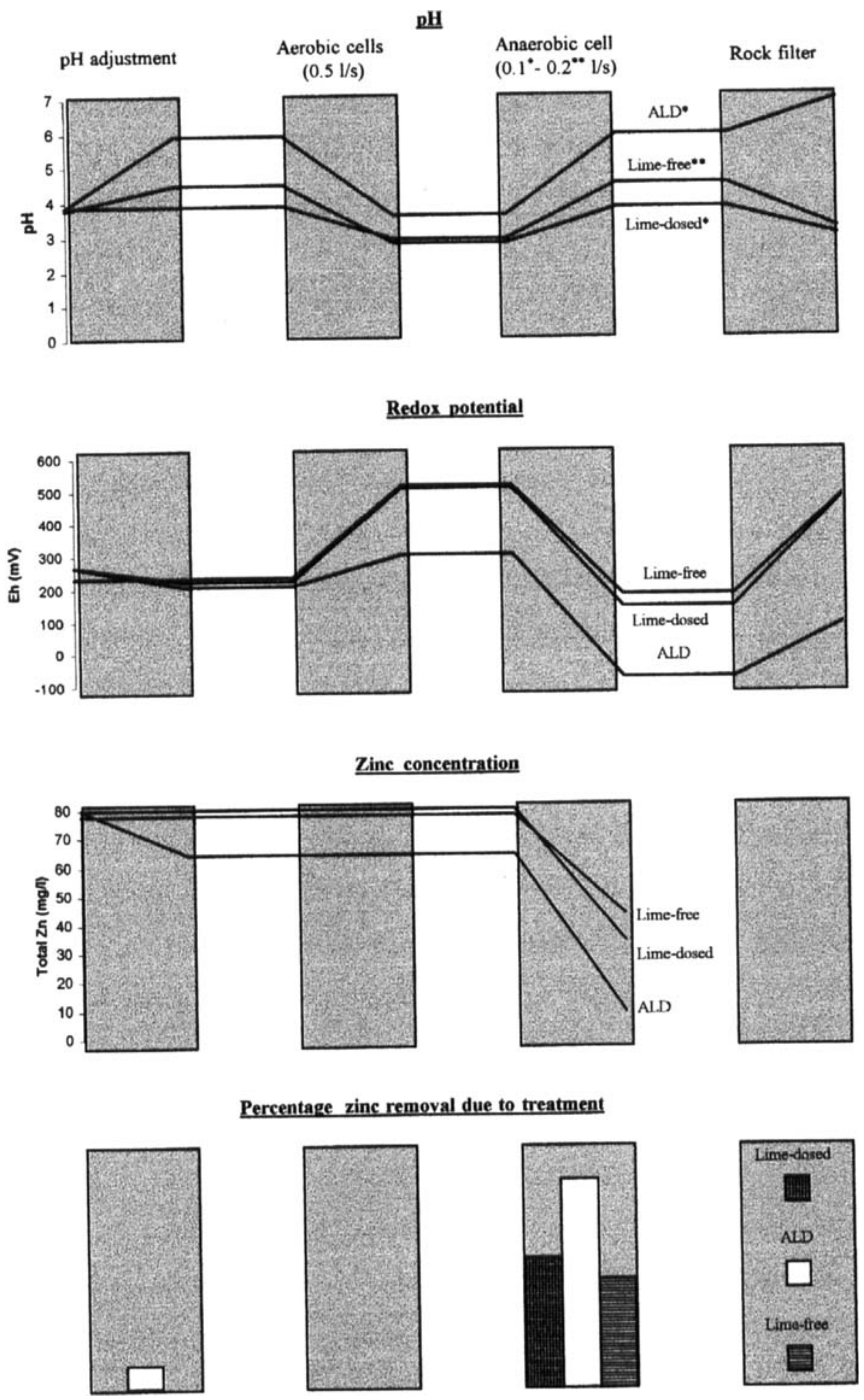

Fig. 9. pH, redox potential, zinc concentration and zinc removal

influent pH 6.0 was increased in the water body of the rock filter to pH 8.0. Although this pH is not sufficiently high to precipitate the manganese, it would appear that the pH in the 'micro-environment' around the algae was higher, because median manganese removal was 97% for the period, equivalent to 0.5 g Mn/m^2. d. The rock filter design theory has been proven, but with the onset of the autumn, the algae (and thus manganese removal) were not sustained.

Pilot-Plant Modifications

Between October 1996 and January 1997, modifications were undertaken, primarily to increase the variety of flow-pathway options available at the pilot plant, to enhance the performance of the lime-free system anaerobic cell by the incorporation of limestone into the substrate mix, and to allow investigation of aluminium removal from the minewater prior to its entry into the ALD. Data relating to the performance of the pilot plant since these modifications will be the subject of a future publication.

Summary and Conclusions

1. In 1994, a pilot passive treatment plant was constructed in the Carnon Valley to investigate the possible use of passive minewater treatment technologies. The pilot plant consists of three separate systems, each of which contains the same main treatment stages, comprising aerobic reedbeds, an anaerobic cell and a rock filter, arranged in discrete cells. Two of the systems also incorporate a type of pH elevating pretreatment in the form of a small lime-dosing plant and an anoxic limestone drain respectively.
2. The pilot plant has been operational since November 1994, and the performance during the period June 1995 to November 1996 is summarized below:
   - (i) A reduction in iron concentration from about 140 mg/l to 36–49 mg/l in the aerobic cells, corresponding to iron removal of 63–74%, or a removal rate of 1.2–3.7 g Fe/m^2. d;
   - (ii) Removal of arsenic to below detection limits in the aerobic cells;
   - (iii) Sulphate removal in the range 0.01–0.04 $moles/m^3$;
   - (iv) Removal of 45–86% of the influent zinc in the anaerobic cells;
   - (v) Removal of cadmium and copper to below detection limits in the anaerobic cells; and
   - (vi) Removal of 97% of the influent manganese load in the ALD system rock filter over a limited 3-month period during summer 1996.
3. An assessment of this performance indicates that the main limitations to increased metal removal efficiency are:
   - (a) *Aerobic cells* – the decrease in pH which occurs as a consequence of ferric hydroxide precipitation;
   - (b) *Anaerobic cells* – the detrimental effect of low pH minewater effluent from the aerobic cells upon bacterial activity, possibly compounded by the minewater short-circuiting through preferential flow pathways, or passing through localized areas where sulphide generation is not occurring; and
   - (c) *Rock filters* – a lack of sustained algal growth has limited manganese removal.
4. Modifications have been carried out to increase the variety of minewater flow pathway options (to overcome some of the performance restrictions noted above), and to enhance the performance of certain components of the pilot plant.

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