Modelling Bioremediation of Acid Mine Drainage in Constructed Ecosystems

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Abstract Acid mine drainage (AMD) is a widespread environmental problem associated with both working and abandoned mining operations. As part of an overall strategy to determine a long-term treatment option for AMD, a pilot passive treatment plant was constructed in 1994 at Wheal Jane in Cornwall, UK. The plant consists of three separate systems; each containing aerobic reed beds, anaerobic cell and rock filters, and represents the largest European experimental facility of its kind. The systems only differ by the type of pre-treatment utilised to increase the pH of the influent minewater (pH <4): lime-dosed (LD), anoxic limestone drain (ALD) and lime free (LF), which receives no form of pre-treatment. This paper presents an assessment of the chemical status of the pilot plant and preliminary results of a dynamic model developed to assist in optimisation of plant performance and the creation of design criteria for future passive schemes.

Keywords: Wetland; Metal removal; Passive treatment

1. INTRODUCTION

Following the closure of coal and metal mines in recent years the problem of acid minewater discharges has become increasingly prominent in the UK. The publicised release from the Wheal Jane mine in the winter of 1992 followed the cessation of pumping a few months earlier. Although there had been a long history of pollution from abandoned coal and metal mines across the UK [Environment Agency, 1994; Rob, 1994; and Henton, 1981], the release of acidic metal-rich minewater from Wheal Jane into the Carnon River and Fal Estuary (Figure 1). produced perhaps the most spectacular incident, and heightened awareness of the problems associated with acid mine drainage. As part of the evaluation of the most cost-effective method for treating the minewater, a pilot passive treatment plant was constructed in the Carnon Valley. This pilot plant was designed to facilitate research into :

- The physical, chemical and biological processes which underlie the relatively poorly understood technology of passive treatment.
- The potential for the application of passive technology to the long-term treatment of Wheal Jane minewater.

Since the plant's construction, extensive water quality, quantity and biological data sets have been gathered which present an opportunity to investigate the benefits of the passive treatment of minewater. Whilst research at the site has evaluated the potential for the application of passive technology in the long-term treatment of acid minewater, there is still much to be

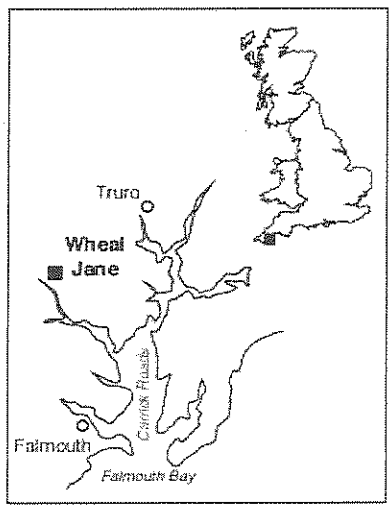

Figure 1. Location of Wheal Jane Pilot Passive Treatment Plant.

understood about the processes which underlie passive treatment. As part of a DTI LINK initiative these data sets, together with newly gathered data, are being exploited to improve understanding of the physical, chemical and biological processes which underlie the technology of passive treatment and provide a model of the bioremediation of AMD at the plant.

There are many approaches to modelling environmental systems ranging from empirical 'black box' models through dynamic lumped process models to distributed full chemical speciation models. The impacts of acid mine drainage on rivers has been modelled by Whitehead and Jeffrey [1995] and detailed process based models of acidification have been developed for upland soil systems [Cosby et al, 1985a and b]. Few models have simulated the impact of constructed wetland treatment of acid mine drainage. Conceptual models have predicted iron retention and cycling in wetland ecosystems receiving coal mine drainage [Mitsch et al, 1981, 1983 and Fennessy and Mitsch 1989a and b]. In addition Flanagan et al [1994] developed a more comprehensive model predicting iron, manganese, aluminium and sulphate retention in a proposed wetland remediation site in Ohio, USA. This model was then evaluated once the wetland had been built [Mitsch and Wise, 1998]. However, there have been few comprehensive studies of passive treatment systems, which have resulted in useful model developments for highly acidic systems.

A key objective of this project will be to develop generic passive treatment system models that can identify the most suitable conditions for the design and operation of future bioremediation schemes for the treatment of AMD.

2. PILOT PLANT RESEARCH

2.1 Pilot Plant Configuration

The passive treatment plant consists of three schemes (Figure 2). These differ only in the pre-treatment utilised to modify the pH of the influent minewater: lime dosing to pH 5 (LD), an anoxic limestone drain (ALD) and no modification (lime free, LF). All three systems include: (i) constructed aerobic reed beds designed to remove iron and arsenic, (ii) an anaerobic cell to encourage reduction of sulphate and facilitate removal of zinc, copper, cadmium and the remaining iron as metal sulphides, and (iii) aerobic rock filters designed to promote the growth of algae and facilitate the precipitation of manganese.

2.2 Monitoring Programme

An extensive record of biological, chemical and physical data exists following completion of the first phase of research at the site during 1994-1997 [Hamilton et al, 1999]. Current research includes weekly water quality monitoring of key points across the site (A1-3, A8-9, A13, B1, B15-16, B20, B22-24, C1, C6-7, C11 on Figure 2). Samples are analysed for a broad range of determinants including pH, D.O., redox potential, alkalinity, dissolved metals and anions. All metal analysis is completed using an ICP-OES in duplicate on both ultra-sonic and cross-flow nebulisers to account for the large variations in concentrations detected. All analysis is completed within 1 week of collection at site in accordance with UKAS and BS5750 quality assurance controls.

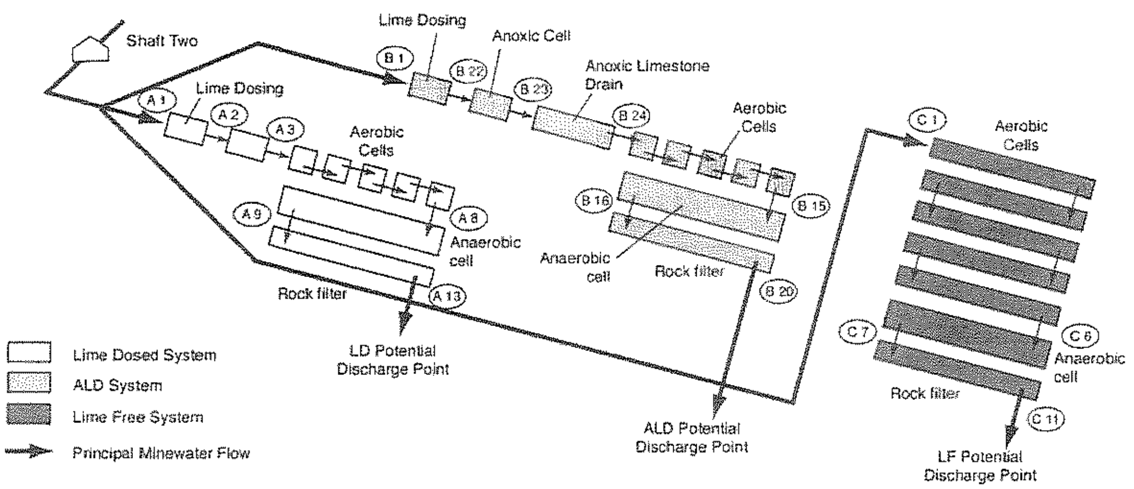

Figure 2. Schematic of Wheal Jane Pilot Passive Treatment Plant illustrating configuration of systems.

Additional microbial and geochemical research is also carried out on an intermittent basis to (i) assess the role of acidophilic micro-organisms in the bioremediation of AMD and the predictive fate of effluent waters, (ii) quantify Fe and SO_4^- oxidation-reduction in intact cores from the aerobic and anaerobic cells, (iii) analyse algal isolates and associated metal precipitation processes, (iv) investigate the geochemical characterisation and stabilities of wetland sediments at the site. Data from a six month period in the previous study (June – November 1996) at the passive treatment plant was initially used to evaluate the model.

3. WHEAL JANE MODEL

The model for the Wheal Jane passive treatment system is based on a set of ordinary differential equations that are solved using a 4^{th} Order Runge Kutta Integration routine with a Merson variable step length procedure. The advantage of this system is that it is fast and the model results are generated rapidly. This allows the user to simulate the system quickly and repeat runs to evaluate changing behaviour patterns. The model consists of 25 equations for each of 17 cells. The 17 cells consist of the limestone treatment tank (Reach 1), the ALD (Reach 2), the 5 aerobic cells (Reaches 3-7), the anaerobic cell (Reach 8) and the 9 rock filters (Reaches 9-17) (Figure 3). The 25 equations consist of the flow, metals, anions, cations, macrophytes, algae, microbial populations and a tracer.

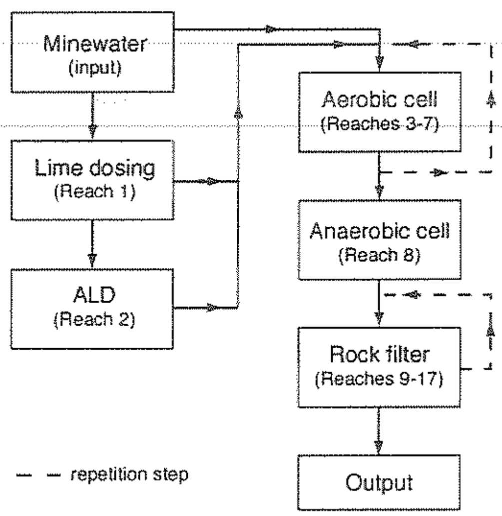

Figure 3. Conceptual diagram of Wheal Jane Model.

The basic model structure comprises of: (i) input minewater chemistry, (ii) lime dosing section (which may be bypassed for LF system), (iii) ALD section (which may be bypassed for LD and LF system), (iv) aerobic cells, (v) anaerobic cells, (vi) rock filter and A total of 21 anion and cation in addition to variables are being modelled (Flow, D.O., B.O.D., Al, As, Ca, Cd, Cl, Cu, Fe, Hg, K, Mg, Mn, N, NH_4, Na, Ni, P, Pb, S, Zn) and (vii) output chemistry macrophyte, algae and microbial activity. Processes to be modelled include:

- Mass balance, chemical equilibrium and precipitation of metals
- Cation-anion balance, pH calculation
- Microbial mediation of sulphide reactions, macrophyte effects on aerobic cells, algal biomass and uptake of Mn.
- BOD decay, DO reaeration
- Temperature and rainfall effects and water balance.

4. AN ASSESSMENT OF THE CHEMICAL STATUS

In order to develop a model for AMD bioremediation at the site, historical and current water chemistry data was analysed to provide an insight into chemical processes occurring and set limits for the model

4.1 Metals Mass Balance

Interim results of the water chemistry appear to support the original research carried out at the site from 1994 - 1998 (Figure 4). All systems appear to remove soluble Fe from the AMD, with removal primarily taking place in the first two aerobic cells.

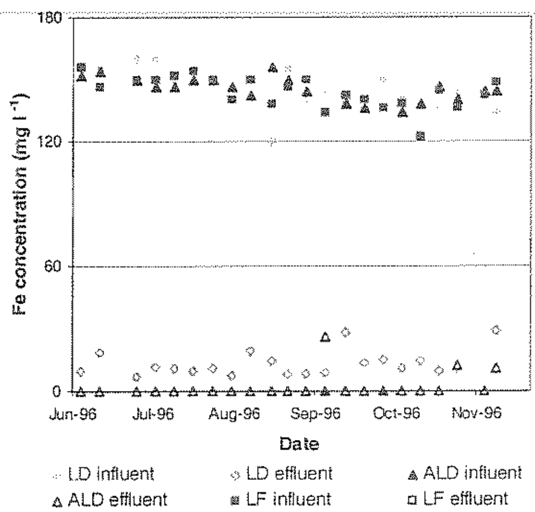

Figure 4. Influent and effluent iron concentrations at Wheal Jane Pilot Passive Treatment Plant (June – November,1996).

Table 1. Median removal rates of major elements at Wheal Jane passive treatment plant, 1999-2001.

System	Al	Ca	Cd	Cu	K	Mg	Mn	Na	SO4	Zn
LD	65%	25%	78%	73%	24%	37%	54%	30%	47%	66%
ALD	90%	-7%	98%	95%	41%	41%	60%	33%	39%	73%
LF	35%	20%	53%	42%	-2%	26%	45%	20%	37%	47%

(LD – Lime dosed system, ALD – Anoxic limestone drain system, and LF – Lime free system)

The ALD configuration has the highest removal rate with a median of 99.5%, with the LD and LF systems removing a median of 96.5% and 94.8% respectively. When comparing the removal rates other metals from the three systems it is noticeable that there is a broad difference in the capacity of each system to remove metals in addition to a wide variance between elements (Table 1).

4.2. Spatial Variations in Key Chemical Parameters

Spatial variations in pH, dissolved oxygen, conductivity, redox and BOD at the pilot passive treatment plant were determined. The inter- and intra- system variations of these parameters were important and they allowed the environmental conditions within each section of the three systems to be analysed. The maximum, minimum and inter-quartile ranges for each reach were calculated for all parameters for the period June- November 1996, to allow limits to be established and determination of important processes to aid model development. Dissolved oxygen plots for this period (Figure 5) show that although heavily depleted in reach 8 (anaerobic cell), the final stages of the treatment process (rock filter, reaches 9-17) are sufficient to return the D.O. concentration to levels recorded at the end of reach 7 (final aerobic cell). This indicates D.O. reaeration is an important process in this section of the treatment plant.

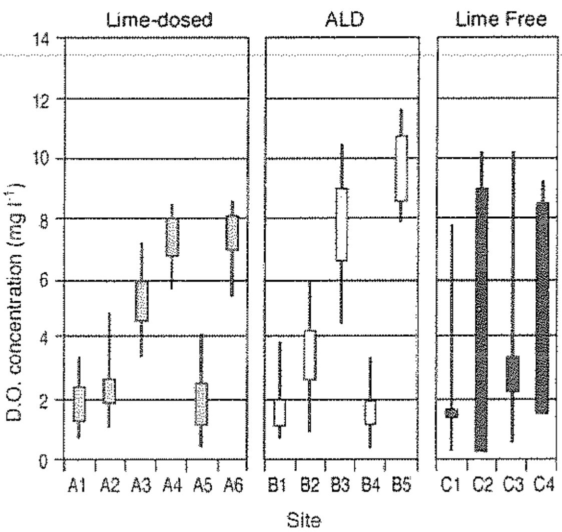

Figure 5. Spatial variations in dissolved oxygen at Wheal Jane Pilot Passive Treatment Plant, June – November, 1996.

4.3 Equilibrium chemistry

The relationship between potential and pH at sites across the passive treatment plant have been mapped (Figure 6) to allow the interpretation of element speciation within the three treatment systems using adapted Pourbaix diagrams [Pourbaix, 1974].

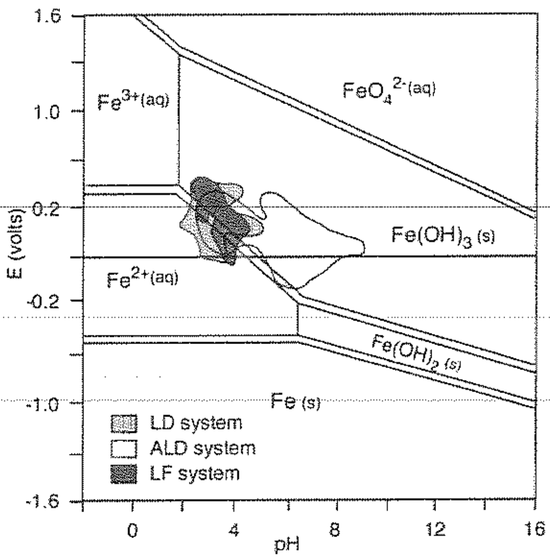

Figure 6. Adapted Pourbaix diagram illustrating iron speciation within the three treatment systems at Wheal Jane Pilot Passive Treatment Plant, June – November, 1996.

These theoretical diagrams depict the thermodynamically most stable form of an element, as a function of potential and pH and show the relative stability of an element and its predominant form under a range of environmental conditions. This simple analysis has allowed theoretical determination of which chemical equilibrium equations need to be included in the model for each element considered.

5. RESULTS AND DISCUSSION

The model simulates the dynamic response of the wetland system on a daily time step. In addition to the mine drainage driving the behaviour of the system, environmental factors such as rainfall, temperature and evapo-transpiration affect the performance of the wetland system. Figure 7 shows the rainfall and temperature patterns for the six-month period from June 1996. The low summer rainfall and high temperatures keep the simulated flows low, as shown in Figure 8, and flows increase as the autumn proceeds. The chemistry of the wetlands also responds to this changing flow pattern and simulated and observed behaviour of Ca, Mg, Na, K, Cl, and SO4 all reduce in the autumn as the flows increase. However, the simulated response matches the observed behaviour well given that no calibration has been undertaken at this stage in the modelling programme.

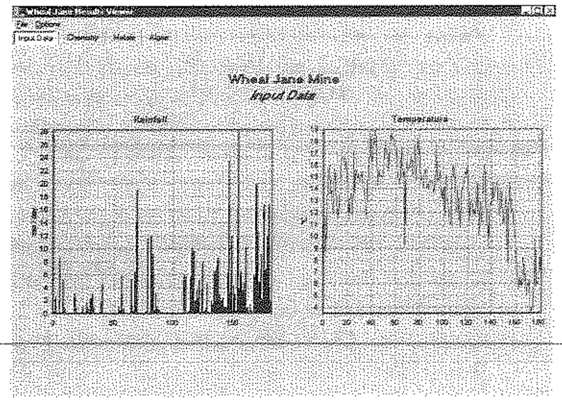

Figure 7. Observed rainfall and temperature at the pilot passive treatment plant, June-November 1996.

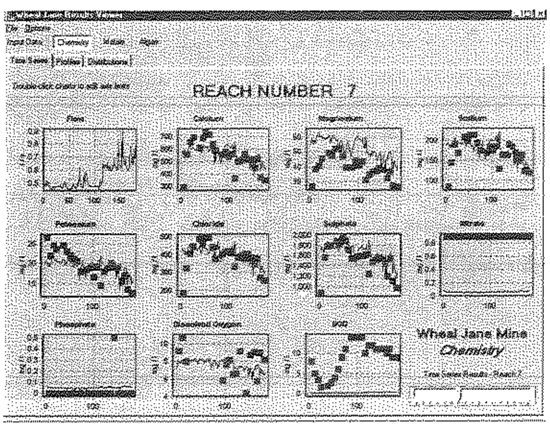

Figure 8. Observed (dots) and simulated (line) flow with metal, anion, D.O. and B.O.D concentrations for the period June – November 1996 in Reach 7 (final aerobic cell).

The main objectives of the modelling study are to simulate the effects of the wetland system on the heavy metals response and to maximise the removal of the toxic heavy metals in the wetland ecosystem. Figure 9 gives a typical response of the metals behaviour at point midway down the aerobic cells. The simulated iron concentrations show a significant reduction in the first few cells of the aerobic zone as is observed in the actual system (see Figure 4). This loss is achieved by a first order kinetic decay in the model equation for iron. However, from a geochemical perspective the process of oversaturation and then precipitation of the iron should be modelled more accurately by a thermodynamic equilibrium model. However these equilibrium models assume stable flow conditions and this is certainly not the case in the wetland ecosystem. However, some combination of equilibrium modelling and rate dependant process model may be required in the final formulation. We are still at the early stages of the modelling study at Wheal Jane and new versions of the model will be developed over the next year.

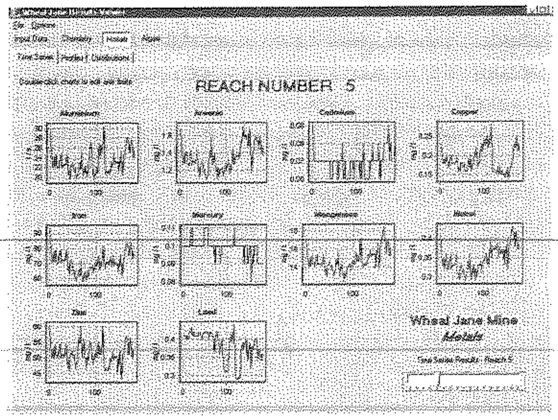

Figure 9. Simulated metal concentrations in Reach 5 (midpoint of aerobic cells), June-November, 1996.

The other metals in the model such as cadmium and zinc are not reduced significantly by the aerobic cells but can be reduced in the anaerobic cell as metal sulphides are formed in the extreme anoxic environment. The reduction in the anaerobic cell is also modelled by a temperature dependent first order process but bacterial populations also play a large role in enhancing the rate of reaction. At Wheal Jane there is a major source of these reducing bacteria from the mine itself and these are transported into the wetland along with the mine effluent waters. Others metals such as manganese are not affected by either the aerobic or anaerobic cells but can be reduced in the final stage of the plant, namely the rock filter section. Here algal growth rapidly changes the carbon dioxide, and hence pH, levels in the rock pools and the alkaline conditions allow the precipitation of the manganese. The early version of the Wheal Jane model has the basic equations for algal growth in the rock filters and these will be calibrated against field data over the next phase of the modelling project.

6. CONCLUSION

Although the model development in the Wheal Jane project is at an early stage, the combination of the field data and preliminary model results are generating some interesting ideas on the processes controlling these wetland ecosystems. Here physical, chemical, macro-biological and microbiological processes interact to create a highly complex system Creating a new model for such a system represents a major challenge.

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