Land Contamination & Reclamation, 11 (2), 2003

DOI 10.2462/09670513.804

Testing and performance of a newly constructed full-scale passive treatment system at Whittle Colliery, Northumberland

Charlotte A. Nuttall

Abstract

Mine water recovery has been taking place following the closure and cessation of pumping at Whittle Colliery (Northumberland) in January 1997. The predicted subsequent uncontrolled outbreaks of ferruginous water threatened to contaminate the Hazon Burn which is a tributary of the River Coquet, a valued amenity and water resource. Consequently, a pump and treat treatment system was commissioned by the UK Coal Authority and constructed late in 1999 by Entec UK Ltd. The treatment system receives water pumped from a purpose-drilled borehole which extends into the Whittle drift. In this way, mine water levels can be kept below predicted decant points (which would otherwise result in discharge at surface) and mine water can be treated in a designated setting. The passive treatment consists of an aeration chamber, two settling lagoons and three aerobic reedbeds. In order to minimise any risk to the River Coquet, this system was tested in January 2002 when river flows would be at their highest. Also due to the low ambient air temperature, the poorest performance of the system would be expected at this time of year. The system received pumped mine water at a range of flow rates over a period of six weeks and was very successful at removing iron. Following these promising results the system became permanently operational in the summer of 2002.

Key words: iron, metals, mine water, recovery, treatment, wetland

INTRODUCTION

Mine water recovery has been taking place throughout the North East of England following the major phase of colliery abandonment that took place in the 1980s (Whitworth 2002). Whittle Colliery closed and pumping ceased more recently in January 1997. Since then mine water levels have been recovering at a rate of around 5 cm/day. Ferruginous discharges which begin to emerge as mine water recovery nears completion may stain watercourses with ochre over distances of many kilometres. This has a smothering effect upon any aquatic fauna and flora which resides in the receiving watercourse (Younger 2000; Jarvis and Younger 1997). The predicted subsequent uncontrolled outbreaks of ferruginous water from the Whittle Colliery workings threatened to contaminate the Hazon Burn, a tributary of the River Coquet, which is an important river in terms of its fisheries, water resources and SSSI conservation status. Consequently, a pump and treat treatment system was commissioned by the UK Coal authority and constructed late in 1999 by Entec UK Ltd.

The treatment system receives water pumped from a purpose drilled borehole which was drilled 70 m into the Whittle Colliery drift. A short period of test pumping was carried out prior to the construction of the treatment system in order to gain information about the likely water quality (Entec 1999). This exercise showed that the mine water was likely to be net-alkaline (following the convention of Younger 1995) and would contain up to 50 mg/L of iron. Mine water is pumped from the Whittle drift borehole and conveyed to the aeration cascade at the head of the treatment system (refer to Figure 1 for a schematic diagram of the treatment system). Following aeration, the mine water simultaneously flows through two parallel settling lagoons

Author
Charlotte A. Nuttall, Hydrogeochemical and Environmental Research and Outreach, School of Civil Engineering and Geosciences, Drummond Building, Newcastle University, Newcastle upon Tyne NE1 7RU, UK

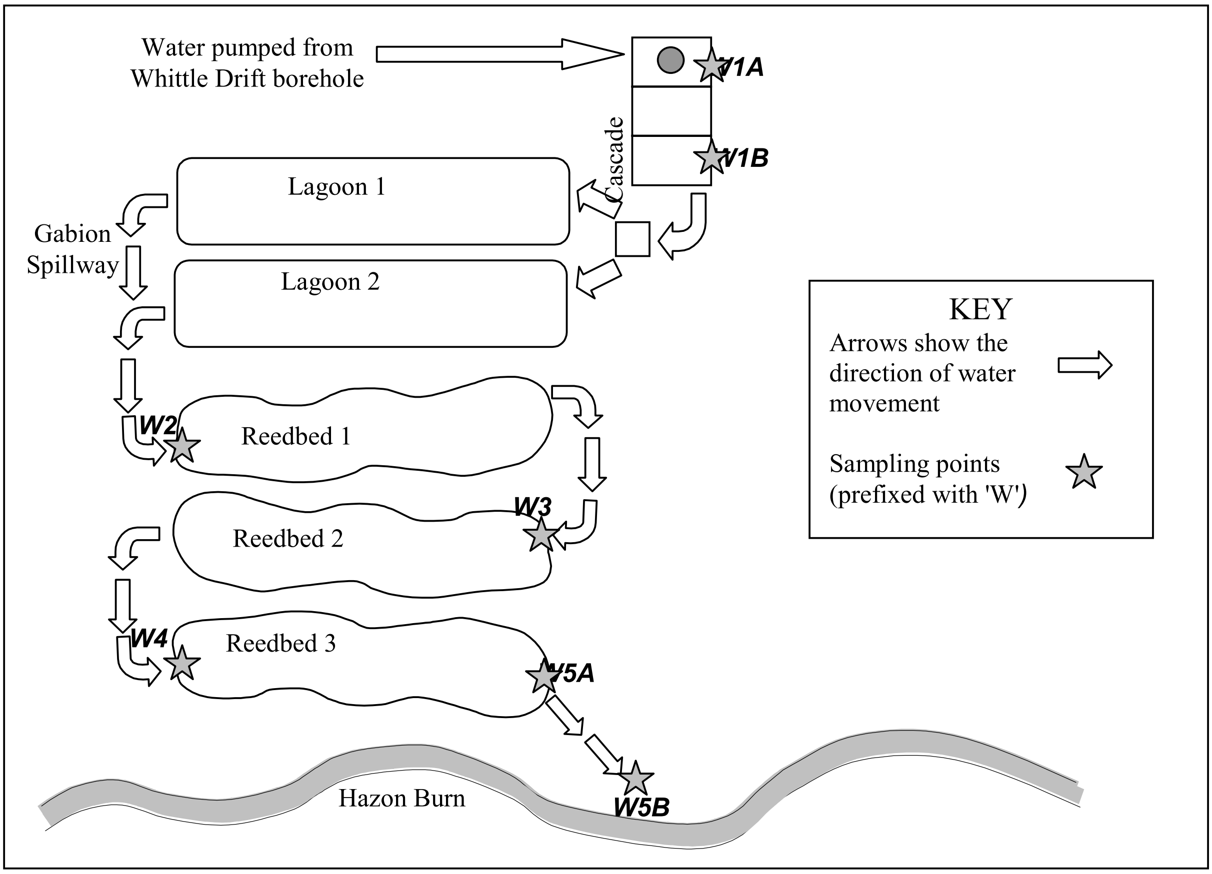

Figure 1. Schematic diagram of the Whittle passive treatment system

(having an area of 800 m^2) where ochre precipitation takes place. Water then discharges from the lagoons into the first of three surface flow aerobic reedbeds.

There are three reedbeds, each having a surface area of 3000 m^2. The middle and lower beds (reedbeds 1 and 3) contain *Typha latifolia* vegetation, the middle reedbeed (reedbed 2) has been planted with *Phragmites*. The purpose of the planting is to distribute flow through the system and polish the final discharge water in addition to aesthetic improvement (Batty 2003, this volume). Following treatment by the reedbed system, mine water is discharged into the Hazon Burn which is a tributary of the River Coquet.

Test pumping was carried out at Whittle Colliery between 14 January and 21 February 2002 to examine the hydraulic response of the mine workings and to determine the emergent mine water quality throughout the course of the test, and also to evaluate the effectiveness of the treatment system in removing iron and manganese. There was some concern that manganese concentrations would exceed limits set by Northumbrian Water at their public supply abstraction point on the River Coquet (although manganese is not ecotoxic, it may stain laundry). Therefore manganese concentrations were closely monitored by Northumbrian Water and the Environment Agency throughout the test.

Sampling procedure

The entire treatment system was sampled daily at the points shown in Figure 1. Field measurements of conductivity, Eh, pH and conductivity were made using a Myron 6P Ultrameter which was calibrated weekly. Dissolved oxygen (DO) and temperature was measured using a YSI 95 DO meter which was calibrated daily. Field measurement of alkalinity was also made using a Hach digital titrator having the range 10–4000 mg/L for $CaCO_3$. Samples which were to be analysed for the cations: calcium, magnesium, sodium, potassium, iron, aluminium and manganese were taken in two preacidified 125 mL polythene bottles. One of these samples was filtered at 0.45 µm in the field, using sealed disposable filters and syringes; the other sample was unfiltered. Unfiltered samples were also taken in an unacidified 125 mL polythene bottle. These unfiltered samples were to undergo analysis for the anions sulphate, chloride and nitrate. Samples were packed

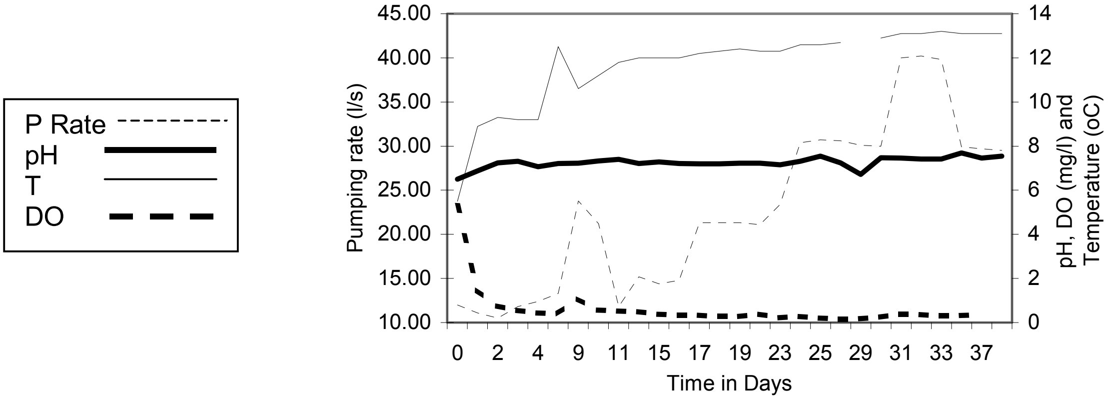

Figure 2. Graph showing how DO decreased, temperature increased and pH remained constant during the test. The vertical broken line indicates when the pumped water changed from shallow, recent recharge water to more deeply-sourced mine water

into cool boxes and then couriered to the Coal Authority (CA) contract laboratories (TES at Bretby) for analysis.

WATER QUALITY DURING THE TEST

Figure 2 shows how pH, temperature, and DO (in mg/L) varied over the course of the test. The graph shows the temperature of the pumped water increasing when the pumping rate was increased to 25 L/s, and decreasing when the pumping rate was knocked back to 11 L/s. The changes in temperature are due to an inverse temperature stratification within the mine system, comprising recent, cooler, shallow-sourced recharge water lying at the top of the water column, and with warmer groundwaters from deeper within the mine system lying beneath. The transition is also clear in the DO results. The approximate completion of the transition between the recharge water and mine water is marked on the graph by a vertical line. Figure 2 shows that the pH of the mine water remained relatively constant during the course of the test, having an average value of 7.25. Notable changes in alkalinity and Eh were also noticed at this point. The Eh became strongly negative at this point reflecting the low DO values observed at this time. However the alkalinity sharply increased to just below 500 mg/L $CaCO_3$ where it remained until the end of the test.

IRON CONCENTRATIONS

Figure 3 shows how the iron concentrations changed during the test. In general, the iron concentrations increased to a value of around 45 mg/L following four days of pumping, where they remained until the end of the test. The change from recharge water to a mine water/recharge mixture was noticed on 18 January and is abruptly marked by increased iron concentrations.

Decreasing the pumping rate (from 23 L/s to 11 L/s on 24/01/02 and from 40 L/s to 30 L/s on 18/02/02) caused decreases in iron concentrations, presumably due to increasing proportions of shallow-sourced recharge water being incorporated into the pumped water. Using the initial better quality recharge water pumped at the start of the test (14 Jan) and the poorer quality mine water pumped towards the end of the test (14 Feb) as end members, geochemical modelling using Netpath has shown that a mixture of 28% of the recharge water and 72% of the deeper mine water would create the water quality achieved on 24 January (when the iron concentrations dropped after the pumping rate had been reduced for the first time). Modelling also shows that a mixture of 33% of the recharge water and 67% of the mine water would create the water quality achieved on 15 of February (when the iron concentrations dropped after the pumping rate had been reduced for the second time).

These findings show that the system is quite sensitive to variations in the pumping rate (and thus presumably driving heads) which allow differing amounts of recharge to enter the system and mix with mine water. The influence of recharge water has unusually high significance in this system, because the workings are relatively shallow and mainly confined to a single seam.

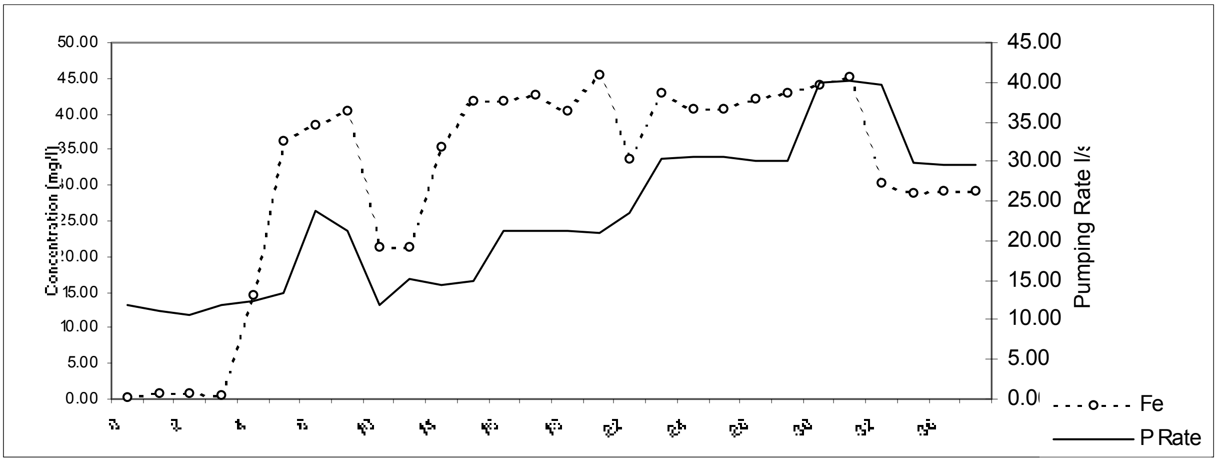

Figure 3. Iron concentrations throughout the test

MANGANESE CONCENTRATIONS

During the course of the test, manganese concentrations of the discharge from the treatment system were carefully monitored daily by the Environment Agency. This was achieved using a Hach pocket colorimeter having the range 0–10 mg/L. The concentrations measured daily at the discharge point were converted into a manganese loading (based on the daily flows in the Hazon Burn and the River Coquet), and consequently a theoretical manganese concentration at the Northumbrian Water intake at Warkworth. It was important that the limit of 43 µg/L manganese was not exceeded at this intake. This limit is set by the Environment Agency to protect the supply at Warkworth, because excessive manganese concentrations can cause staining of laundry.

Figure 4 shows how the manganese concentrations changed during the course of the test. Manganese concentrations declined during the test until they reached a value of approximately 1.5 mg/L. As observed with the iron data, there was also a peak in manganese levels on 18th January when the initial, shallow recharge water had been depleted. Variations in the pumping rate appear to have very little effect upon the manganese concentrations. Figure 4 clearly shows manganese concentrations decreasing, even though the pumping rate was increasing. On the occasions when the pumping rate was increased, manganese levels appear to decline more rapidly, indicating that the initial elevated manganese concentrations were probably the result of a first flush.

MINE WATER HYDROGEOCHEMISTRY

Throughout the test, the mine water remained net alkaline. The high alkalinity values associated with the deeper mine water can be attributed to various sources, in particular ‘stone dust’ ($CaCO_3$) (which was spread throughout the mine during working as part of standard precautions against explosions) and interaction with the overlying limestone sequence. The raw mine water data (i.e. samples taken at the top of the cascade) were plotted on a Piper diagram (Figure 5) (Appelo and Postma 1993). The diagram also shows the two distinct types of water mentioned previously. The better quality recharge water plots towards the calcium and magnesium bicarbonate field, representing shallow recharge water that has recently permeated the overlying limestones. The magnesium component suggests that the limestones in this area must contain appreciable quantities of magnesium carbonate ($MgCO_3$). This water also plots slightly towards the sulphate axis – the sulphate component in these waters being derived from pyrite decomposition within the mine. The water from deeper within the system also contains a significant sulphate component, but, unusually, plots towards the sodium axis, suggesting that several mechanisms have been involved in the evolution of this water. Initially a calcium carbonate facies water was created, which then interacted with pyrite in the workings to create a calcium sulphate water. Calcium ions were then lost by ion exchange with sodium ions occurring within clays present throughout the geological sequence. These sodium ions then have the effect of making the water plot further towards the sodium sulphate hydrochemical facies.

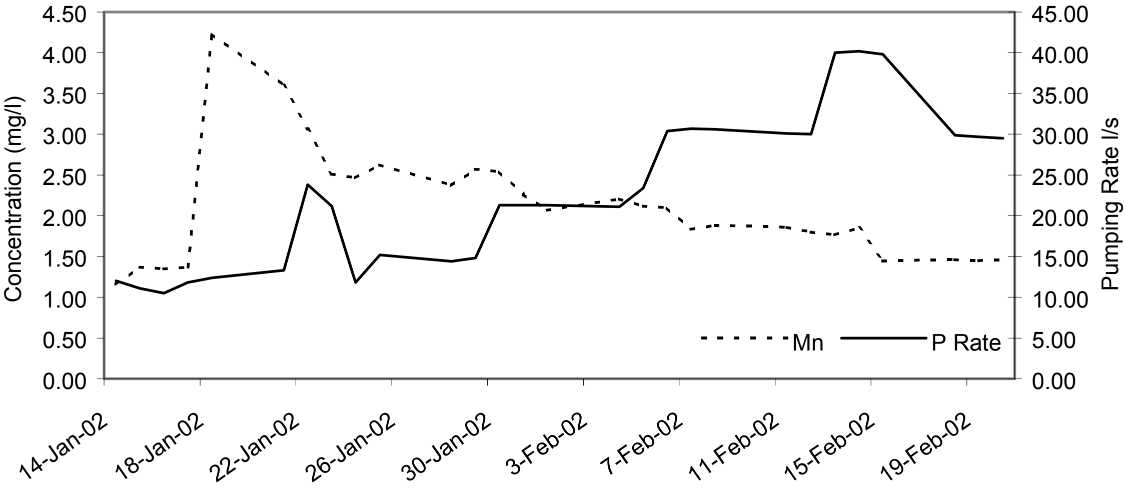

Figure 4. Manganese concentrations throughout the test

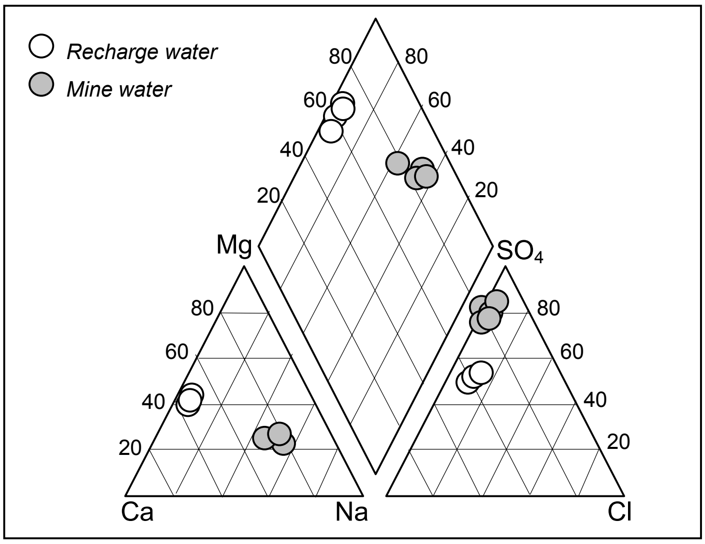

Figure 5. Piper diagram showing the two distinct water types encountered during test pumping

PERFORMANCE OF THE TREATMENT SYSTEM

Stepped test pumping was carried out at rates of 12–40 L/s over a five-week period. The system took one week to fill with mine water. The performance of each component of the treatment system was then evaluated.

THE AERATION CASCADE

The purpose of the aeration cascade at Whittle was to raise the dissolved oxygen content of mine water and encourage the conversion of ferrous iron (Fe^{2+}) into ferric iron (Fe^{3+}). This facilitates the precipitation of ferric hydroxide (ochre) in the settling lagoons and throughout the remainder of the treatment system. Additional aeration of mine water was provided by a gabion style spillway which conveyed the mine water from the settling lagoons into the first reedbed. The aeration chamber and the lagoon outlet were very effective at increasing dissolved oxygen concentrations. The average dissolved oxygen content of the influent minewater was 0.5 mg/L (4.8% saturation). By the time that the mine water had reached the bottom of the cascade the dissolved oxygen had been increased to an average value of 8.0 mg/L (74.3% saturation). Once the mine water had flowed over the spillway into the first reedbed, the dissolved oxygen had increased again to around 11 mg/L (92.8% saturation). The conversion of ferrous to ferric iron was also confirmed by the lagoons quickly turning orange as ochre precipitated from solution.

REMOVAL OF IRON AND MANGANESE BY THE SYSTEM

Using data gained from analysing the raw mine water entering the treatment system and the discharge from the system, it was possible to calculate the percentage removal rates of iron and manganese throughout the whole system. An average of 55 kg of iron was retained within the entire treatment system each day (equating a 97% removal rate). An average of 1.05 kg of manganese was retained daily by the system (equating a 34% removal rate). The iron removal rate remained above 95% throughout the test, but manganese removal rates quickly declined during the test, dropping to around 10% by the end of the test. These low removal rates for manganese are not surprising given the difficulty of precipitating manganese from solution in aerobic, surface flow systems whilst iron is still present in solution (Hem 1962; Johnson 2002). The initial higher manganese removal rates encountered at the start of the test represent a 'honeymoon' period, with higher removal rates attributed to sorption on to substrates and surfaces within the lagoons and reedbeds. After about four days of operation this period of manganese sorption is complete and removal rates decline.

MANGANESE AND IRON LOADINGS THROUGHOUT THE SYSTEM

Using the daily pumping rate together with the daily manganese and iron concentrations, it was possible to calculate the metal loadings at each sample point in order to gain an idea of the removal of metals. A calculation of the metal loadings generated throughout the system was made using the data gained from laboratory analysis.

It is possible to apply these average loading figures to each element of the treatment system (i.e. the settlement lagoons and each of the three reedbeds) to determine how much metal is being removed at each step. These data can then be used to work out metal removal per unit area of treatment system. The results are summarised in Table 1.

Table 1 shows that the lagoons and the first reedbed remove the majority of the iron (40% and 46% respectively) and the lagoons remove the majority of the manganese (7%) with the remainder of the treatment system removing very little of this metal. The second reedbed removes another 11% of the iron but the third reedbed currently removes very little on average. There are two likely reasons for this:

(i) it is easy to remove the higher concentrations of iron, but as the iron concentration falls below 1 mg/L it becomes more difficult to remove from solution;

(ii) the vegetation in reedbed three was both young (planted recently) and senescent (due to the time of year) at the time of the test. Once the vegetation is dense, it can be expected to polish the low concentrations of iron much more effectively (Batty 2003, this volume).

The difficulty in removing the small amount of remaining iron is due to this iron being complexed with other anions. Geochemical modelling using the WATEQ4F code (Ball and Nordstrom 1991) was carried out on the water entering the final wetland. This showed that in this water the remaining iron is complexed with chloride, carbonate and sulphate. Iron removal rates per unit area were calculated in each element of the treatment system.

The oxidation lagoons gave the highest removal efficiency; this is due to the enhanced sedimentation rate of iron oxide flocs (at higher iron concentrations i.e. at the influent end of the system, the density of iron oxide flocs is greater and therefore settling rates are higher (Younger *et al.* 2002)). The iron removal rates

Table 1. Daily metal removal in each element of the treatment system

	Area (m^2)	Fe removed (kg/day)	Mn removed (kg/day)	Fe removed ($g/m^2/d$)	Mn removed ($g/m^2/d$)
Lagoons	800	30.4	0.3	38	0.4
Reedbed 1	3000	35.6	0.1	11.9	0.03
Reedbed 2	3000	8.4	0.1	2.8	0.03
Reedbed 3	3000	0	0.1	0	0.03

per unit area of treatment system in the reedbeds are also significant (being favourably comparable with removal rates at several sites in the eastern US (Younger *et al.* 2002) and sites in the UK (Laine 2002)). These results are very encouraging, especially the fact that the system was not operating under optimal conditions, mainly due to the time of year. Therefore system performance should show even greater efficiency during the warmer months when enhanced plant growth will also contribute to iron removal.

IMPACTS UPON THE RECEIVING WATERCOURSE

There was very little difference between all of the field determinands (with the exception of conductivity) upstream and downstream of the site discharge. The Hazon Burn usually has a pH of around 8.3, an alkalinity of 134 mg/L (as $CaCO_3$) and a DO of 13 mg/L. Temperature ranged throughout the test from 1.9°C to 8.3°C, depending on prevalent air temperature. Suspended solids were governed by the amount of flow in the river. Therefore very little impact was found (with respect to the Hazon Burn) in terms of these determinands. Over the first four days of the test there was very little difference in manganese concentrations upstream and downstream of the discharge because the treatment system was filling during this phase. Some peaks in conductivity and sulphate concentrations occurred both upstream and downstream of the site discharge, and are therefore not directly due to the discharge. However, there were occasions (especially towards the end of the test) when the site discharge did cause increases in sulphate and conductivity, albeit these will not have any ecological impact upon the Hazon Burn. Generally iron concentrations were around 1.5 mg/L and manganese concentrations remained below 0.5 mg/L. Peaks in the iron concentration both upstream and downstream of the site discharge were apparent on occasions. The fact that a peak value is also recorded upstream of the site indicates that this peak may not have been caused by the discharge from the site. There must be some additional inputs of iron upstream of the W6 sample points (probably spoil leachates from the mine site itself, which is not in CA ownership). This fact is confirmed when looking at the data, which show that on many occasions the iron concentrations upstream of the discharge (W6) were higher than the iron concentrations downstream (W7) i.e. the discharge from the site was actually causing a dilution of iron in the Hazon Burn. This peak also occurs before rainfall, probably indicating that the flows in the Hazon Burn were lower, hence making the peak more noticeable (Rukin 2002).

Manganese concentrations also show similar upstream and downstream peaks, strongly suggesting that the same upstream source also contains elevated manganese. There was an increased manganese concentration downstream in the Hazon Burn as the test proceeded and the pumping rate increased. However, the manganese concentration never rose above 0.5 mg/L and manganese concentrations at the Warkworth intake were never exceeded.

CONCLUSIONS

The treatment system was very effective at removing iron from the mine water, leading to a final discharge iron concentration of less than 1.5 mg/L. On average 74 kg of iron was retained daily within the entire treatment system, corresponding to an overall iron removal rate of 97%. On average 0.6 kg of manganese was retained daily by the system, corresponding to an overall removal rate of 34%.

Analysis of the sampling data show, that the lagoons and the first reedbed remove the majority of the iron and the lagoons remove the majority of the manganese. The second reedbed removes less iron (11%) and the third reedbed removes very little, because iron concentrations are low at this point in the system and it is always more difficult to remove the last few mg (at least until the vegetation in the bed reaches full density). During the course of test pumping at Whittle Colliery, pumped mine waters changed from shallower recharge water to deeper mine water. The pH remained relatively constant throughout the test, having an average value of 7.25, and the water remained net alkaline, confirming that the choice of an aerobic reedbed treatment system was suitable to treat this water.

Increases and decreases in pumping rate provoked concomitant increases and decreases in iron concentrations due to the mechanism of mixing the deeper mine waters with the shallower less contaminated recharge waters. Manganese concentrations were unaffected by changes in pumping rate. Iron concentrations reached a maximum value of 45 mg/L when the pumping rate was at its maximum (40 L/s). Manganese concentrations were initially 4 mg/L and then showed a declining trend, resulting in a manganese concentration of 1.5 mg/L in the untreated water at the end of the test.

The discharge from the treatment system caused noticeable (but ecologically insignificant) elevated conductivity and sulphate concentrations in the Hazon Burn. Peaks in iron and manganese concentrations were noted upstream and downstream of the discharge point, suggesting that there are other sources of these metals entering the Hazon Burn. Manganese concentrations in the Hazon Burn were slightly elevated downstream of the site towards the end of the test (when river flows dropped), although they never exceeded 0.5 mg/L.

ACKNOWLEDGEMENTS

The author would like to thank Keith Parker and Dave Stafford from the Coal Authority for allowing her to present their data. The views expressed here represent those of the author.

REFERENCES

Appelo, C.A.J. and Postma, D. (1993) *Geochemistry, Groundwater and Pollution*. A.A. Balkema, Rotterdam.

Ball, J.W. and Nordstrom, D.K. (1991) *User's Manual for WATEQ4F, with Revised Thermodynamic Data Base and Test Cases For Calculating Speciation Of Major, Trace And Redox Elements In Natural Waters*, pp. 91-183. US Geological Survey Open-File Report.

Batty, L.C. (2003) Wetland plants – more than just a pretty face (this volume).

Entec UK Ltd. (1999) *Whittle, Northumberland. Report of the Pumping and Treatability Trail.* Report to the UK Coal Authority.

Hem, J.D. (1964) *Chemistry of Manganese in Natural Water.* USGS Water Supply Paper, 1667-B.

Jarvis, A.P. and Younger, P.L. (1997) Dominating factors in mine water induced impoverishment of the invertebrate fauna of two streams in the Durham Coalfield, UK. *Chem. and Ecol*., **13**, 249-270.

Johnson, K.L. (2002) The importance of aeration in passive treatment schemes for manganese removal (this volume).

Laine, D.M. (2002) Engineering design aspects of passive in situ remediation of mining effluents (this volume).

Rukin, N. (2002) Whittle minewater treatment system: in-river attenuation of manganese (this volume).

Whitworth, K. (2002) The monitoring and modelling of mine water recovery in UK coalfields. In: Younger, P.L. and Robins, N.S. (eds) *Mine Water Hydrogeology and Geochemistry.* Geological Society, London, Special Publication.

Younger, P.L. (1995) Hydrogeochemistry of mine waters flowing from abandoned coal workings in County Durham, UK. *QJEG*, **28**, S101-S113.

Younger, P.L. (2000) Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation. *J. Contam. Hydrol.* **44**, 47-69.

Younger, P.L., Banwart, S.A. and Hedin, R.S. (2002) *Mine Water Hydrology, Pollution, Remediation*. Kluwer Academic Publishers, The Netherlands.