Land Contamination & Reclamation, 11 (2), 2003

DOI 10.2462/09670513.807

Whittle mine water treatment system: in-river attenuation of manganese

Nick Rukin

Abstract

Much work has been undertaken on the design of treatment systems to remove iron from ochreous mine water discharges. Unlike iron, manganese removal is far more difficult and generally requires active chemical dosing rather than passive treatment. The need for manganese removal can therefore significantly change the economics, management attention and sustainability of a site. Understanding natural attenuation of manganese in river systems is therefore key to deciding whether (active) manganese treatment is needed to protect downstream receptors.

Nuttall (2002, this volume) describes the effectiveness of the passive treatment system at Whittle in reducing both iron and manganese concentrations in ochreous mine waters. This paper discusses the results of in-river monitoring and provides evidence for manganese removal downstream of the discharge point. In addition to dilution, attenuation appears to be in the order of 20 to 50%, depending on relative rates of mine water discharge and river flows. Such attenuation means that active treatment may not be needed for the long-term operation of the Whittle scheme. Operation of the scheme commenced in July 2002, with monitoring to further examine evidence for manganese attenuation and any impact on the ecology of the recipient watercourses.

Key words: Hazon Burn, in-river attenuation, manganese, mine water treatment, Whittle Colliery

INTRODUCTION

Whittle Colliery lies in Northumberland, northeast England, some 7 km inland from the North Sea, close to the village of Warkworth (see Figure 1). The colliery is now disused and is filling with water. Without control of water levels by pumping and treatment of the poor-quality mine water, it has been predicted that discharge to local watercourses will occur over the next few years. Further background details of the colliery's history and of the flooded strata are provided by Nuttall (this volume).

An abstraction borehole and passive treatment system for iron removal, described by Nuttall (this volume), has been installed to pump and treat mine waters from the former Whittle Colliery. The pumped raw water is characterised by high concentrations of iron (up to 43 mg/L), manganese (stabilised from 4.4 to 1.8 mg/L over three weeks) and sulphate (2470 to 3110 mg/L). It is neutral (pH 6.95 to 7.20) and net alkaline (alkalinity between 400 and 490 mg/L $CaCO_3$). During a five week trial of the treatment system in early 2002, iron was successfully removed (to <1 mg/L), but manganese concentrations remained relatively high in the system's discharge to a local watercourse: the Hazon Burn.

Manganese is generally recognised as being difficult to treat using passive treatment systems, and it is assumed that dilution is the only mechanism that will reduce concentrations in receiving watercourses. During the treatment trial, water quality was monitored at several locations (see Figure 1) both upstream and downstream of the treated discharge, to examine the impact and fate of mine water contaminants, in particular manganese, on the receiving watercourses. The fate of manganese is of particular interest to the Whittle site, as besides potential impacts to salmonid-grade watercourses, there is a public water supply abstraction downstream at Warkworth which occasionally reaches its upper limit on manganese concentrations. Significantly increased manganese loadings at the waterworks could therefore force the need for active manganese treatment at the Whittle site.

Author
Nick Rukin, Entec UK Ltd, 160-162 Abbey Foregate, Shrewsbury SY2 6BZ, UK

HYDROLOGY

The Whittle treatment system discharges into the Hazon Burn, which flows southeastwards for approximately 2 km and falls between 40 and 45 m from the mine water discharge point to its confluence with the River Coquet (see Figure 1). From the confluence with the Hazon Burn, the River Coquet meanders about 11 km and falls about 20 m in a northeast direction, past Warkworth before turning to the southeast and discharging to the North Sea at Amble. A public water supply is taken from the River Coquet at Warkworth water treatment works (WTW), upstream of Warkworth itself.

Flows in the Hazon Burn have not been routinely measured, but the River Coquet is gauged at Morwick some 3.5 km downstream of the confluence with the Hazon Burn. Mean and 95 percentile flows are 7.7 m^3/s and 1.3 m^3/s respectively (Institute of Hydrology 1998).

Additional streams or burns enter the River Coquet between the Hazon Burn confluence and Warkworth WTW. Of these, the Tyelaw Burn is of particular note because it enters the Coquet 300 m upstream of Warkworth WTW and drains an area with colliery spoil heaps: additional sources of both iron and manganese.

THE TREATMENT SYSTEM

The passive treatment system at Whittle has been described by Nuttall (this volume), and has been designed to remove iron from mine waters pumped from the flooding workings. The system consists of an abstraction well completed in the Whittle Colliery workings, an aeration cascade, two parallel oxidation lagoons and three in-series reed beds. During the test, pumping rates were varied between 15 and 40 L/s to test the system performance. The performance of the treatment system is also described by Nuttall (this volume). Operation of the system commenced in July 2002 at a fixed pumping rate of 15 L/s.

WATER QUALITY

Sampling and analysis

During the treatment trials, surface water quality was monitored and sampled at seven locations (R4 to R13

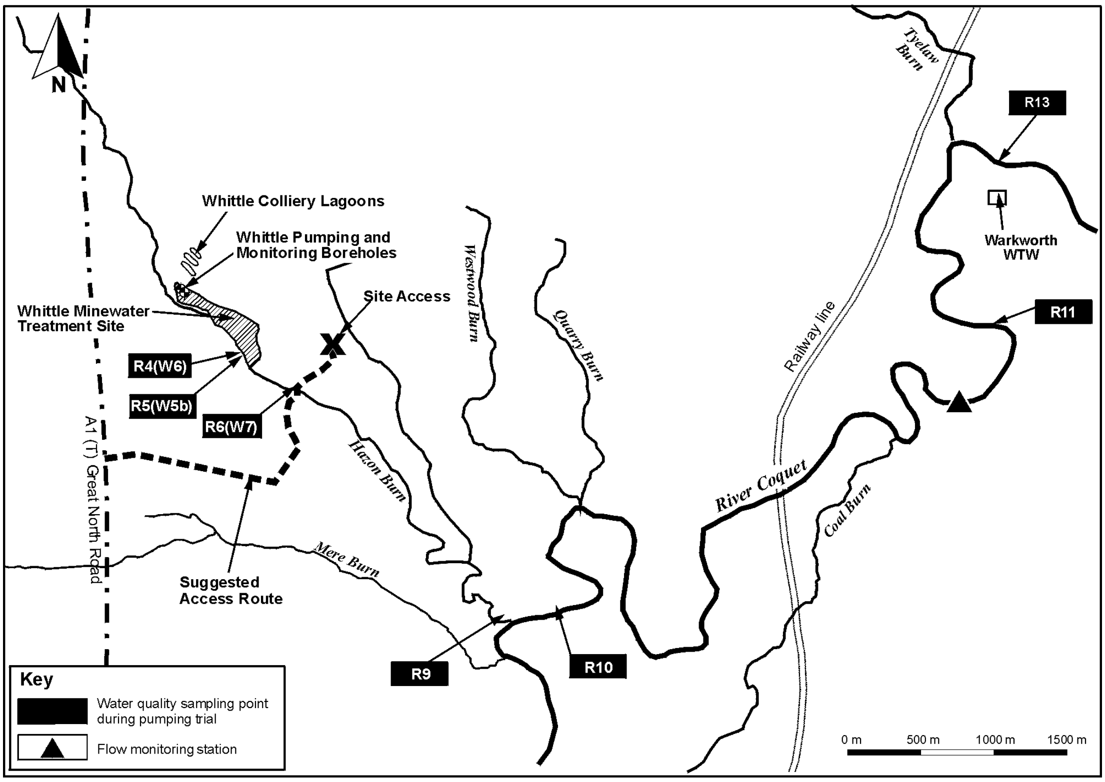

Figure 1. Location of Whittle Colliery, sampling points and gauging stations. Note: R8 is approximately 3 km upstream – SSW – of R10.

on Figure 1) in the river system. These were the Hazon Burn: upstream of the discharge point – R4, 300 m downstream of the discharge – R6, and at the confluence with the Coquet – R9. Similarly, the River Coquet was monitored upstream of the confluence with the Hazon Burn (R8), 300 m and 4 km downstream of this confluence (R10 and R11 respectively), and at Warkworth WTW (R13). In addition, the discharge water quality (R5) was monitored.

Samples were collected each weekday during the trials by the Environment Agency. These samples were analysed for pH, EC, major ions, BOD, ammoniacal nitrogen, dissolved metals (Fe, Mn) and total metals, (Fe, Mn and Al) and dissolved oxygen. Samples from points R4-6 were also collected by the University of Newcastle and Entec on behalf of the Coal Authority. The results were generally in agreement and, for consistency, only Environment Agency supplied data have been presented and used in the preparation of this paper.

Background water quality

Upstream water quality in the Hazon Burn over the five weeks of the test, sampled at R4 (see Figure 1 for location), shows dissolved oxygen at 90–100% saturation, basic pHs (7.8 to 8.2), relatively low concentrations of sulphate (19 to 59 mg/L), moderate alkalinity (68 to 173 mg/L $CaCO_3$), and variable suspended solids concentrations (2 to 588 mg/L). Total iron concentrations are notable (1.2 to 6.9 mg/L) and a significant proportion of this is present in dissolved form (0.45 to 0.61 mg/L). Manganese concentrations, largely present in dissolved form, were typically between 0.05 and 0.10 mg/L.

Background water quality in the River Coquet (R8) is generally good, supporting salmonid fisheries, and has low iron (<1.0 mg/L), manganese (<0.03 mg/L), sulphate (<20 mg/L) and suspended solids (<100 mg/L) concentrations. It also has high dissolved oxygen saturation and basic pHs (7.2 to 8.4).

Raw and treated water quality

Raw water from Whittle Colliery is characterised by high dissolved iron (up to 43 mg/L) and manganese (4.4 to 1.8 mg/L). Water quality evolved during the five week treatment trial, with increases in iron content and decreases in manganese content. Figure 2 shows changes in water quality with respect to total iron and manganese with time in raw water and treated water. The treated water quality has a significantly lower iron content but manganese remains elevated at around 1.7 mg/L. The discharge water also has a high sulphate concentration (up to 3180 mg/L).

FATE OF MANGANESE IN THE RIVER SYSTEM

Introduction

It is commonly assumed that once manganese enters a watercourse from a (treated) mine water discharge, then the only mechanism likely to reduce its concentration in the receiving water course is dilution. However, if it can be shown that manganese concentrations decrease by more than can be explained by dilution alone, then this provides evidence for other attenuating processes such as precipitation, sorption and settlement. This section examines water quality data in the Hazon Burn and River Coquet for evidence of such attenuating processes.

Estimation of diluting flows

Estimating the effects of dilution is most easily undertaken by comparison of flow rates in the mine water discharge and the receiving watercourse. However, there were no direct measurements of flows in the Hazon Burn during the test, and so flows have been deduced by consideration of the decreases in sulphate concentration from the treated discharge into the Hazon Burn. Sulphate was considered to behave conservatively, as sulphate removal processes such as reduction and precipitation were highly unlikely to occur in the conditions (well oxygenated and low calcium) prevalent in the Burn. On this basis, comparison of sulphate concentrations upstream and downstream of the treated mine water discharge was used to estimate dilution and hence flows in the Hazon Burn. Flows in the Hazon Burn were derived from dilution of sulphate, using the expression:

$$([C_{\text{Hazon d/s}} - C_{\text{Hazon u/s}}] / C_{\text{mine water}}) = (Q_{\text{mine water}} / [Q_{\text{Hazon u/s}} + Q_{\text{mine water}}])$$

where:

$C_{\text{Hazon u/s}}$ = sulphate concentration in Hazon Burn upstream of treated mine water discharge (mg/L);

$C_{\text{Hazon d/s}}$ = sulphate concentration in Hazon Burn downstream of treated mine water discharge (mg/L);

$C_{\text{mine water}}$ = sulphate concentration in treated mine water discharge to Hazon Burn (mg/L);

$Q_{\text{Hazon u/s}}$ = flow (to be derived) in Hazon Burn upstream of treated mine water discharge (L/s);

$Q_{\text{mine water}}$ = mine water discharge rate (L/s).

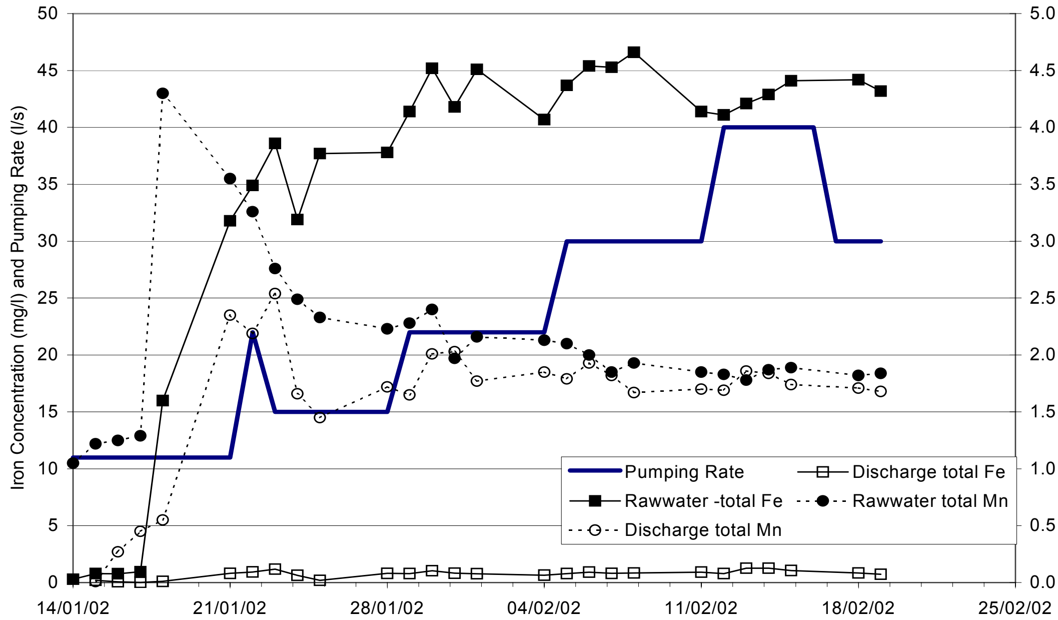

Figure 2. Changes in raw water and discharge water quality during the trial pumping

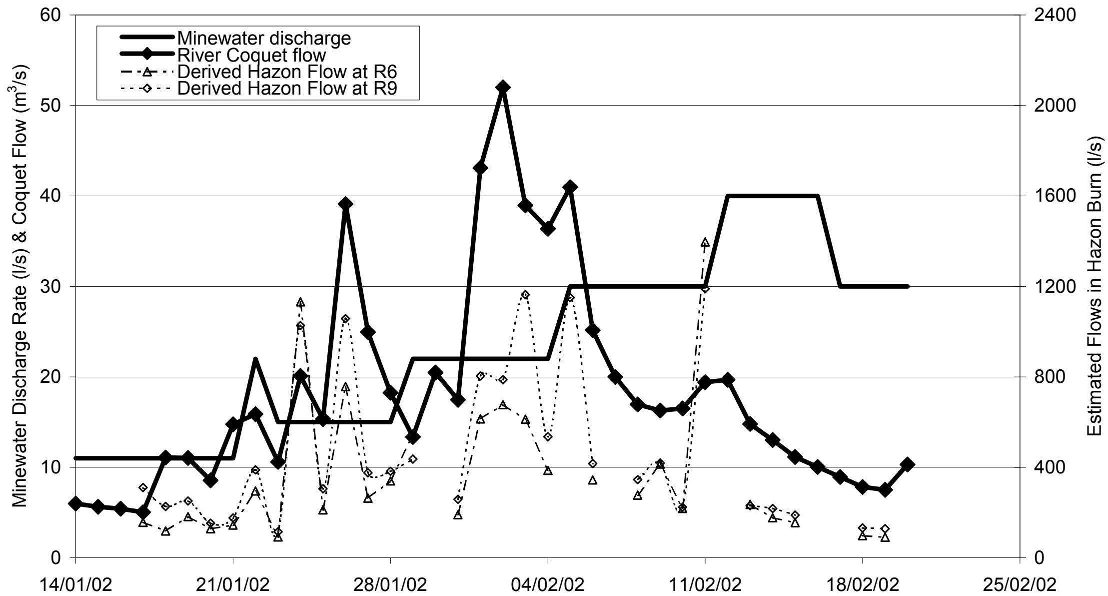

Figure 3. Measured flows in the River Coquet, derived flows in the Hazon Burn and mine water discharge rates. Note: derived flow rate refers to Hazon Burn flow rates excluding the mine water discharge.

Figure 3 shows the derived flow in the Hazon Burn. Measured flows in the River Coquet at Morwick are also shown for comparison. Flows in the Hazon Burn appear to have varied in a similar way to those on the River Coquet. It is noted that there was a reduction in sulphate concentration between R6 and R9, indicating an increase in flow along the course of the Hazon Burn of the order of 10–20%.

Attenuation of manganese in the Hazon Burn

Increases in manganese concentration above background were evident in downstream samples and this

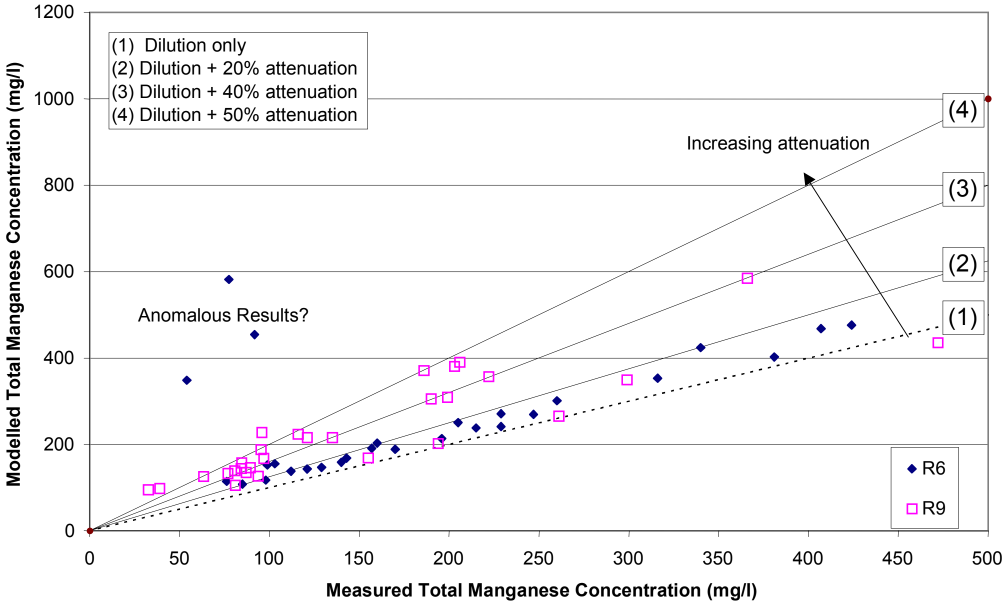

Figure 4. Comparison of modelled and measured total manganese concentrations in the Hazon Burn

difference increased with increased discharge rate. At the end of the test, concentrations of between 0.4 and 0.6 mg/L were detected at Hazon Ford (R6), whereas at the confluence with the River Coquet (R9) concentrations were lower, reaching only 0.2 to 0.4 mg/L. Comparison of total manganese with dissolved manganese concentrations suggests that most of the manganese is present in dissolved form except when there are peaks in background suspended solids.

The lower concentrations of manganese in the Hazon Burn compared to the treated mine water discharge will, in part, be due to dilution, but other processes such as precipitation, sorption or settlement could be occurring. To examine this in more detail, total manganese concentrations in the Hazon Burn resulting from only dilution of the treated mine water discharge (Mn_{tmw}) have been estimated using the measured discharge rates (Q_{mw}) and the sulphate-derived estimates of flows (Q_{hazon_est}) in the Hazon Burn using the formula:

$$Mn_{dilution\ only} = ([Mn_{u/s} \times Q_{Hazon\_est}] + [Mn_{tmw} \times Q_{mw}])/(Q_{mw} + Q_{Hazon\_est})$$

where $Mn_{u/s}$ is the upstream concentration of total manganese, and other variables are as defined above.

The assessment has been undertaken for both monitoring points (R6 and R9) on the Hazon Burn, and results are compared with measured concentrations. Figure 4 shows that measured total manganese concentrations at R6 are similar to the modelled concentrations, assuming dilution alone with a difference of about 10%. This suggests some possible attenuation in addition to dilution, but is within the likely margins of error. The difference is much more marked for R9 close to the confluence with the River Coquet. At this location, attenuation appears to vary between 0% and 50%. It is noted that any additional dilution occurring between R6 and R9 (e.g. from side streams) is taken into account by the decrease in concentrations of sulphate and in turn the predicted flows. Consequently, changes in manganese concentration relative to sulphate or derived flows are most likely to be related to attenuation.

To examine if the amount of attenuation additional to dilution at R9 is related to flow rates in the Hazon Burn, Figure 5 compares the difference between modelled (dilution only) and measured concentrations of total manganese, as a percentage of the modelled concentration, with derived flow rates in the Hazon Burn.

The data in Figure 5 suggest a relationship between decreasing attenuation rates and increasing flow rates. The data also suggest that attenuation is less at increased mine water discharge rates for a given flow. Overall the results indicate that the Hazon Burn typically attenuated between 20% and 40–50% of the manganese loading present in the discharged treated mine water.

Higher flow rates are associated with shorter travel times and higher velocities, giving less time for reaction (precipitation or sorption) and/or settlement of manganese. Figure 6 shows estimated flow rates plotted against suspended solids concentrations and dissolved oxygen saturations.

This illustrates that whilst the Hazon Burn appears to remain fully oxygenated at a range of flow conditions, as expected, the ability to carry suspended solids rises with higher flow rates. It is also noted that in general, suspended solid concentrations are higher upstream at R6 than at R9 for a given flow, suggesting higher velocities in the upper stretches and settlement of solids downstream.

Attenuation of manganese in the River Coquet

Flows in the River Coquet are measured at Morwick and are compared to deduced flows in the Hazon Burn in Figure 3. The data suggest that flows in the Hazon Burn are typically about 2% of those in the River Coquet, giving a substantial (×50) additional dilution factor.

Unlike the Hazon Burn, where total and dissolved manganese concentrations are very similar, dissolved manganese is typically less than 50% of the total manganese concentration in the River Coquet.

Total manganese concentrations varied through the test, most likely as a result of variations in suspended solids, but there was no clear increasing trend. Dissolved manganese concentrations did show an increasing trend, with concentrations rising at Warkworth (R13) to about 0.030 mg/L from a background (R8) upstream of the confluence with the Hazon Burn of less than 0.015 mg/L. It is of note, however, that while there was a significant peak downstream of the confluence with the Hazon Burn (R10), this peak was much dissipated by Warkworth Moor Ford (R11) with maximum concentrations of 0.015 mg/L reached. This suggests additional inputs of dissolved manganese downstream of R11, probably related to inflows from Tyelaw Burn. This supposition is supported by elevated concentrations of dissolved manganese measured at R13 in the first few days of the test when the Whittle treatment system was still filling and there was no discharge to the Hazon Burn.

To check whether the concentrations measured at Warkworth Moor (R11), upstream of this additional source, are consistent with the inflow of the Hazon Burn (R9), theoretical concentrations, assuming dilution only, have been modelled using the formula:

$$Mn_{dilution\ only} = ([Mn_{Hazon\_R9} \times Q_{Hazon\_est}] + [Mn_{u/s\ \ Coquet} \times Q_{Coquet}]) / (Q_{Hazon\_est} + Q_{Coquet})$$

where:

$Mn_{dilution\ only}$ = theoretical concentration (µg/L) of dissolved Mn downstream of the Hazon/Coquet confluence;

Mn_{Hazon_R9} = concentration (µg/L) of dissolved Mn at R9 (Hazon Burn);

Q_{hazon_est} = estimated flow (m^3/s) in Hazon Burn at R9 (based on sulphate dilution);

$Mn_{u/s\ Coquet}$ = measured dissolved Mn concentration (µg/L) upstream of the Hazon/Coquet confluence (R8);

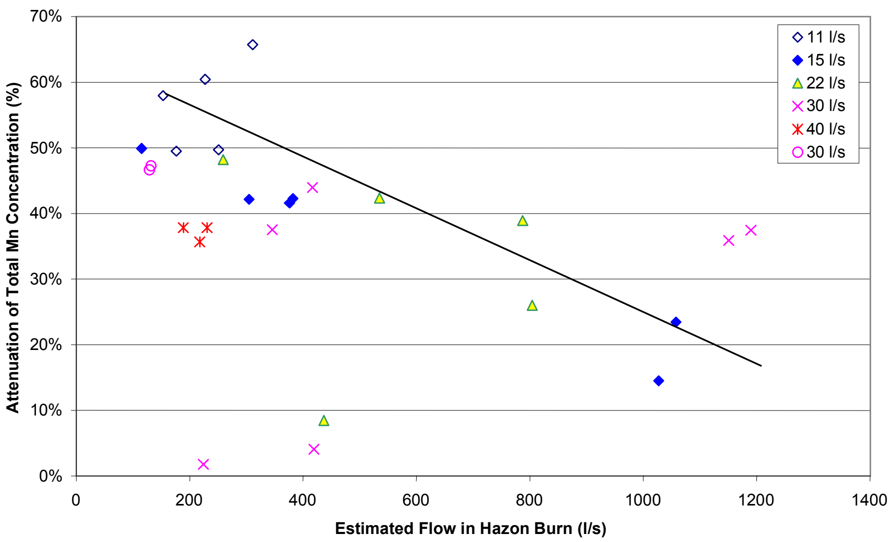

Figure 5. Variation in the attenuation of total manganese with flows in the Hazon Burn

Comparison of the modelled with the measured dissolved manganese concentrations (Figure 7) suggests reasonable agreement between the two, and in turn provides little evidence for attenuation within the River Coquet, other than by dilution. The differences between R10 and R11 on the River Coquet are therefore likely to be related to additional diluting flows along this stretch of river.

The reasons for lack of attenuation in the River Coquet, other than by dilution, are not clear. Manganese attenuation in the Hazon Burn appears to be related to settlement of solids. As suspended solids concentrations upstream (R8) and downstream (R11) on the Coquet do not appear to systematically decrease (see Figure 8), this suggests that the absence of settlement in the Coquet may be the cause of this negligible manganese attenuation.

Impact of manganese attenuation on aquatic ecology

The Environment Agency carried out invertebrate surveys before and during the trial treatment test, to check

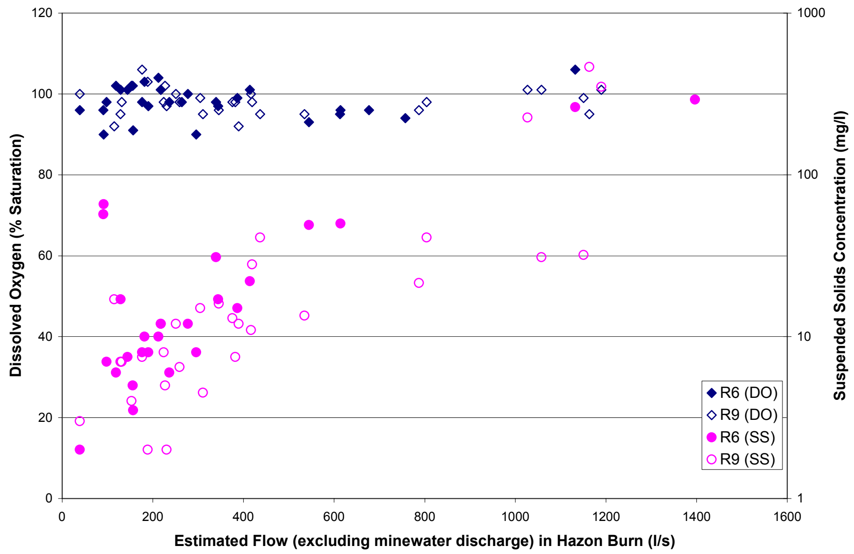

Figure 6. Variation in dissolved oxygen and suspended solids content with derived flows in the Hazon Burn

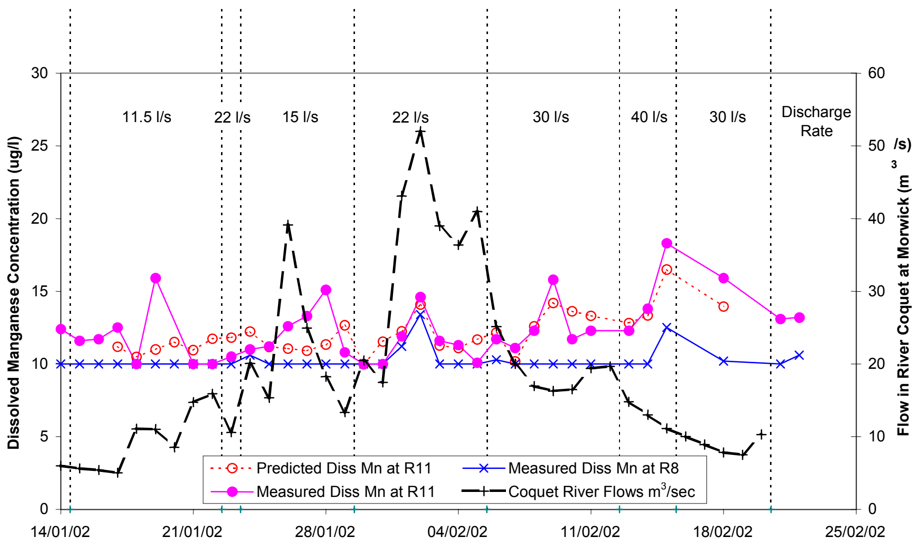

Figure 7. Manganese concentrations in the River Coquet

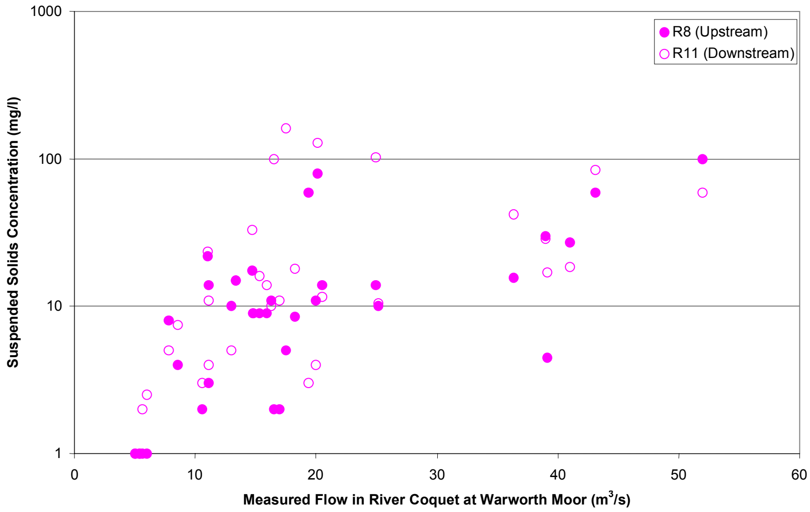

Figure 8. Variation in suspended solids content with measured flows in the River Coquet

for any impacts to the aquatic ecology of the Hazon Burn. From the data collected, no clear impact could be determined. Given that the concentration of manganese in the Hazon Burn will be significantly below 1 mg/L, it appears unlikely that bed smothering effects will occur. However, further ecological monitoring is to be carried out now the system is under operation, to check for any longer term impact.

CONCLUSIONS

Water quality monitoring data and estimates and measurements of river flows have been used to establish that manganese concentrations arising from the discharge of treated mine waters decrease in the receiving watercourse by more than can be explained by dilution alone.

300 m downstream of the point of discharge, the attenuation is minimal: of the order of 10%, but (1700 m) further downstream this additional attenuation amounts to a decrease in concentrations of between 10 and 50% over that which could be explained by dilution. Higher rates of attenuation appear to correlate with lower flow rates and lower concentrations of suspended solids in the receiving, fast-flowing, steep-gradient burn. This suggests that manganese is either precipitating out or adsorbing onto the suspended solids and then settling out downstream. Further downstream, below the confluence with the slower flowing River Coquet, there appears to be little evidence for additional attenuation, and settlement of solids, but dilution is very large.

The observed attenuation in the Hazon Burn means that active manganese treatment is unlikely to be needed to protect the Warkworth WTW for the long-term operation of the Whittle scheme. Ecological impacts are unlikely to be significant, and initial data support this. Further monitoring will examine any longer term impacts on the aquatic ecology of the receiving streams.

ACKNOWLEDGEMENTS

This work was carried out on behalf of the Coal Authority in close co-operation with the Environment Agency, Northumbrian Water Limited and the University of Newcastle.

REFERENCES

Institute of Hydrology (1998) *Hydrological Data UK: Hydrometric Register and Statistics 1991-1995*.

Nuttall, C.A. (2002) Testing and performance of a newly constructed full scale passive treatment system at Whittle Colliery, Northumberland. This volume.