Assessing the importance of diffuse mine water pollution: a case study from County Durham, UK.

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Key words: mine water, diffuse source, point source, catchment management, Water Framework Directive

ABSTRACT
In the UK and Europe mine water management has, to date, focused almost exclusively on addressing point sources of pollution. However, with the introduction of the EU Water Framework Directive (2000/60/EC), there is a need to address mine water pollution from a catchment management perspective. For this reason it is necessary to investigate diffuse sources of mining pollution. This paper relates the outcomes of a study of the River Gaunless catchment in County Durham, UK. These studies have shown that up to 45% of the iron load to the River Gaunless may be due to diffuse sources during dry weather conditions, and over 95% of the iron in the river may be attributable to diffuse sources during wet weather conditions. Identification and quantification of the most important diffuse sources (e.g. surface runoff from spoil, re-suspension of ochre from streambeds) is ongoing. This paper describes the results of the investigation to date in detail, and also discusses preliminary results of a 12 month investigation to identify the exact diffuse sources of iron pollution to the River Gaunless. The implications of the study for future mine water management are discussed.

INTRODUCTION

Diffuse mine water discharges and the Water Framework Directive
The WFD has the admirable ambition of restoring the watercourses of Europe to 'good status' (in ecological as well as chemical and physical terms) by 2015. In those catchments which host active or abandoned mine sites, polluted mine drainage often represents a considerable obstacle to achieving compliance with the WFD. For instance, in England and Wales alone, recent estimates by the Environment Agency (EA) suggest that some 1800 km of river reach, and up to 9000 km^2 of public supply aquifers are "at risk" of failing WFD objectives on account of mining-related pollution (www.environment-agency.gov.uk and Potter *et al.* 2004).
The WFD puts great emphasis on catchment-scale management of pollution sources and highlights the need to create new tools to tackle diffuse water pollution. While considerable progress has been made in recent years in developing a suite of 'active' and 'passive' remedial technologies for problematic mine waters (e.g. Younger *et al.*, 2002; PIRAMID Consortium, 2003), these have been designed principally for *in-situ* remediation of point mine water discharges. Diffuse mine water pollution can be considered as being one of the biggest challenges in relation to compliance with the WFD in catchments affected by mine drainage for two reasons. Firstly, on virtually every occasion in which an attempt has been made to quantify the relative proportions of diffuse versus point sources of mine water pollution, the diffuse component has been found to be substantial (e.g. Howes and Sabine, 1998; Nuttall and Younger, 1999; Younger, 2000). Secondly, the shortage of proven technologies suited for remediating diffuse sources means that, even where their extent has been quantified, relatively few realistic remedial options yet exist.

Ferruginous mine water pollution: point and diffuse
Iron pollution in water courses is a problem common to areas of former and active mining activity. Iron-rich, or ferruginous waters can impact on the quality of surface waters primarily through the smothering of benthic habitats with iron hydroxides. The formation of ochre, which follows the oxidation of ferrous iron to ferric iron and the subsequent spontaneous hydrolysis of the latter, also impacts on the chemical quality of water by (1) increasing the chemical oxygen demand of the water and (2) lowering the pH of watercourses (because ferric iron hydrolysis releases H^+) (e.g. Younger *et al*., 2002). Although dissolved iron is not as ecotoxic as many metals associated with mine water pollution (e.g. Zn, Cd, Cu and Ni), the increase in H^+ associated with the decrease in pH can be directly toxic to aquatic biota. In addition, the vivid orange to red smothering of ochre in rivers provides the most striking visual impact, directly leading to public perceptions of degraded water quality at impacted sites.
In areas of former mining activity, the onset of the most pronounced mine water pollution usually follows the rebound of groundwaters towards pre-mining levels once pumping activity in the coalfield has ceased. This process accelerates mineral weathering, namely the oxidation of pyritic / sideritic strata previously buried and/ or submerged in hitherto reducing environments in the mine workings (Younger, 2002). Discharges of mine water from deep mines usually emerge from shafts or adits, and are thus typically considered as point discharges.
The contribution of point sources to contaminant loadings in a catchment can be quantified, but it does rely on gathering simultaneous measurements of flow-rate and water quality. Although technically not challenging, installation of flow measurement devices is often logistically difficult, and as a consequence there is a paucity of contaminant load data for many mining-impacted catchments. Knowing the loading arising from point sources, the diffuse component can then be derived as the balance of in-stream contaminant loadings. In theory it should

be possible to discern the specific locations and processes by which diffuse iron enters a catchment. This has proved difficult in practice, however, and it is a specific objective of our work to improve understanding of these issues.

Diffuse iron pollution can arise from a number of sources including:

1) Diffuse seepage in the immediate vicinity of point discharges (e.g. Howes and Sabine, 1998).
2) Direct discharge of polluted groundwaters through the hyporheic zone.
3) Runoff from spoil heaps rich in pyritic material. These include both metal mine and coal mine spoil which can produce ferruginous drainage with much higher Fe concentrations than deep mine drainage due to the greater atmospheric contact in the spoil heaps (Younger *et al.*, 2002). (Such runoff can be also considered as point discharges however where spoil heaps have conspicuous preferential drainage flow paths into surface water bodies).
4) Remobilisation of previously deposited ochreous material in both instream and floodplain sediments. 'Hotspots' of contamination can occur in areas of high iron loading and preferential deposition (e.g. the channel reaches directly downstream of major point sources) which become secondary diffuse sources of pollution (e.g. in large runoff events).

If the 'good status' demanded of the WFD is to be achieved in the first instance and more importantly, maintained indefinitely, in catchments impacted by mine water pollution, consideration must be given to the timescales over which mine water pollution, both point and diffuse, persists. Unlike point sources, for which there is some information detailing long-term attenuation and residual loadings (e.g. Younger, 1997; ERMITE Consortium, 2004, Younger and Banwart, 2002), few data exist which quantify the long-term contributions and variations in diffuse sources. Studies of metal mine contamination (principally Pb, which is largely transported in adsorbed form on sediments in neutral to alkaline waters) have highlighted the longevity of contaminated sediments as secondary diffuse pollution sources in river basins. Through computer simulation, Coulthard and Macklin (2003) suggest that over 70% of deposited contaminants remained in a 1450 km^2 catchment some 200 years after mine closure. Although ochre is likely to be more mobile than sedimentary metal contaminants, the timescales over which diffuse sources remain active and a threat to WFD compliance are likely to be significant (i.e. decades).

The research undertaken in this study aims to improve the understanding of diffuse iron pollution in a mature mined catchment through quantifying and partitioning the contribution of point and diffuse sources of iron pollution under varying flow conditions.

STUDY SITE

To its confluence with the River Wear, north of the town of Bishop Auckland in north east England, the River Gaunless catchment covers an area of 93.0 km^2. The catchment drains the eastern slopes of the North Pennines. From its headwaters the river drains east, over a distance of 32 km, to Bishop Auckland (Figure 1). Over this distance elevation drops from the highest point at Grey Carrs (461mOD), in the far west catchment, to approximately 65mOD near the catchment outlet at Bishop Auckland. The catchment is predominantly rural (dominated by livestock farming) with the riparian settlements of Bishop Auckland, South Church and West Auckland located towards the east of the catchment. The catchment is entirely underlain by Coal Measures strata which were extensively deep-mined for more than 150 years prior to 1976. Following the cessation of mining in the catchment, mine water rebound to the surface was complete by 1979; stable long-term iron concentrations can be expected to have been attained by all mine water discharges in the catchment by about 1981 (Younger, 2000). Occasional dramatic mine water discharge incidents have been recorded in the catchment, which highlights the structural instability of the shallow mine workings as a pollution threat (Younger, 2000).

Iron pollution is a persistent problem in the River Gaunless with total iron (dissolved and suspended) rarely below 0.5 mg l^{-1} in much of the catchment. In the urban area between Fieldon's Bridge and Bishop's Park (Figure 1), the Gaunless is often cloudy, prompting repeated complaints from local residents. Investigations into this problem have shown that the cloudiness is due to elevated suspended iron concentrations, though the iron is apparently not suspended in the form of ferric hydroxide (which is orange) but as an unusual (organic) complex of a dark grey colour (the River Gaunless is also impacted by municipal wastewater discharges).

Although recent investment in the sewerage infrastructure around Bishop Auckland, and the creation of a fish pass on a weir near Bishop Auckland has improved the fisheries in the catchment (Railton, 2004), extensive ochre smothering of benthic habitats and high dissolved Fe loadings are likely to remain detrimental to aquatic biota in parts of the catchment. Mine water pollution may well become the limiting factor to further improvement to the catchment water quality. The threat of point and diffuse inputs into all three WFD River Basin Districts in the Gaunless catchment (see Figure 1) was also highlighted in a recent EA risk assessment/ catchment characterisation exercise (www.environment-agency.gov.uk). The major mine water discharges in the catchment are highlighted on Figure 1 with summary details in Table 1.

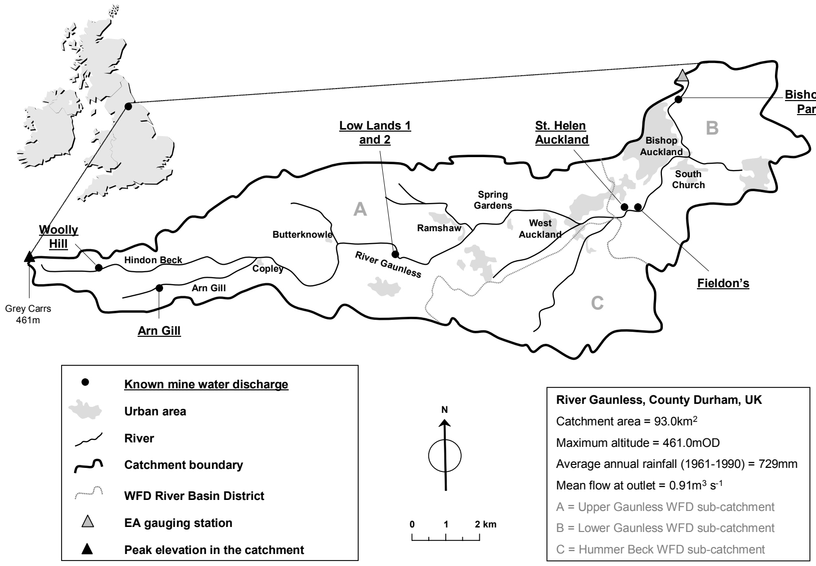


Figure 1: Schematic map of the Gaunless catchment highlighting known point mine water discharges, urban areas and WFD management boundaries.

METHODS

Previous attempts at quantifying the proportion of diffuse and point iron loadings in the River Gaunless catchment (see Younger, 2000) have utilised EA public archive data and derived flow data (via manipulation of mean daily flow records for a gauging station on an adjoining river, using an area-proportional transfer algorithm), as flow gauging in the Gaunless commenced only recently. This current research endeavours to quantify the instream iron loadings and point source contribution more accurately through employing synchronous sampling and flow gauging of both point mine water discharges and instream sample points throughout the catchment under varying flow conditions. In addition, instrumentation of the point mine waters will facilitate more reliable estimates of flow. The sampling network has also been expanded from previous studies to encompass sampling stations up to the catchment headwaters (previous sampling only went up to the settlement of Butterknowle, some 7km downstream of the first major point mine water discharge) and sampling of major tributaries along the course of the Gaunless. High-resolution reconnaissance surveys (encompassing field walk-by and water sampling) have also aimed to identify any previously unknown point mine waters in the catchment to permit better quantification of point sources.

Discharge	Grid Ref	Flow (l s^{-1}) (approx.)	Mean dissolved Fe (µg l^{-1})	Mean total Fe (µg l^{-1})	Comments
Woolly Hill	NZ 044248	3	2050	3700	Mine water discharge mixed with upland runoff (catchment area 0.3km^2)
Arn Gill	NZ 065243	2	2110	3140	Treated by volunteer wetland
Low Lands 1	NZ 134251	25	6950	7400	Major shaft outburst in 2000
Low Lands 2	NZ 135251	2	20700	23200	Original Low Lands discharge around 100m downstream of LL1
St Helen Auckland	NZ 197268	23	1750	2030	Treated by a (temporarily decommissioned) constructed wetland
Fieldon's	NZ 204267	<0.2	-	26000	Intermittent discharge close to major up-welling of mine water through the bed of the Gaunless
Bishop's Park	NZ 217301	9	5960	6420	Major discharge close to catchment outlet

Table 1: Point mine water discharges in the Gaunless catchment (see Figure 1 for locations).

The data presented here encompass summary EA archival iron concentration data over the period 1990-2005 and recent iron loading data collected during summer 2005 across the catchment. The latter provide a good example of low flow iron loadings in the catchment. High flow data has yet to be collected (due to the dry weather over the course of the recent sampling period), so EA public archive data is also used to illustrate wet weather iron loadings in the catchment (after Younger, 2000).

For recent water samples, two acidified polypropylene bottles were filled at each sample station, one of which was filtered using 0.2µm cellulose nitrate filters (to quantify dissolved Fe in the sample) and one unfiltered (to quantify total Fe in the sample). Samples were analysed for Fe (and other major elements) using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Flow at the mine water and instream sampling locations was measured via a suite of methods including current meter (50mm impeller), Acoustic Doppler Current Profiler (ADCP), bucket-and-stopwatch and hydraulic equations for pipe flow (based on recorded average velocity).

RESULTS AND DISCUSSION

Iron profiles in the River Gaunless

Table 2 summarises the dissolved and total (= dissolved + suspended) iron concentrations in the Gaunless catchment over the period 1990-2005. The sampling locations are presented in downstream order from the station upstream the settlement of Butterknowle to the catchment outlet downstream of the Bishop's Park mine water (see Figure 1). The data show total iron concentrations in the Gaunless to be consistently above the accepted EA Environmental Quality Standard (EQS) for iron (1000 µg l^{-1} as total iron). The problem is particularly pronounced in reaches downstream of point mine water discharges (e.g. downstream of Low Lands, Fieldon's and Bishop's Park) where instream peak total iron values in excess of 5 mg l^{-1} are regularly recorded. The data also show that the dissolved iron fraction typically accounts for less than half of the total iron in the river. The balance is accounted for by suspended (particulate) iron likely to arise from three sources:

1) Oxidation and subsequent hydrolysis of iron in the water column to form ferric hydroxide (ochre). The neutral pH typical of the Gaunless means that all dissolved iron will be in the ferrous form. The presence of substantial ferrous iron in the river is consistent with the discharge of reduced groundwaters from the point sources (see Table 1: the dissolved Fe component accounts for over 85% of the total iron in the mine waters sampled at point of discharge: e.g. Low Lands 1 and 2, Bishop's Park, St Helen Auckland).

2) Entrainment of ochre previously deposited on the streambed in conditions of high flow, particularly in the reaches that exhibit perennial ochre staining.

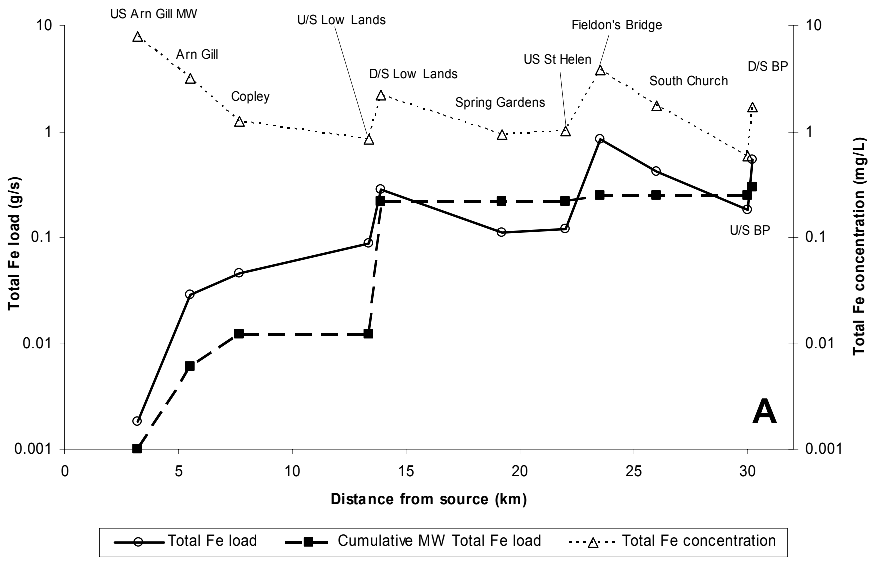
3) Erosion and transport of terrestrial sediments during runoff events (e.g. from the bare spoil abundant in the upper parts of the catchment, or erosion of bank sediments rich in iron).

These processes are likely to be of varying importance during different flow conditions. As processes 2 and 3 are associated with conditions of high flow, it may be possible to distinguish the relative contribution of these processes by assessing iron profiles in the catchment at differing flow conditions. Given that the point mine water discharges (Table 1) are relatively consistent in flow and chemistry (being fed by large ground water bodies in flooded mine workings), process 1 would be expected to dominate in low flow conditions, and represent a consistent, quantifiable, input of iron under higher flow conditions.

Site name	Grid ref. (Prefix NZ)	n =	Dissolved Fe			Total Fe		
			Mean	S.D.	Max	Mean	S.D.	Max
U/S Butterknowle	115250	40	138	107	409	425	891	5450
U/S Low Lands	133251	112	397	316	2520	886	1363	9700
D/S Low Lands	135250	120	818	395	1700	1356	423	2130
U/S Ramshaw	154260	100	258	178	1490	927	940	6680
Spring Gardens	173266	36	213	111	563	919	1829	10700
West Auckland	184267	150	187	134	630	-	-	-
Fieldon's Bridge	204266	46	158	91	423	907	1531	8520
U/S Fieldon's MW	205266	17	153	67	946	354	70	9520
D/S Fieldon's MW	206267	17	149	53	237	419	73	481
Wear Valley DC Depot	218285	33	199	139	676	1210	1497	7350
South Church	219284	101	201	139	722	1274	1407	8250
Cemetery (Bishop Auckland)	216292	47	174	97	417	1262	1960	12800
A689 (Bishop Auckland)	213300	37	177	119	700	981	1025	6330
U/S Bishop's Park	217302	7	907	2070	5600	1399	2352	7190
U/S Wear confluence	214306	99	170	121	593	978	927	7530

Table 2: Summary statistics for dissolved and total iron (µg l^{-1}) in the River Gaunless, January 1990 - June 2005 (U/S = upstream; D/S = downstream; MW = mine water; DC = District Council). (Updated from Younger, 2000)

Figure 2a and 2b compares instream total iron loadings (i.e. concentration multiplied by flow) and concentrations in the River Gaunless between low flow (14/06/2005) and high flow (26/02/1996) conditions. The figures also highlight the cumulative contribution of point mine water discharges to total iron loadings in the river (see Table 1) with downstream propagation through the catchment. In dry conditions the trend of iron concentration largely reflects that of the loading curves (with the exception of the headwaters, where flow was so low that the loading values are relatively low regardless of iron concentration), suggesting that most of the iron is entering the catchment in dissolved (ferrous) form (see Table 1) and being oxidised in the water column.



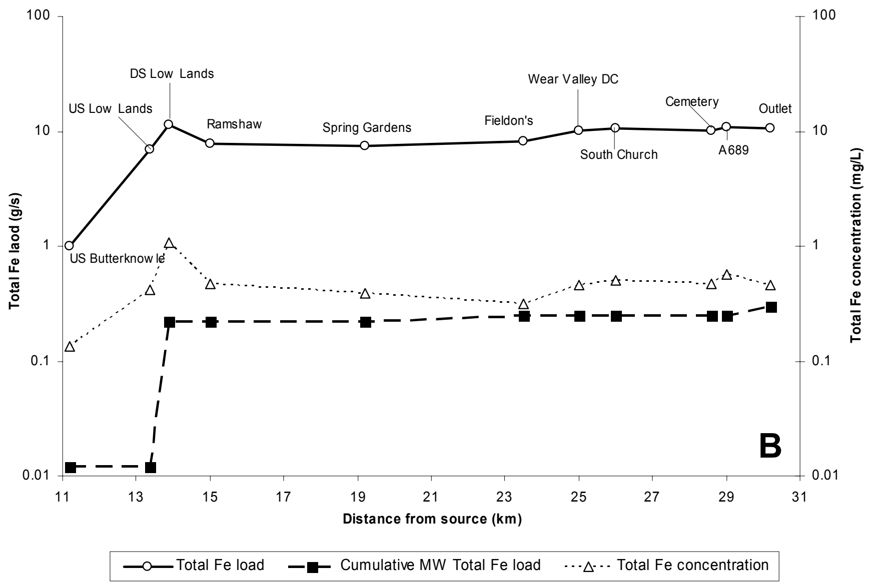


Figure 2: Total iron load and concentration profiles in the River Gaunless under low flow (Fig 2a) and high flow (Fig 2b: updated from Younger, 2000) conditions. (Note the differing horizontal axis in the two plots).

The low flow data (Figure 2a) show that the cumulative loading of point mine water discharges is typically less than the measured total iron loadings for much of the river. In the upland headwaters, the two known point mine waters account for only 26% of the loading at the confluence of the Hindon Beck and Arn Gill at Copley (Figure 1). In addition to the point mine water discharges and remobilisation of ochreous bed sediments in these upland areas, iron from oxidised peat (particularly where peat-rich soils are ploughed) may be of significance to instream loadings. Indeed, this was a process visibly contributing to the high total iron concentration (7.9 mg l^{-1}) recorded at the uppermost sampling site (U/S Arn Gill mine water). With the addition of the two prominent point discharges at Low Lands the point source mine water contribution accounts for up to 77% of the instream iron loading at the sample location 100 metres downstream of the mine waters (D/S Low Lands). Simple mass balance of iron loads between the upstream and downstream sample points at Low Lands showed that the Low Lands point mine waters accounted for 107% of the increased loading between those two locations. This suggests there is a loss of iron as precipitated ochre on the streambed in the reach immediately downstream of the mine waters. This pattern of iron oxidation/deposition is further evidenced by the very low iron loadings at the next downstream sample location (Spring Gardens) where iron load decreases to levels similar to the sample location upstream of Low Lands (around 0.1 g s^{-1} of Fe). The perennial ochre staining in the reach downstream of Low Lands (> 1 km) is visible confirmation of this, and this area is considered to be the principal potential source of remobilised ochre in the catchment during high flows.

Instream total iron loadings are seen to subsequently rise again in the vicinity of St Helen Auckland, where the discharge from the St Helen Auckland mine water treatment wetland (temporarily decommissioned) and the Fieldon's mine water enter the Gaunless. Immediately downstream of these discharges (at Fieldon's Bridge) however, the cumulative mine water contribution is seen to account for only 29.3% of the instream iron loading. This suggests a significant diffuse input (in the region of 51.6 kg day^{-1} of Fe on 14/06/05) in the reach above Fieldon's Bridge. A likely source for this input is direct discharge of iron contaminated groundwaters, which lie close to the surface level of the floodplain in this area, due to mine water rebound.

Downstream of Fieldon's Bridge a fall in instream loading is apparent as the Gaunless passes through the settlements of South Church and Bishop Auckland. The decrease in load shortly downstream of the point mine water input at Fieldon's mirrors the pattern at Low Lands. This suggests that although the point discharges elevate instream loadings immediately downstream of the point discharge, loss of iron as ochre on the stream bed is significant in attenuating iron loading in the water column; within 2-3 km of the point source iron load in the river returns to similar levels as measured upstream of the mine water.

At the final point mine water input at Bishop's Park (DSBP) the known point mine waters again account for no more than 55% of the recorded instream loading toward the catchment outlet. This again clearly suggests major diffuse inputs of iron in the vicinity of Bishop's Park (equating to 21.1 kg day^{-1} of Fe on 14/06/05), which presumably enter the river via diffuse seepage around the point source, or as direct groundwater discharge to the river via the hyporheic zone.

Figure 2b is the equivalent plot for wet weather conditions based on EA public archive records (note: the data only extend as far upstream as the Low Lands area of the catchment). While both the concentration and loading curves resemble each other (as in Figure 2a downstream of Copley), the cumulative mine water contribution is substantially less than the total load in the river. A peak in both the iron concentration and load is still apparent at Low Lands, but the cumulative mine water load now accounts for only 2% of the instream load. This clearly suggests a substantial increase in diffuse sources during high flow conditions. Downstream of Low Lands, the decrease of iron load observed during low flow (e.g. around Spring Gardens) is no longer apparent, with a consistent increase in iron load observed with propagation downstream. This pattern points toward a significant component of remobilised ochre in wet conditions between Low Lands and West Auckland (see Figure 1). Downstream of West Auckland, no abrupt peaks in instream load are apparent at the St Helen Auckland or Bishop's Park point discharges highlighting the diminished importance of these sources, in terms of total instream iron load, during high flow. Towards the catchment outlet (DS BP) it is clear that point sources account for no more than 3% of the instream iron loading during large runoff events in the catchment. At present it is difficult to quantify the components of the instream iron with great certainty, but if it is assumed that the diffuse sources operative under dry weather (which yield a net total of 21.1 kg day^{-1} of Fe by the catchment outlet: see above) are similar in wet weather (which for the case of direct groundwater discharge is likely to be the case), then in-channel sources (i.e. remobilisation of ochreous bed sediments) alongside increased surface runoff of iron-rich terrestrial sediments may account for up to 894 kg day^{-1} of iron during wet weather.

Management options

Approaches to mine water management at the catchment scale are often focussed towards identifying principal sources of pollutants detrimental to catchment water quality and ecology, and undertaking targeted remediation at the sites where limited funds will reap the maximum improvements to water quality (e.g. Kimball *et al.*, 1999). Hypothetical estimates of residual loadings can be made for the Gaunless catchment if such a management approach was adopted. The three point sources of mine water at Low Lands 1, St Helen Auckland and Bishop's Park would be obvious candidates for remedial action given the high iron loadings produced by these sources (see Table 1). If target effluent total iron concentrations of 0.5 mg l^{-1} are assumed (a suitable estimate given the influent concentrations), the difference between point source contribution at present and under the hypothetical remediation scenario can be subtracted from the recorded instream loadings presented in Figure 2a. Figure 3 displays these residual total iron concentrations (Fig 3a) and loadings (Fig 3b) based on the data collected on 14/06/05 under low flow conditions. Given that remedial action at point sources will be of greatest influence at low flow (due to the greater contribution of point sources to instream loadings), such an exercise highlights the period at which potential remedial action would be at its most effective. In high flow conditions, (in which instream total iron concentrations rarely exceed the EQS of 1.0mg l^{-1} anyway) the dominant influence of diffuse sources would mean the signal of any remedial work would be minimal.

Figure 3a shows that instream total iron concentrations remain above 1.0 mg l^{-1} for all the sample locations upstream of the first potential treatment site at Low Lands. These upstream areas are fed by point (Arn Gill, Woolly Hill) and diffuse (e.g. extensive areas of spoil, oxidised peat) iron sources, but low flow rates mean that iron loadings are low in these areas (see Figure 3b). Downstream of Low Lands the instream concentrations remain below 1.0 mg l^{-1} to Fieldon's Bridge. It is in this reach downstream of Low Lands where the most pronounced benefits of any remedial work would be seen. Given the high contribution (around 77%) the point sources at Low Lands make to low-flow instream iron concentrations at present (2.2 mg l^{-1} on 14/06/05), it is no surprise that a dramatic reduction in instream iron concentration (to 0.7 mg l^{-1}) is apparent under the remediation scenario. In the reach around St Helen Auckland and Fieldon's Bridge however, remedial work would be less

effective due to the large diffuse iron contribution from groundwater sources. Here, the predicted instream concentrations are 2.8 mg l^{-1} and remain close to 1.0 mg l^{-1} up to the catchment outlet in precisely the reach where complaints of cloudy water are made (see study site section).
The predicted total iron loading data (Figure 3b) further highlight the beneficial impact of potential treatment at Low Lands (where the downstream load is reduced from 0.28 to 0.09 g/s Fe), but also the large iron loadings that remains in the lower catchment. Although a reduction in instream loadings is apparent after remedial work in the lower catchment, the diffuse sources in the vicinity of Fieldon's and Bishop's Park (which mass balance for 14/06/05 shows account for around 80% of the increase in loading between upstream and downstream sample locations at both the St Helen Auckland and Bishop's Park point mine waters) still provide significant iron input to the Gaunless. This exercise highlights that although there are significant localised improvements in iron loadings and concentrations under the remediation scenario, the diffuse sources in the catchment are likely to make much of the Gaunless remain in breach of (or very close to) the EQS for total iron concentrations of 1.0 mg l^{-1} in low flow.
Wider management options for diffuse mine water pollution remain limited at present, with most mine water treatment technologies currently considered 'proven' being designed for point sources. The most exhaustive study to address catchment-scale mine water management options to date is that of the EU 5th Framework project ERMITE (EVKT-CT-2000-00078), which resulted in the publication of "Technical and

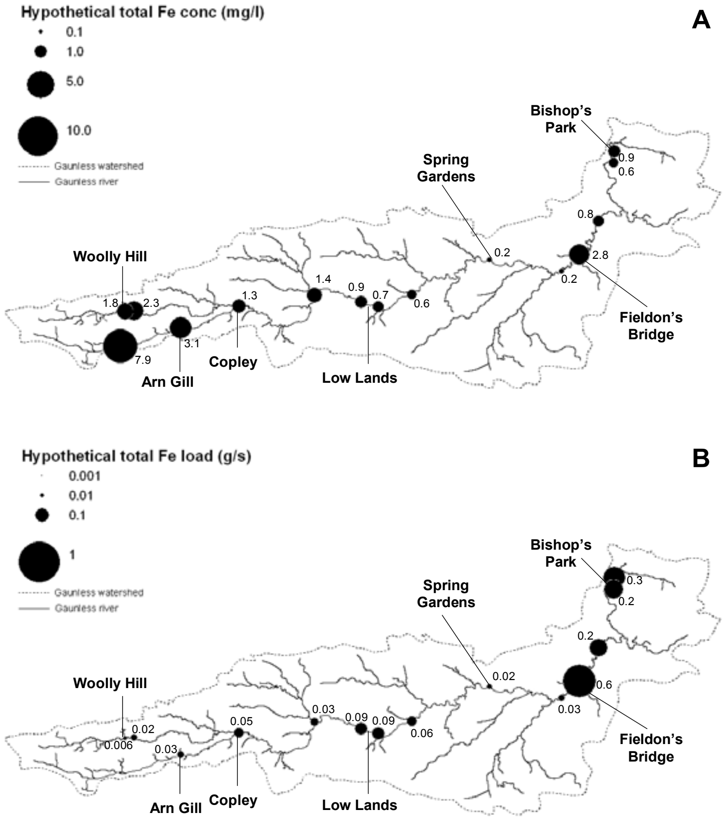


Figure 3: Hypothetical total iron concentrations (Fig 3a) and total iron loadings (Fig 3b) under low flow conditions with remediation of point mine waters at Low Lands, St Helen Auckland and Bishop's Park.

managerial guidelines for catchment scale management of mine water impacts" (ERMITE Consortium 2004). The remedial paradigm known as "monitored natural attenuation" (MNA), which has been developed principally with polluted aquifers in mind, has potential applicability to diffuse mine water pollution. MNA relies on natural processes to achieve the best overall environmental result. As such it recognises that many active interventions have environmental costs of their own (e.g. quarrying limestone in an area of high landscape value to treat mine water elsewhere). For MNA to be fully justified, it needs to be based on well-designed monitoring and modelling coupled to rigorous economic analyses (e.g. Younger *et al.* 2005a). Of course, in the process of attempting to 'justify' MNA in this manner, it may well emerge that treatment of one or more point sources in a catchment is worthwhile after all (cf Younger *et al.* 2005a), as may well be the case in the Gaunless catchment.
In some cases, it may be possible to use existing technologies (e.g. permeable reactive barriers at the toe of heavily polluting spoil heaps) to directly intercept and remediate diffuse mine water pollution sources (see, for example, Younger *et al.*, 2005b). Other technological interventions can also be imagined, such as:

- near-channel, sub-surface dosing systems (similar in form to infiltration galleries which are sometimes used to pump water from river-aquifer systems) to introduce beneficial solutes into the paths of discharging diffuse mine waters; such systems could be installed using “no dig” pipe laying techniques (shallow directional drilling and pipe-jacking) which have become widely used in the water industry over the last 15 years.
- ‘gradient control pumping’, in which wells are used to locally reverse the hydraulic gradient in the hyporheic zone during periods of low flow in rivers, when impacts would otherwise be most severe.

Before substantial progress is likely to be made in the development of new technologies along these lines, a more profound understanding of diffuse pollutant release processes will need to be developed. The outcomes of the ongoing investigations in the Gaunless catchment aim to assist this through providing more robust estimates of the contribution and partitioning of diffuse sources under varying flow conditions in the catchment. The work will also incorporate geochemical investigations into the provenance of instream iron loadings. Elsewhere in the UK, studies of hyporheic zone processes in mine-water impacted rivers in England and Wales are currently underway which will also go some way to improving the basis for management of diffuse sources.

CONCLUSIONS

The data collected to date in the Gaunless catchment has highlighted a significant contribution of diffuse sources to instream iron loadings under both low flow (up to 45%) and high flow (over 95%) conditions. In low flow conditions, this diffuse input appears to be dominated by direct groundwater discharge into the streambed. At higher flows, the remobilisation of ochre from bed sediments appears to be the major contributor to instream iron loadings. Projected low flow loadings under a hypothetical remediation scenario for the three main point sources in the catchment suggests clear localised improvements in iron loadings and concentrations, but the diffuse sources will continue to keep much of the catchment uncertain of compliance with WFD water quality objectives.

Wider planning for remediation of diffuse sources requires a greater appreciation of the modes of pollutant release in mined catchments. In particular, the partitioning between groundwater outflows and surface runoff, especially where complex hyporheic zone cycling of contaminants is feasible, will require substantial further study in many catchments. In addition, it will often be important to establish whether diffuse pollutants are truly ‘new’ to the river channel (e.g. by ferrous iron entry through groundwater upflow through the streambed) or remobilised pollutants that were previously present in the bed sediments. Ongoing research in the Gaunless catchment will explore some of these hydrogeochemical issues under varying flow conditions. Even after such issues have been resolved, it will still be necessary to undertake rigorous economic analysis (using the approaches outlined by ERMITE Consortium, 2003) if rational, defensible remediation planning is to be pursued.

ACKNOWLEDGEMENTS

We are indebted to the Environment Agency (England & Wales), which continues to fund our work on the River Gaunless (Project Ref. NC/03/20 30021844). We are particularly grateful to Dr Hugh Potter, Senior scientist with the Environment Agency, for his support and assistance. We also extend our thanks to the Environment Agency staff of the Northumbria & Yorkshire Region, who have generously provided archive data to support this work.

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