MINE WATER MANAGEMENT AT THE CATCHMENT SCALE: CASE STUDIES FROM NORTH-EAST ENGLAND[1]

Emma Gozzard[2], William M. Mayes, Michelle I. Morrison, and Adam P. Jarvis

Abstract. Recent implementation of the EU Water Framework Directive necessitates addressing water quality issues at the catchment scale. In this study, contaminant loading of all point discharges have been measured, establishing the overall impact of mine waters within the catchments, and allowing the derivation of contributions of diffuse mine water pollution to these totals. The results of two ongoing case studies of mine-impacted river catchments in the north-east of England are presented. The Allen catchment, Northumberland, is impacted by discharges from abandoned Pb/Zn mines with up to 6 mg/l Zn and 0.2 mg/l Pb, which significantly exceed European ecotoxicological standards by up to a factor of 75 and 20 respectively. The Gaunless catchment, County Durham, receives uncontrolled discharges of coal mine waters with up to 8 mg/l Fe. Preliminary findings show that during both low and high flow conditions diffuse iron pollution contributes significantly to in-stream iron loadings. Probable pathways include direct groundwater input and remobilisation due to scouring of streambed sediments.

Additional Key Words: diffuse sources, point sources, Water Framework Directive

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[2] Emma Gozzard, PhD student, Institute for Research on Environment and Sustainability (IRES), University of Newcastle upon Tyne, Newcastle upon Tyne, NE1 7RU, UK., William M. Mayes, Research Associate, IRES, University of Newcastle upon Tyne., Michelle I. Morrison, Research Associate, IRES, University of Newcastle upon Tyne., Adam P. Jarvis, Environment Agency Research Fellow, IRES, University of Newcastle upon Tyne.

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Introduction

To date, the principal research focus of mine water pollution has been to quantify and remediate the environmental impact of pollution occurring as a result of discharges from abandoned mine shafts and adits, which are generally categorised as point sources of pollution. It is imperative that when evaluating the total impact of toxic contaminants to surface waters all inputs are considered. Contributions from diffuse sources increase total metal loading (contaminant concentration multiplied by the flow rate) within rivers, and previous studies have suggested this diffuse component may be of major importance, both spatially and temporally (Mayes et al., 2005; Ander et al., 2000; Younger, 2000; Vink et al., 1999). During wet periods the levels of heavy metals in streambed sediments are generally less than in dry periods (Mayes et al., 2005; Ranville et al., 2004; Lin and Chen, 1998) due to a reduction in the relative importance of processes such as direct groundwater transfer, and the re-suspension of metals occurring as a consequence of scouring and changes in pH or reduction-oxidation (redox) conditions.

In order to successfully manage mine water pollution, and in light of current European Union (EU) legislation, the water quality of any given river must be assessed on a catchment-scale basis. The most important European legislation regarding future mine water management is the implementation of the Water Framework Directive (2000/60/EC) (WFD). The overall requirement to achieve "good chemical and ecological status" of all watercourses by 2015 has specific emphasis on the management of entire river catchments (HMSO, 2003). This not only aims to establish good quality waters, it also aids in determining the cost effectiveness of various contaminant treatment methods by considering the effects of all pollutant discharges within any given catchment. A recent Environment Agency characterisation exercise suggests that 260 waterbodies, covering 2711 km of river are "probably at risk" or "at risk" of not achieving WFD standards, with regard to diffuse sources of pollution (www.environment-agency.gov.uk). Of these, it is estimated that approximately 5% of diffuse source pressures arise from mine water pollution alone (DEFRA, 2005). Findings in this paper suggest this figure is considerably under-estimated, indicating the importance of quantifying diffuse sources of pollution and relating their importance in considering remediation options.

EU Environmental Quality Standards (EQS), which are the targets that must be met to achieve WFD objectives, are set under List I and II of the EU Dangerous Substances Directive (76/464/EEC) (HMSO, 2003). For mining related contaminants, the WFD states concentrations must not exceed ecotoxicological thresholds specified under List II (Table 1.).

Table 1. Ecotoxicological thresholds in accordance with the WFD (Gray, 1999).

Substance	EQS (mg/l)	Measured as:
Arsenic	0.050	Dissolved fraction †
Iron	1.000	Dissolved fraction †
Lead	0.010	Dissolved fraction †
Zinc	0.075	Total
pH	6.0-9.0	-

† Filtrate collected using 0.45 µm pore size filter paper.

Over catchment scales there may be numerous point and diffuse sources of mine water contamination, making it difficult to assess total environmental impacts and treatment options. In-situ treatment of point mine water discharges may improve surface water quality, but downstream increases in contaminant loadings, due to diffuse pollution, may negate benefits arising from this treatment. To assess catchments effectively, loadings must be established in order to determine these possible influences from diffuse sources of mine pollution over spatial and temporal scales. This necessitates the implementation of continuous flow measuring devices. By looking at point source and total in-stream discharge-concentration relationships, loadings from diffuse inputs can be established. From this, the importance of diffuse pollution can be quantified and the overall objective of determining how best to manage, from both an environmental and economic point of view, surface water quality can be attained.

Approach and Methodology

A desk study determined potential sources of mine water discharges, which resulted in the completion of a reconnaissance survey within the Allen catchment to identify point sources of mine water contamination (Fig. 1). Field measurements indicated waters with high conductivities, which can be indicative of mining related pollution (due principally to elevated sulphate concentrations). Samples were collected in clean polypropylene bottles. For each sample site, one aliquot was acidified with concentrated HCl, to 1%, for subsequent analysis for total cation concentrations using a Varian Vista Inductively Coupled Plasma – Optical Emission Spectrometer (ICP-OES). A second, un-acidified, aliquot was filtered using Whatman 0.45 µm cellulose nitrate filters for anion analysis using a DIONEX Ion Chromatograph (IC) (Table 2.). Samples were stored at 4ºC prior to analysis, and analysed within 2 days of collection.

Previous efforts to quantify diffuse and point Fe loading within the Gaunless catchment (Younger, 2000) utilised Environment Agency (EA) public archive data and derived flow data (via manipulation of mean daily flow records from a gauging station on an adjoining river). The current research attempts to more accurately quantify both point and in-stream loadings through employing synchronous sampling and flow gauging at previously used sites. Samples from the River Gaunless were collected and analysed as above. The flow rate of point and in-stream sampling sites was measured using various methods, depending on sample location, including 50 mm impeller, Acoustic Doppler Current Profiler, bucket-and-stopwatch and hydraulic equations for pipe flow (Mayes et al., 2005).

Case Study 1: River Allen

Site Description

The rivers East and West Allen, which converge to form the River Allen (a tributary of the River Tyne, Northumberland), drain a 190 km^2 catchment (Fig. 1), primarily comprising of carboniferous Upper Limestone surface rock. Mining in the Allen Valley commenced in the seventeenth century, continuing until the early 1970s. During this time the area became a major centre for lead/zinc mining, with most production occurring between 1815 and 1920 (Turnbull, 1975). Primarily, lead extraction from galena became the major process in the area, although the ore also contained Zn minerals, principally sphalerite. Zinc in the Allen Valley had no apparent commercial value until the nineteenth century when continental supplies of Zn were not sufficient to meet increasing demands. Although the mine workings are now long-abandoned, the hydrology and hydrochemistry of the Allen catchment remains deeply influenced by its mining history (Turnbull, 1975). Groundwater flow within the valley is predominantly influenced by the presence of drainage levels, the principal one being the 9 km long Blackett level (Fig. 1), which drains much of the area surrounding the East Allen (Dunham, 1990).

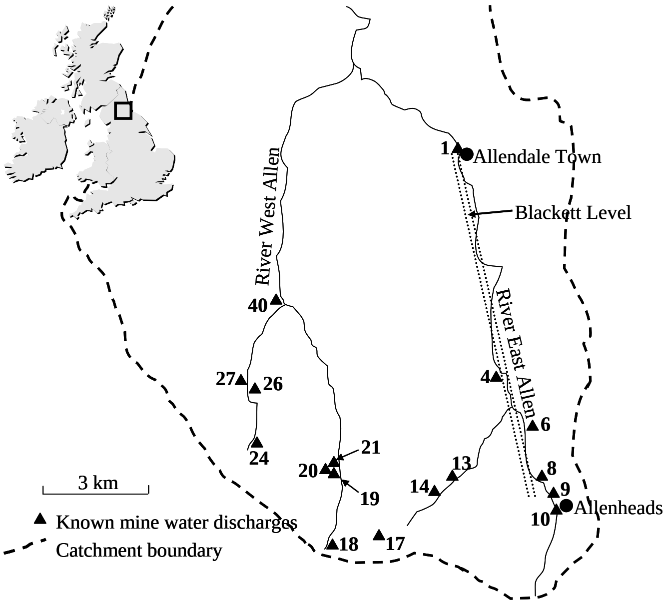

Figure 1. Location of point mine water discharges within the River Allen catchment.

Results and Discussion

Table 2 shows concentrations of key metals for point source mine water discharges in Rivers East and West Allen.

The data in Table 2 illustrate that all Pb and all-but-two (sites u/s 13a and 14) Zn concentrations exceed EU quality standards by up to a factor of 75 and 20 respectively (Table 1.), indicating the necessity to further monitor and manage metal pollution inputs within the Allen catchment. Several Fe concentrations exceed EU concentration limits, and there is evidence of precipitation of $Fe(OH)_3$ below these discharges. Clearly there is the potential for this sediment to remobilise, as diffuse pollution, during wet weather conditions.

To date this study has identified elevated metal concentrations in both the West and East Allen. While pollution due to mine waters on the West Allen is generally due to elevated Zn and As concentrations, on the East Allen mine waters are predominantly contaminated with Pb. Dunham (1990) shows that the Allen Valley was subject to much tectonic activity, which resulted in the intrusion of a large crystalline dyke, known as the Burtreeford Disturbance. The West and East Allen valleys are separated by this disturbance, which may account for the difference in mineralization and, thus, for the different character of mine waters in each sub-catchment. The elevation of As concentrations within the West Allen may suggest a specific association with Zn minerals, but is a subject for further investigation.

Table 2. Water quality of point sources of mine water pollution and in-stream sites within the Rivers East and West Allen (Location of site numbers illustrated on Fig. 1).

East Allen	**pH**	**µS/cm**	**mg/l**				
Site		**Cond'ty**	**SO_4^{2-}**	**As**	**Fe**	**Pb**	**Zn**
1	7.1	589.0	75.47	0.013	0.616	0.032	0.169
4	7.6	213.0	12.50	0.016	1.976	0.029	0.094
6	7.3	322.0	13.30	0.022	0.937	0.035	0.097
8	7.1	402.0	25.36	0.023	0.485	0.027	0.273
9	6.5	111.0	28.89	0.021	0.453	0.044	0.768
10	6.9	409.0	23.04	0.021	9.927	0.034	0.118
u/s 13a [†]	5.6	39.0	nd *	0.016	1.386	0.013	0.053
13a [†]	7.6	695.0	111.67	0.020	1.242	0.030	0.343
13b [†]	8.1	404.0	28.65	0.023	2.506	0.046	0.372
13c [†]	7.8	494.0	71.57	0.015	1.023	0.031	0.301
d/s 13c [†]	6.4	47.0	nd *	0.012	1.324	0.016	0.085
14	6.7	465.0	29.85	0.018	2.536	0.029	0.070

West Allen	**pH**	**µS/cm**	**mg/l**				
Site		**Cond'ty**	**SO_4^{2-}**	**As**	**Fe**	**Pb**	**Zn**
17	6.9	457.3	60.39	0.084	14.226	0.037	0.114
18	6.3	532.0	37.15	0.220	1.278	0.196	6.139
d/s 18	7.8	230.0	nd *	0.011	0.142	0.052	1.562
u/s 20	7.3	305.0	nd *	0.001	1.012	0.038	0.291
20	7.0	728.0	152.90	nd *	0.540	0.038	4.549
d/s 20	7.0	nd *	nd *	0.013	0.957	0.037	0.461
21	7.9	686.0	168.27	0.301	0.482	0.021	1.974
24	7.2	473.4	nd *	0.273	10.931	0.014	0.422
26	7.6	350.0	13.13	0.180	0.747	0.038	0.097
27	7.3	301.0	39.64	0.144	0.780	0.021	0.215
40	6.8	351.0	21.84	0.179	0.447	0.020	0.129

[†] 13a and 13b are different point sources entering the same river reach, with 13b approximately 15 m downstream of 13a. 13c is an in-stream sample taken approximately 50 m downstream of 13b.

* nd = no data

Although diffuse mine water pollution has been cited as a significant issue in the past, such studies have rarely looked at contaminant loadings, knowledge of which are actually critical for effective management of this type of pollution. By establishing the dynamics of pollutant contaminant loads, in this study we will directly assess the benefits accruing from potential treatment of point sources of pollution in light of the contribution of diffuse sources of pollution to contaminant loads in the catchment as a whole. However, due to installation difficulties of flow measurement structures (landowner permissions, regulatory requirements and physical installation difficulties associated with working multiple sites in a catchment), metal loadings within the River Allen catchment have not yet been determined. Flow weirs are currently being installed with a view to complete a study analogous to the work on the River Gaunless (Case Study 2, below), which is at a more advanced stage, in order to compare past metal and coal mining catchments.

Case Study 2: River Gaunless

Site Description

The River Gaunless catchment (Fig. 2.) is situated approximately 14 km south-west of Durham, in County Durham. A tributary of the River Wear, the Gaunless catchment covers an area of approximately 93 km^2. Upper Coal Measures strata were extensively deep mined in the area from the early 19th century until 1976 (Younger, 2000). Following complete cessation of mining, mine water rebound was complete by 1979. By approximately 1981 the iron concentrations of the resulting surface discharges were largely stable, albeit there have subsequently been notable, though isolated, incidents of sudden out-rushes of highly contaminated mine waters following catastrophic failure of blockages in mine entrances. (Younger, 2000).

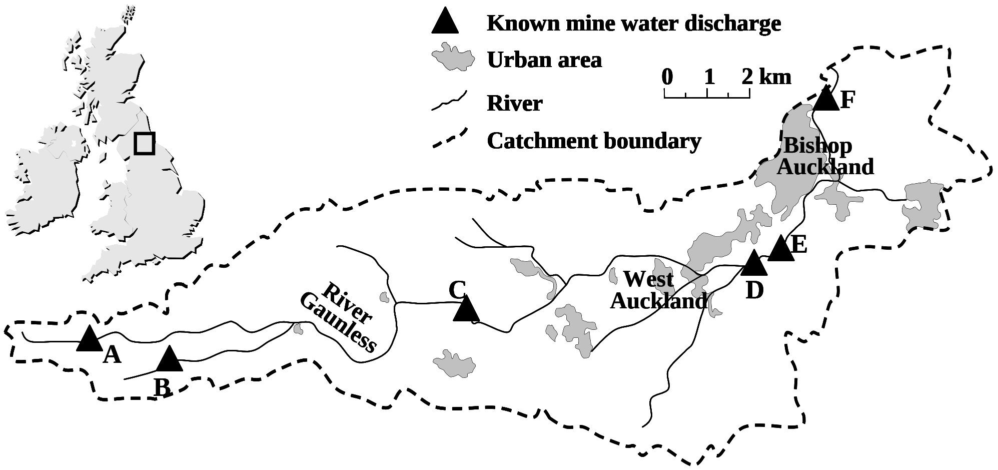

Figure 2. Map showing location of point mine water discharges within the Gaunless catchment.

In much of the River Gaunless iron pollution is a persistent problem, with total iron concentrations rarely falling below 0.5 mg/l. Along one reach of the river, upstream of Bishop Auckland, complaints from local residents have prompted investigations into the increased turbidity of the river for which an organic suspension of iron has been cited as a possible cause (Mayes et al., 2005).

Results and Discussion

Tables 3 and 4 summarise Fe concentrations and loadings in the River Gaunless catchment. Locations A thru F denotes known mine water discharge. Sample sites are presented in downstream order and relative to the known mine water discharge, upstream (u/s) or downstream (d/s). A large fraction of elevated Fe concentrations are observed downstream of point discharges (Table 3.). Total concentrations and loadings are more pronounced during periods of high flow (Table 4.), suggesting that an increase in suspended iron has occurred.

Table 3. Summary of iron loadings and concentrations in the River Gaunless during low flow (adapted from Mayes et al., 2005).

Site name	**Site designation on Figure 2.**	**Fe Conc (mg/l)**	**(g/s)**
		Total	**Fe Load**
u/s Arn Gill	u/s B	7.884	0.002
Arn Gill	B	3.143	0.028
d/s Arn Gill	d/s B	1.252	0.046
u/s Low Lands	u/s C	0.855	0.088
d/s Low Lands	d/s C	2.202	0.282
In-stream	–	0.944	0.111
u/s St. Helens	u/s D	0.813	0.130
Fieldon's Bridge	E	3.841	0.845
d/s Fieldon's Bridge	d/s E	1.732	0.416
u/s Bishop's Park	u/s F	0.586	0.180
d/s Bishop's Park	d/s F	1.726	0.541

Table 4. Summary of iron loadings and concentrations in the River Gaunless for high flow (adapted from Mayes et al., 2005; Younger, 2000).

Site name	**Site designation on Figure 2.**	**Fe Conc (mg/l)**		**(g/s)**
		Dissolved	**Total**	**Fe Load**
d/s Arn Gill	d/s B	0.135	1.200	1.00
u/s Low Lands	u/s C	0.413	0.174	6.90
d/s Low Lands	d/s C	1.080	1.929	11.40
In-stream	–	0.468	2.819	7.80
u/s St. Helens	u/s D	0.385	2.971	7.40
u/s Fieldon's Bridge	u/s E	0.317	3.025	8.20
d/s Fieldon's Bridge	d/s E	0.460	2.456	10.10
In-stream	–	0.508	2.340	10.60
In-stream	–	0.469	2.432	10.20
u/s Bishop's Park	u/s F	0.568	2.276	10.90
d/s Bishop's Park	d/s F	0.455	2.795	10.65

Figure 3 compares in-stream iron loadings and concentrations during low flow (14/06/2005) and high flow conditions (26/02/1996), and illustrates the downstream cumulative contribution of point mine water discharges to this effect.

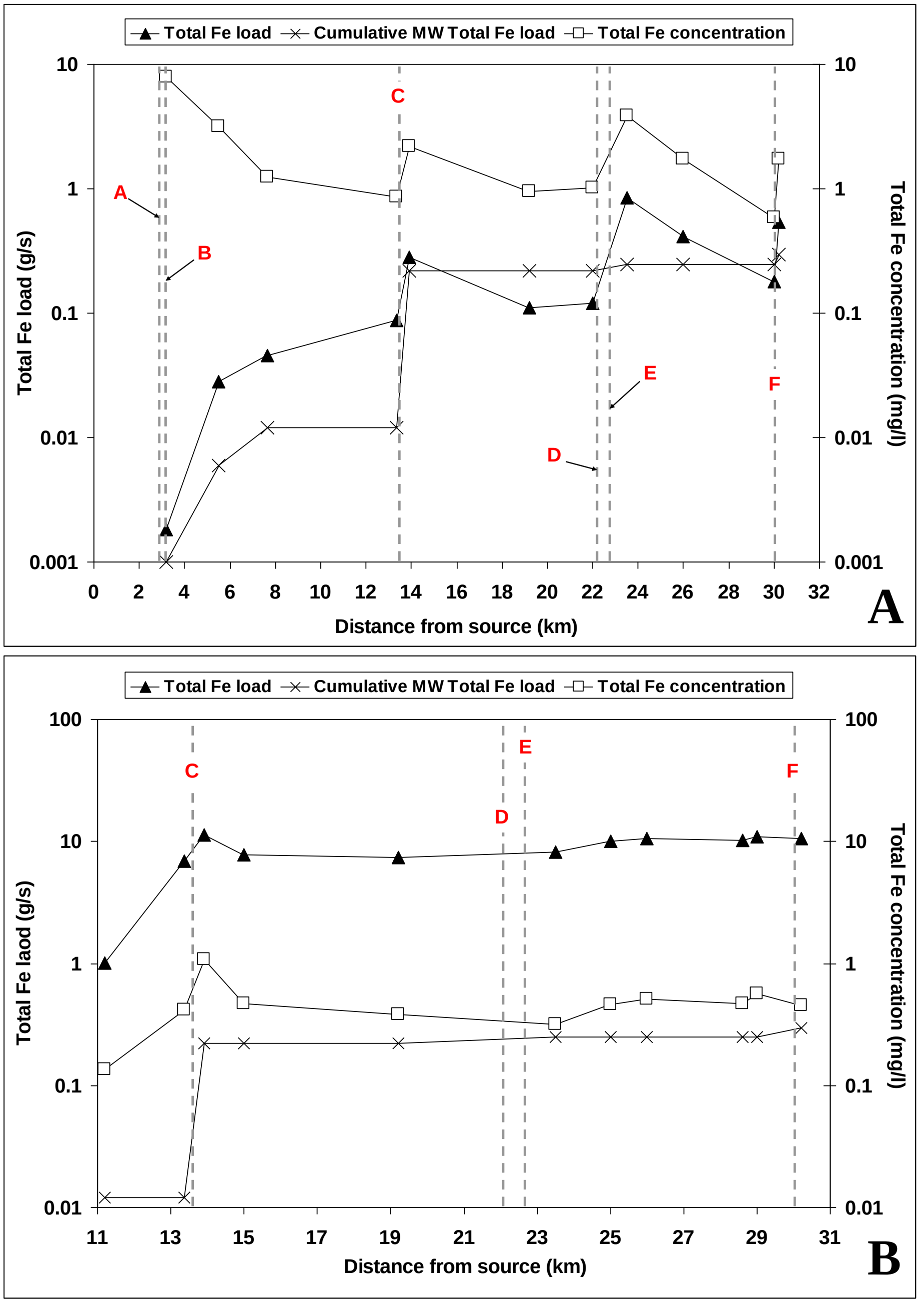

Figure 3. Iron profiles in the Gaunless under low flow conditions (A) and high flow conditions (B) (adapted from Mayes et al., 2005). N.B. Red letters/dashed lines correspond to point mine water discharges (Fig. 2.).

In low flow conditions (Fig. 3A) the trend of in-stream iron load appears to be strongly, though not exclusively, influenced by point mine water discharges, i.e. increases in Fe load are evident downstream of mine water discharges. This suggests that the majority of Fe entering the river is in the Fe^{+2} form, with subsequent oxidation and precipitation of $Fe(OH)_3$ as evidenced by decreasing river Fe concentration downstream of point discharges. The only point discharges that do not appear to result in an increase in both Fe concentration and load downstream of the point of discharge are sites A and B, where very low flows are evident (Mayes et al., 2005). Point discharge C accounts for much of the in-stream Fe loading as indicated by a rise in the cumulative Fe load. Directly downstream of this site the decrease in Fe concentration and load can be attributed to ochre precipitation on the streambed. Increase in Fe loadings, but negligible cumulative input seen at sites D and E, suggests a significant input from diffuse sources. Since the water-table in this area is very close to surface, due to mine water rebound, these diffuse inputs may well take the form of groundwater inflows to the river via the hyporheic zone (Mayes et al., 2005). Again, a decrease in in-stream loadings is seen downstream of the point discharge to levels similar to those upstream of sites D and E. This suggests that although point discharges may elevate in-stream iron loads, ochre precipitation onto the streambed represents a significant loss of Fe from the aqueous phase (Mayes et al., 2005). Site F emulates the trend seen at sites D and E, indicating that, once more, diffuse inputs of Fe are responsible for the increase in in-stream loadings.

Figure 3B shows Fe loadings within the Gaunless under high flow conditions, based on Environment Agency public archive records[1]. The trends in Fe concentration and in-stream Fe loading curves are comparable to those shown in Fig. 3A, but the total in-stream load is considerably more than the cumulative point source contribution due to non-point source inputs of Fe (Mayes et al., 2005). An increase in in-stream Fe loading is observed at site C, but the cumulative Fe load has less input than during low flow conditions. This implies that diffuse inputs are very substantial during wet periods. The significant decrease in Fe loadings downstream of discharge C, during low flow conditions, is not evident. Instead, a steady increase in downstream loadings is observed, which may be attributed to intensified diffuse inputs, initiated by wet weather conditions, e.g. streambed sediment re-suspension as a result of scouring (Mayes et al., 2005). Unlike Fig. 3A, no substantial loading input from sites D, E and F is observed, highlighting the unimportance of these point sources in contributing to in-stream Fe loads during storm events. Thus, during wet weather conditions these preliminary results suggest that diffuse sources, particularly sediment re-suspension and surface runoff from exposed spoil heaps, are very significant contributors to total iron loading in this river (Mayes et al., 2005).

Conclusions

Point mine water discharges, within the Allen catchment, are a significant source of metal contamination. Zinc and Pb concentrations exceed current EU standards by up to a factor of 75 and 20, respectively. Previous studies have suggested that diffuse pollution processes are important within old mining catchments. However, while this past research is beneficial, contaminant loadings obtained from continuous flow monitoring, will provide a more accurate understanding of these processes and how they occur. From this, an assessment can be made as to whether environmental and economic benefits arising from point source treatment prevail over diffuse pollutant enhancement.

In the River Gaunless, a significant contribution of diffuse source iron occurs under both low flow and high flow conditions. Direct groundwater input, via the streambed, appears to dominate diffuse input during dry periods, however $Fe(OH)_3$ precipitation results in decreasing in-stream loadings. During episodes of high flow, point sources of Fe contribute little to total in-

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[1] N.B. The data only extends as far upstream as Site C.

stream loads, which seems to be diffuse input dominated as a result of metal remobilisation due to scouring of streambed sediments.

Further investigation to quantify diffuse inputs and pathways during varying weather conditions will aid in determining how to monitor and manage mine water catchments effectively from both an environmental and economic point of view.

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