Challenges of Watershed Mine Drainage Characterisation and Remediation at Scale: Force Crag Base Metal Mine, Cumbria, UK

Catherine J. Gandy[1], Adam P. Jarvis[1], Nick Cox[2], Stephen Lofts[3], John Malley[4], Arabella M.L. Moorhouse-Parry[2], Katherine S. Neate[1], Barbara Palumbo-Roe[5], Hugh A.B. Potter[6]

[1]*School of Engineering, Devonshire Building, Newcastle University, Newcastle upon Tyne NE1 7RU, United Kingdom, catherine.gandy@newcastle.ac.uk, adam.jarvis@newcastle.ac.uk, k.neate2@newcastle.ac.uk*

[2]*The Coal Authority, 200 Lichfield Lane, Mansfield, Nottinghamshire NG18 4RG, United Kingdom, Nick-Cox@coal.gov.uk, AbbyMoorhouse@coal.gov.uk*

[3]*UK Centre for Ecology & Hydrology, Lancaster Environment Centre, Library Avenue, Bailrigg, Lancaster LA1 4AP, United Kingdom, stlo@ceh.ac.uk*

[4]*National Trust, Bowe Barn, Borrowdale Road, Keswick CA12 5UP, United Kingdom, john.malley@nationaltrust.org.uk*

[5]*British Geological Survey, Nicker Hill, Keyworth, Nottingham NG12 5GG, United Kingdom, bpal@bgs.ac.uk*

[6]*Environment Agency, Horizon House, Bristol BS1 5AH, United Kingdom, hugh.potter@environment-agency.gov.uk*

Abstract

The challenges of watershed mine drainage characterisation and remediation are reported. Whilst the substantial benefits of point source remediation under low flow conditions are demonstrated, the dominance of diffuse sources on instream zinc flux at higher flows limits the overall improvement in downstream water quality. A watershed approach to remediation is therefore required with consideration given to remediation of diffuse, as well as point, sources. The design and installation of infrastructure, such as flow-monitoring devices and boreholes, throughout the Force Crag mine watershed has enabled a comprehensive investigation of the nature and importance of the various pollution sources.

Keywords: Mine Drainage Characterisation, Remediation, Diffuse Sources, Zinc, Bacterial Sulfate Reduction

Introduction

Abandoned base metal mines are a major source of aquatic pollution in the UK contributing more than half of the mass flux of zinc and cadmium to freshwaters in England and Wales (Mayes *et al*. 2010). The majority of these mines are located in upland areas with steep topography which adds to the practical difficulties of executing mine water management at scale. Remediation efforts are typically targeted at point sources of pollution, such as abandoned mine entrances. However, diffuse inputs, such as runoff from mine waste heaps, remobilisation of metals from streambed sediment and the direct influx of groundwater, also contribute to the overall metal burden in receiving watercourses and have proven to be particularly important during higher flow conditions (Gozzard *et al*. 2011; Jarvis *et al*. 2019; Mighanetara *et al*. 2009). A watershed approach to remediation is therefore required to encompass both point and diffuse sources of pollution.

The UK's first full-scale passive treatment system for metal mine drainage was commissioned in 2014 at Force Crag, Cumbria, following 10 years of watershed mine drainage characterisation and system design. A synoptic mass balance approach to assessing point and diffuse sources of pollution (Runkel *et al*. 2016) identified the main point source of pollution to be remediated. The treatment system harnesses bacterial sulfate reduction to immobilise the main contaminant metals, zinc, lead and cadmium, within the compost substrate of two identical vertical flow ponds. The final discharge enters a nutrient-sensitive upland river, the Coledale Beck. Appropriate infrastructure was designed and installed to allow close control and monitoring of flow-rate and water quality within the treatment system, including in the receiving watercourse to enable the benefits of treatment to be quantified. Additional infrastructure, such as boreholes, has recently been installed to enable an assessment of groundwater-surface water interactions and gain an understanding of the influence of riparian subsurface flows on metal flux.

This paper outlines the approach taken to characterise mine drainage within this watershed to enable design of an appropriate remediation system and evaluates the performance of the system in terms of its benefits to the receiving watercourse under varying hydrological conditions. Ongoing research to identify important diffuse sources of pollution is also discussed.

Methods

The synoptic mass balance approach to assessing point and diffuse sources of pollution involves synchronous measurements of flow-rate and water quality at both point sources and instream locations. Such monitoring was carried out on 14 occasions prior to treatment system commissioning and encompassed the full range of hydrological conditions. Instream locations were chosen upstream and downstream of both point sources and suspected diffuse sources. A suite of flow monitoring infrastructure, including flat V-weirs and sharp crested V-notch weirs, has been installed in the Coledale Beck catchment. Flow monitoring was undertaken at additional locations using salt gulp-injection dilution gauging. Further synoptic monitoring has been undertaken on 7 occasions since treatment system commissioning in addition to approximately fortnightly monitoring of the treatment system. This included measuring influent and effluent concentrations and flow-rates together with water quality and flow-rate of the Coledale Beck downstream of the treatment system.

Water samples were collected in 30 mL polypropylene bottles with those for subsequent metals analysis acidified with 1% v/v concentrated nitric acid. Samples for filtered metals analysis were filtered through a 0.45 µm cellulose nitrate filter. All samples were stored at 4 °C prior to analysis. Total and filtered metals analysis was undertaken using a Varian Vista-MPX ICP-OES or Agilent 770 Series ICP-MS. Anions analysis was conducted using a Dionex DX320 ion chromatograph. Field measurements of pH, temperature, ORP and electrical conductivity were made on site using a pre-calibrated Myron L 6P Ultrameter. Total alkalinity was determined at the time of sample collection using a Hach Digital Titrator with 1.6N sulphuric acid or 0.16N sulphuric acid with a Bromcresol-Green Methyl-Red indicator.

Results and Discussion

Synoptic monitoring identified the Level 1 discharge as the main point source of pollution to the Coledale Beck. Zinc is the principal contaminant metal of concern (mean total 3,129 µg/L) but lead (mean total 38.3 µg/L) and cadmium (mean total 15.1 µg/L) are also present at elevated concentrations. During low flow conditions, Level 1 accounts for the majority of the zinc in the Coledale Beck downstream of the mine site (fig. 1). However, as the Coledale Beck flow-rate increases, the instream zinc flux also increases sharply (fig. 1) and this increase is not accounted for by the Level 1 point source alone. Under the highest flow conditions monitored (670 L/s), total zinc flux in the Coledale Beck reached 14 kg/day, with Level 1 representing only 26% of this total (3.65 kg/day). Although other, minor, point sources contribute to the increased zinc flux it is diffuse sources of zinc that dominate the instream zinc flux in the Coledale Beck as flow-rate increases (Jarvis *et al*. 2019).

Despite the increased contribution of other point and diffuse sources of zinc with increasing flow in the Coledale Beck, the Level 1 discharge remains the single greatest point source contributor to instream zinc flux under all flow conditions and was therefore selected for remediation. In a combined initiative between the Coal Authority, Environment Agency, National Trust (the landowner) and Newcastle University, the UK's first full-scale passive treatment system for metal mine drainage was commissioned in 2014 to treat the Level 1 discharge. Passive systems are the preferred option in the UK due to the remote upland settings in which abandoned metal mine discharges are typically located, which make active treatment logistically difficult. Another key requirement is to keep treatment system size to a minimum due to land constraints. The treatment system at Force Crag comprises two downwards flow Vertical Flow Ponds (VFPs) which operate in parallel. The design flow rate of the system is 6 L/s, with each VFP receiving 3 L/s from the Level 1 discharge. At the base of each VFP is a perforated pipe network which is overlain by a 200 mm layer of carboniferous limestone to maintain permeability. Overlying the limestone is a 450 mm layer of compost substrate comprising 45% v/v PAS100 compost, 45% v/v woodchips, and 10% v/v dried activated sewage sludge. The compost provides a long-term source of carbon and encourages the development of anoxic conditions, essential for survival of the sulphate reducing bacteria. The woodchips, meanwhile, assist with provision of porosity while the activated sewage sludge acts as an initial source of available carbon for metabolism of the sulphate reducing bacteria. The effluent waters from each VFP pass through a small aerobic wetland before discharging into the Coledale Beck. The remaining Level 1 water discharges, untreated, directly into the Coledale Beck. Whilst most compost bioreactors reported in literature have hydraulic residence times on the order of days, based on laboratory-scale (Mayes *et al.* 2011) and pilot-scale (Gandy *et al.* 2016) investigations the treatment system at Force Crag was designed to have a hydraulic residence time of 15 to 20 hours.

The treatment system has been successful in reducing the influent total zinc concentration from a mean of 3,129 μg/L to a mean of 279 μg/L (mean zinc removal of 90.4%) (Table 1). Other metals, such as lead and cadmium, are also successfully removed with mean treatment efficiencies in excess of 90% (Table 1). Variations in system performance, resulting in low treatment efficiencies at times, were due to operational changes. Similarly, a decrease in sulfate concentration observed between the influent (mean 26.6 mg/L) and effluent (mean 16.5 mg/L) indicates that bacterial sulfate reduction is an important removal mechanism within the treatment system.

Simultaneous monitoring of the treatment system and the Coledale Beck downstream of Force Crag mine over a wide range of hydrological conditions has enabled an assessment of the overall benefits of the treatment system to the Coledale Beck. A substantial improvement in downstream

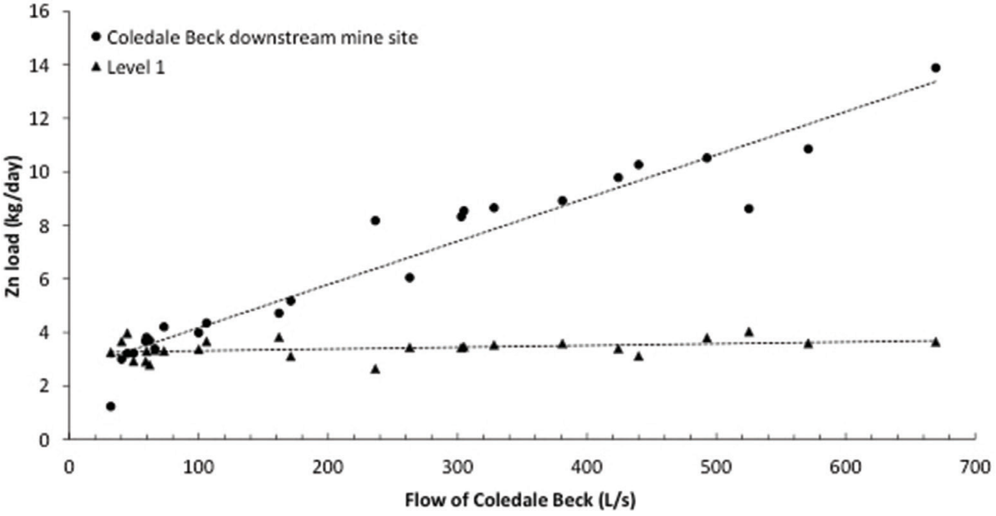

Figure 1 *Zinc flux in the Level 1 discharge and the Coledale Beck downstream of the mine site prior to remediation.*

Table 1 Mean influent and effluent total concentrations, and treatment efficiency, of zinc, lead and cadmium in the Force Crag treatment system. The range of values is given in parentheses.

Parameter	Zn	Pb	Cd
Influent concentration (µg/L)	3,129 (1,253-4,490)	38.3 (10.6-151.9)	15.1 (6.3-21.5)
Effluent concentration (µg/L)	279.2 (17.0-1,460.9)	3.67 (0.31-15.0)	1.25 (0.10-5.20)
Treatment efficiency (%)	90.4 (43.6-99.5)	91.0 (57.4-99.6)	90.6 (55.2-99.4)

water quality has been observed under low flow conditions (< 270 L/s) with total zinc concentration reduced from a pre-treatment system maximum of 860 µg/L to below 600 µg/L (Fig. 2). At higher flows, however, the benefits are limited. This is partly due to additional Level 1 water entering the Coledale Beck under such flow conditions since the treatment system only treats 6 L/s of Level 1 water with the remaining Level 1 water (up to 25 L/s) entering the Coledale Beck untreated. Consequently, at higher flows, the contribution of the Level 1 discharge to the instream zinc concentration increases. However, as demonstrated by Jarvis *et al.* (2019), and shown in Fig. 1, additional, diffuse, sources of zinc dominate the instream zinc flux under higher flow conditions. These findings have serious implications for watershed management since, despite the substantial environmental benefits of remediating the Level 1 discharge under low flow conditions, diffuse inputs of zinc limit the benefits of remediation at higher flows. To reduce the absolute flux of metals downstream, therefore, remedial efforts must also focus on diffuse sources.

Current research, in partnership with the British Geological Survey and UK Centre for Ecology and Hydrology, is investigating the influence and nature of groundwater-surface water interaction to the overall metal flux in the Coledale Beck. Further synoptic mass balance monitoring has been undertaken with a more intensive focus on an approximately 400 m reach to investigate the influence of riparian and hyporheic flows. Previous catchment-scale synoptic monitoring identified significant discrepancies between the sum of the point source zinc inputs and the

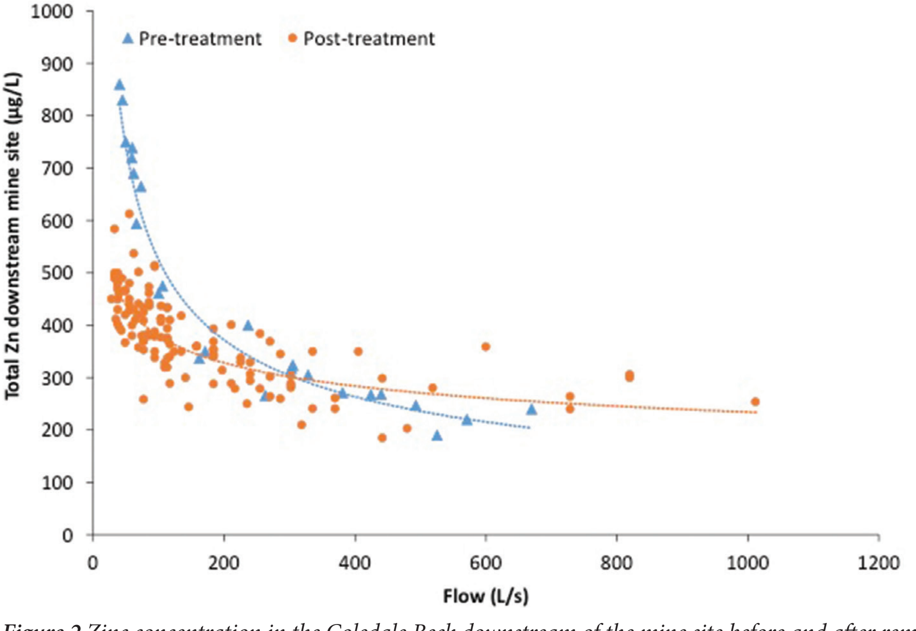

Figure 2 Zinc concentration in the Coledale Beck downstream of the mine site before and after remediation. The Environmental Quality Standard (EQS) for filtered zinc downstream of the mine is 12.3 ug/L and so the Coledale Beck is significantly polluted.

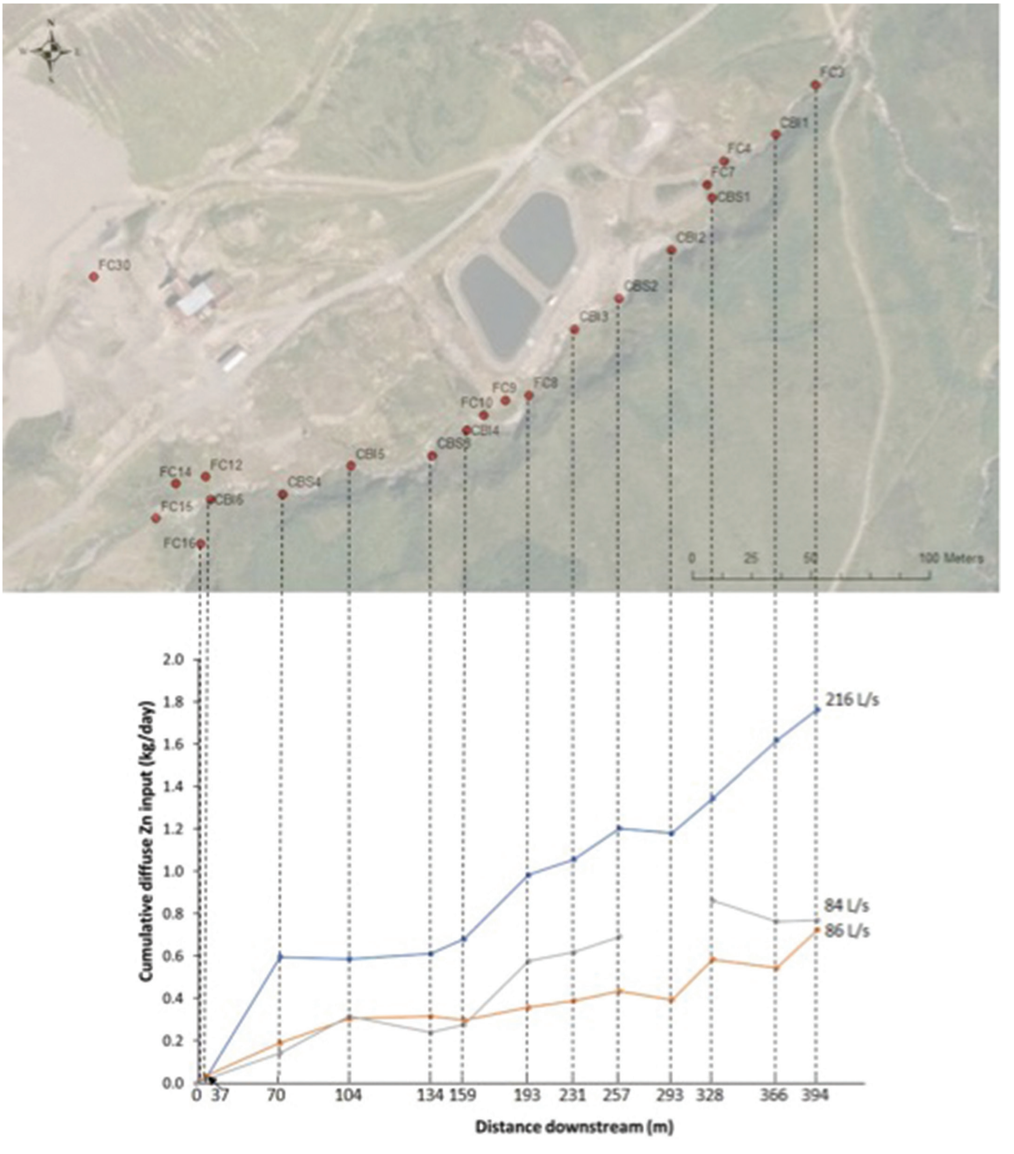

Figure 3 Cumulative diffuse zinc input to the Coledale Beck over a 400 m reach during intensive synoptic mass balance monitoring. The flow-rates shown are for the most downstream monitoring point on the Coledale Beck.

overall zinc flux within this reach, particularly under higher flow conditions. Intensive synoptic monitoring, encompassing a total of 13 instream locations, 6 point source inputs and a tributary, has been undertaken on 3 occasions. Diffuse zinc input is defined as the difference between (1) the sum of the upstream zinc flux plus any point source zinc fluxes within each stream reach and (2) the instream zinc flux at the downstream location of that reach. The cumulative diffuse zinc input is the sum of these reach-scale diffuse inputs from upstream to downstream. As shown in Fig. 3, the cumulative diffuse zinc input increases downstream under both flow conditions monitored but the rate of increase is greater at higher flows. Under low flow conditions (86 L/s,) the total diffuse zinc flux over the 400 m reach was 0.7 kg/day whilst under higher flow conditions (216 L/s) it

Figure 4 Location of boreholes installed in riparian zones and mine spoil.

was 1.8 kg/day. Such intensive monitoring enabled the identification of several stream reaches over which a marked increase in diffuse zinc flux occurred, under both flow conditions, and this informed site selection for the installation of boreholes in the riparian zones (Fig. 4).

Conclusions

This work demonstrates the need for a watershed approach to mine water management. The Coledale Beck catchment is one of the best instrumented catchments in the UK with the installation of flow-gauging infrastructure enabling accurate monitoring of flow-rates in the main river channel, tributaries and point sources. Synoptic mass balance monitoring using this infrastructure identified the main point source of pollution and informed design of the UK's first full-scale passive treatment system for metal mine drainage. Whilst the benefits of remediating point sources are clearly evident at low flow, diffuse sources of pollution limit the overall benefits at higher flows. Ongoing research aims to identify these diffuse sources with further infrastructure such as boreholes recently installed to assess groundwater-surface water interactions and gain an understanding of the influence of riparian subsurface flows on metal flux. The techniques employed at Force Crag are applicable to other base metal mines in the UK and internationally.

Acknowledgements

The research was funded by the UK Government Department for Environment, Food & Rural Affairs and Environment Agency (Project No. SC090024/1) and the UK Coal Authority. We are grateful for the assistance of Mr Patrick Orme and Ms Jane Davis with fieldwork and laboratory work and to the National Trust for site access. The views expressed are those of the authors and not necessarily those of the Coal Authority, Environment Agency or National Trust.

References

Gandy CJ, Davis JE, Orme PHA, Potter HAB, Jarvis AP (2016) Metal removal mechanisms in a short hydraulic residence time subsurface flow compost wetland for mine drainage treatment. Ecological Engineering 97:179-185

Gozzard E, Mayes WM, Potter HAB, Jarvis AP (2011) Seasonal and spatial variation of diffuse (non-point) source zinc pollution in a historically metal mined river catchment, UK. Environ. Pollut. 159:3113-3122

Jarvis AP, Davis JE, Orme PHA, Potter HAB, Gandy CJ (2019) Predicting the benefits of mine water treatment under varying hydrological conditions using a synoptic mass balance approach. Environ. Sci. Technol. 53(2):702-709

Mayes WM, Davis JE, Silva V, Jarvis AP (2011) Treatment of zinc-rich acid mine water in low residence time bioreactors incorporating waste shells and methanol dosing. Journal of Hazardous Materials 193:279-287

Mayes WM, Potter HAB, Jarvis AP (2010) Inventory of aquatic contaminant flux arising from historical metal mining in England and Wales. Science of the Total Environment 408(17):3576-3583

Mighanetara K, Braungardt CB, Rieuwerts JS, Azizi F (2009) Contaminant fluxes from point and diffuse sources from abandoned mines in the River Tamar catchment, UK. J. Geochem. Explor. 100(2-3):116-124

Runkel RL, Kimball BA, Nimick DA, Walton-Day K (2016) Effects of flow regime on metal concentrations and the attainment of water quality standards in a remediated stream reach, Butte, Montana. Environ. Sci. Technol. 50:12641-12649