Methodology for assessing water pollution and risks associated with abandoned lead-zinc mining at Wanlockhead and Leadhills, southwest Scotland, UK

Lee M Wyatt, Arabella M L Moorhouse, Ian A Watson, Steven Kershaw

The Coal Authority, 200 Lichfield Lane, Mansfield, Nottinghamshire NG18 4RG, UK
leewyatt@coal.gov.uk

Abstract Within the UK, no organisation is currently responsible for pre-2000 abandoned non-coal mines. Commonly, following cessation of mining, limited work was undertaken to remediate these mine sites and associated mineral processing areas. Consequently these landscapes are often dominated by disused mine entries, spoil mounds, smelting mills and other associated features. Due to the unmaintained nature of these locations, there are often numerous risks present including blockages, collapses and contaminated ground. The Coal Authority has investigated metal contamination in two water-bodies in southwest Scotland, employing a dynamic, flexible sampling strategy enabling the prompt identification of possible sources in a changing environment.

Keywords metal mine water, abandoned mines, mining legacy, risk of abandoned mines, dynamic methodology of water investigation

Introduction

The villages of Leadhills and Wanlockhead are two former lead (and zinc) mining villages located in southwest Scotland, situated towards the headwaters on the Glengonnar Water and Wanlock Water respectively. Mining in the area dates back to the 13th Century (Rowan *et al.* 1995), however the most intensive period of activity occurred between the 17th Century and mid 20th Century. The Scottish Environmental Protection Agency (SEPA) have monitored these two water-bodies and determined that both are failing the Environmental Quality Standards (EQS) defined for these rivers (SEPA 2011). In 2010 and 2012 the Coal Authority were commissioned to undertake two studies to determine the sources of pollution and identify any 'blow-out' risks associated with a blocked mine drainage adit. Due to the restriction in timescales and expenditure, the Coal Authority implemented a dynamic and adaptable approach to assess these study areas. This paper outlines the methodology used for these studies, and highlights a number of the key risks and findings identified from the investigations.

Methodology of assessments

Methodologies employed for undertaking a study investigating the sources of pollution are typically based on a fixed monitoring and sampling regime, over a minimum time period of one year; with sample locations usually determined through a 'desk-top' study and 'walk-over' survey. However, for the studies described in this paper, the time-scales were limited to 5 and 11 months, and included a strict sampling budget. In order to obtain instructive results and provide sufficient data for an informative assessment to be made, the Coal Authority had to adapt and use an alternative strategy.

The first stage of each study followed the typical approach, where a desk-top study of each area was undertaken to identify the extent of the mining area, the mining zones, any potential point sources (*i.e.* mine adits) and sites of diffuse pollution (*i.e.* ore processing areas; see Fig. 1), in conjunction with a review of any relevant studies and reports. The desk-studies were subsequently followed by a walk-over survey of the study areas. The walk-over survey assists with the assessment of any point sources identified in the desk-top study, in addition to providing valuable information relating to the nature of the possible sources of contamination, and highlighting possible pollution pathways to the principal receptors (*e.g.* freshwater streams and rivers). Furthermore, the walk-over survey also identifies other features, which may benefit the study such as extra potential monitoring points (see Fig. 1) in addition to detecting other unforeseen risks (*i.e.* blowouts). The walk-over is restricted to a single 'one-off' visit to the study area, and any observations made during the inspection, combined with the climatic conditions on the day, can have an influence on all subsequent visits and assessments. As the two studies commissioned by SEPA were constrained by both time and expenditure, it was determined that a more adaptable approach was required to fully assess the study areas.

Leadhills (Glengonnar Water) Study This study had a restricted time-scale of 5 months, which is usually regarded as insufficient to undertake a complete study, as the full extent of any seasonal variations are not represented in the reporting period. However, some historical data for the area were available, which combined with the 5 month study, allowed an assessment of the pollution sources and some blowout risks to be determined. The key concerns addressed by the study included determining the extent of the environmental pollution of lead (Pb), zinc (Zn) and cadmium (Cd; *i.e.* SEPA 2011) and their sources, combined with an appraisal of the risk of a sudden outburst (blowout) of mine water from the blocked Gripps Drainage Level (Fig. 2; Schmolke 1998, Coal Authority 2011). The initial desk-top study and walk-over survey identified 12 key monitoring points along the Glengonnar Water, which defined the point sources of pollution (Fig. 3), in addition to locating three shafts, which would allow the level of the water in the mine workings and the pressure acting on the blockage to be determined. For the duration of the study, a continual assessment of the data and observations obtained in the field resulted in an additional 15 sites being identified and tested (Fig. 2). These included an overflow pipe relating to the Horse Level Adit, a number of seepages from the base of two air shafts along the Gripps level, a number of 'springs', which on site testing suggested may

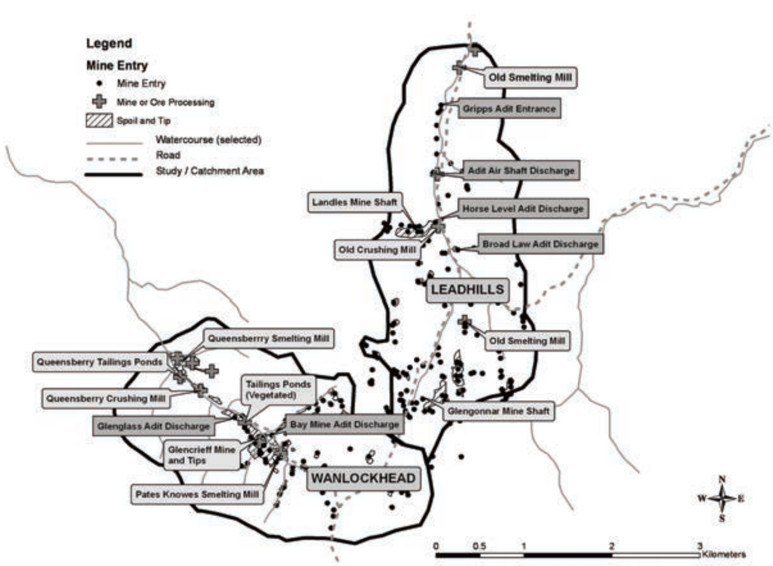

Fig. 1 *Map of the main mining features for both study areas.*

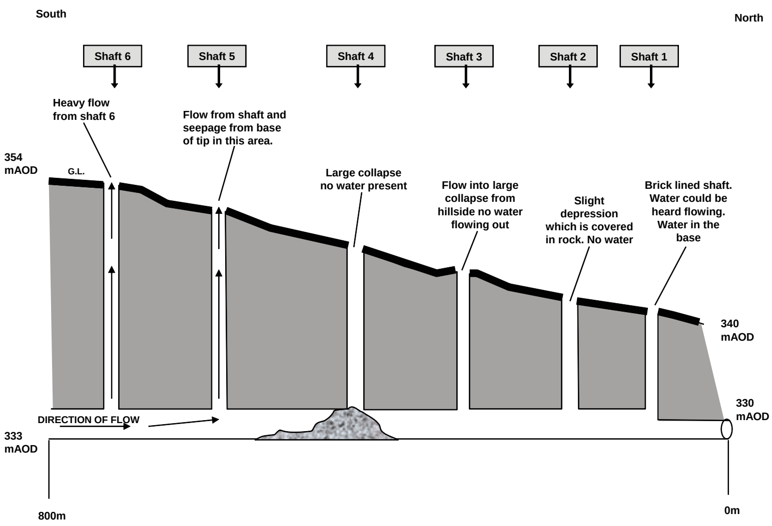

Fig. 2 *Diagrammatic section of the Gripps Drainage Adit and blockage.*

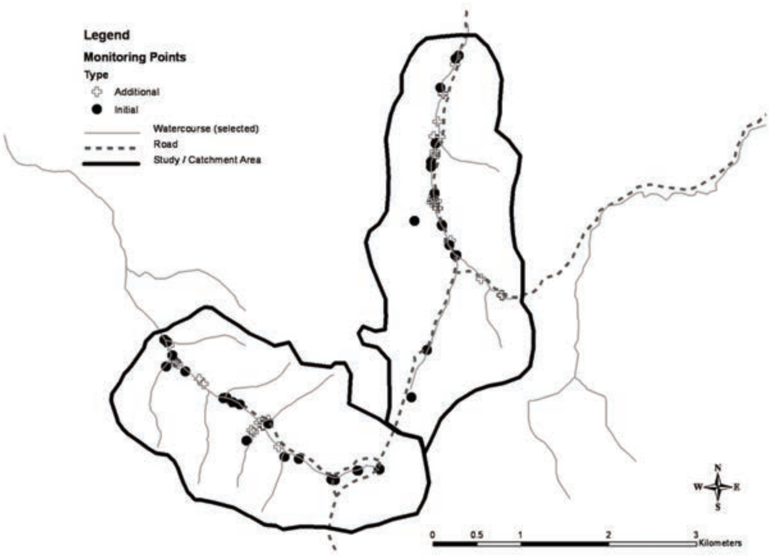

Fig. 3 *Map of the initial and additional monitoring points for both study areas.*

be mine water, and a selection of specific sampling sites, which related directly to the specific weather conditions (*i.e.* high rainfall) on the day of the visit.

Wanlockhead (Wanlock Water) Study This study had a limited time-scale period of 11 months to undertake a complete study of the Wanlock Water and assess the sources of the environmental pollution caused by Pb, Zn and Cd (SEPA 2011). The initial desk-top study and walk-over survey initially identified 22 individual monitoring sites along the Wanlock Water (Fig. 1), which included two mine adit discharges, two possible mine adit discharges, and numerous locations to assess the impact from diffuse sources. With a continual assessment of the new data and observations made, combined with conditions relating to the changeable weather conditions, a total of 25 additional sites (Fig. 3) were also identified. These included for example, ephemeral or intermittent streams, springs and seepages from the tips and ore processing material.

Throughout both studies the general strategy employed was to identify the key monitoring locations, which were sampled throughout the duration of the study. These included upstream and downstream river samples of the study area; upstream and downstream of the known point sources; and upstream and downstream of any large areas of potential diffuse, and possible point, sources. Weather conditions varied considerably between each visit, therefore instantaneous assessments were made on site to determine any additional sampling requirements, for example transient runoff from tailings ponds or intermittently flowing adit discharges. Throughout both of these studies, extra sampling was also used to assess any new water sources found post the initial walk-over survey.

Upon receipt of the results from the laboratory after each visit, the sampling requirements for future site visits were re-appraised to ensure that any previously unknown sources of contamination were tested for. This ensured that over the 11 month period, sufficient analyses were obtained to allow a representative view of the chemistry of these samples to be acquired. This dynamic approach allowed the sample points identified in the study to be re-classified so that sites could be either removed, or added to the programme as judged necessary. Overall, the fixed sampling points enable the identification of the key pollution sources in the study area. Furthermore, comparisons of the ad-hoc samples can also be made against these fixed sites where necessary, to elucidate the possible effects of any temporal sources of contamination. Both the study sites are located in upland areas, where there is typically a high annual precipitation in excess of 1,500 mm/a (Rowen *et al.* 1995) which are likely to vary greatly; throughout the study period, the annual rainfall was approximately 1,750 mm/a.

Changes made to initial sampling

Leadhills (Glengonnar Water) Initially the routine sampling was designed to assess impacts from the known mine water discharges from the Horse Level Adit, the Gripps Drainage Adit and the associated shaft 6 discharge (Fig. 2). Prior to the study, it was believed these mine water discharges were the main contributors to the elevated concentrations of Pb, Zn and Cd determined in the river. After studying the first set of results from the river water and adit discharges, it became evident that the mine water discharges were not the main source of Pb and Cd contaminants (*i.e.* concentrations of these metals were low in the mine water). During the first visit, and subsequent visits, it was concluded there was no, or very little flow, in the Glengonnar Water at its confluence with the Dead Burn tributary, therefore, one of the intermediate sample points was removed from the programme. In addition to this, two ephemeral mine water sources were found (Coal Authority 2011); one source originated from an overflow pipe associated with the Horse Level Adit, the other source is a low flow, high concentration discharge from the Broad Law Adit. In wet weather conditions seepages and upwellings were observed to occur from the base of air shaft mounds 4 and 5, and water was also seen emerging from a tension crack along the top of the Gripps Drainage Adit (Coal Authority 2011). With low Pb and Cd concentrations in the mine water, an increased effort was made to determine the source(s) of the Pb pollution. This was achieved by undertaking soil/sediment samples of the flood plain and surrounding area, in conjunction with additional water samples from the Glengonnar Water, to aid with identifying the primary sources. It was concluded that the principal source of the Pb and Cd was from the alluvial floodplain material (*i.e.* up to 10 % Pb wt/wt; Coal Authority 2011) which contained sediment from historical mining and ore processing waste in the form of particulate lead.

Wanlockhead (Wanlock Water) This study began with a programme to assess the impacts from the known mine water discharges from the Glenglass Adit, Bay Mine Adit and two unnamed adits upstream of the mining museum in Wanlockhead. Prior to the study, the source of the Pb, Zn and Cd were uncertain but were believed to originate from the mine water and possibly other "unknown" sources. Following the initial three sampling visits it was concluded that the two unnamed adit discharges were predominantly "clean" water with little, or no, detectable Pb, Zn or Cd concentrations (Coal Authority 2013); these samples were therefore removed from the routine sampling programme. Furthermore, after reviewing the initial set of results it was evident there was also very little, or no Pb, Zn or Cd contamination entering into the Wanlock Water upstream of Straitsteps Mine (Coal Authority 2013). It should also be noted that the Wanlock Water is a losing stream between Straitsteps Mine and the Bay Mine Adit discharge (and probable resurgence) and is often dry before reaching Bay Mine Adit. In a similar scenario to Leadhills, it was found that the Pb and Cd pollution does not originate primarily from the mine water (Coal Authority 2013) but from an alternative source. Assessment of the river water samples showed a stepped increase in the river concentrations of Pb and Cd downstream of Glencrieff Mine and the final downstream sample. Water flows originating from an old crushing mill and un-vegetated tailings pond associated with Queensberry Smelting Mill (Fig. 4), first observed after 3 months of monitoring, were scheduled for additional, regular monitoring in order to determine whether these areas were the principal sources of the pollution. Although the seepages and flows from these ore processing areas are small, they contain elevated concentrations of Pb, Zn and Cd (Coal Authority 2013) when compared to the mine water discharges (*i.e.* a factor of 5 to 10 times greater).

Conclusions

Although the time-scales and budgets for undertaking idealised sampling programmes were restricted, the Authority were successfully able to identify and provide an estimate of the contaminant loadings of Pb, Zn and Cd affecting both the Glengonnar Water and Wanlock Water as required by SEPA. The process of using a set number of fixed routine sample points combined with ad-hoc or flexible sampling points can be used to determine and target metal contamination in a relatively limited timeframe. However, this process requires a continual and comprehensive assessment of the entire study area, only achieved by making detailed observations at each locality and checking the whole area on each visit for any

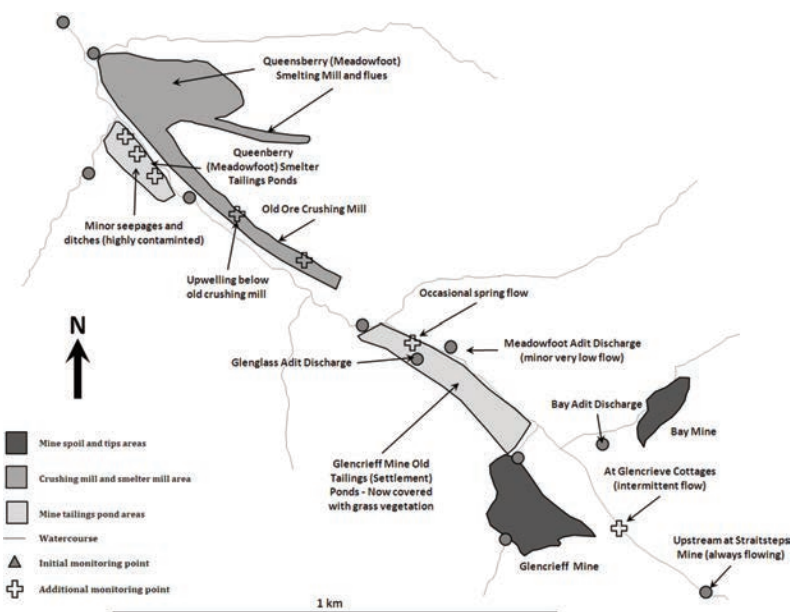

Fig. 4 *Diagrammatic plan of part of the Wanlock Water study area.*

changes. For this reason it is important the samples are collected by a small pool of individuals who are very familiar with the site. Some approximate estimates can be made using the limited data, (if it is assumed the study is undertaken during a typical 'normal' year for rainfall) to give an idea of the sizing criteria required to remediate any pollution. It also allows for a programme of more detailed future works and strategies to be undertaken whilst still gathering key parameters such as chemistry and flow data. However, due to limited time-scales and, in particular, the limited number spot flow measurements, this method should be used with care, especially if attempting to undertake a more detailed design and sizing investigation for any remedial works. Despite this limitation however, on occasions when prompt remediative measures are required this type of sampling methodology can provide invaluable information in a reasonably short timeframe.

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