CL:AIRE

RB 18
(September 2014)
ISSN 2047-6450 (online)

research bulletin

CL:AIRE research bulletins describe specific, practical aspects of research which have direct application to the characterisation, monitoring or remediation of contaminated soil or groundwater. This bulletin describes national-scale impacts of abandoned non-coal mine water pollution.

Prioritisation of Abandoned Non-coal Mine Impacts on the Environment

1. INTRODUCTION

Pollution arising from abandoned mines has long been recognised as an environmental concern in the UK. Mine water pollution occurs due to the exposure of sulphide minerals during mining. In coal mine workings the key mineral is pyrite (iron disulphide, chemical formula FeS_2) (fool's gold), whilst in metal mining operations it could be one or more of a number of metal minerals, including galena (lead sulphide, PbS) and sphalerite (zinc sulphide, ZnS), as well as pyrite in some cases. These sulphide minerals are subject to oxidation when exposed to air, and these oxidised mineral residues are soluble in water. Thus, when water contacts the oxidised residues, either during mining operations, or especially after abandonment of the workings, the water becomes polluted with metals. In addition, the sulphur (S) is released, and becomes oxidised to sulphate (SO_4), which in itself can be problematic in surface and groundwaters, especially in arid and semi-arid climates. In the case of pyrite, the reactions above are also highly acid-generating, and therefore in the absence of any reactions to neutralise the acidity mine waters may have very low pH (pH 4 and less is not uncommon), which is highly damaging to freshwater ecology. An example of a non-coal mine water discharge is shown in Figure 1, in this case showing the characteristic orange staining caused by an elevated iron concentration.

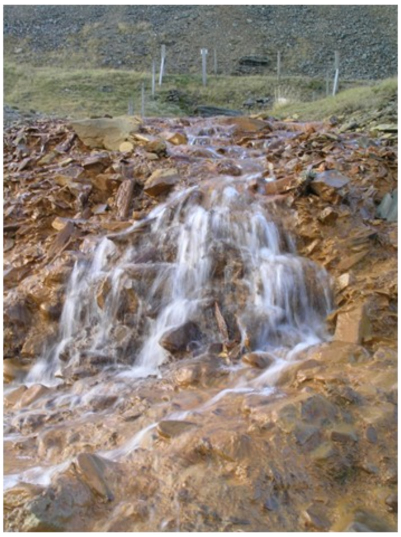

Figure 1: The Pugh's adit mine water discharge in mid-Wales, which contains elevated concentrations of both zinc and lead, as well as iron (Photograph: Dr Adam Jarvis, Newcastle University).

Since 1994 the Coal Authority has taken the lead in addressing many mine water pollution problems where they arise from deep coal mines (see http://coal.decc.gov.uk). The primary objective of these systems is to neutralise acidity (raise pH) where required, and then remove the metal contaminants, which in the case of coal mine water discharges is principally iron (Fe). The Coal Authority currently operates approximately 60 full-scale coal mine water treatment systems around the UK, as well as managing an extensive groundwater monitoring network in former coal mining regions. However, whilst the Coal Authority's programme of coal mine water treatment initiatives has resulted in substantial environmental improvements across the UK, there is not an equivalent body with responsibility for the management of pollution problems from abandoned non-coal mines (primarily metal mines), and therefore until recently polluting discharges from non-coal mines have remained untreated across the UK in all but one case[1]. In recognition of the need to address this type of pollution, the Department for Environment, Food and Rural Affairs (Defra) allocated £10 million for the Coal Authority and Environment Agency to implement abandoned non-coal mine water pollution feasibility studies and treatment initiatives in England from 2011-2015.

Numerous investigations of *individual* abandoned non-coal mines, or *individual* streams and rivers in their vicinity, have demonstrated that discharges may have a deleterious impact on receiving watercourses and their ecology (e.g. Armitage, 1980; Fuge *et al.*, 1991), principally due to the elevated concentrations of metals such as zinc, lead, and cadmium, and in some instances low pH. Some studies have collated information about non-coal mine water pollution over a wider area (e.g. Mullinger, 2004). In many cases it has been shown that the very high concentrations of metals in these non-coal mine water discharges result in elevated concentrations in receiving watercourses, and consequently failures of Environmental Quality Standards (EQS), which are the standards against which the overall chemical quality of the freshwaters of England and Wales are assessed.

However, while investigations of individual non-coal mine water discharges and impacts in discrete geographical areas are useful, a key building block of the Coal Authority's successful programme of coal mine water treatment initiatives was a *national* assessment of the impacts of these discharges on the receiving environments using a single, consistent, methodology (the basis of the approach is

[1]The discharge from the Wheal Jane tin mine, Cornwall, first emerged as a massive outburst of highly polluted water, causing a visible plume of orange pollution in the Fal estuary in 1992. Such was the impact of the discharge, and the publicity associated with it, that a treatment system had to be installed (by the Environment Agency, on behalf of Defra) to remediate the ongoing discharge of polluted water from the mine (see CL:AIRE, 2004 for further details).

This bulletin was written by Adam Jarvis, Newcastle University; Steve Hill, Coal Authority; Hugh Potter, Environment Agency; Peter Thorn, Atkins; William Mayes, University of Hull. For further information please email adam.jarvis@newcastle.ac.uk or tel: +44(0)191 208 4871

described by Davies *et al.*, 1997). This enabled evaluation of which were the most polluting coal mine discharges, and therefore which should be prioritised for treatment. The absence of such a national-scale assessment of abandoned non-coal mine water pollution impedes any effort to develop a properly prioritised national strategy to address such pollution problems. The advent of the EU Water Framework Directive (2000/60/EC), in particular, heightened the need for such an assessment of non-coal mine impacts, not least because of the requirement to begin to address such pollution issues with a justifiable 'programme of measures' for environmental improvements.

In 2007 Defra, the Environment Agency and the Welsh Government therefore funded a two year research project to develop and apply a methodology for prioritising abandoned non-coal mine impacts on the environment of England and Wales. This bulletin describes the methodology, and the results of its application, revealing the true extent of non-coal mine water pollution across England and Wales for the first time. One objective of the research project was to provide the Environment Agency with a database that could be updated as new information became available. This CL:AIRE bulletin presents such updated results in light of new water quality data, and at the time of writing this is therefore the most up-to-date publication with respect to the national-scale impacts of non-coal mine water pollution. In addition to presenting these data, the bulletin discusses the implications of the results of the work for future management of abandoned non-coal mines.

A much more complete discussion of the methodology and the results and implications of its application can be found in the series of 13 reports, published by the Environment Agency in 2012, that are available for free download from https://www.gov.uk/government/publications/prioritisation-of-abandoned-non-coal-mine-impacts-on-the-environment. Mayes *et al.* (2009) have also published an accessible synthesis of the methodology development and national results, and subsequently an analysis of the results in the context of overall metal fluxes to freshwaters of England and Wales from industrial and other sources (Mayes *et al.*, 2010).

2. METHODOLOGY DEVELOPMENT

The methodology developed for prioritising the impacts of coal mine waters on the environment (see Davies *et al.*, 1997) was based around the severity and extent of pollution of receiving watercourses, both in terms of chemical and ecological (specifically benthic invertebrate) impacts. A major influence on the outcome of the application of the method was the iron concentration in the discharge and the extent of discolouration of receiving watercourses due to this iron. However, many non-coal mine waters do not contain appreciable concentrations of iron, and therefore direct application of this approach to non-coal mine waters would likely fail to correctly prioritise the impacts of the many non-coal discharges which are highly polluting due to the presence of metals such as zinc, lead and cadmium, but often contain little or no iron.

The coal mine water prioritisation methodology was also labour- and resource- intensive to apply, requiring on site sampling, and analysis of both chemical and ecological variables at various points below mine water discharges. Given the wide geographical distribution of non-coal mine water discharges across England and Wales, and the resource limitations for development of a methodology, such an approach could not be taken in this case.

Therefore the non-coal prioritisation methodology was developed using existing data. Specifically, this took the form of a spatial analysis of (1) former non-coal mining activity (either a mining area if mineralised zones present, or known mine sites) and (2) failures in streams and rivers of Environmental Quality Standards (EQS) for a suite of metals (and one metalloid) comprising arsenic, cadmium, copper, iron, manganese, nickel, lead and zinc. This analysis was undertaken using GIS (MapInfo v9.51). Overlaid on a base map of the surface water bodies[2] of England and Wales, these data permitted the categorisation of the surface water bodies as *Impacted*, *Probably Impacted, Probably Not Impacted*, or *Not Impacted* by non-coal mine pollution. The categorisation was based on the conditions shown in Table 1.

Table 1: Conditions for categorisation of surface water bodies as *Impacted, Probably Impacted, Probably Not Impacted*, or *Not Impacted* by non-coal mine pollution

Impacted	Water body containing one or more (metal) EQS failures **AND** containing former non-coal mine site(s)
Probably impacted	Water body containing one or more (metal) EQS failures **AND** in a mining area **AND** contains no known mine sites; **OR** Water body in a mining area **AND** has EQS failure in immediate downstream water body
Probably not impacted	Water body is classed as a mining area **AND** has no EQS failures in water body; **OR** Water body is categorised as mining area **AND** has no EQS failure in downstream water body
Not impacted	A non-mining water body not categorised in any of the three former categories

The two "probably" categories indicate a degree of uncertainty with respect to the link between mining activity and water quality impacts, and for these water bodies more detailed local investigations would be recommended, to either elevate the water body to *Impacted* or re-categorise the water body to *Not Impacted*. Even before commencing the investigation it was appreciated that there would be gaps in data. It was for this reason that one objective for the final database and GIS interface was that it should be amenable to updating on a periodic basis as new data became available.

The approach to prioritisation is summarised diagrammatically in Figure 2, specifically in the upper half of the flow chart under the title 'Phase I: Identification of non-coal mine pollution'. As Figure 2 indicates, the second phase of the methodology is 'Impact prioritisation and validation'. Only those water bodies categorised as *Impacted* or *Probably Impacted* are carried forward to this phase, the purpose of which is to assess, in more detail, the priority water bodies i.e. those in which non-coal mine impacts are greatest.

[2]'Surface water bodies' are the geographical units of rivers, lakes, etc. that the Environment Agency uses for regulatory purposes, and are typically river catchments or sub-catchments. At the time of the methodology development in 2007/08 there were 6910 surface water bodies in England and Wales (the number has since decreased due to water body boundary changes).

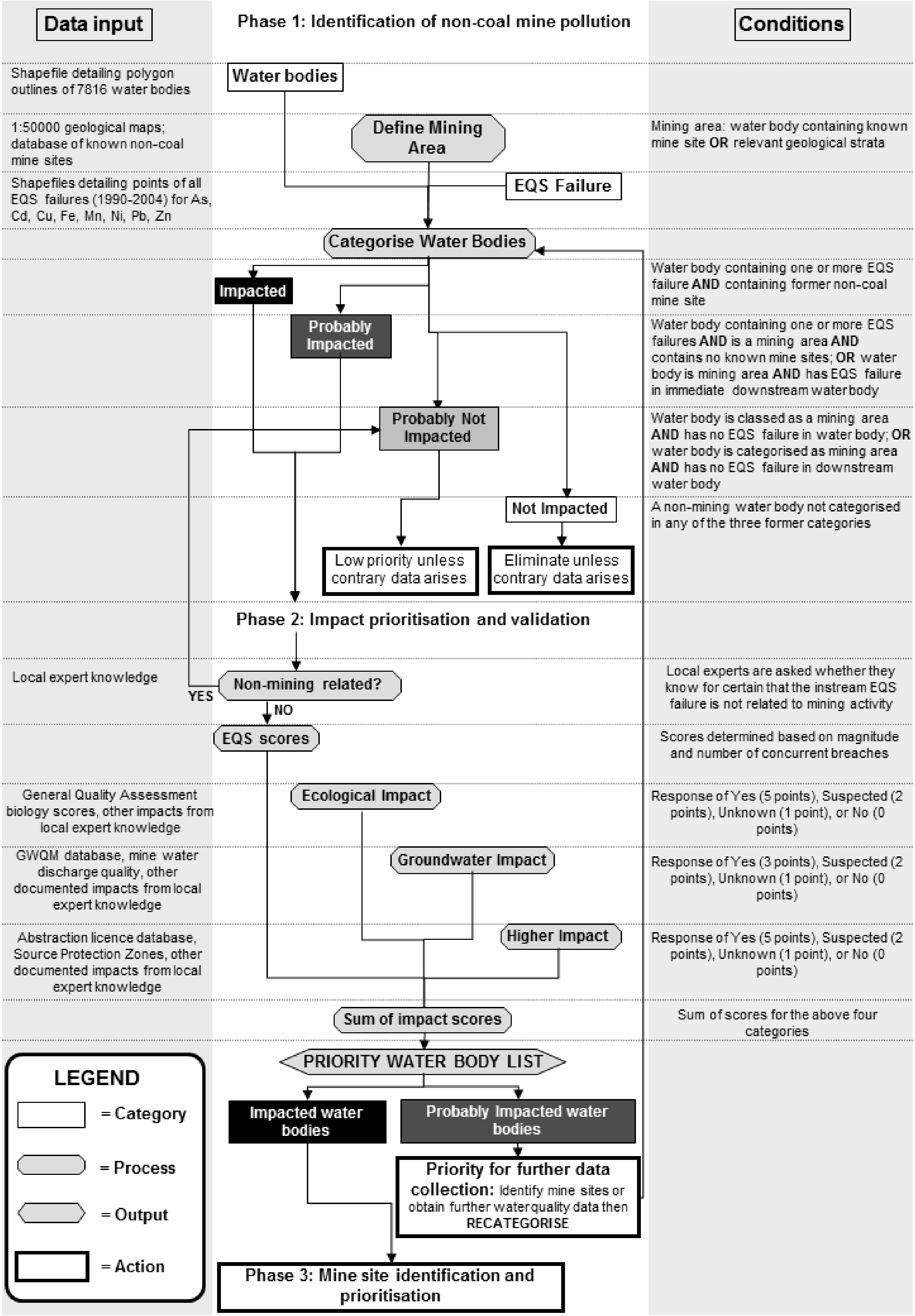

Figure 2: Flow chart illustrating approach to categorisation of impacts of non-coal mines on water bodies of England and Wales (adapted

This more detailed assessment is based upon:

1. The magnitude and number of concurrent breaches of EQS for the 7 metals and 1 metalloid listed above
2. The ecological impact based on biological metrics of water quality and local knowledge
3. The impacts on groundwater based on Environment Agency data and documented impacts
4. Higher impacts, based on locations of abstractions, groundwater source protection zones and expert knowledge

From each of the above a numeric score was derived, the sum of which provided the priority water body list (Figure 2). The full details of the scoring approach, including the EQS values used, are provided by Mayes *et al.* (2009).

Those water bodies on the Priority list categorised as *Probably Impacted* are those for which the key priority is the collection of further data (identify mine sites and obtain more water quality data) such that these water bodies can be re-categorised. The *Impacted* water bodies from this Priority list are carried forwards to the final phase of the methodology, 'Phase 3: Mine site identification and prioritisation', as indicated at the bottom of Figure 2.

The purpose of the final phase of the methodology was to gather information about the mine sites within *Impacted* water bodies, to begin to establish which specific mines are responsible for the impacts in these water bodies. This was accomplished principally via a questionnaire to Environment Agency staff across England and Wales, with additional information provided by district and county councils. The information requested is summarised in Table 2.

Table 2: Additional information requested about mine sites in *Impacted* water bodies

Question / information requested	Comment
Water Body ID and Name	Information provided by Project team
EQS failure co-ordinates and score	Information provided by Project team
Categorisation (e.g. *Impacted* etc.)	Information provided by Project team
Locations of point mine water discharges within water bodies with EQS failures, or in water bodies immediately upstream of water body with EQS failure	Required to prioritise *Impacted* and *Probably Impacted* water bodies
If there is a mine water discharge (either point or diffuse) known or suspected then further information on the discharge is required (e.g. quality, flow, impacts)	Including receiving watercourse name, groundwater, ecological and higher impacts, stakeholder information, and water quality
Knowledge of historical mines, irrespective of water pollution issues	Including mine location and name (if known), airborne pollution risk, safety concerns, stability concerns and outbreak risk

3. RESULTS

Results of original prioritisation exercise

The results of the original prioritisation exercise are shown in Figure 3 and Table 3. Figure 3 clearly illustrates the predominance of the *Impacted* category of water bodies in former metal mining districts of England and Wales, as expected. These areas are the South West, Wales, the North West and North East. Table 3 shows that 223 water bodies were categorised as *Impacted* by abandoned non-coal mine pollution, with a further 246 falling into the *Probably Impacted* category. The number of water bodies in these top two categories amounts to 6.8% of all water bodies in England and Wales, illustrating the substantial national impact of this single form of pollution. Although more detailed monitoring would be required in individual water bodies to establish an accurate figure, the number of water bodies affected suggests that up to 6,500 km of streams and rivers may be impacted by non-coal mine water pollution. Further interrogation of the results, reported in Mayes *et al.* (2010), reveals that for some of the common metals discharged, abandoned metal mines are by far the most important source of metal flux (mass per unit time) to the freshwaters of England and Wales; approximately 50% of the total flux of lead and zinc to freshwaters arises from abandoned non-coal mines, with all other permitted discharges (from sewage works, industry etc.) combined contributing the other half.

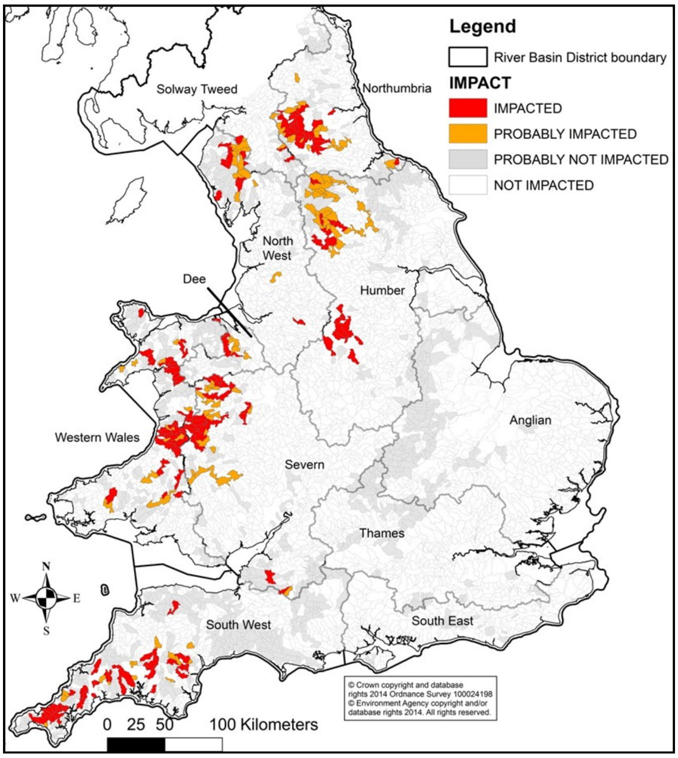

Figure 3: Categorisation of water bodies of England and Wales according to abandoned metal mine impacts (updated from Mayes *et al.* (2009) using unpublished Environment Agency data)

Furthermore, this is likely an underestimate of the true scale of non-coal mine water pollution, since flux data are unavailable for many known discharges (efforts to gather more comprehensive data are underway at the time of writing).

Results of updated prioritisation exercise (2013)

Gaps in data were a recognised issue in the original categorisation and prioritisation of water bodies impacted by abandoned non-coal mines. Indeed, as previously noted, the ability to add to the database over time was a key objective of the original development of the methodology. Since the methodology was first applied, improvements in data coverage and completeness have been made. In addition, some changes to the methodology itself have been made:

- Changes to the water body boundaries (more details below),
- Amendment of some EQS limits (particularly Zn for which a standard that takes account of bioavailability and ambient background concentrations is being introduced (UK Technical Advisory Group on the Water Framework Directive, 2013)),
- Removal of the Higher Impact category from the prioritisation exercise, as its use introduced potentially misleading results (e.g. identification of 'Higher Impacts' that were not in fact due to abandoned mines),
- Removal of manganese from the group of metals used in the exercise, as it is not a good indicator of non-coal mine pollution.

Table 3 compares the number of water bodies in each category for the original and updated exercise. In the intervening period between the original and updated categorisation there have been significant changes to the boundaries of water bodies. Specifically there has been a reduction in number; there were 6,910 water bodies during the original exercise, but only 4,485 in the more recent categorisation (Table 3). There has been improved monitoring in the *Impacted* and *Probably Impacted* water bodies, which has allowed re-categorisations, particularly from the *Probably Impacted* category to either the *Impacted* or *Probably Not Impacted* categories. The absolute number of water bodies in the top two categories has decreased, principally because the size of water bodies has increased e.g. what were previously two *Impacted* water bodies may now only be one *Impacted* water body (albeit potentially with multiple discharges of polluting mine water). As a consequence of these changes in water body boundaries, and improved monitoring, the percentage of water bodies *Impacted* or *Probably Impacted* by abandoned metal mine pollution has decreased, from 6.8% after the original exercise to 5.9% in the updated categorisation. In the original exercise this equated to a maximum length of stream and river impacted of ~ 6,500 km. Improved monitoring, and also changes to EQS limits for key metals (especially zinc), results in this figure being revised downwards in the updated categorisation, to a maximum of 3,900 km. As noted previously, more detailed monitoring would be required to improve the accuracy of this estimate, but nevertheless the scale of the impacts of non-coal mine water pollution is clearly very substantial. With respect to the severity and scale of impact, it is also important to appreciate that abandoned mine water discharges are long-term sources of pollution (as discussed by Younger (1997), for example), and therefore relying on natural attenuation to remedy the problem is not a practically useful solution.

4. DISCUSSIONS & CONCLUSIONS

The results of the categorisation and prioritisation exercise clearly illustrate the substantial scale and impacts of abandoned non-coal mines on the freshwater environment of England and Wales.

Table 3: Categories of water bodies after the original and updated categorisation

Category	Original categorisation	Updated categorisation	Explanation
Impacted	223	159	EQS failure in same water body as mines
Probably Impacted	246	108	EQS failure in water body in mining area (= mines suspected but not identified) OR EQS failure in water body immediately downstream of water body known or suspected to contain mines
Probably Not Impacted	1271	1047	Mining area with no EQS failure downstream
Not Impacted	5170	3171	Non-mining area
Total	**6910**	**4485**	

Abandoned non-coal mines alone are a bigger source of metals to freshwaters than all other permitted discharges combined, and the dominance of these sources is only likely to increase as more data are collected. For those sites for which flux data exist, Mayes *et al.* (2010) calculated that 193 tonnes / annum of zinc are discharged from abandoned non-coal mines. Of the other metals (and one metalloid) subject to this analysis (As, Cd, Cu, Fe, Mn, Ni and Pb), only iron has a greater flux (550 tonnes / annum)[3]. However, the total flux of iron is heavily influenced by a number of individual discharges that have very high iron flux values (e.g. The County adit, Wheal Jane tin mine, Cornwall; Saltburn Gill ironstone mine, Cleveland). In terms of the prevalence of EQS failures zinc is the most important metal contaminant, albeit metals such as cadmium and lead may be of greater concern since they are classed, in regulatory terms, as Priority Hazardous and Priority Substances respectively, due to greater concerns about their toxicity.

In terms of addressing these pollution problems, it was noted earlier that there is currently no individual organisation in the UK with an explicit remit to address non-coal mine water pollution. However, very positive steps have been made in recent years. For example, in April 2011 Defra released £110 million to address a variety of water quality issues in England up to 2015, and £10 million of this was specifically allocated for the Environment Agency and Coal Authority to begin to tackle non-coal mine pollution problems, partly in light of the results of the prioritisation exercise discussed here. The Environment Agency has instigated a number of detailed investigations of the *Impacted* water bodies identified in the work described here, with around 20 detailed river catchment investigations underway to establish the most important sources of non-coal mine pollution in those particular water bodies. The Coal Authority, with its experience of addressing coal mine water pollution, is carrying out feasibility studies at priority discharges, and at the time of writing, is building two large-scale non-coal mine water treatment systems: at the Saltburn Gill ironstone mine in

[3] For comparison, it has been estimated that in 2008 the Coal Authority's coal mine water treatment scheme were preventing the release of 1800 tonnes / annum of iron entering freshwaters (Environment Agency 2008). The magnitude of iron flux from abandoned coal mines was therefore historically more severe than metal mines, but coal mines rarely contain appreciable quantities of the divalent metals that are the focus here e.g. Zn, Cd, Pb.

Cleveland, and the Force Crag mine (which mined lead, barite and zinc) in Cumbria. It has been calculated that the environmental, social and economic benefits of remediation exceed the full-life cycle costs of these schemes. That is to say the remediation could be considered sustainable, following the SuRF-UK definition (CL:AIRE, 2010).

Challenges remain, however. These primarily relate to catchment-specific issues of (a) determining key sources of pollution within water bodies and (b) identifying effective and appropriate treatment options for these key sources of pollution. With respect to the first of these issues, a number of investigations have highlighted the importance of diffuse sources of mining pollution to the overall burden of metals in receiving watercourses (e.g. Gozzard *et al.*, 2011; Mighanetara *et al.*, 2009). Under high flow conditions diffuse sources of mining pollution may contribute as much as 90% of the total metal flux in the receiving watercourse downstream (Gozzard *et al.*, 2011). Such diffuse sources may include surface runoff from exposed waste spoil, direct inputs to streams of polluted groundwater, and metal-contaminated stream bed sediments remobilised during higher flow conditions. It is necessary to quantify the importance of such diffuse sources in order to appreciate the potential benefits of treatment of point sources (which are the obvious candidates for remediation). Doing so is not straightforward, however, as it necessitates synchronous measurement of flow and water quality at multiple locations across a catchment, and across a variety of hydrological conditions. This can be both costly and logistically difficult, since it requires teams of suitably experienced personnel working at sites repeatedly in an effort to understand how the importance of different sources of non-coal mine pollution varies under different hydrological conditions.

There is a general consensus that for abandoned mine water discharges 'passive' treatment is far preferable to 'active' treatment. Passive treatment systems are gravity-fed units that rely on naturally occurring biogeochemical reactions to remove metal contaminants, and therefore no energy or chemicals are routinely involved in the treatment process (albeit both may potentially be required at the end of life of a system when the reactive media requires removal and / or some form of replenishment). Active treatment, by contrast, involves the use of energy or chemicals (or both) to effect treatment. Whilst the capital costs of these two generic types of treatment may in fact be similar, the operational costs of active treatment are far greater. In addition, all but the smallest active systems are typically more visually intrusive which, in the upland locations of many non-coal mine sites around England and Wales, is an important consideration. But passive treatment also presents difficulties. Principal among these are that (a) very few passive treatment technologies have been demonstrated to be effective for the removal of metals such as zinc and cadmium over the long-term, and under field conditions, and / or (b) passive treatment systems require a much larger footprint of land than their active equivalents, which can preclude their installation, especially at upland sites. For both active and passive systems the disposal of metal-rich treatment substrate / waste sludge remains an issue; metal recovery and reuse would be the ideal solution to this problem, but currently such systems are still in developmental stages, and may well require close process control to work effectively (and therefore tend towards the active category of treatment).

The development of a methodology for identification and prioritisation of non-coal mine water discharges was an important first step in addressing the single most important source of metals pollution to freshwaters in England and Wales. However, moving forwards it will be necessary to determine cost-effective and reliable approaches to quantifying the importance of different pollution sources in non-coal mine catchments, and also to develop a wider array of sustainable treatment technologies for these pollution sources.

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