# Mine waste or mine voids: which is the most important long-term source of polluted mine drainage?

Paul L Younger

Professor of Hydrogeochemical Engineering,
School of Civil Engineering and Geosciences,
University of Newcastle NE1 7RU, UK
e-mail: p.l.younger@ncl.ac.uk

## Abstract

In seeking to abate the environmental impacts of mining operations, much attention is focused on improving the management of mine wastes. Mine voids, on the other hand, are rarely discussed. A review of data from a range of mining sites around the world strongly suggests that, in the long-term (i.e. including the post-abandonment phase of the mine life-cycle) mine voids are quantitatively more important than mine waste depositories as sources of polluted mine drainage. Some of the reasons for, and ramifications of, this observation are examined.

## 1. Introduction

The international mining industry acknowledges that the mitigation of impacts associated with acidic and / or metalliferous mine drainage waters are amongst the most significant environmental challenges faced by the industry. Although major steps have been taken by many mining companies to meet this challenge, occasional major incidents serve to underline the difficulty of getting management strategies right all of the time. When things do go wrong, the consequences can be dire, and the pressure from outside the industry for major changes in operational procedures can become very intense. Problems associated with mine wastes have understandably been the focus of much concern internationally in the wake of the now-infamous tailings dam failures at Aznalcóllar (Spain) in 1998 and Baia Mare (Romania) in 2000 (see UNEP, 2000). These are just two of the latest incidents of tailings dam failures which have dogged the mining industry for decades (for further listings, see ICOLD/UNEP 2001, and Younger *et al.*, 2002). However, the location and timing of the Aznalcóllar and Baia Mare incidents ensured that they received major public attention, resulting in the launching of important policy initiatives by major international organisations including UNEP and the European Union (EU) (*inter alia*) to address the management of mine wastes. Whilst neither denying the site-specific impacts of these two incidents nor belittling the generic lessons which may be drawn from them (UNEP, 2000) it is nevertheless prudent to consider whether the current focus of attention on the regulation of mining wastes alone (as distinct from the mined voids themselves) really addresses the key environmental issues associated with mine sites.

One of the key characteristics of the global mining sector from the mid-20th Century onwards has been the dramatic expansion of surface mining, which currently accounts for around 80% of global mineral production. As surface mining necessarily involves wholesale excavation of overburden (in contrast to deep mining, which delves beneath it) it is not surprising that more than 70% of all the material excavated in modern mining operations world-wide is waste, and that more than 99% of all mine waste rock is being generated by surface mines (Younger *et al.*, 2002). The preoccupation of active mining companies with managing such large volumes of waste rock, as well as the tailings produced by mineral processing operations, appears to have fostered the impression (since bolstered by incidents such as those at Aznalcóllar and Baia Mare) that mine wastes are the principal sources of environmental damage associated with mines. For instance, in the recently-completed international initiative on "Mining, Minerals and Sustainable Development" (http://www.iied.org/mmsd), key issues relating to mine voids (such as polluted pit lakes in abandoned surface mine voids and uncontrolled discharges from abandoned underground workings) were relegated to low-priority sub-headings in the technical element of the project entitled "Large Volume Wastes". Similarly, the Swedish national R&D programme on mining and the environment is entitled "Mitigation of Mine Waste Impacts" (MiMi; www.mimi.kiruna.se). Yet how true is it that mine wastes are the defining technical issue for mining environmental management at the start of the 21st Century? And even if mine wastes dominate the agenda for working surface mines, is this still true for the full life-cycle of a mine, including the infinite post-closure phase?

There is a strong *a priori* hydrogeological reason for supposing that mine voids are more likely than mine waste depositories to be the dominant source of large-scale and long-term water management problems associated with mine sites. Because the geometry of orebodies cannot be controlled, whereas the 'footprints' of mine waste depositories are deliberately minimised for economic reasons (i.e. to minimise use of costly land), abandoned mine voids (deep and surface) tend to underlie and / or laterally drain far greater land areas than their corresponding waste depositories. Since the capture of precipitation is directly proportional to surface area, mine voids generally intercept much more natural water than mine waste depositories. This is the key reason for anticipating the predominance of mine voids over mine waste depositories as sources of polluted drainage (at least in volumetric terms).

This paper examines this postulation and related concepts by drawing together observations from a large number of abandoned mine sites. Some of the implications of the findings of this work for the development of truly effective regulation and management of the environmental impacts of mining are then highlighted.

**2. Sources of mine-derived pollutants: waste depositories versus mine voids**Table 1 summarises a number of case studies from around the world which compare the relative volumes of polluted drainage coming from mine waste depositories and mine voids at particular sites. One of the largest-scale studies summarised in Table 1 is the national reconnaissance of mine water pollution in Scotland (Younger, 2001), in which data were collated from all of the mining districts in the country (which are almost all entirely abandoned now). The breakdown of sources of polluted mine drainage given for Scotland in Table 1 illustrates an overwhelming preponderance of flooded mine voids over mine waste depositories as significant sources of polluted drainage. Of course this volumetric breakdown is not the entire story, for waste rock depositories, being generally shallower than mine voids, tend to be far more exposed to the Earth's atmosphere than are the deeper portions of flooded voids, and the sulphide minerals which they contain are therefore more likely to be subjected to oxidation, leading to the release of acidity. This means that mine waste depositories "punch above their weight" in the degree to which they release pollutants: many waste rock pile leachates are acidic, whereas many deep mine discharges revert to being alkaline in the long-term. Thus in terms of the loadings of contaminants released by the two source zones, we obtain the following breakdown for the Scottish example:

- flooded mine voids: 72%
- old tailings deposits / waste rock piles: 28%

Even taking this adjustment into account, the predominance of mine void sources is still beyond question.

**Table 1 - breakdown of water pollution sources between mine waste depositories and mine voids for a range of abandoned mine sites around the world**

| Site (country) | Total discharge rate of polluted drainage | % of total sourced from waste depositories | % of total sourced from mine voids |
|---|---|---|---|
| Hlobane Colliery (South Africa) | 31.5 Ml · $d^{-1}$ | 6 | 94 |
| Milluni Sn-Ag Mine (Bolivia) | 9 Ml·$d^{-1}$ | 2 | 98 |
| National reconnaissance of coal, oil shale and Pb-Zn mines (Scotland) | 204 Ml · $d^{-1}$ | 2 | 98 |
| Upper Silesian Coal Basin (Poland) | 720 Ml·$d^{-1}$ | 0.2 | 99.8 |
| Nenthead Pb-Zn mines (England) | 4 Ml·$d^{-1}$ | 40 | 60 |
| Youngdong Coal Mine (South Korea) | Not recorded | 30 | 70 |
| Deerplay Colliery (England) | 2.7 Ml·$d^{-1}$ | 4 | 96 |
| Cleveland Ironstone Mines (England) | 6.5 Ml·$d^{-1}$ | 4.5 | 95.5 |
| San José  Ag-Sn Mine (Bolivia) | 0.7 Ml·$d^{-1}$ | 5 | 95 |

Note: Data collated from various papers in the volume edited by Younger and Robins (2002), Kim and Chon (2001), other sources cited by Younger *et al.* (2002), studies posted on the PECOMINES web-site (ftp://ftp.ei.jrc.it/pub/PECOMINES), and unpublished data held by the author.

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A similar breakdown could no doubt be prepared for the vast Appalachian coalfields of the eastern USA, where the majority of mines are now also abandoned. Taking only that part of the Appalachian coalfield which falls within Pennsylvania, it is reported by mine water specialists in the US Department of Energy that the largest mine water discharges by far are those which emerge from flooded abandoned deep mines (G. Watzlaf, US DoE, Pittsburgh, *personal communication*, 2002). Major deep mine outflows in that region typically exhibit flow rates falling within a range from around 70 to as much as 250 l·$s^{-1}$, whereas the largest discharges arising from old mine spoil heaps and / or bodies of strip mine backfill rarely exceed 15 l·$s^{-1}$.

Such figures help to inject a sense of proportion into the current international trend to stress the resolution of "mine waste" issues as the key to reducing the impact of mining on the water environment. Viewed in the light of Table 1, it is reasonable to suggest that too narrow a focus on the environmental management of mine waste depositories may actually be misguided.

In seeking to explain why mine voids are often more important volumetric sources of pollution than mine waste depositories, two factors must be clearly understood: the geochemical similarities between mine voids and mine wastes, and the hydrological differences (at least in terms of the scale of their usual catchment areas) between the two. These two factors are explained in the sections which follow.

**3. Geochemical characteristics: mine wastes and mine voids as a *continuum***

While a distinction has necessarily been drawn between mine waste depositories and mine voids in order to illustrate the importance of the latter as a pollutant source, it is important to realise that 'mine wastes' and 'mine voids' actually form a single *continuum* in geochemical terms. Clearly, there are natural geological similarities between waste rock removed from a mine and country rock left behind in the mine voids: a pyritic shale is a pyritic shale, no matter where it currently lies. While mineral beneficiation processes (particularly milling to reduce grain size) may increase the geochemical reactivity of gangue in comparison with its un-mined counterpart, pulverisation of non-productive rocks also occurs within the voids as a consequence of blasting and ripping activities.

It is also important to realise that not all "mine waste" is deposited in spoil heaps or tailings dams: it is common mining practice (and often best environmental practice also) to leave as much of the "mine waste" as possible within the mine voids. This not only avoids the unnecessary costs of hauling non-productive material (thus saving energy and the environmental costs of its generation), but also minimises environmental hazards of airborne pollutant dusts etc. Different mining operations vary markedly from one another in the degree to which they leave waste rock behind in the voids. At one extreme are the typical "strip mines" or opencast bituminous coal mines typical of eastern North America, Europe, and South Africa. In these operations, stripped overburden is immediately tipped behind the advancing working bench in the open pit. Except where the ratio of overburden to coal is in low single figures, the bulking-up of the cast overburden results in complete back-filling of the mine void by the time mining is complete.

At the other extreme are large open pit mines working low-grade ores which carry only modest mantles of overburden. In such mines, only those rocks which are known to be below the present or medium-term future economic grade for the ore in question (which are often the very rocks in which environmentally-problematic minerals such as pyrite naturally predominate) will be left within the void. The same principle applies to many shallow lignite bodies, such as those currently mined in Germany and Poland. However, even where very little shattered overburden is left lying within the voids, the walls of a typical mine comprise fractured exposures of the full range of mined lithologies, the *in situ* weathering of which can give rise to substantial quantities of leachate, which often pollute the pit lakes which accumulate in such voids after the mine is closed (see Younger and Robins, 2002).

Turning to underground mines, the same kinds of principles apply. For even though underground mining typically results in far less handling of overburden than surface mining, the fractured mass of enclosing country rock which remains in and around the worked voids after extraction has taken place is typically indistinguishable in geochemical terms from the 'waste rock' which would have been produced had the same deposit been surface-mined. Given the close genetic links between mine wastes and mine voids, therefore, it is not at all surprising that the mine voids themselves should be significant sources of contamination when subjected to leaching.

The key point is that, as far as mineralogy and potential for pollutant release are concerned, 'mine wastes' and the rocks present in mined voids are geochemically cognate and pose similar environmental problems. While it would be rash to argue for all mine voids to be regulated in the same manner as mine waste depositories, it is important to remember that the two are often geochemically indistinguishable.

All else being equal, therefore, on geochemical grounds one might expect mine wastes and mine voids to be roughly similar in terms of their relative contributions to the total volume of polluted drainage leaving a given mine site. However, as Table 1 makes clear, this is very often not the case, especially in cases where the mine in question has been long abandoned. What explains such a preponderance of polluted mine void drainage over mine waste leachates?

## 4. Hydrological catchment area: key to the volumetric predominance of mine voids as pollutant sources.

In the Introduction to this paper, the geometrical contrasts between mine voids and mine waste depositories were highlighted and invoked to explain corresponding contrasts in hydrology. It is worth considering these contrasts in a little more detail, for they are not all bad news. For instance, the shallowness of mine waste depositories (rarely exceeding a few tens of metres at any one site) and their relatively restricted areal extent (rarely totalling more than a few hundred hectares at most sites) means that they are are relatively amenable to simple remedial interventions, such as clay-capping or the installation of water covers (e.g. Younger *et al.*, 2002).

By contrast, abandoned flooded voids (especially those in underground mines, but also major surface-mine pit lakes):

- often extend to great depth (a few hundred metres in surface mine pit lakes, and hundreds to thousands of metres in underground mines)
- can be vast in areal extent (e.g. interconnected voids are known over areas in excess of 2000 $km^2$ in some of the larger European coalfields)

Besides ensuring that mine voids typically catch far more rainfall, and intercept far more groundwater than mine waste depositories, these vast dimensions effectively preclude the simple capping or submergence strategies which have proven so efficacious for surface deposits of mine waste. Looking on the bright side, however, the very long residence times of waters in such vast systems of mine voids, and the persistence of anoxic conditions at depth (at least after the initial flushing of the flooded voids is complete) serves to maximise the potential for natural attenuation of mine water contaminants. In some case, such natural attenuation is sufficient to render some mine water discharges ecologically innocuous. On the other hand, in cases where such attenuation is insufficient, chronically polluted mine discharges can persist for centuries and even millennia after the cessation of mining. Examples of polluted drainage emerging from mines abandoned as long ago as the Bronze Age (@ 4000 to 5000 years ago) are increasingly being recognised in the Old World, particularly in Spain, Portugal, Greece and the UK.

It is nevertheless true that the worst pollution tends to emanate from the most recently-flooded voids (the “first flush” phenomenon; Younger *et al.*, 2002), an observation which has significant implications for the long-term management of mine water pollution.

## 5. Quantifying the problem - inventories and impact assessment

It is axiomatic that the effective of cure of any particular ailment is best sought after an accurate diagnosis of the problem has been made. Hence, when attempting to quantify and prescribe solutions for problems of polluted mine drainage, it is important to establish (with as much certainty as possible) the origins of a particular source of contaminated water. For instance, if it proves to be a shallow-sourced leachate from a waste rock pile, then (as outlined above) this is likely to be significantly easier to remediate at source than if it were found to be drainage from flooded deep mine voids. Notwithstanding the value of such a distinction, discrimination between waste-sourced and void-sourced leachates can be extraordinarily difficult at many abandoned mine sites, in which original mine access features are often buried beneath piles of mine waste. The unequivocal identification of a given source of mine water at such sites is best undertaken by a specialist, who will bring to bear on the problem heuristic knowledge of a wide range of disciplines (including geology, geomorphology, hydrogeology, hydrogeochemistry, plant biology, mining engineering and industrial archaeology).

There is as yet no world-wide compendium of the damage caused to surface waters by abandoned mine discharges; no such compendium yet exists even for a highly-developed continent, such as Europe. The most comprehensive national dataset currently available is that for the UK, which indicates that some 400km of watercourse are currently degraded by abandoned coal mine discharges, with a further 200km or so similarly contaminated by abandoned metal mine discharges. (Within these UK totals, well over 90% of the total polluted drainage turned out to be accounted for by discharges from polluted mine voids rather than from old mine waste depositories). By extrapolation from these findings, weighted by the distribution of coalfields and orefields in mainland Europe, it is likely that the equivalent figures for the current fifteen EU Member States will eventually prove to be on the order of 2,000 to 3,000 km of watercourses polluted by coal mine drainage, and 1,000 to 1,500 km polluted by metal mine discharges. This suggests that the total length of watercourses polluted by mine drainage in the present EU may well prove to exceed 5,000 km. When the large mining active and historical industries of many Newly-Associated States (NAS) and prospective candidate member states are taken into account, the total for the future, enlarged EU is likely to be substantially greater than this.

It is instructive to consider what the costs of establishing the facts at the continental scale may prove to be.  For the identification and impact assessment of all of the major sources of polluted mine site drainage in the UK, approximately €1.4M were spent over a period of about three years.  A figure of around €1.2M has recently been reported for a similar national survey in Portugal.  To judge from these figures, the total bill for establishing the nature and extent of the environmental legacy of historic mining in the other thirteen EU Member States is unlikely to be much less than €12M; including the NAS and future candidate member states, the total bill may well be twice this figure.

Inventorisation techniques for problematic mine sites have been a matter of some debate of late.  There are two schools of thought as to how best such inventories should be assembled:

(i) to inventorise all historic and current mining sites

(ii) to assess impacted watercourses in present and former mining districts and identify the major sources of polluted drainage

Recent experiences in the UK strongly favour the latter approach, for the simple reason that very few old mine sites actually give rise to polluted drainage.  For instance, in the Durham Coalfield of North-East England, there are more than 20,000 recorded mine entrances, yet only about 50 of these have been found to actually give rise to polluted discharges in the post-closure period.  Hence an impact-led approach to inventorisation can be expected to be far more cost-effective than a comprehensive survey of all known mining sites.  This is not to pretend that existing impact assessment methods for mine waters are flawless (e.g. Kuma *et al.*, 2002).  In particular, there is a clear need to take socio-economic factors into account, such as poverty issues associated with environmental degradation in the vicinity of settlements which have already been badly affected by mining and unemployment after the cessation of mining. However, none of the shortcomings from which current assessment techniques suffer are insurmountable.

Having constructed an inventory for each Member State, whatever this has cost will prove modest in comparison with the total costs of remediation. For instance, the UK government's rolling programme of mine water remediation currently spends in excess of €1.5M per annum on the construction of new remediation schemes, and a similar sum on the annual maintenance of all previously-constructed remediation systems. While the figures may at first reading appear daunting, they must be viewed in perspective, for they are vanishingly small in comparison to the wealth historically generated from the corresponding mining at these sites, wealth which continues to circulate in national economies many centuries after it was first released from the geosphere.

## 6. Towards rational regulation and management

This paper has argued that substantial improvements in the long-term environmental performance of the mining sector are unlikely to be realised if the focus of new regulatory activity is solely on mine waste depositories. Unless mine voids are adequately catered for when managing the social and ecological impacts of mine sites (both active and abandoned), the overall gains in sectoral environmental performance will be relatively marginal.

The current EU initiative (draft directive) to improve the management of waste from the extractive industry offers the best opportunity to date to directly promote best environmental practice in the European mining and quarrying sectors. However, reducing the focus of attention to waste rock piles and tailings dams would mean missing the main culprit of long-term (post-abandonment) pollution, i.e. contaminated drainage from flooded mine voids. While it would be imprudent to attempt to manage all abandoned mine voids as if they were deliberately-constructed waste repositories, there is no scientific case for drawing a hard and fast distinction between 'mine wastes' and the geochemically identical materials which give rise to pollution of water flowing through old mine voids. In practical terms, however, it is clear that a distinction is desirable. Possibly the best approach to ensure adequate regulation of both mine wastes and mine voids is to ensure that any future directive concerning the management of wastes from the extractive industry be constructed such that it provides a direct link between the management of mine wastes *per se* and the management of polluted drainage from mine voids. Polluted drainage is logically best regulated within the context of the recently-enacted Water Framework Directive (WFD) (2000/60/EC). However, the technical management of mine voids is undertaken by the same organisations which manage mine wastes, and (as has already been emphasised) mine wastes and mine voids form part of a geochemical *continuum*. There is therefore a strong case for ensuring that the emerging regulatory framework for mine wastes be definitively linked to the river basin management activities which are the domain of the Water Framework Directive. Exploring the links between these two domains of regulatory responsibility is one of the key tasks of the current European Commission 5th Framework R&D project ERMITE ('Environmental Regulation of Mine Waters in the EU'; see [www.minewater.net/ermite](http://www.minewater.net/ermite)).

Preliminary findings of the ERMITE project provide pointers to what form legislative links between the WFD and the emerging mining waste regulations might take. Recognising that existing water pollution control legislation largely covers potential problems of pollution from active mine sites, it is evident that the key requirement is to make sure abandoned mine sites are adequately regulated. While the proposed directive on management of wastes from the extractive industry ought to ensure (as far as is ever possible) the adequate restoration and after-care of waste rock piles and tailings dams, the problem of pollution from the mine voids themselves is arguably poorly-regulated at present. This is in part due to the failure of the relevant authorities to grasp that large systems of inter-connected mine voids frequently take many years to flood up to surface decant levels, in many cases giving rise to polluting discharges long after the former mine site has been otherwise restored. By then, the original operator may be long gone, the original mining company in liquidation and the responsible individuals inaccessible for various reasons (some more sombre than others). When implementation of the Water Framework Directive then fails at such sites, it will be precisely because of a breakdown in communication (i.e. transmission of crucial information) greatly exacerbated by the passage of time. It is therefore suggested that the most prudent approach to this problem is to frame any future directive on the management of wastes in the extractive industry such that it places an obligation on mine operators such that <u>prior to the closure of the mine</u> they pass certain minimal information to those authorities which are responsible for implementing the Water Framework Directive.

A suitable legislative model for such an obligation already exists in the form of the UK "Mines (Notice of Abandonment) Regulations 1998". Drawing upon that precedent, the following phraseology is suggested for national legislation:

> Not less than 6 months (and not more than two years) before final closure of a mine, the mine operator shall provide the competent authority responsible for the management of river basins with the following information:

- The layout of the mine workings which are to be allowed to flood after mining ceases, including a geological overview (with particular reference to the presence of any sulphide minerals and buffering minerals such as calcite)
- The quantity and quality of water encountered in mine during working (over at least the last two years prior to the date of the report)
- Predictions of the locations, quantities and impacts of any future polluting discharges to groundwaters and /or surface waters (including marine waters) and plans for mitigation of any negative impacts
- Proposals for monitoring the process of flooding of the mine voids, to provide early warning of the need to instigate mitigation measures

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