Deep mine hydrogeology after closure: insights from the UK

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Abstract. Although the UK has had an extremely rich history of deep mining, at the start of the 21st Century most mines are already abandoned and in various stages of flooding. Lessons of generic value have been obtained in the UK over the last decade, particularly in relation to the reactivation of mine subsidence processes during flooding of old workings, and the generation and release of polluted drainage. As researchers and practitioners have attempted to characterise and (in some cases) predictively model such processes, new analytical techniques have been developed. These range from simple 'rules of thumb' for pollution intensity prediction to sophisticated 3-D models of flow through networks of mine roadways routed through variably-saturated porous media.

‘A Tainted Legacy’

The former prodigious productivity of the UK's deep mining industry not only fuelled the industrial revolution, yielding riches which continue to circulate in global financial markets, but also left a significant heritage of historical mine sites. For instance, it is nowadays possible for tourists in the UK to marvel in safety in ancient underground mine voids dating from the Neolithic Age and the Bronze Age, as well as in several well-preserved examples of modern deep coal mines. However, less attractive legacies of millennia of deep mining have become all too apparent as most major UK coalfields (and all but a few mines working for industrial minerals and metals) have finally closed over the last decade. Once mines are abandoned and dewatering systems are withdrawn, the workings flood, in many cases giving rise to a range of environmental problems. Most prominent among these problems is the generation and release of polluted drainage, but hazards due to renewed mine subsidence and / or accelerated emissions of dangerous mine gases (i.e. explosive or asphyxiative) are also locally exacerbated by the process of deep mine flooding. Political decisions in the early 1990s have resulted in the UK abandoning entire coalfields long before this has taken place in most other European countries. For this reason alone, mining and environmental professionals in the UK have learned a number of lessons over the last decade which may well be applicable to many other deep mine settings elsewhere in the world. This paper aims to summarise some of these lessons for the benefit of the wider international mine water management community. As such, this paper emphasises recent UK literature, but it should be noted that references to the wider international literature can be found in the works cited here.

Hydrogeological lessons from UK deep mine closures

Some of the key lessons learned from the experiences of coalfield / mine closure in the UK in the decade 1992 - 2002 have concerned the following topics:

- reactivation / exacerbation of land subsidence by processes associated with flooding of strata and old workings by rising mine waters
- the mineralogical and geochemical aspects of water quality deterioration during the flooding of mine voids
- the functional relationship between the duration of mine flooding and the temporal changes in pollutant loadings after decant of the flooded workings to the surface and / or adjoining aquifers
- scale-appropriate modelling of mine water 'rebound' processes (i.e. flooding of extensive networks of underground voids)

We will now consider each of these in more detail, each of them in turn in the sections which follow.

Rising mine waters and reactivation of subsidence

The prediction, control and (where necessary) mitigation of the effects of surface subsidence due to deep mining has now reached the level of a fine art in many advanced mining countries. In the UK, the pinnacle of achievement in developing a predictive capacity for mining subsidence was attained in 1975, with the publication of the second edition of the national "Subsidence Engineers' Handbook" (SEH) a compendious practical manual which has never been superseded (NCB 1975). The SEH was developed from an enormous database of observed subsidence and associated strain measurements, and it remains extremely useful and generally reliable for predicting both surface subsidence (especially that due to longwall mining) and the subsurface strains associated with the process of settlement above caving workings in Carboniferous coal-bearing strata. The ability to predict maximum tensile strain at a specified stratigraphic position above active longwall workings is particularly useful in the design of safe undersea and subaquifer workings (e.g. Orchard 1975; Dumpleton 2002). One of the principal drivers behind the development of the SEH was the need for officers of the nationalised coal industry to be able to fairly adjudicate legal claims for damage due to mining subsidence which were continuously received from surface property owners in coalfield areas. From the database which underpins the SEH, it is clear that all significant surface movements caused by the goafing of a given longwall panel occur within a few years (usually 2 - 3, rarely as long as 5) after the completion of panel extraction. Indeed, this observation came to be enshrined in the legal codes governing subsidence compensation arrangements.

Given this background, subsidence engineers can be forgiven for concluding that once the collieries they used to work in had been closed for a few years, they would at least be spared from adjudicating further claims for compensation for subsidence. After all, flooded workings benefit from the additional buoyant support offered by the water they contain, which helps to minimise long-term settlement of voids. However, before mines flood to equilibrium levels, certain processes which occur while water levels are still rising can temporarily exacerbate subsidence. Significant subsidence damage and associated geomorphological changes have recently been recorded in various UK coalfields subject to ongoing rebound, giving rise to compensation claims which the present custodians of the historic liabilities of the coal industry (i.e. the subsidence section of the governmental Coal Authority) did not expect to be receiving. From the scattered evidence gathered to date, it would appear that there are at least three mechanisms by which mine water rebound can reactivate surface subsidence:

(i) the weakening of the floors (and to a lesser extent the roofs) of mine voids by the reaction of certain types of strata to sudden submergence, and

(ii) direct erosion of mine voids, shaft caps and adit plugs etc by the pressure and kinetic energy of rapidly-flowing mine water

(iii) reactivation of previously-dormant faults which are intersected by old mine workings subject to recent flooding for the first time.

Moisture weakening void roof and / or floor strata

It is a common characteristic of many coal-bearing sequences that the workable coal seams are immediately underlain by soft, relatively plastic mudstone horizons often termed "seat-earths" (Murchison and Westoll 1968). These seat-earths are essentially buried soils, which often contain the fossilised rootlets of the swamp vegetation which flourished in the coal-forming swamps. When dry, these seat-earths can retain sufficient strength for most mining purposes (e.g. support for pillars of intact coal, and firm bedding for mine infrastructure, such as conveyor lines, rails etc). However, when they are wetted by the impingement of mine waters following the cessation of dewatering after mine closure, seat-earths can lose much of their strength. No longer able to bear the stresses passed on to them by loaded support pillars, the seat-earths can deform rapidly, leading to pillar collapse and surface subsidence (e.g. Smith and Colls 1996), often in the form of crown holes. In some cases, crown holes of this type can intersect surface water bodies, leading to a dramatic increase in water ingress to the flooding workings below.

Such an example occurred in November 2000 adjacent to Newcastle International Airport, when a large collapse crater developed above actively-flooding workings led to drainage of an entire pond of surface flood waters (estimated volume ~ 5 Ml) draining into the underground voids in the space of a few hours.

A class of subsidence features which are more subtle in appearance than crown holes, but which affect far larger surface areas (up to several km^2), are thought to be associated with flooding of abandoned longwall panels in some areas, notably in eastern Northumberland (Jackson N., pers. comm. 2001). The formation of these large-scale reactivated subsidence troughs presumably involves a combination of mechanisms, such as rib pillar failure and / or weakening of shaley clasts in goaf by wetting, leading to greater settlement under the same imposed load as the clasts deform and porosity is reduced. This latter mechanism is well known from recently-flooded opencast backfill (see Younger *et al.* 2002), which is geotechnically very similar to longwall goaf. At the time of writing, the characterisation of these large-scale subsidence troughs is under investigation.

Finally, it should be noted that flooding of deep coal mine strata can in some cases lead to 'upsidence' (i.e. raising of the ground surface), presumably due to wetting of expansive clays in the sequence. Although this process has been documented from the Netherlands (Bekendam and Pottgens 1995), but has not yet been reported in the UK.

Direct erosion by pressure / kinetic energy of flowing mine water

Where mine water is free to flow through open voids, especially above the water table, it can erode the walls and floor of the voids sufficiently that collapse occurs. In recent years, such erosive behaviour has been the cause of several major UK mine water discharges spontaneously shifting their points of surface emergence. Table 1 summarises some of these cases, highlighting incidents in which this process led to bypassing of mine water treatment facilities, flooding of residential areas / public roads and other nuisances.

Where rising mine water is impounded behind piles of roof-fall debris and / or engineered stoppings (e.g. shaft caps or adit portal plugs, which are generally installed for public safety reasons when the mine is abandoned) hydraulic head can build up to such an extent that the strength of the impounding feature (or of its interface with the surrounding strata) is overwhelmed, resulting in a sudden outburst of mine water. An infamous example of this genre led to the major outburst of ochreous water from the Wheal Jane mine in Cornwall in January 1992 (see Younger and LaPierre 2000). A variant of this process occurred in June 2000 at the former Low Lands Colliery, Co Durham (UK). The brick-lined shaft at this site had been capped with a 0.3m concrete slab when the shaft was abandoned in the 1960s. Exceptionally high heads were recorded throughout the local coalfield area in early 2000, following the record wet winter of 1999-2000. Not only did the outburst at this site destroy the shaft cap, but the water which emerged from the shaft was so rich in ferrous iron that the entire downstream course of the adjoining river was stained with ochre as the Fe^{2+} oxidised in the channel. Shaft-cap destruction by pressurised mine water has occurred more than once in this district: in

1979, a factory in the nearby town of St Helen Auckland had to be demolished after pressurised mine water destroyed a shaft cap which was present in the foundations of the building (Younger *in press*).

Table 1. Summary of some recent cases of erosion of mine voids by flowing water in abandoned UK deep mines, and some consequences of this phenomenon.

Site ***(MINE TYPE)***	**Year**	**Event**	**Consequences**	**Source**
Randolph Pit (Fife, Scotland) **(*COAL*)**	1985	Decant of deep mine water to adjoining Michael Colliery by erosion of pathway through goaf	Large increases in water make and turbidity at Michael Colliery	Younger and LaPierre (2000)
Gripps Level (Leadhills, Scotland) **(*LEAD*)**	1991	Adit roof collapse due to erosion by water led to impoundment of a large volume of mine water	Tension cracks formed on hillside and began to discharge water, threatening village below with severe flooding.	Schmolke (1998)
Nangiles Adit, Wheal Jane (Cornwall, England) **(*TIN / ZINC*)**	1992	Unanticipated accumulation of ~ 50 Ml of acidic water behind a pile of roof-fall debris, which suddenly gave way, releasing water.	Spectacular outburst of acid water caused major ochreous plume in Fal Estuary, causing public outcry which led to major treatment scheme.	Younger and LaPierre (2000) and references therein
Spittal (Berwick, England) **(*COAL*)**	1998	Erosion of adit blockage by impounded water	Flooding of 19 houses and a hotel with ochreous water	Younger (2001a)
Gwenffrwd (South Wales) **(*COAL*)**	1999	Erosion of roof-fall impoundment in lower adit led to down-draining of water hitherto decanting via upper adit.	New emergence point was distant from existing RAPS-based treatment plant; local river became polluted once more	Younger and LaPierre (2000)
Tailrace Level (Co Durham) **(*FLUORITE*)**	2002	Erosion of adit by mine water leads to collapse, impounding mine water which then decants at a new point 250m upstream of the existing treatment plant site	Increased the length of the Rookhope Burn which is polluted and made long-term treatment more difficult to implement.	J Teall, Environment Agency (pers. comm.)
Sheephouse (West Yorks) **(*COAL*)**	2002	Erosion of adit by water led to relocation of mine water discharge	Temporary flooding of the main Sheffield - Manchester road with ochreous water: messy and a hazard to traffic	A. England, IMC Ltd (pers. comm.)

Fault reactivation

Faults play an ambiguous role in mining hydrogeology (Younger and Adams 1999), functioning variously as conduits for, or barriers to, groundwater flow. Which role a given fault will play depends on local geological conditions and the state of the fault plane itself (e.g. is it clean, or filled with fault-gouge). In major UK coalfields, the largest faults (which have throws of as much as 200m) displace the strata to such an extent that mine workings were usually discontinued on either side of them. After mine abandonment, these large faults tend to function as barriers to mine water flow (Younger 1998). On the other hand, some of the lesser faults (i.e. those with throws of up to a few tens of metres) caused significant nuisance in some sub-aquifer workings, as they reduced the effective cover to water-bearing rocks, thus allowing ordinary longwall faces to induce extraordinarily voluminous feeders (Saul 1970). The interaction of mine water and fault planes appears not to be limited to the period of longwall extraction. For instance, since the abandonment of the last deep coastal collieries of County Durham (northern England) in 1994, faults which had previously been utterly dormant have begun to move again (Young and Culshaw 2001). The displacements, though relatively modest and almost aseismic in comparison with fault movements in the world's tectonically active regions, are sufficient to cause severe damage to buildings, and cracking of public road surfaces. The timing of the renewed fault movement appears to coincide with the flooding of horizons of extensive abandoned coal workings which penetrate the faults. Similar examples of fault reactivation coinciding with flooding of deep workings are also recorded from the coalfields of the English Midlands and South Wales (Donnelly 2000).

Deterioration of water quality during mine flooding

By far the most widespread and environmentally damaging consequence of deep mine abandonment is the generation and surface discharge of poor quality mine water. Being the major problem associated with mine abandonment, it has also received the greatest coverage in print, and will therefore be dealt with only briefly here, by outlining the significant advances in the understanding and characterisation of the problem which have emerged in the UK in recent years.

Dissolution of 'acid-generating salts'

Most classic descriptions of the phenomenon of 'acid mine drainage' focus on the direct oxidation of pyrite to form dissolved iron, sulphate and proton acidity, typically described by a summary reaction such as:

$$FeS_2 + \frac{7}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad [1]$$

While this may be an adequate model for surface mines or waste rock piles in which frequent rainfall washes most surfaces, it is not very appropriate for working deep mines. In a deep mine, the water make normally enters via a few major feeders, and is led by a limited number of drainage pathways to dewatering sumps. Thus most of the mine is not in contact with flowing water, albeit limited moisture is ubiquitous in the form of the humidity of the mine atmosphere. Under these conditions, pyrite oxidation does not proceed all the way to dissolved products in one reaction sequence, but rather results in the pyrite being replaced by secondary minerals. This occurs by reactions such as:

$$3\,FeS_2 + 11\,O_2 + 16\,H_2O \rightarrow Fe^{(2+)}Fe_2^{(3+)}(SO_4)_4.14\,H_2O + 2\,SO_4^{2-} + 4\,H^+ \quad [2]$$

in which pyrite (FeS_2) is weathered to form a ferrous-ferric hydroxysulphate mineral, in this case römerite. Römerite is only one of a number of similar minerals formed by wetathering of pyrite in water-sparse environemnts; other such minerals include melanterite, coquimbite, szomolnokite, copiapite, aluminocopiapite and various types of jarosite (Bayless and Olyphant 1993). Besides the acidic metals these minerals contain, they also tend to sorb protons (such as the four H^+ ions shown on the RHS of the preceding reaction). These minerals have been collectively termed "acid generating salts" (AGS) (see Bayless and Olyphant 1993; Younger *et al.* 2002). AGS tend to form conspicuous white / yellow efflorescent crusts on pyritic beds within mines. When the beds hosting these efflorescent crusts are finally flooded after mine closure, the AGS dissolve congruently and (with the possible exception of jarosite; Saaltink *et al.* 2002) extremely rapidly. In doing so, they impart to the water a low pH (typically around 2.5) and extremely high dissolved concentrations of problematic metals (Fe, Al, Zn, Cu, Cd etc). It should be noted that acidic pH values can even develop where the orebody is limestone-hosted, so fast are the dissolution kinetics of the AGS compared to that of calcite (e.g. Johnson and Younger 2002). Younger (1998) termed this abrupt deterioration in mine water quality a 'geochemical trauma', and since it has often caught unsuspecting mine owners off their guard, it can lead in turn to a management trauma. In essence, therefore, the formation of AGS during the working of a deep mine results in large-scale storage of soluble acidity in the unsaturated zone, but this acidity is rapidly released to solution upon flooding of the mine voids after dewatering ceases.

'Stone dust' and other emollients

Fortunately AGS are not the only minerals contributing to the solute loadings of waters rising through abandoned mine workings. Other minerals with relatively rapid dissolution kinetics serve to counteract the acidification of mine water. Most notable is calcite, but dolomite can also be important locally. However, neither of these two minerals are particularly abundant in UK Carboniferous coal-bearing sequences. Far more common in that geological setting are various iron-rich carbonate minerals, such as siderite ($FeCO_3$) and ankerite (ferroan dolomite). While these will locally react with acidic waters to neutralise them, the beneficial impact on pH persists only as long as the water remains anoxic, for upon aeration the dissolved ferrous iron imparted by these minerals is rapidly oxidised to the ferric form, each mole of which will hydrolyse to release three moles of proton acidity. For this reason, the iron carbonate minerals have no net neutralisation potential (see Younger *et al.* 2002, for further discussion / literature review).

In terms of naturally-present carbonate minerals, therefore, the UK Coal Measures are relatively poor in carbonate-based neutralisation potential. However, an ubiquitous mine-safety practice inadvertently serves to counteract this paucity of natural carbonates: in order to minimise the risk of coal powder explosions, mining regulations in the UK (as in many other countries) require the liberal spreading of finely-comminuted limestone powder in all major roadways. This limestone powder (referred to as 'stone dust' in the industry) is so fine-grained as to be somewhat hydrophobic, but once suspended in the water column its fine-grained nature ensures it is highly chemically reactive, serving to rapidly neutralise dissolved acidity. The dissolution of stone dust was inferred by Wood *et al.* (1999) to explain the coincidence of peak Fe, SO_4, Ca and HCO_3^- concentrations during the 'first flush' period of several abandoned underground mines in Scotland.

Even where stone dust was never used (as in metal mines) or where it has been totally dissolved, neutralisation reactions clearly continue to influence mine water quality (e.g. Banwart and Malmström 2001), even in the absence of *any* naturally-occurring carbonate minerals (e.g. Strömberg and Banwart 1994). It is now clear that such neutralisation reflects the incongruent dissolution of aluminosilicate minerals, which have very sluggish dissolution kinetics when compared with carbonates (Banwart *et al.* 2002). Aluminosilicate minerals are, of course, abundantly present in virtually all mine water settings, and they can serve to significantly affect the proton balance of a given water provided this has sufficient hydraulic residence time in the strata (e.g. Younger *et al.* 2002). Issues of 'hydraulic residence time' are only one manifestation of an important (but frequently overlooked) facet of the geochemical evolution of mine waters: the mediating role of hydrological processes, which control both the availability of key reactants and the transport of dissolved products from the reaction sites. The following section considers recent findings on this topic in a little more detail.

The longevity of mine water pollution

It has been recognised since at least the 1970s (Cairney and Frost 1975) that the deterioration in mine water quality which occurs during the flooding of previously dry workings is a temporary phenomenon, so that water quality gradually improves again once a steady outflow from the workings (by natural decant or pumping) is re-established. The fact that mine water quality is subject to natural amelioration processes over time has considerable engineering significance, for it provides a conceptual framework within which holistic, long-term remedial strategies for polluted waters can be developed and sustained (e.g. Younger 1997, 2001). For this reason, various UK authors have studied this phenomenon in some detail, most notably Frost (1979), Glover (1983) and Younger (1997, 1998, 2000a). The current state-of-the-art in predicting the duration of various episodes of contamination in a given mine water discharge is set out in detail by Younger (2000a), and is thus only summarised below.

The peak concentrations of contaminants in water flowing from a flooded deep mine typically occur shortly after the time at which water first begins to decant from the workings. Thereafter, the contaminant concentrations tend to decline exponentially (Fig. 1) during a period of water quality improvement which Younger (1997) termed "the first flush". After completion of the first flush, a long-term asymptotic water quality is established which represents the dynamic balance between ongoing pollutant release (e.g. by seasonal formation and dissolution of AGS within the zone of water table fluctuation) and pollutant attenuation (dissolution of carbonates, aluminosilicates etc). Of key interest to design engineers are the following aspects of this time-variant behaviour:

- the peak contaminant concentration
- the duration of the first flush
- the long-term 'asymptotic' contaminant concentration

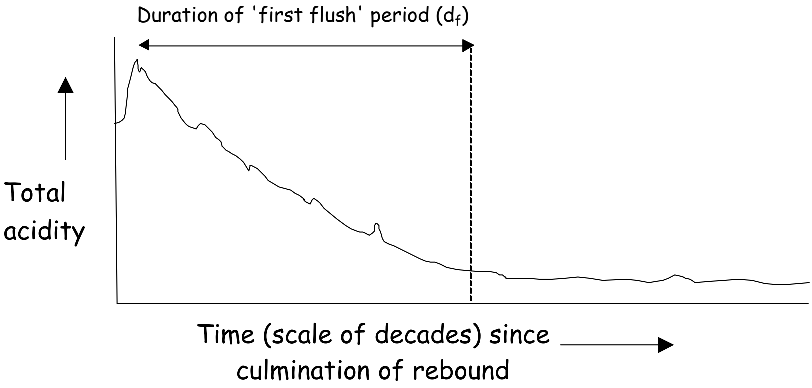

Fig. 1. Typical exponential decline in contaminant concentrations observed over time after water begins to discharge from newly-flooded deep mine workings.

Peak contaminant concentrations

Scrutiny of all readily-available records from UK mines has supported the development of predictive criteria relating peak contaminant concentrations (especially Fe concentrations) to the pyrite content of the strata. Where direct assays of pyrite content are not available (as is often the case), the more widely-available data for total sulphur content can be used instead. On this basis, the following broad classes of peak iron concentration are estimated (Table 2):

Table 2. Estimating peak Fe concentrations in water flowing from newly-flooded deep mines as a function of the total sulphur content of the mined horizons.

Total sulphur content (wt %)	**Typical observed range of values for peak Fe concentration (mg/l)**
< 1	0.01 - 0.5
1 - 2	0.5 - 100
2 - 3	100 - 350
3 - 4	350 - 1200
4 - 5	1200 - 1500

In many cases, a multiple-seam sequence will have been worked in which each seam has a different mean sulphur content. Predictive use of Table 2 for such cases demands the calculation of a weighted average total sulphur content, for which the weights are provided by the relative extent of workings in each of the seams.

Where no total sulphur data are available at all, the only recourse is to estimate likely pollutant generation potential on geological grounds (Younger 2000a, 2001), such as proximity of the mined bed to a 'marine band' (i.e. a bed which clearly underwent deposition / diagenesis by marine waters, and which is therefore likely to contain reduced inorganic sulphur compounds such as pyrite).

Duration of the 'first flush'

The first flush phenomenon is essentially a process of displacement of the initial flooded volume of mined ground by less-contaminated water which recharged the mined ground after completion of rebound. As such, the duration of the first flush is principally a function of the void volume of the flooded mined system and the rate of recharge. While it is possible to estimate the void volume of the flooded mined system from mine survey records, considerable uncertainties are associated with such estimates for at least two reasons:

(i) the volume of voids includes not only those represented by open mine voids, but also those for areas of 'goaf' (collapsed roof strata), for which direct measurement is usually impractical, and reliable estimation techniques are few (e.g. Rogoż 1994)

(ii) There is usually insufficient information available to allow accurate estimation of the volume of unmined strata around the mine voids which have been dewatered by mine drainage (e.g. Adams and Younger 2002).

If the volume of voids is difficult to estimate accurately, the situation is even worse in relation to recharge rate, which is notoriously difficult to characterise in virtually all hydrogeological systems (Lerner *et al.* 1990).

Fortunately the very process of mine water rebound sheds some light on the magnitude of both parameters, for rebound rate is also a function of void volume and recharge rate. Logically, therefore, a functional relationship ought to exist between the duration of the first flush period (d_f - see Fig. 1) and the time which it took for the mine to flood completely following the cessation of pumping (d_r). From analysis of available records for UK deep mines, Younger (2000a) found that:

$$d_f \approx 4 \cdot d_r \qquad [3]$$

Beyond the first flush: long term prognoses

Once the limit time d_f has finally been exceeded, an 'asymptotic water quality' will persist until exhaustion of the various pollutant source / sink minerals in the zones of ongoing oxidation. To a first approximation (Younger 2000a), it is normally found that the asymptotic concentrations of key solutes after the first flush are typically an eighth to a tenth of the initial peak concentrations (e.g. divide the Fe concentrations in Table 2 by some factor in the range 8 - 10). However, as reliable data upon which this approximation is based available relate only to time-scales of up to 100 years after mine abandonment (e.g. Wood *et al.* 1999), it is not possible to extend predictions to the long term in this simple manner without site-specific geochemical assessments. For instance, where sulphides are likely to be depleted before carbonates, for instance, alkaline conditions will persist in the long term. However, where the carbonates are likely to be depleted before the sulphides, re-acidification of mine waters may eventually occur. (Examples of the latter phenomenon are now beginning to emerge at certain sites in northern Europe; e.g. Younger 2000b; Strömberg and Banwart 1994). Where accurate site-specific data exist for discharge flow rates and chemistry, and for the mineralogical composition of the mined strata, it is possible to use mass-balance based geochemical modelling techniques to obtain more credible estimates of the rates of depletion of the key minerals, and therefore to calculate the likely duration of a given level of acidity (e.g. Banwart and Malmström 2001; Banwart *et al.* 2002).

A key point to bear in mind in such exercises is that, in flooded mines, sulphide oxidation is effectively limited to the unsaturated and seasonally-saturated zones only, and simply cannot occur at any great depth below the water table. On the other hand, dissolution of buffering carbonate and aluminosilicate minerals can occur both above and below the water table. Hence a simple mineralogical balance of sulphides versus carbonates (such as is yielded by conventional 'acid-base accounting' techniques) does <u>not</u> tell use whether a system will stay alkaline or eventually become acidic; rather, such data must be interpreted within a holistic framework which takes present and future hydrogeological conditions into account (e.g. Hattingh *et al.* 2002; Younger *et al.* 2002).

Rebound modelling

For effective planning of remedial interventions to intercept polluted mine waters before they cause damage to the surface environment, it is necessary to be able to predict d_r (equation [3]). A number of techniques have been derived for this purpose, which have been extensively reviewed by Younger and Adams (1999). Of the various predictive methods developed to date, two categories have been found to be particularly useful. These are briefly described below. Whichever modelling technique is eventually selected for a particular application, parameterisation of the models is a major undertaking for all but the simplest of mined systems (Sherwood 1997; Adams and Younger 2001, 2002). To assist the process, the use of 3-D visualisation software has recently been shown to provide a cost-effective means for manipulating the vast quantities of spatially-distributed data upon which conceptual hydrogeological modelling of large systems of inter-connected mine workings must be based (Dumpleton *et al.* 2001).

Semi-distributed lumped-parameter models

Also known as 'pond models' (e.g. Younger and Sherwood 1993; Sherwood 1997; Younger and Adams 1999; Banks 2001; Whitworth 2002) and 'box models' (e.g. Rogoż 1994; Gatzweiler *et al.* 1997), these models reduce the complexity of both mined void volumes and recharge processes by 'lumping together' large volumes of extensively-interconnected mine voids as single hydrological units ("ponds"). While such models can be implemented using purpose-written codes (e.g. the GRAM model; Younger and Sherwood 1993; Sherwood 1997) they are often sufficiently simple that they can be implemented within a spreadsheet environment (e.g. Banks 2001; Whitworth 2002). Within any one pond, the water table will be virtually flat, and water can migrate between neighbouring ponds only via a limited number of 'decant features' (such as old mine roadways, and / or areas of coalesced goaf; see Sherwood 1997 for real examples of such features). In practice, the identification of decant features can be greatly aided by means of appropriately-designed mine water tracing experiments (for guidance, see Wolkersdorfer 2002).

In applying semi-distributed 'pond' models to real systems, it is important to determine whether the rate of water inflow to the flooding working during rebound will be independent of, or dependent upon, the current hydraulic head within the workings (Younger and Adams 1999). In some cases, inflows during rebound have proven to be head-independent, and the models which assume a constant recharge rate to the workings (e.g. the GRAM code; Younger and Sherwood 1993; Sherwood 1997) have been successfully applied (Younger and Adams 1999; Burke and Younger 2000). In other cases, much of the inflow to the mine voids proves to be head-dependent, so that a modified version of the GRAM algorithm must be used, such as that described by Banks (2001) and applied to an abandoned base-metal mine in Bolivia by Banks *et al.* (2002).

In general, pond-based rebound models are best applied to relatively large-scale mine systems (e.g. underlying areas of hundreds to thousands of km^2). The principal applications of the GRAM model to date have been for systems of several hundred to more than 2000 km^2 in aerial extent. Where a smaller system of voids must be analysed in greater detail, it is probably best to use the more physically-realistic models described in the following section.

Physically-based, distributed models

In the most generic conceptualisation, deep mines undergoing flooding are most reasonably regarded as systems of conduits (representing mine roadway networks / stopes, in which flow may well be turbulent) routed through heterogeneous, variably-saturated porous media (representing the enclosing rockmass, both intact strata and rocks which have fractured in response to mining of voids nearby). Models based on this type of conceptualisation are best based on orthodox physical equations, and demand spatial discretisation and distribution of parameter values. For this reason, they are termed "physically-based, distributed models", and they are invariably solved using numerical methods such as finite differences (in distinction to the largely analytical methods used to solve 'pond' models).

There are a number of ways in which a physically-based model suitable for mined voids may be represented mathematically. For instance, a multiple-fracture system based on Navier-Stokes theory is one option. In many natural aquifers, in which the “conduits” are irregular, planar fractures, this approach is probably most appropriate. In most mined systems, however, the major conduits are tube-like roadways which are better represented as pipes rather than planar fractures (Younger and Adams 1999). A number of different representations of turbulent flow in a pipe network are commonly used in practice (e.g. the Darcy-Weisbach formula and the Hazen-Williams formula). Detailed analyses of the performance of the most well-used formulae for the range of hydraulic conditions likely to be encountered in most mine water rebound problems found no great difference in the results produced between one formula and another (Sherwood 1997; Younger and Adams 1999). For this reason, the most computationally-inexpensive formulation is the logical choice for a physically-based rebound modelling code. The VSS-NET is a purpose-written code in which a 3-D pipe network formulation (based on the Darcy-Weisbach formula and the Gradient Algorithm network solver) is routed through a 3-D, column-oriented (as opposed to layer-oriented), block-centred finite difference grid which is configured to solve for saturated-unsaturated flows (Adams and Younger 2001).

The gains in realism associated with using complex physically-distributed models such as VSS-NET are offset by the relatively high costs of parameterisation (either in terms of gathering the spatially-distributed data needed to support parameter selection, or in the sheer-scale of data manipulation that may be needed before runs can be commenced). For this reason, VSS-NET and similar models are probably best applied to systems comprising just one or two adjoining mines, underlying areas of < 100 km^2.

Conclusions

Lessons learned from the closure of British deep mines (principally coal mines, but to a lesser extent also gold and base metal mines) over the last decade have yielded a range of practical conceptual modelling approaches and software tools which are potentially applicable to the prediction and management of deep mine closure in many other geological settings. Some of the key advances relate to the following phenomena / techniques:

- exacerbation of land subsidence by processes including slaking of seat-earths and fault reactivation by rising mine waters
- the role of AGS in the deterioration of mine water quality during flooding, and the roles of carbonates, aluminosilicates and 'stone dust' in buffering
- the duration of the first flush (typically four times the time it took for the mined system to flood) and peak pollutant concentrations (typically ten times greater than long-term values)

- scale-appropriate modelling of mine water 'rebound' processes (i.e. flooding of extensive networks of underground voids) using both semi-distributed 'pond' models and physically-based, hybrid pipe network / porous media modelling codes such as VSS-NET

Application of generic characterisation / modelling techniques which have now been widely-tested for UK systems provides the essential background for long-term planning of sustainable management of abandoned underground mines (Younger 2000a), not least the rational design of active and passive water treatment systems (e.g. Younger *et al.* 2002; Wolkersdorfer and Younger 2002).

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