PREDICTIONS AND REALITY: GENERATION OF STRONGLY NET-ACIDIC MINE WATERS THROUGH FLOODING OF UNDERGROUND COAL MINE WORKINGS WITH LIMESTONE ROOF STRATA, BLENKINSOPP COLLIERY (NORTHUMBERLAND, UK)[1]

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Abstract. Blenkinsopp Colliery (Northumberland, UK) was the second-last underground coal mine in production in the former Great Northern Coalfield of England. The immediate roof beds of the single worked seam included a thick limestone bed; an unusual occurrence in UK coal mines. Hydrogeochemical investigations of the water encountered underground during the working of the mine revealed that specific qualities of water were logically related to details of the flowpaths the waters were inferred to have taken to reach the accessible sampling points. Working from this information, and taking into account observations of mineralogical and mining engineering aspects of the workings, a conceptual model was developed which assisted in predicting the likely response of the colliery to abandonment and flooding. In particular, it was predicted that, despite the presence of limestone in the roof and in goaf materials, the early outflows from the mine would be sufficiently acidic that they would require active treatment. Flooding of the mine is now complete, and post hoc analyses have largely vindicated earlier predictions of the time it would take for the mine to flood to surface, and the approximate post-flooding flow rates. The prediction that the water would be strongly net-acidic has also been borne out by observations: it is clear that the presence of limestone in a mined sequence is no guarantor of a neutral-pH discharge. However, the extremely high iron concentrations encountered post-flooding ($\leq$ 1000 mg/l Fe^{+2}) have exceeded expectations by a factor of around 3.3. Improvement in the understanding of likely quality, perhaps by means of tracer tests in recently flooded workings, could help reduce risks related to treatment scheme design, thus enabling more robust design and budgeting to be carried out as early as possible in the post-closure management period.

Additional Key Words: acidity, coal, limestone, mine, prediction, water, UK.

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Introduction

It has been appreciated since at least the mid-1970s, when the first documented cases were published (e.g. Cairney and Frost 1975; Frost 1979; Henton 1979, 1981), that the flooding of coal mine workings after closure tends to lead to a marked deterioration in water quality. More recent research (reviewed in detail by Younger et al. 2002) has further developed our understanding of the array of geochemical processes responsible for both water quality deterioration (primarily the dissolution of pyrite oxidation products) and for natural attenuation of the resulting pollutants (involving neutralization of mine waters by dissolution of carbonate and silicate minerals). The process of flooding is an inevitable result of the withdrawal of dewatering facilities despite the persistence of ground water inflows to the mined system. The terms "ground water rebound" or "mine water rebound" are often used to denote the process of water level rise during flooding. Completion of rebound is marked by a cessation of further water table rise within the mined system, which denotes the attainment of a condition in which outflows from the flooded mine system match residual inflows. The outflows which terminate rebound most often take the form of point discharges of polluted mine water to surface water catchments via old mine entrances or seam outcrops, though in some cases outflow may also occur to an overlying aquifer. Depending on the scale of the mine system in question and on the rate of ground water inflow which it receives, completion of rebound may take a number of years, or even a few decades.

In order to lay adequate plans to prevent any deterioration in the water quality status of rivers and / or aquifers following completion of rebound, which would be contrary to the requirements of the EU Water Framework Directive, water managers need to be able to estimate the timing of, and degree of water quality deterioration associated with, specific instances of rebound. A recent review of the evolution of predictive methodologies for such problems has been provided by Younger and Robins (2002). Depending on the scale of the system in question, the amount of data available, and (critically) the resources dedicated to the predictive work, forecasting of rebound timing can be achieved using a range of methods, including empirical extrapolation of observed rebound curves, semi-distributed mass balance modelling and rigorous physically-based 3-D numerical modelling (e.g. Adams and Younger 2001). Forecasting of changes in water quality during and after rebound is even more difficult than predicting rebound rates. The earliest published methodology (Glover 1983) established an empirical approach which has subsequently been refined (Younger 2000) and applied to number of real cases. Rigorous, predictive geochemical modelling of water quality changes during rebound using established thermodynamic software such as PHREEQC has been attempted in a number of cases (e.g. Younger et al. 1995; Chen et al. 1999). Such predictive exercises have tended to reveal limitations in our process understanding and/or in our knowledge of the abundances of key mineral phases in mined systems. Reconstruction of observed changes in water quality by means of 'inverse modelling' (using the NETPATH code and, more recently, the inverse modelling package of PHREEQC) has gone some way to indicating the relative importance of various buffering minerals. Calcite is an obvious postulate as a buffering mineral. However, in most UK coalfields the Coal Measures sequence (Westphalian: Stephanian) is devoid of discrete limestone beds, and also lacks disseminated calcite within the clastic strata themselves. In these cases, the main buffering phases appears to be the Ca-Mg-Fe carbonate mineral ankerite, which is often present as cleat surface linings in many coal seams (Younger 2004). In the Lower Carboniferous coalfields of northern and western Northumberland, however, discrete limestone beds are often present in close association with the coal seams, and where mining has been undertaken by longwall techniques, limestone can be the dominant lithology in the 'goaf' (i.e. mining-induced breccias) which form in collapsed panels from which coal has previously been removed. This apparently benign circumstance is tempered by the fact that the marine depositional environment of these strata also resulted in abundant diagenetic development of fine-grained pyrite within the coal seams and seat-earth mudstones. There is thus a close juxtaposition of acid-generating and buffering phases in this setting, and the details of hydrological pathways can be crucial in determining the overall balance of acidity in a given mine water. This paper explores the implications of these observations for a practical case of current concern: the August 2002 closure of Blenkinsopp Colliery, the last working coal mine in the Lower Carboniferous of Northumberland.

Blenkinsopp Colliery: Geology, Hydrogeology, Mining History

Blenkinsopp Colliery is located in northernmost England, close to the Anglo-Scottish Border, and immediately south of the line of the Hadrian's Wall World Heritage Site (Fig. 1). The nearest sizeable town, Haltwhistle (Northumberland), lies some four kilometres to the east of the mine site.

The Colliery worked a single seam of coal, known as the Little Limestone Coal, which immediately underlies the 15m-thick limestone bed of the same name (Fig. 2). These strata, and all the super-incumbent beds below rockhead, are of Namurian (Lower Carboniferous) age. The floor of the worked coal seam is a pyritic mudstone. The sedimentary sequence overlying the Little Limestone mainly comprises cyclothemic alternations of thinly-bedded (generally < 0.5m) mudstones, siltstones, sandstones and occasional limestones.

Three of the thicker sandstone units in this sequence (Fig. 2), namely the 12.5m-thick Firestone Sill (base 65m above the roof of the worked coal seam) the 10m-thick White Sill (base 40m above seam roof) and the 11m-thick Pattinson's Sill (base 24m above seam roof) are minor aquifers, which feed significant quantities of water into the workings. The Little Limestone itself is massive, sparsely jointed and of low transmissivity. While it did yield some significant feeders when first broken by caving of the No 1 Shearer Face (see Fig. 3) in 1994, the limestone has very low specific yield and all available evidence suggests that it quickly drained down to the level of active mining, with most residual feeders originating from the still-saturated sandstone aquifers above. The colliery has been worked for several centuries, with the earliest recorded workings dating from the early 19th Century (by which time they were already at a depth of several hundred metres, and more than 2km from the portal of the mine). The colliery was originally worked until the 1940s, after which time it was abandoned for some thirty years, before being re-opened in the 1970s as a private licensed mine, until the most recent (and probably final) closure in August 2002.

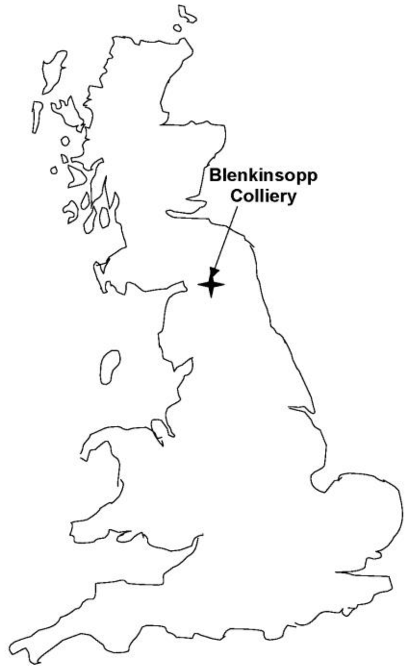

Figure 1. Location of Blenkinsopp Colliery (UK)

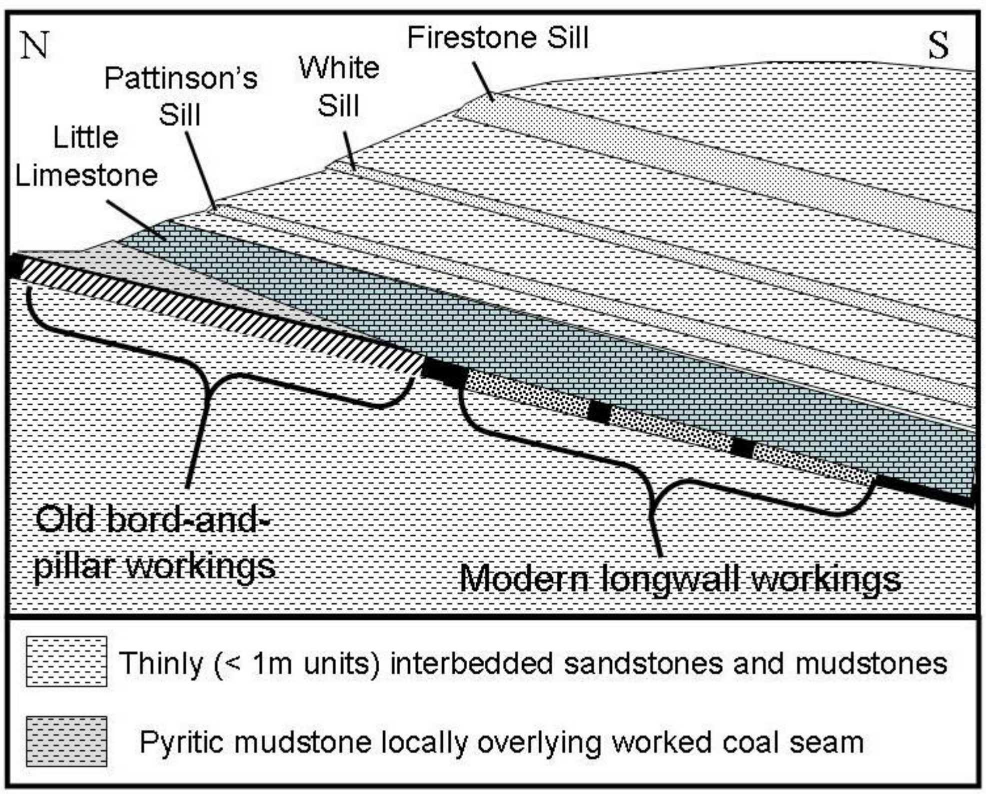

Figure 2. Schematic geological cross-section through Blenkinsopp Colliery, showing named sandstone aquifers (stippled) above the workings, the overlying Little Limestone, and the presence of pyritic shale as roof measures in the near-surface part of the mine.

Figure 3 shows the layout of the workings. Blenkinsopp Colliery comprised two distinct bodies of workings (which were originally separate mines), i.e. the Wrytree workings and the Castle Drift workings. Access to both of these bodies of workings was primarily by means of inclined drifts, of which the 1-in-6 Castle Drift was the main production and man-access drift during the later years of working. The Smallburn Shaft is a 4m diameter cylindrical structure 100.22m in total depth. A run of tubbing from surface to 37m depth holds back loose sands and gravels of Quaternary age, and also serves to hold back some of the waters of the Firestone Sill aquifer. This shaft was never used for regular man-access, but rather as the downcast ventilation shaft and the route to surface for the dewatering pipe ranges.

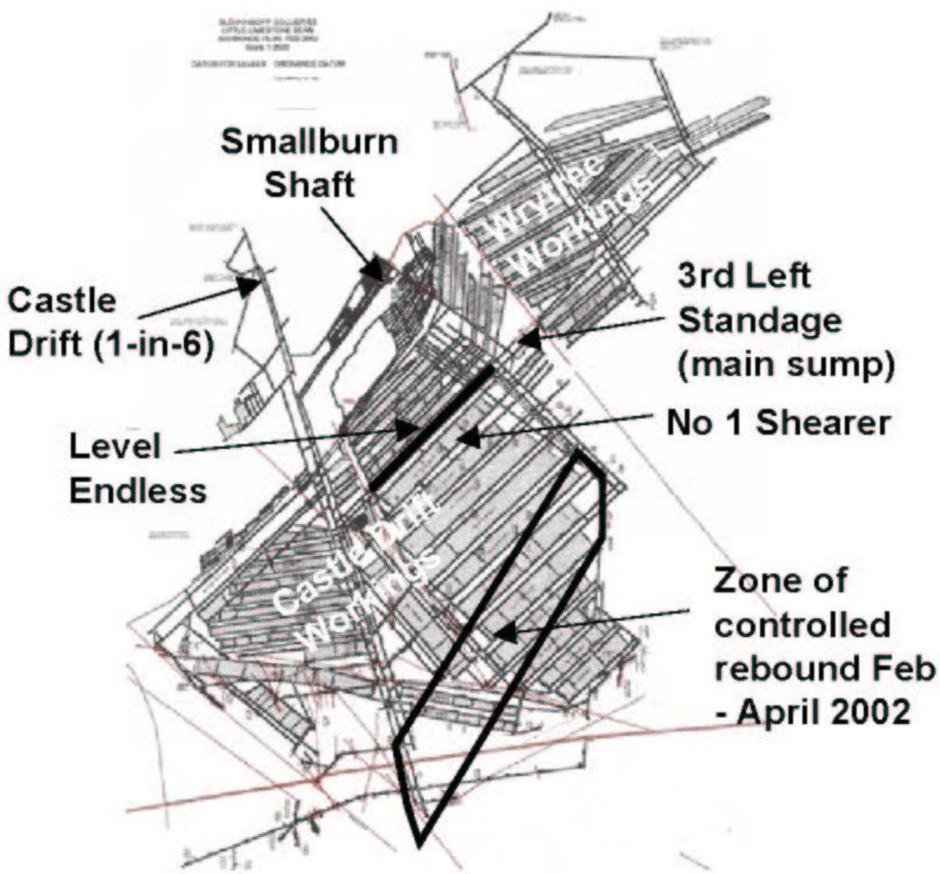

Figure 3 - Annotated mine plan for Blenkinsopp Colliery highlighting features discussed in the text. Geological dip is to SSE, parallel to Castle Drift.

Blenkinsopp was one of the last collieries in England to use traditional hand-filling methods for loading coal from working faces, and modern mechanized longwall working (using drum shearers and self-advancing hydraulic supports) was only introduced in 1994. Conventional longwall was actually difficult to apply in this colliery, because the great strength of the Little Limestone meant that it caved to form goaf only irregularly, and often in very large blocks. A 'hanging roof' often developed during shearing, leading to problems with face "weightings". Furthermore, sudden caving of very large blocks of limestone directly onto face supports (which occurred on a few occasions) was capable of flattening these completely. The strength of the limestone roof also gave rise to some impressive features in the mine, such as a number of uncaved hand-filler panels which had stood unsupported for more than ten years by the time of closure. The very good roof conditions also meant that old bord-and-pillar workings dating from the 1830s and 1840s, which in most collieries would by now have degraded beyond repair, were for the most part standing intact after 170 years. In these old workings, in accordance with antique regional practice, the top two feet of coal were always left in place as "top coal". The effective worked thickness of coal in this district of the mine was thus around 1.27m (compared with about 1.52m elsewhere in the mine).

Some lateral variations in the geology of the Little Limestone Coal and its roof strata detracted from the economic viability of the mine within the artificially hostile market for indigenous coal created by successive UK governments. A mid-seam parting of pyritic mudstone was found to become ever thicker as the mine workings proceeded towards the southeast, eventually exceeding 0.5m in the most south-easterly workings. This resulted in an increase in the ash and sulfur contents of the run-of-mine coal, significantly reducing its market value. At the southwestern edge of the workings shown on Fig. 3, the seam was pierced by a sub-vertical dolerite dyke (dipping to the southwest at around 60^{o}). Contact metamorphism by this dyke reduced the volatile content of the coal over an area of several hundred square metres, effectively turning the coal into a semi-anthracite. While elevated rank coals such as this once attracted high premiums, the low volatile content rendered this coal unsuitable for its sole remaining market (i.e. blending for use in coal-burning power stations). Finally, as the seam is followed up-dip towards outcrop, for instance by ascending the Castle Drift, a thin parting of pyritic mudstone begins to appear between the coal and the overlying limestone, an observation with importance for predictions of post-rebound evolution of water quality.

Detailed monitoring of quantities of pumped water was undertaken in various parts of the mine between 1994 and 2002. The results of this period of regular monitoring can be summarized as follows. The total water make of the Blenkinsopp workings varied between extremes of 3615 m^3/d and 6583 m^3/d, with a median value of around 4500 m^3/d. The variations were seasonal, with minima occurring between July and mid-November, and maxima between mid November and late June. Peak annual flows of around 5100 m^3/d normally occurred in February. The distribution of this total water make within the workings was such that around 18% originated in the Wrytree workings, 18% originated from old bord-and-pillar workings in the Castle Drift workings, around 25% corresponded to the residual water make from the first shearer panel to cave in the mine (No 1 Shearer panel; Fig. 3), 30% originated from all the other shearer panels combined, and finally around 9% was sourced from inflows local to the main pumping sump in the 3rd Left Standage.

Hydrochemistry of Blenkinsopp Colliery during working

Water pumped from the mine (via the Smallburn Shaft) and numerous individual inflows of water within the workings were repeatedly sampled during 2001 - 2002. Table 1 summarizes the findings of these investigations. Water quality in this mine system is clearly heterogeneous.

Nevertheless, a few generalizations can be made. It is clear that the overall mixture of water pumped from the shaft, and thus, unsurprisingly, most individual sources of water in the workings was net-alkaline (i.e. alkalinity > acidity) ranging up to around 45 mg/l. Acidic waters were regularly found in only two settings within the mine:

(i) water running across the pyritic seat-earth floor in old bord-and-pillar workings (e.g. sample 7), which had extremes of pH (2.0) and iron (1293 mg/l)

(ii) water in the recently-flooded No 7 to No 5 Shearer panels (e.g. sample 9).

The evolution of the latter waters has considerable importance in terms of understanding the likely evolution of the Blenkinsopp waters during rebound. Before flooding of these panels commenced early in 2002, water pumped from them had a pH of 6.8, with 23 mg/l Fe, 905 mg/l SO_4 and an alkalinity of 141 mg/l as $CaCO_3$ equivalent. After the period of rebound, samples collected in May 2002 showed a much lower pH (4.7 - 5.1), around 50 - 60 mg/l Fe, 1242 - 1496 mg/l SO_4 and zero alkalinity. Continued monitoring of waters pumped from this area showed a relatively rapid recovery in quality, so that by 20th June 2002 the following parameters were recorded: pH 6.2, 39 mg/l Fe, 800 mg/l SO_4 and alkalinity 35 mg/l as $CaCO_3$ equivalent. The inference is that:

- generation of acidic leachates occurred rapidly as water levels rose, due to dissolution of secondary minerals (which were conspicuously present as efflorescent crusts on floor shales and in the prominent inter-seam parting in this part of the mine)
- neutralization of these acidic leachates occurred rather more slowly, by means of open-system dissolution of calcite present in limestone clasts in the goaf.

Further bolstering confidence in the capacity of the limestone goaf to neutralize acidic leachates and thus limit the mobility of Fe is sample 11, which is water draining from a completed shearer panel which had been flooded for more than a year, before a borehole was drilled into its goaf from a down-dip position (to remove the potentially dangerous accumulation of water before some (ultimately abortive) development work). The high alkalinity (136 mg/l as $CaCO_3$) and low Fe concentration (4.2 mg/l) of this water are very encouraging in terms of the kind of water the deepest workings of Blenkinsopp are likely to yield in the long-term.

One possible use of the type of data presented in Table 1 is the identification of types of water which can be expected to be head-dependent. These will by and large be deep-seated groundwaters, typically characterized by elevated mineralization, and probably also by elevated temperature. Inspection of the data presented in Table 1 suggests that the most deep-seated groundwaters are characterized by temperatures in excess of 13^{o}C, and typically also by conductivities in excess of 1500μS/cm. If this threshold is applied to the waters encountered in the pit, simple calculations lead to the conclusion that around 60% of the total water make can be interpreted as being head-dependent in nature.

Table 1 Summary of typical chemical characteristics of mine waters encountered in Blenkinsopp Colliery during 2001 - 2002[1]. Fig 3 identifies locations.

Water source	**pH**	**T (°C)**	**Cond. (μS/cm)**	**Alk. (mg/l[2])**	**Fe (mg/l)**	**Mn (mg/l)**	**SO_4 (mg/l)**
1. Wrytree water (entire make) pumped to sump in Castle Drift workings	6.72	13.0	1265	68	30	0.9	539
2. Local drainage to Smallburn Shaft from old bord-and-pillar workings up-dip	6.84	11.7	672	176	2	0.1	160
3. Water pumped from main sump (3rd Left) up to Smallburn Shaft (= all water in workings except for local drainage to shaft)	7.41	13.4	1749	168	20	0.5	701
4. Residual water make from No 1 Shearer Panel, sampled at Main Gate tank	7.1	12.8	750	230	2.6	0.08	129
5. Drainage from old hand-filler faces flowing into Castle Drift	6.9	16.5	1220	15	5.6	0.1	621
6. Roof drippers associated with fault cut by the Level Endless	6.7	13.8	3220	n.d.	134	5.3	2088
7. Extremely acidic water in floor pools of old bord-and-pillar workings between Smallburn Shaft and Castle Drift	2.0	13.0	7695	0	1293	9.9	6054
8. Water draining into 2 SW development heading from old bord-and-pillar workings up-dip	6.9	12.9	958	285	5.8	0.5	212
9. Water pumped from recently-flooded workings in the 3rd South district	4.7	15.1	2360	0	48.5	1.8	1496
10. Roof drippers from base of Little Limestone in the deepest part of the workings (12W development heading)	6.6	19.5	1533	n.d.	13.6	0.4	163
11. Drainage from a previously-flooded shearer face (No 21) which was drained down after the water had been static within the goaf for more than one year	6.5	17.8	1764	136	4.2	1.4	838
12. Final mix of water pumped to surface at Smallburn Shaft	6.7	12.5	1536	62	35	1.1	826

[1] Note that not all sample points were synchronously visited, hence mis-matches between 2, 3 and 12, which one would expect to be similar in quality. [2] as $CaCO_3$ equivalent.

Conceptual Model for Post-Abandonment Flooding and Changes in Water Quality

Prior to closure, a conceptual model was developed for the likely system response to abandonment and flooding, based on the observed water flows and qualities during the working of the mine and on the distribution of pollutant source / sink minerals within the workings (which is related both to geology and the type of mining voids present in different parts of the mine). This conceptual model may be summarized in the following suite of assumptions:

(i) The rate of ground water inflow to the workings would gradually decrease as the workings slowly filled with water, due to the gradual decline in head differences between the interior of the mine and the source aquifers.

(ii) The final, residual water make of the mined system following completion of rebound (corresponding to local infiltration) would be around 40% of that measured during mining.

(iii) Water quality evolution could be expected to occur rather differently in the deep modern workings than in the shallower more ancient workings, according to the following principles:

- In the deeper workings, ready availability of calcite in the form of limestone clasts in longwall goafs would likely result in neutralization of the acidity derived from dissolution of pyrite oxidation salts (which are abundantly present in the seam, inter-seam parting and floor strata). The evolution of water quality in these deep workings could be expected to closely resemble that observed during the flooding of the No 7 to No 5 Shearer panels in April to June 2002, as described above.
- In the shallower workings, which are up-standing 19th Century bord-and-pillar workings, with either 30 to 60cm of 'top coal' still in place or else pyritic shale as the immediate roof bed, acidic leachates could be expected form in abundance. However, the isolation of the overlying limestone from the voids means that there would be far less scope for neutralization reactions here than would be expected in the deep workings. While some neutralization might be afforded (by disseminated ankerite (albeit none was observed in the seam during mining), calcitic stone dust (spread in line with explosion prevention precautions, and which will only dissolve once hydrophobic coatings on particles are breached), and some aluminosilicate minerals) overall it was expected that mine waters rising through this zone would undergo net acidification.

(iv) Following completion of flooding and the onset of mine water outflow to the surface environment, a flushing process would likely ensue, resulting in an improvement in mine water quality over time, in accordance with the generic model proposed by Younger (2000). Long-term mine water quality would likely resemble that observed in a number of other abandoned collieries which worked the same coal seam in this area.

Quantification of the predictive model

The foregoing conceptual model was converted into an equivalent quantitative model using the array of modelling approaches described by Younger and Adams (1999) and Younger (2000). The key findings of this predictive work may be summarized as follows:

A. The only likely point of emergence for the bulk of the Blenkinsopp mine waters after the completion of rebound was considered to be the Smallburn shaft, and the earliest date at which overflow might occur was thought feasible was May 2004, though applying the assumption of a 60% reduction in inflows during rebound, numerical modelling suggested that overflow was more likely to commence within a month or two of April 2005.

B. Post-rebound flow rates expected from the shaft were anticipated to average about 1800 m^3/d (varying between 1560 m^3/d in the summer, and 2040 m^3/d in winter).

C. Post-rebound water quality was regarded as likely to vary over time. The first waters to emerge from the shaft were considered likely to be acidic, reflecting the dissolution of pyrite oxidation products (iron hydroxysulphates) in the bord-and-pillar workings closest to surface. pH was thought likely to be less than 4 (possibly around 3.5) with elevated total iron (perhaps exceeding 300 mg/l). To judge from experience in other collieries around the UK (Younger 2000) it was considered unlikely that these conditions would persist for more than a year or two before more buffered waters originating from the deeper flooded workings would mix with the more acidic waters at the top of the water column and give rise to an improvement in mine water quality. Persistence of a degree of stratification of water quality post-rebound could not be ruled out however (cf Nuttall and Younger 2004). Eventually, water quality was considered likely to settle down to near-neutral pH, with total iron only around 14 mg/l in the long-term (as observed at other abandoned collieries in this area); however these long-term conditions were not expected to be established until 7 or more years after commencement of overflow.

On the basis of these predictions, it was recommended that provision be included in the plans for post-rebound treatment to ensure it would be possible to undertake active treatment of the discharge during the first few years after completion of rebound, with a gradual move to only passive treatment as the water quality of the overflow gradually improved.

Post-analysis: comparing hydraulic predictions with observed behaviour

The recovery of the minewater was monitored in the Smallburn Shaft from September 2003. Given the depth of the shaft of 100.22m, a base level of +25m OD, this monitoring was limited to mine water recovery in workings above this level. As such monitoring of recovery began on 24 November 2003 once this level had been reached.

The water level in the shaft rose at a relatively consistent rate of approximately 0.29m/d over the early stages of recovery up until early July 2004 at which point the recovery slowed to 0.14m/d over the middle period of recovery from early July to late October 2004, after which it reduced dramatically. It is possible that this reduction in rebound rate represents a sudden increase in specific yield, as leakage into adjoining (presumably previously drained) river gravels became possible. The water level in the shaft on 3 November 2004 was approximately 119.77 m OD, similar to the water level in an adjoining stream, known as the Tipalt Burn. This stream passes approximately 50m to the north of the Smallburn Shaft, flowing eastwards to its confluence with the River South Tyne, approximately 3 km east of the shaft. Once the water level in the shaft reached the elevation of the Tipalt Burn, the recovery rate declined to approximately 0.05m/d until reaching a level of 123.02 m OD on 17 January 2005, 2.2m below the top of the shaft cap.

The pump in the shaft was activated on 18th January 2005, both to prevent uncontrolled overflow and to expedite the process of commissioning of recently constructed mine water treatment facilities. (The early initiation of pumping meant that a suspension of pumping would be possible without immediately giving rise to an uncontrolled overflow, in the event of unforeseen problems with the treatment facilities). Given the rate of recovery recorded in the final stages, it is estimated that overflow from the shaft would have occurred in early March 2005 if pumping had not commenced. This compares remarkably well with the prior prediction of “within a month or two of April 2005” (prediction A in the preceding Section).

When mine water levels were at their highest within the shaft, a proportion of the mine water was seen to be discharging to surface via shallow sand and gravel deposits of Quaternary age, associated with the floodplain of the Tipalt Burn. For instance, at point on the Tipalt Burn closest to the shaft, ochreous water was seen to be emerging from bank side gravels. In addition, the HDPE liner of lagoons prepared for treating the pumped mine water was locally billowed upwards by an inflow of ochreous water, and a few minor seepages of the same water were also seen emanating from soil located south and up topographic gradient of the shaft. It is important to note that these manifestations of outflow from shallow Quaternary deposits are not ascribable to leakage from the shaft liner itself, as this had recently been pressure-grouted all the way to bedrock to avoid this possibility. Rather, they indicate direct hydraulic continuity between the worked bedrock strata (including the nearby access drifts) and the overlying unconsolidated sands and gravels. When taken together with the observed decline in rebound rate when the mine water levels reached the same elevation as the Tipalt Burn, this is clear evidence that at least part of the recharge to the mine during working was by induced inflows from the Tipalt Burn, via the Quaternary sands and gravels.

In the early stages of pumping, water was extracted at approximately 14 l/s (1210 m^3/d) in order to lower the water levels in the workings sufficiently that the outflows beneath the lagoon liner ceased, and the direct seepage through the bank of the Tipalt Burn dried up. These goals were achieved when the water level in the shaft had been lowered to approximately 120.4 m OD, at which point the pumping rate was gradually reduced to hold the water level steady at this elevation. At the time of commissioning, a pumping rate of 10 l/s (864 m^3/d) was found to be sufficient to hold the water level in the workings steady at 120.4 m OD. This rate is obviously representative of the rate of recharge entering the workings above this level, in addition to cumulative lateral and vertical inflows to the mine roadways.

Given the generally consistent width of workings perpendicular to dip (Fig. 3) it is reasonable to assume that for every unit water level rise an equal volume of storage is filled. As such, the 864 m^3/d rate above c.120 m OD for a 0.05 m/d rise equates to 2419 m^3/d below this level for a 0.14 m/d rise and 5011 m^3/d below for a 0.29 m/d rise, assuming the recharge flux rates are directly proportional to change in elevation head in the shaft. The observed and calculated recharge fluxes of 864 m^3/d at high elevations and 2419 m^3/d at medium elevations compare favourably with the prior calculations of 1560 m^3/d in the summer and 2040 m^3/d in winter (prediction B in the preceding Section). The prior calculations did not explicitly take into account the influence of induced recharge from the Tipalt Burn, which now appears to be significant. While the earlier estimates took this component of recharge into account in part (as it must have been present in feeders which eventually reported to the then-accessible workings at depth) the direct nature of the hydraulic connection was not known, and thus the effect of diminishing recharge as the mine water level reached that in the Burn could not be predicted.

Nevertheless, the overall loss of water make during rebound can now be calculated to have been approximately 50% as water rose between the lower and mid levels, and 60% as it rose between the mid and upper levels, which compares favourably with the 60% loss previously predicted on the basis of hydrochemical evidence (see preceding Sections).

Post-analysis: comparing geochemical predictions with observed behaviour

Monitoring of water quality was carried out on samples bailed from Smallburn Shaft during recovery. This was carried out in order to try and establish the quality of water that would need to be treated once it emerged or was pumped from the shaft. The water quality was generally ‘good’, in that it had very low concentrations of ions such as sulphate and iron which would have been expected if typical Blenkinsopp mine water (Table 1) were present in the shaft. The sulphate concentrations in these grab samples ranged between 44.2 and 224 mg/l and total iron concentrations ranged between 0.16 and 3.03 mg/l, with alkalinity ranging between 170 and 266 mg/l as $CaCO_3$. This was evidently not typical local mine water; rather it appears to reflect the quality of the abundant water which cascaded into the shaft from the Pattinson’s Sill, White Sill and Firestone Sill aquifers.

Once pumping commenced the true nature of the ‘first flush’ mine water quality was quickly established. Total iron concentrations were on the order of 1,000 mg/l of which almost all was Fe^{2+}. The mine water was therefore aerated and dosed with sodium hydroxide in order to precipitate iron in its ferric form in the lagoons. The Fe concentrations were 4 times greater than the predicted upper bound of 300mg/l. In fact they are comparable to the highest concentrations ever found in the workings, which were associated only with small, isolated low-pH feeders (e.g. analysis 7 in Table 1). That the bulk flow from the mine should have a quality as poor as the lowest flow sources sampled during mining is a salutary lesson in the degree to which water quality deterioration can occur during rebound. While increases in iron concentration by a factor of 10 are common (Younger 2000), in this case the overall increase has been by a factor of 28 (= 1000 / 35, the Fe concentration in the final mix of water pumped from the shaft during mining; analysis 12, Table 1).

The raw water contained calcium on the order of 500 mg/l, suggesting substantial dissolution of calcite within the workings, albeit this was insufficient to result in a net-alkaline water. The sulphate concentrations in the raw water were in the order of 3,000 to 4,000 mg/l. At concentrations in excess of about 2000 mg/l, sulphate tends to react with dissolved calcium to precipitate gypsum (hydrated calcium sulphate); this process is thought to account for observed decreases in Ca concentration as the water flows through the surface treatment lagoons.

The pH of the raw mine water at the point of first emergence was relatively high, generally between 3.9 and 6.1 (average 4.75), despite very high total acidity on the order of 1000 mg/l expressed as $CaCO_3$. This apparent dichotomy is well-known in mine water chemistry. It reflects partial neutralisation of the mine water within the workings by calcite dissolution in the absence of atmospheric O_2 (which is reflected in the fact that all Fe in the raw water is in the Fe^{2+} form). Once the mine water is exposed to the surface atmosphere, degassing of CO_2 (another product of calcite dissolution, manifest in temporary alkalinities of up to 180 mg/l in the raw water) and ingress of O_2 destroys the temporary neutralisation and the pH falls as Fe (now oxidised to the Fe^{3+} form) hydrolyses and liberates protons (Younger *et al.* 2002). Thus in the absence of NaOH dosing, the post-oxidation pH of the mine water matches very closely the predicted pH of around 3.5 and less than 4.

The source of the calcite responsible for the partial, temporary neutralisation of the mine water underground may not only be limestone goaf. During the working of the mine, sludge from the treatment lagoons (which was known to contain much unreacted lime ($Ca(OH)_2$) was backfilled into old workings within a few hundred meters of the shaft. Any unspent lime might be buffering the minewater and adding to the calcium concentration.

Overall the prior predictions of water quality correctly identified the likely net-acidity of the mine water, though the extremely high Fe concentrations exceeded expectations by a considerable margin.

Discussion

Predictive modelling has been shown to yield reasonable estimates of rates of recovery and likely time of emergence. The estimate of final water make post rebound was also reasonable, although association of surface water features should be looked at more closely in future models. These estimates were invaluable in ensuring that remedial works were put in place rapidly, within the predicted time frame. Should this not have happened then the resultant impact on surface watercourses would have been dramatic.

The quality modelling was also successful, although to a lesser extent and with significant lessons to be learned. Although the predictions correctly identified high concentrations of metals and other ions in the ‘first flush’, the predicted Fe concentrations were exceeded in practice by a factor of 3.3. The higher concentrations of iron have resulted in significantly higher volumes of sludge being generated and quantities of caustic soda being used than had been anticipated. This has cost, maintenance and management implications which have also led to major budgetary changes to the scheme. Therefore, the better the chemical predictions that can be made the lower the risks for scheme design and budget in the future. Having said that, there is nothing in the earlier literature to suggest a pre/post mining ratio of Fe increase as high as 28, reported here.

Quite why the post-rebound Fe concentrations reached such high levels is difficult to explain, especially in the light of Table 1 and observations during mining. One possibility is that the treatment sludges which were disposed of in the mine during working have been mobilised. However, the very low Eh which reductive dissolution of solid $Fe(OH)_3$ would not readily be reached in the absence of a labile carbon source; the lack of strong H_2S odours and the sustained high SO_4^{-2} concentrations in the raw mine water strongly suggest that Eh is not low enough within the workings for this to be a feasible explanation.

The realisation that induced recharge from the Tipalt Burn is a significant element in the mine water budget highlights the uncertainty which surrounds the prediction of shallow flow paths after rebound, in workings which were previously unflooded and therefore impossible to investigate hydrogeologically. Although it might be supposed that mapping of inflows during working might have led to prior identification of this inflow, in reality the shallowest workings (in which such an inflow might have been identified on hydrochemical grounds, before acquiring a mine water signature) could not be entered safely, due to extensive pillar-robbing above the rest water level prior to renewed dewatering in the early 1970s. For the same reason, it remains unclear how different areas of partly-flooded shallow workings feed the groundwater flow system which culminates in the pumped discharge from the Smallburn Shaft. While there is evidence of substantial calciate dissolution in the workings (yielding dissolved Ca of 500 mg/l), this is currently swamped by the liberation of acidity due to dissolution of previously oxidised pyrite during rebound. It remains to be seen whether the elevated Fe is in part explicable by far more fierce active pyrite oxidation in the zone of water table fluctuation than was occurring when the water table was deep and the recharge was making its way to the active workings via well-washed pathways. The undoubted existence of well-buffered waters in the limestone goaf shearer panels at great depth (e.g. analyses 9 and 11, Table 1) appears to be having little influence on the mixture of water currently reporting to the pump in the Smallburn Shaft. This implies that deep circulation is sluggish in this system, despite the existence of very high permeabilities. In principle, tracer tests could be used to investigate post-rebound mine water flow pathways (Wolkersdorfer 2002). Although the design and implementation of such tests would require the use of a number of deep, well-constructed injection and monitoring boreholes, they might yield sufficient information to support design of alternative water management strategies, such as relocating the pump intake in the deep section of the mine, to pull shallow acidic water down through the limestone goaf areas deep underground, so that they would benefit from buffering before reaching the treatment plant at surface.

Conclusions

Blenkinsopp Colliery (Northumberland, UK) was the second-last underground coal mine in production in the former Great Northern Coalfield of England. It was in many ways an unusual mine, not least in possessing a thick (15m) limestone bed in the immediate roof beds of the single worked seam. (Most UK collieries worked strata devoid of limestone beds). Hydrogeochemical investigations of the water encountered underground during the working of the mine revealed the presence of highly heterogeneous water quality. It emerged that specific qualities of water were logically related to details of the flowpaths the waters were inferred to have taken to reach the accessible sampling points. Working from this information, and taking into account observations of mineralogical and mining engineering aspects of the workings, a conceptual model was developed which assisted in predicting the likely geoenvironmental response of the colliery to abandonment and flooding. On the basis of this conceptual model, estimates were made of the time required for the workings to flood to surface, and of the water quality likely to be encountered after decant of water to the surface environment, providing the basis for planning remedial interventions. In particular, it was predicted that, despite the presence of limestone in the roof and in goaf materials, the early outflows from the mine would be sufficiently acidic that they would require active treatment. Flooding of the mine is now complete, and post hoc analyses have largely vindicated earlier predictions of the time it would take for the mine to flood to surface, and the approximate post-flooding flow rates. While the predictions also correctly predicted that the water would be strongly net-acidic, the extremely high iron concentrations have exceeded expectations by a factor of around 3.3. The presence of limestone in a mined sequence is no guarantor of a neutral-pH discharge. Improvement in the understanding of likely quality, perhaps by means of tracer tests, could help reduce risks related to treatment scheme design, thus enabling more robust design and budgeting to be carried out at as early a stage as possible in the post-closure management period.

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Literature Cited

Adams, R., and Younger, P.L., 2001, A strategy for modeling ground water rebound in abandoned deep mine systems. Ground Water, 39, pp 249 - 261. http://dx.doi.org/10.1111/j.1745-6584.2001.tb02306.x.

Cairney, T., and Frost, R.C., 1975, A case study of mine water quality deterioration, Mainsforth Colliery, County Durham. Journal of Hydrology, 25: 275 - 293. http://dx.doi.org/10.1016/0022-1694(75)90026-8.

Chen, M., Soulsby, C., and Younger, P.L., 1999, Modelling the evolution of minewater pollution at Polkemmet Colliery, Almond catchment, Scotland. Quarterly Journal of Engineering Geology, 32: 351 – 362. http://dx.doi.org/10.1144/GSL.QJEG.1999.032.P4.04.

Frost, R. C. 1979. Evaluation of the rate of decrease in the iron content of water pumped from a flooded shaft mine in County Durham, England. Journal of Hydrology, 40: 101– 111. http://dx.doi.org/10.1016/0022-1694(79)90090-8.

Glover, H.G., 1983, Mine water pollution - an overview of problems and control strategies in the United Kingdom. Water Science and Technology, 15: 59 - 70.

Henton, M.P., 1979, Abandoned Coalfields: Problem of Pollution. The Surveyor, 153: 9 - 11.

Henton, M.P., 1981, The problem of water table rebound after mining activity and its effects on ground and surface water quality. In van Duijvenbooden, W., Glasbergen, P., and van Lelyveld, H., (Editors), Quality of Groundwater. (Proceedings of an International Symposium, Noordwijkerhout, The Netherlands, held 23 - 27th March 1981). Elsevier, The Netherlands. pp 111 - 116. http://dx.doi.org/10.1016/s0166-1116(08)71891-0.

Nuttall, C.A., and Younger, P.L., 2004, Hydrochemical stratification in flooded underground mines: an overlooked pitfall. Journal of Contaminant Hydrology, 69: 101 - 114. http://dx.doi.org/10.1016/S0169-7722(03)00152-9

Wolkersdorfer, C., 2002, Mine water tracing. In Younger, P.L., and Robins, N.S., (eds) Mine Water Hydrogeology and Geochemistry. Geological Society, London, Special Publications, 198: 47 - 60. http://dx.doi.org/10.1144/gsl.sp.2002.198.01.03.

Younger, P.L., 2000, Predicting temporal changes in total iron concentrations in groundwaters flowing from abandoned deep mines: a first approximation. Journal of Contaminant Hydrology, 44: 47 - 69. http://dx.doi.org/10.1016/S0169-7722(00)00090-5.

Younger, P.L., 2004, Coal mining waste and coal mine voids: their environmental impacts. In Gieré, R., and Stille, P. (editors) Energy, waste, and the environment: a geochemical perspective. Geological Society, London, Special Publication. (in press).

Younger, P.L., and Adams, R., 1999, Predicting mine water rebound. Environment Agency R&D Technical Report W179. Bristol, UK. 108pp.

Younger, P.L., and Robins, N.S., 2002, Challenges in the characterisation and prediction of the hydrogeology and geochemistry of mined ground. In Younger, P.L., and Robins, N.S., (eds) Mine Water Hydrogeology and Geochemistry. Geological Society, London, Special Publications, 198: 1 - 16.

Younger, P.L., Banwart, S.A., and Hedin, R.S., 2002, Mine Water: Hydrology, Pollution, Remediation. Kluwer Academic Publishers, Dordrecht. (ISBN 1-4020-0137-1). 464pp. http://dx.doi.org/10.1007/978-94-010-0610-1.

Younger, P.L., Barbour, M.H., and Sherwood, J.M., 1995, Predicting the Consequences of Ceasing Pumping from the Frances and Michael Collieries, Fife. In Black, A.R., and Johnson, R.C., (Editors), Proceedings of the Fifth National Hydrology Symposium, British Hydrological Society. Edinburgh, 4-7th September 1995. pp 2.25 - 2.33