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Hydrochemical stratification in flooded underground mines: an overlooked pitfall

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Abstract

The fact that flooded underground mines are commonly hydrochemically stratified is often not appreciated. Water samples taken from the water surface in partly flooded shafts are often wrongly assumed to represent the water quality existing throughout the entire water column. In some cases, treatment systems have been designed on the basis of these often misleading water surface samples. Stratification can build up within a slowly recovering system where there are few lateral inflows and outflows to the system. Less mineralised, shallow-sourced water enters at the top of the water column and more heavily mineralised water tends to remain at the base of the water column. This water has a high dissolved solids content due to dissolution of increasing amounts of pyrite oxidation salts and other minerals as the water level rises through the old workings. However, such stratification can easily be lost following hydraulic disturbance of the system (either by pumping or by natural decant when the water level reaches an outflow pathway from the mine system, such as an old adit or shaft collar) and often results in surface discharges of poor water quality. Test pumping of one such stratified system (Frances Colliery, Scotland) has provided useful information about how stratified systems develop, and how they can behave when disturbed. The water quality observed after stratification was disturbed by pumping was worse than would have been anticipated on the basis of water samples taken from the surface of the water column prior to pumping (with concentrations of contaminants such as iron and zinc being around two orders of magnitude greater than in water surface samples). Taken together with other information from the literature, the experience at Frances Colliery supports the proposal of criteria for recognising when stratification of mine water quality might be anticipated, thus facilitating the timely deployment of measures required for its detection at an early stage.

Keywords: Stratification; Mines; Abandoned; Water; Pumping; Pollution

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1. Introduction

Following mine abandonment and cessation of pumping, the flooding of underground workings temporarily leads to the development of relatively stagnant bodies of water sometimes referred to as "ponds" (Adams and Younger, 2001). Like any relatively static water body, these ponds have the potential to become stratified. In this case, hydrogeochemical stratification is common, with better quality water derived from shallow-sourced water lying above poorer quality water derived from dissolution of the products of pyrite oxidation. Such stratification in mine workings has been sporadically recognised in the UK and the USA since the 1970s (e.g. Cairney and Frost, 1975; Ladwig et al., 1984; Younger and La Pierre, 2000; Johnson and Younger, 2002). However, the implications of its existence have rarely been studied and there is very little existing literature on the subject (Ladwig et al., 1984; Younger and La Pierre, 2000; Rüterkamp, 2001). This paper will discuss the nature, causes and implications of mine water stratification, drawing upon a current, unusually well-documented example, Frances Colliery (Fig. 1) which lies near Kirkcaldy in East Fife (Scotland). Frances is connected underground to two other abandoned deep mines (Randolph and Michael) which are in turn interconnected with several others (Fig. 2a). Since 1995, when pumps were withdrawn from Frances and Michael, mine waters have been recovering throughout the East Fife coalfield (Younger et al., 1995), and in the next few years, it will become necessary to pump and treat these waters to prevent uncontrolled emergence of mine water (Younger, 2001). Consequently during the summer of 2000, test pumping was carried out at Frances by International Mining Consultants (IMC) on behalf of the Coal Authority (CA), an agency of the UK

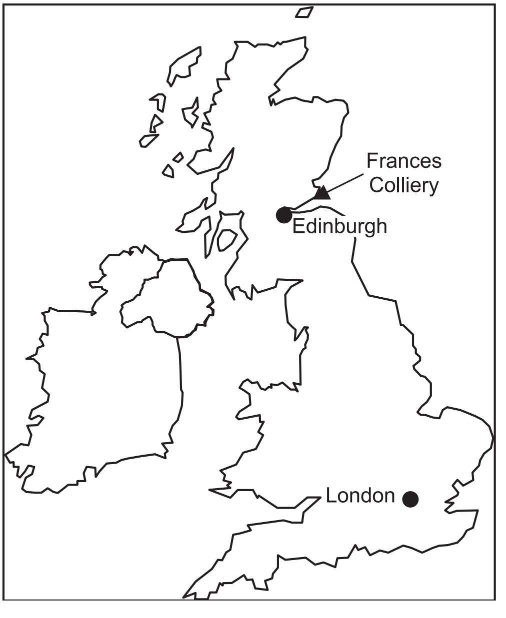

Fig. 1. Map showing the location of Frances Colliery within the UK.

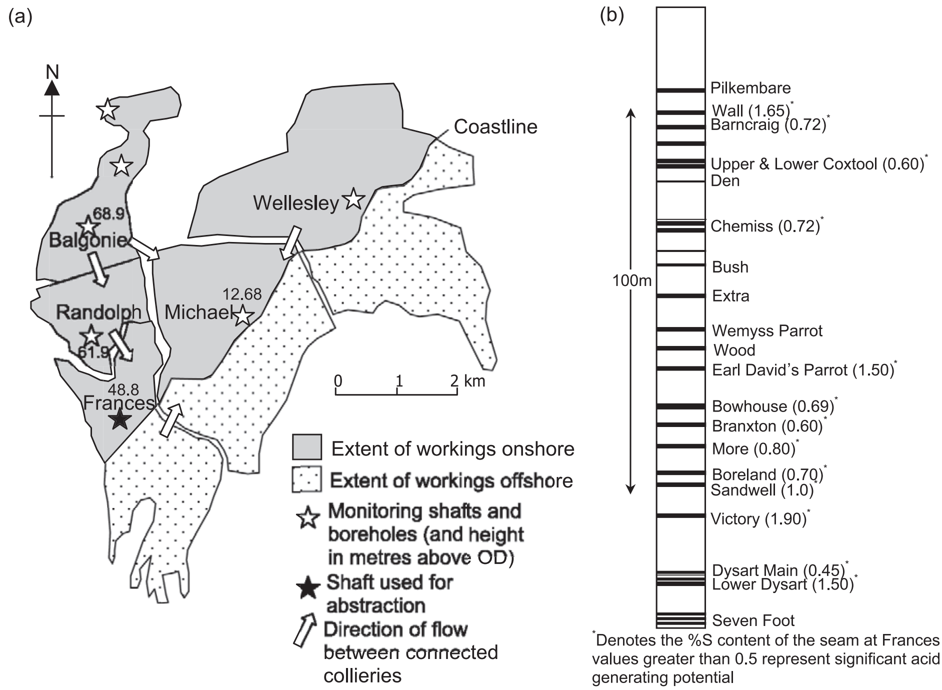

Fig. 2. (a) Map showing the abandoned collieries of the East Fife Coalfield (after Sherwood, 1997) emphasising the major mines adjoining Frances. Shaded areas are those underlain by old workings and the arrows show the direction of water movement and the approximate position of interconnection between each colliery. (b) Generalised Westphalian coal seam sequence for East Fife (after Knox, 1954) showing sulphur contents of some of the seams as reported at Frances Colliery (data supplied by British Coal in 1994).

government. The purpose of this test pumping was to determine the best pumping rate to maintain the mine waters at a prescribed level within the coalfield and to examine any changes in water quality which pumping might induce. These investigations have yielded a data-set of particular value in understanding stratification, as well as illustrating one of the main reasons why stratification is of practical interest. Initial optimism over the level of treatment which a given mine water may need is soon confounded when it becomes evident that the bulk of the water is of poorer quality than the first waters pumped, which turn out to have represented relatively benign "upper" waters from the stratified water column.

2. Geological setting of study area

The East Fife Coalfield is composed of Coal Measures strata of Carboniferous (Westphalian) age that were subjected to folding during the Late Carboniferous. This folding created a series of NNE–SSW trending anticlines and synclines. Frances Colliery (NT 309938) lies near the central trough of one of these synclines, in which a thick (approximately 500 m) Coal Measures sequence (consisting of alternating sandstone, limestone and shale beds) is preserved, containing 20 coal seams which were formerly deemed to be of workable thickness (Knox, 1954).

The observation that the total sulphur content of coal seams is a reliable indicator of their capacity for generation of acid mine drainage has been described by Caruccio and Ferm (1974) and Younger (1993, 2000). The geological sequence at Frances (Fig. 2b) contains several high sulphur coals associated with marine bands (i.e. beds of clastic sediment deposited in marine/brackish water environments which are notoriously rich in pyrite). The Dysart Main Seam, for instance, which was the most widely worked seam in the coalfield, is a high sulphur seam especially in the adjacent Randolph Colliery where it was found to contain up to 3% sulphur by weight. Other seams contain even more sulphur (e.g. the Lower Dysart and Victory seams; Fig. 2b). There is documented evidence (Kerr, personal communication, 2000) that water pumped from Randolph Colliery in the past had low pH (as low as 3) and high iron concentrations (up to 700 mg/l). An inspection of the shaft section for Frances shows that four roadway insets are submerged; these roadways access the Lower Sandwell, Lower Dysart, Lethemwell seams and also the pit bottom. It is necessary to consider these roadways as potential sources of poor quality water (especially the roadways that follow the high sulphur seams e.g. the Lower Dysart). Data from these roadways were also used to assess the flow regime within the mine as described in the Hydraulic analysis section.

3. Test pumping at Frances Colliery

When Frances Colliery finally closed, and operational pumping in the Frances and adjoining collieries ended in December 1995, this marked the end of dewatering in the East Fife Coalfield as a whole, and the beginning of regional water table recovery in

Table 1
Pumping rates and iron concentrations at Frances and Michael Collieries prior to closure in 1995

Frances			Michael		
Date	Pumping rate (l/min)	Iron concentration (mg/l)	Date	Pumping rate (l/min)	Iron concentration (mg/l)
April 1993		18.1	April 1993	15,502	41.1
May 1993	8710		May 1993	15,766	
June 1993	4082	20.1	June 1993	15,929	35.9
July 1993	3927		July 1993	16,807	
August 1993	4523	17.2	August 1993	18,325	38.9
September 1993	4201		September 1993	16,561	
October 1993	4591	6.5	October 1993	19,398	39.3
November 1993	4882		November 1993	19,216	
December 1993	4582	14.3	December 1993	17,302	34.6
January 1994	4801		January 1994	13,874	
February 1994	4410	16.2	February 1994	12,261	38.1
March 1994	5655		March 1994	12,270	
Average	4942	15.4	Average	161,010	38.0

numerous interconnected collieries (Younger et al., 1995). Table 1 shows the former pumping rates at both collieries during 1993 and 1994. It also shows the iron concentration of both of these discharges. The table shows that Michael was pumped at a higher rate than Frances and that the discharge from Michael contained more iron than that from Frances. A legal agreement signed at the time of closure stipulated that when the recovering mine waters reached 56 m below Ordonance Datum (bOD), pumping should be recommenced to control water levels sufficiently to prevent uncontrolled gravity-flow discharges of ferruginous mine waters in sensitive surface water catchments nearby (Younger et al., 1995; Sherwood, 1997; Younger, 2001). As 56 m bOD began to be approached by the rising mine water, test pumping was commissioned by the UK government's Coal Authority to help identify the pumping rate necessary to achieve a steady water level within the flooded workings. An ancillary aim was to examine any changes in water quality which might occur during test pumping as an aid to outline treatment process design (as will be seen, this initially ancillary objective soon came to assume a certain centrality in management priorities due to surprises arising from stratification processes).

4. Hydraulic analysis

Test pumping at Frances was undertaken from 7th of August 2000 to 24th September 2000. A three-step test was carried out as detailed in Table 2. During this time, water levels were lowered by around 3 m. Hydrological evidence suggests that when the large, open voids within flooded collieries are pumped, as pumping rate increases, turbulent flow becomes the dominant flow regime and the amount of laminar flow in the system decreases; this is of hydrochemical significance since turbulence leads to far greater mixing of waters than does laminar flow. Turbulent flow has been successfully modelled in open mine roadways for relatively simple single-seam systems by Adams and Younger (2001) and Nuttall et al. (2002). However, parameterisation for a 20-seam system as at Frances would be very complex indeed. Therefore, at Frances, it is necessary to rely upon simpler analytical tools to provide information about the dominant flow regime. Several lines of evidence indicated the existence of turbulent flow in the Frances system. Plotting discharge (Q) against the specific capacity (s/Q) enables determination of the predominant flow regime (i.e. laminar or turbulent) occurring within a system to be made (Driscoll, 1987). It is possible to calculate the approximate percentage of laminar flow (L_p) in the

Table 2
Positions of the submerged roadways at Frances showing Reynolds Numbers for each

Inset name	Inset depth (m bOD)	Reynolds Number	No. of roadways at shaft
Lower Sandwell	115.79	350	1
Dysart Main	Roadways closed	–	Not applicable
Lower Dysart	188.94	190	2
Lethemwell	270.72	242	2
Pit Bottom	282.18	242	1

system from the specific capacity curve by determining the slope (C) and the y-intercept (B) and applying Eq. (1) (Driscoll, 1987):

$$L_{\mathrm{p}} = \frac{BQ}{BQ + CQ^2} 100 \quad (1)$$

A rough calculation of the percentage of laminar flow present in the system at Frances indicates that there is a large component of turbulent flow. This increases as the mined voids are pumped at higher discharge rates until at the end of the test over 90% of the flow was estimated as being turbulent.

The second piece of evidence for the presence of a predominantly turbulent flow regime comes from the calculation of Reynolds Numbers. For Frances, a detailed section of the shaft was available which showed that five worked seams are submerged (Table 2). However, the roadways driven along the Dysart Main Seam are believed to be sealed by steel doors. It was possible to calculate the Reynolds Numbers for the four open submerged seams which intersect the shaft using Eq. (2). In the submerged portion of the shaft, there are six roadways from which water can flow towards or away from the shaft (refer to Table 2 for the number of roadways driven at each seam/shaft intersection). In order to calculate Reynolds Numbers, we assume that the flow in any one of these roadways will be of the order of $Q/6$ (where Q is the pumping rate); although in reality, it is unlikely that each roadway will make an equal contribution to the flow. The roadways also differ in cross-sectional area (e.g. the Lower Sandwell roadway has a cross-sectional area of 19 m and the Lower Dysart roadway has a diameter of 35 m), hence, the differing Reynolds Numbers calculated for each seam (Table 2).

$$R = \rho dv/\eta \quad (2)$$

Where ρ = fluid density, d = pipe diameter (or roadway diameter in this case), v = flow velocity (calculated from Q and the cross-sectional area of the roadway) and η = viscosity (in this case, the viscosity of water used was $1.14 \times 10^{-5} \mathrm{m^2/s}$).

In general, turbulent flow begins to occur at Reynolds Numbers exceeding 10. Table 2 shows that the Reynolds Numbers gained for Frances greatly exceed the value of 10 and therefore turbulent flow must be dominant within these workings. The presence of a predominantly turbulent flow regime may have long-term implications for the efficiency with which such large open mined voids can be pumped, since localised drawdowns at the pumped shaft will be substantially greater than would be anticipated under laminar flow conditions. This would result in greater pumping heads being required to achieve the same regional drawdown as would be predicted using conventional groundwater flow modelling.

5. Sampling methods

Water samples from the Frances shaft were taken using a depth sampler which can be lowered to a specific position within the shaft and then closed (by dropping a messenger weight down the cable) to trap a sample from that depth. In the field, measurements of conductivity, Eh, pH and temperature were made using a Myron 6P Ultrameter which was calibrated each day. Alkalinity was also measured in the field using a Hach digital titrator. Unfiltered cation samples (for analysis for total Ca, Mg, Na, K, Sr, Fe, Al and Mn) were taken in preacidified 125 ml polythene bottles. Anion samples (for analysis of SO_4 and Cl) were taken in unacidified 125-ml bottles. Analysis was carried out at the University by atomic absorption using a Unicam 929 AA spectrometer (for cations) and ion chromatography using a Dx-100 (for anions).

6. Stratification and pumped water quality at Frances Colliery

Site operators had taken depth samples from the Frances shaft on three occasions before the test pumping began (Fig. 3) at positions suggested from inflections on conductivity and temperature logs run down the shaft on several occasions following mine abandonment. The conductivity and temperature profiles gave evidence of influxes of waters of distinct quality at around 221 m bOD within the shaft. The depth samples showed that the water lying towards the base of the shaft was of lower pH and higher salinity than the shallower waters. The top 200 m of the water column was of better quality (i.e. iron concentrations of less than 10 mg/l, pH of around 7 and a conductivity of 3000 μS/cm). The deepest 70 m of the water column sampled contained the poorest quality water (i.e. iron concentrations greater than 500 mg/l, a pH of around 5 and a conductivity of 20,300 μS/cm).

The profiling and depth sampling carried out prior to test pumping were invaluable for revealing the existence of stratification within this system, and the site operators initially hoped that if the mine water was pumped from a relatively high level within the shaft then the top layer of better quality water could be pumped from the workings without entraining poorer quality water from depth. Unfortunately (as has also happened at metal mine sites in the UK and elsewhere; Younger and La Pierre, 2000; Johnson and Younger, 2002), this did not turn out to be the case.

Table 3 summarises how mine water chemistry changed during the test. Initially, the pumped discharge was net alkaline with a pH of 6.5, an alkalinity of around 400 mg/l (as

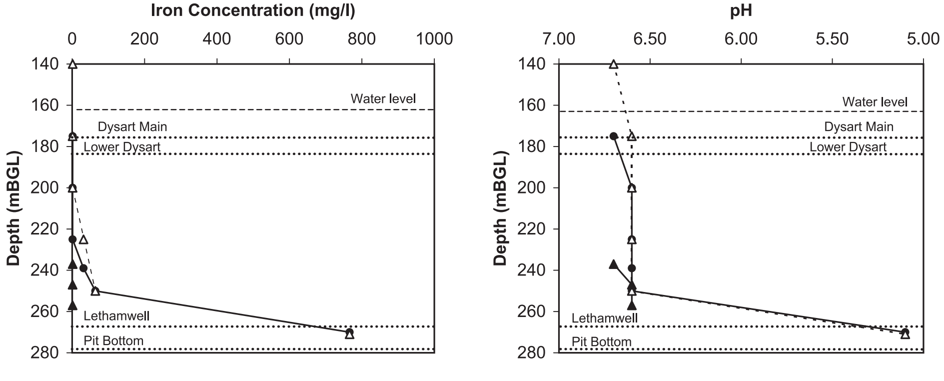

Fig. 3. Graphs showing stratification of various determinands in Frances Shaft shortly after cessation of pumping (▲ = 12/12/95) and at two times during the period of mine water recovery (● = 02/07/97△ = 25/08/98). The relevant coal seams are marked on the plot.

Table 3
Summary of water quality of the Frances pumped mine water at various stages throughout the pumping test

Determinand	Initial	1 Day	9 Days	48 Days
pH	6.34	5.22	4.99	4.8
Alkalinity (as mg/l $CaCO_3$)	437	75	0	0
Conductivity (μS/cm)	5557	25,550	27,610	26,500
Total Fe (mg/l)	6.5	406.7	546.8	596.6
Al (mg/l)	B.d.[a]	14.65	22.58	51.6
Mn (mg/l)	3.41	24.96	26.75	24.9
SO_4 (mg/l)	4975	4223	6755	6254
Cl (mg/l)	14,930	13,063	18,324	18,281
Ca (mg/l)	487.5	836.5	770	903.5
Na (mg/l)	955.5	4316	5122.5	4935.5
K (mg/l)	46.5	98	108	94
Mg (mg/l)	182	896.5	873.5	930

[a] B.d.: below detection limits of 0.5 mg/l for Al.

$CaCO_3$) and an iron concentration of around 10 mg/l. However, following 16 h of pumping, the discharge became net acidic with a pH of 4.8, an alkalinity of 75 mg/l (as $CaCO_3$) and an iron concentration of 400 mg/l. Aluminium (which had previously been below detection limits) was now encountered at concentrations of around 15 mg/l. By the end of the test, the discharge had no alkalinity and the pH had dropped to around 4. Metal concentrations had also increased again (Table 3), with almost 600 mg/l of iron and 52 mg/l of aluminium. The pumped mine water was discharged into two purpose-built treatment lagoons whence it was discharged to the North Sea (Firth of Forth).

Chemical analysis revealed that the samples became markedly more saline over the course of the test. When the pumped Frances mine waters are plotted on a piper diagram (Fig. 4), two distinct end members were defined. One end member, which plots nearer the

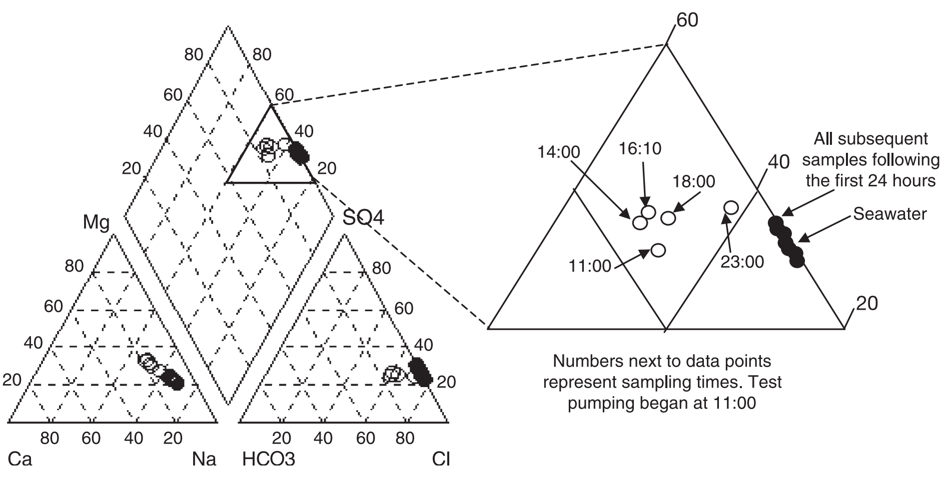

Fig. 4. Piper diagram plotting the Frances pumped mine waters. Inset diagram shows the evolution of mine water composition over the first 24 h of the test (test pumping began at 11:00).

centre of the diagram, represents the better quality water from the surface of the water column which was pumped at the start of the test and had a conductivity of around 5000 μS/cm. This water is presumably derived mainly from shallow-sourced recharge into the shaft and was pumped during the first 16 h of the test. The other end member was the water that was pumped at the end of the test (conductivity 26,000 μS/cm), which plots towards the sodium and chloride fields, and thus the seawater plotting position. The presence of a seawater component was also confirmed by isotope analysis of samples taken throughout the test. This strategy corroborates earlier suggestions that there was a seawater component in the water pumped from Frances during mining (Younger et al., 1995; Younger, 2001). This result is interesting, inasmuch as the undersea portions of the workings were always very dry (W. Kerr, former Frances mine manager personal communication, 2000), and repeated safety assessments in these mines never found evidence for sea water ingress.

7. Discussion

Mine water stratification is a phenomenon of both coal and metal mines in which distinct changes in water quality parameters are encountered with increasing depth. Stratification can be detected by undertaking depth sampling and/or geophysical logging of the water column in a mine shaft or borehole. If stratification is present, better quality water will normally be found lying above poorer quality water. Depth sampling at several sites e.g. Wheal Jane (an abandoned tin mine in Cornwall, UK; Younger and La Pierre, 2000), Frazers Grove (an abandoned fluorspar mine in County Durham, UK; Johnson and Younger, 2002), the anthracite mines of Eastern Pennsylvania, USA (Ladwig et al., 1984) and at the abandoned Frances Colliery (this study), has shown that stratification in mine waters is not usually gradual. Often, the position down a shaft at which water quality changes corresponds to an inflow from a previously worked roadway or tunnel. As was previously mentioned, at Frances, the major change in quality corresponded to the connection with the adjacent Randolph workings via the Dysart Main seam.

Younger and La Pierre (2000) noted that the occurrence of stratification implies that mechanical mixing within the water column is at a minimum and that any flow which does enter the stratified system can be assumed to be predominantly laminar. This further suggests that there are few lateral inflows and outflows in existence. This statement can be supported by findings of the test pumping at Frances and also by referring to the existing literature.

Johnson and Younger (2002) studied the recovery of mine water at an abandoned fluorspar (previously lead–zinc) mine in County Durham (UK). They found that the shaft at this site was stratified while steady mine water recovery was in process. However, when the rising water reached a surface adit that intersected the shaft, mine water began to flow along this route. This was accompanied by a disruption in the flow regime. Turbulent flow which was induced as the mine water flowed along the roadway allowed some mixing within the shaft, causing the geochemical stratification to be lost. Water that flowed along the level emerged at the surface and had a zinc concentration which peaked at 120 mg/l, whereas previous depth sampling during the stratified period found zinc concentrations of no more than 10 mg/l at the surface of the water column (Johnson and Younger, 2002).

These findings were mirrored at Frances, when during the initial stages of the test, iron concentrations rapidly increased from around 50 mg/l to over 400 mg/l overnight. The following sequence of postulated events explains how stratification may build up within a system and how it may subsequently be lost (refer to numbered points in Fig. 5).

(1) The shaft fills up to the point just below an intersecting roadway. Stratification of the water column takes place. Poorer quality water is restricted to the bottom of the shaft and better quality water remains above.
(2) The water level rises steadily and the water reaches a connection. As the water flows along this route and fills the adjacent workings, stratification is lost due to turbulent flow along the roadway causing mixing within the main water column (as observed at Frazers Grove Mine; Johnson and Younger, 2002).
(3) As the water fills the adjacent workings via the connection, a more stable rise in water level will continue. Stratification may then redevelop.
(4) A pump is installed within the shaft. When pumping begins, the initial water quality reflects that found at the top of the shaft, and this quality remains until approximately one shaft volume has been cleared. By this time, the turbulence induced by the act of pumping has caused mixing of all the water in the shaft and poor quality water will be gained (this was observed at Frances Colliery).

To shed further light on the rapid changes in water chemistry at Frances, some mixing calculations were performed. These involved making some basic assumptions. The end members for the mixing series were taken as:

(i) The initial water taken from the top of the stratified water column as pumping began.

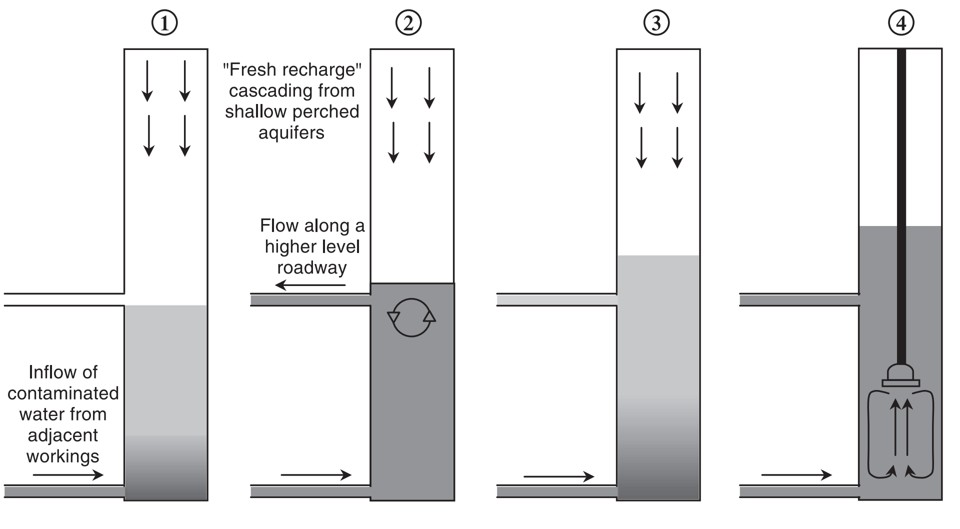

Fig. 5. Schematic diagram showing how stratification can build up within a system (refer to Discussion for an explanation of each point).

(ii) The most contaminated water taken from the base of the stratified shaft by depth sampling before test pumping began.

All other waters encountered during the test were assumed to represent various mixtures of these two waters. The mixing calculations were based upon the iron concentrations of both end members i.e. 3.4 and 766 mg/l, respectively. Iron data were used because data were more readily available. However, in order to corroborate the mixing calculations, the available chloride data were also used (chloride behaving more conservatively than iron); the results were in good agreement (Fig. 6). It was anticipated that there would be a gradual relationship between the amount of mine water mixing and the cumulative volume pumped as the test proceeded (Fig. 6). Instead, the plot obtained shows a large step increase in iron concentrations (and consequently the amount of deduced mixing) after approximately 2500 m^3 of mine water has been pumped.

Shaft logs and sections for Frances show that the shaft at Frances Colliery is elliptical with a long-axis diameter of 6.86 m and a short-axis diameter of 3.05 m. The area of the shaft was calculated as 19.3 m^2. At the start of the test, the depth of the water column in the shaft was around 131 m. Therefore, the volume of water in the shaft at the beginning of the test was 2528 m^3. Comparing this volume to Fig. 6, it becomes apparent that the drastic changes in water quality occurred after one shaft volume equivalent had been pumped. This realisation can help explain the changes in water quality that occurred. Initially, the shaft was mainly filled with shallow-sourced water, but at depth, there is a more contaminated inflow which has its source in roadways which connect to the known acid-generating workings of the adjacent Randolph colliery; this inflow gives rise to stratification. However, the Randolph workings are well inland and not undersea; therefore, the saline net-acid mine water gained from test pumping at Frances must be a

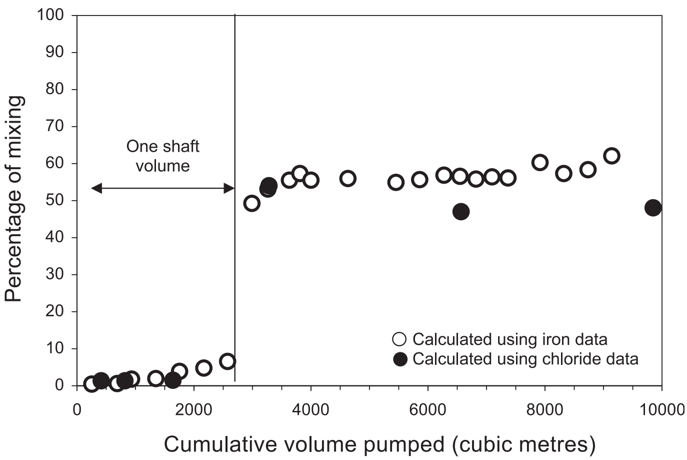

Fig. 6. Graph showing the amount of mine water mixing with the shallower recharge water against the cumulative volume pumped for the first 10,000 m^3 of pumping. Note the abrupt change in mixing after one shaft volume has been pumped (○ represents mixing calculations using Fe concentrations, ● represents mixing calculations using Cl concentrations).

mixture of seawater ingress and acid mine drainage sourced from workings in high-sulphur seams, such as those at Randolph. The sulphate to chloride ratio for seawater (1:19, Appelo and Postma, 1996) was used to calculate the amount of mixing between seawater (from saline intrusion into the workings). These calculations showed that up to 30% of seawater was mixed with the acid mine drainage.

When pumping commenced, the induced turbulence began to break up the stratification, leading to mixing of the poor quality deep inflow water with the better quality, shallow-sourced water. At this time, approximately 10% of the poorer quality inflow water was mixing with the better quality, shallow-sourced recharge. After approximately 16 h of pumping, one shaft volume had been pumped. The dilution effect of the shallow-sourced water in the shaft had now been greatly reduced so there was less of the better quality water available for mixing. The proportion of poor quality inflow water steadily increased over the remainder of the test. Due to the fact that the better quality, shallow-sourced water was not replaced as quickly as the mine water was pumped, increasing amounts of the poorer quality water were incorporated into the mixture, this led to an eventual mine water containing just under 600 mg/l of iron. Fig. 6 shows the amount of mixing occurring over the first 10,000 m^3 of water pumped. Changes in pumping rate did not appear to directly affect mine water iron concentrations; however, it is likely that the increases in pumping rate led to an increase in the degree of turbulence and hence depth of mixing around the pump.

An additional empirical observation made at Frances (and also supported by existing literature, Johnson and Younger, 2002; Ladwig et al., 1984) is that the concentrations of the major contaminant metals such as iron and zinc are some two orders of magnitude greater at the bottom of a stratified system than at the top. This observation may be useful when trying to predict the likely eventual water quality of a mine system where available data are limited.

8. Conclusions

Experiences from the test pumping carried out at Frances Colliery underline the importance of determining the extent of stratification within a mine system. System-wide mine water stratification can cause rapid, unexpected changes in water quality of sufficient magnitude to badly upset the design and functioning of any treatment system. If stratification is present, it can be assumed that the poorer quality water will be more representative of the long-term water quality. Some guidance on dealing with stratified systems can be given on the basis of the experiences at Frances, combined with reports from previous literature:

(i) Stratification is likely to develop in a shaft if water levels in the mine system are gradually recovering.
(ii) Stratification is most likely to develop if a shaft has only a small number of potential inflow or outflow routes (i.e. old mine roadways).
(iii) Attempts to selectively pump only the better quality water from the top of a stratified system are highly unlikely to be successful due to turbulence induced by pumping, which will disrupt the stratification and lead to extensive mixing of waters.

(iv) Information about the seams or veins associated with any inflows may be a useful indicator of water quality associated with a particular horizon e.g. high sulphur coal seams will have a greater acid-generating potential. Any information that is available from any interconnected mines may also be useful for providing an insight into future water quality.
(v) The differences in the concentrations of metals such as zinc or iron may be two orders of magnitude greater at the bottom of a stratified system than at the top.
(vi) If a stratified system is pumped, changes in water quality are most likely after one shaft volume has been pumped i.e. after the majority of the relatively benign shallow-sourced water has been removed.

Stratification is easily detectable by depth sampling or conductivity/temperature logging providing that shafts and boreholes are accessible. If possible, test pumping is also useful to give information about the evolution of water quality over time, but the duration of test pumping must exceed t_{min} which is defined by:

$$t_{\mathrm{min}} = \text{Pumping Rate}/\text{Shaft Water Volume}$$

If treatment systems are to be designed for waters in currently stratified systems, then they must be designed on the basis of samples taken at depth within the system, because the turbulence induced by pumping (or gravity discharge) will eventually cause these poorer quality waters to appear at the surface.

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