Pumping rates and the iron content of shaft mine water

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This paper attempts to determine the mechanism by which pumping rate controls the iron content of water pumped from a deep shaft coal mine.

Mine water pumped to the surface is a mixture of ferruginous drainage from the flooded workings with drainage from the non-flooded workings. Model studies indicate that the concentration of iron in the water from flooded workings is independent of the pumping rate. The iron content of the water pumped to the surface is dependent on the relative amounts of the two drainage components and this is controlled by the pumping rate. The implications of these effects for pollution abatement policies are illustrated and discussed.

It has been reported[1] that the concentration of iron C_C mg/l in the water pumped from a flooded shaft mine (Mainsforth) in the North Eastern coalfield varied with pumping rate $Q' m^3/s$ according to the regression equation:

$$\text{Log } C_C = 1{\cdot}684 + 0{\cdot}102 \text{ Log } Q' - 0{\cdot}000858t \qquad (1)$$

where t was the number of days after the restarting of pumping to maintain a constant mine water level.

Ineson[2] indicated that the iron content of water from a mine in South Wales also increased directly with pumping rate. No data were presented, however. Variations in iron content with pumping rate are of potential importance for several reasons, but perhaps most important is the fact that if the conditions of consent for a given discharge were to set limits to the allowable iron content, the effect of pumping rate would have to be considered. A clearly established relationship, between pumping rate and iron content, might also encourage the adoption of some degree of flexibility in pumping arrangements, that might enable the degree of stream pollution at low stream flows to be reduced.

Controlling mechanisms

Using the sampling system developed by Frost et al[3], the author confirmed observations,[4] made previously[5,6] in the USA, that mine drainage tends to stratify within the shafts of all flooded mines. On one occasion samples were taken at depth intervals from a non-pumping shaft whilst water was pumped from an adjoining shaft. Table 1 compares a partial chemical analysis of this discharge with those of the depth samples. Clearly the discharge mainly consisted of the more mineralised drainage (water type B) from the lower flooded workings with the inclusion of lesser amounts of water (type A) from the unflooded workings at higher levels.

One way in which the pumping rate may exert control, therefore, is by determining the relative amounts of these two waters in the discharge. Secondly, it could determine an overall mass transfer coefficient for the removal of oxidised pyrite from rocks within the flooded workings.[1]

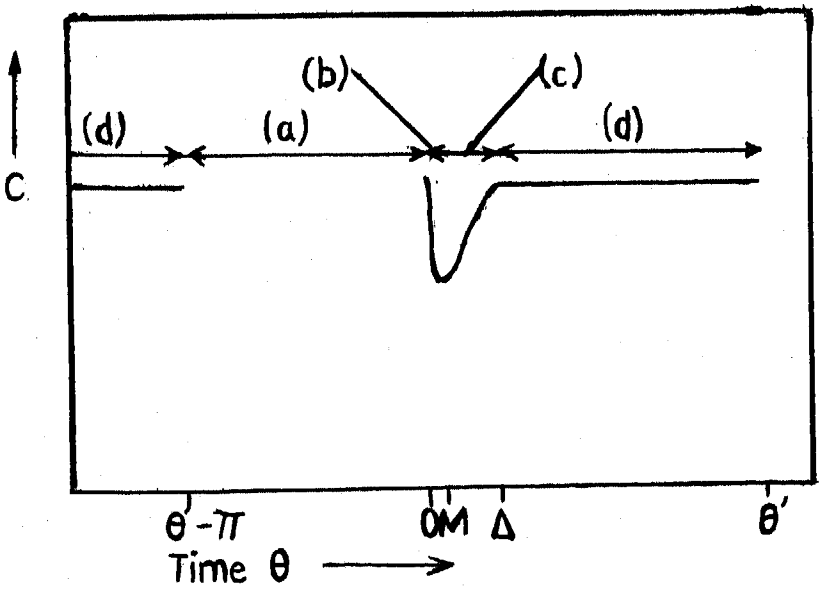

Figure 1: Diagrammatic representation of the sequence of events in intermittent pumping showing four phases.

Model

Derivation

It has been shown[3,7] that intermittent pumping results in marked compositional variations in the water discharged from a shaft mine. These are shown schematically in Figure 1. Water stored in the pipe range from the previous cycle is initially discharged, followed by water type A which (with no pumping) preferentially accumulates in the upper regions of the flooded shaft. Gradually, more water from the flooded workings is pumped to surface, until the two drainage components are discharged at approximately constant rates and a quasi-steady state is reached. It is only then that representative samples of the discharged water may be taken.

From these water quality variations over a pumping cycle, the iron content of the drainage from the flooded workings may be estimated as follows: The total rate of groundwater inflow, Q, to the mine is equal to the sum of the rates of formation of water types A and B, ie

$$Q = Q_A + Q_B \qquad (2)$$

The pumping rate, Q', may be related to the groundwater inflow rate by:

$$Q' = KQ \qquad (3)$$

where K is a constant under a given set of conditions.

Whence:

$$Q' = K(Q_A + Q_B) \qquad (4)$$

The total volume of water, V, discharged in phases (b)–(d) is given by:

$$V = \theta' Q' \qquad (5)$$

A combination of equations (4) and (5) yields:

$$V = K\theta' (Q_A + Q_B) \qquad (6)$$

Assume that there is zero net accumulation of water A in phases (a)–(d). The total volume, V_A, of this water discharged in phases (b)–(d) is given by:

$$V_A = \pi Q_A \qquad (7)$$

The total volume, V_B, of water B discharged in phases (b)–(d) is given by:

$$V_B = V - V_A \qquad (8)$$

whence combining equations (6), (7) and (8) yields:

$$V_B = K\theta'(Q_A + Q_B) - \pi Q_A \qquad (9)$$

The total mass of any dissolved species discharged from the mine in phases (b)–(d) is given by:

$$\int_0^{\theta'} Q'C.d\theta = V_A C_A + V_B C_B \qquad (10)$$

where C is the concentration of that species in the water discharged at time θ.

Combining equations (7), (9) and (10), and substituting I for $\int_0^{\theta'} C.d\theta$ yields:

$$Q'I = \pi Q_A C_A + (K\theta' Q_A + K\theta' Q_B - \pi Q_A) C_B \qquad (11)$$

Equation (4) may be recast as:

$$Q_B = Q'/K - Q_A \qquad (12)$$

and combination of equations (11) and (12) yields:

$$Q'I = \pi Q_A C_A + \theta' Q' C_B - \pi Q_A C_B \qquad (13)$$

TABLE II: Data for the determination of Q_A at Mainsforth pumping station

Constituent	*C_A (mg/l)*	*I** (mgh/l)*	*C_C** (mg/l)*	*Q_A (m^3/s)*
Total	0·3			—
Iron	6·6	—	31·3	—
(Fe)	—			—
Total	0·00			0·0159
Manganese	0·40	24·14	2·29	0·0189
(Mn)	0·85*			0·0241
Total	511			0·0233
Hardness	614	9,444	861	0·0314
(as $CaCO_3$)	590*			0·0294
Sulphate	318			0·0252
	686	15,000	1,472	0·0348
(SO_4)	597*			0·0320
Total	273			0·0202
Alkalinity	378	5,491	499	0·0345
(as $CaCO_3$)	368*			0·0328
Chloride	40			0·0245
	98	1,918	188	0·0371
(Cl)	69*			0·0302

* *Compositional minimum values for* 19–20 *Feb.* 1974. *See references* 4 *and* 7. *Other values for C_A are taken from Table* 1.

** *Refers to the pumping cycle of* 19–20 *Feb* 1974. *See references* 4 *and* 7.

Over the quasi-steady state period, the time averaged concentration of dissolved species in the discharge is defined by:

$$\frac{1}{\theta' - \Delta} \int_{\Delta}^{\theta'} c.d\theta = \frac{Q_A C_A + (Q' - Q_A) C_B}{Q'} \qquad (14)$$

Multiplying equation (14) by $\pi Q'$ and substitution of C_C for $\frac{1}{\theta' - \Delta} \int_{\Delta}^{\theta'} C.d\theta$ gives:

$$\pi Q' C_C = \pi Q_A C_A + \pi Q' C_B - \pi Q_A C_B \qquad (15)$$

TABLE 1: Chemical analyses of the water in Mainsforth west shaft and the discharge from the east shaft on 11-10-74. Water level —33·9 m AOD. All chemical analyses are reported as mg/1.

Sample level in west shaft (m AOD)	*Total hardness as ($CaCO_3$)*	*Sodium (Na)*	*Total iron (Fe)*	*Total manganese (Mn)*	*Sulphate (SO_4)*	*Total alkalinity as ($CaCO_3$)*	*Chloride (Cl)*
—40·5	511	73	0·3	0·05	318	273	40
—53·6	563	181	3·0	0·12	473	324	66
—64·9	586	—	5·8	0·28	550	336	78
—74·1*	564	183	3·0	0·15	471	318	67
—92·4	564	197	3·2	0·15	568	318	72
—117·3†	614	300	6·6	0·40	686	378	98
—144·8	619	308	6·8	0·41	684	381	99
—170·1**	884	825	21·7	1·43	1,529	636	237
Drainage discharged from the east shaft	792	688	16·5	1·08	1,335	595	219

* 3.6 *m above the inset of seam J.* † *Opposite L_2 seam inset.* ** 6·1 *m above the inset of seam N.*

Combination of equations (13) and (15) yields:

$$C_B = \left(\frac{\pi C_C - I}{\pi - \theta'} \right) \qquad (16)$$

whilst rearrangement of equation (15) yields:

$$C_B = \frac{Q' C_C - Q_A C_A}{Q' - Q_A} \qquad (17)$$

Application

Since both C_C and I may be determined numerically from chemical analyses of samples taken over an entire off-peak pumping cycle, C_B may be easily found from equation (16). Data collection is a time consuming affair, however, and a less demanding, more routine method depends on obtaining one value for C_B as above and an independent determination of C_A. Equation (17) may then be used to estimate the value of Q_A and, subsequently, to monitor C_B with only the pumping rate and iron content of the steady state discharge needing to be determined. C_A may be determined directly by taking depth samples from the pumping shaft or an adjacent shaft. Alternatively, a first approximation may be made by equating C_A to the compositional minimum of the pumping cycle.

The above methods have been used to evaluate data obtained from Mainsforth pumping station, details of this station having been reported pre-

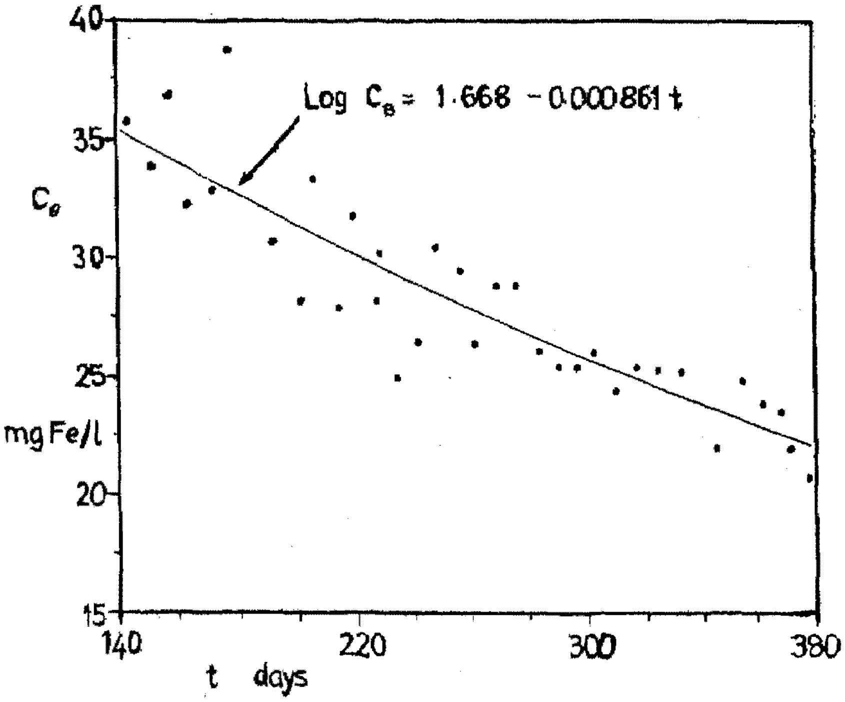

Figure 2: Reduction in the estimated iron content of the drainage from the flooded workings.

viously.[1,7] In Table 2 it may be seen that, in this case, the values of Q_A estimated from the direct and approximate determination of C_A do not differ significantly. In the remainder of this analysis values of 0·0265 m^3/s and 3·3 mg.Fe/l have been adopted for Q_A and C_A respectively.

The model has been checked and found to give reasonably good results. Both the predicted flow rate of water in the upper seams (Q_A) and concentration of iron in the flooded workings (C_B) agreeing quite well with direct independent measurements.

From previously published Q' and C_C values, equation (17) has been used to derive a series of C_B values, plotted in Figure 2. A linear regressional analysis of the variation of Log C_B with t yields the regression equation:

$$\text{Log } C_B = 1{\cdot}668 - 0{\cdot}000861t \quad (18)$$

with a correlation coefficient of 0·902 statistically significant at the 0·1% level, and a half life for C_B of approximately 350 days. However, a multiple linear regressional analysis of the variation of Log C_B with Log Q' and t yields a partial correlation coefficient for the partial regression of Log C_B on Log Q' of only 0·020 which is statistically insignificant. Thus the variation in the concentration of iron in the drainage from the flooded seams is essentially independent of the pumping rate, and may be best described by equation (18).

Discussion

The above results are contrary to those which might be anticipated from a theoretical description[1] of the flushing process. It might be thought, though, that any such control exerted by pumping rate would be masked by that exerted by antecedent pumping rates and regimes—the nominal retention time of water in the mine being in excess of 217 days. Thus data supporting the contention that pumping rate influences the rate of removal of pyrite oxidation products from flooded rocks is perhaps more likely to be obtained from a mine subject to a lower degree of flooding than Mainsforth.

Nevertheless, the iron content of the quasi-steady state discharge does increase with increasing pumping rate. This effect is more likely to be of significance where the two water types are markedly different—perhaps where the drainage from the flooded workings is acidic. Consider a hypothetical discharge for which C_A, C_B, Q_A, and Q_B have the values 0 mgFe/l, 600 mgFe/l, 0·014 m^3/s and 0·086 m^3/s respectively, dealt with by 4 pumps, each of capacity 0·050 m^3/s and all suspended at levels just below the water surface. The values of C_C which might be obtained are given by equation (14), and are plotted against Q' in Figure 3. Pumping rate would clearly be an important factor to take into consideration when sampling such a minewater and interpreting its analysis.

The discharge of mine water from underground to the surface is essentially excluded from the provisions of British pollution law. If future legislation should end this situation, it is

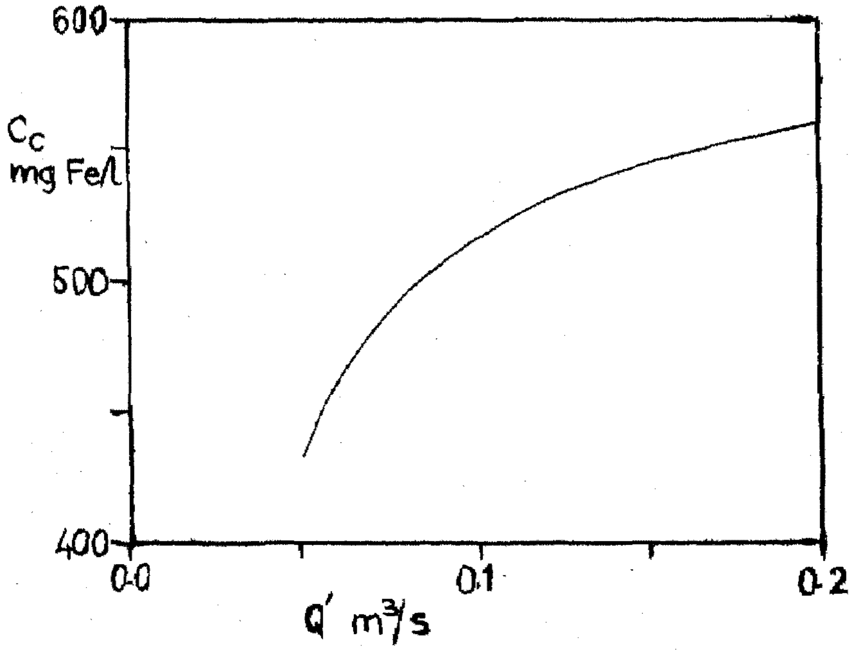

Figure 3: The effect of pumping rate on the iron content of mine water for a hypothetical case.

probable that separate consent conditions would be set (by the Water Authorities) for each new discharge—as is currently applied to the discharges from other industries. In the setting of these consent conditions the influence of pumping rate would have to be taken into consideration. For example, a corollary of the present study is that the daily iron load discharged from a mine—which might be regarded as its potential for causing pollution—is independent of the pumping rate employed, provided that the same volume of water is discharged over a 24 hour period. This is generally obtained in practice, where the aim is to keep the flood water at a relatively stable level.

If the concentration of iron or of acidity in a discharge is critical during periods of low stream flow, pumping might perhaps be phased to allow lower pumping rates to be employed at these times, pumping at higher compensating rates at other periods. Lower pumping rates would affect reductions in both discharge loads and discharge concentrations.

Conclusions

The iron content of a quasi-steady state discharge from a flooded shaft mine increases directly with pumping rate. It appears that the rate of discharge of the more mineralised and ferruginous drainage from the flooded workings is dependent on the pumping rate, but that the drainage from the higher non-flooded workings is pumped at a constant rate. The concentration of iron in the drainage from the flooded workings appears to be independent of pumping rate.

The effects of pumping rate should be considered when sampling mine water discharges and interpreting their analysis, and in the setting of consent conditions for a discharge. ■

Dr Frost is with the Water Research Centre, Stevenage.

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