Approach to Remediation of Ferruginous Discharges in the South Wales Coalfield

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ABSTRACT

The closure of most of the Welsh deep coal mining industry has resulted in a substantial increase in the number and impact of ferruginous minewater discharges due to the recovery of ground water levels. These discharges have resulted in environmental damage to many of the rivers in the affected areas.

This paper discusses the approach to investigations to derive possible solutions to the problems of ferruginous discharges. The discussion is based on a number of studies carried out by the authors in South Wales and overseas. The need to develop a conceptual model of the hydrological system is discussed. This has to include the hydrological regime, the past mining activities and the hydrochemistry of the ferruginous discharge.

Once the conceptual model is understood, possible solutions to reducing the impact of ferruginous discharges can be considered. The paper stresses that consideration must be given to source and migration control of the iron or the transporting water, as well as discharge treatment, if the most cost effective and acceptable means of solving the problem is to be found.

It is important to balance the cost of remediation with the environmental benefit. A technique of assessing the iron load in the receiving water using probabalistic and risk assessment techniques is described.

It is concluded that the use of these techniques and consideration of the conceptual model of the system can provide opportunity to solve the problem of ferruginous discharge by means other than direct treatment of the discharge.

INTRODUCTION

The closure of most of the Welsh deep coal mining industry has resulted in a substantial increase in the number and impact of ferruginous mine water discharges due to the recovery of ground water levels. These discharges have resulted in environmental damage to many of the rivers in the affected areas.

The National Rivers Authority (Welsh Region) (NRA) has carried out studies to assess the extent of the problem and to evaluate possible cost effective solutions. Similar assessments of the problem have been carried out by other NRA regions but unfortunately the NRA does not have the power or budgets to carry out the remedial works.

This paper discusses the approach to investigations to derive possible solutions to the problems of ferruginous discharges. The discussion is based on a number of studies carried out by the authors in South Wales and overseas. The methodology and approach will illustrate the importance of understanding the conceptual model of the ferruginous discharge process and the need to understand the risk associated with remedial works.

The views expressed in this paper are personal to the authors and do not necessarily reflect the views of either employers or clients.

PROBLEM DEFINITION AND APPROACH

Ferruginous discharges occur as a result of the process generally referred to as Acid Mine Drainage (AMD). In many cases the discharges themselves are not acid, but the chemistry of their formation involves the evolution of sulphuric acid from sulphide minerals, water and oxygen. It is known that levels of 1 to 2 mg/l of iron can cause ferruginous staining. Some of the larger discharges in South Wales contain about 5 or 6 mg/l iron while some contain over 100 mg/l Fe.

Ferruginous discharges have been occurring in South Wales for many years but it is with the recent closure of the last deep mines that the problem has dramatically increased and brought about wider impacts.

The key factors in proposing practical solutions to AMD are an understanding of the causes of the ferruginous discharge at each site and of the range of solutions which may be considered. The geology, topography and extent of old mine workings will usually limit the number of practical solutions, enabling studies to be rapidly concentrated on the useful areas.

An investigation therefore has three main components:

- Identification of the causes(s) of the discharge
- Assessment of environmental impact
- Identification and evaluation of appropriate controls

Successful understanding of the AMD problem requires input from hydrogeologists and mining engineers with local knowledge, as well as hydrochemists and engineers specialising in AMD remediation.

Cause of discharge

The first requirement of an AMD investigation is to understand the cause of the particular discharge and develop the conceptual model of the hydrogeological system. This includes an understanding of the mining history, extent and nature of mining, the hydrogeological regime, the hydrochemistry of the source, the movement of the AMD products and whether the processes are active or a result of remobilisation of previous deposits.

Environmental impact

An assessment of the environmental impacts including biological, fisheries value and the aesthetic impact of the discharges is required preferably using a simple ranking system. More sophisticated survey and assessment techniques are available (NRA R&D Note 37, R&D Report 6), but they are expensive and would be more appropriately carried out as part of detailed site investigation should it be economically justified.

Control strategies and solutions

For each site, a conceptual model of the system has to be prepared to illustrate the AMD source, the cause of the discharge and the possible hydrogeological and hydrochemical processes. From this, possible alternative remedial options can be identified and assessed, broadly costed and compared to the environmental benefit. More detailed mine plans and geology and additional hydrological information may provide a more detailed understanding of each site, but this level of investigation is usually not warranted in the first phase of investigation.

CAUSE OF THE DISCHARGES

Mining activity

Most of the present discharges result from underground mining activities which have led to the physical exposure of sulphide minerals in development adits, drives and shafts, as well as at the working faces. In addition, dewatering activities have led to the development of unsaturated conditions within the bedrock, which results in the vertical flow of oxygenated waters and allows for the potential ingress of oxygen.

The older mines were developed from surface outcrop in the upper coal measures but the more recent mines were in the deeper seams of the middle and lower coal measures accessed through vertical shafts. It is the upper coal measures which tend to contain higher levels of iron sulphide as well as some being present in the thick sandstone units which constitute the main aquifers in the coal measures.

Surface mines have not generated the same magnitude of problem as yet. The spoil material in the backfill as well as the waste dumps can contain pyrite which can produce AMD products. Often there is a delay of many years before the effects are noticed.

Ground water recovery and mobilisation of iron

Closure of the mines and cessation of pumping enables the ground water to recover. Recovery rates are variable but in South Wales recovery in many cases has occurred within a year or two. The ground water system tries to recover to its pre–mining condition but near surface and outcrop workings act as drains and result in mine water discharges before full recovery can be achieved. The migration of ground water through old workings which have been exposed to oxidising conditions for many years results in the ferruginous discharges. The source of iron can be previously deposited material in the aquifer and workings under dewatering conditions or from active oxidation of pyrite in the old workings.

ENVIRONMENTAL IMPACT

It is not the intention in this paper to discuss the environmental impact in detail as the effects and their assessment are complex. The impact generated by most of the discharges in South Wales, apart from a few notable exceptions, is primarily aesthetic with the characteristic red staining occurring at iron concentrations as low as 1ppm. There are some local effects on aquatic life, fish feeding, spawning and migration due to the blanketing effect of the iron precipitates. Some of the discharges are acidic but there is very little evidence of pollution due to elevated trace metals or other toxic elements.

The flow of the discharges ranges from less than $100m^3$/day to over $20{,}000m^3$/day and the iron concentration ranges from 2.0 to 200 ppm Fe. The magnitude of the impact is a function of the magnitude and flow regime of the receiving water as well as the initial chemistry and iron loading.

POSSIBLE CONTROL STRATEGIES

Solutions to AMD problems are often focused on treatment of the discharge, without regard for possible ways of preventing or reducing the problem. The primary purpose of developing a conceptual model is to highlight possible alternative means of solving the problem.

Control can be considered at three stages of the AMD process:

i) ***Source control** based on measures to prevent oxidation, acid generation and contaminant leaching*. If the development of soluble contaminants can be prevented in the first instance then there is no source from which migration can occur. Such source control is preferred as the primary or most positive control or barrier. Examples of *primary controls* would be flooding to prevent oxidation and alkaline addition to precipitate metals. Air sealing of adits can be beneficial in reducing iron load because active oxidation does require significant volumes of oxygen.

ii) ***Migration control** based on measures to prevent migration of contaminants*. This is termed *secondary control* and is considered when the source is already in existence or where its generation cannot be practically inhibited and migration of the contaminants must be prevented. Examples are plugs, covers and surface water diversion ditches, neutralisation zones and geochemical and biochemical barriers. In South Wales much of the pollution load is collected by water passing through the old, unsaturated workings. Changing the drainage path could provide the necessary reduction in iron load that would reduce the impact.

iii) ***Release control** based on measures to collect and treat contaminated drainage*. This is termed *tertiary control* and is generally applied only when primary and secondary controls are ineffective or too costly. Collection and treatment is usually the `control of last resort' as it requires long term operation and maintenance, implying long term management, costs and liability. However, it has proven to be necessary to utilise tertiary control at numerous mine sites where discharge standards could not be achieved by primary or secondary control measures. Examples include lime and sulphide precipitation treatment facilities. Less expensive, low care treatment facilities (sometimes referred to as passive treatment) such as wetlands, biological sulphate reduction and methods such as anoxic limestone drains (ALD's) also fall within this category.

SITE ASSESSMENT

Conceptual hydrogeological model

The first stage of a site assessment is to develop a conceptual hydrogeological model relating the water balance between recharge, ground water and surface water and the movement of ground water through the natural system. Mining interferes with the system and alters the way in which ground water flows and the levels to which ground water will ultimately recover. Ground water will still flow according to hydraulic gradients, but mine openings create preferential drains.

Mine plans show the extent of known workings, access points, such as shafts and adits, ventilation shafts and often some pumping data. Seam elevations may also be given which enable the shape of the seam surface and its relationship to the discharge to be evaluated and the relative proportions of flooded and unflooded workings to be estimated. The probable route of ground water through the workings, seams, aquifers or geological structure can be assessed from information on the plans, geological sections and our understanding of the hydraulic gradients. It should be noted however that particularly where shallow coal seams are concerned, the plans may be incomplete or non existent and assumptions have to be made.

Interconnection with other mines in the same seam and workings in other seams is also assessed to develop a conceptual model of how and why the discharges are occurring.

Discharge water quality and iron load assessment

There is often limited flow rate data and chemistry data available for the discharge and receiving water flows. The first step in the study for the assessment of the potential iron loadings being generated at each site therefore, is to synthesize the flow rate or hydrograph for both the discharge and the receiving water based on the nearest complete data set. Similarly, only partial databases are available for the iron concentration in the discharges. It is reasonable to assume average values based on limited data sets if the release of iron is controlled by chemical equilibrium, i.e., dissolution of secondary mineral phases. This estimate could be incorrect if the mechanism for release is dominated by active oxidation of sulphide minerals. For the latter case, the iron concentration in the discharge would vary with flow, with either a decrease or an increase in the iron concentration could be observed at peak flows. This can be confirmed with limited field work and sampling.

Key chemical factors

The chemistry of ferruginous discharges and their treatment, is very complex. There are some key factors which can be used to identify what the dominant process for iron generation is and what treatments would be most effective. These factors are summarised below:

- Ratio of flow in discharge to receiving water
- Ratio of iron content in discharge to the iron content of the receiving water
- Ratio of total to dissolved iron
- Redox potential and dissolved oxygen
- Sulphate content
- pH
- Alkalinity

The first objective in reviewing the chemistry is to identify which of the two primary iron release mechanisms is dominant:

1. Active oxidation of primary sulphide minerals
2. Dissolution of secondary mineral phases

Where the iron concentration is controlled by the active oxidation of the primary sulphide minerals, the rate of release is dictated by the reaction kinetics and the rate of transport, i.e., rate of flow. If all of the reacting surfaces are contacted by base flow, under which conditions all of the reaction products are transported away from the reaction sites, an increase in flow would result in a dilution of the reaction products. Thus a decrease in the dissolved iron concentration would be observed.

Where the dissolution of secondary mineral phases constitutes the primary mechanism, a steady or constant concentration of the soluble species (e.g., iron), in equilibrium with the secondary mineral phase, tends to develop. This concentration remains independent of the flow conditions. The form of the iron and the water chemistry will therefore give important guidance as to the treatment methods that could be adopted.

Assessment of abatement options

To design remedial works a target is required in terms of the quality of the receiving water downstream of the discharge mixing zone. As an example the following were used in assessments in South Wales.

- Total iron $\leq$ 1.0 mg/l
- $6 \leq pH \leq 8$
- Total aluminium $\leq$ 1 mg/l at $6 \leq pH \leq 8$
- No discolouration of the river bed or deposition of ferruginous material below the mixing zone of the discharge

The initial approach to assessment was to evaluate the technical feasibility for possible control technologies on a 1 to 5 rating basis, where 1 is low. The technical performance rating factor represents a composite of the following elements:

- Technical feasibility for implementation (is it technically possible to implement the control measure?)
- Reliability rating (is it a proven measure?)
- Performance rating (determined by the level of loading reduction that could be achieved)
- Type of measure (active, passive or walk-away)

The technical feasibility and reliability ratings are based on experience elsewhere. The performance rating is a function of the type of source that is to be controlled and its configuration with respect to the point of discharge. For example, where an adit discharge is identified as a result of active oxidation within underground mine workings, flooding of the mine workings by installing a bulkhead would carry a high technical feasibility as, in an appropriate location, it can be done relatively easily. It has also been proven to be reliable and effective in inhibiting oxidation. It represents a walk-away solution and as such would command a high rating. However, if the host rock is highly porous, such as permeable sandstones, or it is known that the area is highly faulted, the technical feasibility of achieving fully flooded conditions decreases. As such, the performance rating would also decrease, proportionate with the level of flooding that could be achieved. The overall rating is weighted by the technical feasibility and consequently, if it cannot be implemented, it scores a low rating.

A second rating factor, the relative cost associated with the implementation of that option, was also assigned to each control option. Low rating is indicative of a high cost. Active systems which collect and actively treat the discharge in a reactor system, require continuous operation and maintenance perhaps `in perpetuity'. As such, it has a high ongoing liability and cost and consequently has a low rating. A walk-away solution on the other hand may command a high initial expenditure but no long term costs and could be more attractive.

In some cases it may be possible that a combination of two or more options may complement each other to provide a better solution than an individual option. This is especially significant where two or more sites are hydraulically connected; a potential solution at one site may impact on the discharge at another. Examples of the rating system are shown in Table 1.

The above method is based on perception and understanding of the individual doing the assessment so at best can only be considered as a relative assessment. Additional information enables the investigator to utilise more objective methods. In South Wales a method was developed to try to remove the subjectivity and to provide repeatability of results. This was based on probabalistic methods and the use of a fault-event tree.

Risk assessment and fault tree

The fault–event tree approach (Roberts et al 1981) has been used to assist in identifying the most appropriate remedial measures for the discharge. The fault tree provides a semi–quantitative means of evaluating, firstly the main source of the iron and secondly, possible remedial measures which may be considered to reduce the problem. It is essentially a systems analysis approach, wherein a simplified generic system is analysed to identify the most likely reasons for the ferruginous discharge. The end point of the system is the compliance point where the concentration of iron in the river must be below a certain defined value. A schematic representation of the flow system is shown in Figure 1.

The probability of failure to meet the target for the existing situation without applying any remedial actions may be assessed using the data obtained from previous monitoring of flows and concentrations. In the absence of detailed information on most of the sites examined in South Wales, fairly complete hydrographs for flow and iron concentration were used from a well monitored site and extrapolated to the other sites. The concentration of iron and the flow rate in the discharge and river are assumed to be a random variable following a normal distribution. The concentration of Fe in the stream is calculated based on the following formula:

$$CR=\frac{Ci.Q+Cd.q}{q+Q}$$

Where:	CR	=	Fe concentration downstream
	Ci	=	Fe concentration upstream
	Cd	=	Fe concentration of discharge
	Q	=	Upstream flow rate
	q	=	Discharge flow rate

The standard deviation and mean was calculated for each of the variables. The probability of the Fe concentration exceeding any particular allowable value at the compliance point was then calculated. A typical result is presented in Figure 2.

Should it be decided that the probability of failure is unacceptably high for a particular rate of discharge, possible remedial measures can be selected and the probable effect on the final iron content assessed. In general, remedial measures are never 100% effective or reliable and there is usually a relationship (though very difficult to quantify) between the effectiveness of any particular measure and its cost. This relationship follows the principle of diminishing returns. The fault tree provides a tool to quickly test (although somewhat subjectively) the reduction in the probability of failure of the system if we implement one or a combination of remedial measures. It also highlights those faults in the system which contribute the most to the probability of failure of the system. Attention can then be focused on the more important faults to ensure that the greatest reduction in the probability of failure is achieved for the least amount of money.

CONCLUSIONS

Ferruginous discharges have occurred due to the recovery of ground water levels following the closure of the coal mines and cessation of pumping. In most cases the discharges have occurred through old adits in the seam outcrop and some have existed for many years and the larger ones are associated with more recent mine closures and the impacts have tended to be more dramatic.

The paper has introduced the problems of ferruginous discharges in South Wales in particular and discussed an approach to assessing the nature of the problem with a focus on possible solutions. The Important aspects of AMD studies are:

- The need to recognise the role of source and migration control as well as end of pipe treatment as solutions to AMD
- The need to understand the mining, hydrological and hydrochemical systems in terms of a conceptual model
- The role of risk analysis and probabalistic methods in the light of uncertain and often incomplete data
- The costs and benefits of remedial works

Under present legislation it is often not possible to place the responsibility for prevention or remediation on a person or organisation (Younger 1993). This is a constraint on the development of methodologies to solve AMD problems but it is hoped that the development of alternative ways of reducing the ferruginous discharge problem cost effectively will encourage more to be done. Planning prior to mine closure would give opportunities for alternative treatment options that otherwise could not be considered. An example would be the use of sulphate-reducing bacteria to provide a valuable reduction in iron loading within the mine workings. The use of this technique is limited by the access to workings, to place a suitable substrate for the bacteria. The application would be extremely useful if access could be obtained prior to mine closure.

In many cases, the available information suggests that improved dispersion of the discharge water in the receiving water will achieve a significant improvement perhaps with some retention facility for the discharge in periods of very low flow in the receiving water.

REFERENCES

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TABLE 1 Summary of Possible Control Measures (Technical Rate/Cost Rating)*

Site	SOURCE COMPONENTS	POSSIBLE SOLUTION												
		Source Control			Migration Control				Treatment					
		Oxygen Exclusion												
		Flooding Bulkhead	Plugs Entry Control	Covers	Surface Diversion	Entry Closure	Internal Diversion	Hydraulic Balancing	Collect & Chemical	Internal SRB	ALD Required	Wetlands (Aerate & ppt)	Controlled Discharge	COMMENT
1	Mynyddislwyn - unflooded	0/-	0/-	0/-	0/-	0/-	0/-	0/-	5/1	0/-	0/-(NR)	4/3	5/4	Disperse
2	Mynyddislwyn - unflooded	0/-	0/-	0/-	0/-	0/-	0/-	0/-	5/1	0/-	0/-(NR)	4/3	5.4	Disperse
3	Unflooded/flooded underground - oxidizing	0/- 0/-	3/? 0/-	0/- 0/-	0/-	0/-	0/-	3/?	5/1	2/?	0/-(NR)	4/2	-/-	H2S°(PO)
4	Unflooded - oxidizing (Big Pit) Flooded - open cast	4/1 0/-	4/1 0/-	1/1 0/-	3/?	-/-	3/?	0/-	5/1	2/4	0/-(NR)	4/3	1/?	
5	Outcrop - oxidizing	-/-	-/-	-/-	-/-	-/-	-/-	-/-	5/1	0/-	0/-(NR)	4/3	1/?	Interception may be required
6	Unflooded/Flooded Underground	3/2	4/3	?	-/-	-/-	-/-	-/-	5/1	-/-	Required	4/3	2/?	High Fe - effective diffusion difficult
7	Oxidizing mine workings above water table Dissolution flow through flooded workings	2/3	4/3	-/-	-/-	2/2	3/3	3/3	5/1	4/3	Beneficial	4/3	-/-	Change in water quality anticipated
8	Unflooded and flooded underground	3/3 -/- 3/3	4/4 -/- -/-	-/- 3/3 -/-	-/- 2/3 -/-	-/- -/- -/-	-/- -/- -/-	-/- -/- 3/4	5/1 5/1 5/1	-/- -/- -/-	0/-(NR) 0/-(NR) Beneficial	4/4 4/3	2/? -/-	Some natural wetland clean-up observed
9	Opencase Unflooded underground workings	-/- 2/2	-/- 3/2	3/2 -/-	2/3 -/-	-/- 3/3?	-/- -/-	-/- -/-	5/1 5/1	-/- -/-	} Beneficial	4/3-2	-/-	Probably not cost effective due to small loading Active mining

* Technical rating-High score = high probability of success
Cost rating-High score = low capital cost

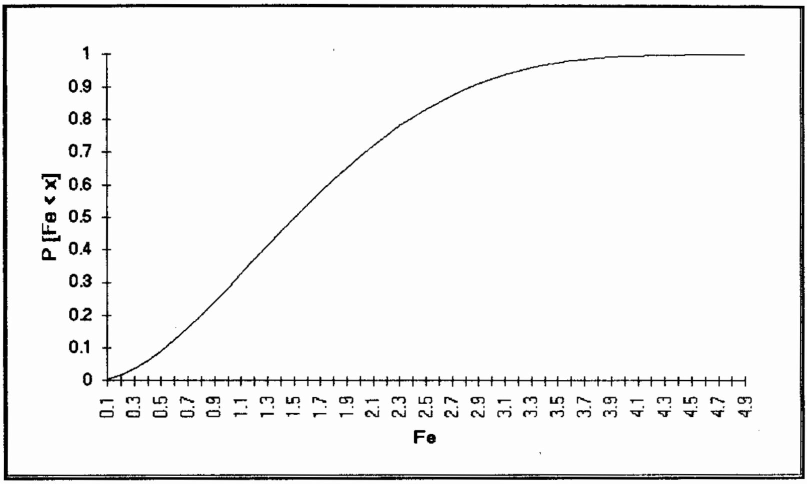

Figure 2a Graph of Cumulative Probability for Fe in Receiving Water at Tir y Berth

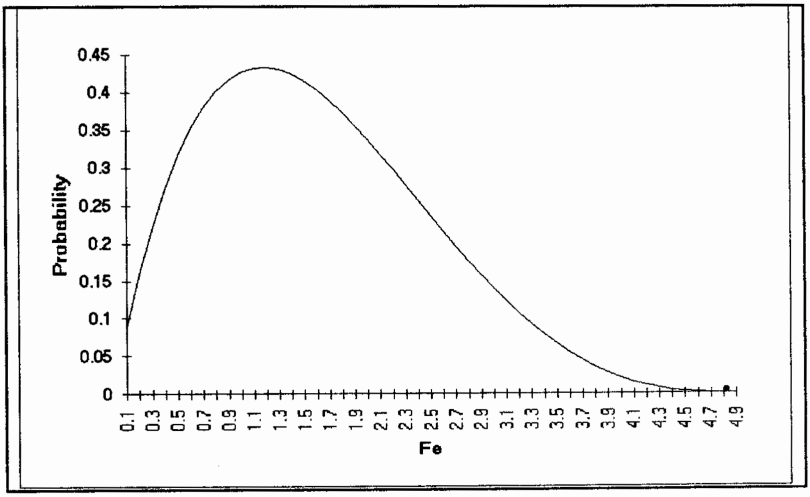

Figure 2b Probability Density Graph of Fe in Receiving Water at Tir y Berth