NRA Wales 93

STUDY OF FERRUGINOUS MINEWATER IMPACTS IN WALES:

PHASE 2a DETERMINATION OF REMEDIAL OPTIONS

VOLUME 1 – MAIN REPORT

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NRA Wales 93

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VOLUME 1 - MAIN REPORT

This Report was prepared under contract to the National Rivers Authority and the Welsh Office. The results of this work will be used in the formulation of Government Policy, but views expressed in this report do not necessarily represent Government Policy.

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GLOSSARY

Anticline	Fold or fold system in the form of an arch
Aquifer	A unit of rock which stores, transmits and yields a significant quantity of water.
Aquitard	A unit of rock which neither transmits nor yields significant quantities of water.
Argillaceous	Fine grained. Usually refers to rocks formed from clay to silt sized particles.
Bord and Pillar	An underground mining method comprising pillars of coal supporting the roof of the workings. The coal is extracted from the bords.
Conformably	A sequence of beds are said to be conformable when they represent an unbroken period of deposition.
Connate Water	Old, highly saline water usually associated with the formation of a sedimentary rock, although may be used to describe any old, saline water.
Isohyet	A line representing equal values of rainfall, similar to a contour.
Pyrite	A mineral composed of Iron Sulphide (also known as Fool's Gold).
Seat Earth	A clay rich unit, often found directly beneath coal seams, which represents the soil in which the coal forming plants were growing (fossil soil).
Siderite	A mineral composed of Iron Carbonate.
Syncline	Fold or fold system in the form of a basin.

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SITE ASSESSMENTS (RIVER NAME FOLLOWED BY SITE NAME)

For each site the following is presented:

- i Geology and Underground Mining
- ii Contamination Sources
- iii Hydrogeological model
- iv Discharge Water Quality and Load Assessment
- v Environmental Costs and Benefits
- vi Options for Remediation and Costs

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STUDY OF FERRUGINOUS MINEWATER IMPACTS IN WALES:
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1 INTRODUCTION

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

The proliferation of these discharges, coupled with an increase in general environmental awareness, has led to public and political pressure for the problem to be solved. As a result, the National Rivers Authority Welsh Region (NRA) have identified a series of studies aimed at evaluating the possibility of permanent and cost effective solutions, as far as is possible. The first phase of work, comprising the identification of all the ferruginous discharges in the coalfields, has been completed by the NRA.

Of these, the most seriously polluting sites have been selected and ranked in terms of the degree of impact. This report, 'A Survey of Ferruginous Minewater Impacts in the Welsh Coalfields', has now been published and the reader is referred to it for more details of the sites identified. The survey only covers discharges from abandoned coal mines.

From the initial study, 15 sites were identified as priority sites for a phase 2A study to assess possible remedial measures. One additional associated site was added during the period of the study. This report presents the results of that study.

1.1 Objectives of Study

The overall objective of this phase of the work is to identify and define the possible options for remedial action for each of the selected sites. For each site, practical options will be considered and a preferred option selected. An estimate of the cost of the preferred options will be presented, together with a summary of the benefits which may be expected.

1.2 Scope of Work

The scope of work is summarised in the Invitation to Tender. Essentially, this phase of work is based on available information supported by a minimum of field work. This report summarises the work done, with conclusions regarding preferred options and costs. The perceived risks of the options presented have been identified and discussed. The study is intended to be used as the basis for formal selection of preferred options for further detailed study and engineering design in a future phase, should the project proceed.

1.3 Project Location

The sites are scattered throughout the South Wales Coalfield from the northern outcrop to the south western coastal boundaries of the coalfield. Ferruginous discharges were identified from the North Wales and the Pembrokeshire coalfields but none of these sites were included in the fifteen sites identified as being of most significance by the NRA. The types of discharge identified are mostly from old shallow workings, but contributions from opencast areas and spoil heaps and discharges associated with the cessation of deep mining may also occur.

IMPACT CRITERIA	IMPACT RATING			
	HIGH (A)	MEDIUM (B)	LOW (C)	NO IMPACT (D)
AREA OF RIVER BED AFFECTED (m^2)	>2500	10-2500	<10	-
LENGTH OF RIVER AFFECTED (Km)	>0.5	0.01-0.5	<0.01	-
SUBSTRATE QUALITY (for fish reproduction)	Rocks/ Stones/ Gravel	Bedrock/ Boulders/ Rock	Artificial/ Sand/ Silt	-
IRON DEPOSITION (visual assessment)	High	Medium	Low	-
TOTAL IRON CONCENTRATION (mg/L in receiving water)	>0.3	2-3	<2.0	-
IMPACT ON pH, DISSOLVED OXYGEN AND TOTAL ALUMINIUM OF RECEIVING WATER	3 fail	2 fail	1 fail	no fail

(These criteria are described more fully in the NRA report.)

Stage 2

From this ranking, 33 discharges were selected for full impact assessment using biological, fisheries and further chemical assessment techniques. The techniques for the second stage assessment are described fully in the NRA report and are summarised

2 PROJECT APPROACH

Ferruginous discharges occur as a result of the process of 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. The detailed chemistry is described in Section 3.6. The term AMD should be thought of as an essential constituent of the discharge process.

The key factors in proposing practical solutions 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 and topography will then usually limit the number of practical solutions, enabling studies to be rapidly concentrated on the useful areas.

The study therefore has two main components:

- identification of the causes(s) of the discharge.
- identification and evaluation of appropriate solutions.

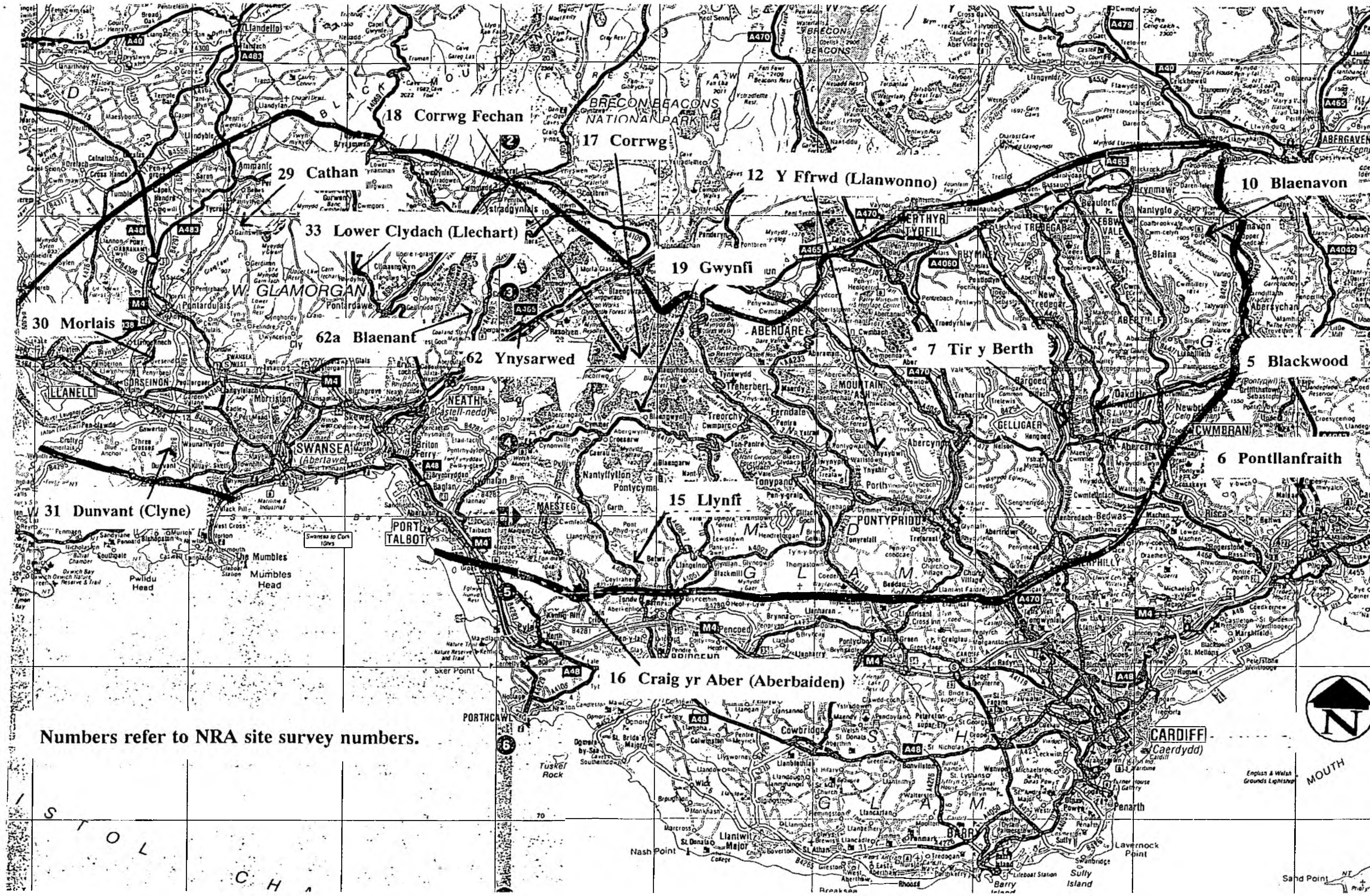
Successful understanding of the AMD problem requires input from hydrogeologists and mining engineers with local knowledge, as well as hydrochemists and engineers specialising in AMD remediation.

2.1 Site Selection

Site selection for the phase 2A study was carried out by the NRA. The following methods of assessment and selection criteria were used:

- **Stage 1**

The 90 discharges identified in the first stage of the Phase 1 study ('A Survey of Ferruginous Minewater Impacts in the Welsh Coalfields', February 1994) included sites on both classified and unclassified river stretches. All sites were initially ranked, according to the following physiochemical criteria, within the two groups (i.e., classified and unclassified stretches).



DATE:7/4/94	PROJ. No: U489	SRK/ NRA ACID ROCK DRAINAGE	SCALE 1:250,000
STEFFEN, ROBERTSON & KIRSTEN CONSULTING ENGINEERS SRK (UK) Ltd., Summit House, 9/10 Windsor Place, Cardiff, CF1 3BX, U.K.		**MAP SHOWING LOCATION OF STUDY SITES AND BOUNDARY OF COALFIELD**	**Figure 1**

below:

1) The biological impact (i.e., reduction of benthic invertebrates) between upstream and downstream of the discharge.

2) The area of the river bed over which the biological impact was evident.

3) The degree of the fisheries impact.

For each of these three components, the impact was rated as high (A), medium (B) or low/no impact (C), according to the following criteria:

1. **Biological Impact**

HIGH IMPACT (A) : A 40% reduction in BMWP scores between the upstream and immediate downstream sites AND a reduction in Log10 abundance of 4 or more families scoring 6 or more on the BMWP score.

MEDIUM IMPACT (B) : EITHER A 40% reduction in BMWP scores between the upstream and downstream sites.

OR A reduction in Log10 abundance of 4 or more families scoring 6 or more on the BMWP score.

NO IMPACT (C) : Neither of the criteria in A or B.

At some sites, the poor upstream water quality was a limiting factor on the biological quality, and it effectively masked the true biological impact of the minewater discharge. In such cases a Biological Override system was used (based on the predicted biological quality upstream in pristine water quality conditions) to predict the likely biological impact of the minewater on a clean water site.

2. **Area of Biological Impact**

The area of river bed over which a biological impact (high or medium) was evident downstream of a discharge was estimated. The impact was ranked into high, medium and low, according to the same area categories used in the "Area of River Bed Affected" in the initial ranking of visual impact (see above).

3. **Fisheries Impact**

Electrofishing data was assessed using the Regional Juvenile Salmonid Monitoring Programme (RJSMP) Classification System (A-E), which is based on the abundance of juvenile (fry and parr) salmonids captured at a site.

The degree of reduction in RJSMP class between sites upstream and downstream of a discharge was used to rate the fisheries impact according to the following criteria:

HIGH IMPACT (A)	A reduction of 2 RJSMP classes
MEDIUM IMPACT (B)	A reduction of 1 RJSMP class
NO IMPACT (C)	No reduction in RJSMP class

It was recognised that both visual/aesthetic (Stage 1) impacts and environmental (i.e., biological and fisheries) (Stage 2) impacts were important factors in determining the sites for further investigation. A combination of the impact assessments from both Stages 1 and 2 of this study were therefore used to select the "worst case" sites for the Phase 2A Remedial Options Study.

The selection was carried out as follows:

(i) Sites which were ranked in the top 10 of either of the Stage 1 rankings (i.e., either classified or unclassified sites) AND which scored A (High Impact) on one or more of the Stage 2 impact criteria (i.e., Biology, area or fisheries) were selected for the phase 2A study.

(ii) In addition, a few other sites were added to the list, either because they were thought to be hydrologically linked to sites selected (e.g., the Sirhowy at Pontllanfraith) or for reasons of public interest (e.g., Ynysarwed/Blaenant).

(iii) This process resulted in the selection of 15 sites for the phase 2A study of remedial options.

(iv) Sites in the Pelenna catchment although included in the Phase I study for comparison purposes were not selected for this study as the Pelenna remediation scheme is already going ahead with EC funding.

Our overall approach has been to review the list of target sites and visit each site with NRA personnel. At the same time we have collected and collated all available information from the NRA, British Geological Survey and British Coal and some other sources.

2.2 Selection of Remedial Measures

For each site, a conceptual model of the system has been prepared to illustrate the AMD source, the cause of the discharge and the possible hydrogeological and hydrochemical processes. From this, possible remedial options were assessed and broadly costed. 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 not warranted during this phase of the study.

At this stage, a simple probabilistic risk assessment has been carried out based on the confidence in the information available, the possible solutions, the costs for each solution and the level of improvement to the environment. The latter is important as there may be some solutions which may be inexpensive but would achieve only a partial reduction in the ferruginous discharge. Each solution can therefore be evaluated on the basis of risk in the result and the cost. It has not been possible to carry out a detailed risk analysis for each site but most sites can be considered generically under two or three 'type' situations. The additional effort required to achieve a better discharge water quality can also be readily identified.

An assessment of the environmental impacts apart from the biological impacts identified by the NRA Survey has also been carried out. This includes the fisheries value and the aesthetic impact of the discharges and has been carried out using a simple ranking system. More sophisticated survey and assessment techniques are available (NRA R&D Note 37, R&D Report 6), but these are beyond the scope of the current study and would be more appropriately carried out as part of the second phase (detailed site investigations and design of remedial measures) of the study.

This overall approach enables all the sites to be considered in a similar manner, before detailed field work is carried out. It will enable the NRA to make decisions on what action to take on an informed basis and target the sites having the greatest impacts in terms of biological quality, area affected, aesthetics and fisheries, as well as targeting the nature of the additional information required so that expenditure is optimised.

3 SETTING

3.1 Topography

The South Wales Coalfield (excluding Pembrokeshire) is situated in the counties of Dyfed, West and Mid Glamorgan and Gwent with a small portion in Powys. The Coalfield is approximately an elongated oval in shape and extends some 90km east-west and up to 30km north-south; its approximate extent is shown on Figure 1. The area is essentially upland, in the form of a plateau dissected by many steep-sided valleys along which rivers flow in mainly straight courses ranging from south-west to south or south-south-east in direction. The highest elevations are towards the northern edge of the Coalfield and are in excess of 500 metres.

3.2 Climate

Average annual rainfall in the Coalfield ranges from 1000mm in the south to 2300mm in the central part associated with the high ground between the Rhondda Fawr and the Avan valley (Sites 17, 18 and 19). The isohyets are generally concentric around this area, with lower rainfall values on the south of the Coalfield than the north. Annual distributions of potential evaporation and rainfall for the Coalfield (divided into western, central and eastern areas) is shown in Figure 3.1. Rainfall occurs throughout the year, with the lowest in the period March to June and the highest from August to January. The greater effectiveness of evaporation in the summer months means that less infiltration and recharge occurs. Of the total rainfall, it is estimated that between

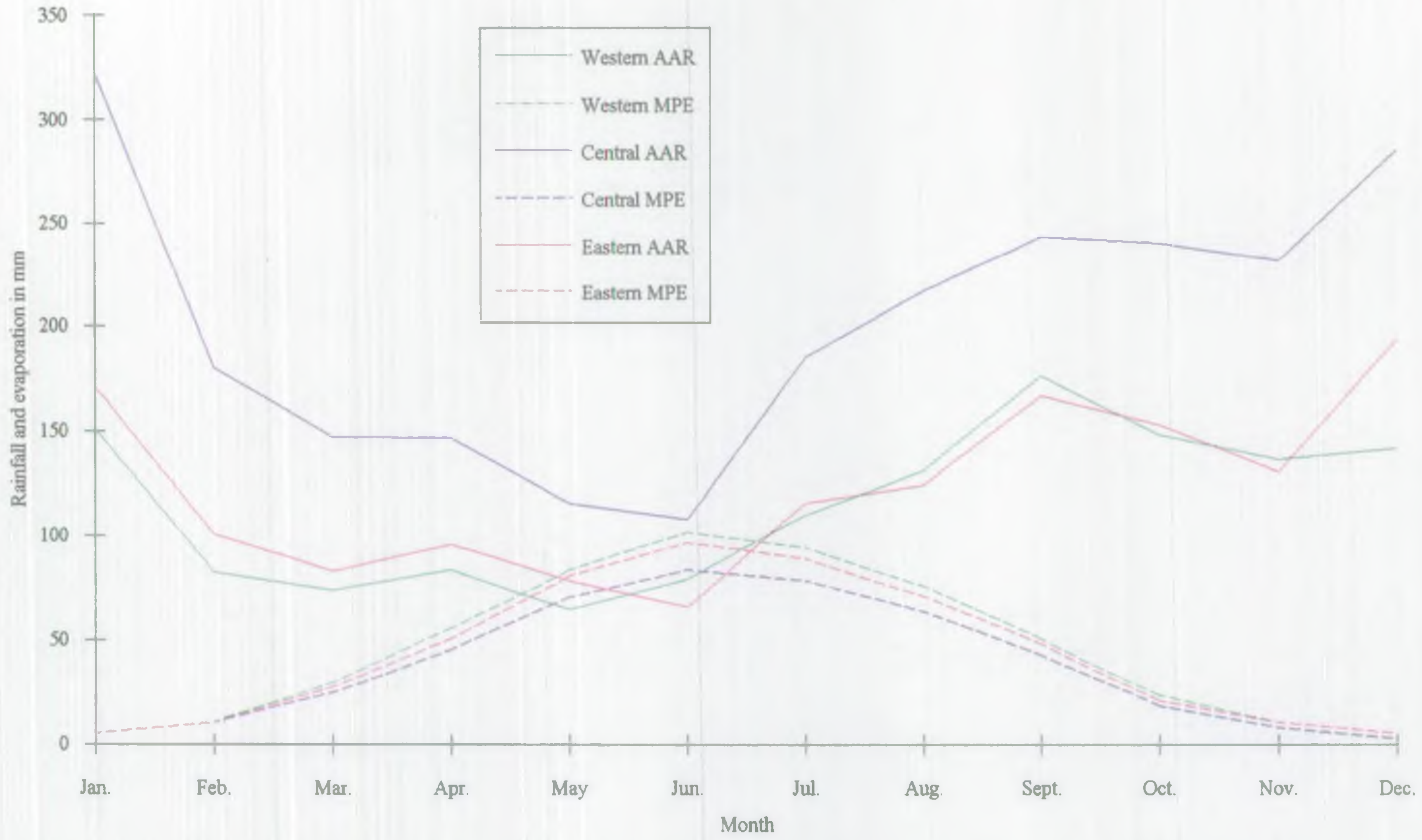
20% and 25% contributes to recharge of the groundwater and prior to mining in the area this would have emerged as baseflow to streams at the base of permeable rock units such as sandstones.

3.3 Hydrology and Ground Water

As mentioned above, 20-25% of rainfall recharges to groundwater, with a lag time of approximately a month between rainfall events and increased base flow. This response can be seen quite clearly in the pumping records for numerous mines, which tended to pump less water (sometimes none) in the summer, but also pumped varying amounts during wetter months, corresponding to the amount of rainfall.

Groundwater typically moves fairly rapidly through the sandstones in the Coal measures, and very much more slowly through the mudrocks. The Coal Measures are generally a sequence of aquifers and aquitards, with variations in flow and permeability brought about by faulting and extraction of minerals which not only leaves voids but results in subsidence and other movement.

Water occurrences in mine workings tend to be dependent on geographical location, the position of a particular working within the stratigraphic succession and the influence of geological structure. In general the intersection of bodies of connate water is rare and the quantities low. The deeper workings in the Middle and Lower Coal Measures have tended to be fairly dry. Collieries in Gwent have recorded "inrushes" into the lowermost seams and a water source below the Coal Measures has often been suggested. In the Pennant measures or in seams at shallow depth, the natural and mining induced joint system render the strata permeable with corresponding high recharge potential. Water can migrate rapidly along joints, although some of the rock material may be of low permeability. Elsewhere, the abandonment of large areas of workings enables water to migrate downdip from crop areas, eventually drowning out large areas of interconnected workings.



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SRK/ NRA ACID ROCK DRAINAGE

GRAPH SHOWING AVERAGE ANNUAL RAINFALL (AAR) 1956-62, AND MONTHLY POTENTIAL EVAPORATION (MPE) FOR WESTERN, CENTRAL AND EASTERN AREAS OF THE SOUTH WALES COALFIELD

Figure 3.1

3.4 Hydrology and Surface Water

The main river drainage systems are orientated roughly north/south, but radiate outwards from the higher ground to the north of the coalfield. The rivers include the Loughor, Tawe, Afan, Taff and Rhymney and their tributaries. The reader is referred to the NRA report 'A Study of Ferruginous Minewater Impacts in the Welsh Coalfields' for more details, as the discharges are illustrated on a catchment by catchment basis.

Several of the above rivers rise in Old Red Sandstone beyond the northern boundary of the coalfield, e.g., Loughor and Taff. The valleys are characteristically steep-sided and narrow, with incised rivers which are generally fast flowing in the middle and upper reaches until they reach the lowland of the coastal plain.

3.5 Geology and Mineralogy

The following sections provide a general description of the geology of the South Wales Coalfield, including the stratigraphy and structure and a summary of the knowledge of pyrite contents of the various horizons.

3.5.1 Stratigraphy

The Coal Measures strata which comprise the rocks of the coalfield rest fairly conformably on older Namurian (or Millstone Grit) rocks. Apart from very limited areas along the southern boundary between Port Talbot and Llantrisant, no younger solid strata overlie the Coal Measures.

A simplified geological column is shown in Figure 3.2, although the presence and thickness of the units varies considerably across the coalfield.

The Coal Measures are sub-divided into Lower, Middle and Upper Coal (or Pennant) Measures. The Lower and Middle Coal Measures outcrop mainly around the low-lying coalfield margins and consist mainly of repeating sequences of mudstone and siltstone with occasional sandstone, together with many coal seams resting on underlying seatearths. In aggregate, the coal seams form an insignificant proportion of the total strata thickness. Minor clay-ironstone bands and nodular horizons, individually only a few centimetres in thickness, occur throughout the succession.

All these strata are considered to have been deposited under freshwater or estuarine conditions. Several thin horizons deposited under marine conditions (known as Marine Bands) also occur, particularly in the lower part of the Lower Coal Measures and upper part of the Middle Coal Measures.

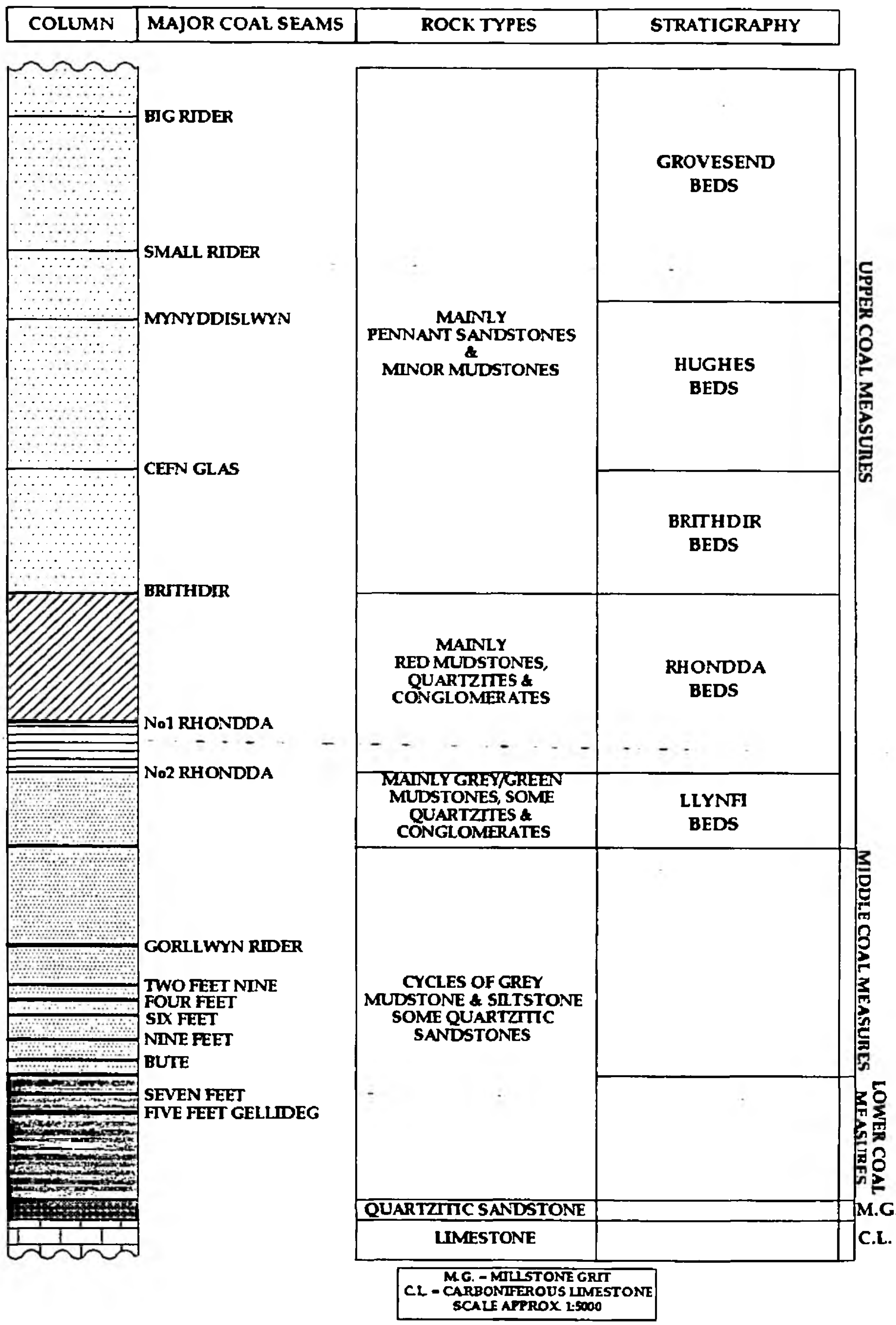
The Upper Coal Measures (Pennant Measures) form the distinctive raised plateau and prominent scarps away from the coalfield boundary and are also the main strata visible in the steep valley sides. In contrast to the underlying sub-divisions, these beds are dominated by thick sandstone units which are massive, current or even-bedded, with occasional conglomerate and grit horizons. Minor developments of mudstone and siltstone occur throughout the Pennant Measures; in the east of the coalfield the basal strata are predominantly argillaceous but westwards the base of the true Pennant Sandstone occurs progressively nearer to the base of the Upper Coal Measures. The Grovesend Beds which are stratigraphically the highest strata in the coalfield and which have limited lateral extent, tend towards being argillaceous in nature.

Comparatively few coal seams exist in the Upper Coal Measures. Non-deposition or washout appears more common than in the seams of the Lower and Middle Coal Measures.

All the major units thicken from east to west, from a total of less than 600 metres around Pontypool to 2500-3000 metres near Swansea.

3.5.2 Structure

The coalfield area is approximately an east/west asymmetric syncline with gentle southerly dips along the northern crop and steep northerly dips along the southern crop. Several further east/west anticlines and synclines occur. However, none of these fold structures persists across the coalfield. The structure is greatly modified by several well-defined trends of faulting which include both normal faults and thrusts. Deformation caused by structure is much more severe in the west and south than in the east.



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SRK/NRA ACID ROCK DRAINAGE

SRK

SIMPLIFIED GEOLOGICAL COLUMN

Figure 3.2

The occurrence of coal seams of 1-3 metres in thickness is greatest in the eastern part of the coalfield with up to 6 seams commonly worked at the collieries in Gwent and locally 8-10 seams in the Maesteg area of Mid Glamorgan. The western part of the coalfield in West Glamorgan and Dyfed has relatively few coals in excess of 2 metres.

Across the coalfield, the coal seams exhibit a well-defined pattern of chemical properties and potential uses. From east to west and to a lesser extent from south to north the coals range from bituminous, with good coking properties, through dry-steam, to anthracite in the west. In addition, at any one locality, the higher seams tend to be less anthracitic than the lower seams.

The extensive perimeter of outcropping seams around the boundary of the coalfield and along the steep valley sides has enabled a high level of mining activity, either directly into the cropping coals by opencast or deep-mining by adit decline ('slant'), or by shafts sunk to the deeper seams. The proportion of outcropping coal is probably higher in the South Wales Coalfield than in any other British coalfield and is reflected by the large number (50+) of licensed mines and opencast sites. Mining activity of this nature is likely to continue while reserves of economic size and suitable access remain.

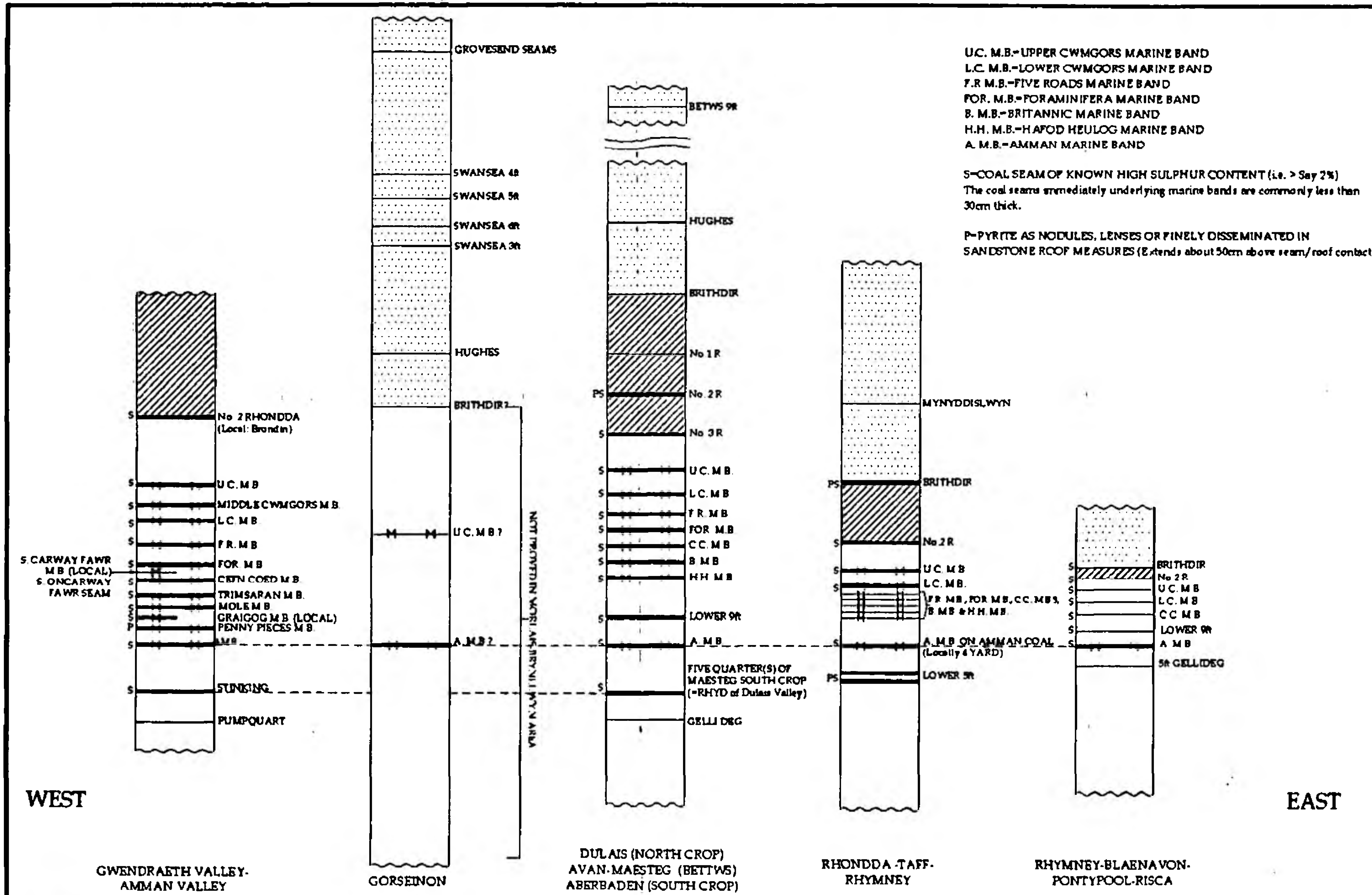
The combination of the location of the formerly much-sought coking and steam coals and generally more favourable geological and mining conditions in the east and east central part of the coalfield has led to high levels of extraction and near-exhaustion of the majority of seams. In contrast, largely due to the severe geology but also due to a more limited demand for anthracite, extraction in the west has been significantly lower.

3.5.3 Mineralization

Pyrite is the primary sulphide mineral associated with the South Wales Coalfield and most frequently occurs with the coals and the Marine Bands mentioned above. In the coal itself, the Upper Coal Measures tend to be more mineralised. Pyrite concentrations of approximately 3% are observed, while the pyrite content of the Lower Coal Measures is typically below 1%. It is therefore anticipated that the majority of the oxidation and metal loading would occur from mine workings located in the Upper Coal Measures.

Pyrite also occurs as nodules, lenses or finely disseminated in the sandstone roof measures up to 50cm beyond the seam/roof contact. Sideritic lenses, with pyrite, occur in some seam and intermediate floor measures such as the Four Feet, Lower Nine Feet, Seven Feet and Five Feet seams.

Figure 3.3 summarises the coal seams or strata known to be high (>20%) in sulphur.



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STEFFEN, ROBERTSON & KIRSTEN CONSULTING ENGINEERS SRK (UK) Ltd, Summit House, 9/10 Windsor Place, Cardiff, CF1 3BX, U.K.		SOUTH WALES COAL SEAMS OR STRATA KNOWN TO BE HIGH IN SULPHUR (>2%)	Figure 3.3

3.6 Geochemistry

A generalised description of the mechanisms of solution and mobilisation of iron as a result of mining activities is given to enable the reader to understand the approach to treatment.

3.6.1 Sulphide Mineral Oxidation

The exposire of sulphide minerals, particularly pyrite, to water and oxygen (either in air or dissolved in water) leads to the oxidation of the sulphide mineral and production of water with high iron and sulphate concentration and low pH (high acidity).

The main oxidation reaction is as follows:

$$FeS_2 + 7/2\ O_2 + H_2O \dashrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$$

If the surrounding environment is sufficiently oxidising, the dissolved perrous iron (Fe^{2+}) may be oxidised to ferric iron (Fe^{3+}) in the following reaction:

$$Fe^{2+} + O^2 + H^+ \dashrightarrow Fe^{3+} + \frac{1}{2}H_2O$$

At pH values above 2.3 to 3.5, the ferric iron will be hydrolysed to ferric hydroxide, which is the red precipitate characteristic of ferruginous discharges. This reaction releases more acidity into the water:

$$Fe^{3+} + 3H_2O \dashrightarrow Fe(OH)_3 + 3H^+$$

The reverse of this reaction occurs when low pH waters remobilise ferric hydroxide into solution. If ferric iron remains in solution, it may be used to oxidise more pyrite.

$$FeS_2 + 14Fe^{3+} + 8H_2O \dashrightarrow 15Fe^{2-} + 2SO_4^{2-} + 16H^+$$

The reactions can be enhanced by the activities of certain iron and sulphide oxidising bacteria, such as Thiobacillus thiooxidans and Thiobacillus ferrooxidans.

The end products of this set of reactions are largely dependent on the pH and oxidising/reducing capacity (redox potential or Eh) of the water and the environment in which the reactions take place. The pH is controlled by the acid generation process and the neutralising capacity of the strata encountered by the water. The most common neutralising mineral is calcite ($CaCo_3$), a major constituent of limestone, which consumes acidity through the creation of HCO_3 or H_2CO_3.

$CaCO_3$ and H^+ --> Ca^{2+} + HCO_3

and

$CaCO_3 + 2H^+$ --> $Ca^{2+} + H_2CO_3$

The pH is raised by such reactions and the iron load is reduced by the precipitation of $Fe(OH)_3$. The sulphate concentration is rarely affected, however.

The Eh (redox potential) is a measure (in volts) of the potential of a system to oxidise relative to a standard hydrogen electrode. Positive Eh values indicate that the system is relatively oxidising and negative Eh values indicate that a solution is relatively reducing. In general, the Eh of a solution can be considered to increase in the presence of oxygen.

Figure 3.4 illustrates the relationship between Eh and pH and iron speciation in water for a total concentration of 10^{-5} moles per litre. The products of the pyrite dissolution and related reactions are dependent on the Eh/pH field in which the system stabilises.

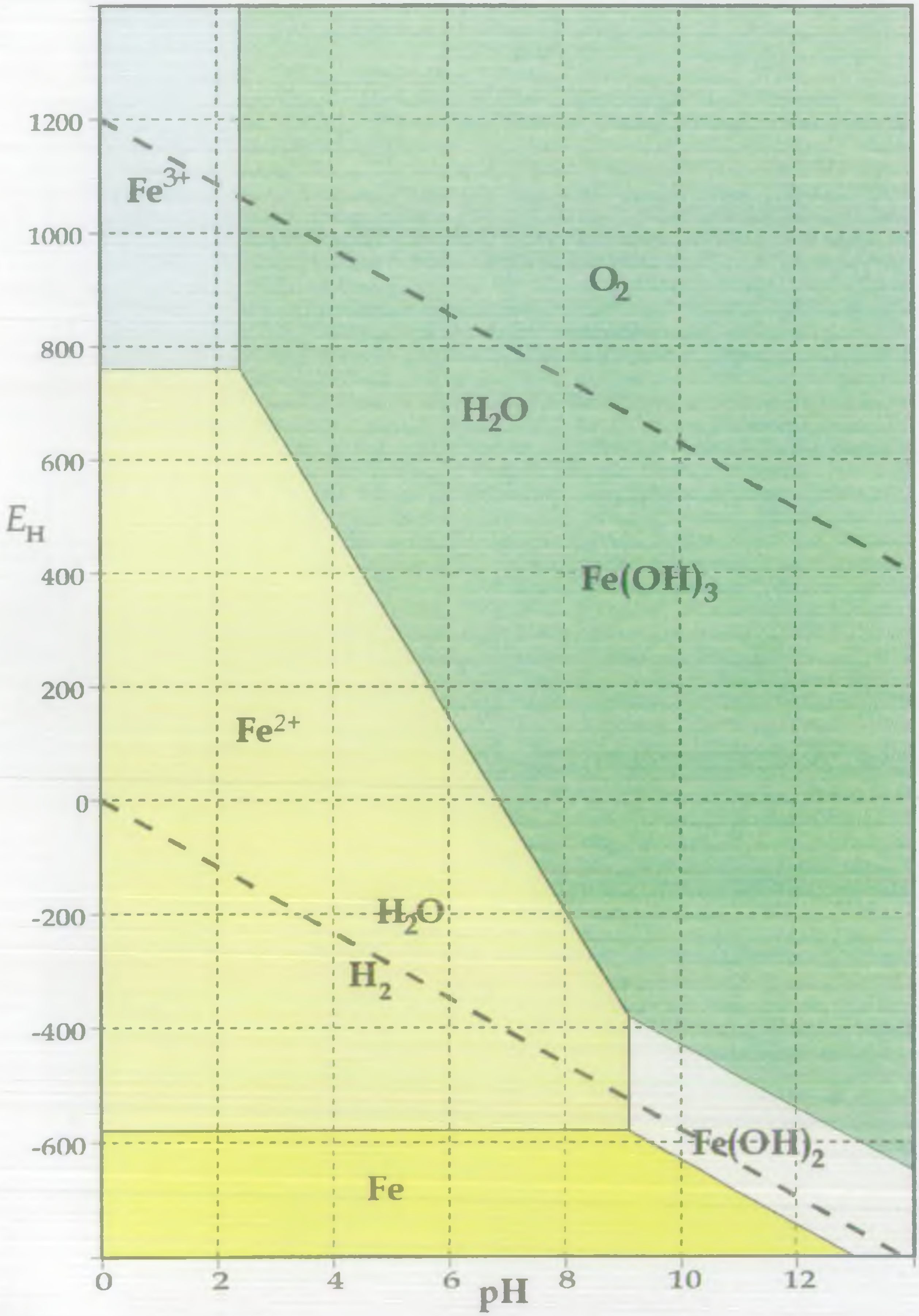
In summary:

- Ferrous iron remains in solution with relatively low Eh conditions. With decrease in pH, the Eh at which ferrous iron is stable increases.

- Ferric iron remains in solution only with low pH and high Eh conditions.

- Ferric hydroxide is stable as a precipitate at relatively high pH values and high Eh conditions. It therefore requires both neutralisation and oxidation for its formation. Such conditions exist in well-aerated flowing streams which have been in contact with calcite (or limestone). In such situations, water with high dissolved iron concentrations mixing with the stream water will drop most of its iron load as ferric hydroxide.

Ground water recharge from infiltrating, aerated preciptation typically carries $10^{-3.5}$ moles per litre of dissolved oxygen. If reacted with pyrite, concentrations of 5 mg/l ferrous iron and 17 mg/l sulphate would be produced in water. Higher concentrations of iron and sulphate may be attributable for a higher rate of oxygen transport, such as be contact with air or by the dissolution of secondary minerals such as jarosite ($KFe_3(SO_4)_2(OH)_6$) and siderite ($FeCO_3$) which can be produced during an earlier phase of pyrite dissolution or remobilisation of precipitated ferric hydroxide. By such mechanisms, iron concentrations of several hundred mg per litre can be achieved.



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SRK		E_H-pH DIAGRAM FOR AN Fe-H_2O-O_2 SYSTEM ($Fe_{tot}=10^{-5}$M)	Figure 3.4

3.6.2 Mining Activities Contributing to the Release of Iron

Underground Mining

Underground mining activities have led to the physical exposure of sulphide minerals in the 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.

In general, the older shallow workings were exploited by bord and pillar mining, whereas longwalling has been the more common method in the deeper workings. A degree of subsidence will take place with both types of mining, but mainly through longwalling. A longwall operation beneath bord and pillar workings will possibly generate maximum subsidence and associated machining of the overlying rocks, probably already weakened by blasting. The broken nature of the rock means that hydraulic conductivity and permeability to air are greatly increased. During active mining, oxygen is introduced to these zones of broken rock by a variety of mechanisms, including mine ventilation, barometric pumping and diffusion.

After mining ceases and the water table is allowed to re-establish, the mine workings often act as drainage systems and the equilibrium water table is lower than that before mining. The consequence is that a residual dewatered zone remains that is subject to ongoing oxidation.

As a result of unsaturated flow conditions during mining, preferential flow paths have tended to develop within the collapsed and dewatered zones. Moisture requirements to sustain oxidation of the sulphide minerals are minimal and as a consequence pyrite oxidation and acid generation proceeds even in zones that are only partially contacted by infiltrating waters. Within these zones of limited flow, solubility criteria for various substances may be exceeded and oxidation products tend to accumulate. Because the primary sulphide mineral is pyrite, in the presence of calcareous host rocks and an oxidizing atmosphere, secondary iron mineralization could comprise jarosites, ferric hydroxides and oxy-hydroxides and siderite. After mining is completed and the water table is allowed to rise, reducing conditions develop within the newly flooded zones. The secondary mineral phases formed under oxidizing conditions then become unstable and ferrous iron is dissolved to the point of equilibrium, as discussed in Section 2.4. This results in elevated iron concentrations within the groundwater regime and ferruginous discharges result.

Deep mining will result in relatively large quantities of coal waste, creating the tips which once typified the South Wales valleys. Most of these tips have now been reclaimed, often reworked at the same time to extract fine coal and few drainage-related pollution problems are known to exist.

Opencast Working

Opencast mining creates large areas of fractured bedrock exposed on the walls and floor of the workings. Consequently, oxidation of contained sulphide minerals would be observed. Where these workings extend below the general topography, the pit drainage system results in a lowering of the water table. This causes unsaturated conditions in the affected bedrock, resulting in increased oxygenation in much the same way described for the de-watering activities associated with underground mining. Recent opencast areas are backfilled after mining is completed, but older sites (1940's onwards) are frequently unrestored and may represent a source of pollution.

Summary of Mechanisms for Iron Mobilization

Ferruginous discharges are observed from surface and underground sources. The mechanisms for iron mobilization can be divided into two: continued or ongoing oxidation of primary sulphide minerals and dissolution of secondary mineral phases.

Continued or ongoing oxidation can be sustained in newly exposed bedrock and subsidence zones at a minimum by oxygen contained in infiltrating water. This may be enhanced, particularly for large open underground mining voids that are directly or indirectly connected to the atmosphere. Consequently, high rates of pyrite oxidation and acid generation may be observed.

Mining voids may contain high proportions of backfilled waste rock, with relatively high pyrite values. The highly fractured nature of this waste provides ideal conditions for continued oxidation. Similarly, the layer of bedrock contained between the pre- and post mining water table is subject to increased oxygenation. The oxygenation is usually enhanced from increased bedrock porosity and permeability as a result of subsidence fracturing. Sulphide minerals contained in these zones continue to be oxidized. Acidity and oxidation products are transported away from the reaction sites by infiltrating water.

The second mechanism for iron release is the dissolution of secondary mineral phases previously accumulated under oxidizing conditions. Flooding of mine workings results in a change in the physico-chemical conditions under which secondary minerals were deposited. These changes render certain mineral phases unstable which are consequently dissolved to equilibrium conditions. The dissolved species are then transported away from the site of original deposition by any groundwater movement that may occur.

3.6.3 Sources of Aluminium in Water

Aluminium occurs in many silicate rock minerals, such as feldspars, feldspathoids, micas and many amphiboles. Aluminium hydroxide (gibbsite) is a fairly common mineral and less common is the basic sulphate, alunite. Aluminium is also common in zeolites.

The Al^{3+} cation predominates in solutions where the pH is less than 4.0. The solubility of aluminium is strongly influenced by complexing. In the presence of fluoride, strong complexes of the following forms are formed: AlF^{2+} and AlF_2^+. Therefore, not all of the reactions by which aluminium is dissolved or precipitated can be treated reliably by equilibrium models.

In the absence of complexing agents and at neutral pH conditions, the solubility of aluminium is low and a dissolved concentration of less than 0.1 mg/l would be expected for the natural water system.

4 REVIEW OF CONTROL STRATEGIES AND TECHNOLOGIES

4.1 Basis for Review

The study completed by the NRA has shown that the release of dissolved iron in mine water discharges to the receiving environment is of primary concern. These discharges impact on the receiving environment when ferric hydroxide is precipitated, causing the accumulation of this precipitate on river beds. Aquatic habitats and benthic populations are as a consequence adversely impacted. These precipitates also impact salmonid spawning areas. High in-stream dissolved iron concentrations may also create a barrier to migratory fish.

Cost effective and efficient remediation or reduction of these ferruginous discharges requires an understanding of the mechanisms of iron release to the mine discharge waters as discussed in Section 3.6. The reason for this is that source control, or prevention, invariably is more effective in the long term than, for example, a collect and treat system. In some cases, where the mobile component or contaminant has already been generated, its release is dependent on a transport mechanism and source control alone may not be effective. Another approach, such as flow diversion and/or collect and treat may be required to meet the discharge objective. In the following, a general discussion of the categories for control and different control technologies that are applied elsewhere in the world is provided.

The literature survey carried out by Imperial College, NRA R&D project 339, "Treatment Processes for Ferruginous Discharges from Disused Coal Workings", has been reviewed at progress report stage. More detail on the control technologies has been included and this is summarised below, with additional detail presented in Appendix A.

4.2 Control Technologies

In the following sections the possible methods to control generation or migration of these contaminants are reviewed in three groups:

i) ***Source control** - 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 or isolation or removal of sulphide minerals.

ii) ***Migration control*** *- 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, geochemical barriers and alkaline addition to precipitate metals.

iii) ***Release control*** *- 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.

The detailed discussion of control strategies is presented in Appendix A.

5 WATER QUALITY OBJECTIVES

Environmental Quality Standards (EQS) have been proposed by the NRA for the receiving waters. It is these standards which must be achieved by any treatment methods proposed. The EQSs are as follows:

Total iron	2 mg/l
pH	6-8
Total aluminium	1 mg/l @ pH 6-8

No discoloration of the river bed or deposition of ferruginous material below the mixing zone of the discharge.

The EQS requires there to be no staining. However, an iron content of 2 mg/l is known to result in staining. The following sections summarise the legal and technical basis for setting the target iron standard lower than 2 mg/l. Further details are in Appendix B.

The EC Directive concerning surface water intended for abstraction of drinking water (75/440/EEC) sets mandatory standards of 0.3 to 2.0 mg/l dissolved iron, depending on the type of treatment that the water will undergo.

A DOE Circular (7/89) sets a national EQS of 1.0 mg/l dissolved iron to protect aquatic life. The relationship between dissolved and total iron will vary according to the chemical reactions which have taken place between the generation of acid water and the ferruginous discharge, but even with a total Fe level of 1 mg/l, some discolouration will occur which will be contrary to the EQS proposed.

At a level of 0.3 mg/l, no visible staining or environmental impact may be expected. However, this standard will be very hard to achieve and may be exceeded upstream of some of the discharges.

In summary, 1 mg/l total iron is thought to protect aquatic life adequately and to minimise staining. This is the standard recommended for proposed treatment options.

6 SITE ASSESSMENTS

6.1 Approach and Methodology

The objectives for the site assessments were to evaluate potential control technologies that may be applicable to each site to achieve a reduction in the ferruginous discharges in a cost effective manner. These assessments are not intended to provide a definitive answer as to which control technology should be applied at each site to provide the optimum solution, but rather to provide guidance as to which alternative(s) shows the highest potential of success.

Potential control technologies that may be applicable to this study are identified in Chapter 4 and detailed in Appendix A. In order to assess the applicability of these technologies, it was necessary to determine the source of the discharge, the pathway of the discharge, the mechanism for the release of soluble iron and estimate the total metal loading.

6.1.1 Geology and Underground Mining

In order to determine the source of the discharge, the approach was to identify seam outcrops, openings to the surface from disused mine workings in the immediate vicinity of the discharge site or the presence of spoil tips or open cast mine workings upstream from the site. This was done by consulting the geological maps, usually at a scale of 6" to a mile (1:10,560) and the mining plans for the area held by British Coal in the Abandoned Mines Records Office. The mine plans of non-operational workings have been drawn for each seam where more than one seam was worked from the same mine. Plans had to be submitted by law for mines closing after 1872, but many earlier plans have also been submitted. Earlier workings may be unrecorded apart from where later workings have intersected them.

6.1.2 Contamination Sources

The potential mechanisms for the release of iron to the discharge flows are discussed in Section 3.6. To allow a qualitative assessment of the mechanism for iron release, the level of flooding within the associated underground workings was estimated.

The source classification was made according to the following categories:

i) Flooded underground mine workings - primarily dissolution of secondary mineral phases;

ii) Unflooded underground mine workings - primarily ongoing or active oxidation of sulphide minerals;

iii) Spoil tips and opencast workings - primarily ongoing or active oxidation of sulphide minerals.

6.1.3 Hydrogeological Model

The hydrogeological model relates to the natural water balance between recharge, groundwater and surface water and the understanding of how groundwater moves through the natural system. Mining has interfered with the system and altered the way in which groundwater flows and the levels to which groundwater will ultimately recover. Groundwater will still flow according to hydraulic gradients, but mine openings create preferential drains.

The mining plans referred to above show the extent of the 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 water through the workings or seams can be assessed from information on the plans, geological sections and our understanding of the hydraulic gradients.

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.

6.1.4 Discharge Water Quality and Load Assessment

Limited flow rate data were available for the discharge and river flows at each site. In most cases only a single flow measurement was available. The first step for the assessment of the potential iron loadings being generated at each site therefore was to synthesize the flow rate or hydrograph for both the discharge and the receiving water (river). This was done by determining a `generic' discharge flow distribution from the data that were available for site numbers 5, 6, 7, as illustrated in Figure 6.1. It should be noted that the data consists of single, point measurements taken at various times of the year and is unlikely to represent the average for that month. The synthesized curve was obtained from the averages for the available data.

The corresponding `generic' hydrograph for the river flow was determined from data for the Rhymney River at Site 7. Again, these measurements were single events and an average curve was estimated by taking into consideration the rainfall curve and the effect evaporation may have had on it. The available data and estimated hydrograph is illustrated in Figure 6.2.

The discharge hydrographs reflect a rainfall response delay of about 1 month compared to the peak in the river hydrograph. The magnitude of the response and delay is a function of the depth and extent of workings. The river flow and discharge hydrographs for any particular site need to be observed in more detail for dilution design purposes.

These generic hydrographs were transposed to each site by fitting these curves to the available data for that site.

TABLE 6.1
Summary of Annual Discharge Loadings and Estimated Receiving Water Iron Concentration

Site	NAME		Flow Rate Discharge (m3/s)	Flow Rate Receiving (m3/s)	Dilution Factor	Fe(T) Conc. (mg/L) Discharge	Fe(T) Conc. (mg/L) Calculated Receiving (D/S)	Calculated Annual Loading Fe (ton)	Calculated Annual Loading Al (ton)	Calculated Annual Loading SO4 (ton)
5	Sirhowy, Blackwood	Mean	0.027	2.289	0.013	3.0	0.042	2.8	0.694	607
		Min	0.004	1.118	0.004		0.006			
		Max	0.060	4.538	0.030		0.152			
6	Sirhowy, Pontllanfraith	Mean	0.053	2.768	0.022	7.0	0.159	11.8	0.036	1077
		Min	0.041	1.352	0.011		0.080			
		Max	0.073	5.487	0.036		0.272			
7	Rhymney, Tir y Berth	Mean	0.236	1.440	0.188	6.1	1.157	45.3	0.437	4960
		Min	0.150	0.359	0.061		0.374			
		Max	0.369	3.920	0.373		2.807			
10	Llynfi, Blaenavon	Mean	0.078	0.120	0.423	1.6	0.703	4.0	0.351	253
		Min	0.061	0.059	0.275		0.264			
		Max	0.104	0.238	0.545		1.492			
12	Clydach Taff, Y Ffrwd	Mean	0.024	0.055	0.336	2.1	0.714	1.6	0.030	26
		Min	0.019	0.027	0.205		0.436			
		Max	0.032	0.108	0.450		1.035			
15	Llynfi, Llynfi	Mean	0.005	0.045	0.116	8.8	1.011	1.4	0.032	12
		Min	0.004	0.022	0.061		0.537			
		Max	0.007	0.090	0.171		1.499			
16	Cynffig, Craig Yr Aber	Mean	0.028	0.105	0.234	16.0	3.469	13.0	0.052	447
		Min	0.022	0.051	0.134		0.466			
		Max	0.037	0.208	0.328		5.242			
17A	Corrwg, Afon Corrwg	Mean	0.011	0.218	0.058	14.4	0.832	5.2	0.015	65
		Min	0.009	0.106	0.088		0.425			
		Max	0.015	0.432	0.029		1.264			
17 B	Corrwg, Afon Corrwg	Mean	0.012	0.229	0.059	10.2	0.599	3.9	0.009	86
		Min	0.009	0.112	0.089		0.306			
		Max	0.016	0.455	0.030		0.908			
18	Corrwg, Corrwg Fechan	Mean	0.006	0.071	0.096	11.5	1.105	2.3	0.004	27
		Min	0.005	0.035	0.050		0.575			
		Max	0.009	0.141	0.143		1.641			
19	Afan, Gwynfi	Mean	0.014	0.087	0.159	7.3	1.160	3.3	0.016	56
		Min	0.011	0.042	0.086		0.634			
		Max	0.019	0.172	0.230		1.690			
29	Loughor, Cathan	Mean	0.003	0.336	0.010	71.9	0.683	6.2	0.082	41
		Min	0.002	0.164	0.005		0.339			
		Max	0.004	0.667	0.015		1.061			
30	Morlais, Morlais	Mean	0.208	0.595	0.287	62.0	17.692	405.9	1.964	5914
		Min	0.162	0.291	0.170		10.508			
		Max	0.277	1.179	0.392		27.732			
31A	Clyne, Dunvant	Mean	0.002	0.010	0.187	7.8	1.447	0.5	0.003	4.194
		Min	0.002	0.005	0.103		0.802			
		Max	0.003	0.020	0.267		2.073			
31 B	Clyne, Dunvant	Mean	0.002	0.010	0.191	26.7	6.536	1.6	0.004	7.596
		Min	0.002	0.005	0.106		3.635			
		Max	0.003	0.019	0.273		9.364			
33	Lower Clydach, Llechart	Mean	0.0009	0.020	0.049	36.3	1.765	1.0	0.009	6.601
		Min	0.0007	0.010	0.025		0.897			
		Max	0.0011	0.039	0.074		3.177			
62	Neath, Ynysarwed	Mean	0.022	0.227	0.101	159.7	15.998	110.0	0.423	1334
		Min	0.017	0.111	0.053		2.326			
		Max	0.029	0.451	0.150		28.115			

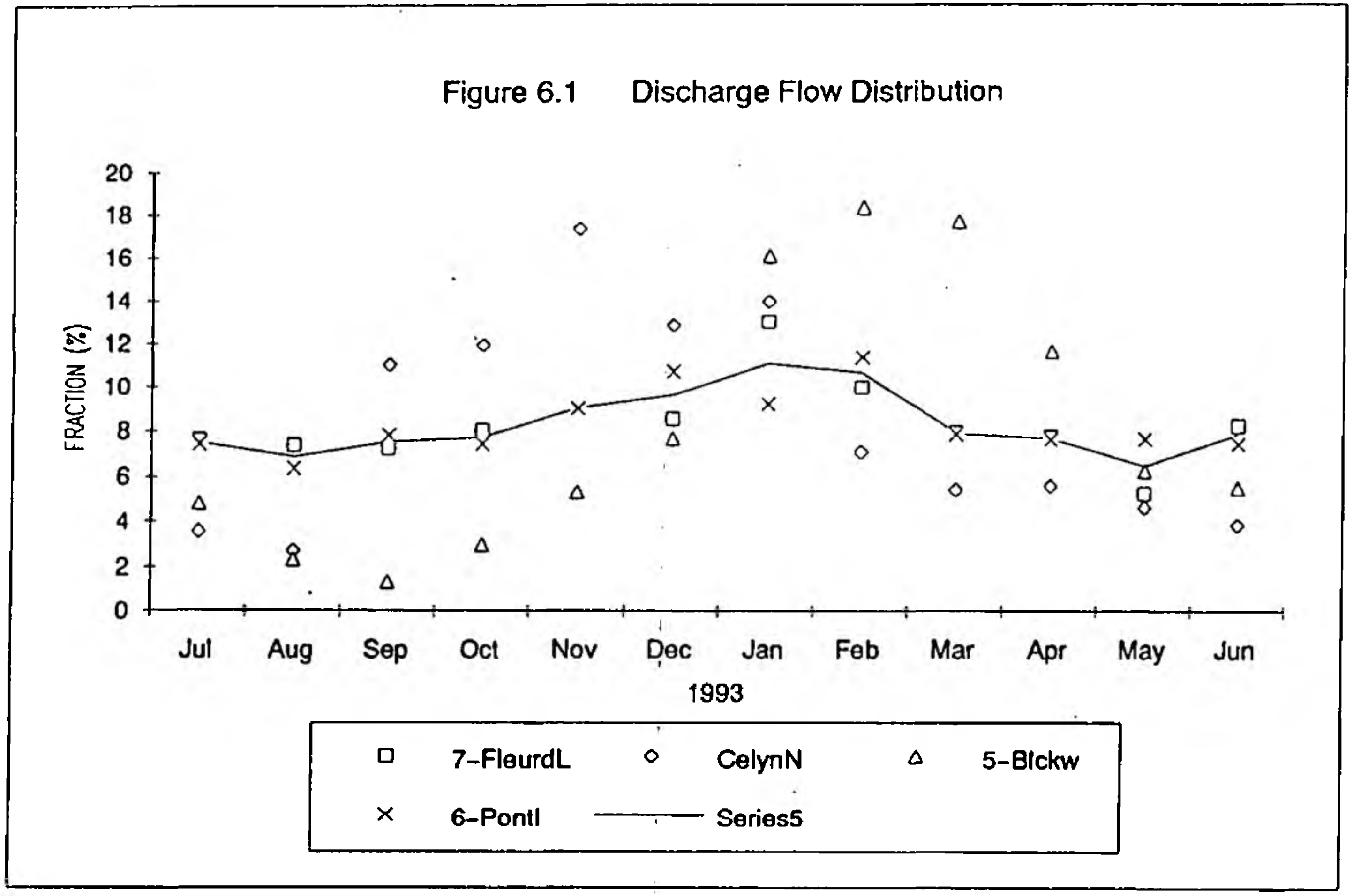

Figure 6.1 Discharge Flow Distribution
FRACTION (%)
20
18
16
14
12
10
8
6
4
2
0
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1993
7-FleurdL
CelynN
5-Blckw
6-Pontl
Series5

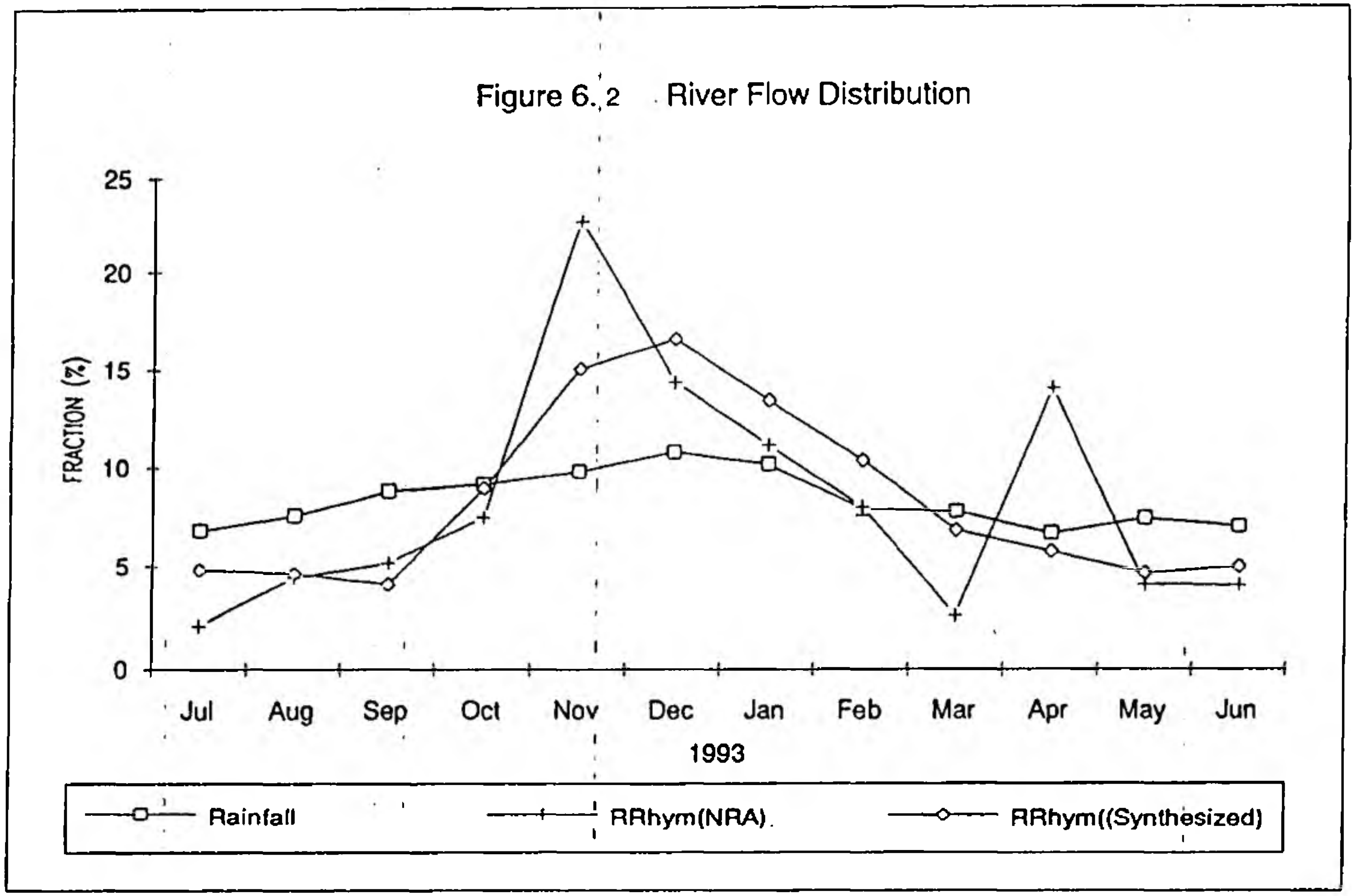
Figure 6. 2 River Flow Distribution
FRACTION (%)
25
20
15
10
5
0
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
1993
Rainfall
RRhym(NRA)
RRhym((Synthesized)

Similarly, only a partial database was available for the iron concentration in the discharges. Typically, averages of the available concentration data were used for the remainder of the year. This would be a reasonable assumption if the release of iron is controlled by chemical equilibrium, i.e., dissolution of secondary mineral phases. This result 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.

It is anticipated that more accurate estimates of the applicable hydrographs and iron concentration profiles will be generated in the next phase of the investigation if required.

The total iron, aluminium and sulphate loads being discharged at each site are given in Volume 2 in the relevant section, and have been summarised in Table 6.1, which inter alia gives the mean minimum and maximum expected iron concentrations in the synthesised discharge before treatment.

6.1.5 The Probability of Exceeding the Standard for Iron

The probability of failure for the existing situation without applying any remedial actions may be assessed using the data obtained from previous monitoring of flows and concentrations and the point estimate method. In this method, the concentration of Fe and the flow rate in the discharge and river are assumed to be a random variable following a normal distribution. Use of the normal distribution is recommended by Harr (1987) in cases where very little information on the actual disbtribution is known. The discharges from two sites (Blackwood and Lynffi) are believed to have distributions other than a normal distribution, however at this level of investigation use of the normal distribution should have little significant impact on the overall results.

The concentration of Fe in the stream is calculated based on the following formula:

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

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

The correlation coefficient was calculated based on the data available. 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. Results have been presented in Table 6.2 and the decision tree is presented in Figure 7.1.

The fault/decision tree should be considered as a tool to assist in decision-making. There are various ways of such a tree being constructed, and the one presented should not be considered as final.

TABLE 6.2

PROBABILITIES OF FINAL IRON CONTENT OF DISCHARGES ACHIEVING REQUIRED TARGET

Site Number/Name		Probability of Iron Exceeding:		
		2 mg/l	1 mg/l	0.3 mg/l
5	Blackwood	0	0	0.59
6	Pontllanfraith	0	0	0.94
7	Tir y Berth	0.32	0.71	0.96
10	Blaenavon	0	0.31	0.97
12	Y Frwdd/Llanwonno	0	0.35	1
15	Llynfi	0.14	0.74	0.99
16	Craig yr Aber	0.83	0.96	0.98
17a	Afon Corrwg	0.04	0.63	0.98
17b	Afon Corrwg	0	0.41	1
18	Afon Corrwg Fechan	0.18	0.76	0.99
19	Gwynfi	0.25	0.79	1
29	Cathan	0.02	0.54	0.98
30	Morlais	0.99	0.99	1
31a	Dunvant	0.44	0.90	0.98
31b	Dunvant	0.97	0.99	0.99
33	Clydach Tawe	0.40	0.65	0.68
62	Ynysarwed	0.73	0.78	0.80
62a	Blaenant	No data	No data	No data

6.1.6 Environmental Costs and Benefits

The environmental costs and benefits have been assessed in two main ways. Initially, the value of the watercourses as fisheries, both in terms of angling interest and as spawning grounds was assessed.

The importance of the watercourse as a fishery has been ranked, with a high value representing an actual or potential fishery loss and a low rank indicating little spawning value and low or no impact.

Other environmental parameters, mainly the aesthetic impacts (which may be more difficult to assign an economic value to) have also been ranked. Methods of assessing these usually involve social survey techniques to derive values for environmental changes, such as the improvement in the appearance of a stretch of river. As the discharges and consequently the environmental damage have already occurred, there is little opportunity to cost the loss in quality or compensation for the change in appearance. Social survey techniques are outside the scope of this phase, but it may be appropriate to use these methods in a more detailed investigation and to attempt to determine what compensation people would be prepared to accept for the river to remain as it is. It is expected that variations in value will occur, particularly where the discharges have been occurring for many years, as compared with sites where the discharge is relatively recent.

Parameters considered include the proximity of each site to footpaths and roads, the visual impact of the downstream area, proximity to built-up areas and to recreation areas. All of these rankings have been summarised in Section 7.

In addition, the environmentally related factors for each site which it was considered could not be realistically ranked are summarised in Section 7. These include site specific factors such as the presence of litter and rubbish on the banks and in the stream bed and the likelihood of visitors to the area of watercourse where ferruginous staining is obvious.

7 ASSESSMENT OF ABATEMENT OPTIONS

7.1 Basis for Assessment

The assessment of control technologies was completed with the objective of attaining the proposed Environmental Quality Standards (EQS) within the watercourses receiving ferruginous mine waters, as provided by the NRA and adjusted as discussed in Section 5 above. The target water quality is as follows:

1. Total iron ≤ 1.0 mg/l
2. 6 ≤ pH ≤ 8
3. Total aluminium ≤ 1 mg/l at 6 ≤ pH ≤ 8
4. No discolouration of the river bed or deposition of ferruginous material below the mixing zone of the discharge.

Within the scope of this study it was not possible to evaluate all of the potential control measures. Therefore, Chapter 4 and Appendix A suggest which options are most worthy of further investigation.

7.2 Assessment of Abatement Options

7.2.1 Field Assessment

The initial approach to assessment was to rapidly assess the technical feasibility for the identified 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); and
- 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 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. The basis for costing is discussed further in section 7.2.3, and comprises estimates for `cost of implementation' (capital costs) and cost associated with long term maintenance (operating costs). Active systems which collect and actively treat the discharge in a reactor system, require continuous operation and maintenance. This constitutes a high operating cost and may require to be operated `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.

The results of this assessment are summarized in Table 7.1. The performance based and cost ratings were developed for each option as a `stand alone' solution. However, 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.

For the assessment of the wetland system as defined in Appendix A, the loading estimates were used to estimate an approximate storage volume required for the accumulation of iron hydroxide sludges within the settling basin for a period of about 10 years, with an annual accumulation to depth of about 0.01 m. A corresponding retention time was estimated based on a pond depth of about 1m above the sludge at all times. This approach was taken to provide a rough guideline as to the overall land requirement for the implementation of such a system. Available conventional wetland design criteria are not based on optimization of the aeration/oxidation step, but are based on inefficient surface flow through the wetland. Typically, conventional design criteria would yield up to 10 times the surface area estimates provided herein, but are considered to be overly conservative. It is considered that for some of the lower flow/load discharges, these estimates would be not unreasonable. These estimates were made based on the assumption that a second, detailed engineering study would be undertaken to provide the necessary design criteria.

TABLE 7.1 Summary of Possible Control Measures See text for site specific details (Technical Rating/Cost Rating)*

Site	NAME	SOURCE COMPONENTS	POSSIBLE SOLUTIONS												COMMENT
			Source Control			Migration Control				Treatment					
			Oxygen Exclusion			Surface Diversion	Entry Closure	Internal Diversion	Hydraulic Balancing	Collect & Chemical	Internal SRB	ALD Required	Wetlands (Aerate & ppt)	Controlled Discharge	
			Flooding Bulkhead	Plugs Entry Control	Covers										
5	Blackwood	Mynyddislwyn - unflooded	0/-	0/-	0/-	0/-	0/-	0/-	0/-	5/1	0/-	0/-(NR)	4/3	5/4	Disperse
6	Pontllanfraith	Mynyddislwyn - unflooded	0/-	0/-	0/-	0/-	0/-	0/-	0/-	5/1	0/-	0/-(NR)	4/3	5/4	Disperse
7	Rhymney at Tir y Birth	Unflooded/flooded underground - oxidizing	0/- 0/-	3/? 0/-	0/- 0/-	0/-	0/-	0/-	3/?	5/1	2/?	0/-(NR)	4/2	-/-	Sludge disp in Brittania H2S Odours (PO)
10	Blaenavon	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/?	
12	Clydach Taff/ Llanwonno	Outcrop - oxidizing	-/-	-/-	-/-	-/-	-/-	-/-	-/-	5/1	-/-	0/-(NR)	4/3	4/3	
15	Llynfi	Opencast/Spoil tips (?) Unflooded underground Flooded underground	)1/?))	3/?	1/?	-/-	-/-	-/-	-/-	5/1	0/-	0/-(NR)	4/3	1/?	Interception wall may be required
16	Craig Yr Aber	Flooded/unflooded workings Spoils	0/- -/-	2/1 -/-	1/? 3/1 (?)	2/3 2/2	-/- -/-	-/- -/-	-/- -/-	5/1 5/1	-/- -/-	)required)	4/3	-/-	
17 17A	Afon Corrwg Afon Corrwg	Unflooded Flooded	3/2 2/2	3/3 3/3	-/- -/-	-/- -/-	-/- -/-	-/- -/-	-/- -/-	5/1	-/?	)required)	4/3	1/2?	17A Discharge from fault structure - interception req'd
18	Corrwg Fechan	Unflooded	4/2	4/3	-/-	-/-	-/-	-/-	-/-	5/1	2/2	0/-(NR)	4/2?	-/-	
19	Gwynfi	Flooded and unflooded	1/?	4/3-2	-/-	-/-	-/-	-/-	-/-	5/1	?/?	0/-(NR)	4/2?	-/-	
29	Cathan	Unflooded/Flooded Underground	3/2	4/3	?	-/-	-/-	-/-	-/-	5/1	-/-	Required	4/3	2/?	High Fe - effective diffusion difficult
30	Morlais	Oxidising 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
31 31A	Dunvant Dunvant Square	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
33	Clydach Tawe	Opencast 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
62	Ynysarwed	Unflooded and flooded workings in Rhondda No2	1/-	4/3	-/-	-/-	-/-	2/2(?)	3/4 (See 62A)	5/1	3/3 (See 62A)	Required	4/3-2	-/-	Connected with Blaenant Dulais
62A	Blaenant Dulais	Discharge directly into river bed	1/-	4/3	-/-	-/-	-/-	3?/?	3/4	3/1	3/3	?	?	?	Little water quality data available

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

7.2.2 Risk Assessment and Fault Tree

The fault-event tree approach 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.

The approach 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, in this case [Fe] $\langle$1mg/l. The system analysed is the entire discharge from the point where water enters the ground through infiltration and then flows to the discharge and the portion of the river affected. A schematic representation of the flow system is shown on the top right hand side of the fault tree.

The system described above is considerably simplified, but is adequate for the purposes of identifying and assessing suitable remedial measures and their potential effectiveness.

If the system were to work perfectly, the concentration of Fe in the river at the compliance point would be less than the permissible concentration at all times. In other words, no matter how much ferric iron comes out of the discharge, all the iron would be precipitated before entering the river, or the rate of release of iron from the source would always be low enough such that the alkalinity, aeration and settling time is always sufficient to ensure that all the iron precipitates. In practice, due to various imperfections in the system, iron will enter the river and unacceptable concentrations may be measured from time to time. The fault tree presents details of the various faults which may occur within the system, together with their interrelationships. In this case, we have defined failure as the probability that the concentration of Fe will exceed the allowable concentration (1 mg/l) at the compliance point. Failure can be defined in some other way, either as a different Fe concentration or for instance as a 15% reduction in the invertebrate biomass.

It is possible to estimate the probability of failure of the system, provided that we have defined what we mean by failure. Should we decide that the probability of failure is unacceptably high for a particular rate of discharge, possible remedial measures are 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.

The top fault is considered to be that the concentration of iron in the river at the compliance point (generally downstream of the mixing zone), exceeds the allowable concentration. The allowable concentration may be varied depending on site specification.

Apart from the discharge point under consideration, other discharges either defined or undefined may exist upstream of the compliance point. Undefined discharges may be discharges which will only occur in future due to the continued flooding of underground workings. The fourth level of the risk tree therefore recognises that other discharges may contribute to the Fe load in addition to the discharge point under consideration.

The immediate cause of the Fe load exceeding x is defined on the 5th level of the fault tree as "The probability that insufficient Fe was removed from the discharge water before it entered the stream, resulting in a concentration of iron in the discharge water at the point of entry into the river, exceeding x/q". The load to be removed is calculated as follows:

Load to be removed between discharge point and compliance point = $C_d.q - C_{allowable}.(q+Q)$ where:

Cd	=	Fe concentration of discharge
q	=	Discharge flow rate
Q	=	Upstream flow rate

There are two intermediate faults which may occur which result in less Fe being removed than is calculated above. These are shown in level 6, namely, the ferrous hydroxide does not settle out of the water, or that the ferrous hydroxide is not formed and therefore remains in solution. Ferrous hydroxide will not settle out if the turbulence is too high or if there is insufficient settling time or settling space. These are shown on level 7.

The probability of a particular fault occurring is shown in the bottom left hand side of each fault box. The probability values for each primary fault must be calculated, guessed or measured for each discharge. Once these values are stated, the probability of faults higher up in the fault tree occurring are calculated using boolean algebra .

Candidate remedial measures are shown in dotted boxes for each primary fault. These are discussed in more detail in Section 4 and Appendix A. By applying one or more remedial measures to a particular fault, the probability of that fault occurring will change, depending on the effectiveness of the remedial measure. Again, the probabilities of the primary faults must be assessed by calculating, guessing or using knowledge of their effectiveness, where they have been applied elsewhere. Certain remedial measures may affect the probabilities of faults to which they are not directly attached. For example, by preventing water from flowing through the mine workings, the quantity of Fe taken up in solution may be reduced. With the reduced quantity, less alkalinity will be required to neutralise the pH. The probability of insufficient neutralisation potential may therefore reduce.

7.2.3 Key Chemical Factors in Decision Making

The chemistry of ferruginous discharges, and therefore treatment, is very complex. There are some key factors which can be used to identify what the dominant process 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 sampling method and location are obviously significant in determining the above factors.

The oxidation of pyrite in the presence of air and water can generate high levels of iron and sulphate with low pH. If some neutralisation has occurred, this will probably be reflected in elevated alkalinity and pH.

If pyrite is in flooded workings, oxidation can still occur, provided the water is well-oxygenated. The iron content would, however, be limited to about 5ppm, with a pH of 4 to 5, without any neutralisation.

The oxidation of iron from ferrous to ferric and precipitation as iron hydroxide result in the release of hydrogen irons. This causes a drop in pH, which could be as low as 4 or 5.

The first objective in assessment is to attempt 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.

These yield different iron concentrations for different flow conditions.

Where the dissolution of secondary mineral phases constitutes the primary mechanism, a steady or constant concentration of the solubilising species (e.g., iron), in equilibrium with the secondary mineral phase, tends to develop. This concentration remains independent of the flow conditions. It is this characteristic that is generally used to identify this mechanism.

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.

The actual iron concentrations will be a function of these and other mechanisms and therefore identification of the primary mechanism is a complex task.

Typically, in unsaturated flow conditions, an increase in flow results in an increase in the surface area (rock face, fractures, etc.) that is contacted by that flow. This means that if not all of the reacting surfaces are contacted by the base flow, a sudden release of stored or accumulated products would be observed with an increase in the flow rate. It is therefore possible that an increase in the iron concentration could be observed. Once the available stored products have been mobilised, and with a further increase in flow, a dilution of the reaction products would be observed and a decrease in the iron concentration would result.

The rate of reaction or reaction kinetics is further determined by the conditions at the source, such as oxygen availability and pH conditions. For example, a decrease in pH to within a level where bacterially catalysed oxidation may occur could result in an increase of several orders of magnitude of the reaction rate. Under such conditions, an increase in iron concentration would be observed at steady flow conditions.

If iron has been precipitated as ferric hydroxide or oxy-hydroxide, a reduction in the pH is required for the remobilisation of the iron under steady redox conditions. However, as shown in the pH-Eh diagram at Figure 3.4, it is also possible that a change in redox potential may result in a phase change, i.e., ferric hydroxide to ferrous conversion, at a steady pH (say < 7.0 - see Figure 3.4). The solubility would increase with decreasing pH and redox potential.

Dissolved species is measured in a water sample that has been passed through a 0.45um filter; total species is obtained without any filtration. In both cases, for metal analysis, the water sample is preserved by adding a small quantity of concentrated acid to the sample. This is done to prevent the precipitation of species in solution.

The total iron present in the water represents both that contained in suspended matter (e.g., $Fe(OH)_3$) and dissolved species (e.g., Fe^{2+}; Fe^{3+}; $Fe(OH)^{2+}$ and any other complexes). The difference between the total and the dissolved represents particulate iron. (However, care should be taken in the interpretation, since very fine iron containing particles may pass through the 0.45um filter.) If the particulate iron is high, a reduction in the iron content is possible by simply providing sufficient settling time at a low stream velocity. High particulate iron, in the case of inactive mines, suggests that the iron is present as the hydroxide precipitate (silts, etc., require physical activity to be released). This means that the conditions at or between the point of generation and the monitoring point are to be oxidising (high availability of oxygen) and that sufficient alkalinity is being released to facilitate the formation of the ferric hydroxide.

Detailed chemical analyses are required to assess the potential equilibrium control mechanisms that are active and assess the mechanisms for neutralisation. For example, the calcium concentration, together with the sulphate analysis, would indicate if a gypsum control is active on the release of sulphate. Where a gypsum control is present, the sulphate concentration cannot be used to assess the rate of oxidation, since it is possible that part of the sulphate generated through active oxidation is being precipitated and accumulated between the point of generation and the monitoring location. Detailed analyses are also useful to determine the characteristics of the neutralising minerals and the pH at which active oxidation is occurring. Different minerals are reactive at different pH conditions. The presence of, for example, silica in a discharge would indicate a low pH at or near the source. Calcite, on the other hand, is reactive at a near neutral pH.

It is important to ensure that samples are taken under controlled conditions at the point of discharge.

Detailed analyses would therefore typically comprise:

- 30 element ICPs for metals, which would include Na, K, Ca, Mg, Si, Fe, Mn, etc.
- Inorganic carbon for dissolved CO3 content plus alkalinity/acidity.
- Major anions (sulphate, chloride, nitrate, etc.).
- Redox and pH.
- Dissolved oxygen.
- Any other components that may be applicable to the site.

7.2.4 Costing

The costing estimates have been based on unit costs for certain types of engineering work, recalculated for each site in terms of eg length of pipes, area of settlement pond required, etc. Higher costs which may be incurred as a result of the inaccessibility of some sites has not been included apart from a 30% contingency cost per site - an element of this has already been included in the feasibility of treatment options assessment sheets completed following the site visits. The costs can only be used for comparative decision-making and no site-specific details have been assessed at this stage.

Table 7.2 summarises the unit costs for typical construction of the components of remedial measures.

They are estimates and should only be used for comparative purposes.

The costs for specific site investigations, location of construction materials and design have not been included.

Where wetlands are proposed remote from the discharge, assumptions have been made for lengths of pipeline to convey the discharge to an alternative site. The use of

.pipelines will depend on the geochemistry of the discharge. It will only be feasible if the discharge can be collected with all iron in solution and with very low dissolved oxygen to avoid precipitation in the pipeline. Possible sites for wetlands have not been investigated therefore this item must be reviewed in phase 2.

TABLE 7.2

SUMMARY OF ESTIMATED UNIT COSTS FOR REMEDIAL MEASURES

			COSTS (£)		Add 30% to all costs for miscellaneous, contingency, etc.
			Capital	Operating	
1.	1.1	Hydraulic balancing boreholes: - 100m 250mm diameter - 100m 150mm diameter - 300m 250mm diameter - 300m 150mm diameter (Interpolate for others, e.g. , 200m)	£12,000) £9,000) £35,000) £30,000)	2 mandays per month £500 per annum	Add 70% for angled drilling. Add £5,000 for headworks, flow control, etc.
	1.2	Shaft sealing and grouting (using drill holes)	£60,000	-	
	1.3	Adit sealing/bulkheads	£15,000	-	
2.		Air sealing adits (through drillholes if adit not open)	£5,000	-	
3.		Wetlands (settlement lagoons) tables for each 10 year period Disposal of slurry required?	25/m² (250,000/Ha) (Ha)	2 mandays per year plus 10% of capital per annum to allow for: · sludge removal or · replacement at 10 years	
4.		Civil works to collect discharge at adit sites to flow small < 1Ml per day. > 1Ml/d Large Rhymney (special case)	£5,000 £10,000 £30,000		
5.		River diffuser works Small Large Add cost of pipework if diffusing upstream or downstream from discharge site	£10,000 £12,500		
6.		Sulphate reduction Site installation for feed system	£40,000	2,000/ton Fe	
7.		Anoxic Limestone Drain (ALD)	£40 per metre	4 tons $CaCO_3$ per year per Ml per day discharge or £10 per ton delivered	

SUMMARY OF UNIT COSTS FOR PIPELINES

Pipelines	Maximum Flow Rate Ml/day	Size (mm)	Cost per 200m length (installed)	Cost per km (installed)
	1	100	12,000	60,000
	4	200	15,000	75,000
	9	300	20,000	100,000
	25	500	40,000	200,000

7.3 Environmental Impacts/Benefits Assessment

Most of the rivers in South Wales are recovering from pollution due to heavy industrialisation. These rivers are developing runs of salmon and sea trout due to natural recolonisation and some restocking programmes by the National Rivers Authority. Those ferruginous sites with an impact on salmon and sea trout recovery potential are indicated in Table 7.3. Plus signs in brackets indicate a minor impact.

Due to time and budget constraints, no attempt has been made to provide an accurate economic evaluation which may take account of fishing expenditure and tourism and transport expenditure, as well as the direct cost of fisheries. More intangible costs also include loss of amenity and possible impact on wildlife, such as otters, herons and kingfishers, which depend on fish for food, and dippers, which depend on invertebrates for food. This has not been covered, nor has the potential for improved value of fisheries due to recovering salmon and sea trout populations.

Six sites have been categorised on the basis of angling values and five sites have been categorised on the basis of replacing trout in spawning streams. Five sites have been given a nil evaluation, mainly on the basis that electrofishing results downstream of discharges had higher trout density than upstream. On this basis, some doubt must exist over the valuation of the River Sirhowy at Pontllanfraith (by comparison with the River Rhymney valuation) because the electrofishing survey showed a higher density of trout downstream.

The presence of other consented discharges with the potential to affect fisheries value, either upstream or downstream, has not been considered. The effect of these if the ferruginous discharge is ameliorated should be considered, but this is outside the scope of work.

The environmental impacts and benefits have been assessed using a weighting system, with a high score being a large or significant impact. The scores are subjective, although the categories for assessment have been chosen so that some degree of objectivity can be introduced. Scores are shown on Table 7.4 and comments on other environmental and aesthetic factors are summarised in Table 7.5. In Table 7.4, the higher the scoring, the greater the impact on the public and on fisheries, and therefore the greater potential benefit of remediation.

Table 7.3 Ferruginous Minewater Impact on Fisheries and Their Values.

SITE NO.	NAME	FISHERIES IMPACT	ELECTROFISHING (No/100m²)				Percentage Difference	HQS% downstream	Other Pollution	Area (m²) Affected	Angling Value	Trout Spawning Value	Salmon, Sea Trout Potential
			Upstream	JSMP	Downstream	JSMP							
5	Sirhowy, Blackwood	-	-	-	-	-	-			4800	+	+	+
6	Sirhowy, Pontllanfraith	C	5.1	D	7.1	C	(+39%)	poorer		12600	+	+	+
7	Rhymney, Tir y Berth	C	4.7	D	3.3	D	-30%	poorer		36000	+	+	+
10	Llwyd, Blaenavon	-	-	-	-	-	-			500	-	(+)	(+)
12	Clydach Taff, Y Ffrwd	-	4.6	C	16.5	C	(+258%)			4400	-	+	-
15	Llynfi, Llynfi	A	92.7	A	20.7	C	-88%		no	5400	-	+	+
16	Cynffig, Craig yr Aber	B	16.5	C	5.1	D	-69%		no	13500	-	+	(+)
17	Corrwg, Afon Corrwg	B	17.8	C	5.9	D	-66%		no	12800	-	+	(+)
18	Corrwg, Corrwg Fechan	C	nil	E	nil	E	-			5100	-	(+)	(+)
19	Afan, Gwynfi	C	3.5	D	8.6	D	(+146%)			5250	-	(+)	-
29	Loughor, Cathan	B	43.6	B	17.2	C	-61%		no	3600	-	(+)	-
30	Morlais, Morlais	A	10.3	C	0	E	-100%	poorer		5000	+	+	+
31	Clyne, Dunvant	C	31	C	56.4	B	(+82%)			3500	-	(+)	-
33	Lower Clydach, Llechart	-	-	-	-	-	-			3000	-	+	-
62	Neath, Ynysarwed		good		nil		-100%			180000	+	-	-
62a	Dulais, Blaenant		-	-	-		-			2000	+	+	+

Refer to section 2.1 and NRA report for impact categories.

TABLE 7.4

IMPACT SCORING OF FISHERIES AND ENVIRONMENTAL AESTHETICS

SITE NO.	SITE NAME	ANGLING VALUE	ACCESS-IBILITY: FOOTPATHS	ACCESS-IBILITY: ROADS	VISUAL IMPACT DOWN-STREAM	PROXIMITY TO BUILT-UP AREA	PROXIMITY TO RECREA-TION AREA
5	Blackwood	5	5	3	2	3	1
6	Pontllanfraith	5	5	3	3	5	5
7	Tir y Berth	5	5	3	4	2	1
10	Blaenavon	1	3	2	2	2	1
12	Y Ffrwd (Llanwonno)	1	3	1	4	1	1
15	Llynffi (Farm)	2	4	2	3	1	1
16	Craig yr Aber (Aberbaiden)	3	5(a)	2	2	1	3
17	Corrwg	2	4	1	4	1	1
18	Corrwg Fechan	1	4	1	4	1	1
19	Gwynffi	1	3	2	3	1	1
29	Cathan	2	5	2	5	1	1
30	Morlais	4	1	2	5	1	1
31	Dunvant (Clyne)	4	5	2	3	3	1
31a	Dunvant Square	*	5	5	3	5	3
33	Lower Clydach (Llechart)	2	2	2	3	1	1
62	Ynysarwed	5	4	5	5	4	5(b)
62a	Blaenant	5	1	3	1	1	4(c)

Angling Value: No impact on angling or spawning (1); Possible impact (2); Probable impact (3); Some reduction in fish/fish barrier (4); More than 50% reduction in fish (5)

Accessibility - Footpaths: Footpath exists within 1km (1); 500m (2); 100m (3); 50m (4); 10m (5)

Accessibility - Roads: Road exists within 1 km (1); 500m (2); 100m (3); 50m (4); 10m (5)

Visual Impact of Discharge: Severe impact (5); Little impact (1)

Visual Impact Downstream: Severe impact (5); Little impact (1)

Proximity to Built-up Area: Houses within 100m 5); Houses and factories within 100m (4); Houses and factories within 100m to 300m (3); Factories and industrial areas within 100m to 300m (2); Houses > 300m (1)

Proximity to Recreation Area: Sports field/recreation facility within 100m (5); Sports field within 100m to 200m (4); Other recreation area within 100m to 200m (3); Any recreation area within 200m to 500m (2); Any recreation area >500m (1)

* Not scored as same fisheries value as site 31

(a) Ridgeway Path; (b) Neath Canal; (c) Mining Museum

TABLE 7.5

SUMMARY OF ADDITIONAL ENVIRONMENTAL FACTORS

(NOT USED IN SCORING SYSTEM)

SITE NO.	SITE NAME	ENVIRONMENTAL/AESTHETIC CONSIDERATIONS
5	Blackwood	Rubbish in trees, along banks and in stream bed, but not likely to be seen by casual visitors to the area.
6	Pontllanfraith	Rubbish in trees, along banks and in stream bed, but not likely to be seen by casual visitors to the area.
7	Tir y Berth	Rubbish in trees, along banks and in stream bed, but not likely to be seen by casual visitors to the area.
10	Blaenavon	Not likely to be seen by casual visitors to the area. New opencast operation dominates area. Big Pit mining museum closeby brings in many visitors, but the relics of industrial development are generally unreclaimed, much derelict land.
12	Y Ffrwyd/ Llanwonno	Not likely to be seen by casual visitors to the area. In an area off afforestation with tracks used by walkers and horse and bike riders. Generally a 'country' area, so discharge is more unexpected and could create a greater impact.
15	Llynfi	No public access apart from footpath through farmyard. Land obviously disturbed by bell pits, but old woodland exists around several of the discharges and the area is obviously tended and grazed, rather than 'natural'.
16	Craig yr Aber	Very likely to be seen by visitors to the country park area and walkers along the Ridgeway path. Area very well wooded and designed for public access and countryside recreation, although the industrial archaeology may well be of interest to some people (old buildings, tram roads, etc.).
17	Corrwg	Remote site unlikely to be seen by casual visitors. Walkers and riders may be impacted. Those interested in industrial heritage may see it. Colliery site in valley bottom and spoil heaps along valley sides, otherwise good 'clean' mountain stream upstream of discharge.
18	Corrwg Fechan	Remote site is unlikely to be seen by casual visitors. Walkers and riders may be impacted. Those interested in industrial heritage may see it. Colliery site in valley bottom and spoil heaps along valley sides, otherwise good 'clean' mountain stream upstream of discharge.
19	Gwynfi	Unlikely to be seen by casual visitors. Forested area nearby in valley, forestry tracks probably used by local walkers and riders. 'Clean' mountain stream upstream of discharge, effects not very noticeable by the time the stream passes through the village.
29	Cathan	Not likely to be seen by casual visitors to the area. Attractive setting of woods and open areas by river, but dramatic impact of discharge. Some litter along banks and in woods.
30	Morlais	Discharge approached from derelict colliery site where fly tipping has taken place and is continuing. Close to motorway, no footpaths, discharge cannot be seen from Heart of Wales railway line (4 trains per day). No obvious access to marshes for birdwatchers, fishermen or cockle gatherers.
31	Dunvant	Village is on tourist route to Gower Peninsula, but does not appear to be 'geared up' for tourists as there are no obvious parking places by the shops or green. Therefore, probably unlikely to be seen by casual visitors. Stream valley very badly littered. Locals report discharge has been occurring for 30-40 years at least. Otherwise, attractive wooded area. Upstream discharge (seeps) have less visual impact than pipe discharge by bridge in village square.
33	Clydach Tawe	Discharge point by recently abandoned private mine. Very untidy derelict site, with litter, wrecked and scrapped vehicles, abandoned sheds, buildings and caravans adjacent to empty derelict farmhouse and buildings. Very unlikely to be seen by casual visitors. May detract from value of farmhouse and buildings which are up for sale.
62	Ynysarwed	Very likely to be seen by passersby on A465 trunk road to Neath and Swansea, and holidaymakers to the area who may be using the canal and surrounding areas for recreation (close to Melincourt Waterfall).
62A	Blaenant/ Dulais	Discharge and downstream impact unlikely to be seen at present, but discharge may be expected to worsen slightly until water levels in the Cefn Coed shift reach equilibrium. Close to forest walk, picnic area and mining museum at the old Cefn Coed Colliery, 4-5km upstream of Aberdulais Falls (National Trust) and Wildlife Park. Sarn Helen Roman Road (used as part of unofficial long distance footpath) runs along the top of the hill between the two discharges and follows the Neath Canal along part of its polluted length.

8 CONCLUSIONS

8.1 Magnitude of the Problem

The study has focussed on the red staining produced by iron hydroxide deposition, although the aluminium content has also been considered. The key aspects are centred on the magnitude of iron loading, the impact on the aquatic environment, the cost of remedial measures and the benefit to be gained from them.

In many cases, the discharges have been occurring for many years and are in places where people either do not notice them or have got used to them. A key decision, therefore, is whether to do anything at all, particularly if the EQS is partially achieved.

8.2 Remedial Options

A wide range of remedial options has been discussed, but at many sites the range of options is limited due to the conceptual hydrogeological models and to some extent by uncertainty about the detailed water chemistry. Where possible, solutions involving modifying or reducing the flow through old workings are proposed, together with a reduction of the oxidation potential by flooding or air-sealing shafts and adits.

The use of sulphate-reducing bacteria is proposed in one or two cases. This technique can provide a valuable reduction in iron loading, but is limited in the present cases due to the limited access to the workings, and therefore provision of the necessary conditions.

This would have more application if access could be obtained prior to mine closure, but this is not the case in any of the existing sites.

End of pipe solutions are the least favoured option, but inevitable in a number of cases. Where possible, settlement lagoons or wetlands are proposed, which require limited maintenance.

In many cases, the available information suggests that improved dispersion of the discharge water in the receiving water will achieve a significant improvement.

8.3 Costs

Table 8.1 summarises the broad estimates of costs for the various sites. The higher flow discharges, such as Morlais and Rhymney, result in costs of several hundred thousand pounds, but the smaller sites requiring only improved dispersion could cost £20,000. Remedial works for nine of the proposed sites would cost between £17,500 and £50,000 each, plus the costs of design and supervision.

TABLE 8.1
SUMMARY OF COSTS FOR PREFERRED REMEDIAL OPTIONS

Site No	Site Name	Remedial Option	% Confidence	Capital Cost	Operating cost/annum
5	Blackwood	Diffuser	90%	£20,000	£2,500
6	Pontllanfraith	Hydraulic balance & diffuser	70%	£37,000	£4,700
7	Rhymney	Hydraulic balance Sulphate reduction Wetland	60% 40% 90%	£130,000 £126,000 £730,000	£13,500 £52,600 £74,500
10	Blaenavon	Hydraulic balance Wetland	70% 90%	£28,000 £50,000	- £6,500
12	Y Ffrwd/Llanwonno	Dam and spillway	75%	£25,000	£4,000
15	Llynfi	Oxygen plugs, wetland	80%	£55,000	£5,000
16	Craig yr Aber	ALD, aeration & wetland	80%	£264,000	£28,900
17	Afon Corrwg	Oxygen plugs, ALD, aeration & wetland	90%	£125,000	£14,000
18	Afon Corrwg Fechan	Bulkhead, wetland	80%	£36,000	£5,100
19	Gwynfi	Oxygen exclusion/wetland	80%	£50,000	£6,500
29	Cathan	Oxygen exclusion/wetland Sulphate reduction	70% 30%	£74,500 £210,000	£8,950 £33,000
30	Morlais	ALD/wetland Pipeline Sulphate reduction	70% 90% 50%	£525,000 £100,000 £160,000	£54,000 £11,500 £816,000
31	Dunvant	Plugging, wetland	90%	£17,500	£1,250
31A	Dunvant Square	Hydraulic balance, ALD, wetland	70%	£61,000	£6,600
33	Clydach Tawe	Oxygen exclusion/wetland	80%	£50,000	£5,500
62	Ynysarwed	Oxygen exclusion, ALD, wetland	80%	£604,000	£62,200
62A	Blaenant	Hydraulic balance, wetland	80%	£225,000	£24,000

NB: Wetlands costings include land purchase price. Wetlands are costed for 10 years and costs do not include sludge disposal but the operating costs at 10% of capital allows for replacement or sludge disposal. The above costs do not include for engineering design.

8.4 Summary of Environmental Benefits and Remediation Costs

The environmental impacts and costs are summarised in Table 8.2, which shows the fisheries value in terms of spawning and angling, a summary of the aesthetic impacts discussed in Section 7 and the biological value derived from the NRA survey. The table also includes the area and length of river affected, as recorded by the NRA field surveys, and the likely capital cost of the remediation schemes proposed.

This should facilitate comparison of all the factors involved and provide a basis for further decision-making.

8.5 Summary of Cost Effectiveness of Remedial Measures

Estimated costs have been presented for the various remedial measures. It has been stated that the costs are guidelines for comparative estimates and can only be improved with additional technical and site survey information. For budgeting purposes, a contingency of 50% should be allowed, plus 10% for engineering design.

There are two main sets of uncertainties to consider in the costs:

- Uncertainty in meeting the target iron concentration.
- Uncertainty on the technical feasibility of the works.

TABLE 8.2
SUMMARY OF ENVIRONMENTAL IMPACTS AND COSTS

SITE NO. AND NAME	FISH-ERIES	AESTHE-TICS	BIOLOG-ICAL	AREA AFFECTED m²	LENGTH AFFECTED Km	COST
5: Blackwood	5	2.8	3	4800	0.40	£20,000
6: Pontllanfraith	5	4.2	5	12600	1.80	£37,000
7: Tir y Berth	5	3.0	5	36000	3.00	£126,000/- £730,000
10 Blaenavon	2	2.0	5	500	0.25	£28,000/- £150,000
12: Y Ffrwd	1	2.0	5	4400	1.10	£25,000
15: Llynfi	4	2.2	3	5400	2.70	£55,000
16: Craig yr Aber	3	2.6	5	13500	4.50	£274,000
17/17a: Afon Corrwg	3	2.2	3	12800	3.20	£125,000
18 Afon Corrwg Fechan	2	2.2	3	5100	1.70	£36,000
19: Gwynfi	1	2.0	5	5250	2.10	£50,000
29 Cathan	1	2.8	3	3600	1.20	£210,000/- £74,000
30: Morlais	5	2.0	5	5000	1.00	£100,000/ £525,000
31: Dunvant	1	2.8	5	3500	1.75	£17,500
31A: Dunvant	1	4.2	5	3500	1.75	£61,000
33: Llechart	1	1.8	5	3000	1.50	£50,000
62: Ynysarwed	1	4.6	3	18000	2.00	£607,000
62A: Blaenant	5	2.0	3	2000	0.50	£225,000

Notes: Fisheries value from Table 7.3 (summary of last three columns)
Aesthetics value from Table 7.4 (mean of scores)
Biological value from NRA report (Table 5, Page 34 - A=5, B=3, C=1)

Other considerations have to be incorporated into decision-making. The first is the availability of funds, and secondly the environmental desirability of remediation discussed elsewhere.

Two final considerations are:

- Multiple remedial works where implementing one remedial measure will improve the probability, and therefore reduce the cost of the second remedial measure. The table can therefore only be used to select the best initial option where there are a number of possibilities for each site.

- The response time of some remedial measures to achieve effectiveness also needs to be taken into account.

TABLE 8.3

SUMMARY OF COST EFFECTIVENESS OF REMEDIAL MEASURES

SITE NO.	NAME	PROBABILITY OF IRON EXCEEDING 1MG/L		COSTS		DEGREE (%)
		PRESENT	REMEDIAL WORKS	CAPITAL	OPERATING PER ANNUM	
5	Blackwood	0	0 + 0.1	20,000	2,500	90
6	Pantllanfraith	0	0 + 0.1	37,000	4,700	70
7	Tir y Berth: 1. Hydraulic balance and diffuser) 2. Sulphate reduction) 3. Wetland)	0.71	0.25 0.30 0.10	130,000 126,000 730,000	13,500 52,600 74,500	60 40 90
10	Llwyd, Blaenavon: 1. Hydraulic balance 2. Wetland	0.31 0.31	0.10 0.10	28,000 50,000	- £11,500	70 90
12	Y Ffrwd	0.35	0.10	25,000	4,000	75
15	Llynffi	0.74	0.15	55,000	5,000	90
16	Craig yr Aber	0.96	0.25	274,000	28,900	80
17	Afon Corrwg (left)	0.63	0.15	125,000	14,000	90
17a	Afon Corrwg (right)	0.41				
18	Afon Corrwg Fechan	0.76	0.20	36,000	5,100	70
19	Gwynffi	0.79	0.10	50,000	6,500	90
29	Cathan: 1. Wetland 2. Sulphate reduction	0.54) 0.54)	0.10 0.30	74,500 210,000	8,950 33,000	90 30
30	Morlais: 1. ALD/wetland) 2. Pipeline to river) 3. Sulphate reduction)	0.99	0.10 0.10 0.50	525,000 100,000 160,000	54,000 11,500 816,000	70 90 50
31a	Dunvant	0.90	0.10	17,500	1,250	90
31b	Dunvant	1	0.20	61,000	6,600	70
33	Clydach Tawe	0.90	0.15	50,000	5,500	80
62	Ynysarwed	1	0.20	607,000	62,200	80
62a	Blaenant	no data	-	225,000	24,000	80

9 RECOMMENDATIONS

Conclusions have been based on limited available information, and general assumptions were made in order to complete the assessments presented. Before design approaches can be considered additional information will be required. Amongst these, the following should be addressed:

- Hydrographs for both the discharge and the receiving water flows were synthesized. These estimates can greatly be improved by additional monitoring, or synthesized by river flow modelling and incorporating available flow data local to each site, instead of the broad approach used in this study. This more detailed information will be required for the detailed assessment and design of control options.

- Water quality data in general is limited to iron, sulphate and aluminium. However, in order to determine possible solubility controls a more complete suite of water constituents, including Ca and Mg, should be obtained. It is recommended that, when available, such detailed water qualities be used to assess actual controls and better define the sources for each discharge. This can be done by using a geo-environmental speciation and equilibrium model such as the MINTEQA2 model developed by the United States Geological Survey.

- Careful control on where and how samples are taken will be necessary to ensure that the iron chemistry and dissolved oxygen is correctly assessed.

- Controlled, diffuse discharge of minewaters has been suggested as a method for abating impact in receiving waters. Such a system would only function well if sufficient dilution is available at all times and the diffusing mechanism is appropriately designed. It is recommended that such a system be tested at a pilot scale to determine the appropriate design criteria.

- The potential for the implementation of a flow control system in conjunction with a diffusing system should also be investigated. Such a system, in essence, would require a reservoir which is used to store excess discharge during low flow conditions in the receiving water and from which the discharge rate would be increased during high flow periods. The flow would be balanced on an annual basis with no net accumulation in storage.

While such a system would require active control that could probably be handled with a controlled pumping system, it would be less expensive to operate than an active treatment system, provided sufficient storage is available.

- All sites will require survey plans to prepare designs and costs for earthworks. Formal cost estimates should be prepared for sealing adits, wetland construction, etc.

- Where hydraulic balancing using boreholes is suggested, exploration holes are required. A site should be selected to drill exploratory holes to assess the feasibility of this technique and the degree to which existing discharge loads can be modified. Costs for such holes are included in the capital costs.

- Where pipelines or ALDs are proposed, it is important that the water can be transported in an anoxic condition, with all iron in solution. This needs to be checked by careful field sampling and analysis.

- The disposal of accumulated sludge from settlement lagoons and wetlands should be more closely investigated in terms of acceptability to landfill, handling and costs of disposal.

PROJECT TEAM

This project was carried out by a team drawn from various SRK offices and local associates. Their contributions are gratefully acknowledged.

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APPENDIX A

REVIEW OF CONTROL STRATEGIES AND TECHNOLOGIES

APPENDIX A

In the discussion, acid generation and sulphide mineral oxidation are interchangeable. While acid generation may occur locally, it is possible that acidic water may be neutralized along its flow path, as is observed for most of the ferruginous discharges.

A1 Source Control - Measures to Prevent Oxidation and Contaminant Dissolution

The control of oxidation and acid generation can theoretically be achieved by:

- excluding sulphides;
- excluding oxygen; or
- excluding water.

Each of these options is briefly reviewed in the following sub-sections.

A2 Exclusion of Sulphides as Applied to Surface Spoils

Removal of Sulphides

The removal of sulphides from net acid generating rock to render the rock non-acid generating has been achieved using flotation methods. The process generally requires crushing and grinding of the rock to liberate the sulphides and is therefore only economic where the sulphides separated in the flotation process have a value sufficient to support the processing costs. There are several examples of porphyry base metal mines where removal of the economic sulphide minerals has resulted in a net acid consuming waste product. This control measure is not economical or practical for application to conditions encountered for the South Wales Coalfield.

Isolation of Sulphides

Isolation of the reactive sulphides by development of a coating on the surface of the sulphide crystals to prevent oxidation has been achieved by adding chemical agents such as phosphates (Hart et al, 1990; Evangelou and Sainju, 1991). An insoluble iron phosphate compound is precipitated at the reaction zone on contact with the phosphate rich solution to form a surface coating. This control measure is most effective within a narrow, slightly acidic pH range, and has to date proven to have only a limited period of effectiveness. It is not suitable for long term application because the surface coatings dissolve (Hart et al.1990).

Segregation and Isolation of Net Acid Generating Rock

Most mine rock or spoil has variable properties with respect to the potential for acid generation. The segregation of acid generating rock from non-acid generating rock can be used effectively to reduce the volume of net acid generating rock (source reduction) (Skousen et al, 1993). With a reduced volume of acid generating rock the isolation and control of the problem rock can be more readily achieved. Rock segregation would only be considered where sulphidic rock can readily be separated from mine rock that has been placed on surface and where a suitable, stable disposal site is available for the long term storage of the sulphidic rock. Few discharges of concern have any significant input from waste rock on surface, therefore this method is not appropriate.

A3 Exclusion of Oxygen

Under Water Placement or Flooding

Placement of potentially acid generating rock under water has two effects:

- since water has a low oxygen diffusivity, the transfer of oxygen to the reactive sulphides is low; and

- with water occupying the void spaces between the solid rock particles the barometric pumping of air into the void spaces is prevented.

The combination of these two effects results in the effective exclusion of oxygen from the sulphides, resulting in effective oxidation and acid generation control. This measure is the principal primary control (oxygen barrier) that has been implemented elsewhere (SRK 1991).

Water covers can be optimized by installing plugs underground to block drainage paths and placing surface deposits of mine rock under water. Discharge water quality from the Walker Mine in California and the Kjoli Mine in Norway was controlled using this method.

Where there is a supply of oxygenated water flowing through the mine rock or another oxidant such as ferric iron, oxidation can be sustained below the flooded level. The contribution to oxidation by these oxidants are however limited by their respective solubilities, and are generally small by comparison.

Low Air Permeability Covers

The nature of the rocks and the extent of mining in South Wales, particularly the presence of old mines for which there are no records make this system difficult (though not impossible) to implement. In some cases, while oxygen will not be excluded the amount entering old workings through adits and shaft may be significantly reduced to the extent that oxidation is reduced.

The placement of dry covers (as distinct from water covers implying flooding) over potentially acid generating rock to exclude oxygen has proven to have limited effectiveness in reducing oxygen entry into coarse mine rock. This is substantially due to the relatively high permeability of partially saturated covers and the effects of barometric pumping and convective and advective transport of air. Even the placement of a 'leak free' geosynthetic membrane cover (SRK, 1991) over coarse mine rock in Norway did not effectively exclude oxygen from the pile. If a saturated layer can be maintained with the cover system then the oxygen flux through the cover can be reduced to low levels (Collin, 1987).

The effectiveness of dry covers increases for very fine grained piles as the advective and convective effects are reduced. While oxygen entry is not prevented entirely, substantial reductions in overall acid generation can be achieved.

Covers are further discussed in Section 4.4.2. As mine rock is not a significant source of discharge, this method is not appropriate for the sites under consideration.

A4 Exclusion of Water

Water is an essential component in sulphide oxidation reactions. It is therefore theoretically possible to prevent acid generation by excluding water. However, pyrite oxidation is known to proceed even at low humidity in air (Lowson, 1982). The exclusion of water from a rock pile or subsidence zone, to the point where humidity is limited, is not practical in a high rainfall area such as Wales.

A5 Control of Contaminant Migration

A5.1 Diversions

Surface diversions to prevent clean water access and leaching of a contaminant source may sometimes be effectively installed upstream of the source. Surface diversions are extensively used in North America and it is generally required that the amount of clean water diversion on a site be maximized.

The most appropriate application that may be considered is diversion of run-off water around subsidence or faulted zones to prevent infiltration to underground mines (this may include lining stream channels where they cross subsidence zones or faults that are connected to the underground mines and show a high hydraulic conductivity).

Underground diversions can be used to reduce the flow of water through flooded parts of the mine where contamination is high. In this manner, cleaner waters may be diverted around known contaminating zones, reducing the overall rate of flushing and therefore the contaminant load to the environment. Diversion plugs may not need to be completely watertight as the resistance to flow may be sufficient to divert the major portion of water around the area to be isolated. Underground diversions may be made both in plan and elevation (i.e., around as well as under or over the contaminant source).

Installation of drill holes to decant comparatively clean water from shafts, or to reduce hydraulic heads elsewhere to minimise flow through mine workings would be another form of diversion (also discussed under hydraulic balancing in Section 4.4.4.).

We are unaware of any underground diversions installed in North America. Design considerations for long term performance would presumably include structural integrity to withstand the applicable pressure heads, resistance to erosion and, if composed of cohesionless backfill, resistance to migration of fines and piping failure.

A5.2 Covers

The transport medium for contaminants is water and the principal source of this water is infiltration of precipitation. The most practical way of controlling infiltration is by means of low permeability covers with the establishment of surface vegetation to improve evapotranspiration and provide erosion protection. The required effectiveness of the cover and the length of time during which control is required are most important considerations in selecting appropriate cover designs. However, the very large areas drained by many of the discharges mean that such covers are unsuitable as remediation measures. Types of covers include soil and complex covers made up of any or all of the following :-

> erosion control layer, moisture retention zone, upper drainage layer, infiltration barrier and a lower capillary barrier.

A layer of calcareous materials could also be incorporated into the cover design to increase the pH of infiltrating water.

Alternative materials to soil have been applied at a number of mine sites where acid generating wastes have been covered. Examples are the use of Cefill (cement/fly ash grout intruded aggregate) at the Bersbo site in Sweden (Lundgren et al, 1991) and various combinations of asphalt, geopolymer and high volume polypropylene fibre reinforced shotcrete in North America (Konasewich, 1990; Wong *et al*, 1993). These are designed to limit cracking by allowing for foundation deformations, thermal expansion and shrinkage.

A5.3 Liners

Liners are placed under the contaminant source as a barrier to migration of seepage from the source. Liners can be constructed of either clay or synthetic geomembranes.

There is little potential use for this technology for remediation of the South Wales discharges, unless mine rock contained in spoil tips is to be relocated. Liners may however be appropriate for the containment of drainage collected for treatment and/or for the sludges produced by such treatment.

A6 Cutoff Barriers

Cutoff barriers function by restricting lateral migration of seepage (Vick, 1990). As a consequence, they are fully effective only when pervious foundation materials are underlain by a continuous impervious stratum of natural material that prevents flow under the barrier. The cut off barrier is then keyed into the impervious layer to form a basin. As shown by Cerdergren (1967), a seepage barrier must completely penetrate the pervious foundation layer and form a tight seal with the impervious stratum in order to reduce seepage significantly. For example, a barrier that penetrates 90% of the pervious stratum reduces seepage by less than two-thirds.

Cutoff Trenches

Cutoff trenches are usually relatively economical to construct when natural clays are present for use as compacted trench backfill. Cutoff trenches are perhaps the most widely used seepage-control method, typically implemented for tailings embankments.

Slurry Walls

Slurry walls can also be used to penetrate a pervious foundation stratum. The technique involves excavating a narrow trench whose sides are supported by a bentonite slurry. The trench is backfilled either with a slurry of soil and bentonite with bentonite containing cement additives, or a plastic concrete (Xanthakos, 1979;

Tallard, 1984). Very low permeabilities can be achieved in the wall. Slurry wall cutoffs have been constructed to depths considerably greater than 30m.

The use of cutoff walls would be restricted to areas where discharge in the near surface zone which appears as diffuse seepages has to be intercepted for treatment. This would avoid the use of collection wells which may be subject to clogging where ferruginous waters are involved.

For cutoff trenches, slurry walls and grout curtains, the depth of the workings and the degree of interconnection induced by faults and fractures means that this method is not applicable for the present project.

Grout Curtains

Grout curtains have long been routinely constructed to reduce foundation permeability for major water-retention dams and can be installed to depths well in excess of 100ft. Grouting techniques, while largely an art, are well developed (Albritton, 1982). The purpose of conventional grouting of dam foundations is structural rather than environmental. That is, grouting is intended to reduce foundation permeability to the extent that foundation pore pressures are not excessive. The quantity of foundation under-seepage is of secondary importance.

Grouting seldom reduces the permeability of the grouted material to less than about 10^{-5} cm/sec (Einstein and Barvenik, 1975), a value that, although adequate for water dam purposes, is not often sufficient to restrict seepage from contaminant sources to an acceptable degree for environmental concerns. Other problems include the high cost of grouting and the potential for acid and sulphate attack of the grout. For these reasons, grouting has not been applied for acid mine seepage control.

The use of grouting around plugs placed in drifts and under cutoff walls however may be necessary to reduce bypass seepage.

Underground Plugs

Plugs are installed in mines for water flow control to prevent inundation of mine workings and protect workers, or to induce mine flooding for the control of oxidation acid generation. The latter is becoming increasingly more common and has been implemented in a number of locations in Canada, USA, and Norway.

Contrary to common perception, environmental control bulkhead design is rarely controlled by structural/strength considerations. Seepage through and around a bulkhead is usually the most important factor. As a result, the length of a bulkhead is increased according to empirical guidelines to limit seepage and erosion of the bulkhead and surrounding rock. Tight bulkheads with high differential pressure heads require grouting of the plug/rock contact and surrounding fractured rock.

Where such isolation and flooding can be achieved the installation of plugs can form a cost effective control on active oxidation.

Plugs installed in highly fractured permeable rock are seldom tight and under such circumstances may be designed for low head and to be leaky. In essence, if the plug itself is impermeable, it becomes a diversion which directs the flow through the surrounding bedrock and as a result of head loss for the water to migrate through the less permeable bedrock, acts as a flow 'retardant'. Neutralization of an acidic stream may for example be achieved by rerouting it through a permeable, calcareous host rock. Flow retardation can also be used to control the contaminant loading emanating from a high source area to a level that can be managed by a conventional treatment system. The latter option is discussed in more detail in Section 4.5.

Where plugs are constructed for the control of acid rock drainage there are two important considerations to be addressed. The first is whether the mine will flood to a level below the pre-mining groundwater table. Drillholes, access points and subsidence may result in a lower level of flooding. If there is mining or subsidence above the flooded level but below the original groundwater level, then there will be on-going acid generation. The second is the quality of the flooding water determined by:

- the quality of the inflowing water; and
- the dissolution of oxidation products accumulated in the mine.

Aspects of plug (or bulkhead) design and construction are discussed further in Garrett and Pitt (1961); Chamber of Mines of South Africa (1983); and Chekan (1990).

Access to underground workings is obviously required for the installation of plugs. This is generally not available in South Wales for reasons of safety, accessibility and existing water levels.

Hydraulic Balancing

Seepage flows are determined by hydraulic gradients. If the hydraulic head surrounding a submerged contaminant source is constant then there will be no driving head across the contaminant source and therefore there will be no advective flux of water or contaminants into or out of the source. This condition is termed hydraulic balance.

Hydraulic gradients have been detected at all the sites. Together with the high intensity of workings along connecting coal measures between mines and often the high permeability of separating barriers (e.g., sandstone pillars) that have been left in place between mines, these hydraulic gradients suggest that mine water is being displaced through the mine workings prior to discharge. Consequently, mobilisation of the stored oxidation products within these workings and dewatered strata is likely the primary source for contamination. Hydraulic balancing would reduce the rate of flux through the mine workings and thus reduce the total loading.

Hydraulic balancing may be achieved by installing spillways (either direct or from distant locations with boreholes) in mine shafts, or boreholes into workings or limited closure of adits, to allow decanting of relatively clean recharge water from infiltration. The significance of infiltration as a transport mechanism is however apparent and the importance of controlling infiltration stressed.

A6.1 Geochemical Barriers

In contrast to physical barriers, geochemical barriers are not intended to stop water flow. Instead, they function by removing contaminants from the percolating water flow. In general, there are two mechanisms by which geochemical barriers immobilize contaminants. The first is sorption, which is the reaction of contaminant molecules with mineral or organic surfaces. The second is precipitation, which is the reaction of the contaminant with another reactant to form an insoluble solid.

Three types of geochemical barriers are considered below:

- native materials (natural attenuators);
- constructed sorptive barriers; and,
- constructed neutralizing barriers.

Natural Attenuation in Native Materials

The native materials surrounding contaminant sources may be capable of geochemically attenuating contaminants. Either sorption or precipitation, or a combination of the two, may be the underlying mechanism.

Natural geochemical attenuation by precipitation is well known in mine geology, as it is responsible for many mineral deposits. Examples of precipitation of contaminants are provided by numerous mine rock piles where acidic seeps, generated in one portion of the pile, are neutralized upon contact with a more alkaline portion, resulting in precipitation of metal hydroxides. In fact, acidic generating conditions in rock piles are often first identified by the occurrence of iron hydroxide stains resulting from secondary precipitation.

Examples of natural geochemical attenuation by combinations of sorption and precipitation can be found at mine sites that use peat bogs or muskeg to treat wastewater. Sorption of metals to organic components of the peat or muskeg is the initial attenuation mechanism. Over longer time periods, reducing conditions within the bog or muskeg lead to metal precipitation as sulphides (Lapakko *et al*, 1986). At the proposed Lisheen Mine in Ireland, for example, it is planned to build a tailings management facility on a peat bog to make use of the naturally low permeability of the bog. Contaminant attenuation by geochemical processes within the peat is seen as an important insurance measure, should the permeability be unexpectedly high in some areas.

Chemical limitations to natural attenuation include the limited attenuation capacity of most sorbing surfaces, the limited neutralization capacity of all alkaline materials, the slow rates at which some sorption or precipitation reactions occur, and the inhibition of sorption or precipitation by "surface blinding".

Constructed Sorption Barriers

Constructed sorptive barriers function by the same sorption mechanism that occurs in some natural attenuators. The differences are that constructed barriers are deliberately placed in the contaminant flowpath, and that a material with a high capacity to sorb target contaminants is normally selected.

There have been numerous proposals to construct high capacity sorptive barriers across the flowpath of mining-contaminated groundwater. For example, the natural mineral zeolite, which has a very high capacity to adsorb metals, has been proposed for use in a trench across groundwater from the Key Lake Mine (pers. comm. Don Lush, 1993). However, the practical constraints and costs of such a facility has not been evaluated and no full-scale implementations are known to us.

Native clays and clay soils have been observed to provide sorptive attenuation capacity under tailings ponds, for example at the Shirley Basin Uranium Mine in Wyoming. In these areas, the attenuation is a secondary benefit rather than a design objective.

The clays and clay soils are selected more for their low permeability than for their attenuation capacity.

It is our opinion that the use of imported materials, such as zeolites, to build sorptive barriers would not be economically feasible. The use of local clays or fly ash may be more cost effective. However, the difficulty in constructing a sorptive barrier would limit potential applications to beneath new surface emplacements and across groundwater discharge areas. Even in these applications, the use of neutralizing barriers is likely to prove more cost effective, for reasons discussed below. We therefore consider constructed sorptive barriers to be a low priority for further investigation.

Constructed Neutralization Zones

Constructed neutralization zones immobilize contaminants by the precipitation or combined precipitation sorption reactions discussed above under natural attenuation. In general, neutralizing zones are constructed by placing alkaline material in the contaminated flowpath. The acidic flow is neutralized upon reaction with the alkaline material, leading to precipitation of cationic contaminants as metal hydroxides and the adsorption of anionic contaminants to the hydroxide surfaces. If the alkaline material contains sufficient soluble calcium, sulphate is also precipitated as a gypsum or calcium sulphate hemihydrate phase.

In contrast to sorptive barriers, which make use of only the surface of the sorbing phase, neutralizing barriers make use of the entire available volume of alkaline materials. It is therefore possible to construct effective neutralizing barriers from relatively low cost bulk materials including mine waste rock with sufficient carbonaceous content. Even the most expensive neutralizing materials in common use, lime and soda ash, are generally orders of magnitude less expensive than, say, zeolites.

The limitations to the use of neutralizing barriers are therefore less related to material cost than to the fundamental physical and chemical constraints.

We see the following potential applications for neutralizing barriers:

- within underground workings;
- near groundwater discharge points; and
- on surface under contaminant sources.

The application within underground workings would only be feasible where access can be obtained. Since the primary object is the removal of iron, installation of such barriers within the underground workings will have the benefit that acidity would be neutralized and excess alkalinity would be provided to the flow before it is oxygenated. It is anticipated that the flows within the underground workings would be relatively anoxic in nature. Consequently, a small proportion of the dissolved iron would be present and would be precipitated upon contact with the calcareous materials. The majority of the iron, present in its ferrous form, would pass through the calcareous material, limiting plugging of the pores spaces and permeability would be retained. The neutralized discharge can then be aerated to oxidize the iron to ferric and precipitate a ferric hydroxide.

Applications for surface discharge waters are discussed below.

Anoxic Limestone Drains

As described earlier, water treatment for the removal of iron is a two step process. The first step involves the oxidation of the ferrous iron to ferric iron, followed by the precipitation of the ferric hydroxide. To achieve this with a passive system, it is necessary to neutralize acidity of the water first, and then perform the aeration and precipitation steps. If this is not done, the neutralizing agent (typically limestone or calcite) would be blinded by surface coatings of iron hydroxide and the full benefit of the alkali would not be achieved.

Anoxic limestone drains (ALD's) have been developed to achieve a high degree of effectiveness while minimizing the accumulation of precipitates. However, this approach is only effective if an anoxic stream containing reduced valency iron is treated. It is therefore necessary to intercept and treat the stream at the point of discharge from groundwater, before it is aerated.

A typical design for an ALD is illustrated on Figure 4.4.5. A trench is excavated at the discharge point to intercept contaminated flow, preferably before it reaches the surface. The trench is then partially filled with reactive limestone. The drain is then protected with a synthetic cover, over which a clay layer is placed. The function of the cover is to ensure that the trench remains anoxic. A topsoil layer is then placed on the clay layer to protect the clay layer from desiccation and to allow revegetation of the area. A design approach similar to that proposed for a complex cover would be followed.

ALD's are generally effective for metal contaminated streams where adjustments in pH can be achieved without resulting in excessive precipitation of hydroxides. In addition, low sulphate waters tend to be more readily treated by this means since little or no gypsum formation would be anticipated. After the neutralized water emerges from the ALD, it is aerated by for example cascading it over rapids and diverted into a settling pond where the iron hydroxide sludges are allowed to accumulate. Periodic dredging of the sludges would be required to maintain the sludge at an acceptable level where particulate matter would not be discharged from the pond.

A7 Collection and Treatment

The effectiveness of a collection and treatment system is a function of:

- the ability to intercept contaminated drainage;
- the ability to modulate the flow by storing the collected drainage until such time as it can be treated (if storage and treatment capacity are inadequate to handle flows during extreme precipitation events there will be a release to the environment); and
- the ability to treat the contaminated water to levels were residual contaminants meet discharge standards.

A7.1 Collection

Collection is achieved by intercepting the contaminated drainage using either:

- a low permeability barrier such as a liner or cutoff wall to direct flow into a pipe or water tight channel to convey the water to the storage pond; or,
- a surface or groundwater flow interception system such as interception trenches, dewatering wells or drains, which direct water into pipes or channels.

As a consequence of salt precipitation (particularly ferric hydroxide) blocking well screens and drainage rock it is often difficult to maintain dewatering systems which include wells or subsurface drains. The tendency is therefore to prefer the installation of barriers in the flow path, where applicable, which cause the seepage to be discharged to a surface ditch. Salt accumulations in the ditch can be cleaned out from time to time.

The effectiveness of intercepting contaminated drainage depends on the amount of seepage which bypasses the cutoffs and ditches. Leakage from the conveying channel can be controlled by lining the channel.

A7.2 Temporary Storage

As reflected by the underground pumping operations, most of the discharges observed appear to be related to active recharge from precipitation. Since water treatment systems have limited operating flexibility, temporary storage capacity is required to retain extreme precipitation event flows until the water can be treated. Storage facilities may require lining to prevent contaminated seepage.

A7.3 Treatment

Hydroxide Precipitation

The objective of this discussion is to address water treatment options that have been applied elsewhere to effectively remove contaminants from discharge streams. The options discussed here will be limited to those directly applicable to the reduction of ferruginous discharges.

In practice, the most frequently applied method for the treatment of iron rich waters is oxidation of ferrous iron to ferric iron, followed by pH adjustment and hydroxide precipitation. Typical process configurations for hydroxide precipitation comprise a holding or equalising stage, a neutralization-precipitation stage, and a settling or clarification stage. The equalising stage is required to maintain a constant feed rate to the system, and where necessary to blend several streams of different flow rates and water quality so that steady operating conditions can be maintained in the neutralization-precipitation step.

The pH adjustment is most commonly done by hydrated lime addition (as a slurry), but other reagents including sodium hydroxide and soda ash are also used. Sodium based reagents preclude the formation of gypsum but result in higher total dissolved values for the treated discharge water stream. The neutralization-precipitation stage is typically completed in a single process step, complimented by pre-aeration or direct aeration. Final clarification is achieved by flocculation and settling of the iron hydroxide precipitates. Settling equipment typically used include high rate thickeners or settling lagoons. While sludge densities of approximately 10% (w/w) are observed, high density processes may achieve sludge densities in the order of 15% (w/w). These processes incorporate sludge recycling to the thickener to promote precipitation and increase dewatering of the sludge.

In Situ Biological Sulphate Reduction

In mine waters, sulphate originates from the chemical and bacterial oxidation of sulphide minerals exposed to air and water during mining activities. Sulphate, and the associated heavy metals solubilized during the oxidation process, may be removed by well established demineralization procedures, such as reverse osmosis, electrodialysis and conventional chemical treatment, however, these processes are costly. More recently, the potential for the application of naturally occurring processes to achieve the removal of contaminants from mine and rock pile water has been recognized.

Natural wetlands have been observed to raise pH and reduce metal concentrations of acidic rock drainage. The biological reduction of sulphate to hydrogen sulphide has been identified occurring naturally in these wetlands. The precipitation of metals as the sulphide mineral following reaction with the hydrogen sulphide is considered to be the primary mechanism by which metal removal is achieved in wetlands.

Sulphate reduction has also been found to occur in a flooded underground mine. At the Løkken mine in Norway, two distinctly different sulphate reducing species have been identified in the mine water, and over time the water quality within the mine has improved (Arnesen and Iversen, 1991). This example presents the alternative of engineering a sulphate reducing reactor within an underground mine, which, amongst others, has the advantage of a reduced seasonal temperature impact on the performance of the system, to which wetlands are subject.

The direct reduction of sulphate to hydrogen sulphide is brought about by specialized strictly anaerobic bacteria and is accomplished by two genera: *Desulfovibrio* (five species) and *Desulfotomaculum* (three species).

Sulphate reducing bacteria are all gram negative, strictly anaerobic, heterotrophic organisms. Sulphates, thiosulphates, sulphites, or other reducible sulphur compounds serve as the terminal electron acceptors in the respiratory metabolism of these bacteria with the resultant reduction of sulphate to hydrogen sulphide.

The organic substrates utilized by these bacteria are generally short chain acids such as lactic and pyruvic acid, which, in nature, are provided through the fermentation activities of other anaerobic bacteria on more complex organic substrates. Therefore, although the sulphate reducing bacteria are only able to utilize less complex organic compounds, a complex organic carbon source may be used in a symbiotic or mixed system, which is most likely to occur in nature. During anaerobic respiration sulphate reducing bacteria utilize lactate to produce acetate according to the following reaction (Cork and Cusanovich, 1979):

$$2CH_3CHOHCOO^- + SO_4^{2-} \rightarrow 2CH_3COO^- + 2HCO_3^- + H_2S \text{ (-34.2 kJ/mol e-)}$$

Acetate in turn may be utilized as follows:

$$CH_3COOH + H_2SO_4 \rightarrow 2CO_2 + H_2O + H_2S \text{ (-17.5 kJ/mol e-)}$$

The production of sulphide ions results in the sulphide mineralization of a number of heavy metals. Iron precipitation as the corresponding metals sulphide proceeds as follows:

$$Fe^{2+} + H_2S \rightarrow FeS + 2H^+$$

The effectiveness of an engineered in situ sulphate reduction system will depend on the rate at which it could occur and the proportion of the contaminated flow that passes through the reducing environment.

The kinetics of sulphate reduction are largely determined by the operating temperature, and the availability and type of organic substrate utilized. Sulphate reducing bacteria typically show optimum activity between about 30°C to 35°C. A Q_{10} temperature dependency is observed; the sulphate reduction activity approximately halves for every 10°C decrease in temperature.

A number of organic waste products have been used for the enhancement of sulphate reducing bacterial activity, including: acetic acid; primary sewage sludge; wood chips and wood pulp wastes; waste activated sludge; cheese whey: molasses; sodium lactate; hay and hay extract; mushroom compost and blends of cow manure and planting soil. Although different rates of sulphate reduction are observed, it is possible to sustain reasonable rates for a wide variety of organic waste products. Usage of an organic substrate will depend on its local availability.

To engineer an in situ sulphate reduction system within the regime of an underground mine, it is necessary to ensure anaerobic conditions, a stable temperature preferably above 10°C, provide a regulated supply of the available organic substrate and ensure that the contaminated flow is routed through the zone of activity. The sulphide sludges generated as a result of sulphate reduction are significantly more dense than the corresponding hydroxide sludges, provide low metal concentrations in solution and are extremely stable under the prevailing (anoxic) conditions.

Wetland Treatment

The complex nature of the old workings, particularly areas for which few records exist, mean that some of the above criteria are difficult to fulfil, particularly maintenance of anaerobic conditions. Lack of access to the old workings and determining the flow paths is also problematic.

Wetland treatment systems can broadly be grouped as oxic and anoxic treatment systems. For the reduction of iron concentrations in contaminated discharges, oxic wetland systems rely predominantly on the natural oxidation of ferrous iron to ferric iron and the precipitation of the hydroxide compound. Consequently, where streams with high dissolved iron concentrations are treated in an oxic wetland system, metal removal is commonly associated with a decrease in pH associated with the hydrolysis of ferric iron.

Anoxic wetland systems rely on the generation of sulphide ions for the precipitation of the sulphide mineral, as described above. The population of sulphate reducing bacteria are typically sustained by providing a solid organic substrate that can be utilized symbiotically by these bacteria.

For both these systems, the actual uptake of iron by plant growth is a small component of the metal removal process. Similarly, sorption process normally contribute to metal removal only in the early operating stages of an engineered wetland system. This mechanism gradually decreases as the sites for sorption are saturated.

Because the primary mechanism for the removal of iron is the precipitation of its hydroxide, the proposed 'wetland' system as referenced elsewhere in this study would be engineered by first providing sufficient aeration of flow to oxidize the ferrous iron to ferric iron, and secondly to provide a settling basin sufficient in size to allow settling of the metal precipitates prior to discharge. The settling basin size would be determined by the rate of sludge accumulation (volume), and the particulate settling time. Where necessary, such a system would be operated in conjunction with an ALD to provided the necessary alkalinity to preclude the development of acidic discharges.

A7.4 Discharge Control

Commonly, in natural water systems, the peak flows of ground water discharges and surfaces stream flows (rivers) do not coincide. Groundwater flows normally lag behind surface flows because of the flow retardation that occurs during infiltration from a rainfall event. Consequently, peak contaminant loadings from groundwater sources do not coincide with peak surface flows. By actively managing the discharge flows, limiting discharge to high flow periods only, contaminant levels in the receiving waters may be controlled to within the water quality objective. While this is not strictly a water treatment approach, the impact on the receiving environment could be reduced.

This method of control may be attractive where impact on the receiving environment is seasonal, for example where lasting staining of river gravels occur during the period where a low surface runoff but a relatively high base groundwater flow is observed. The water management scheme would then simply require that the discharge be stored in a reservoir (such as the underground workings) during the low flow season, and that it be drawn down during the high flow season. Such an approach may be deemed acceptable where no other alternative exists and where such management will achieve the water quality objectives. Discharge flow management, in conjunction with diffusers to spread the discharge across or along the stream bed, can both reduce staining in the mixing zone and result in lower total and dissolved iron levels closer to the discharge point.

APPENDIX B

LEGAL AND TECHNICAL BASIS
RIVER STANDARDS

APPENDIX B

Iron standards are given in the EC Directive concerning surface water intended for abstraction for drinking water (75/440/EEC). Three categories of surface water are defined by the extent of treatment to be provided. Thus A1 is simple physical treatment, A2 is normal physical and chemical treatment and A3 is extensive physical and chemical treatment. The iron standards are :

Category of Water Treatment	Mg/l dissolved iron 95 percentile concentration	
	Mandatory	Guide
A1	0.3	0.1
A2	2.0	1.0
A3	2.0	1.0

The EC Directive on pollution caused by certain dangerous substances discharged into the aquatic environment (76/464/EEC) requires member states to reduce pollution by List II substances by means of the environmental quality objective approach. Iron is not on List II but the DOE advice on the implementation of the directive ('Water and the Environment', DOE Circular 7/89) states that iron should be treated in the same way as discharges containing a List II substance. The national EQS for iron is listed as follows:

Protection of aquatic life:1.0 mg/l dissolved iron annual average

The EC directive on the quality of freshwater needing protection or improvement in order to support fish life (78/659/EEC) sets standards (guide or imperative) for designated waters which may be classed as salmonid waters or cyprinid waters. Iron is not mentioned in the directive.

The effect of minewater discharges on water quality objectives, which may have a statutory basis in future, is a cause for concern. The legislation is enacted by S.104 of the Water Act 1989 which is consolidated in S.82 of the Water Resources Act, 1991. It is understood that current proposals for the protection of river ecosystems proposed by the NRA are being considered by DOE but these do not include an iron standard at present.

British Coal's assessment of the environmental impact of different concentrations of iron on watercourses is shown in the following table (from "Technical Management of Water in the Coal Mining Industry", NCB, 1982).

Table B2
Effect on a watercourse of contamination by iron compounds

Total Iron Content mg/litre Fe	Appearance	Effect on biological systems
0.5	Normal	None
1.0	Visible	Minimal
> 5.0	Severe discolouration	Severe, not toxic to fish but food chain destroyed

This acknowledges a visible impact at 1 mg/l total iron concentration.

Alabaster and Lloyd (1980) state, with respect to the direct toxic effect of iron on fish, "there is no evidence that average concentrations less than 25 mg/l have done any harm to fish or fisheries". They note, however a special case whereby iron oxide precipitating from acid solutions above pH 5.5 containing 3 mg/l iron onto the gills of trout, kills them. Six of the 34 highest ranking ferruginous minewater sites in the NRA survey report iron levels in excess of 3.0 mg/l. The majority of minewaters, however, had been neutralised by limestone in the coal measures. Direct toxicity to fish is, therefore, unlikely to be a factor at these sites.

The main environmental impacts are not due to direct toxicity but to indirect effects of iron oxide staining and deposition. The impacts are :

i. aesthetic pollution;

ii reduced biological production due to reduced light penetration adversely effecting photosynthesis by benthic algae; this in turn adversely affects the invertebrates which feed on algae. Moreover, the iron deposits provide an unsuitable habitat for some invertebrate species. This reduction in secondary production reduces the food available for fish and leads to a reduction in growth and production;

iii the change in micro habitat caused by iron deposition results in the loss of many species of invertebrate;

iv the survival of any salmonid eggs, laid in gravel in the iron staining and depositing areas, is likely to be adversely affected due to interference with oxygen exchange.

The DOE, in its treatment of iron as a List II substance, commissioned a report on environmental quality standards. The report by Mance and Cambell (1988) (WRC) includes a review of both laboratory and field data. On the basis of literature on toxicity of iron to freshwater fish, they suggest the following tentative EQS values:

Rainbow Trout	0.5 mg/l total iron annual average
Rainbow Trout &	0.3 mg/l dissolved iron at pH7
Brook Char	0.04 mg/l dissolved iron at pH (6.5

The field data collected by the authors indicated that fish populations existed at higher levels of iron. From this data they recommended an environmental quality standard of 2 mg/l total iron annual average (excluding extreme values).

A review of literature on toxicity of iron to other freshwater life led the authors to suggest that iron deposits smothering the substrate have a more important effect than direct toxicity. They recommended the same EQS as for fish but with the caveat "that conditions likely to cause ochre deposition should be avoided in consenting discharges as such deposits have a detrimental physical impact on freshwater invertebrates".

It is considered that the authors recommended a pragmatic and fairly unrestrictive EQS for the protection of fish, and failed to recommend standards to protect invertebrates. The WRC advice above became translated in the DOE circular 7/89 to a standard of 1 mg/l dissolved iron annual average and a general footnote that "(c) In some cases more stringent values may be appropriate locally to protect sensitive flora and fauna" (see appropriate WRC report).

In the case of minewater discharges, the iron may be in dissolved ferrous form or particulate ferric form, depending on conditions underground and prior to discharge. In the case of the ferruginous springs at Tir y Berth on the River Rhymney, for example, the minewater contains almost entirely dissolved iron which then becomes oxidized to ferric hydroxide and deposited on the river bed. If one were interested in the toxicity of iron, then dissolved iron would be the relevant parameter. As the main environmental impact is the aesthetic pollution and ecological effects of iron hydroxide deposition, then the relevant parameter is total iron. This includes both the particulate iron and dissolved iron which is available for oxidation to the particulate form.

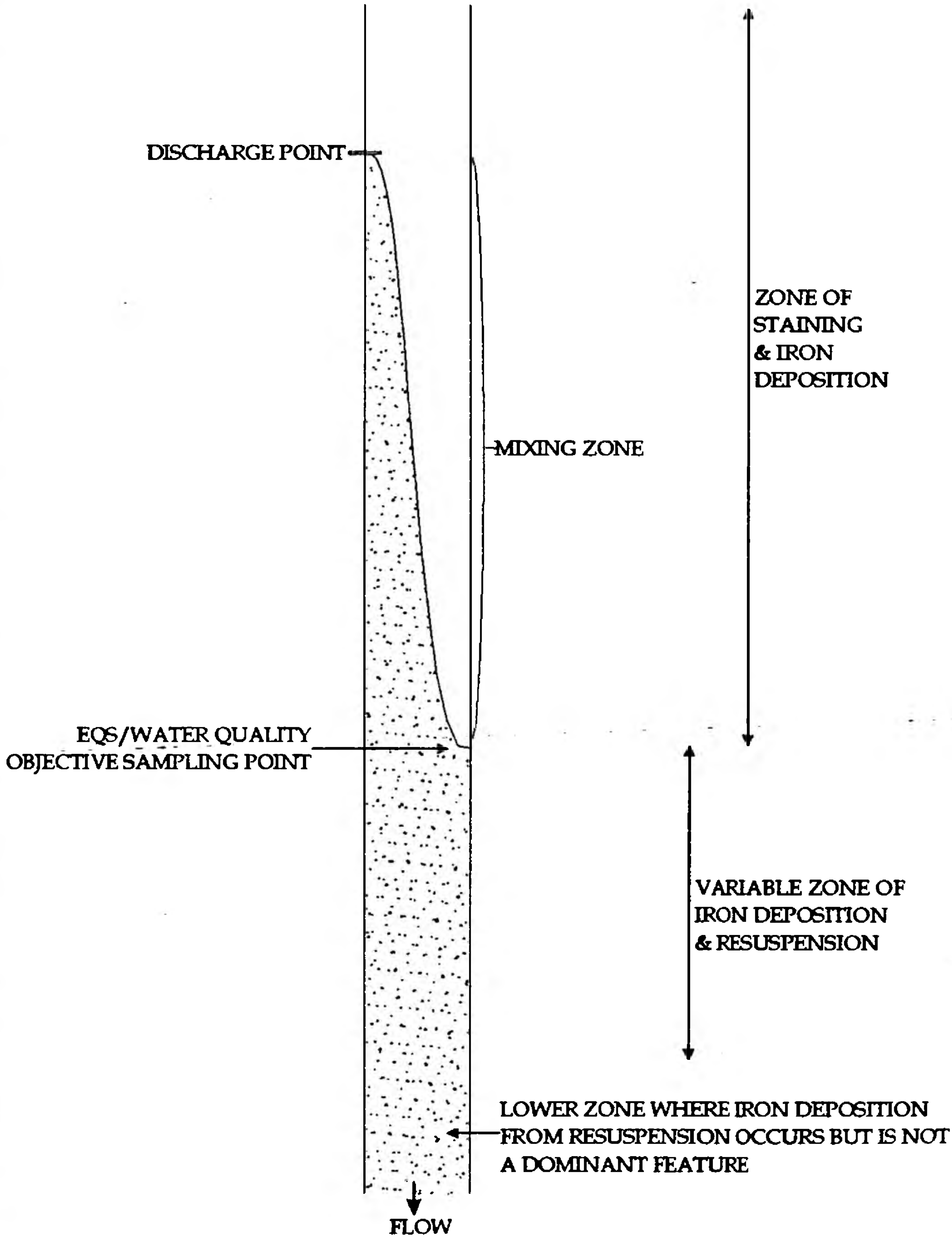
An EQS is relevant after allowing for dilution in a mixing zone downstream of the discharge point. This is shown diagrammatically in Figure B1. With a mine water discharge there are other processes at work such as oxidation of dissolved iron and deposition of particulate iron. This extends beyond the mixing zone and can be considered as a main zone of staining and deposition where active oxidation occurs and a secondary zone of deposition of particulate iron from oxidation in the river upstream and resuspension of precipitated iron from upstream. The extent of this zone is variable with river flow. The zone is shorter in high flows and longer following low river flows usually in the summer months.

Staining occurs in the area of river where oxidation of dissolved ferrous iron takes place. Part of the flow of a river is under the gravel and any oxidation here is likely to cause more settlement of iron oxide because the flow is slower than above gravel. The staining and deposition by iron oxide under gravel causes binding and blinding of the substrate. This adversely affects the invertebrate fauna and suitability for salmonid spawning.

The changes in composition of iron as one proceeds downstream is shown in Table B3 for the River Rhymney at Tir y Berth on 15/10/92 (NRA data).

Table B3
Iron Concentrations at Tir y Berth, River Rhymney

Site	Dissolved Iron (mg/l)	Total Iron (mg/l)
Upstream	0.1	0.2
Minewater	7.3	7.4
50 m d/s	1.0	1.2
1.5 Km d/s	0.6	—
3.0 Km d/s	0.1	0.8



DATE:13/4/94	PROJ. No: U489	SRK/NRA ACID ROCK DRAINAGE	
SRK		DIAGRAM TO SHOW MIXING ZONE AND TYPICAL DISPERSION OF IRON IN A STREAM	Figure B.1

The main processes are initial dilution of minewater by the receiving river, a reduction in dissolved iron as one proceeds downstream due to oxidation, and a reduction in total iron as one proceeds downstream due to deposition. An EQS should apply after initial mixing and dilution. The EQS should be related to the worst case of dilution by the rivers dry weather flow.

The choice of bands for the ranking exercise in the NRA survey report was as follows :

A.	High impact	)3.0 mg/l total iron
B.	Medium impact	2.0 to 3.0 mg/l total iron
C.	Low impact	(2.0 mg/l total iron

The report states that 11 sites exceeded the environmental quality standard of 2 mg/l. This is out of a total of 90 sites sampled and classed as ferruginous. Thus 72 sites were in the low impact category, giving a highly skewed distribution on the basis of this classification. Staining and deposition of iron oxide and biological impact was observed at total iron levels of less than 2 mg/l so that this classification of iron levels is mainly of value for relative purposes of ranking.

However, significant environmental effects in terms of fish impacts were found at 17 sites where the $Fe_{(TOT)} < 1.0$ mg/l and 2 sites were $Fe_{(TOT)} < 0.5$ mg/l.

As the ranking of ferruginous discharges has been carried out on the basis of physico-chemical features and biological and fisheries impact, the remaining importance of the EQS for iron is in determining a suitable standard for a treated discharge. This affects the cost of treatment on one hand and the degree of benefit on the other.

Although a systematic review of iron standards in other countries has not been carried out, higher standards have been adopted than in the UK. In South Africa, the recommended value for the protection of aquatic life (1980) is 0.2 mg/l minimum and 1.0 mg/l maximum and, in Australia (1992), a value of 1.0 mg/l is quoted (the information does not state total or dissolved iron). In the USA, the Environmental Protection Agency (1976) recommends a limit of 1.0 mg/l total iron. In Canada, a limit for total iron in the Great Lakes (IJC 1978) is 0.3 mg/l, and the same limit is set by the Ontario Ministry of Environment (1984).

The Manitoba limit is 1 mg/l total iron (1983).

Although the EQS of 2.0 mg/l total iron recommended for the UK appears less strict, there is the proviso that more stringent standards may be appropriate to protect sensitive aquatic life.

We recommend a maximum target of 1 mg/l total iron, which would significantly reduce staining and minimise impact on aquatic life.

APPENDIX C

SHAFT FILLING
PRACTICES CARRIED OUT BY
BRITISH COAL

APPENDIX C

Shaft Filling Preparation

1. Strip out pipework (general services, water mains etc), (not always done).

2. Remove cages (not always done pre 1974).

3. Cut guide ropes and remove (not formerly done).

4. Taff Merthyr current situation : Brithdir inset being drilled and grouted to seal off water). (Not knowingly done before in South Wales coalfield).

Filling

5. Basal part of shaft filled with non-degradable hardcore such as dolomite (sandstone occasionally used but can cause ignitions; also limestone which is cheaper than dolomite), thickness varies but usually 20 - 50 m (<5 diameter).

6. Back fill with clean, non-combustible, non-organic material (coking waste is commonly used).

7. Insets with water makes are sealed using clay plugs. Local boulder clay is normally used, similar to that used by Opencast Executive to seal high walls (usually obtained from opencast soil dumps at active sites). Thickness usually spans about 5 m above and below inset position.

8. Other, non-water making insets are often secured by non-degradable hardcore to specified thickness (about 20 - 50 m).

9. No examples of shaft lining material (brickwork etc) being removed are known.