Man's Influence on Freshwater Ecosystems and Water Use (Proceedings of a Boulder Symposium, July 1995). IAHS Publ. no. 230, 1995.

Heavy metals from acid mine drainage – impacts and modelling strategies

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Abstract Mine drainage is increasingly becoming a problem in the UK as water tables rise and acid drainage waters rich in heavy metals impact river systems. The impacts of mine drainage at two sites, the River Pelenna in Wales and the Wheal Jane Mine in Cornwall is assessed. Mathematical models have been developed and applied to investigate heavy metal pollution in the Pelenna case study and the models used to evaluate management strategies.

INTRODUCTION

There is a long history of pollution from abandoned coal and metal mines across the UK. Bird (1987) describes heavy metal pollution in the Tawe River in South Wales, and Henton (1981) describes pollution of the River Ore in Central Fife, Scotland. More spectacular pollution incidents have occurred, such as the pollution of the Fal estuary in Cornwall by drainage from the Wheal Jane mine. With the running down of the British coal industry, the problem of acid mine discharges from abandoned mines has become increasingly prominent in recent years (Pearce, 1994; Robb, 1994).

Pumping of water from mines has the effect of reducing local water tables. Following the cessation of pumping in abandoned mines, water tables rebound or rise and groundwater will eventually seep from mines as natural discharges. During the course of mining, changes in rock structure include fissuring and channelling. Air penetrates the rock allowing the formation of iron sulphate salts which can be dissolved in groundwater. Contaminated groundwater contains dissolved iron salts and high levels of other metals such as zinc, aluminium and cadmium together with sulphuric acid. This particularly toxic cocktail affects aquatic flora and fauna and coats the river bed with orange ferric hydroxides and a bacterial slime.

In recent years the restoration of aquatic ecosystems through treatment of acid mine discharges has been proposed and in places attempted. In rivers affected by acid mine discharges the costs of conventional remedial action are often prohibitive because the distributed nature of the releases make chemical treatment very expensive. An alternative strategy is biological treatment in manmade wetlands which allows precipitation

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and immobilization of metals within the substrate prior to the release of the discharge to rivers (Hedin *et al.*, 1989). In the eastern United States this strategy is presently being applied to the acid mine discharges from some 300 mines (McIntyre *et al.*, 1990).

The interaction of factors (e.g. climate, geology and hydrological pathways etc.) controlling metal concentrations in polluted waters and the extent to which they have a detrimental affect on the ecosystem of a river are both complex and site specific. In order to determine a cost effective treatment strategy, it is necessary to identify the major polluting discharges and determine the optimal level of treatment in each case. This paper describes how a computer model can be used to assist in the development of a practical management plan.

The use of the computer model QUASAR (**QUA**lity **S**imulation **A**long **R**ivers) to assess the treatment requirements of acid mine discharges in the River Pelenna system in Wales is described.

WHEAL JANE MINE SYSTEM

The presence of rich mineralization in West Cornwall has led to a long history of mining activity in the area dating back to before the fifteenth century. Tin mining at Wheal Jane mine in the Carnon Valley was still active as recently as 1991. After closure, problems were encountered with pumping and treating large volumes of mine drainage water.

In January 1992 adverse weather conditions in conjunction with a possible underground collapse led to the discharge of several million gallons of contaminated water into the Carnon River and Restronguet Creek. Previously, surface water quality had been poor due to the impact of earlier metalliferous mining, but this vastly polluted discharge was unacceptably visible and of great concern to the public and local official organizations.

Local geology of the mine consists of Devonian slates and shales containing mainly sulphide ores. Oxidation of sulphide minerals produces extremely acidic drainage waters, thus inducing greater dissolution and mobility of trace metals. During the January 1992 incident, concentrations of these elements in the river and estuary were elevated beyond European Environmental Quality Standards (EQS) by factors of several hundred, for example, cadmium (EQS = 1 $\mu g\ l^{-1}$) and zinc (EQS = 500 $\mu g\ l^{-1}$) concentrations attained levels of 600 and 450 000 $\mu g\ l^{-1}$ respectively (NRA Water Quality paper). Boreholes supplying drinking water, aquatic fauna and flora and recreational activities were considerably threatened. Figure 1 shows the time series of zinc and cadmium during the first flush of pollution.

Most species of marine life present in the Restronguet Greek are metal tolerant to a certain extent due to constant exposure to metalliferous contamination over the past few centuries. The Creek is inhabited sparsely by tolerant species such as a polychaete *Nereis diversicolor* and a bivalve *Scrobicularia plana* (Bryan & Gibbs, 1983) but more vulnerable habitats of *Zostera* (eel grass) and maerl (coral-like seaweed) also exist. Local fishermen were concerned about the impact on shellfish, especially as these species bioaccumulate trace metals. Significant effects immediately after the discharge were not apparent. Longer-term effects on the ecosystem are still being determined.

Processes of mine water remediation have been refined over the past several years to cope with increasing volumes of waste from the Wheal Jane mine. Dewatering pumps

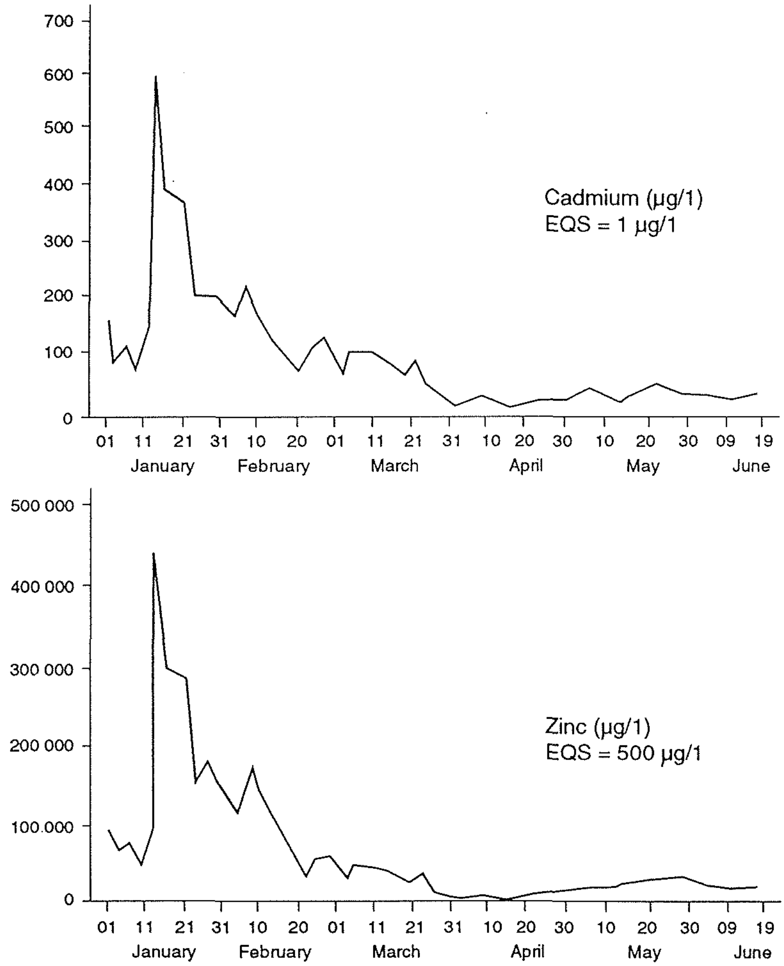

Fig. 1 Water quality in the Carnon River, 1992.

were switched off immediately after the mine was formally declared abandoned in March 1991. Water in the mine shaft continued to rise until extra treatment facilities were initiated later that year. Larger volumes of water were pumped into a "tailings dam", mixed with lime and allowed to settle. The resultant floc was removed and disposed of, subsequently decreasing the acidity of the remaining water in the dam.

The operational capacity of the tailings dam was doubled to over 9000 million m^3 day^{-1} in January 1992 after the incident, but this was still only a temporary measure. Plans to develop a longer term solution were introduced in December 1992 by the National Rivers Authority and were expected to be completed within 3 years. The scheme involves: flow control of waste mine water; treatment with lime to reduce acidity eg. using limestone drains and organic slurry ponds; precipitation of metals by use of oxidation ditches, sludge recirculation and sludge drying; and finally artificial marshes designed to improve water quality further. The treatment plant is just beginning operation and will be assessed in the coming months.

QUASAR – MODEL DESCRIPTION

The QUASAR model has been developed to assess the environmental impact of pollutants on river water quality (Whitehead, *et al.*, 1979; 1981). Essentially the model performs a mass balance of flow and water quality down a river system. Water quality changes due to biological behaviour and chemical decay processes are considered, and the model has been developed to take into account natural, anthropogenic and accidental inputs. Within QUASAR the river is divided into a number of reaches. Reaches are chosen such that boundaries occur at points in the river where there are likely to be significant changes in the water quality or flow, for example due to the confluence with a tributary, the location of an abstraction or effluent discharge, or the location of a weir.

QUASAR can be run in two modes: a stochastic mode for design or planning applications, and a dynamic mode for pollution incident simulations. In both the case studies discussed in this paper, the model was used in planning mode. This mode invokes a stochastic modelling procedure, known as Monte Carlo simulation, which aims to provide information to aid in long-term planning of water quality management (Warn, 1982). As with any stochastic modelling the intention is to generate synthetic sequences of data which maintain the key statistics (mean and standard deviation) of the true data series. In planning mode a cumulative frequency curve and distribution histogram of each water quality determinand are generated by repeatedly running the model using different input data selected according to probability distributions defined for each input variable. The model equations are run using random numbers as the input values until either steady state has been reached or for a maximum of 30 time periods. Steady state is said to have been achieved when the results of successive runs differ by less than 1%. Five hundred and twelve random numbers are generated. The output is stored and used to produce cumulative frequency distributions and distribution histograms. Further details of the Monte-Carlo simulation technique and QUASAR are given elsewhere (Whitehead, *et al.*, 1979; 1984).

THE RIVER PELENNA CASE STUDY

The upper reaches of the River Pelenna (Fig. 2), including its tributary the Gwenffrwd, presently fail to meet the European Inland Fisheries Advisory Council (EIFAC) standards for salmonid fisheries due to the presence of high concentrations of heavy metals. In particular iron in the water emanating from disused mines creates dissolved iron concentrations in the river which are significantly above the EIFAC limit of 1.0 mg l^{-1}. The river has been affected by mine water discharges for more than 25 years, coal extraction having ceased in the area in the 1960s. Deposits of iron hydroxide floc have smothered the river bed with a characteristic yellow-orange precipitate and caused a significant decrease in aquatic life. Fish are virtually absent from a 17 km stretch of the river. EIFAC also stipulate that, for salmonid waters, the pH must be in the range 6.0-9.0. In some reaches of the Gwenffrwd the average pH is slightly below 6.0.

In 1992 the National Rivers Authority (Welsh region), in conjunction with West Glamorgan County Council, initiated a development project with the aim of treating the acid mine discharges into the River Pelenna. It is intended that the scheme will demonstrate the applicability of wetland treatment systems in Europe. The aim is to reduce the amount of iron discharged to the river, in order to enable restocking of the river by salmon. To ensure that the pH is maintained above 6.0 in both the Pelenna and Gwenffrwd, it is planned that, where possible, acid mine discharges will be passed through anoxic limestone drains prior to entering the manmade wetlands (West Glam, 1993). The Institute of Hydrology was commissioned by the National Rivers Authority to undertake a modelling study of the Pelenna and Gwenffrwd in order to identify the key mine discharges affecting iron concentrations and to assess the level of treatment that would be required to enable the river to be repopulated by salmon.

Figure 2 is a schematic of the relevant area, showing the locations of the principal mine water discharges and the water quality sampling points. The area of concern is approximately 6 km^2 of upland heath which, in addition to the discharges from the old mines, has many small streams running down to meet the river along its course. The National Rivers Authority (Welsh Region) have been monitoring river water quality in

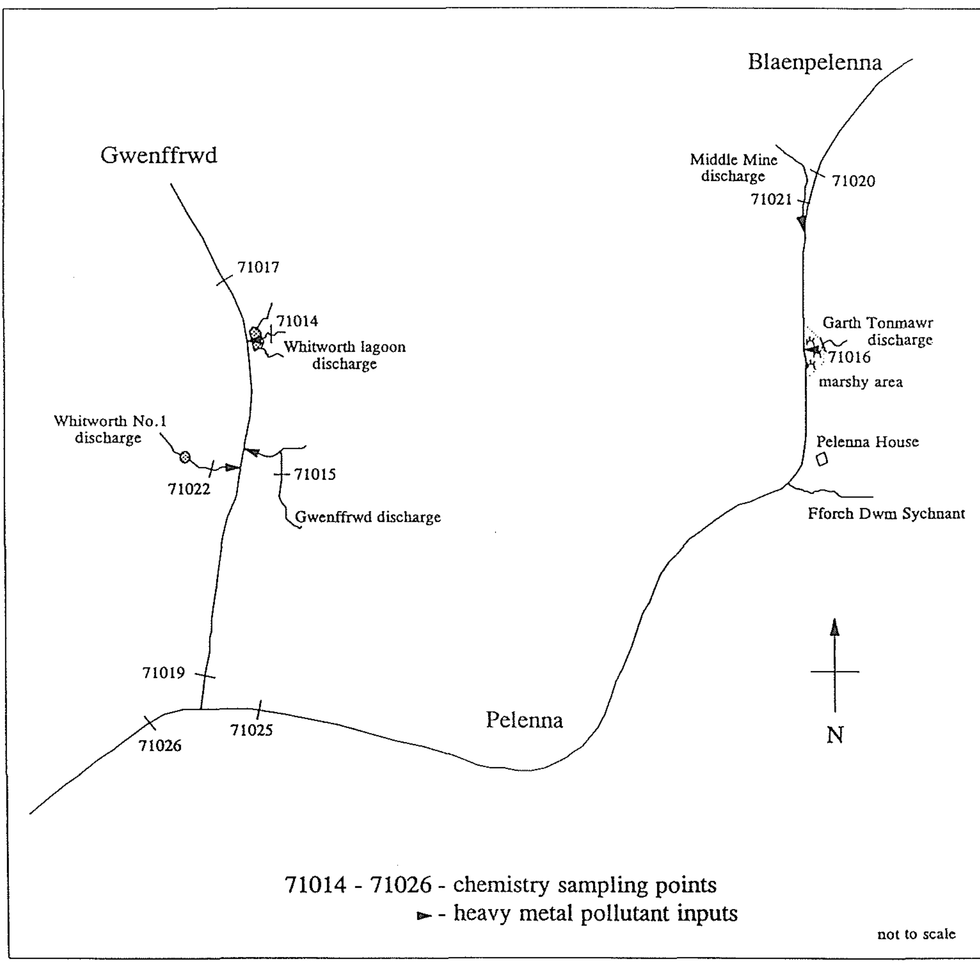

Fig. 2 Locations of mine discharges and measurement points along the Pelenna and Gwenffrwd.

the catchment at irregular intervals since 1980. An average of 23 spot samples from each of five locations on the Pelenna and Gwenffrwd were collected for chemical analyses prior to October 1991. However, no samples were taken from the mine discharges, and in some years no samples were collected at all. Since October 1991, spot samples have been obtained at approximately monthly intervals from the coal mine discharges as well as from both the Pelenna and Gwenffrwd. In this study, the data obtained in 1992 and 1993 were used to determine the mean, standard deviation and shape of the probability curve for the input variables into each of the model reaches. Within the QUASAR model the Pelenna and Gwenffrwd were divided into 11 reaches in order to isolate the effects of each of the acid mine discharges. Figure 3 is a schematic of the model structure.

Since the EIFAC criterion relates to dissolved iron concentrations, measurements and model simulations of total iron concentration were converted to dissolved iron concentration. This was done using an empirical relationship derived from measurements of dissolved and total iron concentrations made in the Pelenna catchment. The relationship defines the distribution of iron between solution and solid phase as a function of pH. The line fitted to the Pelenna data is given below. It was fitted by trial and error and is slightly biased towards higher pH values.

$$\frac{Fe_{(s)}}{Fe_{(aq)}} = 9.65 \times 10^{-7} pH^{6.2327}$$

Table 1 shows the mean dissolved iron concentrations along the river. Where no measurements have been made, these values were obtained using the model to simulate existing conditions. The flows and iron concentrations in the inputs to the river are shown in Table 2. Where flows were not measured (e.g. the diffuse inputs into a river reach) mass balance considerations were used to estimate them.

Concentrations of dissolved iron upstream of the mine water discharges meet the EIFAC criterion in both the Gwenffrwd and the Pelenna, with means of 0.4 and 0.6 mg l^{-1} respectively. With the contributions from the mine waters, the mean concentrations further downstream in these two channels reach maximums of 4.3 and 3.0 mg l^{-1} respectively, thus preventing the introduction of salmon. As shown on the map (Fig. 2), there are three major mine discharge sites on the Gwenffrwd, with a further two on the Pelenna upstream of the Gwenffrwd's confluence. It can be seen from Table 2 that the main polluters in terms of iron input are the Whitworth Lagoon outfall on the Gwenffrwd and the Garth Tonmawr discharge on the Pelenna.

On the Gwenffrwd, although the Whitworth No. 1 discharge contains very high iron concentrations, the mean flow from this mine is low and its polluting effect is much less than the discharge from Whitworth Lagoon. The average flow of the Gwenffrwd Mine discharge is approximately two-thirds that from Whitworth Lagoon, but its iron concentration is only about one quarter. Consequently, in polluting terms it is also less significant than that from Whitworth Lagoon. On the Pelenna, the discharge from Middle Mine contains very little iron and it has an insignificant impact on the dissolved iron concentration in the river.

SCENARIO MODELLING

A previous study (Ishemo & Whitehead, 1992) indicated that it would be possible to

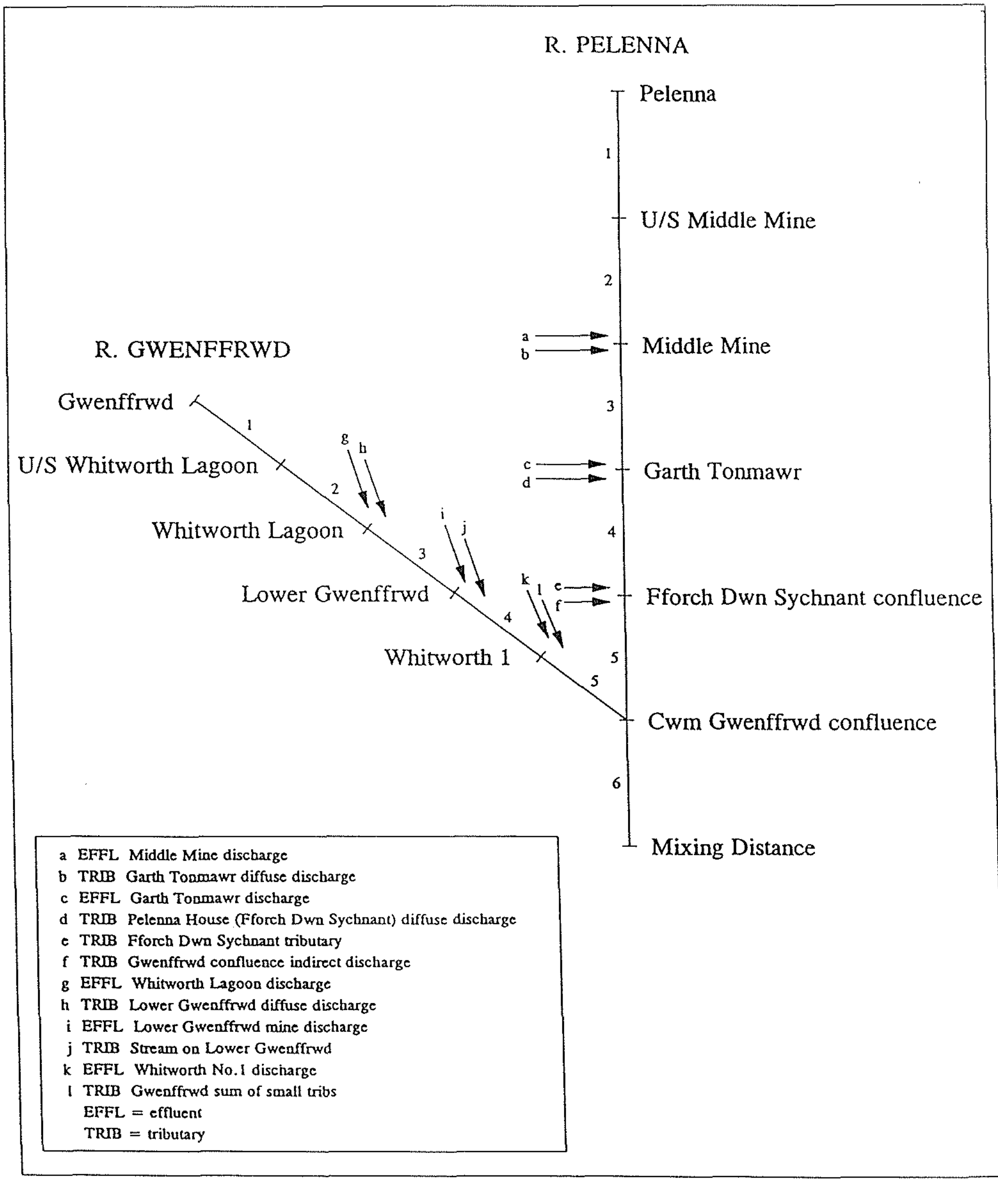

Fig. 3 Schematic representation of the Pelenna, used in QUASAR.

meet the EIFAC dissolved iron criterion for salmonid waters by the reduction of total iron in the Whitworth Lagoon discharge by between 90% and 95% and in the Garth Tonmawr mine discharge by between 50% and 55%, providing the mean river pHs in the Gwenffrwd and the Pelenna were maintained above 6.0.

These results were re-evaluated using additional data collected during 1992 and 1993 and various scenarios were tested using the model. Since the concentration of dissolved iron in the water is pH dependent, scenarios involving different pH regimes were also tested.

Figure 4 shows the results, under present pH conditions, of reducing the mean total iron concentrations by 90%, 85%, 75%, 50% and 25% in all the acid mine discharges,

Table 1 Mean dissolved iron concentrations along the Gwenffrwd and Pelenna.

	Fe (mg l^{-1})
Gwenffrwd upstream	0.4
Downstream of Whitworth Lagoon discharge	4.1^{+}
Downstream of Gwenffrwd discharge	4.3^{+}
Downstream of Whitworth No. 1 discharge	3.8
Pelenna upstream	0.6
Downstream of Middle Mine discharge	0.9^{+}
Downstream of Garth Tonmawr discharge	3.0^{+}
Downstream of Fforch Dwm Sychnant	1.3
Downstream of Gwenffrwd confluence	1.1

$^{+}$ from QUASAR, no observed data at this location.

Table 2 Mean flow and dissolved iron concentrations in mine drainage and streams entering the Gwenffrwd and Pelenna.

	Flow (l s^{-1})	Fe (mg l^{-1})
Gwenffrwd upstream	140.0	0.4
Whitworth Lagoon outfall*	14.0	38.8
Diffuse addition of flow	35.3	0.4^{+}
Gwenffrwd mine water discharge*	10.9	10.3
Whitworth No. 1 discharge*	3.1	24.0
Tributary on Lower Gwenffrwd	5.6	0.4^{+}
Diffuse addition of flow	14.8	0.4^{+}
Pelenna upstream	152.0	0.6
Middle Mine discharge*	58.5	0.8
Diffuse addition of flow	35.3	0.6^{+}
Garth Tonmawr discharge*	28.7	21.0
Diffuse addition of flow	4.7	0.6^{+}
Fforch Dwm Sychnant	55.3	0.6^{+}
Diffuse addition of flow	78.0	0.6^{+}

* Acid mine discharge; $^{+}$ no observed data so total iron concentration assumed to be the same as that in the flow into upstream reach of the river.

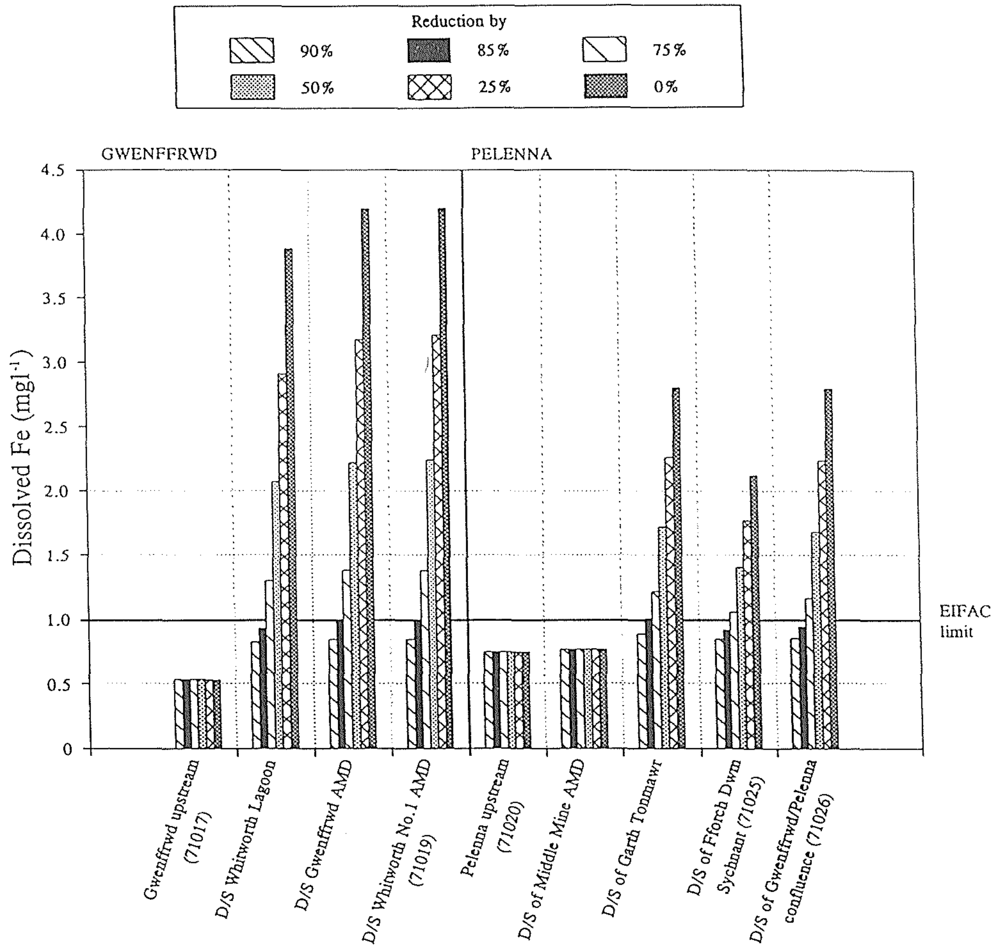

Fig. 4 Scenarios showing the effect of reduction in Fe concentrations in all acid mine discharges except Middle Mine (pH as observed).

except that from Middle Mine. Figure 5 shows the same scenarios assuming pH of 6.0 or greater in the river. In these latter scenarios, at each location, if the existing river pH was greater than 6.0 it was left unchanged, but was increased if less than 6.0. The results indicate that in order to attain the EIFAC limit of 1.0 mg l^{-1} of dissolved iron, the total iron in all the mine discharges, except Middle Mine must be decreased by between 85% and 90%, whether or not the pH is increased to 6.0.

In order to test the previous study proposition, that it would be possible to achieve the EIFAC dissolved iron criterion for salmonid waters by reduction of total iron concentrations in the Whitworth Lagoon and the Garth Tonmawr discharges alone, several scenarios were run in which the discharges from the other mines were left untreated. The model was run with more severe reductions in the total iron content of the Garth Tonmawr discharges than was previously recommended. From both mines iron concentrations in the discharges were reduced by 90% and 95%. For each reduction, three scenarios were simulated:

(a) the existing pH regime;
(b) the pH in the Pelenna and Gwenffrwd increased to at least 6.0; and
(c) the pH in the Pelenna and Gwenffrwd increased to 7.0.

Figure 6 shows the results of these scenarios. The results show that under no circumstances would it be possible to achieve the EIFAC limit on the Gwenffrwd without treatment of either, or both, the Gwenffrwd and Whitworth No. 1 acid mine discharges. Even with a 95% reduction in iron in the Whitworth Lagoon discharge and with the Gwenffrwd River pH maintained at 7.0, mean dissolved iron concentration would be 1.3 mg l^{-1} downstream of the Whitworth No. 1 discharge. Downstream of the Gwenffrwd and Pelenna confluence, dissolved iron concentrations would just exceed the EIFAC criterion, except with a 95% reduction in total iron content in the Whitworth Lagoon and Garth Tonmawr discharges and pH increased to between 6 and 7 on both rivers. These results indicate that the discharges from the Gwenffrwd and Whitworth No. 1 mines, while much less polluting, would significantly influence the water quality of the Gwenffrwd River if only the discharge from Whitworth Lagoon was treated.

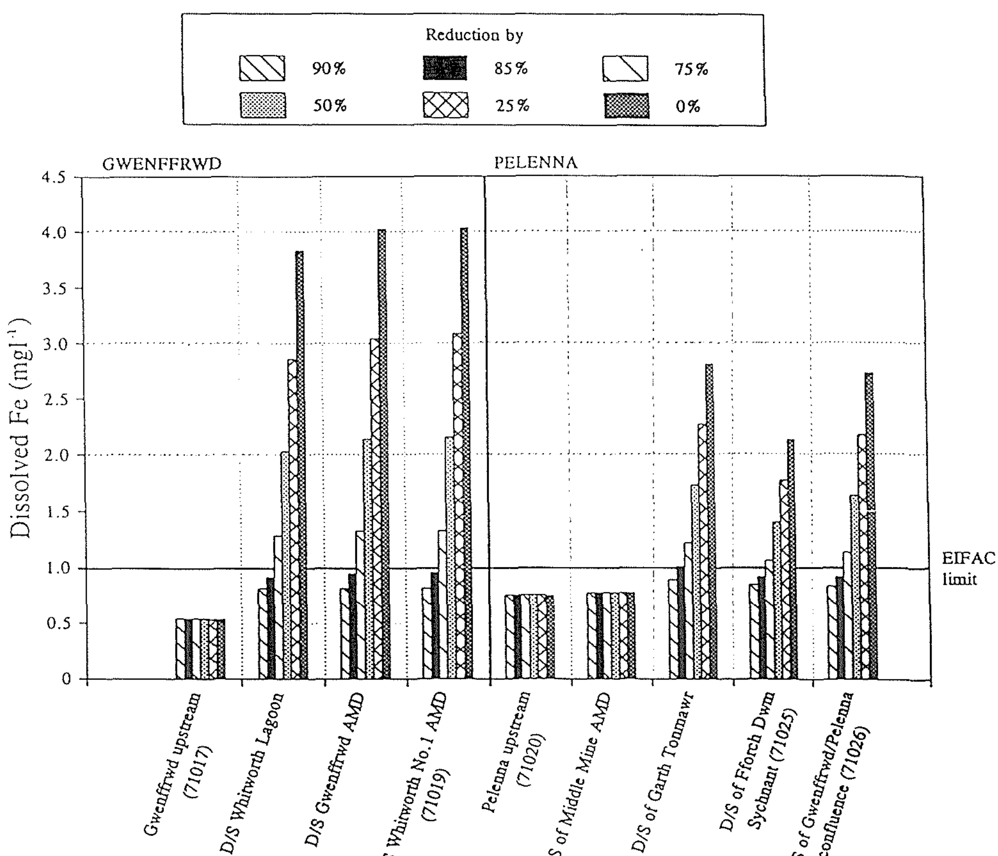

Fig. 5 Scenarios showing the effect of reduction in Fe concentrations in all acid mine discharges except Middle Mine (pH ≥ 6).

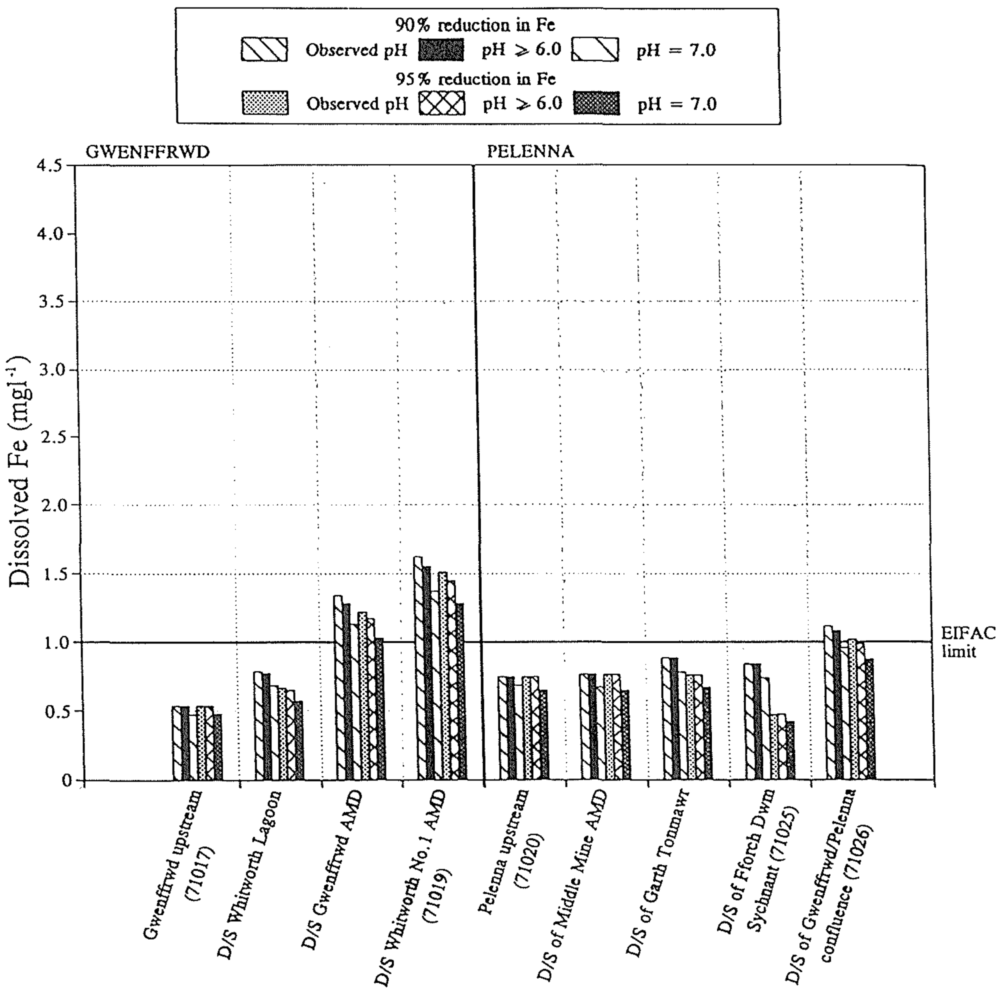

Fig. 6 Scenarios showing the effect of treatment of only Whitworth Lagoon and Garth Tonmawr acid mine discharges.

CONCLUSIONS

The QUASAR model has proved to be a useful tool for analysing pollutant discharges from abandoned mines. The dominant discharges have been identified together with the level of treatment required to meet river quality objectives.

In the Pelenna case study, the scenario simulations suggest that if the stipulated EIFAC limit for mean dissolved iron concentration of 1 mg l^{-1} is to be attained within both the Pelenna and the Gwenffrwd Rivers, total iron concentrations must be reduced in all the acid mine discharges, except that from Middle Mine, by 85% to 90%. Although, in terms of iron, the principal polluter on the Gwenffrwd is the acid mine discharge emanating from Whitworth Lagoon, the results from this study suggest that treatment of this pollution source alone on the Gwenffrwd will not suffice. The total iron content in the acid mine discharges issuing from Gwenffrwd Mine and Whitworth No.

1 must also be reduced by between 85% and 90%. In addition the iron content of the discharge emanating from Garth Tonmawr must be reduced by about 90% in order to ensure that the Pelenna attains the EIFAC criterion downstream of its confluence with the Gwenffrwd.

The question of which treatment method is acceptable will depend on many factors including the load reduction required, the location of the site, the type of effluent and the costs of treatment. Chemical treatment is often too expensive for remote diffuse sources of pollutants and a wetland scheme is far more practical, being technically superior and considerably cheaper.

The National Rivers Authority estimate that in the UK some 170 discharges from abandoned coal and metal mines cause significant pollution problems in about 610 km of river (NRA, 1994). It is not practical to attempt to alleviate the effects of all these discharges. It is necessary to determine the relative contribution which discharges from abandoned mines make to the poor water quality of receiving rivers and the extent to which treatment, of whatever kind, must be applied to produce an improvement. This paper has demonstrated that a relatively simple computer model is a useful management tool and can assist in evaluating and prioritizing work that needs to be done to improve the quality of receiving waters.

Acknowledgements The authors are grateful to the Welsh Region of the National Rivers Authority for support in undertaking this modelling project. The results reflect the opinions of the authors and not necessarily those of the National Rivers Authority.

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