The development of a temporary treatment solution for the acid mine water discharge at Wheal Jane.

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ABSTRACT

The closure of Wheal Jane, a tin mine in South West England, led to rapid ground water level recovery and the discharge of acidic, metal-rich water. A simple contingency plan, involving crude lime treatment, restricted pumping and limited settlement of solids was introduced and this worked well for two months, until a number of problems led to the programme being suspended. Mine water built up underground and, on 13 January 1992, a plug in a drainage adit failed, releasing several million gallons of extremely contaminated water. This had considerable impacts on the chemistry and appearance of a short length of river and about 50 km^2 (20 square miles) of estuary and coastal water. The contingency programme was re-introduced and modifications have been made to improve efficiency. As conditions within the mine have changed, largely in response to rainfall and time, the pumping rate and lime dosing have been altered. Control systems have been established to ensure optimum pH for precipitation of the principal metals. An organic flocculant dosing system has been added to improve solids settlement rate. The conjunctive use of an operational tailings dam for settlement of such a high volume of solids is novel. During the early stages of mine water discharge, when metal loadings were particularly high, the operation and effectiveness of the treatment process was constrained by the operating regime required to ensure the continued integrity of the tailings dam. In particular, it was necessary to restrict the size of the supernatant pond within the design parameters of the dam. An operating strategy was developed to allow the tailings dam to be used efficiently to deposit both the mine tailings from an adjacent process plant and metalliferous sludge from mine water treatment. This involved significant modification of the dam to form a paddock system, in which coarse tailings could be deposited to form a wide peripheral bund, improving storage capacity and enabling sludge to be deposited more efficiently. The temporary system has worked well in providing time to develop a long term strategy for the treatment of mine water.

INTRODUCTION

The closure in 1991 of Wheal Jane, a tin mine in South West England (Figure 1), led to rapid ground water level recovery and the discharge of acidic, metal-rich water [1]. During recovery, discussions between the National Rivers Authority, the mining company and consultants resulted in the adoption of a contingency plan designed to protect the aquatic environment. This paper describes some of the successes and failures of the contingency plan, and how it has been modified to improve efficiency of treatment, and also considers briefly how a long term solution might be achieved.

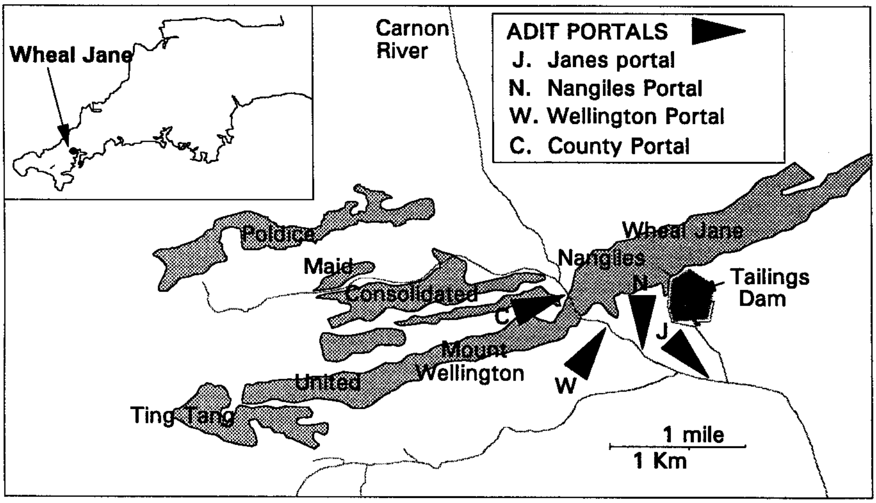


Figure 1. Map showing mining district, river, Wheal Jane & significant adits.

INITIAL TREATMENT

First discharge occurred from the Wheal Jane adit on 17 November 1991, at a rate of about 5,000 m^3d (1 mgd). This rate was a reflection of the dry weather experienced during the preceding months. The quality of the discharge was relatively good when compared with that observed in the shaft during recovery, as shown in Table 1. Nevertheless, within hours of the discharge commencing, an emergency settlement pond constructed immediately downstream of the adit had been overwhelmed and the quality of the Carnon River began to deteriorate, as shown in Table 2.

Table 1. Quality of the rising mine water and of the initial discharge

Shaft water	pH	Cu	Zn	Fe	Cd
23 April 91	2.6	4.4	156	243	-
22 May 91	2.9	1.9	93	149	-
25 June 91	3.1	17.6	750	383	-
26 July 91	6.4	0.2	14	4	0.03
23 Aug 91	2.7	8.3	1980	2035	3.96
24 Sept 91	2.7	3.9	2035	1144	3.74
16 Oct 91	3.6	1.4	600	590	0.90
24 Oct 91	3.3	2.6	1075	4170	1.70
5 Nov 91	6.0	0.8	65	2	0.10
Discharge	**pH**	**Cu**	**Zn**	**Fe**	**Cd**
17 Nov 91	2.8	15.2	346	232	0.80
18 Nov 91	2.8	19.3	819	975	1.57

Except for pH, all units in mg/l

Table 2. Water quality in the Carnon River before and immediately after first discharge

	pH	Cu ug/l	Zn mg/l	Fe mg/l	Cd ug/l	As ug/l
15 Oct 91	5.6	0.45	4.5	0.2	8	20
17 Nov 91	4.9	1.1	9.0	4.0	25	38

The valve on the plug at the Wheal Jane adit portal was closed, lime was added to the adit and treated water was pumped at the rate of 5,000 m^3d to the adjacent Clemow's Valley tailings dam. This was, and is, still being used by Carnon Consolidated Ltd., which processes ore from another mine at this site. It was fortunate that the tailings dam was available, otherwise further and continued pollution of the Carnon River would have been inevitable.

Initial lime dosing into the adit was crude and difficult to control and, as this preceded pumping, there were problems with the destruction of the ferric hydroxide precipitate, which inhibited settlement in the tailings dam. Although less than optimal, the system worked well until late December 1991, when high winds caused re-suspension of the precipitate and reduced the quality of the discharge from the dam. Raising the decant level to prevent water leaving the dam was of limited effect as the operational safe storage limit, defined by the freeboard, was being approached. In addition, there were difficulties with poor quality water being re-circulated for use in the milling process. These factors led to pumping being stopped on 4 January 1992 and the water level was allowed to rise naturally in the workings. It was considered that storage capacity underground would be adequate until the weather improved and a further discharge could be made from the dam.

THE POLLUTION EVENT

Water continued to rise within the workings and, on 13 January 1992, a plug installed in the 1970's to prevent surface water ingress to the mine through an adit at Nangiles, an adjacent and connected mine, failed. (Nangiles had been abandoned in the early part of this century.) The nature of the Nangiles plug was unknown to the staff dealing with the problem, and access to these old workings to investigate the presence of such structures was impossible for safety reasons. This failure released about 30,000 m^3 (7 mgd) of contaminated water and sludge into the Carnon River over a period of a few hours. About 200 tonnes of metals were discharged to the Carnon River in the first 24 hours. On succeeding days the flow declined but remained substantial - over 6,000 m^3d (1.3 mgd) - for one month. Typical quality during the remainder of January 1992 is shown in Table 3.

Table 3. Chemical quality of the Nangiles discharge, 14 - 30 January 1992

	Range
pH	2.6 - 3.1
Fe	1720 - 1900
Zn	1260 - 1700
Al	170 - 197
As	26 - 29
Mn	11 - 25
Cu	14 - 18
Ni	4.2 - 5.1
Cd	1.4 - 1.9
Pb	0.2 - 0.3
Cr	less than limit of detection

Except for pH, all units in mg/l dissolved.

The effect of the discharge was spectacular. Two kilometres downstream of the mine, about 50 km^2 (20 square miles) of estuarine and coastal waters turned orange due to the creation of ferric hydroxide. Environmental Quality Standards for most metals were exceeded by several orders of magnitude, as shown for selected determinands in Table 4.

Table 4. A comparison of river water quality with Environmental Quality Standards

	EQS	Before the pollution	Peak of pollution
pH	6 - 9	3.5 - 6.3	3
Cd ug/l	1	30	600
Zn mg/l	0.5	19.5	440
Cu mg/l	0.028	0.9	7
Fe mg/l	1	13.2	600
As mg/l	0.05	0.27	6

MODIFICATIONS TO TREATMENT

Pumping was restarted immediately after the discharge in January 1992. This operation was transferred from the adit to the main shaft in stages so that, by the end of February 1992, 10,000 m^3d (2 mgd) were being pumped from the main shaft. The redundant lime dosing facility at Wheal Jane was recommissioned, lime was delivered from a silo 100 metres from the shaft, and treated water flowed by gravity through an existing pipeline, in which mixing took place, to the tailings dam. A long chain, anionic polymer flocculant was added to the treated mine water to improve settlement rate.

The volume of ferric hydroxide produced was large and much of the available storage space in the tailings dam was used, necessitating modifications and an increase in height of the dam wall earlier than originally planned. A higher pumping rate from the mine shaft was inappropriate until more space had been constructed. In any event, due to the harsh operating conditions, the submersible pumps suffered frequent failures, necessitating recovery and replacement, an operation lasting several hours and leading to a rise in water level on each occasion. This increased the risk of, or the actual, flow of untreated water from Nangiles. Lime was added to mine water in the shaft in an effort to protect the pumps, and the efficiency of this operation was improved substantially when a continuous pH monitor, linked to an alarm, was installed in the pumped water stream. During this emergency period, which lasted for much of 1992, there was a delicate balance between optimum use of the available facilities and continued pollution of the environment.

By October 1992, raw mine water quality had improved and less ferric hydroxide was being precipitated. This, together with the increased availability of depository space following rapid design, mobilisation and construction of the confining wall, and the prediction of increased flow following winter rainfall, led to a third pump being installed in the shaft. Further increases in pumping rate were impossible due to the constraints of pump size and mine shaft dimensions. As a result, all three pumps were overwhelmed in December 1992 and again in December 1993 when peak flows of 40,000 m^3d (9 mgd) and 45,000 m^3d (10 mgd) were recorded.

A recent change to pumps with smaller diameters and greater efficiency has allowed peak capacity to be increased to 30,000 m^3d (7 mgd). The present objective is to maintain a constant water level in the mine, at a point which prevents discharge of untreated water through the

Nangiles adit. An additional benefit is that mineralised rock will not go through the cycle of drying and wetting, thus minimising the production of acidity and contamination of the mine water. Typically, pumping rates now vary between 10,000 m^3d and 30,000 m^3d and are controlled by float switches with fine tolerance.

Lime dosing using the existing plant was difficult to control. Slurry production was continuous and its density was variable. There was inadequate conditioning time in the plant and it is likely that some lime remained dry and ineffective. The long feed line often became blocked and caused frequent breakdown of the plant. Without adequate control, acid conditions developed rapidly in the tailings dam and this could take many days to correct. At pH <8, metal deposition was less efficient and cadmium concentrations in the discharge often exceeded the preferred value of 2 ug/l.

System control was based on a pH monitor at the entrance to the tailings dam, but rapid electrode armouring and the in-built circuit delay led to variations in pH between 5 and 12. The installation of additional pH monitors, flow gauges and alarms, linked by telemetry to the site office, gave early warning of problems, a better understanding of the treatment system, and the opportunity for fine tuning which resulted in increased efficiency, particularly in the quantity of lime used. This is shown in Figure 2 which indicates higher and more stable pH in the tailings dam following progressively tighter control.

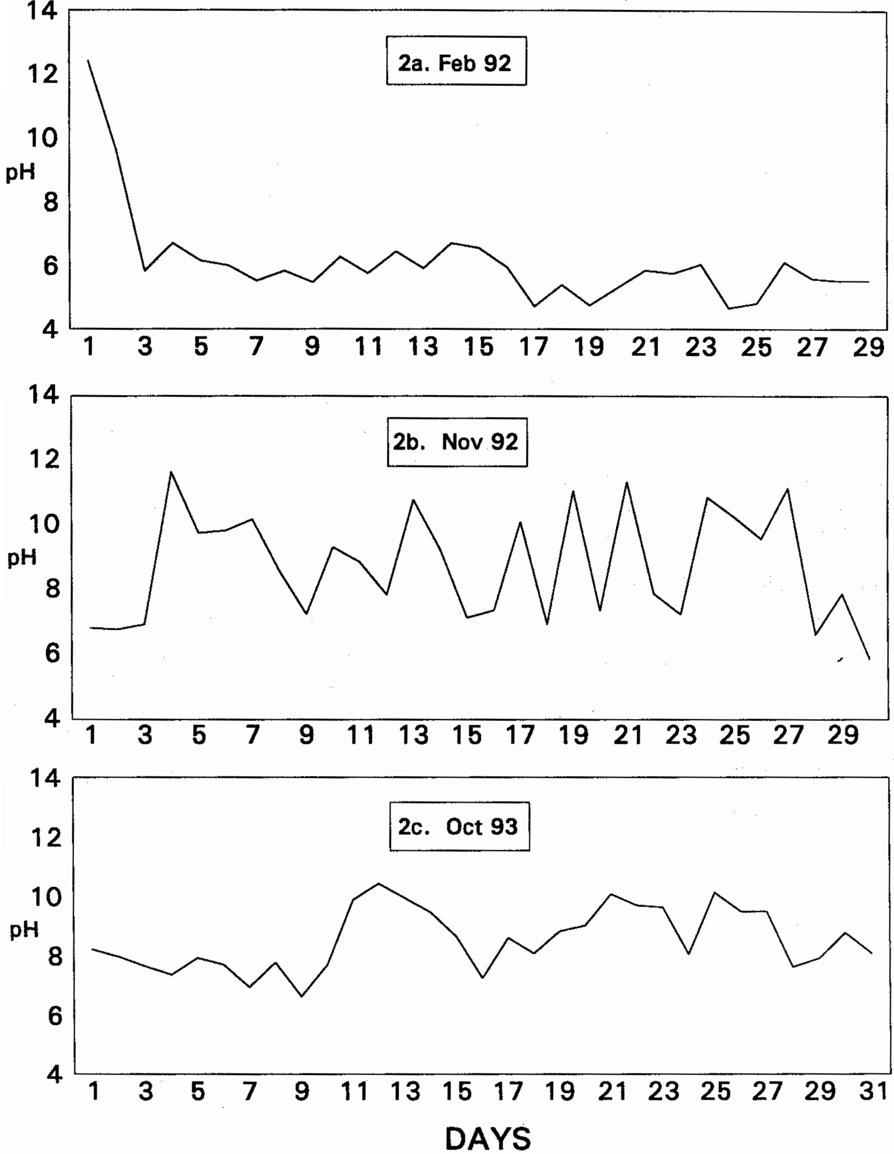
However, by the end of 1992, it was apparent that the existing lime silo was deteriorating. Increasing effort and expenditure were needed to maintain the high efficiency. Recently, a larger and better controlled system has been installed, based on two lime silos, each with a mixing tank, and a flexible, short delivery system. This has resulted in even greater efficiency and substantial cost saving.

Initial uncontrolled deposition of metal hydroxides in the tailings dam led to the rapid use of available storage volume, thereby reducing decanting flexibility, with subsequent short circuiting and poor effluent quality. A distribution ditch was excavated around the periphery, allowing delivery of treated water and tailings to a number of discharge points on the reservoir edge. Effluent quality was improved but the distribution system led to the encroachment of low density ferric hydroxide floc on the structural zones of the dam wall, with consequent stability implications.

The crest of the tailings dam has been raised on an annual basis to achieve the necessary storage requirements for the mine waste. The primary aim has been to ensure safe and economic storage of the tailings derived from the ore processing carried out on the site. The dam has undergone a number of design changes during its 23 year life to suit the changing and variable demands of economics, metallurgy and the ore being processed [2].

Tailings deposition has traditionally been undertaken using sub-aerial techniques to maximise storage, minimise annual capital works and achieve optimum unit storage costs. When pumping was restarted, after the pollution event in January 1992, the re-introduction of a large volume of mine water to the dam required construction works to ensure that the freeboard limits, defined as the level difference between crest and reservoir, would not be exceeded. The main criteria were the maintenance of operational freeboard and the ability to increase the capacity of the dam to enable continued use without impairing the integrity of the dam.

Figure 2. pH variation in Tailings Dam decant.



The construction of the dam required the formation of suitable foundations, for each lift, from successive tailings layers placed in a controlled fashion. The separation of the low density, low strength metalliferous sludge from the confining wall zone was thus essential. This was achieved by the construction of a paddock, separated from the reservoir by a peripheral internal wall, as shown in Figure 3. This construction enabled the deposition of the coarse fraction of the tailings adjacent to the main wall to form the future foundation zone. Geotechnical testing has shown the material deposited to be similar to that placed in previous periods and thus suitable for foundations and future wall raising.

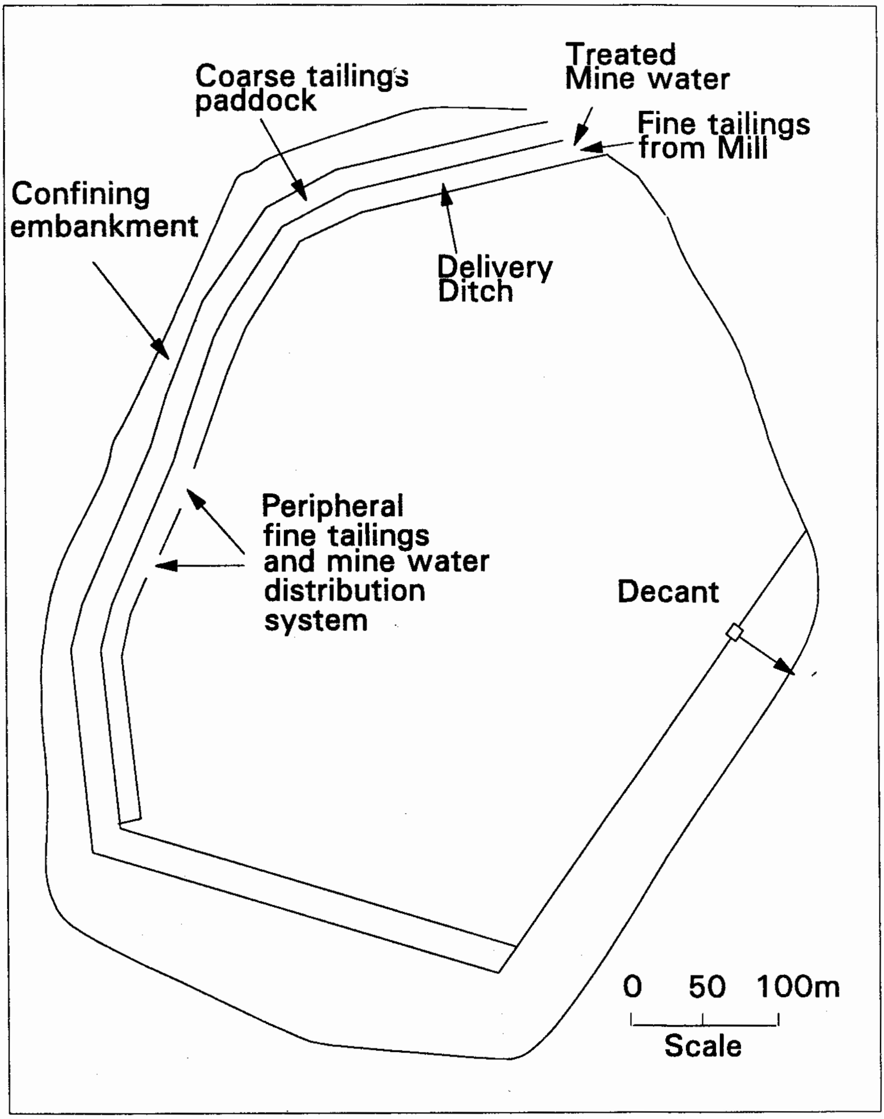
Geotechnical tests on the sludges produced by the sedimentation of the metal-rich mine waters indicated very low settled densities with similarly low consolidation rates. The implication for the dam was that a significant increase in storage volume would be required. The settled densities of the sludge and tailings achieved in the laboratory are shown in Table 5. The hydroxide flocs have a large surface area and form loose structures with high moisture content, which inhibits consolidation under loading. To avoid both the practical difficulties and the costs of a rapid increase in the capacity of the dam, an alternative and more efficient method of deposition had to be achieved. Previous studies on the site had resulted in the use of mine tailings to increase settlement rate of limited quantities of metal hydroxides. This method was simulated in the laboratory and found to enhance significantly the settled densities and to improve consolidation rates, also shown in Table 5. The deposition system was thus further modified to enable the advantages of joint sedimentation to be realised, and the new inner ditch distribution system delivers the treated mine water and fine tailings around the periphery. This method has since been proved by field testing to achieve improved densities throughout the depository and further work is in hand to prove the overall impact on storage.

Table 5. Typical laboratory dry densities for deposited materials.

	Initial settled value tonnes/m^3	Under consolidation load of 50 kN/m^2 tonnes/m^3
Metalliferous sludge	0.05	0.08
Fine tailings and sludge	0.12	0.32
Fine tailings	0.45	0.95
Coarse tailings	1.15	1.40

Despite the improvements to the treatment system, which is shown schematically in Figure 4, problems continue to occur as a consequence of introducing large quantities of mine water and low density solids to the dam. The shallow nature of the lagoon enables ready resuspension of the sediment during winds above Force 4 and, as the dam is in an exposed position, such winds occur frequently. However, with appropriate pH control, decant operation and good deposition management, resuspension can be minimised.

Figure 3. Tailings dam showing paddock and delivery ditch.



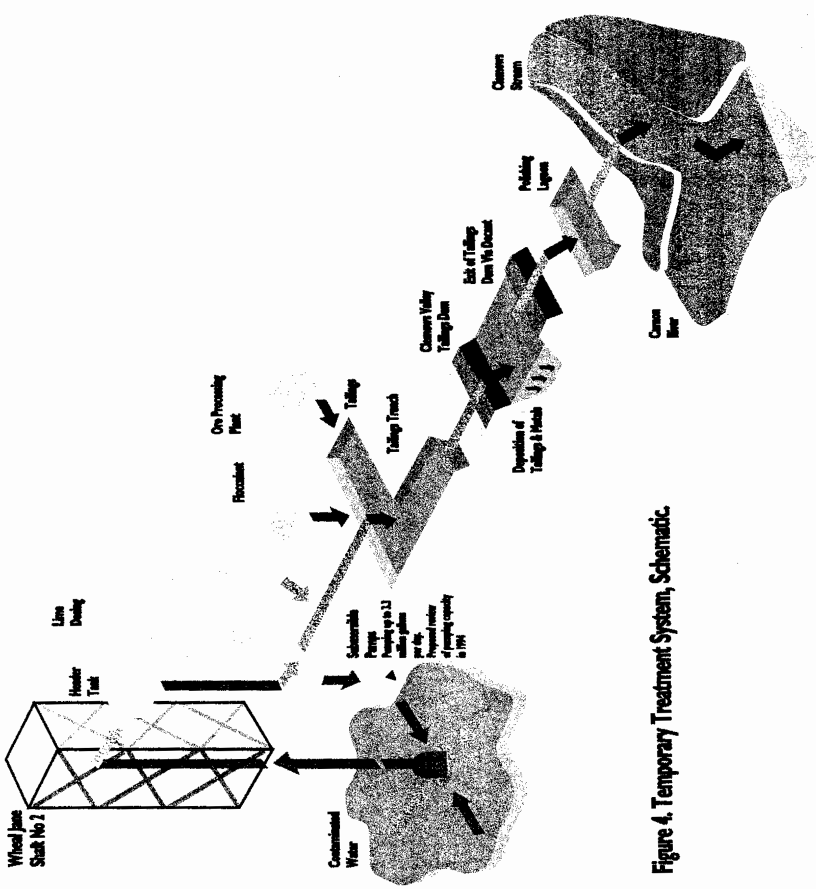


Figure 4. Temporary Treatment System, Schematic.

Discharge from the dam is usually around pH 8.5. Significantly higher values are not discouraged, since they provide added buffering capacity and they minimise the effects of acid toe drainage and irregular water recycling to the mill. Overall, there has been a marked improvement in discharge quality, as shown for cadmium in Figure 5. Between February 1992 and May 1994, over 10,000 tonnes of metal have been removed from the mine discharge. Earlier removal efficiency was about 87%; now it is 97% and discharge quality is usually better than that of the receiving water. In turn, this has had an effect on water quality in the Carnon River which is now better than prior to mine closure. Concentrations of cadmium and zinc in the river are shown in Figure 6. Much of this change is due to improved conventional treatment and management of the tailings dam, but also to improved raw mine water quality. Although pH remains at about 3, metal concentrations in the mine water have followed an exponential decay, as shown for iron in Figure 7. Other metals follow a similar pattern. It is likely that concentrations will remain at relatively high levels for a considerable time, possibly hundreds of years, as other adit discharges from abandoned Victorian mineworkings in the catchment indicate.

Figure 5. Effluent quality, May - July 1992 and March - May 1994.

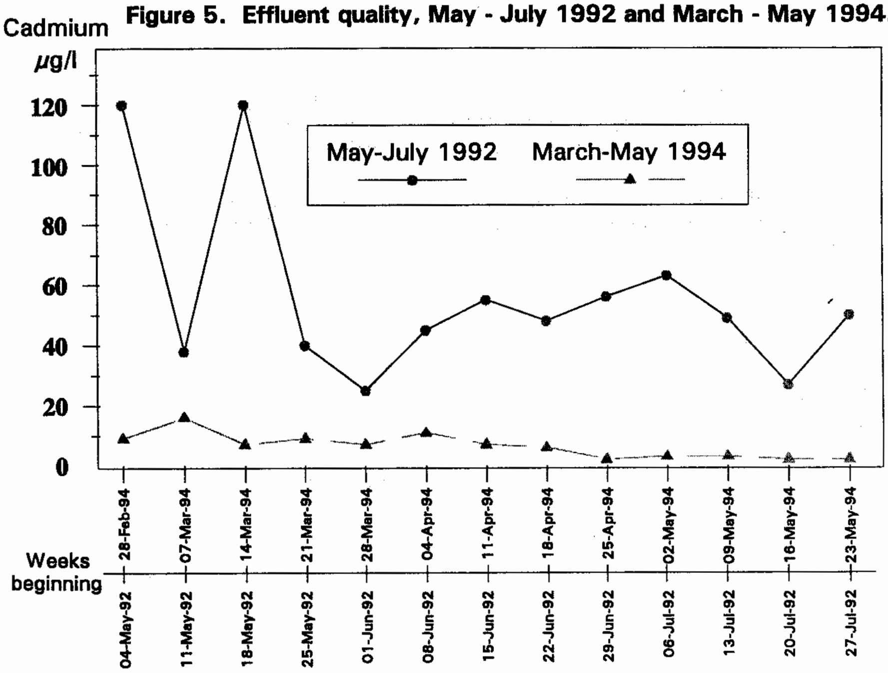


Figure 6. Cadmium and Zinc concentrations in the Carnon River at Devoran Bridge, January - July 1992.

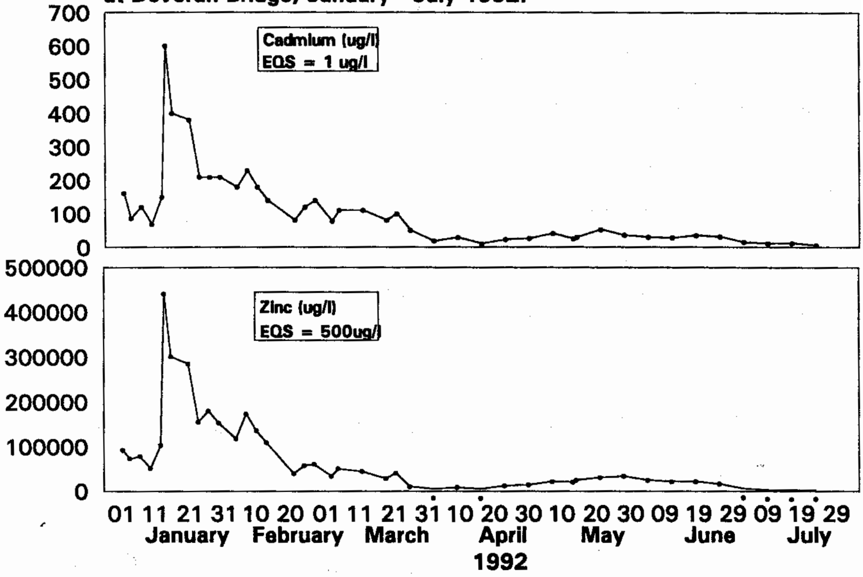
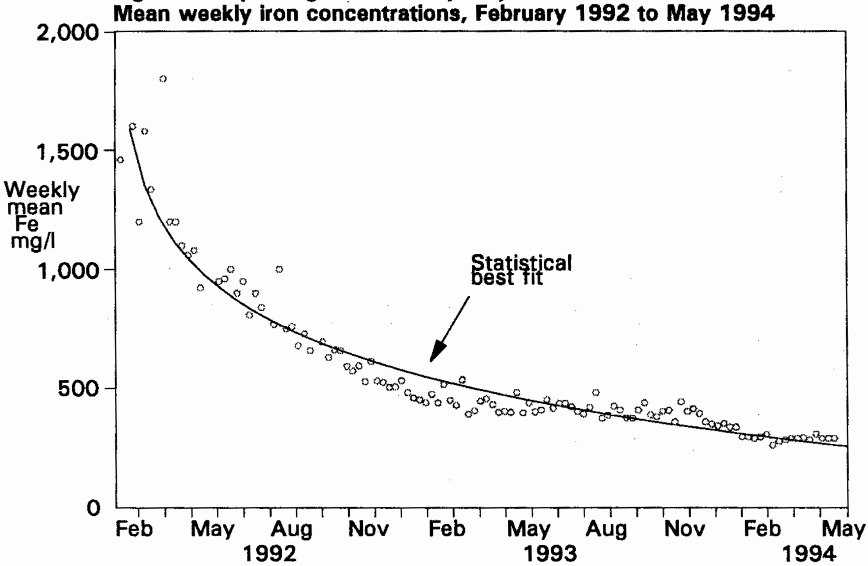


Figure 7. Improving raw water quality at Wheal Jane.
Mean weekly iron concentrations, February 1992 to May 1994



A LONG TERM SOLUTION

Conventional treatment on this scale is expensive and, as the tailings dam has a limited life as a depository for mine wastes and mine water sediments, the present solution can only be a temporary one. Current estimates suggest that the tailings dam will be filled within five to eight years. The problem of acid mine water discharge will continue well beyond this point and, therefore, a long term solution is required. This must be affordable, be implemented early, have a viable means of sludge disposal, and enable appropriate environmental quality standards to be met. Methods likely to fulfil most of these criteria are passive, i.e. physical, chemical and biological methods which operate with minimal interference from man. However, it is recognised that such systems are not completely maintenance free.

The combination of large and variable flow, high levels of acidity and high concentrations of many dissolved metals is exceptional. Initial technical evaluation of passive methods indicated that no single technique offered a solution to the Wheal Jane problem [3]. A strategy has been adopted to pilot test a number of active and passive methods, and to continue the use of conventional treatment, prior to recommending a full scale system. Funding was obtained from the U.K. Government for this development programme, which is now under way. Pre-treatment by lime dosing, de-oxygenation and the use of different sizes of anoxic limestone drains is being followed by passing the water through a series of shallow, aerobic marshes, deeper anaerobic cells and rock filters. The effects of varying the flow rates and loading factors are being assessed. Combined treatment systems are under consideration to assess the optimum long term option.

CONCLUSIONS

Many of the problems in dealing with the discharge from Wheal Jane are due to its size and complexity. The combination of high and extremely variable flows, high acidity and high concentrations of metals is unique in the United Kingdom and exceptional on a world wide basis.

Although the time and location of the discharge were predicted accurately, this was not the case for quantity and quality, both important issues in the planning and development of an adequate treatment system. In addition, no-one could have predicted the collapse of the Nangiles plug, the nature of which was unknown.

A problem is always more difficult and costly to resolve the later one comes to it. In this case, a longer lead in time would have allowed the gathering of more data, improved interpretation and perhaps the possibility of carrying out works which would have minimised or even removed the risks of environmental pollution. Despite the problems, a treatment system has been developed using the existing facilities on the site to minimise the impact of acid mine water from the abandoned Wheal Jane workings on the aquatic environment. The temporary treatment system has successfully addressed the disposal of metalliferous sludges and mine tailings in a single depository and provided time for an appropriate longer term treatment system to be developed.

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