AVOCA MINES: UNCONTROLLED ACID MINE DRAINAGE IN IRELAND

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ABSTRACT

The Avoca Mines are abandoned copper and sulphur mines in County Wicklow, in southeastern Ireland, about 70 km south of Dublin. Copper mining began in about 1720, and both copper and pyrite were mined periodically in the 19th and 20th centuries before their most recent closure in 1982. The mines lie on either side of the Avoca River, and drainage adits from both sides discharge acid mine drainage (AMD) into the river. The river is severely affected by the AMD and is one of the most polluted stretches of river in Ireland. In recent years a number of environmental studies have been carried out, mostly financed under the EU LIFE Programme, to characterise the mine area and investigate possible approaches to remediation of the pollution.

The dry weather flow in the Avoca River is in the range of 600 to 1000 litres per second. This compares with a groundwater discharge via the two main adits of around 20 litres per second, to which AMD-contaminated baseflow to the river may add another 20%. In winter, the combined adit discharges increase to about 120 litres per second, and there is also a small AMD contribution from surface runoff from areas of mining spoil. The AMD from the adits is characterised by low pH (typically 3.5), high electrical conductivity (typically 2.3-2.9 mS/cm) and high levels of metals and sulphate. The river pH is lowered from a normal 6.7 upstream of the AMD to about 5.0 below the adit discharges.

Remedial options investigated to date have included a pilot plant for treatment of the AMD by magnesium hydroxide (available as a by-product of an industrial process) and re-vegetation trials on old spoil heaps. Whatever rehabilitation option is adopted, its successful operation will depend on a proper understanding of the relationship between the hydrochemistry of the AMD and the hydrology and hydrogeology of the Avoca mines.

Future rehabilitation will also need to take account of the area's mining heritage, including conservation of the 19th century mine buildings and some other remnants of its industrial archaeology.

"There is not in the wide world a valley so sweet
As the Vale in whose bosom the bright waters meet...."
("The Meeting of the Waters", Thomas Moore, about 1805)

THE AVOCA MINES AREA

The Avoca Mines lie in the eastern foothills of the Wicklow Mountains, in the Vale of Avoca in southeast Ireland, about 70 km south of Dublin (Figure 1). The Avoca River separates the East and West Avoca Mines. To the north of the mines, the Avonmore and Avonbeg Rivers converge at the 'Meeting of the Waters' to form the Avoca River. The Vale of Avoca is a noted beauty spot and tourist attraction, made famous by the eminent poet Thomas Moore almost 200 years ago and more recently by the popular BBC Television programme "Ballykissangel".

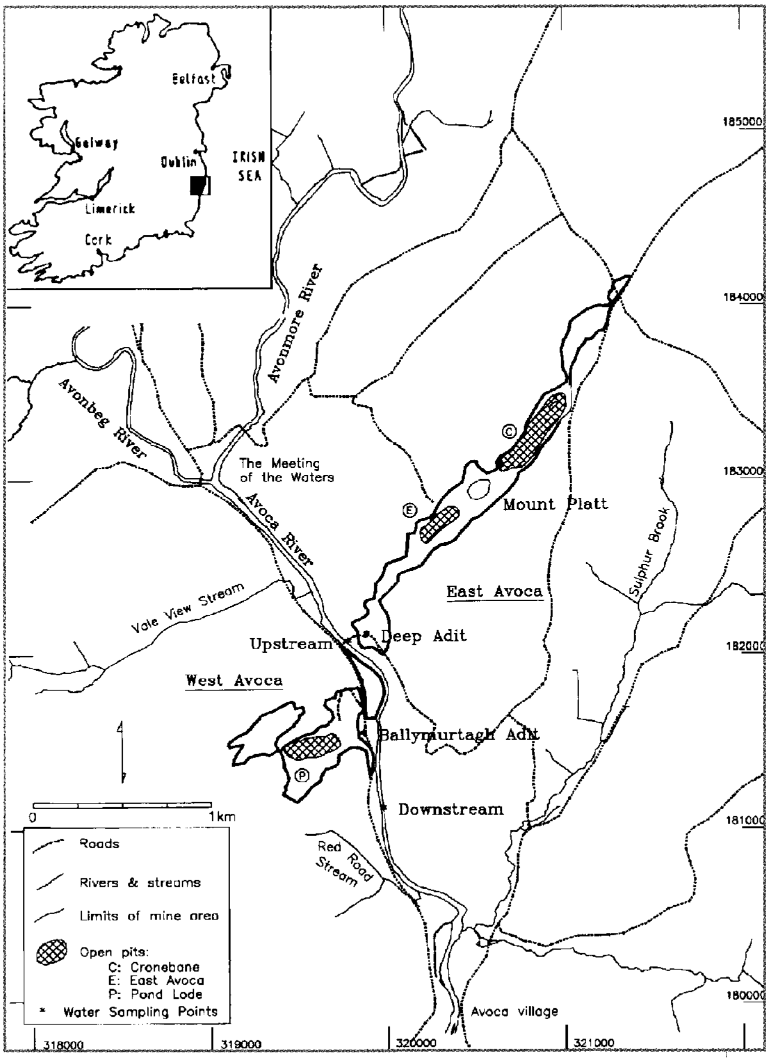

Figure 1. The Avoca area.

6.5 km south of the mines the river coalesces with the Aughrim River and flows to the sea 7.5 km further downstream at Arklow. In total the Avoca catchment covers an area of 652 km^2. Several small streams contribute to the Avoca River, notably Sulphur Brook to the south of East Avoca Mines, and the Vale View and Red Road streams to the north and south respectively of West Avoca Mines.

GEOLOGY

Southeast Ireland lies within the Caledonian - Appalachian orogenic belt south of the Iapetus Suture. The Duncannon Group volcanic rocks, which host the mineralisation at Avoca, represent the preserved remnant of a continental margin volcanic arc formed above a southeast-dipping subduction zone.

The predominant formation in the area is the Avoca Formation of the Duncannon Group, which has a lenticular shape following the regional NE-SW Caledonian trend. It varies in width from 2 to 4 km wide and is subdivided into three members (McArdle 1993):

The Castlehoward Member: The oldest of the three units, this is largely confined to the Avoca River valley and the district to the northeast. Consisting of sericitic tuffs with felsitic horizons, its thickness varies from 450 to 1200 m.

The Kilcashel Member: This varies from 700 to 1050 m thick and consists of chloritic tuffs with abundant chlorite which are frequently silicified and altered. Thickest in the Avoca River valley, it gradually thins to the southwest and northeast.

The Tigroney Member: This is the youngest unit and varies from 350 to 1800 m thick, being thickest within the Avoca River valley. It is dominated by sericitic lithic and crystal tuffs and felsites, but also contains significant chloritic crystal tuffs and distinctive horizons of lapilli tuff.

All lithologies in the Avoca area have undergone essentially similar structural evolution. The Avoca Formation and its enclosing sediments young and dip towards the southeast. A set of normal faults running NW-SE and a complementary set running NNE-SSW have been identified, some of which cut through all members of the formation.

Quaternary deposits are generally very thin, bedrock being within 1m of the surface on the higher ground, including the mined areas. The lower ground is blanketed by Till. Within the Avoca River valley much thicker deposits of Recent alluvium are developed, with some lenses of sands and gravels occurring around the Meetings of the Waters.

MINERALISATION

The mineralisation at Avoca occurs as massive and stringer sulphides and is regarded as volcanogenic in origin i.e. deposited as a direct product of volcanic activity. The massive sulphides occur at the top of the Kilcashel Member as banded sulphides a few metres thick, and it is here that much of the former mining activity was focused. The deposit is composed predominantly of pyrite (FeS_2) which makes up over 95% of the ore. Chalcopyrite ($CuFeS_2$), sphalerite (ZnS) and galena (PbS) were locally significant, but zinc and lead were not mined to any real extent. The stringer sulphides occur in concordant zones up to 30 m wide. In addition to the main sulphides, minor minerals present include arsenopyrite ($FeAsS_2$), tetrahedrite ($(Cu,Fe)_{12}Sb_4S_{13}$) and bismuthinite (Bi_2S_3) as well as some gold and silver.

MINING HISTORY

There are references to mining in the Avoca District as far back as the 2nd century and again in the 15th century when small iron oxide deposits were exploited. Written records go back to the 18th century when silver was extracted from the easily worked weathered zone at Cronebane and copper was discovered below this. Copper mining began in about 1720 at East Avoca and spread along the district. From 1839 onwards pyrite mineralisation provided economic sulphur ore and this became the main product at Avoca as the Sicilian sulphur trade with Britain was disrupted. Mining of copper and sulphur continued until 1888 when the mines became derelict. An estimated 0.22 Mt of copper ore grading 6.45% Cu and 2.4 Mt of pyrite ore grading 35% S were produced in the 18th and 19th centuries. During World War II the mines provided an emergency supply of sulphur with 16,000 t of pyrite being extracted for domestic needs.

The more recently exploited ore zones lie within 2 km of the Avoca valley and there have been two periods of continuous mining for copper since World War II. Underground production commenced in West Avoca in 1958 when the mine was deepened to 200 m below sea level and new deep reserves were outlined. However, production problems were encountered and mining ceased in 1962. During this period the deeper reserves were not developed. A total of 2.85 Mt of ore grading 0.74% Cu was produced between 1958 and 1962.

The West Avoca mine was reopened in 1969 with underground work extended to 300 m below sea level. Work in open cast pits also commenced in East Avoca with the Cronebane Open Pit being excavated between 1971 and 1978 and the East Avoca Open Pit between 1978 and 1982, when mining eventually ceased in the area. A total of some 12M t of ore has been extracted from the mines over their working life. Substantial volumes of sub-economic Cu and S mineralisation remain underground. The mine workings cover an area of about 60 ha.

A pilot study to extract gold from the spoil was carried out in the Cronebane Pit in the late 1980s but was unsuccessful.

When the mining was abandoned in 1982, no measures were put in place to rehabilitate the site other than to secure the underground workings against accidents. The AMD from the mine renders the Avoca river seriously polluted below the mine as far as the estuary at Arklow, about 13 km downstream (Byrne and Gray, 1995). The river has been unable to support significant fish life for over 200 years (Bayly, 1816).

MINING METHODS

West Avoca: In the 18th and 19th centuries, mining was based upon the selective extraction of high grade sulphide with narrow stopes 1 to 3 m wide, on average, leaving a substantial amount of ore underground. Using this method the miners reached 100 m below sea level. The driving of a new access tunnel in 1955, the Knight Tunnel, opened all the work places to immediate access. Open stoping techniques were then employed, leaving behind unworked pillars to maintain stability. The subsequent mining of these pillars led to substantial caving at the surface. Cut and fill mining was also used.

Tigroney (East Avoca): Many levels were was driven, down to 100 m below sea level, and ore was hauled to surface. The very acidic mine water drained to an old deep drainage adit 15 m below the main adit and then by gravity to the Avoca River.

Cronebane (East Avoca): In the 18th and 19th centuries the clayey consistency of the ore made mining difficult as the tunnels collapsed due to unstable ground. However, in the 1970s this made it easier to extract ore by open pit methods. The ore was stripped using scrapers and bulldozers after digging with a mechanical hoe. Eventually, deeper ore was also extracted from solid rock by blasting. The waste from Cronebane was piled at the western end of the pit where it now forms "Mount Platt" which has an elevation approximately 40 m above the original ground level.

A 30 ha tailings disposal site was constructed in 1972 at Shelton Abbey, some 6 km downstream, beside the river (Platt, 1974). The tailings site is not dealt with in this paper.

METEOROLOGY AND HYDROLOGY

Mean annual rainfall at Avoca (1971-80) was 1171 mm. Flows in the Avoca river are 'flashy' and respond quickly to rainfall events, implying that most of the effective rainfall discharges very rapidly as runoff (Flynn, 1994). In 1995 the dry summer resulted in very low flows (600 to 1000 l/s).

Flow gauging at four stations in the Avoca River (Figure 1) in the summer of 1995, using the velocity-area method, indicated a decrease in flow (approx. 23%) in a downstream direction between the upper two gauged sections, probably as a result of leakage into the underlying alluvium. Below the second station, the river gained flow again.

There are two principal drainage adits in Avoca, one on either side of the river. The Tigroney Deep adit ('Deep Adit') drains most of the underground workings in East Avoca, while the Road adit ('Ballymurtagh Adit') does likewise in West Avoca.

Discharges from the mines have been monitored by V-notch weirs, one at the East Avoca Deep Adit and two at the Road Adit. Adit discharges were very low over the summer of 1995, averaging 9.8 and 7.6 l/s for the East and West Avoca mines respectively, but the mean flow monitored in West Avoca over the summer of 1997 was somewhat higher, at 14.7 l/s (Harper, 1997). Data from previous monitoring by Wicklow County Council and the University of Dublin show that these flows can increase substantially in the winter months. Mean discharges for January - April 1994 were 38 l/s and 24 l/s for East and West Avoca mines respectively, including a maximum discharge of 65 l/s from East Avoca and 58 l/s from West Avoca. Monthly mean flows in February 1995 were over 72 l/s from East Avoca and 37 l/s from West Avoca (Gray, 1998). There appears to be a lag of two to three days between recharge into the system and an increase in discharge from the adits.

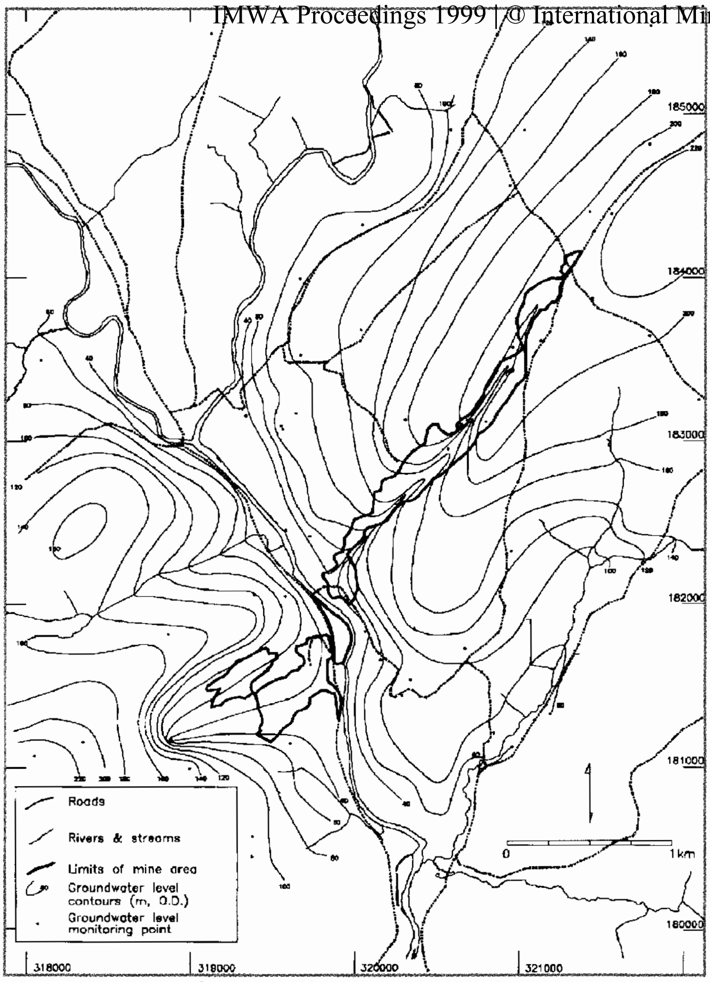

Figure 2. Groundwater level contour map of the Avoca area.

HYDROGEOLOGY

A borehole inventory in 1995 identified a total of 73 wells, springs and shafts, of which 54 were suitable for groundwater level monitoring and were monitored every 2 weeks to establish water level variations (Figure 2). Water samples for major and minor ion analysis were collected from June to October 1995, from boreholes within the project area and also at selected surface monitoring points. Measurements of electrical conductivity, pH and temperature were taken on site.

Groundwater levels were generally between 5 and 15 m below ground level during the summer of 1995. Fluctuations were small except along the steep valley sides, where water levels were deeper, and immediately around the mines (Figure 2). One well on the edge of the Cronebane Open Pit showed a fall in water level of 14 m in 25 days. Within the mined area, water levels were much lower than in the surrounding bedrock. Levels in the Vent Shaft and Twin Shafts were 135 m and 99 m below ground level respectively and remained constant throughout the dry summer.

Six additional boreholes (five cored (NQ) and one augered) were drilled to provide monitoring points in areas of scant data, permeability tests, and further lithological and overburden data. The bedrock proved to be of variable quality, with rock quality designation (RQD) values being poor (<30%) in the upper 20 to 30 metres. Most groundwater flow is likely to occur within this upper fractured zone.

Sample location	EC mS/cm	pH	SO_4 mg/l	Fe mg/l	Zn mg/l	Cd mg/l	Cu mg/l	Al mg/l
Upstream	0.11	6.71	11.9	0.224	0.369	<0.025	<0.01	0.185
Deep Adit	2.31	3.41	1365	104.4	57.11	0.17	0.645	116.5
Ballymurtagh	2.90	3.57	1761	154.1	27.31	0.068	0.989	67.45
Downstream	0.17	5.08	40.5	1.896	1.618	<0.025	0.107	1.965

Table 1. Summary of surface water sampling in summer 1995 (after O Suilleabhain 1996).

Test pumping of the investigation boreholes confirmed the poor aquifer characteristics, with transmissivity values ranging from 0.04 to 11.5 m^2/day. In some instances there was evidence of dewatering of fractures during testing. Storativity is also low, and relatively large fluctuations in water levels occur in response to relatively small variations in aquifer recharge and discharge. Hydraulic conductivities of 0.01 to 0.13 m/d for the unmined bedrock and 5 to 35 m/d for the mined area were inferred from a numerical modelling study of the mines (Lindner 1996). The numerical modelling confirmed that the flow regime is significantly influenced by the mine workings.

Testing of the spoil heaps at "Mount Platt" also showed very low permeabilities, due to the high proportion of fines in the spoil material, with 44 to 51% being finer than 0.063 mm. Compaction effects may also reduce the permeability.

HYDROCHEMISTRY

The Avoca Mines are active AMD-producing sites (Flynn, 1994; Gray, 1994, 1998). Table 1 summarises the results of surface water sampling during 1995. Water in the Avoca River upstream of the mines is relatively uncontaminated, with low EC and near-neutral pH. The adit discharges are of very poor quality, with low pH, high EC and very high metal and sulphate levels. This has an immediate effect on the river, despite dilution, as the pH falls to 5 and metal and sulphate levels rise significantly. (See Aslibekian and Gray, 1999, for details of the hydrochemistry at Avoca.)

The pH of the regional groundwater outside the mined area is rather low, ranging from 5.5 to 6.5, reflecting the chemistry of the volcanic bedrock which contains no significant carbonate to buffer the groundwater. Elevated levels of Fe, Zn, Mn, and Cu were noted in samples from local wells. Within the mined area the groundwater has a high EC, low pH and very high metal and sulphate levels, typical of AMD-affected waters. At West Avoca, water samples from the shafts were relatively AMD-free, due to their location outside the ore zone and southwest of the open pits and spoil heaps.

The water quality in the Avoca River downstream from the adits is poorer than would be expected if the adits were the only source of AMD contamination. This implies a further contribution of AMD from baseflow to the river. However, the study suggests a total AMD contaminated baseflow of 3 to 6 l/s. Assuming a mean annual adit discharge of 15 l/s from each adit, total AMD output from the mines can be estimated at 35 l/s or 1.1 million m^3/year. In addition, there is likely to be an additional 1-2 l/s (annual average) of AMD to the river from run-off from the unvegetated spoil heaps around the mines.

An important consideration in the evaluation of treatment options (see below) is the variation in AMD composition with flow rate. Monitoring of adit flow rate and EC at West Avoca in the summer of 1997, for example, showed a strong positive correlation between these two parameters (Harper, 1997). The reasons for increased AMD concentration with increased adit flow rate are not well understood. One possibility (among many) is that additional AMD is being produced just above the water table in the mine, but is only released into the adit when the water level rises further and flushes this zone.

OPEN PITS

Of five open pits originally excavated at Avoca, two survive: Cronebane Open Pit (62,000 m^2) and East Avoca Open Pit (20,000 m^2), both east of the river, separated by "Mount Platt" (Figure 1). Both pits are largely unvegetated and are important sinks for rainfall, channelling water to the underground workings and thereby contributing to AMD. Their steep walls are unstable and liable to collapse. They do, however, supply nesting sites for peregrine falcons and bats, which are protected species in Ireland.

A third pit, the Pond Lode Open Pit in West Avoca, is currently used by the County Council for landfill ('Ballymurtagh Landfill'), but this is due to close in the next year or two.

OPTIONS FOR REHABILITATION

The Avoca Mines represent a mining locality with a long history where very little rehabilitation has yet taken place. However, pressure is mounting from various sources to 'do something'. A range of options can be envisaged, from 'Do nothing' to comprehensive measures encompassing underground workings, adit discharges and spoil heaps. In each case the associated costs and benefits need to be evaluated, and the local and state authorities are moving towards such evaluation. In recent years the "mining heritage" aspects of the Avoca mines area have come to be recognised and are now a significant factor in any consideration of the area's rehabilitation (Thomas and McArdle, 1998). Conservation of the mining heritage must include the architectural remains (e.g. shafts and 'Cornish' engine houses); it is unclear to what extent it should include the adits, open pits and spoil heaps.

Chemical Treatment of adit discharges. Under the EU Life Programme a pilot plant to treat the adit discharges to an acceptable quality, by neutralisation, aeration and sedimentation, was successfully constructed and tested in 1997 (Prescott and Kilkenny, 1997; Harper, 1997; Gallagher et al., 1998). The plant used waste magnesium hydroxide from a factory 130 km away, and produced a metallic sludge which requires disposal. It is suggested that this could be disposed of into the East Avoca Open Pit, where it could have a long-term beneficial effect in ameliorating the acid percolate. The cost of constructing a full-scale treatment plant, using an average of 9 tonnes per day of magnesium hydroxide, is estimated at Euros 3.5M to 4.3 M, and the annual running cost at Euros 340,000, excluding the cost of providing magnesium hydroxide on site.

While the pilot plant trials have given encouraging results, there are a number of important issues to consider in the implementation of such a system. The treatment plant would be quite large and perhaps visually unattractive, and suitable sites are limited. It would have to be sized to cope with something close to the maximum flow from the adits, although effluent treatment plants are most efficient when dealing with a steady and predictable throughput. It would not deal with the AMD output from surface run-off (mainly in winter) or baseflow (in summer). The plant would have to work on a 24-hour, 365-day basis for the indefinite future, and would depend on a continued supply of cheap chemical (magnesium hydroxide). Plant breakdowns or shutdowns for any significant period could lead to renewed heavy pollution of the river, undoing everything previously achieved.

A local authority or state agency might be reluctant to assume the legal, financial and administrative responsibility of running a treatment works indefinitely, given the potential consequences of a substantial breakdown.

Passive treatment of AMD. Passive treatment of AMD could involve anoxic limestone drains (ALDs), successive alkaline producing systems (SAPs), and engineered compost-based wetlands. Such a system, if successful, would have the advantages of low maintenance costs, little visual impact, a potential for community involvement, and ample warning of gradual deterioration in performance over time, allowing for phased rehabilitation. A major problem of the site is the unfavourable topography. However, in recent years several wetland systems have been engineered in the UK and other countries on similarly unfavourable sites, and ways are being found to minimise the wetland areas needed (Younger, 1998; Laine, 1998). Another option might be to pipe the effluent some distance to a more suitable site downstream.

No studies have yet been made which would enable a comparison of costs and benefits between active and passive treatment of the adit discharges. Again, such a system would not deal with AMD-containing run-off or baseflow.

Reduction of AMD generation and adit discharges. Any effluent treatment system would benefit from a reduction of the rate of AMD generation in the mine and orebody, reduction of the concentration of the AMD before it leaves the mine, and reduction of the flow of AMD into the river.

These objectives might be assisted by backfilling or plugging as much as possible of the adits and mine workings above river level. This should (a) reduce the rate of flow of AMD into the river, (b) reduce the rate of flow into and through the mine workings, and (c) substantially raise the permanent water table in the mine area, thus reducing the unsaturated zone where oxidation of AMD-generating minerals mainly occurs. It would also be helpful if the material used for backfill would have neutralising properties.

The engineering feasibility of such measures at Avoca has not been studied. Difficulties would include uncertainties about the long-term security of adit plugs, the possibility of creating new and unpredictable routes for uncontrolled effluent discharge at higher levels, the cost of locating and backfilling the workings, and the cost of importing large quantities of backfill.

Rehabilitation of spoil heaps. The abandoned mine spoil heaps at Avoca, with an estimated volume of over 1M m^3 in East Avoca and over 400,000 m^3 in West Avoca, and extending over some 26 ha, are an additional source of acid drainage to the river, besides being largely bare of vegetation and hence visually unattractive. Projects have been undertaken to test possible rehabilitation methods, using locally derived sewage sludge and crushed limestone (Kilkenny and Good, 1996; Enviroplan, 1997; Steffen, Robertson & Kirsten, 1997; Gallagher et al., 1998). These trials have shown that the spoil can be successfully revegetated to improve their appearance, but that this will not significantly reduce their pollution potential unless some form of impermeable capping is installed, which would be an expensive procedure (estimated at Euros 60,000 per ha).

Unless the spoil heaps are to be preserved in their present state as part of a 'Mining Heritage' option, revegetation will probably form part of any general rehabilitation plan. One option might be to preserve just one area of spoil heap in its present unvegetated state, while revegetating the rest to reduce the visual impact on the Vale.

FUTURE STUDIES

Future studies of the Avoca site should concentrate on the development of a practical cost-effective solution and should include:

- Identification of the relative contributions of surface and underground sources of AMD.
- Modelling of the mine as a combined 'pipe+permeable medium' hydrologic system, allowing testing of the effect of various measures on the local hydrogeology.
- Further detailing of active treatment systems.
- Possibilities of low-maintenance passive treatment solutions.
- Possible types and sources of backfilling media.
- Possible techniques for locating and backfilling the underground voids.
- Integration of AMD control with overall mine rehabilitation.
- Development of costed feasible solutions.

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