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A SYNOPTIC OVERVIEW OF THE AVOCA-AVONMORE CATCHMENT AND THE MINES

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The Avoca River catchment is situated mainly in Co. Wicklow extending slightly southwards into Co. Wexford (Fig 1). It covers an area of 625 km², and is bounded on both sides by E.U. designated salmonid rivers. The catchment is predominantly upland. In the upper reaches, the watershed consists of the Wicklow Mountains to the east, north and north-west, and the Croghan Mountain forms the watershed on the southern boundary in the lower reaches (Fig 2). The dendritic watercourse runs in a south-south-easterly direction, flowing into a main artery known as the Avoca River, which in turn flows into the Irish Sea at Arklow. Although severely polluted in its lower reaches with some 10 km affected, the Avoca catchment as a whole is an exceptionally clean river system with an established fishery, as well as many fish farms located on its tributaries.

Fig. 1. The Avonmore-Aughrim-Avoca catchment in relation to Ireland showing the location of the mining strip and tailings pond.
Fig. 2 The Avonmore-Aughrim-Avoca catchment showing all main tributaries.
The upper catchments of the river system occur predominantly on blanket bog and as such are affected by the irregular hydrological characteristics of the peat, that is, its fluctuation from wet to dry depending on rainfall. This irregular hydrology is augmented by the underlying impervious rock of many of the sub-catchment areas which are prone to flash flooding or spates (Crowley, 1989).

THE AVOCA RIVER AND ITS TRIBUTARIES

Four tributaries the Avonmore, Avonbeg, Aughrim and the Ow, which are fed by a number of secondary rivers, constitute the basic river system. The Avoca itself originates at the Meeting of the Waters in Co. Wicklow at the confluence of the Avonmore and Avonbeg Rivers. It flows south-eastwards for 15.2 km through the Vale of Avoca to enter the Irish Sea at Arklow (Fig. 2).

The Avonmore River rises at Laragh in the Wicklow Mountains where a number of upland feeder rivers converge. The rivers form a number of lakes, i.e. Lough Tay and Lough Dan are formed from the Cloghoge and Inchamore Rivers; Lough Ouler from the Glenmacnass River; Lough Nahanagan from the Glendasan River; and the upper and lower lakes of Glendalough from the Glenealo River. The Avonmore flows southwards from Laragh via the towns of Clara and Rathdrum where it joins the Avonbeg at the Meeting of the Waters.

The Glenmalure River feeds into the Avonbeg which flows along a southerly 26.4 km stretch to the Meetings of the Waters. Table Mountain is the source of the Glenmalure River which is fed mainly by east flowing streams from Lugnaguilla Mountain. This mountain is also the source for the Ow River which runs almost parallel with the Avonbeg for 18.8 km until it joins with the Aughrim River. The river then flows east-south-eastwards for 9.2 km where it converges with the Avoca River at Woodenbridge (T191 770). The Derry Water, Moyne and Goldmine are the more notable rivers which feed into the Aughrim River.

With the exception of the lower stretch of the Avoca River, which is lowland depositional, all rivers in the catchment are classed as upland erosional.
The river system and general topography of the Avoca region is due to the glaciers and ice-sheets of the Quaternary glaciations. The chief glacier which formed the Avonmore valley was formed by the confluence of glaciers passing along Glenmalure, Glendalough, Glendasan and the other glens of north-east Wicklow (Fig. 3). Lough Tay, Lough Ouler and Lough Nahanagan on the upper reaches of the Avonmore River are ice gauged corrie lakes, whereas Lough Dan and the Glendalough lakes were formed as a result of ice damming and subsequent moraine deposition in the valleys.

Fig. 3. Map showing the distribution of the local glaciers in the Wicklow Mountains.

Glaciers strewed the surface of the Palaeozoic country east of the Wicklow Hills with numerous blocks of the Leinster granite. Many of these weigh in excess of fifty tons, the best known is the Mottee stone a grey granite boulder weighing over 200 tons which sits on the summit of Conary Hill (T208 771) overlooking the Meeting of the Waters. It was carried over 20 km from Glenmalure. On their retreat, the Wicklow Glaciers left behind them the moraines which now span, for example, Glendasan and the deepened and straightened u-shaped valleys of Avonmore, Avonbeg and Avoca.
GEOLOGY

A thick series of lower Palaeozoic silty and shaly sediments extends over the south-east of Ireland, amongst which protrudes the large Leinster Granite Massif of Caledonian age (Fig. 4). The existence of this great plutonic mass of Leinster granite (approximately 1,000 km²) has dominated the scenery of south-east Leinster more than any other geological factor. The upland regions of County Wicklow are composed predominantly of this hard, weather resistant, acidic, crystalline granite which was intruded at depth in the Tertiary era and exposed over time by erosion (O'Connor and Buck, 1978). The granite varies somewhat in composition throughout its length. From Baltinglass through Avoca it is felspathic, while it is rich in white mica towards the northern end at Killiney. The red feldspar pegmatities and the alterations associated with them are associated with mineralization (Elsdon and Keenan, 1982). The surrounding rocks are older Ordovician slates, shales and volcanics (Fig. 5).

The rocks surrounding the Leinster granite are essentially older Ordovician shales and volcanics, as well as slates, mica schists and associated phyllites. They contain chloritic minerals, arising from regional and contact metamorphism of various grades. These rocks are host volcanogenic sulphide ores, deposited in a submarine environment at the end of a period of acidic volcanism during Ordovician times (Platt, 1977). Within the Wicklow mountains, fragments of schist survive to form the summit of Lugnaquilla, Leinster's highest mountain (Fig. 5). Despite the presence of the scattered remnants of the undestroyed roof of the batholith, the scenery of the Wicklow mountains owes its character to the Leinster granite. Where the granite has been unroofed by the sub-aerial agents it generally forms a rolling landscape of broad domed uplands. This contrasts in form with the more sharply peaked hills and the deeply incised valleys developed on the surrounding schists of the metamorphic aureole. As the valleys of the Wicklow mountains pass through the metamorphic zone they contract, as in the outlet of Glencree on the east. Since the zone is broader on the east than on the west, in conformity with the granite, the ravines in the schist on the east are long. Waterfalls also mark the points of intersection where the granite had incorporated lenses of schist within the mass. The rocky walls of the Upper Lake Glendalough, the ravines and waterfalls (e.g. at Powerscourt, Lough Tay, and at the head of Glenmacnass) are all due to the hard schists. The slates, in contrast with the smaller bosses to the south-east, have likewise
Fig. 4. Geological map of south-east Ireland
Fig 5. Diagrammatic section across the Wicklow Mountains showing remnants of the roof of the Leinster granite and the unconformity at the base of the Carboniferous 1. Cambrian; 2. Ordovician; 3. Leinster granite; 4. Carboniferous Limestone with basement conglomerate (Elsdon and Keenan, 1982).

been altered, though the aureoles are much narrower.

Apart from the effect of the Ordovician and Caledonian rocks on the topography, the real significance of these formations in the catchment is their contribution to the formation of Ireland’s most important metalliferous belt. In the aureole rocks movements of ore carrying fluids from the molten granite magma resulted in the deposition of iron-pyrite, zinc, tin, lead, and copper along the margin of the granite. These ores, formed in rectilinear fissure veins, were extensively mined during the last century at Glendalough, Glenmalure and Glendasan. The remarkably straight and regular lodes at these sites were once Ireland’s major source of lead and zinc (Figs 6 and 7). For example 64,000 tonnes of lead ore were produced at Glendasan from 1850 to 1890. The mining was mainly in the form of adits driven back into the steep valley walls but all activity has now ceased leaving the abandoned workings scarring the hillsides.

Along the gently-inclined eastern flank of the granite stretches a belt of volcanic and intrusive rocks some 6 - 14.5 km wide and over 129 km long. It runs in a northeast-southwest direction between the coasts of counties Wexford and Wicklow. Near the northern part of the belt lies the Avoca mineralised ground, lying east northeast to west south-west, with a strike length of several kilometres (Fig. 8), a cross strike width of more than 305 metres and a vertical depth exceeding 450 m. The host rocks are essentially a
chlorotic faces.

AVOCA ORES AND MINERALISATION

The Avoca ores are massive sulphide volcanogenic deposits of Ordovician age. Ore deposition occurred in a submarine environment at the end of a period of acidic volcanism. Within the Avoca deposit the literature distinguishes two contrasting types of copper mineralization, both with associated sub-economic lead and zinc. Both massive sulphide and disseminated sulphide ('stringer') ores occur (McArdle, 1994).

1) Massive sulphides, consisting of banded pyrite material with dispersed chalcopyrite, which formed syngenetically on the sea floor. The massive ores lie within the black chlorotic schists. These ore grades at Avoca range from 0.8% to 1.2% copper with up to 40% sulphur. Since 1970, more than 1.5 million tonnes of massive ore grading approximately 1% Cu have been extracted from both East and West Avoca, but all major massive ore zones have not yet been exhausted.

2) Disseminated sulphides, 'stringers' (pyrite-chalcopyrite) occur within altered acidic ashes. These are the produce of diageneric processes immediately following ash eruption and preceding lithification. Hence, these ores are hosted by the chlorotic silicaceous tuffs and are more complex in nature than the massive ores. They were the source of much of the copper extracted at East Avoca Open Pit, the Pond Lode Open Pit and the Cronebane Open Pit. Stringer ore grades in Avoca range from 0.6% to 0.8% copper with 6% to 10% sulphur. Since 1970 over 4,000,000 tonnes of stringer ore have been extracted from East and West Avoca (Fig 9).

In addition to the above, a number of minor ore types occur, including sulphide-cemented breccia zones in rhyolite bodies with associated slumped sulphides, and complex copper-lead-zinc sulphides in either a carbonate or pyritic matrix. Table 1 shows the detailed lithostratigraphical features of the ore environment.
Fig. 6. Map of the Liganure mining district showing the various mining sites
Fig. 7. Map of the Glenmalure District showing the regular lead veins.
Fig. 8. Map of Avoca and Aughrim District showing the expanse of the strike length.
Table 1. The Lithostratigraphical features of the Avoca ore environment (Platt, 1980).

<table>
<thead>
<tr>
<th>Top</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhyolite</td>
<td>2,000 m</td>
</tr>
<tr>
<td>Sericitised rhyolitic tuff</td>
<td>150 m</td>
</tr>
<tr>
<td>Fine-grained sediment</td>
<td>148 m</td>
</tr>
<tr>
<td>(Magnesian tuff)</td>
<td>70 m</td>
</tr>
<tr>
<td>Black Shale</td>
<td>5 m</td>
</tr>
<tr>
<td>Dolomitised tuff</td>
<td>50 m</td>
</tr>
<tr>
<td>Iron sediments)</td>
<td>10 m</td>
</tr>
<tr>
<td>Massive Cu-Pb-Zn sulphides</td>
<td>3 m</td>
</tr>
<tr>
<td>Massive Cu-Fe sulphides</td>
<td>10 m</td>
</tr>
<tr>
<td>Medium coarse-grained volcanics</td>
<td>1,200 m</td>
</tr>
<tr>
<td>(Chloritised rhyolitic tuff with</td>
<td>200 m</td>
</tr>
<tr>
<td>chalcopyrite stringers)</td>
<td></td>
</tr>
<tr>
<td>Quartz eye tuff</td>
<td>1,000 m</td>
</tr>
</tbody>
</table>

Bottom Rhyolite 1,000 m

The weather has caused leaching of iron and sulphur from the deposits since pre-glacial times, so the deposits in Avoca are relatively enriched with copper (Platt, 1973). The mines have been exploited in the past to obtain a number of minerals including gold, silver, pyrite, copper, iron, lead and zinc (Kinahan, 1878). The most important base metal sulphides found in Avoca are chalcopyrite (CuFeS2), the main copper ore mineral; pyrite (FeS2), an important by-product of copper mining, and the most abundant Avoca sulphide mineral; sphalerite (ZnS), which is of minor importance; and galena (PbS) which has no commercial value (Platt, 1973, 1974). The Avoca pyrite was used as a source of sulphur, which eventually became the main product of the mines, exceeding copper production (Platt, 1973). A full list of minerals found in the Avoca mines is shown in Table 2.
Fig 9. Lithographical formations of East and West Avoca
AVOCA MINE

The location of the Avoca mines or 'Ovoca' mines as they were once known (Smyth, 1853; Kinahan, 1878), is some 70 km south of Dublin in the south-east of Co. Wicklow, 10 km north of the port of Arklow (Fig. 1). It lies in open rolling farmland 200 m above sea level, deeply incised by the glaciated valley of the Avoca River which bisects the mine area into east and west Avoca. The recently exploited ore zones at Avoca lie within 2 km of the Avoca Valley, but ancient mine workings are found in a belt extending up to 8 km both north-east and south-west of the mine. The Avoca mine site is situated in south County Wicklow Ireland (N 52° 52.3' W 6° 13.3') approximately 1.4 km upstream of Avoca village, Co. Wicklow. The site consists of a narrow belt of pyritic and low grade copper ore deposit (average 0.6% Copper). Mining activity on the site arose from mineral deposits which are products of the same volcanic event but are split into two sections by the Avoca river and referred to as West Avoca and East Avoca. The mines are now abandoned, but their presence is still conspicuous due to large spoil heaps, sunken shafts, and the remains of Cornish beam engine houses dating from the 19th century. The Avoca mines complex comprises several sites: the Ballymurtagh, Ballygahan, Tigroney, Cronbane, Conary and Kilmacoo mines (Platt, 1973).

Table 2. Minerals found in or near Avoca mines.

<table>
<thead>
<tr>
<th>Site</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goldmine river</td>
<td>Gold, Silver</td>
</tr>
<tr>
<td>Ballygahan Upper and Lower</td>
<td>Pyrite, Copper</td>
</tr>
<tr>
<td>Ballymurtagh</td>
<td>Copper, Pyrite, Iron (Haematite/ Limonite),</td>
</tr>
<tr>
<td></td>
<td>Auriferous Gaussen</td>
</tr>
<tr>
<td>Tigroney</td>
<td>Copper, Pyrite</td>
</tr>
<tr>
<td>Cronbane</td>
<td>Pyrite, Copper, Silver lead, Silver</td>
</tr>
<tr>
<td>Conary Upper</td>
<td>Pyrite, Copper, Silver lead, Lead, Zinc, Gold</td>
</tr>
<tr>
<td>Kilmacoo</td>
<td>Copper, Lead, Zinc, Pyrite, Antimony, Arsenic, Silver lead</td>
</tr>
</tbody>
</table>

-17-
History of Avoca Mines

The mines as a whole are thought to have been worked almost continuously from Bronze Age times (Irish Mining and Exploration Group, 1979). There are written records from the mines dating from 1752 (Platt, 1974) but previous references also exist. In 150 A.D. Ptolomey is said to have referred to Avoca as a mining area and in the Annals of the Four Masters in the 5th Century there are said to be many references to the mining of minerals in Wicklow, including gold (Irish Mining and Exploration Group, 1979). Further evidence of the age of the mines was found in 1843, when ancient workings were discovered at the Hill of Lyra, almost a mile south west of Woodenbridge. Around the same time an oak frame was discovered under 5-6 feet of drift which is supposed to have had a connection with the miners from ancient times (Kinahan, 1878). From this evidence it is clear that the mines have been worked for centuries.

Copper mining began in 1720 at East Avoca with pyrite becoming more important for it's sulphur content from 1830's to 1888. Between 1898 and 1910, 20,000 tons of sulphur fines were produced from below surface at Cronebane and from 1942 to 1947 16,000 tons of pyrite were mined. Mining carried out before the 1950's is generally referred to as the Old Men's mining (Fig 10). The Mogul Mining Corporation of Canada was licensed to develop the ore bodies from 1958 to 1962 under the name of St. Patrick's Copper Mines Ltd., concentrating on the ore residue remaining from 19th century workings rather than on developing new ore bodies (Milner and McArdle, 1992).

All mining carried out up until this point was subsurface, creating a network of shafts and adits in the bedrock on both sides of the river. Open pit mining was begun in 1958 by St. Patrick's Copper Mines (SPCM) to extract the c. 1% Cu from the hanging wall of the Old Men's excavations in West Avoca. SPCM also mined underground at Tigroney on the East side of the river to produce several 100,000's tons of ore grading at 0.87% Cu. SPCM ceased mining in 1962 and the operation was put in receivership due to the low ore yield combined with low copper prices.

During this period at Avoca SPCM produced a total of $3 \times 10^6$ tons of ore grading at 0.75% Cu. In 1966 a proposal was accepted from a consortium of companies to take over the mining lease in return for carrying out detailed underground exploration of the area. They proved that sufficient ore was
Longitudinal Section of the Ovoca Copper and Sulphur District

Fig. 10. Early mapping of the Avoca mines complex.
present to support a medium-sized operation. In 1969 Discovery Mines Ltd. took over a major part of the operation, continuing until 1982 under the name of Avoca Mines Ltd. At the peak of production in the 1970's the company provided employment for up to 2,000 people. Underground mining and development was resumed at West Avoca by Avoca Mines Ltd. extending the workings eventually to a depth of 300 m below sea level. On the eastern side the shaft network reached a depth of 92 m below sea level. Underground mining continued until closure in 1982. Open cast mining was carried out on the east side of the Avoca from the early 1970's creating two large open pits, the East Tigroney and Cronebane Pits. Cronebane Pit ceased production in 1974 and the East Tigroney Pit operated between 1978 and 1982. The ore from Cronebane Pit was estimated at 450,000 tons at 1.75% Cu and the ratio of waste to ore during the stripping process was 2.5:1. The gangue from Cronebane Pit was deposited between the two pits to form one large spoil heap now called Mount Platt, which has an elevation of c. 40 m above sea level. The ore from East Pit was taken by trucks to the mill at West Avoca and the tailings from the mill pumped along a 6 km long pipe to the tailings pond at Shelton Abbey (Fig. 1).

The Avoca Mines have been closed since 1982, but mining has not necessarily ceased in the Avoca district. During the later part of the 1980's, the site was used to develop a new process to extract gold from spoil (thiourea process) by Conary Minerals Ltd.. Since 1992 all mining and extraction activities have ceased, and the site is now under the direct control of the Department of Energy.

Mining technique at the Avoca mines

At West Avoca the copper ores were contained in two separate horizons which were folded into a 'U' shape. Both arms of the 'U' were found to have an equivalent dip of 55°. This pattern was repeated further north of the main copper ore bodies (Platt, 1973).

Four operations were carried out concurrently. The first was underground mining west of the Avoca which produced 2300-2500 tons of ore per day. The second was a small open-pit mining operation in West Avoca which mined low grade ore remnants which had been rejected by previous operations. Approximately 500 tons of ore were produced each day. Third
was reclamation of 18th and 19th century spoil heaps. The concentration of copper in these was sufficiently high to be considered ore by standards of the day. The final operation was an open-pit stripping operation at Cronebane in East Avoca, one mile north east of the west Avoca underground mine. This commenced in 1971 and produced up to 600 tons of ore per day. The ore was manually cleaned of debris and sampled in the pit before being loaded to dumpers and moved to the concentrator plant in west Avoca where all ore was processed.

Rock and broken ore from west Avoca was moved using Wagner Scooptrams and was eventually brought to a central crushing plant in the central South Lode area. Ore pieces greater than 91.4 m³ were removed to the crusher for secondary blasting and the residue was crushed to a size of 15 cm. Waste broken underground was loaded for trucking and disposal as backfill. The crusher fed crushed ore onto a conveyer belt which in turn fed to an ore bin excavation which held approximately 1,500 tons of ore. The bin fed the first of a series of three conveyors at 17° grade which brought the crushed ore to the concentrator storage bin at the surface (Platt, 1973).

One hundred gallons of waste water was generated per minute in west Avoca. This was channelled to the pump station and settling pumps near the Ballygahan shaft. The water was discharged to the more acidic Avoca river after suspended solids were excluded from it. The river down-stream from Avoca contained no significant life forms. It was felt that leaching and natural drainage from the pyritic mine host rock area was responsible, and had probably always prevented such life occurring. (Platt, 1974). Therefore no effort was made to counteract pollution since it was felt that the impact of effluent deliberately discharged into the river was insignificant.

_Milling technique at the Avoca mines_

The mill was located in west Avoca and was constructed for the 1958-1962 period. It was overhauled and redesigned in 1969-70 for the Discovery Mines Ltd. operation. In this operation it treated around 3,200 tons of ore feed per day, seven days a week. During milling metal-containing rocks or ores are ground to fine powder and are separated magnetically or chemically into metal rich fractions and finely ground tailings, or waste material (Freedman and Hutchinson, 1981; Ogram and Fraser, 1978).
The mill had two circuits, one to handle approximately 2,700 tons per day of west Avoca feed from all sources, and the other to handle 500-600 tons per day of Cronebane ore feed. The Cronebane ore had to be kept separate as it contained a high percentage of activated zinc. Fresh ore from Cronebane was dumped on a 1200 ton storage pad and fed to a rotary hammer mill which crushed the material to 2.5 cm segments. The ore was slurried in a logwasher and the slurry was then passed to a pump box and cyclone closed circuit. Coarse slurry went to a ballmill, and fine slurry to a flotation process. The flotation of the Cronebane ore was similar to that of ore obtained from west Avoca. However, extra steps were sometimes necessary in order to control acidity and depress the concentration of zinc in pyrite and copper flotation stages.

The 15 cm ore produced from the West Avoca operations by the crusher was stored in a 1500 ton surge bin at the surface. From here it went to a crushing circuit and was crushed by stages to 1.3 cm. This product was then conveyed to storage bins with a capacity of around 6,000 tons and from here went to two identical grinding circuits. Circuit consisted of a 2.7 x 3.6 m primary ball mill, a 2.7 x 2.7 m secondary ball mill, and a hydrocyclone classifier. The secondary ball mill was in circuit with the cyclone.

The ball mills were lined with corrugated plates and were loaded with three inch steel balls. The weight of the balls, the speed at which the mill turned and the rate at which ore and water were fed to the mill were calculated and fixed to give the optimum grind for eventual concentration of copper minerals. Sophisticated grinding technology was needed in Avoca to liberate chalcopyrite as monomineralic grains as the aim was for each particle leaving the mill to have only one mineral. The closer the intergrowth of the sulphide minerals, the finer the grind had to be. The retention time of fine ore in the mills sometimes had to be extended in order to allow for this. Lime and sodium dithiophosphate were added to the primary mill to prepare the grind for concentration. The grind leaving the mill was cycloned and any particles greater than the required size went to the secondary mill for further grinding.

The finely ground product went to conditioning tanks where frother was added to aid the concentration of copper minerals. An alkaline mix was required for this process, and was supplied by the addition of lime at the
primary grinding stage. Air was then bubbled through the grind to take advantage of the property of sulphide minerals under certain conditions and in the presence of certain chemical additives of adhering to air bubbles blown through the grind mix. Sulphides floated to the surface on the bubbles and were skimmed off, leaving the remainder of the rock behind.

The conditioning tanks prepared the west Avoca grind for chalcopyrite flotation. Rough and scavenger concentrates of chalcopyrite were finally produced. The scavenger concentrates were returned for regrinding and reconditioning. The rough concentrates continued to another bank of flotation cells for cleaning and the cleared copper concentrates were thickened and pumped to rotary vacuum filters for dewatering. The final copper concentrates had a grade of approximately 21% copper which represented a 93% recovery from the W. Avoca ore, and a 75% recovery from Cronebane ore.

Tailings from copper cells flowed to conditioners and banks of flotation cells. The ore was depleted in copper but contained pyrite, an important secondary product. The conditioners and flotation cells formed a pyrite concentration circuit. Copper sulphate was added to the grind pulp in the concentrators in order to activate zinc minerals for removal to tailings and sulphuric acid was added in order to elevate the pH to 6.5. Zinc was removed by use of sodium isopropyl xanthate and frother substances before pyrite concentration occurred. Pyrite concentrate was cleared in one stage and dried in a manner similar to copper concentrates. It was later sold to N.E.T. (Nitrigin Eireann Teoranta), a local fertilizer factory, now called I.F.I. (Irish Fertilizer Industry). The industry required a minimum of 80,000 tons per year with a grade of approximately 48% sulphur (Platt, 1973) for the manufacture of sulphuric acid.

Waste disposal

In 1955 the option of expanding the Avoca mines into a large-scale operation was considered. Disposal of the tailings was seen as the most difficult problem to be surmounted, and there were four options available for consideration.

1. To place a dam on the upland area above the mine.
2. To discharge the tailings into the Avoca river.
3. To discharge them into the sea at Arklow.
4. To build a containing tailings dam in the Avoca valley.

It was felt that to place a containing dam above the mine would be dangerous, unaesthetic, and also impractical, as the waste would have to be pumped upwards to the site thus increasing the cost of the operation. The discharge of waste into the river or sea was the earliest historical method of tailings disposal (Vick, 1983), but would have been objected to on the grounds that it would affect river and marine life (Platt, 1974). It was therefore decided that a containing dam in the valley was the best available option. The 79-acre Avoca riverside meadow at Shelton Abbey (Platt, 1974) was considered to be the most suitable site available.

The siting of tailings dams is very important. Ideally the dam should be as close as possible to the mill in order to reduce the expense of providing and laying down pipes. It should be downhill from the mill to reduce the cost of pumping the slurry, but not on a steep gradient, as if this is the case the cost of pumping water back to the mill for recycling is high. However, in the Avoca mines water was not recycled so this was not a significant factor in siting the dam (Vick, 1983).

A site with sufficient storage capacity to fulfil the requirements of the mine for several years to come with use of the least amount of embankment fill material is preferable (Vick, 1983). Embankments of less than 100-200 feet high are considered optimal (Vick, 1983); those higher than about 400 ft generally have associated design and construction problems. Embankments about 50 ft in height are most commonly constructed as they provide sufficient storage space for a number of years while eliminating the problems associated with construction and stability of taller structures (P. Timpson, pers. comm.). At the time of construction of the dam, a minimum retention period of five days was recommended, with a pond of 10-25 acres for each 1,000 tons of tailings solids discharged per day (Bell, 1974). As the rate of deposition of tailings was 3,000-3,200 tons per day (Platt, 1974; Platt, 1973), a site of 32-80 acres was required. It was estimated that the Shelton Abbey site would provide storage space for tailings for up to 10 years based on deposition over a seven day week (Platt, 1973). If this estimate had been met the site would now hold almost $77 \times 10^6$ tons of tailings. However during the 1970's the walls of the impoundment were raised a number of times to extend
the capacity of the dam. Therefore the exact quantity of tailings stored is unknown.

A site with low groundwater is considered to be better than a high groundwater site as in the latter the amount of dry fill available for embankment construction is limited, and once constructed, leaching quickly occurs, allowing contaminants to enter the groundwater (Vick, 1983). The Shelton Abbey townland was reputed to have an efficient decant system. It was judged that the heavy metals in solution in the decant liquids were negligible in amount, and so need not be removed. Tailings were settled out and clear liquid was discharged into the Avoca. The pH of the discharge was approximately 5.0, as opposed to water discharged from W. Avoca which had a lower pH of around 3.7, and contained dissolved metal salts and suspended solids (Platt, 1974). Discharge assays were taken by the mining company which gave the levels of copper as 60 ppm, of zinc as 180 ppm, and of lead as negligible.

Some of the functions of tailings dams include the removal of suspended solids by sedimentation; neutralisation of the waste (Williamson et al., 1982); formation of heavy metal ion precipitates as hydroxides are settled out (Bell, 1974); perpetual retention of settled tailings and precipitates; stabilisation of oxidizable components of the waste; and storm water storage and flow balancing (Williamson et al., 1982).

Sources of environmental problems from the mines

The environmental factors associated with the Avoca mines are largely confined to a relatively restricted area in the vicinity of the pyritic geological formations, and downstream in the catchment. However, it is not the actual extraction of the mineral so much as the disturbance it causes which produces the pollution. Ten years after the cessation of intensive mining activities, the Avoca River is still being polluted by water draining out of the disused mines and spoil heaps.

Water is both a vital raw material for, and a major waste from mining. Much of the net influx is from natural sources such as, groundwater percolating through the rocks or draining in from surface run-off and rainfall. The main problem results from the chemical breakdown, under conditions of natural
weathering, of the pyrite (iron sulphide) in the rocks of the Avoca region. Pyrite is particularly prolific in the central mining belt and may constitute up to 90% of some rock strata. It oxidises easily to ferrous sulphate and sulphuric acid, and the production of acid is enhanced by the associated presence of copper sulphide (chalcopyrite) and zinc sulphide (sphalerite). Natural leaching and weathering ensure that the mine effluent is rich in sulphuric acid and dissolved metal salts. Some of the leach liquor wells naturally into the Avoca River from hillside springs, or seeps in from the sub-river bed faults.

In the 18th and 19th centuries little or no waste was brought to the surface in either the East and West Avoca mines. Waste was back-filled underground and ore was hoisted for dressing at the surface. This consisted of the manual breakage of lumps of ore with a hammer, the ensuing pieces being sorted into an acceptable product and a waste. This process was termed 'cobbing.' It is estimated that up to $1 \times 10^6$ tons of cobbing waste exist at Avoca, covering large areas of ground in piles up to 12 m in height. Weathering and oxidation have taken their toll on the cobbing piles which are in a constant state of natural leach. The cobbing areas are devoid of vegetation, and the soils surrounding them are scoured to sterility.

Avoca's spoil heaps also invariably lack vegetation, due to their residual toxicity and nutrient deficiency. Waste heaps which are over 200 years are still devoid of vegetation. Their surface structure is friable and dry, and are subject to wind erosion as well as intermittent leach action by rainfall.

The water and tailings waste from the mining and milling operations were discharged into settlement and treatment lagoons, termed 'tailings ponds.' Up to 99.6% of the extracted material for Cu can end up as processed waste (or tailings). Avoca mines maintained a tailings pond at Shelton Abbey constructed on a 79-acre Avoca riverside meadow 3.2 km north-west of Arklow and 6.4 km south of the mine area. The dam itself was built of rock and clay material ripped and dug from the immediate dam area. This has now been re vegetated through the implementation of rehabilitation programme carried out in the early 1980's. Its success was at least partially due to the use of natural materials removed from the surrounding area during the original dam construction (O'Neill, 1993).

The presence of the Avoca river valley between the two major deposits
provided a convenient means of drainage for the mine workings which are naturally inclined towards the valley. In 1962, it was established that the mine in West Avoca was making c. 900 - 1200 litres of water per day, depending on seasonal rainfall. Some 50% of this came from the end of the deep tunnel servicing the West side of the mine and had a pH of 7. The remainder, which was very acidic at pH 3.4, seeped through the mine and was removed at various levels. The effluent was drained south in a concrete flume alongside the main road before being discharged into the river at a weir, 300 m downstream from the main entrance to the modern mine. This is still the point of discharge for acid mine waters generated in the flooded underground workings at West Avoca. In 1973, the mine was reported to be making 450 litres of "mildly acidic" water per day and still being discharged into the river. On the East side the very acidic mine water drained to the Tigroney Deep Adit, an old deep drainage adit 15 m below the main adit and then by gravity to the Avoca. This adit is currently the main source of acid mine drainage from the underground workings of East Avoca.

Water pollution problems are more insidious than the despoliation of scenery as they are less obvious but ecologically more damaging.

CATCHMENT CHARACTERISATION

Soil Classification

As a result of glacial history and the presence of major rock formations, there is a wide variation in soil parent material types, from which in turn a diverse group of soils has developed. Seven principal soil types which are classified under broad physiological divisions occur within the catchment (Fig. 11).

1. Peaty Podzols are dominant at higher altitudes of the catchment at between 250-1000 m on the granite mountain areas. The topography is hilly near the mountain tops, with flat to very steep slopes between 5°-12°, and rock outcrops are common. The soils are characterised by a peaty surface horizon of course texture, moderately to imperfectly drained. Sphagnum species, which are widespread, enhance acidification by binding cations and exchanging them for H⁺. The blanket peat which occurs is normally 1-2 cm
deep, wet and poorly drained. In general the peaty podzols are of a very limited use due to their high elevation, inaccessibility, peaty surface with low lime and nutrient status and iron pan development. They are not suitable for tillage or intensive grassland their use being confined to mountain sheep grazing, amenity, and some forestry.

2. *Lithosols* also dominate the higher altitudes, as the parent material on which it is based consists primarily of the granite found on the steep slopes of the mountains with very shallow and stony soils. However, these soils only exist in the north-northwest of the catchment and only marginally border the source of some of the tributaries. Outcrops of rock and boulders are common in these areas. The vegetation of lithosols is characteristic of dry acid conditions with partial skeletal cover. They usually have a shallow black turfy layer which is excessively drained and has a very low base status.

3. *Blanket peat* exists in the extreme northern part of the catchment and is characterised by high level blanket peats which are acid and poorly drained. The general topography on which they occur is mainly rolling with elevation ranging from 150-1000 m. Vegetation of this soil includes species such as *Calluna vulgaris*, *Polytrichum spp.*, *Eriophorum spp.*, *Vaccinium oxyccoccus* and *Potentilla. sp.* which can be excessively grazed. Alternative uses of the land are very limited due to its organic nature, elevation and wetness.

4. *Brown podzolics* (a) are quite dominant in the central catchment and are found in areas of Palaeozoic shales and miccaschists from block or glacial drift with elevation of 152-366 m on slopes ranging from 4°-20°. These soils are shallow and well drained with heath vegetation. The soils are mainly loam-clay loam and have a low base status.

5. *Brown podzolics* (b) are less dominant and can be categorised as rolling lowland, found below 152 m. These podzolics are well drained with clay loam-loam soils of low base status. Vegetation is mostly old pasture species, primarily *Agrostis. sp.*.

6. *Acid brown earths* dominate much of the lower lying reaches of the catchment. These are well drained soils with low-medium base status. Their moisture holding capacity is good with the presence of small stones encouraging drainage. These soils have a wide use range which includes tillage, grassland, fruit and vegetable crops.
Fig. 11 Soil associations of County Wicklow including Avoca-Avonmore catchment.
7. *Gleys* surround the lower broadened stretch of the Avoca river before its entry to the Irish sea. These soils have poor drainage due to the high water table at this point. They can, however, be drained by surface operation and proper management to establish productive pastures and tillage.

**Buffering capacity**

The geology and soils are major factors influencing the surface water chemistry in the catchment. With regard to the mineralogy and geochemistry of the rocks in the area, the dominating influence on the water chemistry and acidity is the content of carbonates and weatherable silicates. Hornung *et al.* (1990) developed a simple classification of rocks based on a combination of earlier classifications. When his classification is applied to the solid geology of the Avoca catchment, it indicates that large areas of the north, central south west of the catchment are underlain by granite rocks and so have little or no neutralising capacity (Fig. 12). The surrounding Ordovician slates, shales and volcanics have a low to medium buffering capacity. Thus, on the basis of bedrock geology, naturally-weakly acidic, low conductivity waters, sensitive to acidification, are predicted to occur over much of the catchment. Since predictions based solely on bedrock geology have limitations, it is more reliable if soil types and their buffering capacity are also included.

The acid-neutralising capacity of soils is largely determined by their content of carbonate and weatherable silicate minerals, cation exchange capacity and base saturation. These properties are dependent on the nature of the parent material, its age, and the weathering and leaching of the soil. A number of soil classifications have been published. Avery (1980) used the base status of subsoil horizons to classify soils on the basis of neutralising capacity. A broadly similar approach was taken for the Avoca region but simplified to give two classes of soils: acid soils with little or no neutralising capacity and non-acid to weakly acidic soils with moderate to large neutralising capacity. The soils associations which dominate the catchment and classified as acid with low neutralising capacity are the peaty podzols, brown podzolic soils and acid brown earths. The predominance of acid soils in the catchment is the result of the interaction of the base poor soil forming materials derived from the acidic granite rocks, slates and volcanics with the humid, cool climate. Variation in stream water acidity may occur as a result of small scale
Fig. 12. The geology of the Avoca-Avonmore catchment.
differences in soils and bedrock geology not shown in the maps used in this report due to their small scale. With the predominance of upland, high rainfall and thin low base status soils based on granite bedrock, much of the catchment (approx. 16,455 ha.) is under forestation as the soils are largely unsuitable for other uses.

Agriculture

The Avoca-Avonmore catchment area is predominantly rural. The impact of agriculture on the landscape of this region is therefore highly significant. Agriculture in the catchment consists of five main categories: tillage, cattle, sheep, dairying and poultry. The most intensively managed sector is dairying. Farming in the area is generally undertaken in a traditional fashion on a small to moderate scale. County Wicklow is dominated by upland soils with 74% of its land over 500 feet above sea level and 26% over 1000 feet (An Foras Taluntais, 1979). Because of the mountains and their attendant outlying hills there is an almost continuous undulating to steeply rolling topography throughout the catchment. There are 2,730 farm holdings in the county, the majority (584) of which cover 30-50 hectares. Smaller holdings of 20-30 hectares are owned by 485 farmers while larger farms of 50-100 hectares are owned by 480 farmers. Few farms are greater than 200 hectares (19 only). The total area used for agricultural purposes is approx. 104,000 hectares. In spite of the high elevation of most of the farmland (brown podzolics and acid brown earths) is given to grassland - approx. 72,000 hectares (pasture - 49,000, hay - 8,000 and silage - 15,000 hectares). Tillage is carried out on 14,000 hectares of acid brown earths and gleys and the remaining 18,000 hectares is given to rough grazing (primarily peaty podzols). Livestock rearing is important within the catchment which produces large quantities of waste therefore the number of animals is of importance. Dairy cows and cattle (126,900) dominate the lowland grasslands, while sheep (550,100) populate the higher altitudes (Fig. 13). The animals use a considerable proportion of the land surface during their life cycles. The average dairy farmer uses approx. 150-180 units nitrogen per acre on the grazing area, while the average dry stock farmer uses about 100 units of nitrogen per acre (Aylmer, 1994).

Land use in the catchment area appears to be dictated to a large extent by the topography, altitude and soil type. Boulders, mostly rounded granite
boulders are a feature of many areas to the east and west of the central massif. They are a particular hazard in some areas and make reclamation of land both difficult and expensive. Much boulder clearing has been carried out, particularly in earlier times, which can be seen from the massive stone walls which occur in many areas. The preponderance of low base status brown podzolics and peaty podzols supporting rough grazing or pasture is illustrated by the large number of livestock, particularly sheep, and the low acreage given to tillage.

Forestry

Ireland is reputed for having the greatest growth rate for trees in Europe, and is the only country which has a disease free status. East Leinster, particularly County Wicklow, is regarded as the cradle of Irish plantation forestry. It is exceptional among the eastern counties in having a large forested area, 26,131 ha (C.S.O., 1991). The forestry industry in the Avoca catchment has been established for over fifty years. The majority of the forestry which is grown mainly for commercial purposes is owned by a state forestry company, Coillte. Figure 18 illustrates the planted and unplanted Coillte properties. The largest forest blocks are on the lower and middle slopes of the main Wicklow mountain range and include the forests of Glendalough, Glenmalure and Greenane. They contain large blocks of thriving conifer forest on land that sixty years ago was largely waste. The areas to be clear felled within the twenty-five year management plan, i.e. pre 2010, are based on the year of plantation and the appropriate growth cycle length. Norway Spruce and Scots Pine, which have a forty-five year growth cycle, were the chief species in the catchment pre-1965. Sitka Spruce and Lodgepole Pine, with a shorter growth cycle of thirty-five years, dominated the plantation post-1965. Sitka Spruce has been progressively favoured by virtue of its performance and is presently the most dominant species in the catchment. In County Wicklow there are 2,420 small forestry holdings of less than 50 acres. Coniferous trees reach the banks of all the main tributaries at various locations and enclose many of the minor rivers (Fig. 14).

Deciduous stands of oak (Quercus sp.) occur midst the coniferous woodlands in the lower-lying surrounds of Woodenbridge. These forests have a characteristic ground flora of woodrush (Luzula sylvatica), while deeper soils support a variety of interesting species. A small percentage of broad-leaved
Fig. 13. Agriculture in the Avoca-Avonmore catchment.
Fig. 14. Forestry in the Avoca-Avonmore catchment.
woodland is maintained for amenity purposes, providing a number of picnic areas and signposted trails. The mixed woodland which extends along the Vale of Avoca from Rathdrum to Arklow is designated an area of outstanding natural beauty and is registered as an area of Scientific Interest by the Office of Public Works, with botanical and ornithological interests of regional importance.

The conversion of arable land or formerly unmanaged land (e.g., heathland) into forests can acidify the soil (Harriman et al., 1994). The impact of afforestation on surface water acidification has only been highlighted in the past fifteen years (Harriman and Morrison, 1982; Stoner et al., 1984). In the early papers the major point of debate was the extent to which natural and anthropogenic factors determined the acidification of surface waters. In managed catchments the effects of ploughing are visually manifest as surface soil disturbance and sediment release into streams. This may have a potentially damaging short-term effect on stream biota but is not considered to be an acidifying process (Harriman et al., 1994). Major concerns associated with the ploughing phase are linked to peak flow increases, while the felling phase may cause increases in summer flows and associated changes in acid-base chemistry. Run-off will probably reach a minimum level as trees reach maturity. At this stage, the concentration effect will be greatest, as will the potential for acidification via ion exchange processes in the soil. Although all states of forest planting, growth, and felling are likely to change hydrologic flow paths, intensity of peak flows, and total water yield, the impacts of these effects on surface water acidification are likely to be small (Harriman et al., 1994).

Industry

Chemical Industry

Irish Fertiliser Industries Ltd. dominates the fertiliser industry in Ireland, and is located on a forty hectare site, on the eastern bank of the Avoca river, 2 km north (upstream) of the town of Arklow. The company which has been in operation since 1965, manufactures 550,000 tonnes per annum of calcium ammonium nitrate (CAN), from ammonia, nitric acid and limestone. These raw materials are obtained from an ammonia-urea plant in Co. Cork, manufactured on site and derived from local sources, respectively. The entire
process of manufacturing CAN involves a complex series of chemical reactions, with waste products rich in nitrogenous compounds being produced, at various stages along the production line.

The production of calcium ammonium nitrate begins with the manufacture of nitric acid. In a converter, ammonia is reacted with air over a platinum-rhodium alloy gauze catalyst, at temperatures between 800-900°C. With the reduction of temperatures to 20-30°C, and the addition of more air, the ammonium is converted to nitrogen oxides at 95% yield. The nitrogen oxides are absorbed in dilute nitric acid or water to yield 55-60% nitric acid, for use in the manufacture of ammonium nitrate. By reacting the nitric acid with more ammonia in neutralisation reactors, 9% ammonium nitrate is produced. This ammonium nitrate is then mixed with either calcitic or dolomitic limestone to make granulated or prilled fertilisers respectively. Both fertilisers contain 27.5% nitrogen.

Contaminated waters arise from the process effluents, cooling waters, the boiler blow-down system and also surface run-off. The latter accumulates a variety of materials originating from spills, leakages, lorry cleaning and also fallout from the stacks. The cooling waters may also be contaminated by leaks and/or absorption of air borne nitrogen compounds. Chlorine and organic biocides are occasionally added to the cooling water system to prevent algal growth, as are zinc phosphonate and chromates, to inhibit corrosion. These may escape from the cooling water cycle and be discharged to the river. The process effluents contain most of the pollutants from the liquid spills, washing liquors or condensate liquids from the various processes. All the waste waters are channelled into various conduits throughout the plant, and converge in a retention lagoon for subsequent discharge into the lower Avoca river. A canal also exists to carry effluent from the factory to Arklow estuary.

Pharmaceutical Industry.

There are two major pharmaceutical companies located in the catchment. Avondale Chemical Company, a US subsidiary of Schering Plough Inc., and Iropharm, a German owned company.

The Avondale company has a large, and generally effective waste water treatment plant, discharging into the Avonmore river. Final effluent quality
is generally satisfactory, with little or no reduction in river quality downstream of the plant. Odours from the process buildings and from the treatment plant have given rise to localized air pollution.

Iropharm is situated downstream of the fertiliser plant and discharges a largely organic waste water. The factory is presently developing treatment processes for its waste, with their wastewater currently being discharged into the river with minimum treatment.

Horticulture

The development of the horticulture industry in Ireland is co-ordinated by An Bord Glas. Despite the competition from well established European producers, there are a number of small to medium sized enterprises in the catchment producing fresh vegetables, mushrooms, and a tree stock nursery. Most of the produce is sold on the local domestic market. Mushroom producers supply a large co-operative based in Wexford, that exports the produce. Some growers also successfully export winter cauliflower and other vegetables for the U.K. market.

Aquaculture

The aquaculture industry in Ireland has received significant financial support from both the Irish and European governments. Initial pilot projects are supported by grants of up to 50%. A further 50% supports the development of the commercial phase. There are presently thirteen trout farms in the country, two of which are located in the catchment: one at Ballinaclash on the Avonbeg river and one lower down in the system, on the Aughrim. The former farm is a small trout smolts unit, situated downstream of the town of Ballinaclash. It uses the water from the Avonbeg river, which it returns to the system after passing through the farm. The other fish farm is located at four different sites along the Aughrim River. IDAS, was established in 1952 and has grown over the years to become the largest producer of freshwater rainbow trout in the country. It has total control over its production, from hatching to packaging of the final product. IDAS not only supplies the domestic market, but is the first Irish trout farm to export to the European and US markets. It produces mainly smoked filleted trout.
Food Processing

There are two food processing companies in the catchment, both of which are involved in the poultry processing sector. The raw materials for these companies are indigenous. The bulk of production is for the domestic market.

Climate

The Avoca catchment has a maritime climate. Rainfall varies widely across the catchment. Precipitation increases in a westerly direction with increasing elevation. Mean annual rainfall in the more elevated part of the catchment (Glenmacnass at 238 m 0 117 023) is over twice that measured on lower ground further east (Arklow at 34 m T 129 798). Rainfall monitoring data shows highest precipitation during September to March, and lowest from May to July. The year 1993 was exceptional having an unusually high annual rainfall overall. Monthly variation can be quite dramatic. For example in May 1991 Arklow recorded a mean monthly rainfall of only 0.2 mm rising to 90.0 mm the following month. Rainfall data collected at a number of stations within the catchment by the Irish Meteorological Service are summarized in Table 2.
Table 2 Rainfall data for four stations within the catchment (in mm) (source Meteorological Office, Dublin).

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<th>Year</th>
<th>Month</th>
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1951-1980 Annual average: 1705.0 1378.0 1189.0 992.0
REFERENCES


An Foras Taluntais (1979) Upland soils of Wicklow have good potential. Farm and Food Research, April edition.


