AVOCA DISTRICT

Background information

Mine Name: Avoca

Mine District: Avoca

Alternative Names:

Elements of Interest:
Pb, As, Sb, Cu, Zn, Cd, Cr, Ni

Project Prefix: AVO-

County:	**Townland:**	**Grid Reference:**
Wicklow	Various	E319800, N182000

Site Description and Environmental Setting

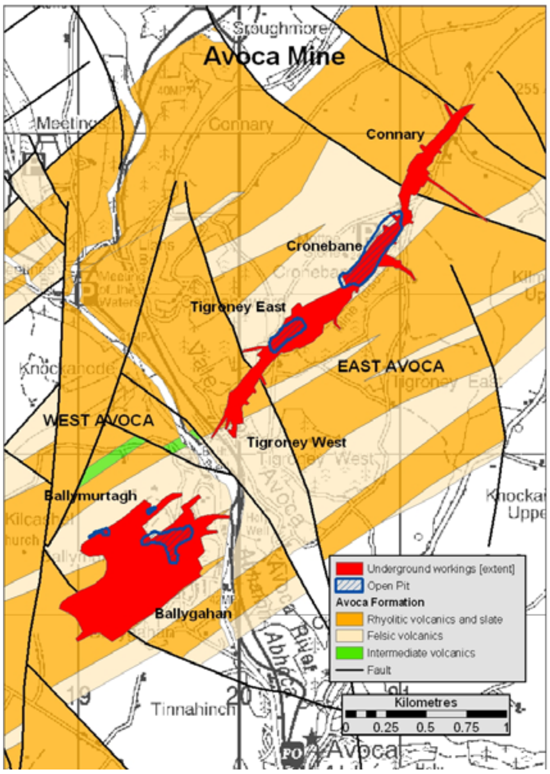
Copper mining began in Avoca around 1720 and continued episodically for the next 260 years. The selective hand-tool mining of high-grade seams of the 18th and 19th Centuries gave way to mechanized mining of relatively low-grade ore in the second half of the 20th Century. Prevailing low copper prices meant that the mine, in its later years, was always a marginal proposition and it eventually went into receivership in 1982. Historically the mine was subdivided into a series of small properties, or *setts*, but in modern times has generally been seen as comprising two distinct areas, East and West Avoca. In addition, tailings were pumped to a site at Shelton Abbey, 8km downstream of the mine. For the purpose of this project, the mine is subdivided into seven sites: **Connary**, **Cronebane**, **Tigroney East** and **Tigroney West** in East Avoca, **Ballygahan** and **Ballymurtagh** in West Avoca and **Shelton Abbey**. The national grid co-ordinates given above refer to a point between the East and West Avoca sites.

The mine underlies the ground that rises to the east and west of the Avoca River. Throughout the mine's history, mine water was drained directly to the river. The mine water at Avoca is both acidic and metal rich, i.e. it is acid mine drainage (AMD), and in consequence the river has suffered severe contamination over the course of 250 years of mining.

The site today is surrounded by farmland, mainly used as pasture for cattle and sheep. There is a relatively high density of houses, chiefly detached single houses, in the area, and some are in very close proximity to the mine site. The former open pit in the Ballygahan site in West Avoca was used as a municipal dump after closure of the mine – this has now been closed and the site has been remediated. The mine site contains large volumes of solid waste in the form of two tailings ponds and numerous unvegetated spoil heaps, as well as several old mine buildings, shafts and open pits – most of these features are readily accessible to the public.

Geology and Mineralization

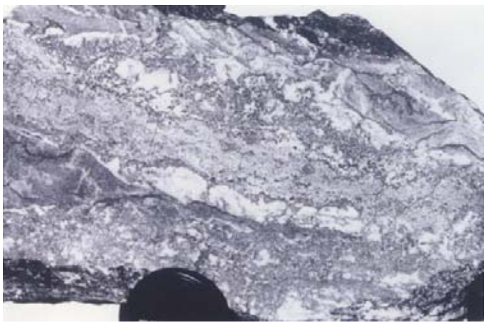
The Avoca deposit is hosted by the Avoca Formation, a northeast-southwest-trending sequence of 455 million-year-old Ordovician volcanic and sedimentary rocks (right). The formation is 2-4 km thick and dips steeply to the southeast. The rocks are cut by the steep bedding-parallel regional cleavage. A series of north-south faults offset the mineralized zones and they have been interpreted as possible feeder zones for mineralizing fluids (McArdle 1993). The mineralization is found mainly within distinctive chloritic tuffs, interpreted as having formed by alteration of rhyolitic and intermediate tuffs on the seafloor during the hydrothermal activity that gave rise to the mineralization (McArdle 1993). Shearing is a distinctive element of the mineralization and is interpreted as having played an important role in the formation of vein-disseminated mineralization.



Three main ore types have been recognized on a macroscopic scale in the Avoca mine area:

1. In the pyritic zones or **banded sulphide ore** (Williams 1984) or **massive ore** (Platt 1973) bands of pyritic ore alternate with bands of sphalerite-rich ore and bands of chlorite and sericite (photo, right). Pyrite (FeS_2) is the dominant mineral; other minerals include chalcopyrite ($CuFeS_2$), sphalerite (ZnS) and galena (PbS). Magnetite, hematite, arsenopyrite (FeAsS), pyrrhotite (FeS), bismuthinite (Bi_2S_3) and native bismuth are minor, gold rare. Such ore is typified by the Pond Lode and North Lode in West Avoca and the Main Lode in East Avoca.

2. In the siliceous zones or **vein and disseminated ore** (Williams 1984) or **stringer ore** (Platt 1973) major pyrite, chalcopyrite, sphalerite and lesser galena occur within a siliceous matrix (photo, right). Arsenopyrite, pyrrhotite, bismuthinite, native bismuth, tetrahedrite ($(CuAgFe)_{12}Sb_4S_{13}$) and bournonite ($CuPbSbS_3$) are minor. The South Lode, south branch of the North Lode and hangingwall in West Avoca and the hangingwall in East Avoca are examples.



3. The **lead-zinc ore** contains banded sphalerite, galena and pyrite with minor arsenopyrite and chalcopyrite in a chlorite matrix. The Lead-Zinc lode at West Avoca and the "kilmacooite" zones at Cronebane and Connary are representative (Wheatley 1971).

4. The **supergene** mineralization includes breakdown products of pyrite, chalcopyrite, sphalerite and galena, such as hydrated iron oxides and covellite (CuS) (Wheatley 1971). Subsurface oxidation extends to a depth of about 60 m below the surface at West Avoca (Wheatley 1971). In East Avoca, the top 30m of Cronebane Open pit was a supergene deposit composed of chalcocite (Cu_2S), covellite and chalcopyrite. It was formed by the weathering of chalcopyrite-pyrite-sphalerite-galena mineralization.

Mining History and Production

Copper mining began in Avoca about 1720 (Griffith 1828) and there were mines at both Ballymurtagh and Cronebane, the latter employing 500 people, at a rate of 8d per day, mining copper and native silver that was found disseminated in the iron ochre gossans overlying the copper ore (Henry 1752). Copper was also extracted from the mine water by precipitation and cementation. The acidity of this water was recognized at an early date (Henry 1752) and not long after commencement of mining and discharge of large volumes of water into the Avoca river, the rich salmon fisheries of the river had been destroyed (Bayly 1816).

There were three major eras of mining in Avoca (Gallagher and O'Connor 1997). In the first, between 1720 and 1816, mining was carried on by private companies in both East and West Avoca. Little is known about the earliest copper mining, but generally the mines in East Avoca (Cronebane-Tigroney) were better managed, especially between 1787 and 1816 when an English company, the Associated Irish Mine Company (AIMC) held the lease. In this period, AIMC produced some 27,000 tonnes of copper ore grading 6.45% Cu.

The second era began around 1826 and lasted until the 1880s. West Avoca mine (Ballymurtagh) was developed and mined efficiently by the Wicklow Copper Mining Company, an Irish public company. Throughout this period, the mines on the eastern side of the river, which now included Connary, remained in private hands. Between 1826 and 1839, the produce was mainly copper ore but in 1839, when supplies of sulphur to the British market were interrupted, the Avoca mines switched to production of pyrites. Most mines continued to produce both copper and pyrites over the next 25 years until 1865 when the opening of the Rio Tinto mines in Spain provided the British market with cheaper sulphur supplies. Thereafter, production declined and by 1888 the mines were derelict, although most had been all but abandoned long before then. Between 1822 and 1888, up to 200,000 tons of copper ore and 2,400,000 million tons of pyrites were mined in Avoca.

The third major period of mining at Avoca was preceded during 1947-1955 by a State-sponsored assessment of the potential for mining which outlined some 14 M tonnes of copper ore grading 1.12% Cu in West Avoca. Instead of selective mining of high-grade seams of copper ore, the modern approach was to be bulk mining of low-grade ore. Between 1958 and 1962, Saint Patrick's Copper Mines Ltd., a Canadian company, extracted some 2,850,000 tonnes of ore grading 0.74% Cu by underground mining in West Avoca and limited underground mining in East Avoca. The operation ceased in 1962, having been under funded from the outset. Avoca Mines Ltd. (AML) recommenced development and mining in West Avoca in 1969 and produced almost 8,900,000 tonnes of copper ore (0.73% Cu) before abandoning the mine in 1982. This operation too was under funded and dependent for profitability of buoyant copper prices that only rarely prevailed. AML operated mainly underground at West Avoca but it was also responsible for excavating the open pit in West Avoca and for the open pit developments on the East Avoca site at Cronebane and Tigroney East.

Total copper production for the period 1720 to 1982 is estimated to be 13.8 Mt @ 0.73% Cu. Estimated current reserves in West Avoca are 4.7 Mt at 0.68% Cu and in East Avoca 14.4 Mt at 0.60% Cu, giving a total of 19.4 Mt at 0.62% Cu.

Geochemistry

The geochemistry of mine waste at Avoca is described separately for each site. However, both stream sediment and surface water chemistry have been assessed in the context of the mine as a whole. Stream sediments, in particular, cannot be linked to any one specific site within the Avoca mine area.

1. Surface Water

Surface water analyses are described in detail for each site in the relevant site report. Some water sampling sites on the Avoca River are not within any particular mine site and hence a brief overview of the variation in the district is provided here. In addition, there is a comparison of the impact on the Avoca River of mine drainage from the East and West Avoca sites.

Fig. 1 shows the variation of Cu and Zn, respectively, in surface water samples taken in the Avoca District in summer 2007. Summer is chosen for illustration purposes because lower flow rates in the rivers give rise to a more pronounced and more persistent downstream impact on water chemistry from mine water discharges. High metal concentrations are apparent at adit discharges on the mine site and can be observed in the river adjacent to the mine. A gradual decline in metal concentrations is apparent with increasing distance from the mine site (Fig. 1). However, this is complicated somewhat by elevated Cu concentrations on the Avonmore River and Vale View stream, upstream of East and West Avoca sites (Fig. 1). The Vale View stream is known to be contaminated by mine water (CDM 2008) but the Avonmore River should not be.

Table 1 summarizes the data for river water samples collected in the district in June 2007. These include samples on the Sulphur Brook and Avonmore River. The maximum values are for those samples collected in the mixing zone where both the Deep Adit and Road Adit discharge into the Avoca River. It is clear from Table 1 and Fig. 1 that significantly elevated metal concentrations persist in the Avoca River at least as far south as Avoca village, the southernmost sample site on Fig. 1. In summer 2007, the measured Zn concentration at this site was 457 µg/l and its hardness 77 mg/l – for such a sample the Draft EC Guideline value for surface water is 50 µg/l Zn (EC 2007). Zn is particularly soluble in water and tends to be more widely dispersed than other metals around mine sites. In consequence, concentrations of other elements of interest at Avoca tend to be much lower than those of Zn. In particular, As is generally below the detection limit in most water samples analysed for the HMS-IRC project, including adit discharges, despite the reducing conditions (low pH) and high concentrations of As in solid mine waste. Nevertheless, it is clear that the mine sites have a significant impact on water quality in the Avoca River.

Table 1 Summary statistics for river water, Avoca, June 2007

	pH	Acidity mS/cm	Cu (tot) µg/l	Pb (tot) µg/l	Zn (tot) µg/l	Cd (tot) µg/l	Cr (tot) µg/l
n	12	12	12	12	12	12	12
Minimum	3.7	4	36	3	121	<1	3
Maximum	7.0	115	323	237	8306	22	12
Median	6.3	7	93	10	402	1	5
Mean	6.1	17.5	114	30	1072	2.8	5.2

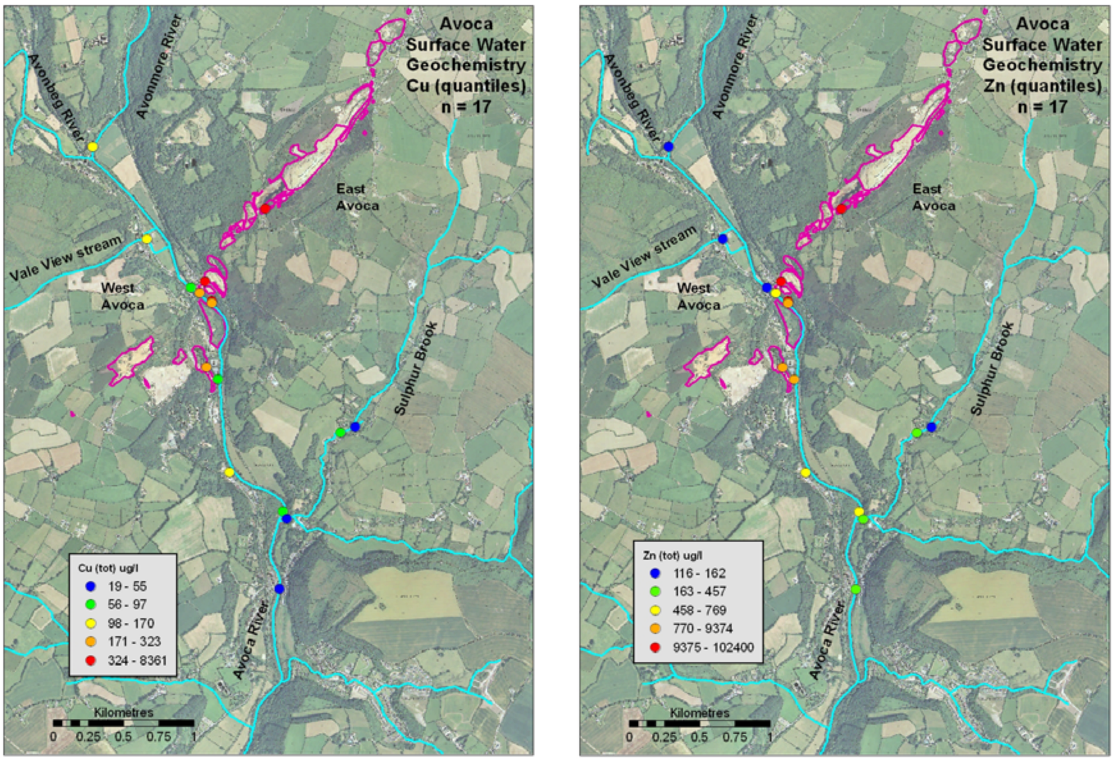


Fig. 1 Distribution of Cu and Zn in surface water samples, Avoca, June 2007

The effect of low pH and/or acidity on the river system has not been assessed directly in studies at Avoca. In general, the impact of either of these parameters is not readily separated from the overall impact of acid mine drainage (Gray and Sullivan 1995). Acidity and pH of river water downstream of the two mine discharges at Avoca are generally within acceptable limits, with medians of 7 mg/l and 6.3, respectively (Table 1). Only in the mixing zone at the point of discharge of the mine water is pH low and acidity high. In the mixing zone, metals co-precipitate with Fe-Al oxy-hydroxides and their concentrations decrease sharply relative to the concentration in the discharges. Only Zn remains predominantly in solution after mixing has occurred (CDM 2008). These hydroxides, in the form of colloids, fine suspended precipitates or amorphous flocs, can have severe direct or indirect effects on biota in the river (Gray and Sullivan 1995).

Gray (1995) calculated the mean annual metal discharge rates to the Avoca River from the two main mine drainages, the Deep Adit in East Avoca and the Road Adit in West Avoca. His data are based on monthly analyses of the discharges and flow rate measurements. The data collected for the HMS-IRC project are necessarily more limited but are presented in Table 2 together with Gray's mean values for comparison.

Table 2: Metal discharge rates, Deep and Road Adits: seasonal variation

	Pb kg/day	Zn kg/day	Cu kg/day	Fe kg/day	Ni kg/day	Cd kg/day
Deep Adit, East Avoca)						
February 2007 (24.1 l/s)	3.1	79.0	2.9	40.3	0.1	0.3
June 2007 (13.7 l/s)	1.5	46.3	1.4	23.9	0.05	0.1
Gray (1995), mean		117	8.1	151		0.35
Road Adit, West Avoca						
February 2007 (26.3 l/s)	0.75	21.4	0.74	232.4	0.15	0.02
June 2007 (13.4 l/s)	0.32	10.8	0.27	111.4	0.07	0.01
Gray (1995), mean		53	2.7	285		0.08

What is immediately striking is that there are very significant differences between the compositions of the discharges east and west of the river. The Deep Adit in East Avoca is responsible for the bulk of the Cu, Pb and Zn that is discharged into the river, whereas the Road Adit in West Avoca contributes most of the Fe. Both adits contribute similar and much smaller quantities of Ni and Cr. The HMS-IRC data and Gray's data are broadly comparable in the sense that they show similar variation between elements. However, absolute quantities measured by Gray were much higher. For example, in January 1995 the metal discharge rates from the Deep Adit for a flow of 21.8 l/s were 175 kg/day Fe, 130 kg/day Zn and 8.6 kg/day Cu (Gray 1995). Whether these differences in absolute concentration of metals reflect differences in analytical conditions or a real reduction in metal discharge rates in the 12 years since Gray's work is not known.

2. Groundwater

The bedrock at Avoca mine is a generally unproductive or minor aquifer in which fractured acid volcanic rocks are the most permeable lithologies (O'Suilleabháin 1996). The surrounding Lower Palaeozoic succession is generally considered an aquitard.

Two field wells were sampled for the HMS-IRC project but neither had concentrations of metals in excess of drinking water standards. Leachate tests were carried out on composite samples for waste piles on most sites (see individual site reports) in an attempt to model potential groundwater concentration below waste heaps. The leachate generally contained high concentrations of metals including Cu, Zn, Pb and Ni, indicating that the solid waste has the potential to cause significant contamination of groundwater.

Analysis of private well water was carried out as part of the Avoca Feasibility Study (CDM 2008). For the 8 wells sampled, most elements of interest were close to or below detection limits and below the drinking water standards (EC 2007). Exceptions were Cu (range 27 – 150 µg/l, median 53 µg/l) and Zn (47 – 234 µg/l, median 108 µg/l) (CDM 2008). Wells drilled into spoil at Tigroney West and Ballygahan intersected the water table. The water contained very high concentrations of metals (see site reports, Ballygahan and Tigroney West).

In summary, leachate from solid waste at Avoca is metal-rich and has the potential to contaminate groundwater. Wells drilled into spoil intersected groundwater that had very high concentrations of metals. However, data from field wells and private wells suggest only limited contamination of water by Cu and Zn.

3. Stream Sediments

Stream sediment samples (<150 µm) were taken at 11 sites upstream and downstream of the mine site. In addition, two samples from GSI's Southeast Ireland Regional Geochemistry programme, in streams downstream of the mine site, are included in the data (Table 3, Fig. 2).

Table 3 Stream sediment samples around Avoca mine site

SAMPLE	Map Number	Easting	Northing	Location
AVO-07-SS001	1	318931	183004	Avonbeg River, upstream of Meetings
AVO-07-SS002	2	319037	183023	Avonmore River, upstream of Meetings
AVO-07-SS003	3	319729	182095	Whitesbridge upstream
AVO-07-SS004	4	319831	182012	Whitesbridge downstream
AVO-07-SS005	5	319971	181881	Avoca River, 100 d/s Deep Adit discharge
AVO-07-SS010	10	320370	179968	Avoca River at Avoca Village
AVO-07-SS011	11	320817	181043	Sulphur Brook, 2.5 km d/s Cronebane
AVO-07-SS012	12	321492	182245	Sulphur Brook tributary u/s of mine
AVO-07-SS013	13	319738	177006	Avoca River, Woodenbridge
AVO-07-SS014	14	321585	175199	Avoca River, Shelton Abbey
AVO-07-SS015	15	322421	174799	Avoca River, 1km d/s Shelton Abbey
GSI-87-1221	16	320930	185180	Rockstown, 1 km d/s Connary
GSI-87-1280	17	321730	182090	Sulphur Brook, 1.2 km d/s Cronebane

In general, Cu, Pb and Zn are elevated in stream sediments downstream of Avoca mine (Table 4). Levels of Pb and Zn are generally elevated in the Avoca River and in the Avonmore and Avonbeg, the two rivers that merge upstream of the mine to form it, owing to contamination from the Pb-Zn mines in Glenmalure and Glendalough. Thus, samples AVO-07-SS001 and AVO-07-SS002 have, respectively, 594 and 640 mg/kg Pb and 433 and 755 mg/kg Zn. In contrast, Cu levels in these samples are much lower (34 and 60 mg/kg, respectively) and are typical of those in stream sediments overlying the Duncannon Group and Ribband Group rocks in the region. GSI's Regional Geochemical programme indicates median Cu values in the Duncannon and Ribband Group rocks that underlie the region to be around 30 mg/kg. Thus Cu is the most useful indicator at Avoca of impacts of the mine on stream sediment composition. Other elements of interest, As and Sb, do not show significant concentrations in stream sediments analysed.

Table 4 Data for stream sediments collected for HMS-IRC project

mg/kg	Pb	As	Sb	Cu	Zn
n	11	11	11	11	11
Minimum	134	33	0.0	34	151
Maximum	1814	101	75	2183	878
Median	411	52	0.0	257	573
Mean	519	54	7	405	508

As can be seen in Fig. 2, Cu is notably elevated in the Avoca River close to and downstream of Whitesbridge and in the Sulphur Brook. Levels of Cu in the Avoca River are above typical background levels in all samples analysed. The sample furthest downstream, at the old fertilizer factory (site 15, Fig. 2) has 177 mg/kg Cu. A man-made drainage ditch carried discharge from Madam Butler's adit at Cronebane (Fig. 2) to the Sulphur Brook until relatively recently and this stream has the highest metal concentrations analysed in stream sediments (2183 mg/kg Cu, 1814 mg/kg Pb at site 11). The small stream draining the Connary area to the north is also contaminated (site 16, Fig. 2). Only the small tributary that meets the Sulphur Brook upstream of the former adit discharge point does not appear to be affected by the mine (site 12, Fig. 2).

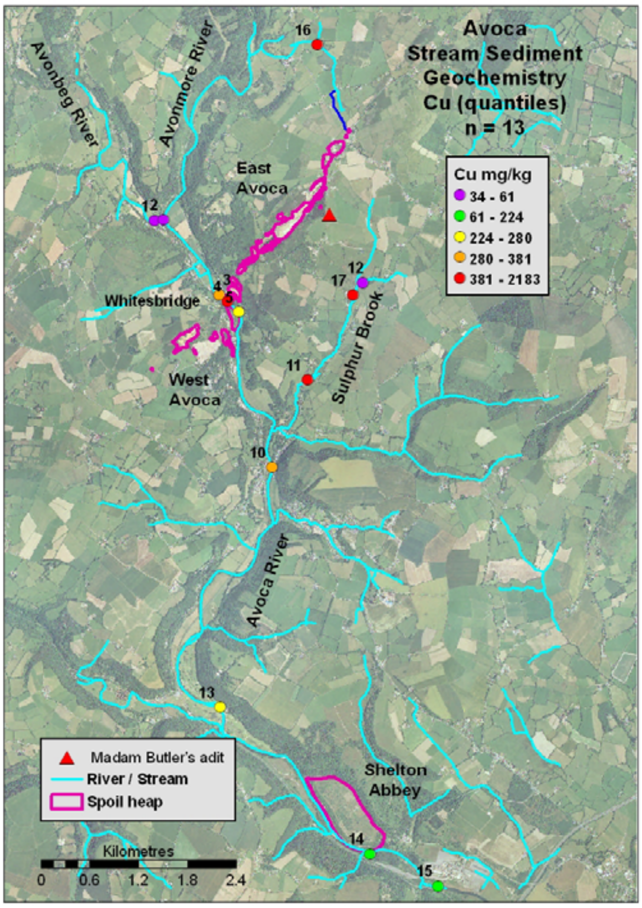


Fig. 2 Stream sediment geochemistry, Avoca

4. Solid Waste

Detailed accounts of the chemistry of solid waste at Avoca are contained in individual site reports. Tables X.5 (spoil) and X.6 (tailings) summarize the data for the main elements of interest in solid waste in the district as a whole. Most spoil heaps at Avoca were created in the 19th century. Inefficient extraction techniques left significant quantities of metals in the waste. The spoil at Avoca can contain in excess of 1% Pb, Cu or Zn. Concentrations of As are also high, although in some samples with high Pb concentration the measured As concentration is exaggerated owing to peak interference by Pb in XRF analysis. Though not major components of the ore, Pb and As are the main element of concern in solid waste. Pb, in particular, is present in relatively high concentrations in most spoil heaps. The median concentration for spoil in the district is 2846 mg/kg (Table 5) and it exceeds reference values such as the UK Soil Guideline Values (750 mg/kg for industrial land).

Concentrations of these elements in tailings are typically much lower, as expected since the tailings were produced by relatively efficient modern processing techniques in which most of the available metal was extracted.

Table 5 Summary statistics, *in-situ* XRF analyses of spoil, Avoca

mg/kg	Pb	As	Sb	Cu	Zn
n	230	230	230	230	230
Minimum	189	19	0.0	8	0.0
Maximum	200512	10316	1629	143580	12177
Median	2846	660	0.0	443	105
Mean	6760	834	78	841	274

Table 6 Summary statistics, *in-situ* XRF analyses of tailings, Avoca

mg/kg	Pb	As	Sb	Cu	Zn
n	111	111	111	111	111
Minimum	41	0.0	0.0	67	0.0
Maximum	537	208	0.0	1028	387
Median	175	57	0.0	197	87
Mean	199	59	0.0	234	103

Fig. 3 shows the spatial variation of Pb in spoil heaps in East and West Avoca. High concentrations of Pb in spoil are clustered around Connary and Tigroney West, with generally lower concentrations elsewhere. Such variations reflect differences in the composition of the original ore material and subsequent movement of material around the site. At Connary the ore contained kilmacooite, as Pb-rich ore whereas the clustering of high Pb concentrations at Tigroney West may reflect the use of this site in the 20th century as a stockpile for ore being transported to the mill in West Avoca.

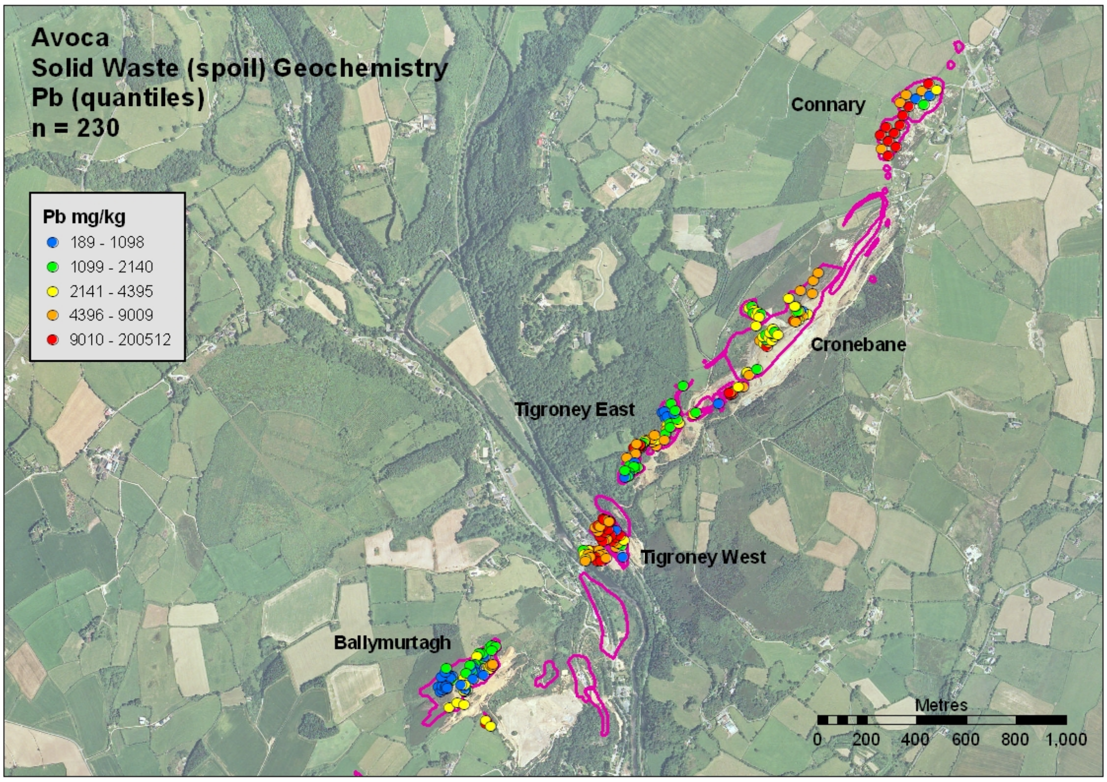


Fig. 3 Distribution of Pb in spoil heaps, *in-situ XRF* analyses, Avoca

5.. HMS-IRC Site Score

Table 7 Site Scores, Avoca District

Waste	Spoil	Discharges	Tailings	Stream Sediments	Totals
1. Hazard Score	**1921**	**2883**	**100**	**105**	**5009**
2. Pathway Score					
Groundwater	535.06	529.33	37.32		1102.61
Surface Water	277.18	818.94	18.09		1114.06
Air	18.29		0.29		18.59
Direct Contact	145.63		15.76		161.38
Direct Contact (livestock)				42.04	42.04
3. Site Score	**979**	**1348**	**71**	**42**	**2438**

The total HMS-IRC site score for the Avoca District is 2438 (Table 7). Fig. 4 shows the breakdown of this score according to waste source. The mine discharges, chiefly those of the Deep Adit in East Avoca and the Road Adit in West Avoca, account for 55% of the total score with spoil heaps making up another 40%. Despite constituting the bulk of the solid waste in the Avoca District (7.56 million m^3 or 86% of total solid waste volume) the tailings at Shelton Abbey and in the emergency tailings pond in West Avoca account for less than 3% of the total score. The discharges have a large combined volume and high metal concentrations and flow directly into local water courses so their high score is not surprising. Although spoil heaps at Avoca can have high metal concentrations, median values for the elements with highest relative toxicity (Pb, As, Ni) are not among the highest measured on Irish mine sites. The score for spoil reflects this.

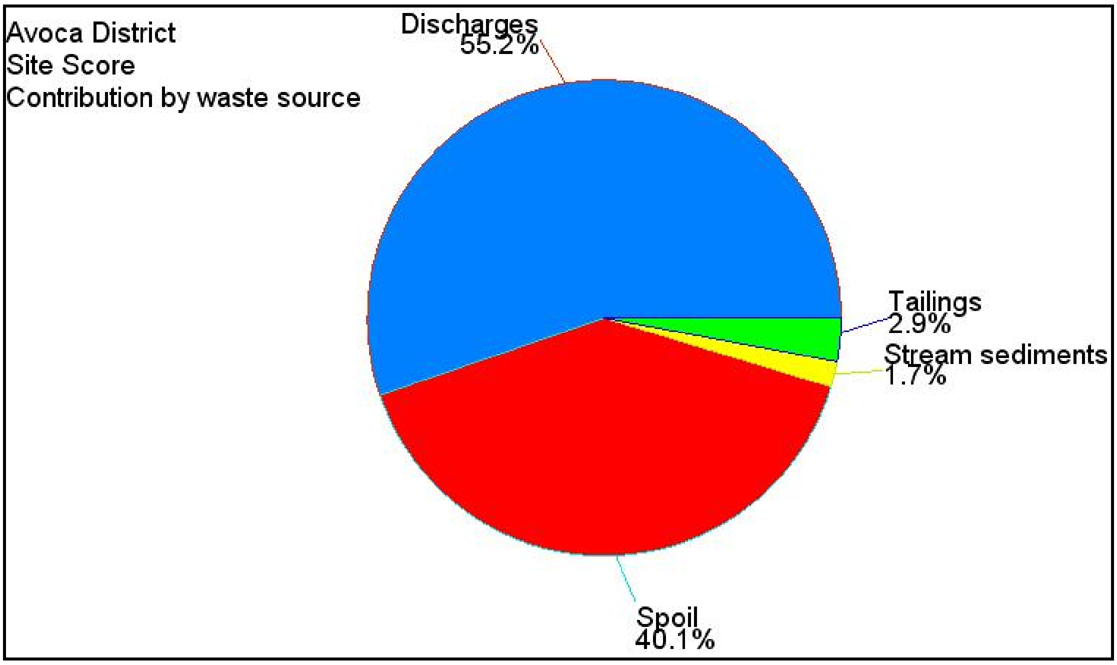


Fig. 4 Avoca District Site Score: contribution by waste source

Fig. 5 shows the breakdown of the Avoca District site score by pathway. Both surface water and groundwater pathways contribute around 45% with the direct contact pathway accounting for most of the remainder. The large volume and area of solid waste represents a significant potential risk to both surface water and groundwater at Avoca but, in the HMS-IRC scoring system, the groundwater pathway generally scores higher. In part, this reflects the fact that most solid waste heaps, certainly those with highest metal concentrations, are not close to surface water courses. In the case of the adit discharges, the two main ones are directly beside the Avoca River and the surface water pathway outweighs the groundwater pathway in their scores. Overall, the pathway scores for solid waste and water discharges balance out.

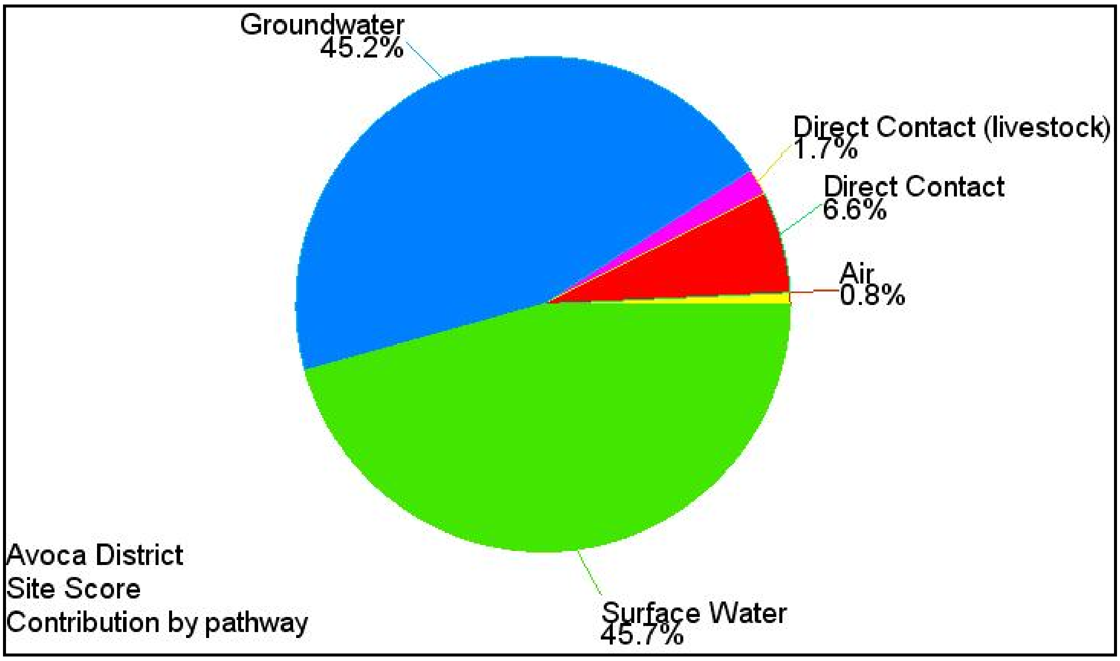


Fig. 5 Avoca District Site Score: contribution by pathway

6. Geochemical overview and conclusions

Avoca has a history of mining extending back over 250 years. A large volume of AMD continues to drain from underground mine workings, causing extensive ongoing pollution of the Avoca River. Groundwater in the immediate vicinity of the mine is also contaminated as a consequence of interaction with solid mine waste. Large volumes of this waste remain on the site and the waste has high concentrations of Pb, As, Cu and Zn, among other metals. Stream sediments downstream of the site have high concentrations of Cu, Pb and Zn and contamination is apparent up to 10km from the site.

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