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Technical Article

An Investigation of Environmental Contamination at the Silvermines Abandoned Mines Site in Ireland Based on the Preliminary Delimitation of Pollution Hot Spots

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Abstract. This paper describes a holistic methodology for the investigation of environmental contamination from abandoned mine sites (AMSs), and is based on a case study of the Silvermines AMS. Groundwater modelling, surface water temperature monitoring, and a geographical information system (GIS) were used to undertake a preliminary delimitation of areas where soil, fluvial sediments, and surface and groundwater were contaminated. Subsequent soil and water sampling and analysis confirmed the accuracy of these predictions. Significant contamination of environmental media in the vicinity of the AMS was largely the product of water-borne pollutants. The concentration of Pb was high in streams receiving direct discharge from the AMS, but decreased rapidly downstream. Concentrations in stream sediments showed the same pattern. Extremely high Pb concentrations were also observed in sediments downslope from the AMS where groundwater discharges into surface drainage. Soil Pb concentrations were highest on floodplains and in areas affected by surface runoff and seasonal groundwater seepage. The methodology described here allows effective and cost-efficient investigation of the environmental impact of AMSs, which in turn provides the basis for site rehabilitation.

Key words: abandoned mine site, contamination, lead, site investigation, GIS.

Introduction

Abandoned mine sites (AMSs) cause significant contamination of environmental media. Dust emission and mine drainage discharges distribute metal compounds from the AMS to its surroundings for many years, so that the affected area is usually much greater than the AMS (Ripley et al. 1996). The extent of the affected areas depends on local environmental conditions and how these relate to the mine location. The traditional approach to an investigation of environmental impacts of an AMS is based on soil or geochemical survey methodologies and hydrological or hydrogeological methods. Often they employ grid-sampling techniques with a sample frequency calibrated to the scale of investigation. Where the affected area is not clearly defined by destruction of vegetation or other types of ecosystem damage, the sampling programme may embrace either too large or too small an area.

We believed that such environmental impact assessment investigations of an AMS could be optimized and conducted within the framework of a preliminary site investigation; research was conducted at the Pb-Zn-Ba Silvermines AMS, County Tipperary, Ireland, from 1997 to 2000. The mine site is located on the northern slope of the Silvermines Mountain. A long history of mining activity there has left surface and underground mine workings, mine waste, and settling ponds (Fig. 1). The deepest ore deposits were mined by underground methods in the Mogul Mines (250-300 m below ground level (BGL)). The Magcobar open pit was worked out to a depth of 80 m, and has some associated underground workings. Surface and underground workings in the Shallee Mine reached 30m BGL (50 m above sea level (OD)), and in Ballygown, reached 40m BGL (90-110 m OD). Mine waste dumps were scattered along the slope between Silvermines stream and Shallee. Waste included spoil heaps, Shallee Pb mine tailing ponds and a number of settling ponds. In addition, the Mogul tailing pond is situated on the River (R.) Kilmastulla floodplain.

Surface mine features, including workings and waste, created interim sources of dust emission over a large area during the long mining history. Natural revegetation occurred after the cessation of mining. During the late XVII Century and XIX Century, smelters were operated in the Silvermines area, which created additional sources of air-borne contamination. Geological characteristics of the area, such as ore mineralogy, host rock composition, and faults, significantly influence the extent of the environmental impact of the mine site. The Silvermines Mountains (490 m OD) and Arra Mountains (560 m OD) further to the north form the southern and northern limbs of the Kilmastulla syncline structure. Erosion resistant rocks of the Pre-

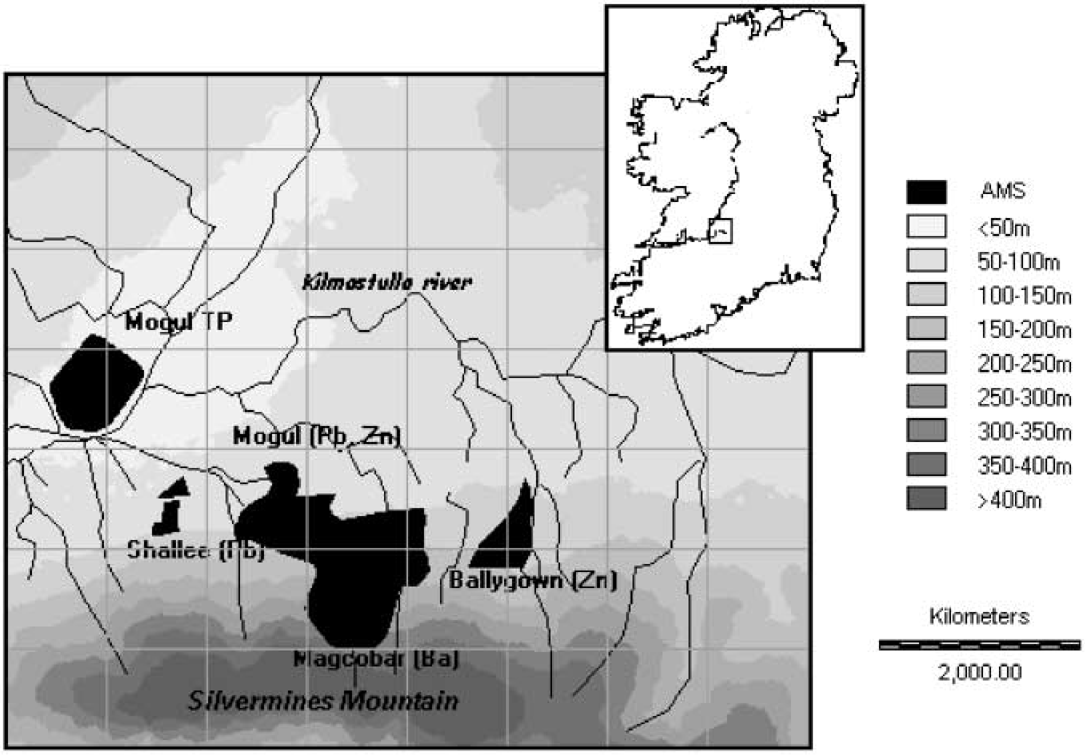

Figure 1. Location of the Silvermines abandoned mine site (AMS) in Ireland.

Carboniferous Formations (slates, sandstone) form the mountainous areas, while the syncline core contains Carboniferous Formations, mainly dolomite and often karstified limestone. The western part of the R. Kilmastulla valley is located within the syncline structure, forming a slightly rolling landscape. Further to the west, the river cuts through the Devonian Formations, generally following the trend of the Silvermines Fault. Local stream courses within the mined area also follow the WNW branch faults of the Silvermines Fault. Regarding buffering capacity, the strata in the Silvermines region may be grouped in two categories (Smith et al. 1994): those providing "infinite" buffering capacity (Carboniferous Formations) and those providing limited buffering capacity (Devonian and to a lesser extent Silurian Formations). It is to be expected that in the Shallee area, the buffering capacity of the environment is lower than further to the east in the mined area.

Local variations in total annual rainfall are primarily controlled by land surface elevation. According to the Irish Meteorological Service, the long-term average annual precipitation in the lowland areas in the Silvermines region is 848 mm/year (50 m OD), whereas rainfall in the mountains is 1633 mm/year (312 m OD). Rainfall also varies annually. Average rainfall for the R. Kilmastulla catchment was estimated as 1130mm/year. The other elements of the water balance in the vicinity of the Silvermines area are given in Table 1.

The main drainage system receiving mine drainage from the Silvermines AMS is the R. Kilmastulla (Fig. 2), which eventually joins the R. Shannon about 15km downstream. The river flow at the gauging station (100sq.km) varies within a considerable range, from over $15 m^3/sec$ to less than $0.2 m^3/sec$. The R. Kilmastulla baseflow rate is up to $0.5 m^3/sec$, with higher river flows indicating a component of direct rainfall runoff from the catchment area.

The northern slope of the Silvermines Mountains forms at least 25% of the R. Kilmastulla catchment area. The water regime in this area may be expected to be considerably affected by mining workings and mine waste. However since the process of mine flooding is completed, the water regime here is considered to be in a steady state. The Kilmastulla channel within the mining area was artificially deepened (by about 10m) and straightened. Some tributary steams, previously discharging into the river, were re-aligned, presumably to reduce peak

Table 1. Water balance in the Silvermines area

Water balance elements	Amount mm/year	Proportion of precipitation
Precipitation	1130	100%
Evapotranspiration	467	41%
Ground water recharge	150	13%
Surface runoff	513	45%

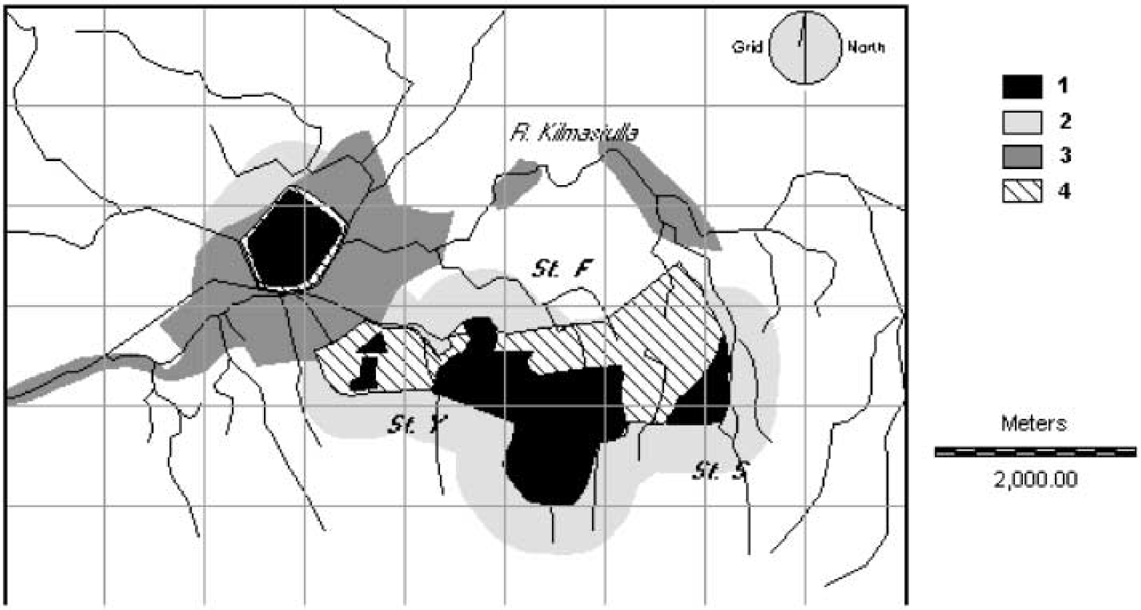

Figure 2. Various areas potentially affected by the Silvermines AMS: (1) the mine site; (2) the area potentially affected by dust emissions; (3) the area potentially affected by alluvium redistribution over floodplains; (4) the area potentially affected by surface runoff from the site. (St. S= Silvermines Stream; F=Foilborrig Stream; Y=Yellow River)

flood levels and erosion at the Mogul tailing pond dam, which is located on the river floodplain.

Mine drainage from the main mined area (apart from the Mogul tailing pond) discharges into the R. Kilmastulla tributaries: the Silvermines and Foilborrig Streams and Yellow River (see Fig. 2). The Silvermines Stream flows through Silvermines village, draining the Ballygown mine site. The catchment of the Foilborrig Stream includes the Magcobar mine site. The R. Yellow drains the western part of the slope, where there are old mines, the Mogul and Shallee mine sites and the Shallee tailing pond. Above the locations of mine drainage discharge, the catchments consist of non-carbonate rock formations, so the natural water in those streams have limited buffering capacity (pH<7.0).

There are a few floodplains areas, located along the R. Kilmastulla and the Silvermines and Foilborrig streams. The R. Kilmastulla is also the main drainage channel for ground water discharge from the mine area. Additionally groundwater discharge zones (including seepage zones) often coincide with fens, situated within floodplains and the mountain foot. A number of streams emerge at the base of mountain slope, reflecting the higher rate of groundwater discharge in this area. The groundwater table is located at a depth of 6-8 m in the lowlands in summer, and less than 1-3 m in winter, when it often intercepts the surface. In upland areas unaffected by mining, water-bearing strata occur within 20-40 m of the surface.

A number of farms and the village of Silvermines are located close to the AMS. Most of the landscape is grassland, with some forestry to the south of the Silvermines village, upslope of the mined area. Grassland is mainly used for grazing, and only a few fields are tilled. Cattle deaths by Pb poisoning have been repeatedly reported (O'Sullivan K 1999). Analysis of the aquatic ecosystem also revealed some evidence of water pollution. On the basis of fish assays (O'Sullivan M 1999), the river was moderately polluted. However studies of Zn-sensitive invertebrates did not suggest significant contamination.

The Silvermines AMS, one of the biggest and oldest in Ireland, is surrounded mainly by fields with complete vegetative cover throughout the year. It has a little visual impact and no evident effects on surface water, and if were not for the death of cattle, the impact of past mining would not be obvious. As is typical for Irish AMSs, the Silvermines site is located within carbonate rock, which is widely considered to act as a buffer against environmental contamination. For this reason, the environmental impact of past Irish mining had in the past generally been considered to be insignificant. However, during the last few years, the environmental concerns of the Silvermines community, triggered by a new landfill development plan and the farm animal deaths, brought national attention to the site.

Methodology

The site investigation was structured around a simplified model of an Environmental Pollution Event, which linked the main processes of pollutant generation, distribution and deposition in the environment. Specifically, it was based on:

(a) The main sources of pollutants are the mine workings and waste facilities, where metals are being mobilized and released into the environment.

(b) Pollutants generated within an AMS and captured by wind or water follow the general pathways of air or water movement and may be deposited along them.

(c) Metal compounds present in soil and natural water in concentrations exceeding trigger values or quality standards may represent an environmental risk.

The delimitation of contamination hot spots were determined by the location of contamination sources and by natural processes, which regulated pollutant transport from source to subsequent pollutant deposition. The primary goal of the investigation was to determine the boundaries of the pollutant sources, both spatially and vertically, and to develop a model of pollutant transport from sources to environmental media along various pathways.

Transport mechanisms include dust distribution by wind and outflow from an AMS by means of surface runoff and groundwater flow from the AMS. Mine drainage may also be discharged directly into surface water through mine adits. Based on Irish conditions, deposition of metal compounds transported along these pathways was expected within the following areas:

(a) down-wind of the AMS, limited to a maximum distance of 500m from the site (Aslibekian and Moles 2000, Gallagher and O'Connor 1997);

(b) the area receiving contaminated runoff from the AMS (Calvo and Perez 1994);

(c) contaminated groundwater discharge zones or zones of mine water discharge into surface waters, where redox conditions in the metal-bearing solutions change abruptly (deposition/precipitation of metal compounds is most intense in such areas); and

(d) floodplains downstream from the AMS, where deposition of contaminated sediments occurs (Hudson-Edwards 1997).

Initial spatial delimitation of these areas was based on the application of a Geographical Information System (GIS) (IDRISI) and groundwater modeling (GWVistas2). More detailed delimitation of groundwater discharge zones into streams and the R. Kilmastulla included the temperature measurement of surface water along watercourses. As groundwater temperature in most Irish aquifers is 10-11°C, a reduction in surface water temperature within various stream sections during summer surveys indicated zones of groundwater discharge.

Sampling, as a second stage of site investigation, included collection of soil (top 10cm), fluvial sediments, and water. Samples were tested for Cd, Pb, and Zn. Additional samples were also collected outside the main risk zones. Two different methods of metal extraction from samples were used to assess metal exchangeable and total concentrations. Exchangeable metals in soil were extracted by EDTA at pH=7.0. For the total metal concentration in soil and sediments, samples were digested using concentrated nitric acid (5ml conc. HNO_3, 0.500 (± 0.001) g, boiled until the liquid volume reduced to one half, filtered and diluted to 25ml). Metal concentrations in filtrates, and also filtered (Watmans No.2 filter) natural water samples, were measured by Atomic Absorption. Accuracy of the results were controlled by the use of reference materials, duplicate sample collection, and duplicate extraction. Some other available data (on R. Kilmastulla water quality from the Irish Environmental Protection Agency, and Environmental Impact Statements for various activities in the area) were also analyzed.

Results

Delineation of Contamination Hot Spots

The characteristics of the Silvermines AMS and the environmental conditions governing the distribution of metal compounds allowed potential contamination areas to be delimited.

1. The AMS forms a major and well-defined contamination hot spot, which includes mine workings and mine waste. It stretches for nearly 5 km along the Silvermines Mountain slope. Most of the underground workings are no deeper than 40-50 m, but exceptions include the Magcobar open pit and the Mogul mine. In addition to those areas, the Mogul tailing pond is located on the northern bank of the R. Kilmastulla, on the floodplain. This area comprises 2.7sq.km (Fig. 2).

Areas potentially affected by contaminated dust emission. In the humid Irish climate, contaminated dust is unlikely to be delivered beyond 500 m from an AMS even in the prevailing wind direction, and mostly affects a 100-200 m zone from the AMS. The area is 8.86sq.km. (Fig. 2).

2. Areas potentially affected by surface runoff from the AMS were delimited using a Digital Elevation Model (DEM) and slope analysis. Due to the fact that this hot spot spatially coincides with the territories potentially contaminated by dust emission and in which dust may be deposited beyond ditches and roads, the main factor used for hot spot delimitation was slope angle. This was based on an interpretation of the slope image of the GIS DEM. The affected area is 1.34sq.km (Fig. 2).

3. Areas potentially affected by contaminated groundwater. The sources of contamination are the mine waste and underground workings, most of which are located in the groundwater recharge zone. Underground workings deeper than 50 m were not considered to be contamination sources because of the limited throughflow that exists at such depths (Daly 1995). Since the mined area lies across the groundwater flow path for about 5 km, and the main discharge artery is located, on average, 1-2 km down-gradient from the sources, the groundwater contamination plume is significant. Spatial delimitation of the plume was based on modeling and GIS (Fig. 3). The calculated plume area comprises 10.8 sq km. Sequential impact of groundwater contamination was also possible in the following locations:

(a) areas with shallow groundwater table occurrence (<1 m) or seasonal groundwater seepage zone, where soil may become contaminated (8.5sq.km);

(b) the stream/river network, where potentially contaminated groundwater may discharge (15 km of stream/river channels);

(c) stream/river sections where groundwater discharge is more intensive, based on an August 1998 temperature survey. Stream sections where water temperature reduction occurred were targeted for sediment sampling.

Surface water may become contaminated within stream/river sections receiving mine water runoff and/or groundwater discharge. The river sections in which water contamination is expected were defined by the location of complete mixing between surface and mine water, and also by the location where dilution was sufficient to reduce metal concentrations to levels lower than standards for surface water (Aslibekian et al. 1999). Sediment and water sampling is not required for water downstream from these locations, providing that river water redox conditions do not change downstream from the mined area. In the Silvermines region, surface water contamination is not expected downstream from the hot spots areas shown on Fig. 2-3. Due to the fact that receiving water in the Silvermines area is generally alkaline throughout the year, river sediments are expected to be contaminated at the locations of the discharge and downstream from it. Contaminated alluvium distribution over floodplains during flood events may result in soil contamination along riverbanks downstream from mine sites. The area of floodplain downstream from the Silvermines AMS is 3.5 sq. km (Fig. 3).

Sampling Programme

Sampling was based on the preliminary delimitation of potential contamination hot spots. It included soil,

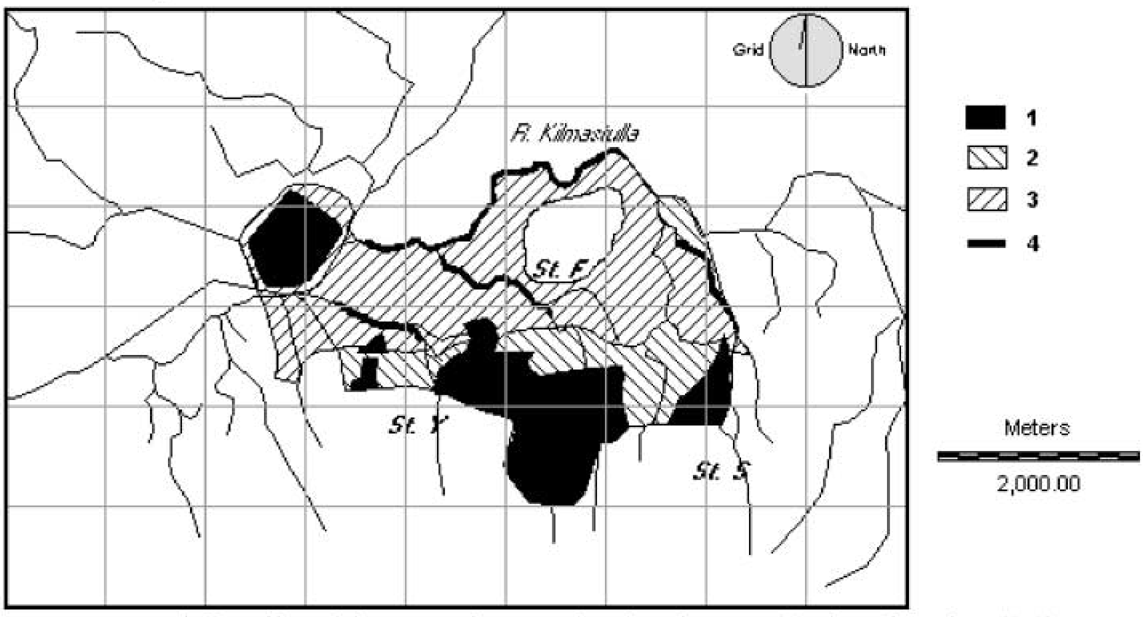

Figure 3. Areas potentially affected by groundwater-related pathways: (1) the mine site; (2-3) occurrence of contaminated groundwater plume; (4) stream sections where reduced surface water temperature indicated groundwater discharge. All streams within the shaded areas may receive contaminated groundwater discharges.

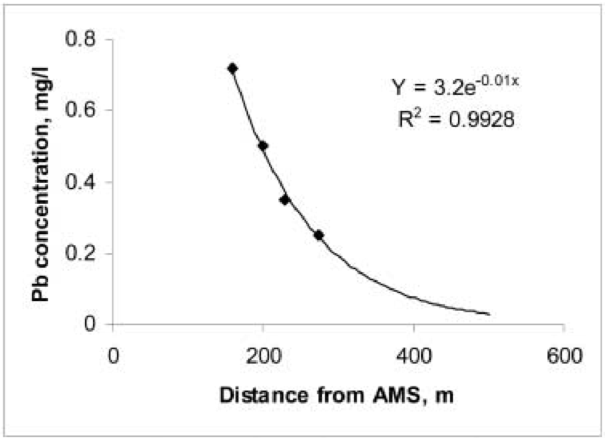

Figure 4. Changes in Pb concentrations in the Silvermines stream downstream of the AMS.

sediment, and water sampling. Pb, Cd and Zn were considered to be the major pollutants. However, only Pb contamination is described in this paper, as Pb was found to be the most hazardous pollutant due to its high toxicity and concentration in various environmental media. Water discharging from the Silvermines AMS contained high Pb concentration at some locations (Table 2). In surface water, the concentration of Pb is greater in the winter season, when surface runoff is more intensive and water pH is lower (Aslibekian et al. 2000). However, never during the period of monitoring (1994-1997) did the R. Kilmastulla exceed the maximum acceptable concentration of 0.05 mg/l. Only water in streams crossing the AMS contained high Pb concentrations (Table 3), which decreased rapidly downstream of the mine site (Fig.4). Due to the high rate of stream flow along mountain slopes, this is most likely related to Pb precipitation rather than adsorbtion.

As a result of metal precipitation from surface water, metal compounds significantly contaminated fluvial sediments. The highest Pb concentration was found in areas where (a) streams cross the AMS and immediately downstream from the mine site; and (b) where groundwater discharge into streams was most intense, as indicated by the stream water temperature survey (Fig. 5, Table 4).

Sequential redistribution of contaminated alluvium over floodplains created the most significant hot spot of soil contamination outside the AMS. The highest total Pb concentration occurred in soil on floodplains and the AMS, where Pb concentrations were in the same range (Table 5). The lowest level of Pb contamination was associated with areas affected by surface runoff. Soils were not contaminated in the area delimited as potentially contaminated by dust emission. Exchangeable Pb content, and consequentially its biological activity, was higher in more acidic soil and where Pb compounds were delivered to soil by groundwater. Pb concentration in soil outside the delimited hot spot areas was well below the trigger values in all 32 sampling locations (Table 5).

Conclusions

1. The pathway approach allows an AMS investigation to be optimized through preliminary delimitation of potentially contaminated spots and a subsequent targeted sampling programme. This was successfully illustrated in the Silvermines AMS case study.

2. This study confirmed that water-related pathways are the main means of pollution transport from AMS in the humid climatic conditions of Ireland. Contamination of natural waters, soil and fluvial sediments may be most likely found in the areas affected by surface runoff from a mine site, groundwater discharge zones, and within floodplains downstream from an AMS.

3. Intensive soil and fluvial sediment contamination in the Silvermines area suggested that environmental conditions with high buffering capacity, such as where carbonate-rich formations occur, do not prevent contamination of these media from AMSs. Due to the high precipitation rate of metal compounds in such environments, alluvium contamination and contamination of soil on floodplains are significant.

4. The methodology for AMS investigation may also provide the basis for future site rehabilitation programmes, which should focus on contamination hot spots and include measures to prevent secondary contamination along water-related pathways.

Table 2. Metal concentrations in mine drainage

Location	Date	EC, µS/sm	pH	Pb, mg/l
Magcobar				
Seepage from spoil heaps	04.98	2150	3.0	0.214
Mogul				
Settling pond 1	07.1996	160	8.4	0.073
Tailing pond	07.99	18000	1.8	2.28
200m downstream from outflow from settling pond 2				
Maximum	1994-1997			0.079
Average for dry seasons	1994-1997	848	8.2	0.017
Average for wet seasons	1994-1997	959	7.8	0.023
Flooded South Ballygown shaft (south of Silvermines)	07.1996	530	7.6	0.019

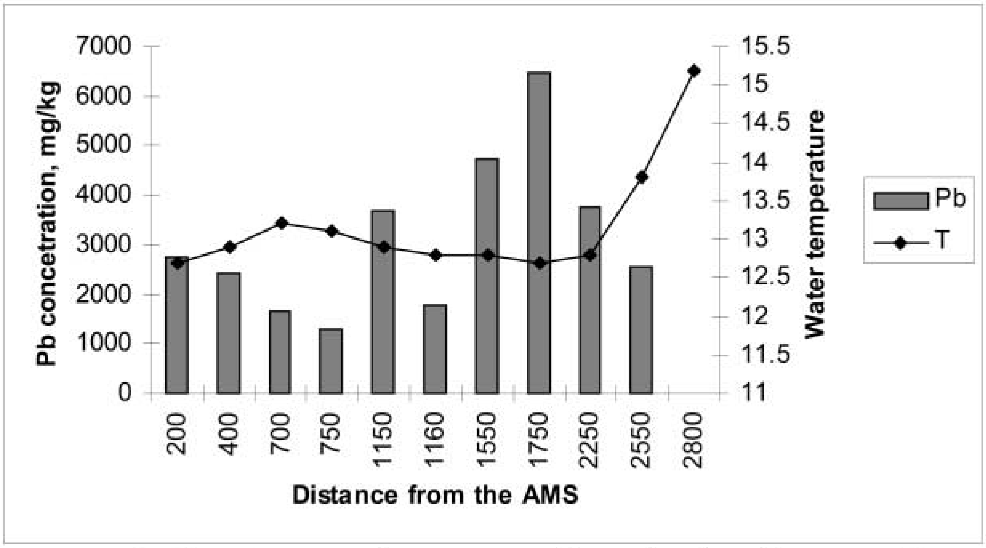

Figure 5. Pb concentration in sediments and temperature fluctuation in surface water (August 1998) in the Silvermine Stream. Temperature reductions indicate stream sections where groundwater discharges.

Table 3. Surface water quality in the vicinity of the Silvermines AMS (EPA data)

	EC µS/sm	pH	Hardness mg/l	Alkalinity mg/l	Pb mg/l
R. Kilmastulla (1994-1997)					
Monitoring station upstream from the AMS					
Mean	519	7.7	241	213	0.003
Max	677	7.9	313	335	0.007
Min	328	7.5	190	114	0.001
STD	78	0.1	48	55	0.002
Monitoring station downstream from the AMS					
Mean	503	8.2	213	159	0.013
Max	634	8.7	290	254	0.035
Min	408	7.7	152	114	0.003
STD	64	0.3	47	37	0.008
R. Yellow (1994-1997)					
Monitoring station downstream from the AMS					
Mean	414	7.9	147	60	0.157
Max	658	8.4	214	97	0.551
Min	173	7.7	54	14	0.053
STD	125	0.2	51	22	0.115
Foilborrig Stream (19.03.98)					
Monitoring stations downstream from AMS					
F-100	537	8.0		59	<0.003
F-200	692	8.2		152	<0.003

Table 4. Metal concentrations of stream bank (groundwater seepage zone) and stream bed

Location of samples	Pb, mg/ kg	pH
Polluted groundwater seepage zone on the stream bank	5350	6.2
Stream bed	2170	6.8

Table 5. Metal concentration in soil (mg/kg)

Area affected		Pb concentration total	Pb concentration exch	Soil pH
AMS	Range	1830-2400(		5.52
	Mean	7900		
Floodplains	Range	6100-1026(	320-3820	5.73
	Mean	4835	1760	
Groundwater seasonal seepage	Range	225-2500	130-1220	5.68
	Mean	1130	600	
Surface runoff (high buffering capacity)	Range	270-1780	130-380	5.68
	Mean	985	220	
Surface runoff (low buffering capacity)	Range	1070-2050	760-1400	4.78
	Mean	1680	1100	
Outside hot spots	Range	16-358		
	Mean	88		
Trigger guidance values		530	25*	

*indicates moderate level of contamination

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