Draft Final Report R&D Project 360

The Use of Constructed Wetlands to Ameliorate Metal-Rich Mine Waters: Stage 1
Study of Natural Wetlands

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1. SUMMARY

Natural wetland areas have been observed to have an ameliorating effect on metal-contaminated mine drainage (MCMD).

This study investigated the effect on water quality of four natural wetland areas in Wales which were receiving waters contaminated by metals from disused metal mines. The four areas were: the Afon Goch, which drains Parys Mountain, an abandoned copper mine on Anglesey; a wetland at the Hafna mine, Gwydir Forest, Gwynedd; a small area of wetland at Esgair Fraith, a former copper/zinc mine, and a wetland at Camdwrbach, a small abandoned lead/zinc mine. The last two sites are near the Nant y Moch reservoir in Dyfed. These four wetlands differed widely in morphology, species composition and influent MCMD composition.

Fieldwork, to determine metal-removal ability of these four wetlands, took place in the second quarter of 1992. This fieldwork involved:

- sampling of influent and effluent flows
- measurement of flows
- characterisation of wetland soils
- mapping of wetland vegetation

Samples of water were analyzed for a range of parameters, including pH, dissolved oxygen, suspended solids, sulphate and a range of metals. Soil samples were analyzed for metals, pH and organic matter content.

Some metal removal was observed, though metal removal ability varied between different wetland areas and, in some cases between sampling visits. The reasons for this variability are discussed. They include differences in hydrology, affecting the amount of contact between water and wetland substrate, possible input of metals from underlying spoil and remobilization of metals from the wetland substrate.

The metal removal performance of natural wetlands could be improved through measures which increase the contact between water and wetland substrate/vegetation, or by adding organic material to the wetland. These measures are discussed in reference to the wetland areas studied.

Natural wetlands are hydrologically complex and elucidation of the many different factors influencing metal removal may not be possible. Constructed wetlands would allow more control over the factors involved and would enable detailed investigation of the metal removal processes taking place.

2. INTRODUCTION

This study investigates the effect that natural wetlands are having on water quality in MCMD - fed catchments in Wales. Four natural wetlands areas were chosen for study. These are detailed in Table 2.1 and shown on Figure 2.1.

Several studies were carried out in the United States in the late 1970s and early 1980s to determine what effect metal-contaminated mine drainage (MCMD) was having on natural, *Sphagnum*-dominated wetland areas. Rather than the expected detrimental effect of the MCMD on the wetland plants, it was observed that the wetlands were healthy and were in fact, removing metals and acidity from the MCMD.

Interest in the use of constructed wetlands to treat MCMD followed these observations. Wetlands are now used worldwide to treat MCMD from coal and metal mines. The literature on this topic has recently been reviewed by Richards Moorehead and Laing Ltd in a separate report to the National Rivers Authority and the Welsh Development Agency.

The choice of wetland area for this study was based on the advice of officials of the National Rivers Authority and other individuals and organisations familiar with metal mining in Wales, together with walkover surveys by Richards Moorehead and Laing Ltd. Criteria for selection of the four wetlands were to include:

- wetlands with different morphologies,
- wetlands with a range of vegetation types,
- wetlands receiving MCMD of different strengths and composition.

Fieldwork occupied the second quarter of 1992.

Table 2.1 The natural wetland areas studied

Area	National Grid Reference	Source of metal contamination
Afon Goch (Gwynedd)	SH 445205 - 460886	Large, abandoned copper mine (Parys Mountain mine)
Hafna (Gwynedd)	SH 783599	Abandoned lead/zinc mine
Esgair Fraith (Dyfed)	SN 740911	Abandoned copper/zinc mine
Camdwrbach (Dyfed)	SN 745891	Small, abandoned lead/zinc/copper mine

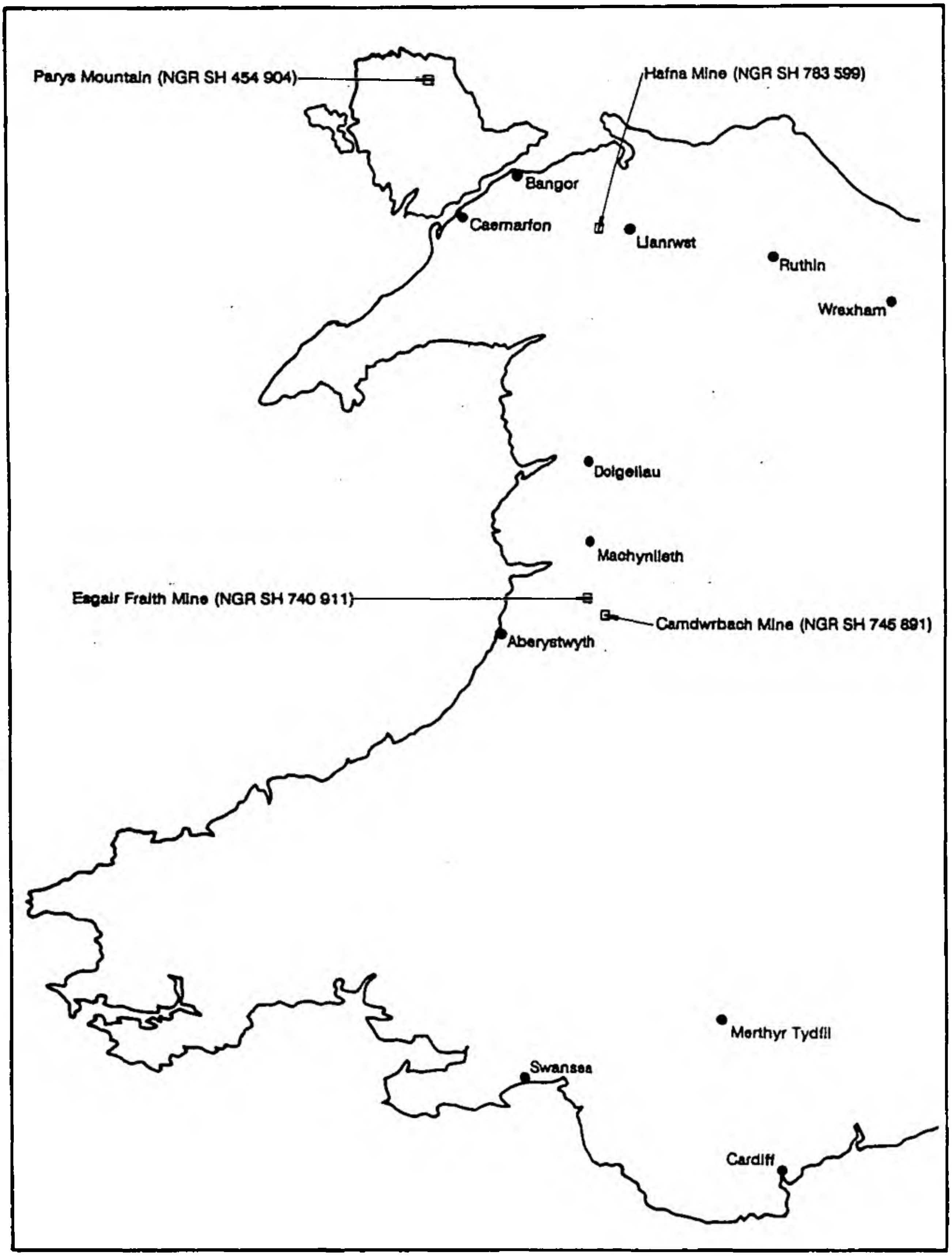


Figure 2.1 Location of the mine sites adjacent to the natural wetland area studied

3. METHODS

3.1 On-site

A range of measurements and samples were taken at each location. Dates and locations are detailed in subsequent sections (Sections 4.3, 5.3, 6.3 and 7.3).

Some or all of the following measurements were made on-site:

Conductivity, using an SME Compact hand-held conductivity meter.

Temperature.

Flow rate was calculated in one of two ways, depending on the size and shape of the watercourse. If there was a convenient filling point, the elementary 'bucket and stopwatch' technique was used. The time taken to fill the bucket to a given volume was noted. Flow rate can be derived directly from this information.

Alternatively, the width of the watercourse was measured together with its depth at several points across the width. Surface flow rate was estimated by noting the time it took a floating object to travel a certain distance, say 2 metres. Flow rate was then estimated as:

average depth x width x surface flow.

All flow rate measurements were repeated several times, and the results averaged.

Water samples were taken using receptacles supplied by the analytical laboratory. For dissolved oxygen determination, a sample was placed in a glass, stoppered bottle making sure no air was entrained. **Dissolved oxygen** was 'fixed' on site using the manganous sulphate and 'alkaline azide' reagents supplied by the analytical laboratory.

Total metal concentrations were determined. For this determination an unfiltered water sample was taken and 'fixed' with acid on-site.

The total metal concentration in a sample is the sum of the dissolved metal concentration and the suspended or particle-borne metal concentration. Dissolved metals are more 'bio-available', hence more likely to be toxic to plants and animals. Where the suspended solids levels are low (< 1 mg/l) it is safe to assume that almost all the metals will be in dissolved forms. However, if suspended solids levels are greater than 1 mg/l, this assumption is unjustified.

Where analysis results showed high levels of suspended solids at a particular water sampling point, an on-site filtered sample was taken on a subsequent occasion. A syringe was used to drive water through a disposable filter with a pore size of 0.45 μm into one of the acid-dosed sample bottles provided by the analytical laboratory. Analysis of this sample gave dissolved metal concentrations.

Soil samples were taken from each wetland are using a hand trowel, generally from a depth of 0.1 - 0.2 metres, to include the organic soil layer.

A hand auger was used to determine the soil profile at several locations within each area. The main objective of this profiling was to examine and estimate the size of the organic layer. The cores produced were identified on-site. Generally it was difficult to obtain cores beyond a depth of 0.6 metres. Auguring was carried out to the maximum practicable depth or until tailings were encountered.

3.2 Laboratory analysis

The laboratories of the National Rivers Authority at Caernarfon were used for the analysis of water and soil samples. These laboratories hold NAMAS accreditation for all the parameters for which analysis was undertaken in this study.

The initial analysis suite for water samples is shown in Table 3.1.

Calcium and manganese were included in the suite to allow for the calculation of water hardness. All other metals were viewed as potential contaminants of the water entering the wetland area. On the basis of the first set of results, it was possible to reduce the analysis suite to provide for more cost-effective analysis. Parameters were removed from the suite if:

* the concentration was unchanged by passage through the wetland;

* the concentration entering the wetland was below EEC standards for toxicity to fish and suitability for drinking water abstraction (Gardiner and Mance 1984);

* the concentration was at the detection limit for all samples from a particular wetland area.

The analysis suite for soil samples was chosen by consideration of the most significant metal contaminants of the water samples. A 'control' soil sample was taken from an uncontaminated but otherwise comparable wetland area for some of the wetland areas. With others, reference was made to typical levels of metals in agricultural soil shown in Table 3.2 to determine 'control' soil contamination levels.

3.3 Calculations

Water hardness was calculated from calcium and magnesium concentrations using the equation in ADAS (1981):

$$H = 2.50 [Ca^{2+}] + 4.12 [Mg^{2+}]$$

where H = the total hardness of the water, in mg/l of calcium carbonate equivalent

$[Ca^{2+}]$ = the total calcium concentration, mg/l

$[Mg^{2+}]$ = the total magnesium concentration, mg/l

The loading of a particular parameter at a given point was calculated by multiplying concentration by flow rate. The result was then multiplied by a correction factor to make the units consistent.

If the concentration of the parameter was in mg/l, this factor was 0.0036.

If the concentration was in μg/l, this factor was 3.6.

Table 3.1 Initial analysis suite for water samples

Parameter	Detection limit
pH	not applicable
Dissolved Oxygen	not applicable
Suspended Solids	1 mg/l
Alkalinity pH 4.5	1 mg/l
Sulphate	2 mg/l
Magnesium	0.1 mg/l
Calcium	1 mg/l
Lead	10 μg/l
Cadmium	0.5 μg/l
Copper	2 μg/l
Zinc	5 μg/l
Arsenic	2 μg/l
Manganese	10 μg/l
Iron	20 μg/l
Nickel	10 μg/l
Aluminium	20 μg/l

Table 3.2 Concentations of heavy metals in agricultural soils
(From Alloway 1990)

Metal	Typical values, mg/kg
Lead	10-30 (rural) 30-100 (urban)
Cadmium	0.2-1.0
Copper	20-30
Zinc	50
Arsenic	1-20
Manganese	1000
Nickel	50

4. THE AFON GOCH WETLAND AREA

4.1 Historical introduction (from Williams 1980)

The discovery of the remains of Roman workings on Parys Mountain, Anglesey in the 1760's lead to determined trials for copper. A great copper deposit was soon discovered; this was worked on a large scale using opencast techniques until the early nineteenth century.

Subsequently conventional deep mining methods were used, reaching a depth of some 150 fathoms. Significant extraction ceased in 1883. Overall production of the mine has been estimated at 132,000 tonnes of copper metal from between 2.6 and 3.8 million tonnes of ore. Profits amounted to some £7,000,000.

Present day remains of the mine, including spoil tips, pits, tailings ponds and the huge opencast, occupy an area of nearly two square kilometres.

Anglesey Mining plc are currently prospecting on the site. An ore body, predominantly zinc ore, has been found at depth. Commercial extraction of this ore awaits the raising of sufficient capital.

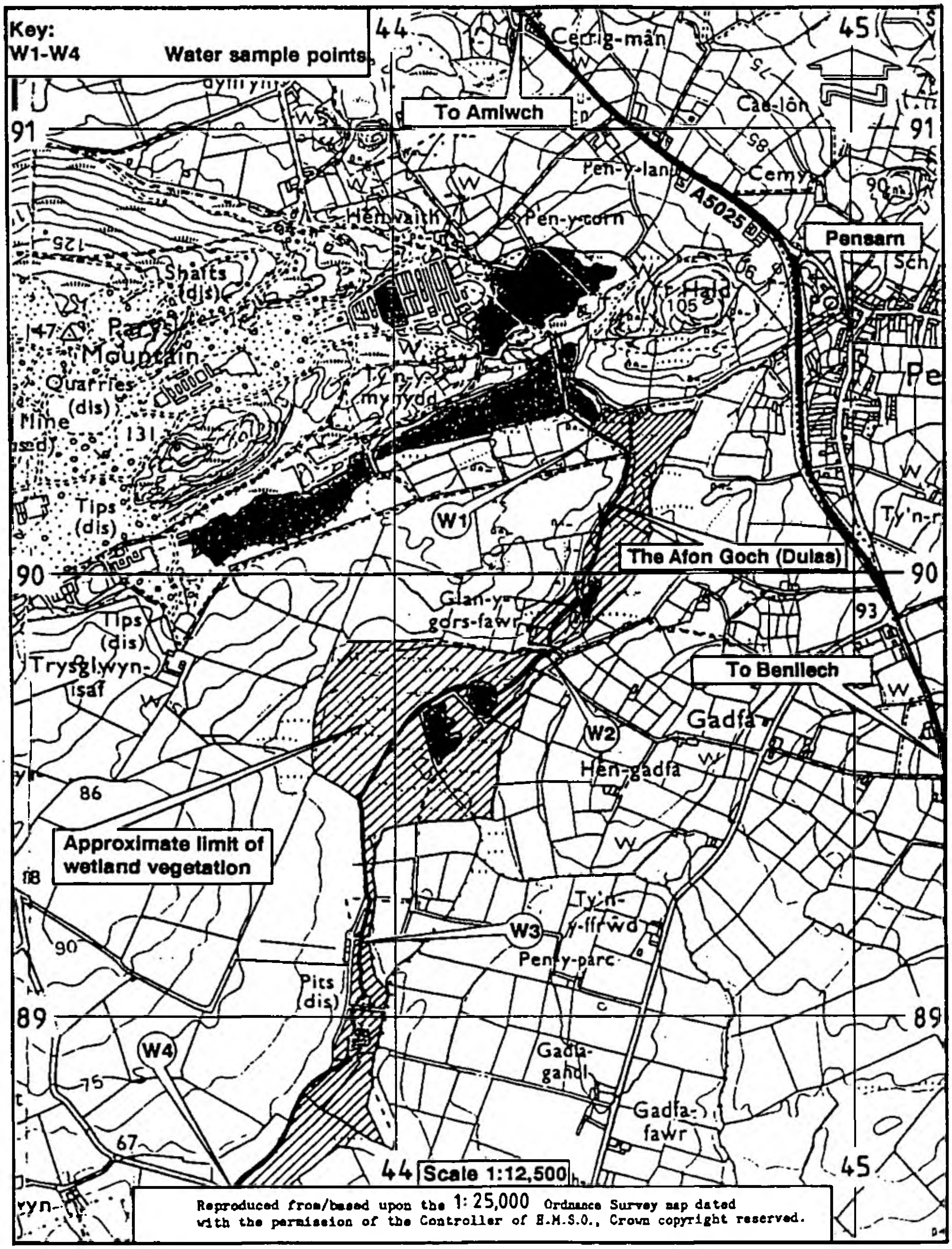
4.2 Description

4.2.1 Morphology

Two rivers termed the Afon Goch originate from Parys Mountain. The Afon Goch (Amlwch) flows northwards, through the town of Amlwch. The Afon Goch (Dulas) flows in an overall south easterly direction, entering the sea at Dulas Bay.

The Afon Goch (Dulas) rises below two tailings ponds at the south-east extent of the Parys Mountain Mine. The upper reaches of this river contain an extensive wetland area, stretching some miles. This is the wetland area selected for study, to determine any effect it may be having on water quality. The river is subsequently referred to in the text as the Afon Goch. An overview of the Afon Goch and the wetland area is presented in Figure 4.1.

Aerial photos and field surveys have indicated that the course of the Afon Goch is significantly different from the course shown on Ordnance Survey maps. In places, the majority of the water flows along features marked as drainage ditches on maps. Figure 4.1 shows the revised course for the river.



Reproduced from/based upon the 1:25,000 Ordnance Survey map dated with the permission of the Controller of H.M.S.O., Crown copyright reserved.

Figure 4.1 The Afon Goch wetland area: location

Samples were taken from four locations along the river. These locations correspond to Points W1, W2, W3 and W4, shown in Figure 4.1 and detailed in Table 4.1. The following discussion of the form of the Afon Goch wetland area is based on observations made near these four locations and examination of maps and aerial photographs. Outflow from the two tailings ponds at SH 453 904 and SH 454 904 is combined into a man-made channel at the head of the Afon Goch. Site W1 is 15 metres downstream of the combination of the two outflows. Immediately downstream of site W1, a large flat area of wetland vegetation abuts the Afon Goch but the channel has been dug to a level below this wetland, thus serving to drain it. The river turns to flow to the south west. Between this bend and Point W2 the river flows through a broad area of wetland vegetation with pools of standing water. The river narrows to a defined channel at W2 before flowing into an extensive wetland area containing two large lagoons (SH 451 897 and SH 452 897). The river leaves these lagoons from the north via a drainage ditch.

The river follows this drainage ditch for some distance before passing through a disused pit, immediately upstream of Point W3. This pit has become colonized by wetland vegetation. A definite channel flows north-south at the east side; to the west of this channel is a broad (about 20 m wide) flat, slightly raised area. Different communities of wetland vegetation were found in the two areas (see Section 4.2.2), but good contact of the water from the Afon Goch with the broad, flat area was observed.

Downstream of W3, the river flows through two further disused pits, similar to the pit upstream of W3, before flowing unimpeded past Point W4, at the road crossing.

Various drainage ditches in the catchment area flow into the Afon Goch along the length studied.

4.2.2 Vegetation

Along the Afon Goch, there are a series of wetlands stretching for many miles. The wetlands vary over this length in vegetation type and cover. The descriptions below are indicative only of the vegetation at each location.

Point W1

The stream is red and with little aquatic vegetation. The main channel is fringed with *Juncus effusus* and runs into a wetland dominated by:

Eriophorum angustifolium
Juncus effusus
with some *Molinia caerulea* and *Deschampsia cespitosa*.

Table 4.1 The Afon Goch wetland area: location of sample points

Water sample points

W1	Downstream of tailings ponds	NGR SH 45440 90335
W2	By Glan-y-Gors-Fawr	NGR SH 45330 89820
W3	Between disused pits	NGR SH 44940 89340
W4	At road crossing	NGR SH 44635 88615

Soil sample points / hand auger profiling locations

A1/S1	10 m upstream of W3, 1 m from the Afon Goch
A2/S2	10 m upstream of W3, 5 m from the Afon Goch
A3/S3	10 m upstream of W3, 10 m from the Afon Goch
A4/S4	At Point W4, 1 m from the Afon Goch
A5/S5	At Point W4, 5 m from the Afon Goch
A6/S6	At Point W4, 10 m from the Afon Goch
S7	Beneath grazing land, some 500 m west of Point W1

Point W2

Upstream of this site is *Juncus/Eriophorum* wetland continuous with that at Point W1. A larger, similar wetland is downstream.

Point W3

Here, there is a mosaic of wetland types and dryer areas. The main channel is dominated in places by *Phragmites*, although these were dormant during the sampling period.

The wetland adjacent to the channel comprises:
Molinia caerulea
Juncus effusus
Eriophorum angustifolium
Deschampsia cespitosa
Equisetum fluviatale.

These vary in dominance throughout the area.

Point W4

The main channel is fringed by *Molinia caerulea* and *Juncus effusus*. The large adjacent wetland contains these species plus:
Deschampsia cespitosa
Cirsium palustre
Cirsium arvense
along with some patches of *Phragmites australis, Rubus fruticosus, Salix caprea and Equisetum fluviatale.*

4.3 Sampling

The locations of water and soil sampling points and hand auger profiling locations are given in Table 4.1. Water samples were taken on 12 March 1992, 3 April 1992, 1 May 1992 and 21 May 1992. Flow measurements could only be made at W1 on 12 March; at all other locations the water was too deep at this date to permit safe entry to measure the cross sectional area which is information necessary for the calculation of volume of flow. Flow measurements were taken at Points W1, W2, W3 and W4 on the last three dates. Soil samples and hand auger samples were taken on 21 May. Soil samples were taken at depths of 10-20 cm below the surface.

Soil sample S1 was taken from beneath grazing land, some 500 m west of Point W1 and some 5-10 cm below the surface. The purpose of this sample was to enable an estimate to be made of 'control' concentrations of metals in soils of the area, including contamination by wind-blown particles.

The suspended solids concentration in water sampled at Point W2 was high (28 mg/l on 12 March). Therefore, on-site filtration was carried out on 1 May 1992 and a filtered water sample taken to determine dissolved metal concentrations in addition to the *total* metal concentration usually determined.

4.4 Water quality

Background water quality information is available from two sources: the National Rivers Authority have periodically sampled at Point W4 and a study carried out for Anglesey Mining plc sampled water at Points W1 and W2. This background information is presented in Tables 4.2 and 4.3.

Results from water samples taken during this study are presented in Tables 4.4 to 4.8.

Comparison of water quality data obtained during the study with background data available does not show any serious discrepancies.

		Sample date					
Parameter	Units	22/ 1/90	18/ 4/90	16/ 1/91	2/ 5/91	20/ 9/91	20/ 1/92
pH		2.9	2.7	2.9	2.9	2.5	2.7
Dissolved Oxygen	mg/l	12.6	11.8	18.5	17.8	12.1	10.1
Dissolved Oxygen	%	93.8	92.5	134	162	109	85.8
Suspended Solids 105°C	mg/l	5	3	2	8	3	< 1
Alkalinity pH 4.5	mg/l	-	-	-	-	-	-
Sulphate	mg/l	-	-	-	-	-	-
Magnesium	mg/l	22.8	31	16.8	23	50.6	28.6
Calcium	mg/l	16.3	18.6	8.4	10.1	48.5	31.04
Lead	µg/l	61	94	105	66	135	99
Cadmium	µg/l	25	47	45	29	48	45
Copper	µg/l	8450	10410	7620	5580	8870	47800
Zinc	µg/l	10400	15100	15600	10100	19900	90300
Arsenic	µg/l	-	-	-	-	-	-
Manganese	µg/l	2050	4720	3380	2580	8260	16350
Iron	µg/l	40900	93700	85700	40000	92600	347900
Nickel	µg/l	25	47	34	35	71	57
Aluminium	µg/l	-	-	-	-	-	-
Hardness	mg/l	135	174	90	120	330	195
Conductivity	µS/cm	982	1600	1276	1310	2290	1430

Table 4.2 The Afon Goch wetland area: background information provided by the National Rivers Authority. Sample point W4.

	Site	W1	W3	W1	W3	W1	W3	W1	W3
Parameter	Units	4/1/90	4/1/90	1/3/90	1/3/90	23/4/90	23/4/90	4/7/90	4/7/90
		Sample date							
pH		2.6	2.7	2.6	2.8	2.5	2.6	2.3	2.5
Dissolved oxygen	mg/l	-	-	-	-	-	-	-	-
Suspended solids 105°C	mg/l	-	-	-	-	-	-	-	-
Alkalinity pH 4.5	mg/l	-	-	-	-	-	-	-	-
Sulphate	mg/l	1200	710	1200	660	1700	1100	1700	1300
Magnesium	mg/l	-	-	-	-	-	-	-	-
Calcium	mg/l	-	-	-	-	-	-	-	-
Lead	µg/l	140	160	90	100	120	120	60	100
Cadmium	µg/l	100	50	90	50	110	60	130	90
Copper	µg/l	22000	9700	23000	9900	2600	16000	29000	18000
Zinc	µg/l	36000	20000	31000	16000	40000	21000	47000	33000
Arsenic	µg/l	100	< 100	100	< 100	100	< 100	< 100	< 100
Manganese	µg/l	8900	4600	7400	3900	15000	7000	9300	8000
Iron	µg/l	310000	120000	280000	110000	390000	170000	300000	190000
Nickel	µg/l	-	-	-	-	-	-	-	-
Aluminium	µg/l	9900	48700	70000	26000	77000	40000	90000	58000
Hardness	mg/l	330	170	260	150	380	240	430	390
Conductivity	µS/cm	2100	1500	1900	1200	2500	1800	3200	2500

Table 4.3 The Afon Goch wetland area: background water quality information provided by Anglesey Mining plc.

Table 4.4 The Afon Goch wetland area: water quality, 12 March 1992

Parameter	Units	W1	W2	W3	W4
pH		2.7	2.9	-	2.9
Dissolved Oxygen	mg/l	13.0	13.7	-	10.3
Suspended Solids	mg/l	4.0	28.0	-	1.2
Alkalinity pH 4.5	mg/l	< 1.0	< 1.0	-	< 1.0
Sulphate	mg/l	1026.63	531.62	-	324.79
Magnesium	mg/l	40.9	24.5	-	17.55
Calcium	mg/l	29.4	26.7	-	24.2
Lead	µg/l	130	66	-	49
Cadmium	µg/l	68.4	34.6	-	20.5
Copper	µg/l	14100	6200	-	3120
Zinc	µg/l	28100	12500	-	6390
Arsenic	µg/l	25.2	11.9	-	4.5
Manganese	µg/l	7040	3700	-	17710
Iron	µg/l	144000	60000	-	214900
Nickel	µg/l	70.1	39.4	-	27.7
Aluminium	µg/l	39.02	19.66	-	11.64
Hardness	mg/l	242	168	-	133
Conductivity	µS/cm	-	-	-	-
Flow rate	l/s	72	-	-	-
Loading:					
Sulphate	g/h	266102	-	-	-
Magnesium	g/h	10601	-	-	-
Calcium	g/h	7620	-	-	-
Lead	g/h	34	-	-	-
Cadmium	g/h	18	-	-	-
Copper	g/h	7620	-	-	-
Zinc	g/h	7284	-	-	-
Arsenic	g/h	7	-	-	-
Manganese	g/h	1825	-	-	-
Iron	g/h	37325	-	-	-
Nickel	g/h	18	-	-	-
Aluminium	g/h	10	-	-	-

Table 4.5 The Afon Goch wetland area: water quality, 3 April 1992

Parameter	Units	W1	W2	W3	W4
pH		2.7	2.7	2.8	2.8
Dissolved Oxygen	mg/l	-	-	17.1	-
Suspended Solids	mg/l	4.8	9.2	< 1.0	2.0
Alkalinity pH 4.5	mg/l	-	-	< 1.0	-
Sulphate	mg/l	1332.77	861.45	609.71	522.33
Magnesium	mg/l	-	-	31.28	-
Calcium	mg/l	-	-	31.66	-
Lead	µg/l	122	82	62	56
Cadmium	µg/l	80.6	55.0	39.7	34.6
Copper	µg/l	15000	10600	9030	6660
Zinc	µg/l	30400	20900	16900	12600
Arsenic	µg/l	26.7	17.8	12.9	10.0
Manganese	µg/l	7690	5110	4300	3290
Iron	µg/l	192900	118400	70200	43800
Nickel	µg/l	85.9	55.4	44.1	39.4
Aluminium	µg/l	-	-	23100	-
Hardness	mg/l	-	-	208	-
Conductivity	µS/cm	2313	1756	1573	1458
Flow rate	l/s	43	53	43	124
Loading:					
Sulphate	g/h	206313	164365	94383	233168
Magnesium	g/h	0	0	4842	0
Calcium	g/h	0	0	4901	0
Lead	g/h	19	16	10	25
Cadmium	g/h	12	0	6	15
Copper	g/h	2322	2022	1398	2973
Zinc	g/h	4706	3988	2616	5625
Arsenic	g/h	4	3	2	0
Manganese	g/h	1190	975	666	1469
Iron	g/h	29861	22591	10867	19552
Nickel	g/h	13	11	7	18
Aluminium	g/h	0	0	3576	0

Table 4.6 The Afon Goch wetland area: water quality, 1 May 1992

Parameter	Units	W1	W2	W3	W4
pH		2.70	2.71	2.71	2.71
Dissolved Oxygen	mg/l	-	-	-	-
Suspended Solids	mg/l	5.2	29.0	2.8	2.8
Alkalinity pH 4.5	mg/l	-	-	-	-
Sulphate	mg/l	1262	787	575	546
Magnesium	mg/l	-	-	-	-
Calcium	mg/l	-	-	-	-
Lead	µg/l	147	93	80	72
Cadmium	µg/l	77.3	49.2	36.6	33.3
Copper	µg/l	17300	7190	7000	5580
Zinc	µg/l	33300	21300	14800	11430
Arsenic	µg/l	15.4	6.1	< 2.0	< 2.0
Manganese	µg/l	7520	4710	3390	3110
Iron	µg/l	141300	104600	44800	37110
Nickel	µg/l	65.1	41.6	36.1	31.8
Aluminium	µg/l	-	-	-	-
Hardness	mg/l	-	-	-	-
Conductivity	µS/cm	2328	1687	1595	1550
Flow rate	l/s	34	92	116	148
Loading:					
Sulphate	g/h	154525	260495	239970	290962
Magnesium	g/h	-	-	-	-
Calcium	g/h	-	-	-	-
Lead	g/h	18	31	33	38
Cadmium	g/h	9	16	15	18
Copper	g/h	2118	2381	2923	2973
Zinc	g/h	4076	7055	6180	6090
Arsenic	g/h	2	2	0	0
Manganese	g/h	920	1560	1416	1657
Iron	g/h	17295	34644	18708	19772
Nickel	g/h	8	14	15	17
Aluminium	g/h	0	0	0	0

Table 4.7 The Afon Goch wetland area: water quality, 21 May 1992

Parameter	Units	W1	W2	W3	W4
pH		2.5	2.5	2.5	2.5
Dissolved Oxygen	mg/l	-	-	-	-
Suspended Solids	mg/l	5.6	22.0	2.4	2.0
Alkalinity pH 4.5	mg/l	-	-	-	-
Sulphate	mg/l	1125	984	915	825
Magnesium	mg/l	-	-	-	-
Calcium	mg/l	-	-	-	-
Lead	µg/l	106	136	59	101
Cadmium	µg/l	94	71	38	33
Copper	µg/l	10700	14500	10720	818
Zinc	µg/l	29790	31160	21170	15960
Arsenic	µg/l	51.0	36.1	22.1	15.9
Manganese	µg/l	9500	9881	6000	4369
Iron	µg/l	229400	217130	88810	58360
Nickel	µg/l	110	56	54	41
Aluminium	µg/l	-	-	-	-
Hardness	mg/l	-	-	-	-
Conductivity	µS/cm	3008	2557	2153	2061
Flow rate	l/s	13.2	29	14.1	15
Loading:					
Sulphate	g/h	53460	102720	46440	44543
Magnesium	g/h	-	-	-	-
Calcium	g/h	-	-	-	-
Lead	g/h	5	14	3	5
Cadmium	g/h	4	7	2	2
Copper	g/h	508	1514	544	44
Zinc	g/h	1416	3253	1075	862
Arsenic	g/h	2	4	1	1
Manganese	g/h	451	1032	305	236
Iron	g/h	10901	22668	4508	3151
Nickel	g/h	5	6	3	2
Aluminium	g/h	-	-	-	-

Table 4.8 The Afon Goch wetland area: dissolved and total metal concentrations, 1 May 1992

Parameter	Units	W2 Total	W2 Dissolved
Lead	μg/l	93	83
Cadmium	μg/l	49.2	44.3
Copper	μg/l	7190	7600
Zinc	μg/l	21300	14300
Arsenic	μg/l	6.1	6.0
Manganese	μg/l	4710	3380
Iron	μg/l	104600	87700
Nickel	μg/l	41.6	46

Table 4.9 The Afon Goch wetland area: soil chemical characteristics

Parameter	Units	S1	S2	S3	S4	S5	S6	S7
pH		2.6	5.7	5.9	6.6	5.2	6.0	5.8
Organic solids	%	73.3	68.5	69.5	52.3	75.0	61.1	19.6
Lead	mg/kg	161	1572	1342	2596	388	525	51.8
Cadmium	mg/kg	27.1	36.1	23.6	16.6	3.32	8.94	0.94
Copper	mg/kg	893	2104	3469	2730	1410	793	74.9
Zinc	mg/kg	647	2798	4380	766	557	652	131
Arsenic	mg/kg	182	193	264	260	83	99	35
Manganese	mg/kg	77	383318	146	143	140	221	528
Iron	mg/kg	212758	259318	189872	168139	44682	102699	32191
Nickel	mg/kg	5.9	14.3	123.0	7.4	14.9	16.2	90.9

The background data cannot be used to calculate metal removal ability as no flow rate information is available. Because of the large number of other watercourses entering the Afon Goch in the catchment it is crucial that metal removal calculations are based on loading figures rather than concentrations to counteract the effect of dilution.

On the basis of the results from the first sampling date, magnesium and calcium determinations, used to derive hardness, were discontinued. Hardness of the water samples along the length of the Afon Goch were showed less variation than that observed in the NRA background data for Point W4. Therefore, any change in hardness as water passed through the wetland could not be reliably attributed to some function of the wetland.

The determination of alkalinity was discontinued since all samples were below the detection limit. No significant change in dissolved oxygen concentration could be observed; this determination was also discontinued. Table 4.8 shows that, as expected at the low pH values metals are almost exclusively in dissolved forms. Some zinc and iron however occurs in a suspended form.

Loading figures could not be derived for Points W2, W3 and W4 on 12 March since as already noted, the cross sectional area could not be measured. Consideration of the water treatment potential of the wetland is based on the loading figures for the three subsequent dates.

Contaminant loading increases with greater flow rates. Since flow rate increases following rain, MCMD production by rainwater infiltration into surface mine waste is implicated by this observation. As contaminant loading is dependant on flow rate, it is not valid to average contaminant loading for the three dates.

Therefore, for these three remaining sets of data, contaminant values for the four Points W1 to W4 were expressed relative to that at Point W1. Relative contaminant loading values for the three dates were averaged and are shown in Figure 4.2.

Any reduction in relative contaminant loading can be considered to be due to removal of metals by the wetland if it is assumed that any other water entering the wetland, through drainage ditches for example, is free from metal contamination.

It is clear from the Figures that the loading at W2 is greater than W1, suggesting an unidentified metal source between W1 and W2. This source may be the remobilization of sediment from historical contamination. It is also clear that the greatest treatment occurs between Point W2 and W3 as might be expected on the basis of the morphology of the wetland between these two points in comparison to that in other parts of the area studied. An 80% removal of arsenic is observed, also a 60% removal of iron and 40% removals of copper, zinc, manganese, lead and cadmium. Only 20% of the nickel loading is removed, and 30% of the sulphate loading.

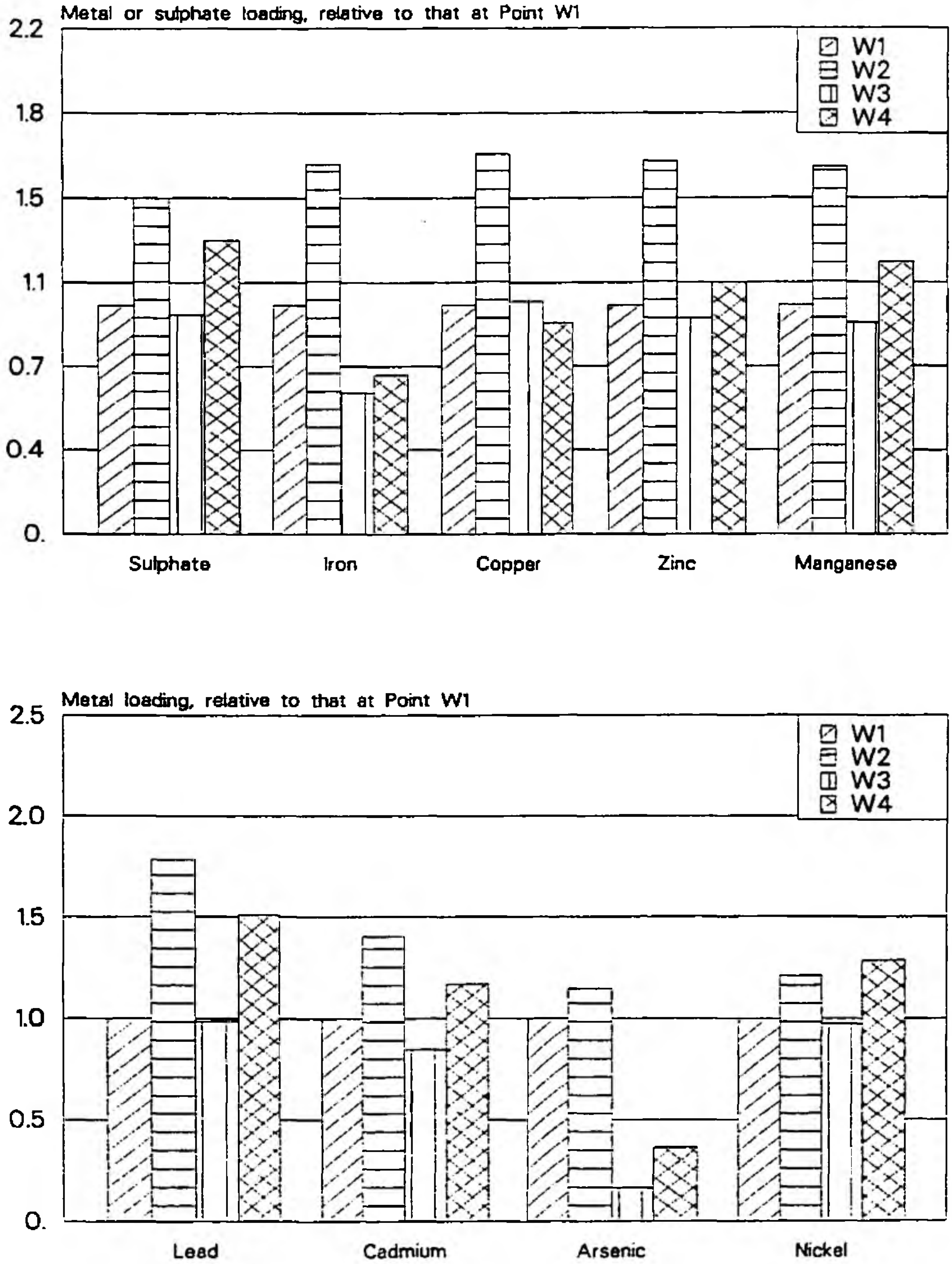


Figure 4.2 The Afon Goch wetland area: contaminant loadings relative to the loading at point W1

It appears that there is a further source of all the contaminants, except for copper, between W3 and W4. Therefore the overall metal removal by the wetland is not as good as suggested by figures for between W2 and W3. Overall, the wetland has no significant effect on nickel, cadmium, lead and sulphate concentrations. Some 60% of the iron present at W2 is removed, some 50% of the copper, 30% of the zinc, 25% of the manganese and 70% of the arsenic.

4.5 Soil profile and soil chemical characteristics

The profile of the wetland soil at Points A1 to A6 is shown in Figure 4.3. The soil profile was investigated at three distances (1 metre, 5 metres and 10 metres) from the Afon Goch at the two locations W3 and W4.

Points A1 to A3 are immediately upstream of W3. The orange colour of the top layer at A1 and A2 suggests that these sediments are oxidising and that precipitation of iron as ferric oxyhydroxides is giving the colour. This precipitation of iron may be microbially-mediated. Removal of other metals may be occurring either with microbial intervention or by 'coprecipitation'. Coprecipitation is the process whereby other metal ions are adsorbed onto the iron oxyhydroxide precipitates as they form. These surface sediments are vulnerable to being flushed away in high flow situations and so precipitation of metals as oxides and hydroxides may not represent a permanent removal mechanism.

Reducing conditions occur in sediments at depths of 0.5 m at A1, 0.2 m at A2 and at the surface of A3. The black colour suggest that iron is in the reduced ferrous form. The faint smell of hydrogen sulphide suggests that sulphate reducing bacteria are active, metal removal by precipitation as sulphides within the substrate may be occurring.

This type of reducing sediment is also present at depth in A4. Examination of profiles A4 to A6 suggests that the processes of metal removal are far less active at W4 than at W3.

The results of soil analyses are shown in Table 4.9. S7 is the 'control' soil sample, S1 to S6 are taken at the same location as the hand auger profiles (A1 to A6), at a depth of 0.1 - 0.2 metres. Soil pH at S1 indicates that at this point there is good interchange between water in the river and soil pore water. For S2 to S6, pH is close to the 'control'. This value of pH is likely to reflect the infiltration of water from other, non acid-contaminated sources.

Levels of lead, cadmium, copper, zinc, arsenic, manganese and iron in the soil samples S1 to S6 are elevated in comparison with S7. This suggests that the metals have been incorporated from the water column into the sediment. Copper, zinc and

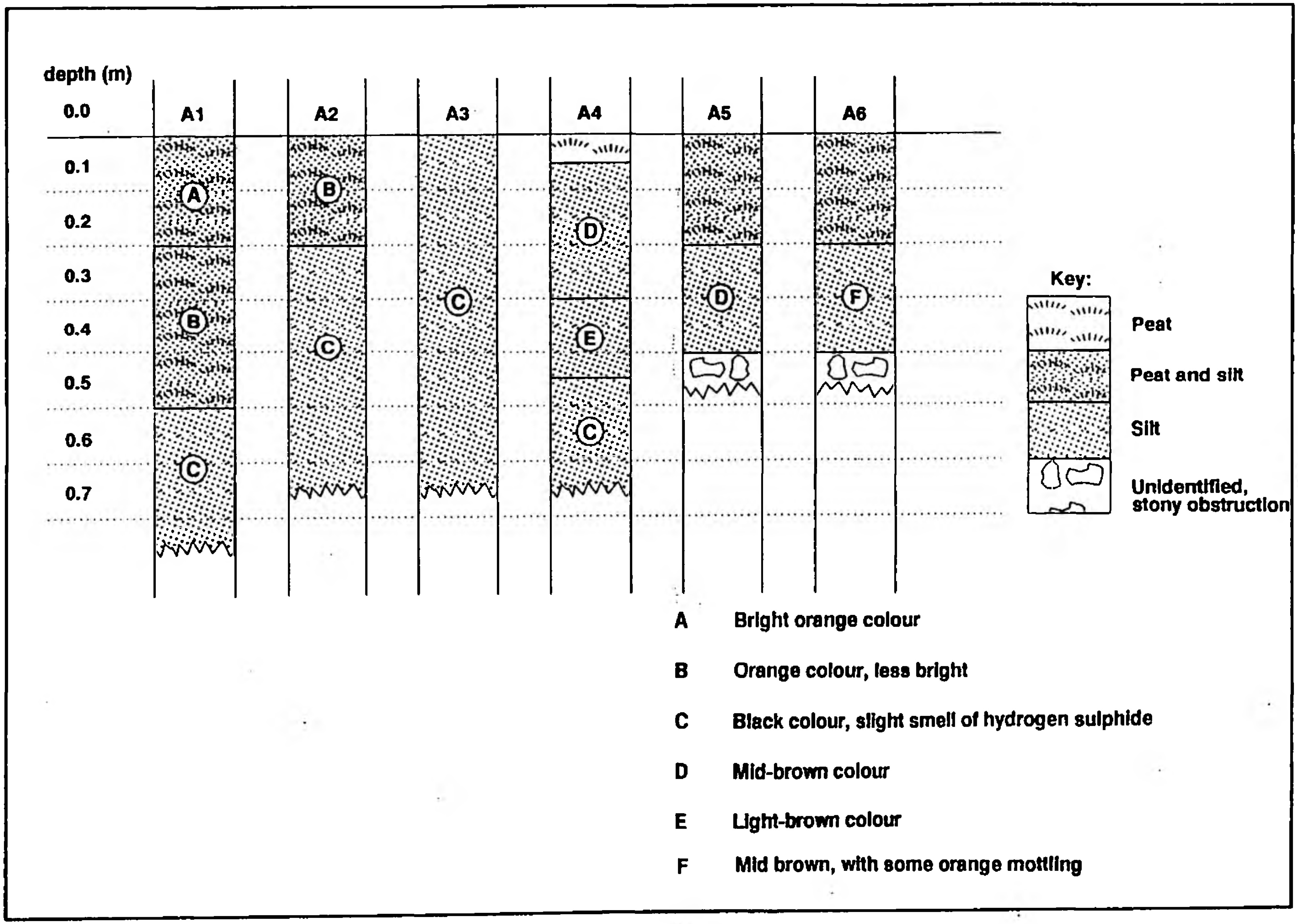


Figure 4.3 The Afon Goch wetland area: hand auger profiles

arsenic levels in the reducing sediment (S3) are higher than in the oxidizing sediment (S1, S2). These metals may be being removed by processes requiring reducing conditions. Soil chemistry results suggest that cadmium, zinc and iron removal is better at W3 than at W4.

5. THE HAFNA WETLAND AREA

5.1 Historical introduction (from Robinson Jones Partnership Ltd 1983)

The Hafna mine probably started operations in 1820 and was worked intermittently until the 1860s. Zinc and lead ores were mined. The Hafna mill was developed on the site in the late 19th Century. Work at the mine and mill had largely ceased by 1915.

The Nant Uchaf tailings dam, below the mine complex, is the site of the wetland area investigated (see Figure 5.1). This was the second tailings dam of the nearby Parc mine; tailings were pumped uphill to this area after the lower dam was filled.

Reclamation of the Parc mine was undertaken in 1977 and a reclamation scheme for the Hafna mine, including the Nant Uchaf tailings dam, was completed in May 1992.

5.2 Description

5.2.1 Morphology (see Figure 5.2)

The Nant Uchaf tailings dam has become colonized by wetland vegetation. The area is contaminated by metals from two main sources: the tailings from the Parc mine themselves, and metal-contaminated mine drainage (MCMD) from the Hafna mine, discharging from the Number Four adit.

Water enters the wetland area from three directions. MCMD from the Hafna Number Four adit enters from the north, past Point W4. This flow used to enter the area of the Nant Uchaf tailings dam some 50 metres to the east of its current entry point but it has been realigned as part of the reclamation scheme.

A small volume of water, the overflow from the domestic water supply for Nant Uchaf, enters from the north-east, past Point W5. This supply is fed by a spring north of the property. Again, prior to the reclamation scheme, this water entered the Nant Uchaf tailings dam some 50 metres to the east of the current position.

In the west a small stream runs into the west end of a concrete pipe. This concrete pipe runs across the middle of the wetland from west to east, then turns to the south to emerge at Point W2. The reclamation scheme has diverted water from the catchment of this small stream, so the volume of water entering from this direction is generally low.

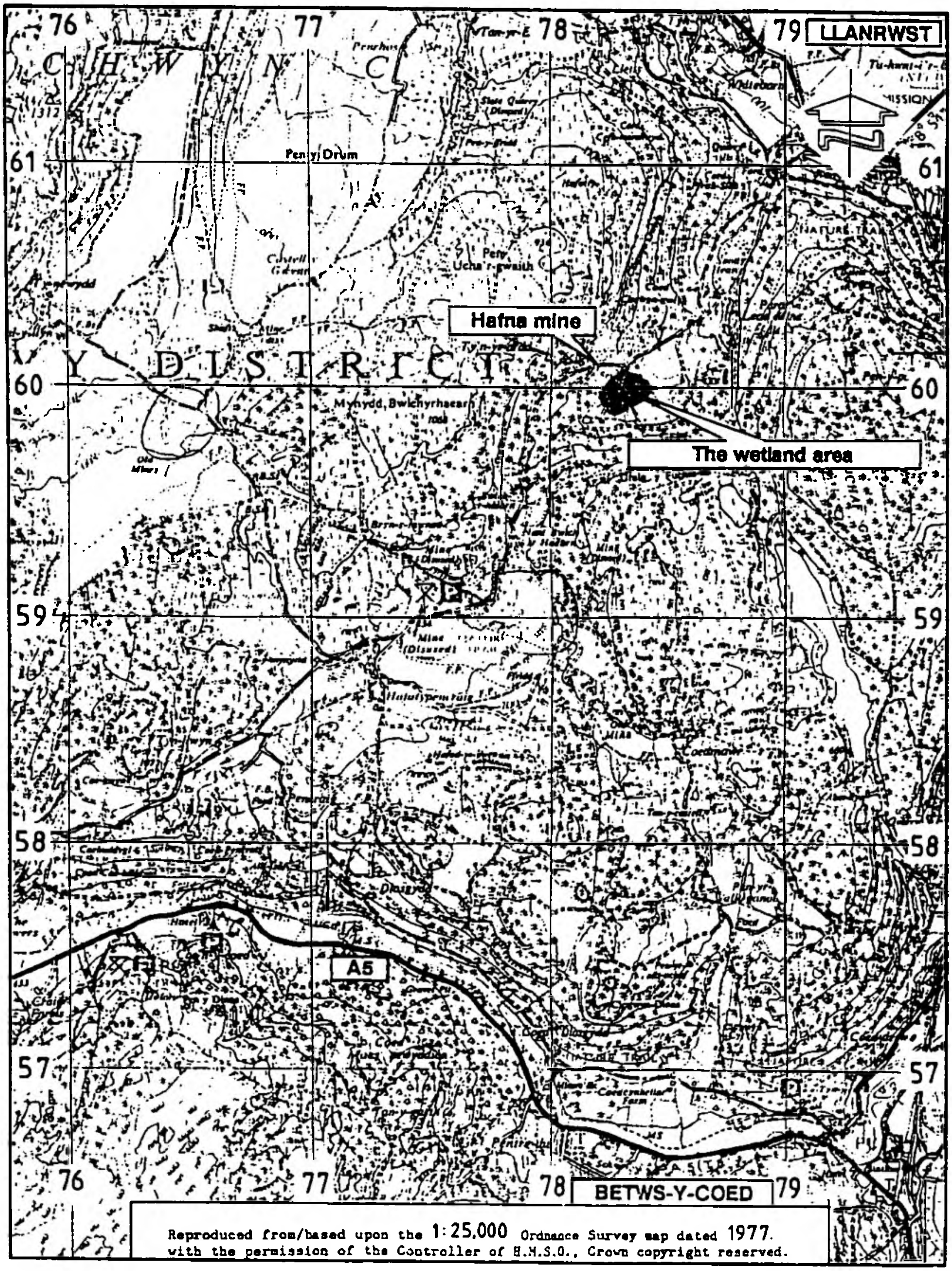


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Figure 5.1 The Hafna wetland area: location

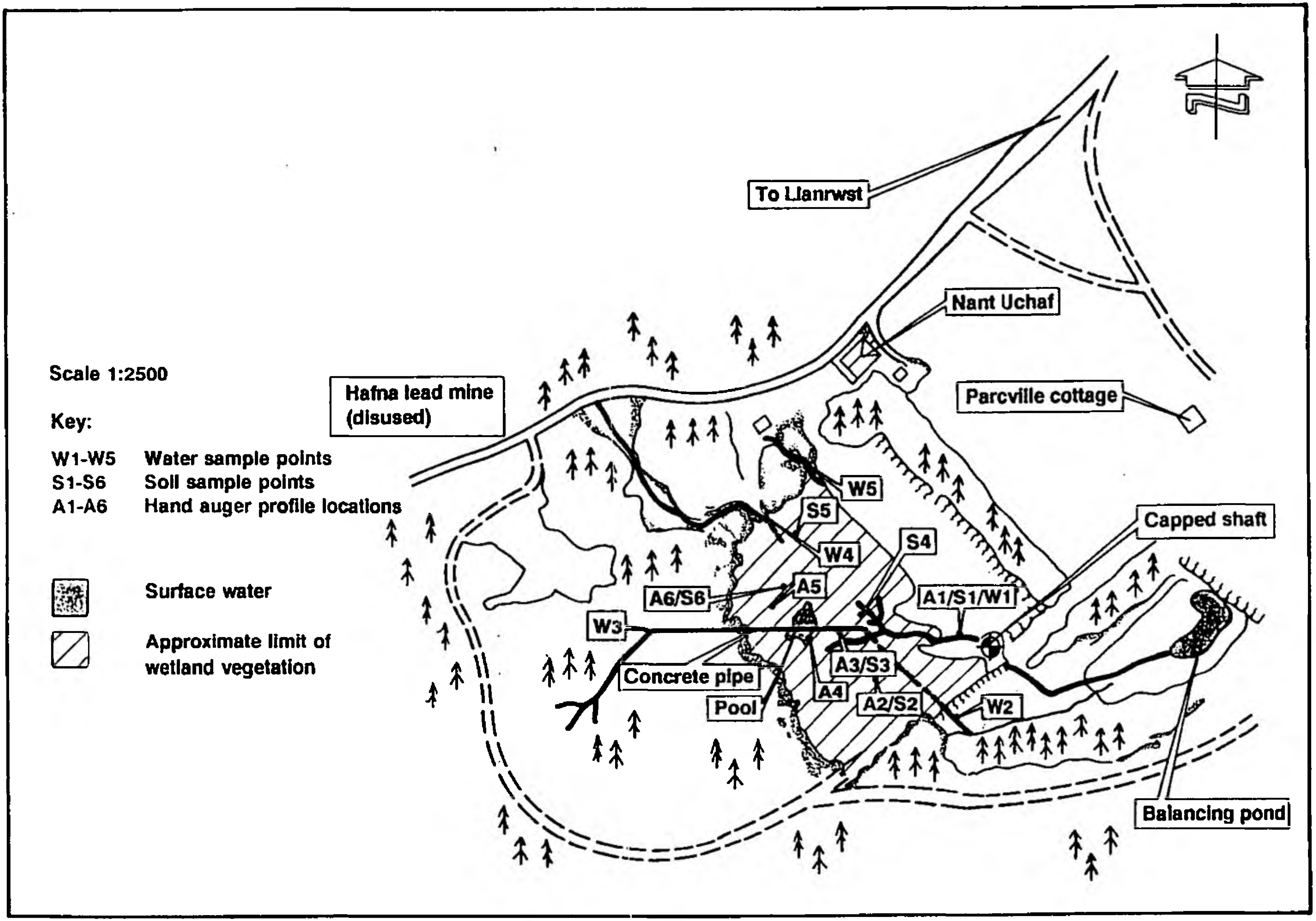

Figure 5.2 The Hafna wetland area: morphology

The pool of standing water in the middle of the wetland area is fed by the flows from the north-east and north and also by rainwater falling directly onto the wetland area. It drains partly through the concrete pipe and partly to the stream flowing to the south-east. The concrete pipe has become buried along most of its length south of the pool, and emerges at point W2. The stream flowing to the south-east is also fed by surface water from other sections of the wetland area. Part of the reclamation scheme involved diverting the flow of this stream around the recently capped shaft. Prior to the scheme, a large volume of water entered this shaft, to emerge from the workings of the nearby Parc Mine.

Thus there are three main directions for surface water entry into the wetland: from the north, the west and the north-east. There are two main routes for exit of surface water: the concrete pipe and the stream flowing past the capped shaft.

5.2.2 **Vegetation** (see Figure 5.3)

The tailing area is comprised of a large area of swamp, probably on tailings, with a central patch of open water. Much of the swamp is taken up by a *Carex*-dominated community with few other species (shown as 'A' on Figure 5.3). A monoculture of *Phragmites* is also present (shown as 'M'). The other areas described are peripheral to the main swamp. The vegetation of these peripheral areas varies depending on the degree of waterlogging/running water entry and the degree of past disturbance in the past. Species lists for the areas shown in Figure 5.3 are given below:

A *Carex*-dominated swamp

Carex acuta
Juncus effusus
Juncus squarrosus
Rumex acetosa
Epilobium hirsutum
Equisitum fluviatale
Geum urbanum
Silene pratensis
Deschampsia cespitosa
Deschampsia flexuosa
Molinia caerulea
Agrostis capillaris
Festuca ovina

Bryophytes:
Philonotis fontana
Bryum pallens

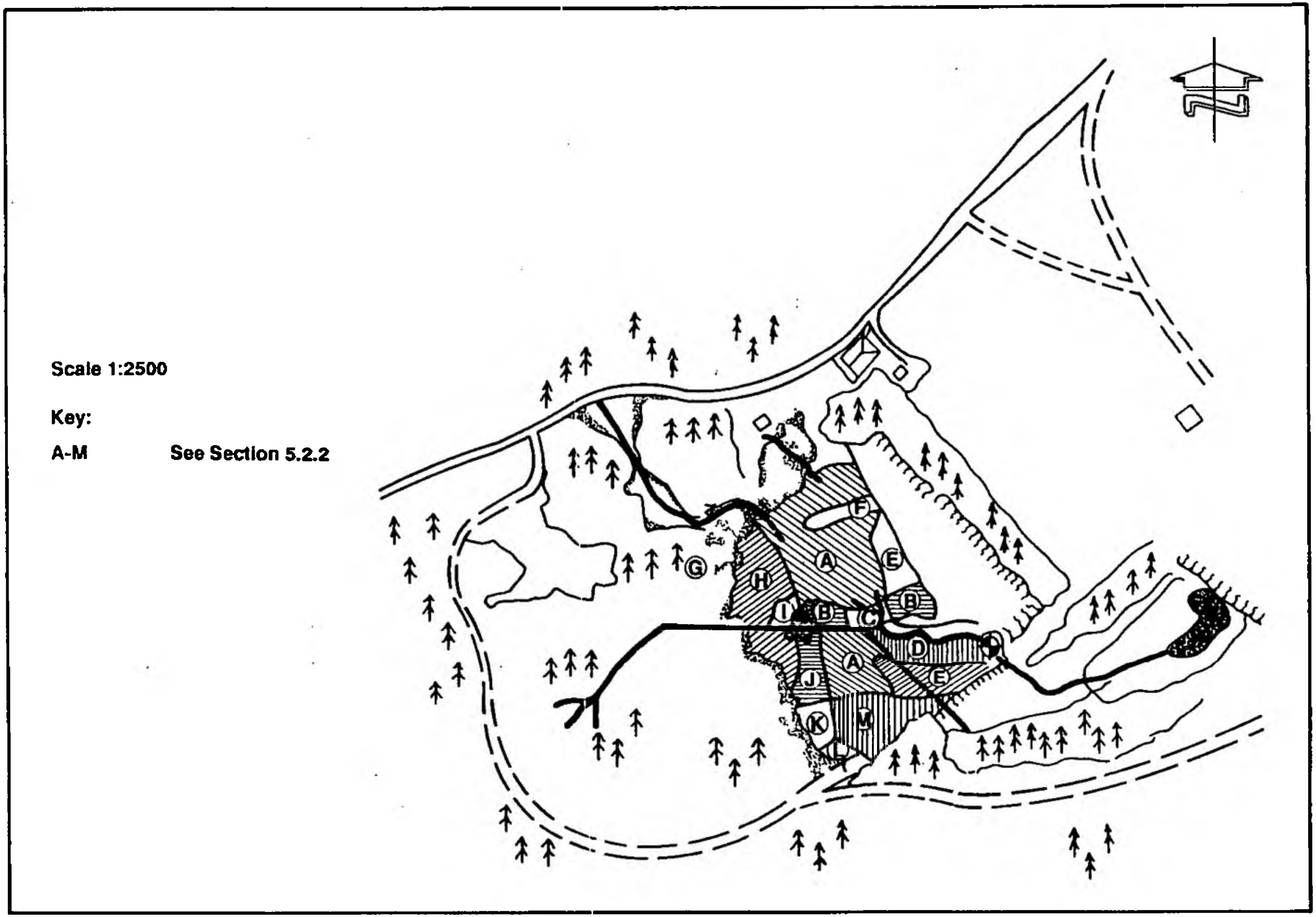

Figure 5.3 The Hafna wetland area: vegetation

B Bryophyte dominated wetland.

Bryophytes:
Philonotis fontana
Bryum pallens

C Similar to A but drier and being invaded by *Picea.*

D Similar to B but more diverse.

Holcus lanatus
Juncus effusus
Equisetum fluviatale
Silene pratensis
Rumex acetosa
Betula spp. colonising drier parts
Philonotis fontana
Bryum pallens
Rhytiadiadelphus squarrosus

E Dryer area with *Betula* and *Picea* invading; evidence of occasional inundation; grades into A.

Deschampsia cespitosa
Festuca ovina
Silene pratensis
Tussilago farfara
Cirsium palustre

Bryophytes and lichen:
Pleurozium schreberi
Bryum pallens
Dicranum scoparium
Rhytidiadelphus squarrosus
Peltigera sp.

F Bank of *Salix* in A.

G *Picea* woodland (planted) with bank of dry acid grassland (see H) abutting A.

H Dry acid grassland.

Festuca ovina
Agrostis capillaris
Deschampsia cespitosa
Calluna vulgaris

I Predominantly bare.

J *Phalaris arundinacea*-dominated swamp.

K *Deschampsia cespitosa*-dominated swamp.

L *Molinia caerulea* dominated swamp.

M Substantial area of monoculture of *Phragmites australis* apparently on tailings. The plants were dormant during the sampling period.

The open water area contains floating and sediment-surface green and brown algae which were not identified.

5.3 Sampling

The locations of water, soil and hand auger sampling points are given in Table 5.1 and shown in Figure 5.2. Water samples were taken on 12 March 1992, 3 April 1992, 1 May 1992 and 21 May 1992.

Point W2 was not sampled on 12 March but was sampled at all later dates. All other points were sampled on all four dates.

Flow rate measurements were taken at the water sample points whenever a water sample was taken.

Soil samples, from points S1 to S6, were taken on 1 May 1992, at the depths indicated in Table 5.1. A hand auger was used to determine the soil profile at Points A1 to A6 on 21 May 1992. A filtered water sample, for determination of dissolved metal concentrations, was taken from point W4 on 3 April and 1 May.

Table 5.1 Hafna wetland area: location of sample points

Water sample sites		Location
W1	Effluent upstream of new bridge	NGR SH 78440 59930
W2	Effluent from old concrete pipe	NGR SH 78430 59920
W3	Influent from west	NGR SH 78350 59940
W4	Influent from north	NGR SH 78315 60045
W5	Influent from north-east	NGR SH 78335 60050
PW1	At portal of Hafna Number 4 Adit (not shown on Figure 5.2)	NGR SH 78120 60135

Soil sample sites		Depth
S1	By W1	0.1-0.2 m
S2	In *Phragmites* monoculture	0.1-0.2 m
S3	One metre off line of concrete pipe, 10 m from of pool	0.1-0.2 m
S4	Two metres north of bend in pipe	0.1-0.2 m
S5	Some 25 m south of W4, as far into the wetland as was safe to proceed	50-100 mm
S6	Under *Carex* wetland, 20 m north of pipe	0.1-0.2 m

Hand auger profile locations	
A1	By W1
A2	By S2
A3	By S3
A4	In pool
A5	Halfway between S6 and concrete pipe
A6	By S6

5.4 Water quality

Background water quality information was provided by Parkman Consulting Engineers for Points W1 and PW1. This information is presented in Table 5.2.

Results from water samples taken during this study are presented in Tables 5.3 to 5.8.

Comparison of water quality information from this study with the background information in Table 5.2 shows no major disparities between the two sets of information. The pH values recorded during this study are approximately one pH unit higher than those in the background information. Lead and nickel concentrations are lower. This may indicate a successful effect of the reclamation scheme at the Hafna mine, although detailed comparisons are hampered by the fact that Parkman's samples have generally been analyzed by methods with higher (coarser) detection limits. It is impossible to estimate metal removal due to the wetland from Parkman's data since not all water enters the wetland past Point PW1 or leaves it past Point W1.

Upon receipt of the results from the first set of water samples (taken on 3 April 1992 for Point W2 and 12 March 1992 for all other areas), influent arsenic, copper, nickel and sulphate concentrations are unlikely to harm aquatic life, by reference to Gardiner and Mance (1984). Thus these parameters were removed from the analysis suite. The determination of aluminium was also removed; apart from an isolated high valve at W2 on 3 April 1992, levels are insignificant. The determination of hardness was also discontinued after the first set of data had been received. The variation of hardness across the five water sample points is less than that observed in the background information in Table 5.2.

Initial observations are that pH and dissolved oxygen concentrations and water hardness are not effected significantly by the passage through the wetland.

Point W2 was not sampled on 12 March 1992.

A hydrological model of the wetland was developed, based on considering flows past points W3, W4 and W5 as the total entry of MCMD to the wetland and flows past W1 and W2 as the total effluent from the wetland.

Results from this model are presented in Table 5.7, and shown graphically in Figure 5.4. Removal of lead is consistent for the three sets of results, averaging at 82% or some 2.3 g/h. Removal of zinc, manganese and iron is highly variable. This variation indicates either that the removal processes themselves vary in their efficiency and or that the model is oversimplified and factors unaccounted for in the model are responsible for the variability. The wetland represents a sink for some 8% of Influent manganese, but a net source of cadmium, zinc and iron based on the average of three sets of results. The set of results from the 21 May 1992 shows the greatest removal for all metals. This suggests that there was a change in the ability of the wetland to

		25/7/91		26/8/91		3/8/91		8/11/91		12/12/91	
Parameter	Units	PW1	W1	PW1	W1	PW1	W1	PW1	W1	PW1	W1
pH		6.0	5.7	6.4	5.6	6.9	6.2	6.6	5.7	5.5	5.7
Dissolved Oxygen	mg/l	-	-	-	-	-	-	-	-	-	-
Suspended Solids	mg/l	-	-	-	-	-	-	-	-	-	-
Alkalinity pH 4.5	mg/l	-	-	-	-	-	-	-	-	-	-
Sulphate	mg/l	-	-	-	-	-	-	-	-	-	-
Magnesium	mg/l	< 6.2	0.1	< 7.2	< 3.9	1.47	1.37	1.8	2	4.12	3.96
Calcium	mg/l	28	< 4.4	46	28	6	6.7	16	23	21.94	19.43
Lead	µg/l	< 200	< 100	< 100	< 100	430	380	20	10	360	550
Cadmium	µg/l	< 50	< 50	< 50	< 50	< 50	< 50	< 10	< 20	10	10
Copper	µg/l	< 100	< 100	100	100	70	90	< 10	20	< 10	< 20
Zinc	µg/l	2900	2500	2700	3200	2910	3750	2900	2300	30	70
Arsenic	µg/l	-	-	-	-	-	-	-	-	-	-
Manganese	µg/l	-	-	-	-	-	-	-	-	-	-
Iron	µg/l	100	100	100	100	500	780	10	30	70	130
Nickel	µg/l	100	100	100	100	10	10	10	10	100	100
Aluminium	µg/l	-	-	-	-	-	-	-	-	-	-
Hardness	mg/l	< 96	< 11	< 145	< 86	21	22	47	66	72	65
Conductivity	µS/cm	-	-	-	-	-	-	-	-	-	-
Flow rate	l/s	-	-	-	-	-	-	-	-	-	-

Table 5.2 The Hafna wetland area: background water quality information information provided by Parkman Consulting Engineers

Table 5.3 The Hafna wetland area: water quality, 12 March 1992

Parameter	Units	W1	W3	W4	W5
pH		6.9	7.1	7.5	7.5
Dissolved Oxygen	mg/l	9.9	11.0	10.9	10.9
Suspended Solids	mg/l	< 1.0	13.6	76.0	4.4
Alkalinity pH 4.5	mg/l	48.0	18.3	49.0	52.0
Sulphate	mg/l	38.75	28.35	32.79	17.19
Magnesium	mg/l	3.18	2.41	3.36	3.18
Calcium	mg/l	27.3	13.5	26.9	26.8
Lead	µg/l	29	175	1130	74
Cadmium	µg/l	13.2	23.4	18.6	5.5
Copper	µg/l	8.2	2.9	8.1	1.7
Zinc	µg/l	2580	3890	3200	950
Arsenic	µg/l	< 2.0	< 2.0	< 2.0	< 2.0
Manganese	µg/l	33.1	43.1	357	13.4
Iron	µg/l	29.7	244.5	2877	175.4
Nickel	µg/l	5.8	4.3	7.4	9.5
Aluminium	µg/l	0.05	0.07	0.87	0.08
Hardness	mg/l	81	44	81	80
Conductivity	µS/cm	-	-	-	-
Flow rate	l/s	3.5	1.0	3.0	0.2
Loading:					
Sulphate	g/h	488.25	102.06	354.13	12.38
Magnesium	g/h	40.07	8.68	36.29	2.29
Calcium	g/h	343.98	48.60	290.52	19.30
Lead	g/h	0.37	0.63	12.20	0.05
Cadmium	g/h	0.17	0.08	0.20	0.00
Copper	g/h	0.10	0.01	0.09	0.00
Zinc	g/h	32.51	14.00	34.56	0.68
Arsenic	g/h	0.00	0.00	0.00	0.00
Manganese	g/h	0.42	0.16	3.86	0.01
Iron	g/h	0.37	0.88	31.07	0.13
Nickel	g/h	0.07	0.02	0.08	0.01
Aluminium	g/h	0.00	0.00	0.01	0.00

Table 5.4 The Hafna wetland area: water quality, 3 April 1992

Parameter	Units	W1	W2	W3	W4	W5
pH		7.0	7.0	-	7.4	7.4
Dissolved Oxygen	mg/l	-	11.3	-	-	
Suspended Solids	mg/l	< 1.0	< 1.0	-	1.2	< 1.0
Alkalinity pH 4.5	mg/l	38.0	49.5	-	52.0	52.5
Sulphate	mg/l	-	46.76	-	-	-
Magnesium	mg/l	-	5.06	-	-	-
Calcium	mg/l	-	39.9	-	-	-
Lead	μg/l	10	28	-	168	7.0
Cadmium	μg/l	12.0	17.5	-	15.1	5.0
Copper	μg/l	-	29.2	-	-	-
Zinc	μg/l	2150	3510	-	2480	769
Arsenic	μg/l	-	< 2	-	-	-
Manganese	μg/l	27.6	20.3	-	41.2	6.0
Iron	μg/l	52.2	305.1	-	16.3	62.2
Nickel	μg/l	-	3	-	-	-
Aluminium	μg/l	-	54	-	-	-
Hardness	mg/l	-	121	-	-	-
Conductivity	μS/cm	229	275	-	244	214
Flow rate	l/s	3.4	3.7	-	4.2	0.10
Loading:						
Sulphate	g/h	-	622.84	-	-	-
Magnesium	g/h	-	67.40	-	-	-
Calcium	g/h	-	531.47	-	-	-
Lead	g/h	0.12	0.37	-	2.54	0.00
Cadmium	g/h	0.15	0.23	-	0.23	0.00
Copper	g/h	-	0.39	-	-	-
Zinc	g/h	26.32	46.75	-	37.50	0.28
Arsenic	g/h	-	0.0	-	-	-
Manganese	g/h	0.34	0.27	-	0.62	0.00
Iron	g/h	0.64	4.06	-	0.25	0.02
Nickel	g/h	-	0.04	-	-	-
Aluminium	g/h	-	0.72	-	-	-

Notes:
There was no water flowing past Point W3 on this date.

Table 5.5 The Hafna wetland area: water quality, 1 May 1992

Parameter	Units	W1	W2	W3	W4	W5
pH		7.1	7.4	7.1	7.7	7.7
Dissolved Oxygen	mg/l	-	-		-	-
Suspended Solids	mg/l	< 1	< 1	< 1	2	< 1
Alkalinity pH 4.5	mg/l	42.5	53	18.5	-	53.5
Sulphate	mg/l	-	-	-	-	-
Magnesium	mg/l	-	-	-	-	-
Calcium	mg/l	-	-	-	-	-
Lead	µg/l	9	33	52	155	15
Cadmium	µg/l	12.7	17.5	19.8	15.3	5.6
Copper	µg/l	-	-	-	-	-
Zinc	µg/l	2330	2670	3460	2400	863
Arsenic	µg/l	-	-	-	-	-
Manganese	µg/l	51.4	38.9	16.7	58.4	5.5
Iron	µg/l	357.3	113.6	18.5	285.7	76.5
Nickel	µg/l	-	-	-	-	-
Aluminium	µg/l	-	-	-	-	-
Hardness	mg/l	-	-	-	-	-
Conductivity	µS/cm	244	229	160	244	229
Flow rate	l/s	5.3	5.1	0.06	5.1	0.1
Loading:						
Sulphate	g/h	-	-	-	-	-
Magnesium	g/h	-	-	-	-	-
Calcium	g/h	-	-	-	-	-
Lead	g/h	0.17	0.61	0.01	2.85	0.01
Cadmium	g/h	0.24	0.32	0.00	0.28	0.00
Copper	g/h	-	-	-	-	-
Zinc	g/h	44.46	49.02	0.77	44.06	0.37
Arsenic	g/h	-	-	-	-	-
Manganese	g/h	0.98	0.71	0.00	1.07	0.00
Iron	g/h	6.82	2.09	0.00	5.25	0.03
Nickel	g/h	-	-	-	-	-
Aluminium	g/h	-	-	-	-	-

Table 5.6 The Hafna wetland area: water quality, 21 May 1992

Parameter	Units	W1	W2	W3	W4	W5
pH		7	7.5	-	7.7	7.6
Dissolved Oxygen	mg/l	-	-	-	-	-
Suspended Solids	mg/l	1.2	< 1	-	2	< 1
Alkalinity pH 4.5	mg/l	44.5	69.5	-	58	54
Sulphate	mg/l	-	-	-	-	-
Magnesium	mg/l	-	-	-	-	-
Calcium	mg/l	-	-	-	-	-
Lead	µg/l	10	34	-	155	21
Cadmium	µg/l	7	19	-	15.3	6
Copper	µg/l	-	-	-	-	-
Zinc	µg/l	2350	4180	-	2890	754
Arsenic	µg/l	-	-	-	-	-
Manganese	µg/l	36	35	-	150	21
Iron	µg/l	170	86	-	3570	1020
Nickel	µg/l	-	-	-	-	-
Aluminium	µg/l	-	-	-	-	-
Hardness	mg/l	-	-	-	-	-
Conductivity	µS/cm	244	305	-	267	244
Flow rate	l/s	3.6	0.9	-	5.5	0.05
Loading:						
Sulphate	g/h	-	-	-	-	-
Magnesium	g/h	-	-	-	-	-
Calcium	g/h	-	-	-	-	-
Lead	g/h	0.13	0.11	-	3.07	0.00
Cadmium	g/h	0.09	0.06	-	0.30	0.00
Copper	g/h	-	-	-	-	-
Zinc	g/h	30.46	13.54	-	57.22	0.14
Arsenic	g/h	-	-	-	-	-
Manganese	g/h	0.47	0.11	-	2.97	0.00
Iron	g/h	2.20	0.28	-	70.69	0.18
Nickel	g/h	-	-	-	-	-
Aluminium	g/h	-	-	-	-	-

Notes:
There was no water flowing past Point W3 on this date.

Table 5.7 The Hafna wetland area: water quality summary

Parameter	Units	3 April	1 May	21 May	Average
Lead					
Influent loading	g/h	2.54	2.85	3.07	2.82
Effluent loading	g/h	0.50	0.78	0.24	0.50
Reduction	g/h	2.05	2.07	2.83	2.32
Reduction	%	81	73	92	82
Cadmium					
Influent loading	g/h	0.23	0.28	0.30	0.27
Effluent loading	g/h	0.38	0.56	0.15	0.37
Reduction	g/h	-0.15	-0.28	0.15	-0.09
Reduction	%	-65	-99	50	-38
Zinc					
Influent loading	g/h	37.77	44.44	57.36	46.52
Effluent loading	g/h	73.07	93.48	44.00	70.18
Reduction	g/h	-35.29	-49.04	13.36	-23.66
Reduction	%	-93	-110	23	-60
Manganese					
Influent loading	g/h	0.63	1.07	2.97	1.56
Effluent loading	g/h	0.61	1.69	0.58	0.96
Reduction	g/h	0.02	-0.62	2.39	0.60
Reduction	%	3	-58	80	8
Iron					
Influent loading	g/h	0.27	5.28	70.87	25.47
Effluent loading	g/h	4.70	9.09	2.48	5.42
Reduction	g/h	-4.43	-3.81	68.39	20.05
Reduction	%	-1649	-72	96	-542

Table 5.8 The Hafna wetland area: dissolved and total metal concentrations

		3 April 1992		1 May 1992	
		W4	W4	W4	W4
Parameter	Units	Total	Dissolved	Total	Dissolved
Lead	µg/l	168	-	155	114
Cadmium	µg/l	15.1	-	15.3	13.1
Zinc	µg/l	2480	2480	2400	2340
Manganese	µg/l	41.2	44	58.4	39
Iron	µg/l	16.3	<20	285.7	11.4

Table 5.9 The Hafna wetland area: soil chemical characteristics

Parameter	Units	S1	S2	S3	S4	S5	S6
pH		7.6	7.2	7.1	8.2	6.6	6.0
Zinc	mg/kg	3583	5624	6068	8238	10330	18467
Cadmium	mg/kg	23.7	30.1	22.5	28.6	35.1	219.3
Manganese	mg/kg	2668	5099	1720	3621	4027	808.4
Iron	mg/kg	18807	19321	46215	57012	26808	25199
Organic solids	%	34.2	45.6	40.1	39.9	86.1	80.7

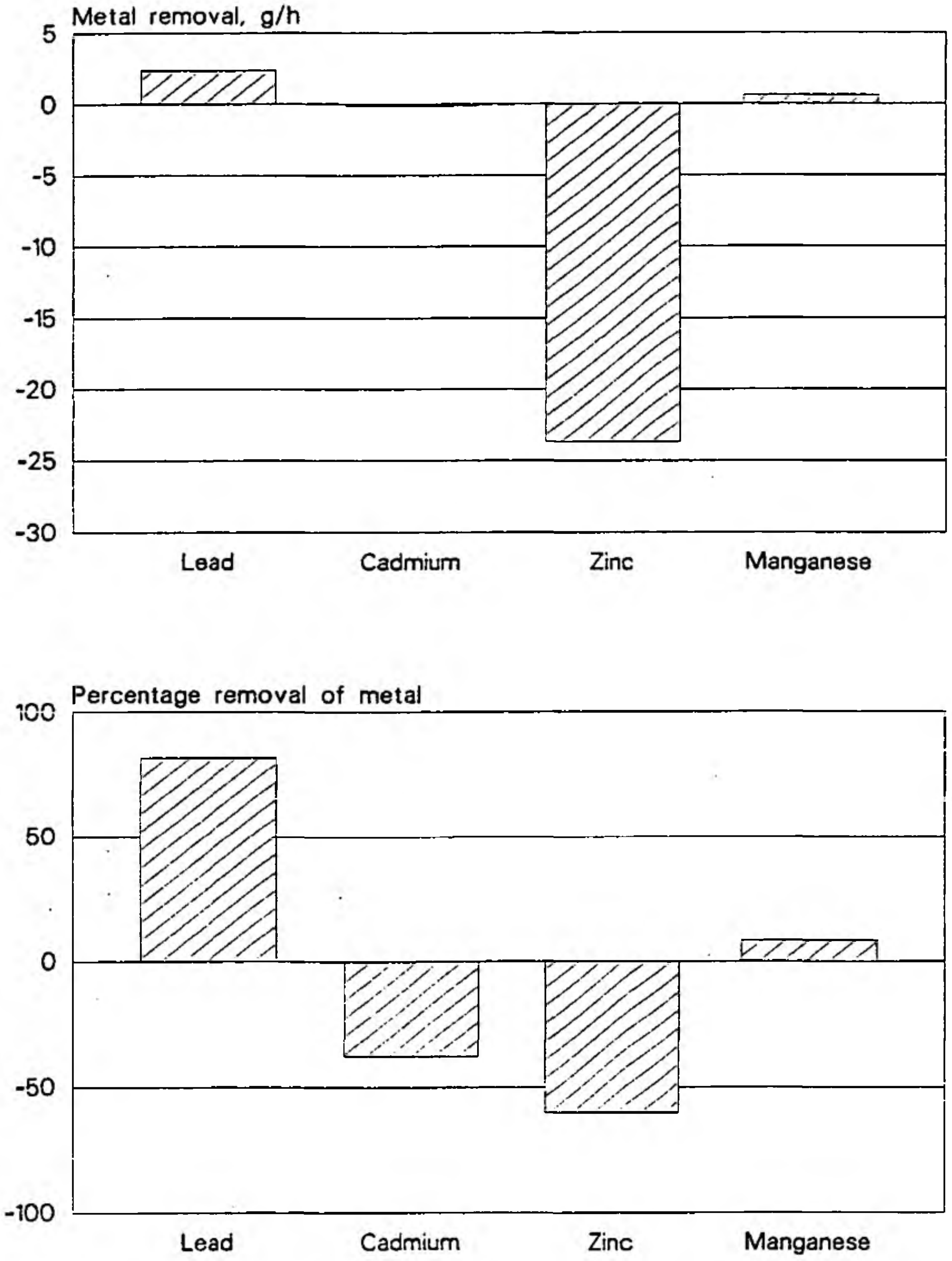

Figure 5.4 The Hafna wetland area: metal removal and percentage metal removal

remove metals. Subsequent sampling visits would be necessary to determine whether this change was due to seasonal effects or not. Averaging the metal removal figures assumes that seasonal changes in removal ability can be neglected.

The data in Table 5.8 suggest that, apart from iron, the metals are present predominantly in water soluble forms. These water soluble forms are more biologically available.

The data suggest that the suspended solids contain iron, and that the soluble iron loading of the wetland is low. At other pHs and other suspended solids concentrations, the partitioning of the metal between suspended and dissolved forms may be different. pH and suspended solids concentrations on 3 April 1992 and 1 May 1992 are comparable.

The decision to determine dissolved metal concentrations was taken on the basis of the high suspended solids concentration at W4 on the first sample date. Such high concentrations were not found on subsequent sampling dates, and may have been due to reclamation work upstream.

Various factors complicate the study of this wetland area. Firstly, the flow path of the MCMD through the area is complicated. The area of *Carex*-dominated swamp to the north of the pool (part of 'A' on Figure 5.3) might be expected to have the greatest metal removal ability since it is relatively large in extent and the flows past Points W4 and W5 enter the area. It was not possible to investigate this area in isolation since there is no defined outflow from this area. Also, the water may flow through the underlying tailings and bypass the wetland. Water flowing along the concrete pipe from the pool to point W2 will emerge virtually untreated.

Secondly, since the area is underlain by tailings it is uncertain what proportion of metal input into the wetland results from influent MCMD and what proportion results from vertical migration of metals from the underlying spoil.

5.5 Soil profile and soil chemical characteristics

The results from the investigation of the soil profile using the hand auger are presented in Figure 5.5. Observations made include:

- The organic layer is thin (less than 0.1 metre) over the majority of the wetland area.
- Despite this, root penetration under the *Carex* and *Phragmites*-dominated areas may be down to some 0.5 metres.
- Fine clayey tailings underlie the south part of the wetland area (based on profiling at A2 and A3) whereas the north part is underlain by coarse tailings. In the pool, coarse tailings lie under fine, clayey tailings.
- At A1 a layer of tailings separates two organic layers. This may be evidence of a past event causing major washing down of clayey tailings to this point, alternatively it may reflect the fact that an abandoned part of the tailings pond, which had naturally revegetated, was used once again.

Chemical characteristics of soil samples S1 to S6 are shown in Table 5.9. Comparison with typical values for agricultural soils (Table 3.2) indicates that the soils are heavily contaminated with zinc, cadmium and manganese.

The soil samples in the *Carex* dominated area ('A'), S5 and S6, are higher in zinc and cadmium then the other four samples, and are lower in pH. This may reflect their closer proximity to the coarse spoil, or may be due to the higher organic content, binding; these metal ions can be adsorbed onto the surface of organic material.

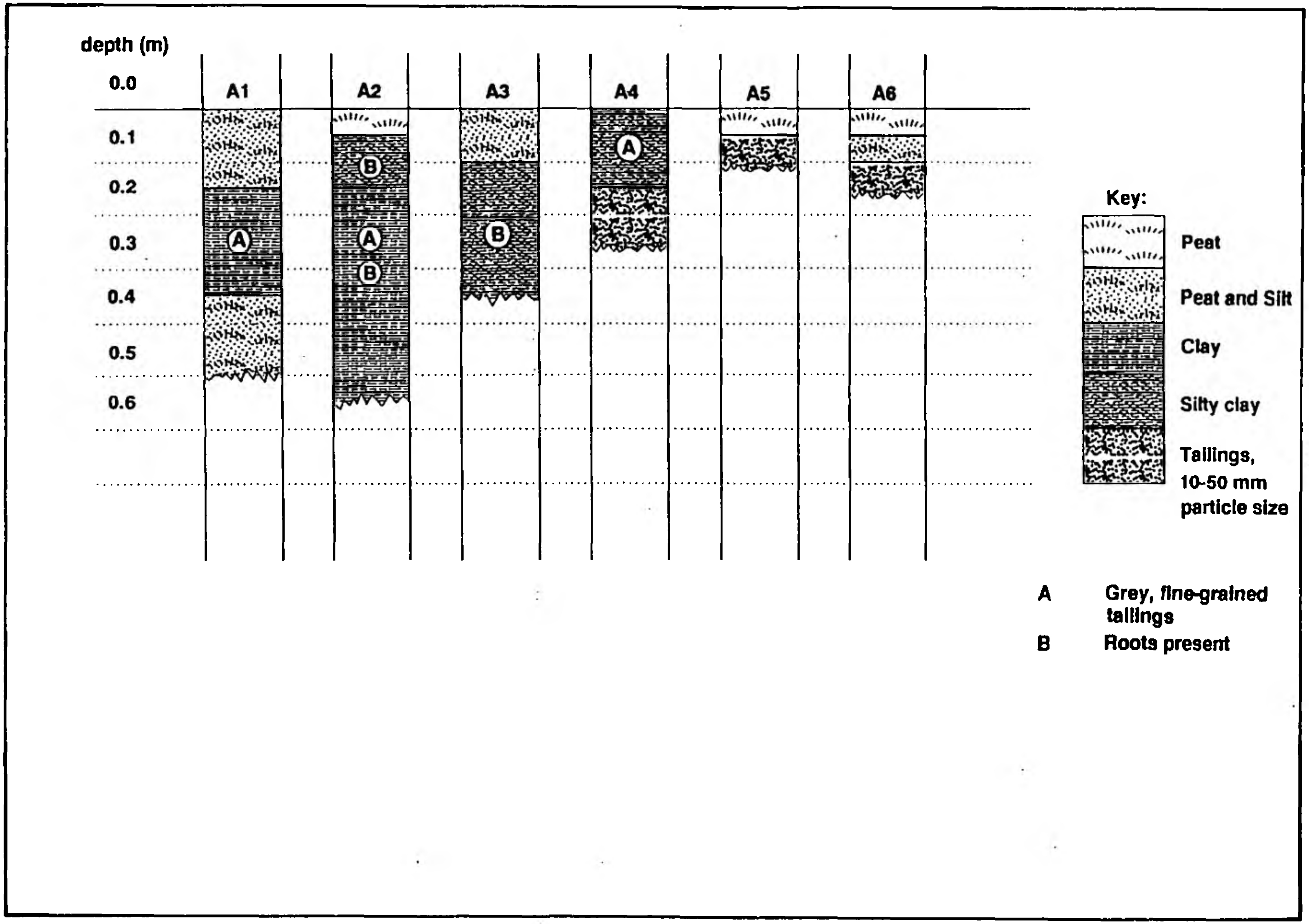

Figure 5.5 The Hafna wetland area: hand auger profiles

6. THE ESGAIR FRAITH WETLAND AREA

6.1 Historical introduction (from Bick 1976)

The nearby Esgair Hir mine (NGR SH 735 912) was first worked in the late seventeenth century. The mine achieved renown for being the first to successfully challenge the Crown monopoly on mineral deposits of gold and silver. The area was subsequently promoted as the 'Welsh Potosi', alluding to the fabulous silver mines of Peru. The area failed to live up to its namesake and instead attracted company after company to their doom.

The Esgair Fraith mine was opened in the 1690s as a copper prospect but was abandoned by 1708 having, in the words of the promoter, "never yielded one farthing profit".

In the 1840s there was heavy investment in the Esgair Fraith mine with the construction of the pumping wheel, roads and barracks. It was worked for a few years from 1854 before losses forced closure, again in 1858, then again for a few years from 1870. A seam of very high grade copper ore was encountered during work between 1877 and 1882 but, with this attempt again, substantial losses forced liquidation of the mining company.

The total output of the Esgair Fraith mine has been estimated at 146 tonnes of lead ore and 2730 tonnes of copper ore.

The location of the Esgair Hir and Esgair Fraith mines and the wetland area is shown in Figure 6.1.

6.2 Description

6.2.1 Morphology (see Figure 6.2)

The Esgair Fraith wetland area consists of two parallel, partially water-filled channels running north to south, with a common outflow to the Afon Lluest-gota (see Figure 6.2). The two channels appear man-made. The west channel is in the location marked as the portal for the deep adit in Bick (1976). Water issues from the ground at the northern corner of the channel. Surface water also runs in from the north west. A stream is marked on historical maps (Palmer 1983) passing through the area occupied by the east channel. This stream cannot now be located and water in the east channel is static.

Water from the blocked deep adit is mixed with surface water before flowing through the west pool then over a small weir into the east pool. The two pools are generally 0.3-0.5 metres in depth. The water then flows as a narrow stream until its confluence with the Afon Lluest-gota.

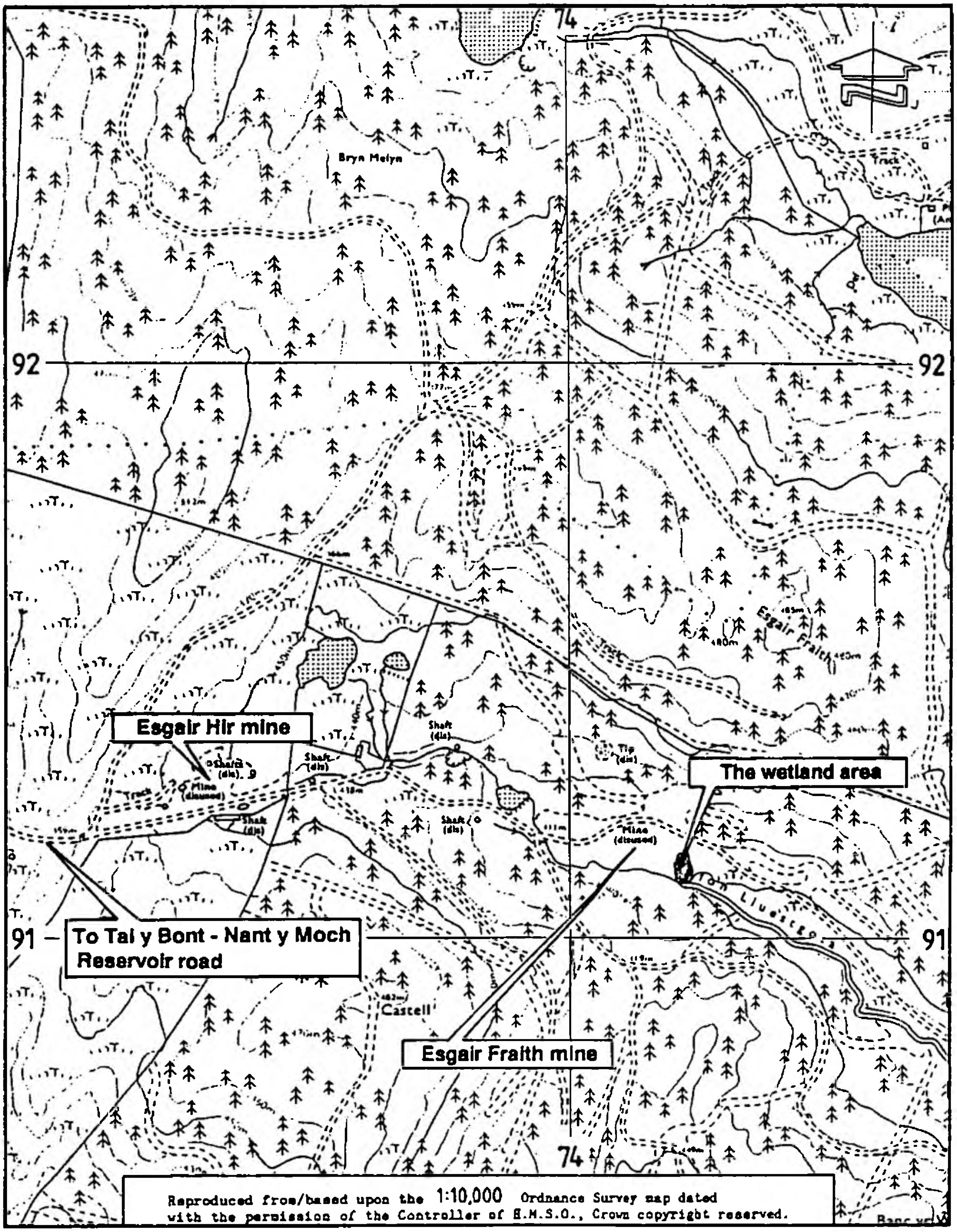

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Figure 6.1 The Esgair Fraith wetland area: location

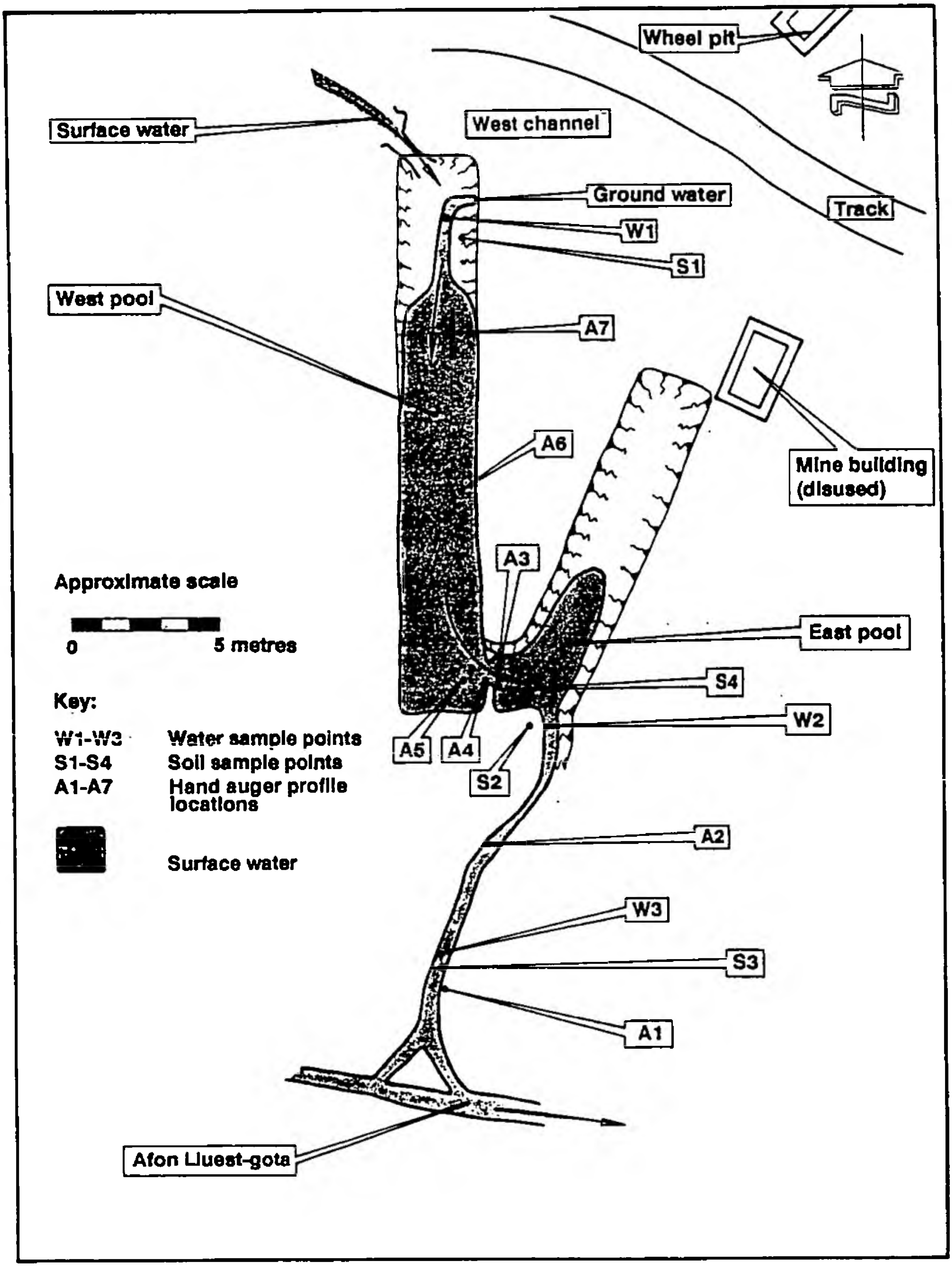

Figure 6.2 The Esgair Fraith wetland area: morphology

6.2.2 **Vegetation** (See Figure 6.3)

The vegetation of this wetland area is a mosaic of wetland and heathland vegetation. Much *Philotis fontana* grows in the water particularly in the western arm. Species lists for areas noted are given below:

A Heathland on dry ridges.

Calluna vulgaris
Galium saxatile
Vaccinium myrtilis
Erica tetralix
Molinia caerulea
Festuca ovina
Deschampsia cespitosa
Juncus effusus
Blechnum spicant

Bryophytes:
Dicranum scoparium
Rhacomitrium lanuginosum
Pleurozium schreberi
Abundant *Cladonia* sp.

B Disturbed area dominated by *Agrostis capillaris*.

C Wet flush.

Molinia caerulea
Deschampsia cespitosa
Festuca rubra
Juncus effusus
Cardamine pratensis
Rumex acetosa
Cirsium palustre

D *Sphagnum* bog.

Sphagnum recurvum
Polytrichum commune in drier parts.

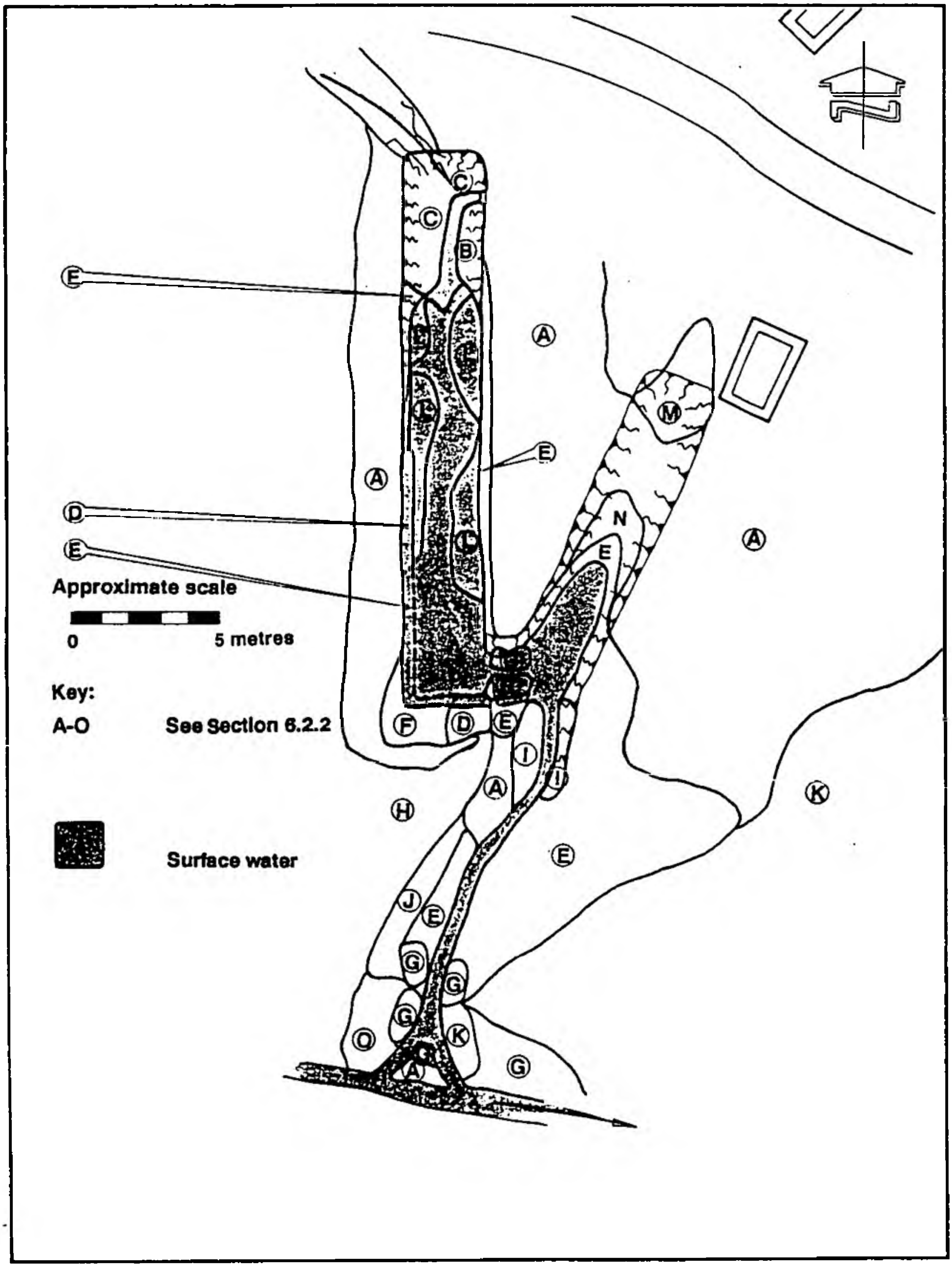

Figure 6.3 The Esgair Fraith wetland area: vegetation

E	Rushes.
	Juncus effusus-dominated
F	Dry bryophyte heath.
	Polytrichum commune *Pleurozium schreberi*
G	Cotton grass bog.
	Eriophorum angustifolium *Festuca ovina* *Agrostis capillaris* *Narthecium ossifragum* in places
H	Acid grassland.
	Deschampsia flexuosa *Agrostis capillaris* *Festuca ovina*
I	Rushes.
	Mixed: *Juncus effusus* *Juncus articulatus*
J	Bog.
	Mixed: *Molinia caerulea* *Juncus effusus* *Sphagnum recurvum*
K	*Molinia*-dominated bog; some *Salix* colonizing.
L	*Philonotis fontana* turf.

M *Chamaenerion angustifolium.*

N Similar to A but dominated by *Nardus stricta.*

O Bare ground.

6.3 Sampling

The location of water and soil sampling points and hand auger profile locations are given in Table 6.1 and shown on Figure 6.2. Water samples were taken on 25 March 1992, 9 April 1992 and 19 May 1992. Flow measurements were taken on the same dates, at points W1 and W3 and at point A2. This latter point was used to estimate the volume of flow at W2 since this was the closest point suitable for volume of flow measurements.

Soil samples S1 to S4 were taken on 19 May 1992, from the depths given in Table 6.1. Hand auguring was carried out at locations A1 to A7 to investigate the soil profile on the same date.

On 19 May an estimate of the retention time of the wetland was made. A short disturbance was created at W1. The cloudy water took less than three minutes to reach the weir between east and west pools. Creating a short disturbance at the weir enabled the retention time of the east pool to be estimated (eight minutes). Therefore, a retention time of eleven minutes was estimated for the wetland.

The cloudy water is not an ideal 'tracer'. Such tracers should be 'neutral' *i.e.* follow the movement of the water exactly and not precipitate under their own weight. They should also not diffuse out in the direction of flow. However, the method employed enables a coarse estimate of retention time and also allows the flow path through the wetland to be observed; in both cases water flows directly from inflow to outflow point.

6.4 Water quality

Results from water samples taken during this study are presented in Tables 6.2 to 6.4.

No background information was available for this wetland area.

The MCMD draining into this area is relatively uncontaminated. Aluminium and zinc exceed EEC standards for drinking water (Gardiner and Mance 1984) but other metals do not.

Table 6.1 The Esgair Fraith wetland area: location of sampling points

Water sample points		Location
W1	Influent, west channel	NGR SH 74050 91150
W2	Outlet from east pool	NGR SH 74055 91130
W3	Twelve metres upstream from confluence with the Afon Lluest-gota	NGR SH 74050 91120

Soil sample points		Depth sampled
S1	Beneath moss by W1	0.3 m
S2	Beside outlet from pool	0.1 - 0.2 m
S3	By W3	0.1 - 0.2 m
S4	Sediment of east pool	From surface

Hand auger profile locations	
A1	By W3
A2	Seven metres downstream of W2
A3	By S4
A4	At weir between west and east pools
A5	In west pool, one metre from weir
A6	Ten metres north of A5
A7	Ten metres north of A6

Table 6.2 The Esgair Fraith wetland area: water quality, 25 March 1992

Parameter	Units	W1	W2	W3
pH		6.8	6.8	6.8
Dissolved Oxygen	mg/l	10.3	10.6	10.9
Suspended Solids	mg/l	< 1	< 1	< 1
Alkalinity pH 4.5	mg/l	14.5	14	13.5
Sulphate	mg/l	11.05	11.57	11.29
Magnesium	mg/l	2.6	2.72	2.61
Calcium	mg/l	6.99	7.14	7.01
Lead	µg/l	19	10	6
Cadmium	µg/l	2.8	2.6	2.6
Copper	µg/l	26.3	22	18.1
Zinc	µg/l	1070	973	904
Arsenic	µg/l	< 2	< 2	< 2
Manganese	µg/l	52.5	48.2	48.6
Iron	µg/l	46.3	21.5	44.6
Nickel	µg/l	8	13	8.8
Aluminium	µg/l	108.2	42.1	62.4
Hardness	mg/l	28	29	28
Conductivity	µS/cm	107	122	-
Flow rate	l/s	3.7	3	4.5
Loading:				
Sulphate	g/h	147.19	124.96	182.90
Magnesium	g/h	34.63	29.38	42.28
Calcium	g/h	93.11	77.11	113.56
Lead	g/h	0.25	0.11	0.10
Cadmium	g/h	0.04	0.03	0.04
Copper	g/h	0.35	0.24	0.29
Zinc	g/h	14.25	10.51	14.64
Arsenic	g/h	-	-	-
Manganese	g/h	0.70	0.52	0.79
Iron	g/h	0.62	0.23	0.72
Nickel	g/h	0.11	0.14	0.14
Aluminium	g/h	1.44	0.45	1.01

Table 6.3 The Esgair Fraith wetland area: water quality, 9 April 1992

Parameter	Units	W1	W2	W3
pH		7.0	6.9	3.5
Dissolved Oxygen	mg/l	-	-	-
Suspended Solids	mg/l	< 1	< 1	< 1
Alkalinity pH 4.5	mg/l	-	-	-
Sulphate	mg/l	13.90	13.97	13.95
Magnesium	mg/l	-	-	-
Calcium	mg/l	-	-	-
Lead	µg/l	13	7	5
Cadmium	µg/l	2.5	2.5	2.6
Copper	µg/l	12.8	13.4	12.5
Zinc	µg/l	910	922	915
Arsenic	µg/l	< 2	< 2	< 2
Manganese	µg/l	-	-	-
Iron	µg/l	-	-	-
Nickel	µg/l	-	-	-
Aluminium	µg/l	37.2	13.5	43.9
Hardness	mg/l	-	-	-
Conductivity	µS/cm	115	122	115
Flow rate	l/s	0.9	2	2.5
Loading:				
Sulphate	g/h	45.04	100.58	125.55
Magnesium	g/h	-	-	-
Calcium	g/h	-	-	-
Lead	g/h	0.04	0.05	0.05
Cadmium	g/h	0.01	0.02	0.02
Copper	g/h	0.04	0.10	0.11
Zinc	g/h	2.95	6.64	8.24
Arsenic	g/h	-	-	-
Manganese	g/h	-	-	-
Iron	g/h	-	-	-
Nickel	g/h	-	-	-
Aluminium	g/h	0.12	0.10	0.40

Table 6.4 The Esgair Fraith wetland area: water quality, 19 May 1992

Parameter	Units	W1	W2	W3
pH		7.0	6.9	6.9
Dissolved Oxygen	mg/l	-	-	-
Suspended Solids	mg/l	< 1	< 1	< 1
Alkalinity pH 4.5	mg/l	-	-	-
Sulphate	mg/l	10.78	13.97	10.35
Magnesium	mg/l	-	-	-
Calcium	mg/l	-	-	-
Lead	µg/l	18.46	7	11.46
Cadmium	µg/l	1.65	2.5	< 0.05
Copper	µg/l	20.28	13.4	15.98
Zinc	µg/l	1014	922	959
Arsenic	µg/l	2.4	< 2	< 2
Manganese	µg/l	-	-	-
Iron	µg/l	-	-	-
Nickel	µg/l	-	-	-
Aluminium	µg/l	38	12	14
Hardness	mg/l	-	-	-
Conductivity	µS/cm	92	84	99
Flow rate	l/s	1.1	1.9	2.7
Loading:				
Sulphate	g/h	42.69	95.55	100.60
Magnesium	g/h	-	-	-
Calcium	g/h	-	-	-
Lead	g/h	0.07	0.05	0.11
Cadmium	g/h	0.01	0.02	0.0
Copper	g/h	0.08	0.09	0.16
Zinc	g/h	4.02	6.31	9.32
Arsenic	g/h	0.01	0.0	0.0
Manganese	g/h	-	-	-
Iron	g/h	-	-	-
Nickel	g/h	-	-	-
Aluminium	g/h	0.15	0.08	0.14

Contaminant loadings of W1, W2 and W3 were averaged for the three sample visits. The averages are shown in Figure 6.4. The wetland is a net source of sulphate, zinc, lead, cadmium, copper and aluminium.

Some removal of lead and aluminium does however occur between W1 and W2.

The metal-removal performance of this wetland is extremely poor.

6.5 Soil profile and soil chemical characteristics

Soil profiles at points A1 to A7 are shown in Figure 6.5. Organic layer depths are quite variable. The north end of the west channel contains *Sphagnum* moss down to about 0.4 m. There is almost no organic layer in the two pools. The material underlying the organic layer is variable; gravel in the north end of the west channel, clayey silt in the south, silty gravel elsewhere.

The chemical characteristics of the soil samples are shown in Table 6.5. Samples are highly contaminated with lead, cadmium, copper and zinc. This suggests some translocation of metals from water to sediment. Soil sample S4 was taken from the surface of the east pool. It contained some vegetation (the bryophyte *Philonotis fontana*), upon which a flocculant precipitate had formed. This sample did not prove to be enriched with any of the metals in the soil analysis suite. Therefore precipitation as a metal removal mechanism is ruled out.

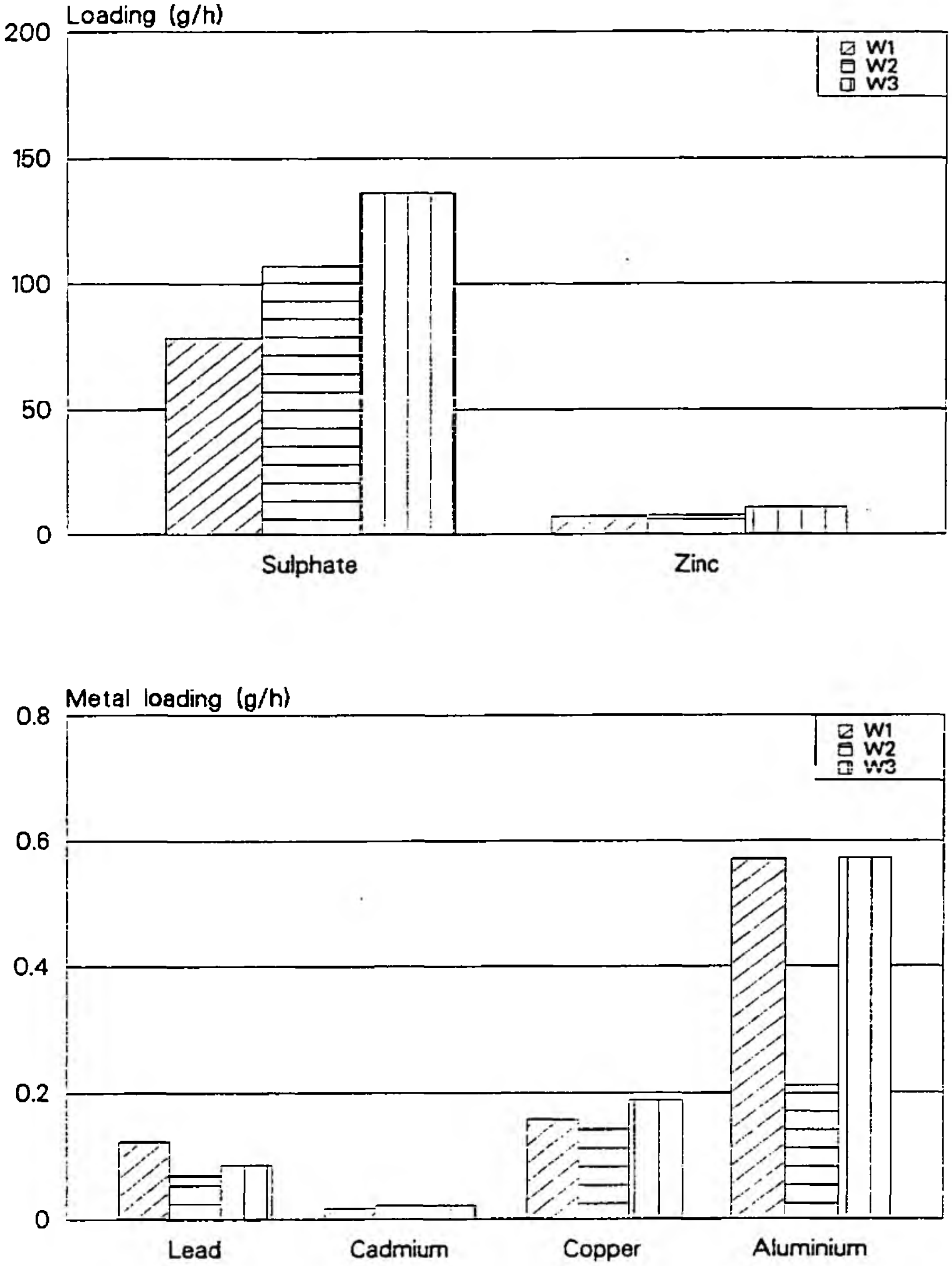

Figure 6.4 The Esgair Fraith wetland area: contaminant loading at points W1, W2 and W3

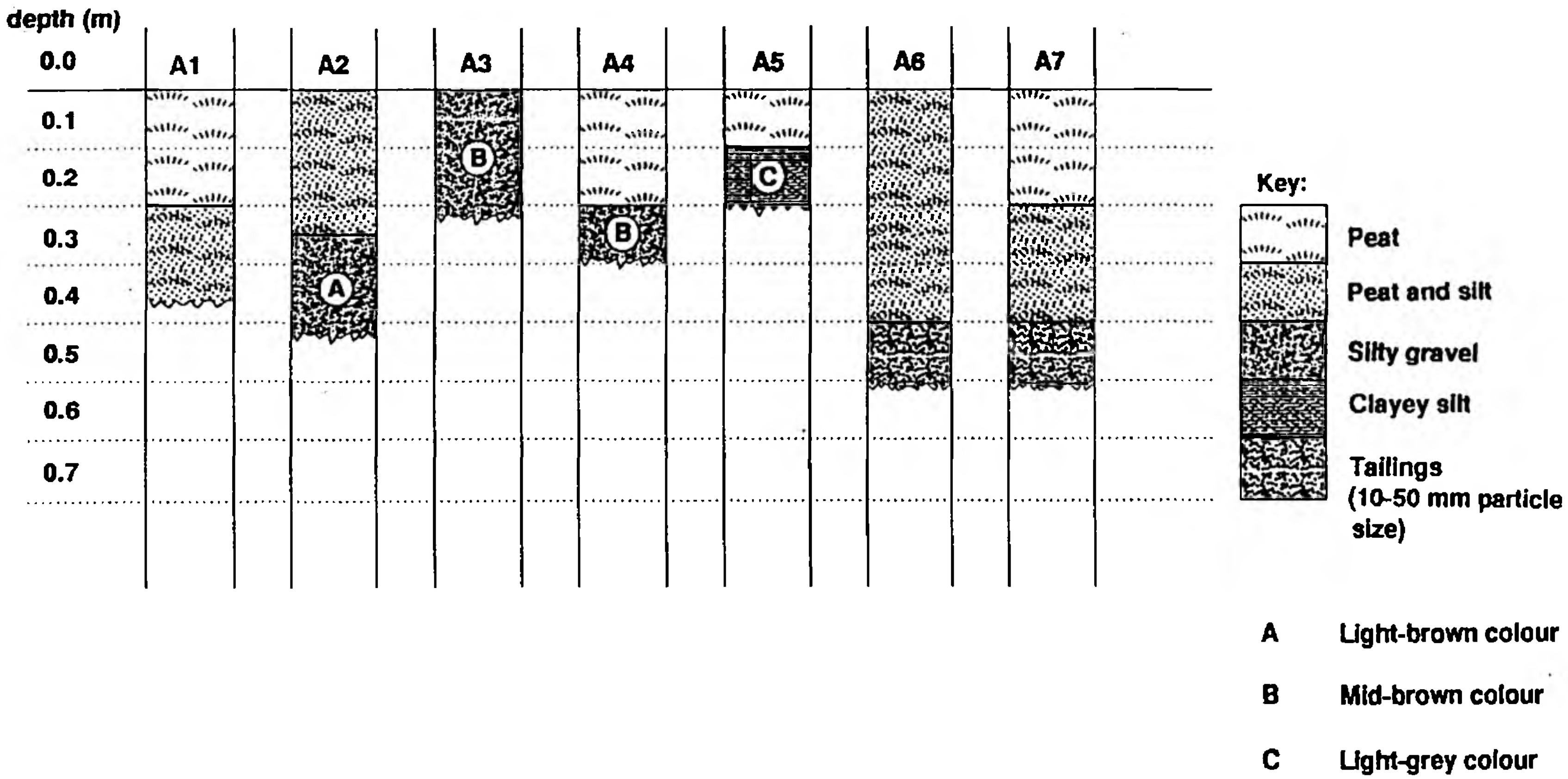

Figure 6.5 The Esgair Fraith wetland area: hand auger profiles

Table 6.5 The Esgair Fraith wetland area: soil chemical characteristics

Parameter	Units	S1	S2	S3	S4
pH		6.4	6.4	6.5	6.4
Organic solids	%	92	92	90	84
Lead	mg/kg	20614	14321	21159	6863
Cadmium	mg/kg	63	20	93	4
Copper	mg/kg	9307	5441	11064	2912
Zinc	mg/kg	9332	6033	15325	3034

Metal concentrations are mg/kg dry weight

7. THE CAMDWRBACH WETLAND AREA

7.1 Historical introduction (from Bick 1976)

Initial workings at the Camdwrbach Mine centred around an adit at NGR SH 738 893. Launched in 1878 and driven in some 90 fathoms (164 metres) the adit was said by the operator to contain rich courses of blende and galena with malachite and grey and black copper ores. The venture collapsed in 1882 having only sold a ton or two of blende.

At the turn of the twentieth century, attention shifted to the east. Near the head of the Camdwrbach stream, at NGR SH 747 892, a new adit was driven in. This venture fared little better, returning only 26 tons of blende and closing about 1905.

Recently, a prospector has reopened the adit at NGR 747892 and dug a trench to drain the water. No further prospecting work had taken place on 19 May 1992.

The locations of the adit, trench and wetland are shown in Figure 7.1.

7.2 Description

7.2.1 Morphology (see Figure 7.2)

The Camdwrbach wetland area is a small area of wetland vegetation some 20 metres by 3 metres in extent. It is situated immediately adjacent to a spoil heap. The particles of spoil are gravel-sized. The wetland is fed by adit water via the recently dug trench. It has a diffuse outflow: some surface water runs from the wetland and some drains through the ground. Care was taken to avoid sampling the wetland where runoff from the spoil could contaminate samples.

7.2.2 Vegetation (See Figure 7.3)

This wetland is dominated by *Juncus* bog. Very little seepage occurs from the adjacent spoil heap into the area sampled, however some seepage occurs from the western end of the spoil heap. Species lists for areas shown in Figure 7.3 are given below:

A *Juncus* bog.

Juncus effusus
Sphagnum spp.

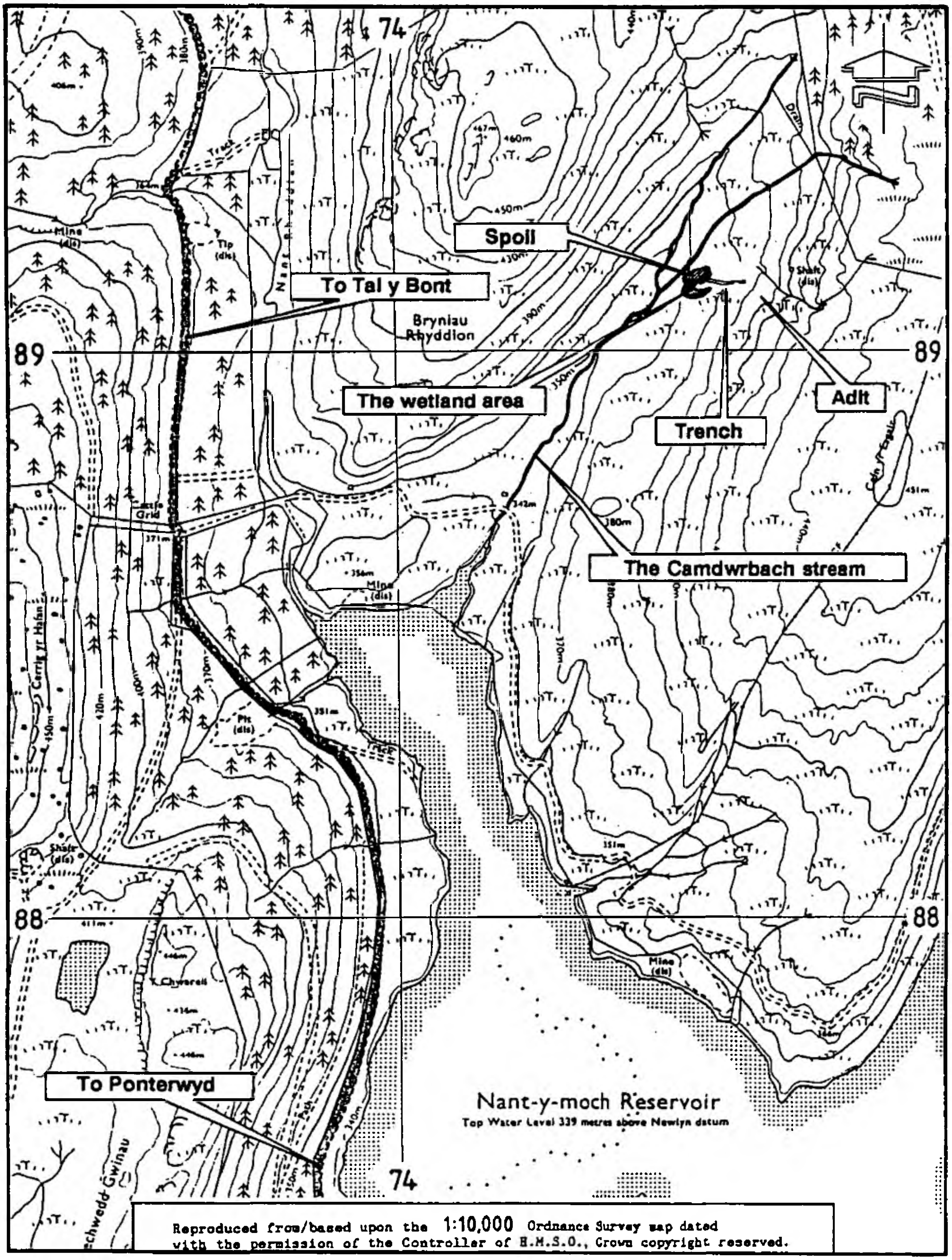

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Figure 7.1 The Camdwrbach wetland area: location

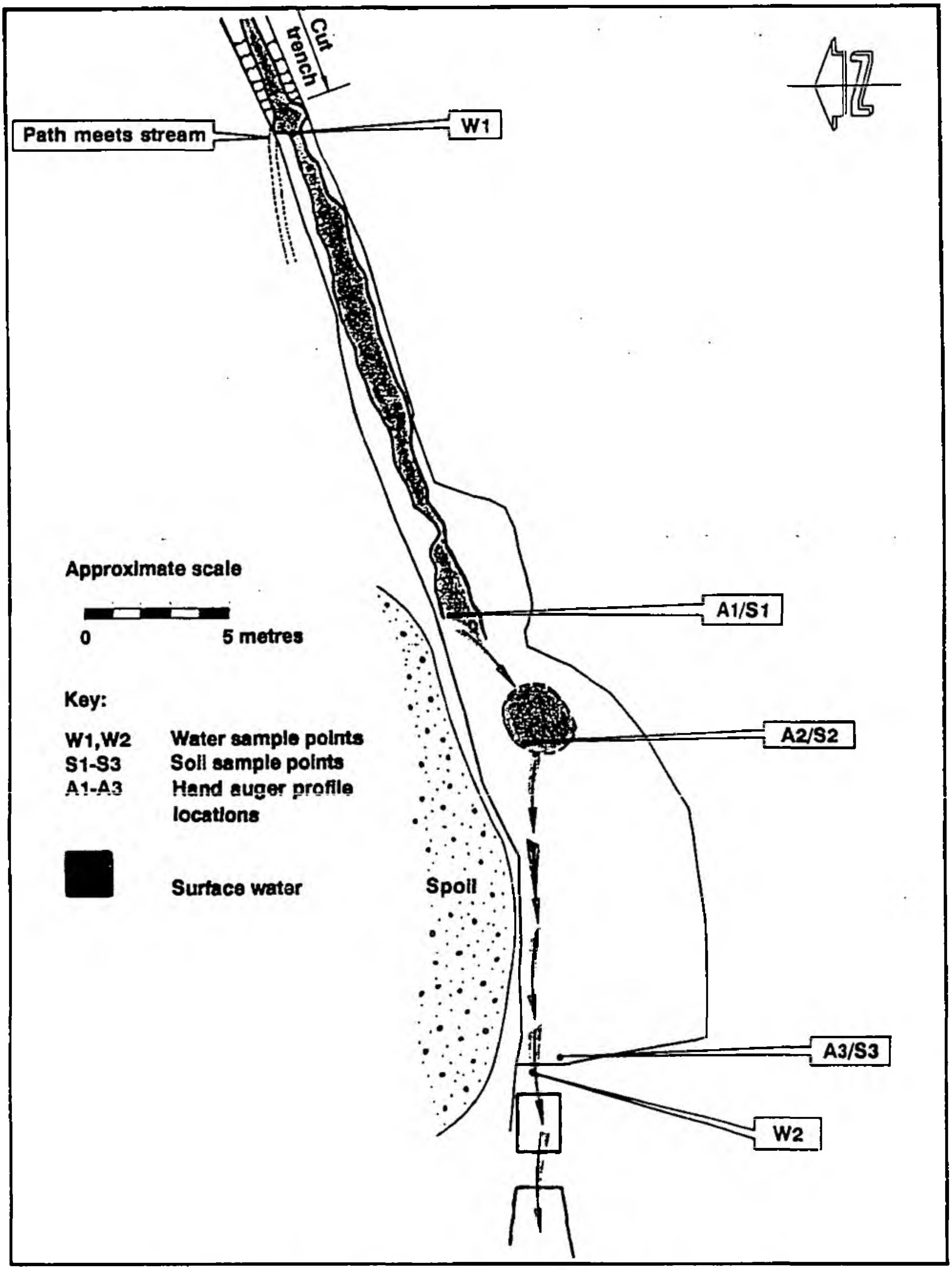

Figure 7.2 The Camdwrbach wetland area: morphology

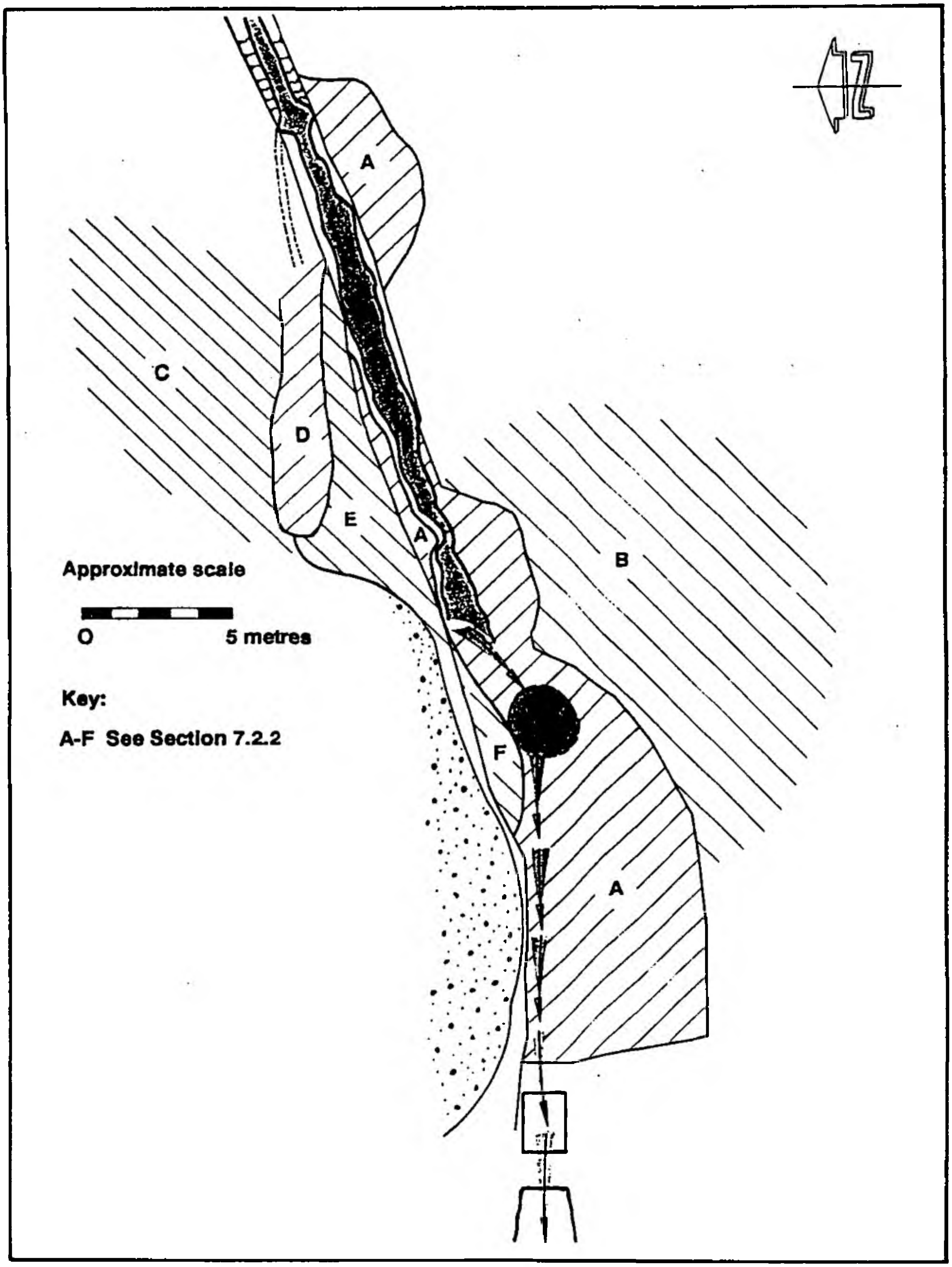

Figure 7.3 The Camdwrbach wetland area: vegetation

B *Molinia* bog.

Molinia caerulea
Some *Juncus effusus* and *Sphagnum* spp.

C Spoil community.

Festuca ovina
Agrostis capillaris
Polytrichum juniperinum
Some *Cladonia*
Much bare ground.

D Disturbed area from trench excavation.

E Fringe of herbaceous species grading into F at water's edge.

Juncus effusus
Agrostus capillaris
Cirsium palustre
Rhytidiadelphus squarrosus
Polytrichum commune

F Herb-rich area at water's edge

Stellaria alsine
Galium saxatile
Cardamine pratensis
Viola palustris
Holcus lanatus
Agrostis capillaris
Festuca ovina
Sphagnum spp.

Algae present in the stream at Point A1/S1 were coated with an orange precipitate.

7.3 Sampling

Water and soil sampling points and hand auger profile locations are given in Table 7.1 and shown on Figure 7.2.

Water samples were taken from points W1 and W2 on 25 March 1992, 9 April 1992 and 19 May 1992. An water sample filtered on-site was taken from point W2 on 19 May, since suspended solids concentrations were high. Soil samples were taken on 19 May 1992. Hand auger profiling of the soil was conducted on the same date.

Soil sample S4 was taken from an adjacent *Juncus* wetland uncontaminated by flow from the adit as a 'control' sample, to obtain local, uncontaminated soil metal concentrations.

7.4 Water quality

Background water quality data for the adit water were provided by the National Rivers Authority. These data are presented in Table 7.2.

Results from this study are presented in Tables 7.3, 7.4 and 7.5.

The data in Table 7.2 tally with results obtained during this study. The adit drainage is not grossly contaminated; only zinc, iron and manganese exceed EEC standards for drinking water (Gardiner and Mance 1984).

Since the water drains from the wetland in a diffuse manner the flow rate at W2 is less than that at W1. It can be argued that the flow rate information at W2 has little relevance. Hence, consideration of metal removal for this wetland area is based on differences in contaminant concentration between water entering and draining from the wetland, rather than changes in contaminant loading.

The data set for samples of 25 March 1992 had to be rejected. The high suspended solids concentrations at W2 reflects the disturbance caused during sampling. Due to this disturbance, effluent metal concentrations are not considered reliable. Considerable care was taken to avoid disturbance on subsequent sampling visits.

Figures for percentage reduction in contaminant concentration were generated for all contaminants on 9 April and 19 May. Averages of the figures for the two dates were calculated and are shown in Figure 7.4. Greater than 75% of reduction was observed for lead, cadmium, copper, zinc, manganese, iron and nickel. The wetland appears to be a source of sulphate.

Table 7.1 The Camdwrbach wetland: location of sample points

Water sample points		Location
W1	At the south end of cut trench, where small path meets stream	NGR SH 74570 89130
W2	At outlet, just up stream of the inflow of runoff from the spoil heap	NGR SH 74520 89115
Soil sample points		Depth
S1	Where flow becomes diffuse and enters *Juncus* wetland	0.1-0.2 m
S2	Ten metres downstream of S1	0.1-0.2 m
S3	By S2	0.1-0.2 m
S4	From adjacent *Juncus* wetland uncontaminated by MCMD from adit	0.1-0.2 m
Hand auger profile locations		
A1	By S1	
A2	By S2	
A3	By S3	

Figure 7.5 gives the reduction in contaminant concentration in terms of 9 g/h. Some 9 g/h manganese and 2-3 g/h zinc and iron are removed.

Reservations are held about these results. The first of these is concern over how representative water sampled at W2 is of the water draining from the wetland. The second is concern relating to the potential for water infiltration from the south and west through the ground down a slight slope into the wetland. Thirdly, there may be contamination of the wetland from the underlying spoil.

Table 7.2 The Camdwrbach wetland area: background water quality information provided by the National Rivers Authority

Parameter	Units	12 July 1990
pH		-
Dissolved Oxygen	mg/l	-
Suspended Solids	mg/l	-
Alkalinity pH 4.5	mg/l	-
Sulphate	mg/l	-
Magnesium	mg/l	-
Calcium	mg/l	-
Lead	µg/l	27
Copper	µg/l	34
Cadmium	µg/l	3
Zinc	µg/l	935
Arsenic	µg/l	-
Manganese	µg/l	-
Iron	µg/l	-
Nickel	µg/l	-
Aluminium	µg/l	65

Table 7.3 The Camdwrbach wetland area: water quality, 25 March 1992

Parameter	Units	W1	W2
pH		7.1	7.7
Dissolved Oxygen	mg/l	8.4	12.1
Suspended Solids	mg/l	1.6	29
Alkalinity pH 4.5	mg/l	72.5	64.5
Sulphate	mg/l	7.99	8.06
Magnesium	mg/l	5.25	5.21
Calcium	mg/l	23.8	24.6
Lead	µg/l	29	102
Copper	µg/l	32.2	34
Cadmium	µg/l	3.1	21.4
Zinc	µg/l	737	740
Arsenic	µg/l	< 2.0	2.5
Manganese	µg/l	1888	1813
Iron	µg/l	856	815
Nickel	µg/l	11.3	75.6
Aluminium	µg/l	171.3	1227.5
Hardness	mg/l	-	-
Conductivity	µS/cm	-	-
Flow rate	l/s	0.90	0.44
Loading:			
Sulphate	g/h	25.89	12.77
Magnesium	g/h	17.01	8.25
Calcium	g/h	77.11	38.97
Lead	g/h	0.09	0.16
Cadmium	g/h	0.01	0.03
Copper	g/h	0.10	0.05
Zinc	g/h	2.39	1.17
Arsenic	g/h	0.0	0.00
Manganese	g/h	6.12	2.87
Iron	g/h	2.77	1.29
Nickel	g/h	0.04	0.12
Aluminium	g/h	0.56	1.94

Table 7.4 The Camdwrbach wetland area: water quality, 9 April 1992

Parameter	Units	W1	W2
pH		7.1	8
Dissolved Oxygen	mg/l	8.6	10.0
Suspended Solids	mg/l	< 1	< 1
Alkalinity pH 4.5	mg/l	-	-
Sulphate	mg/l	10.24	11.11
Magnesium	mg/l	-	-
Calcium	mg/l	-	-
Lead	µg/l	21	< 1
Cadmium	µg/l	3.9	0.6
Copper	µg/l	32.1	4
Zinc	µg/l	917	190
Arsenic	µg/l	< 2	< 2
Manganese	µg/l	2510	75.1
Iron	µg/l	709	54.1
Nickel	µg/l	39.1	2.7
Aluminium	µg/l	0.1	44
Hardness	mg/l	-	-
Conductivity	µS/cm	214	191
Flow rate	l/s	0.89	0.35
Loading:			
Sulphate	g/h	32.81	14.00
Magnesium	g/h	-	-
Calcium	g/h	-	-
Lead	g/h	0.07	-
Cadmium	g/h	0.01	0.00
Copper	g/h	0.10	0.01
Zinc	g/h	2.94	0.24
Arsenic	g/h	0.00	0.00
Manganese	g/h	8.04	0.09
Iron	g/h	2.27	0.07
Nickel	g/h	0.13	0.00
Aluminium	g/h	0.00	0.06

Table 7.5 The Camdwrbach wetland area: water quality, 19 May 1992

Parameter	Units	W1	W2
pH		7.2	7.9
Dissolved Oxygen	mg/l	-	-
Suspended Solids	mg/l	1.6	1.2
Alkalinity pH 4.5	mg/l	-	-
Sulphate	mg/l	8.41	9.00
Magnesium	mg/l	-	-
Calcium	mg/l	-	-
Lead	µg/l	18.91	3.2
Cadmium	µg/l	< 0.05	< 0.05
Copper	µg/l	28.51	4.07
Zinc	µg/l	947.4	150.4
Arsenic	µg/l	2.8	2.4
Manganese	µg/l	2680.8	14.06
Iron	µg/l	576.3	< 0.02
Nickel	µg/l	9.62	< 1.0
Aluminium	µg/l	65	32
Hardness	mg/l	-	-
Conductivity	µS/cm	229	214
Flow rate	l/s	1.03	0.2
Loading:			
Sulphate	g/h	31.18	6.48
Magnesium	g/h	-	-
Calcium	g/h	-	-
Lead	g/h	0.07	0.00
Cadmium	g/h	-	-
Copper	g/h	0.11	0.00
Zinc	g/h	3.51	0.11
Arsenic	g/h	0.01	0.00
Manganese	g/h	9.94	0.01
Iron	g/h	2.14	-
Nickel	g/h	0.04	-
Aluminium	g/h	0.24	0.02

Table 7.6 The Camdwrbach wetland area: dissolved and total metal concentrations
Date of samples: 19 May 1992

Parameter	Units	W2 Total	W2 Dissolved
pH		7.9	-
Dissolved Oxygen	mg/l	-	-
Suspended Solids	mg/l	1.2	-
Alkalinity pH 4.5	mg/l	-	-
Sulphate	mg/l	9	-
Magnesium	mg/l	-	-
Calcium	mg/l	-	-
Lead	µg/l	3.2	< 1.0
Cadmium	µg/l	< 0.05	< 0.05
Copper	µg/l	4.07	< 20
Zinc	µg/l	150	136
Arsenic	µg/l	2.4	< 2
Manganese	µg/l	14.06	44
Iron	µg/l	< 0.02	96
Nickel	µg/l	< 1.0	2.3
Aluminium	µg/l	32	63

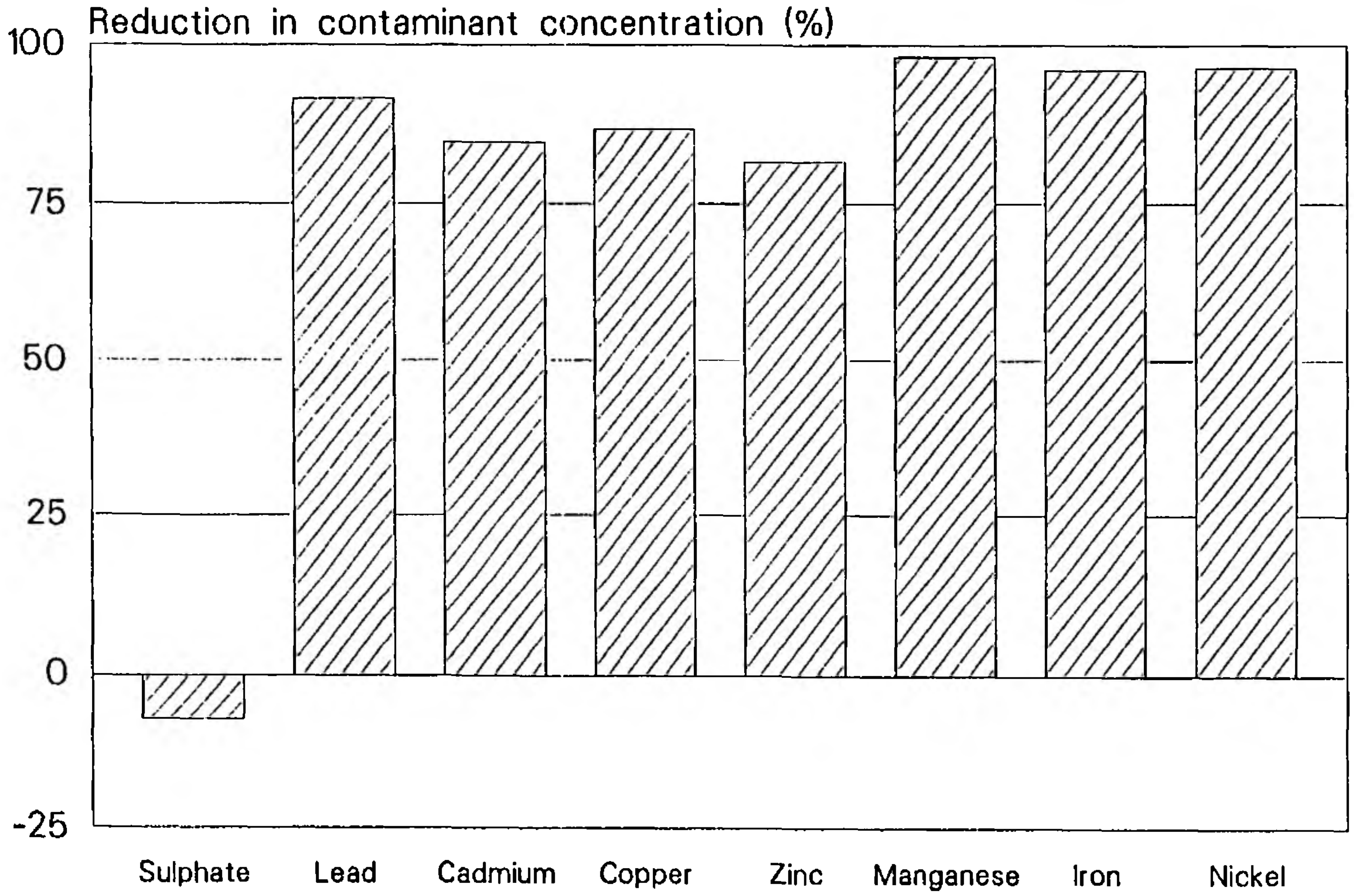

Figure 7.4 The Camdwrbach wetland area: contaminant removal, as a percentage of influent concentration

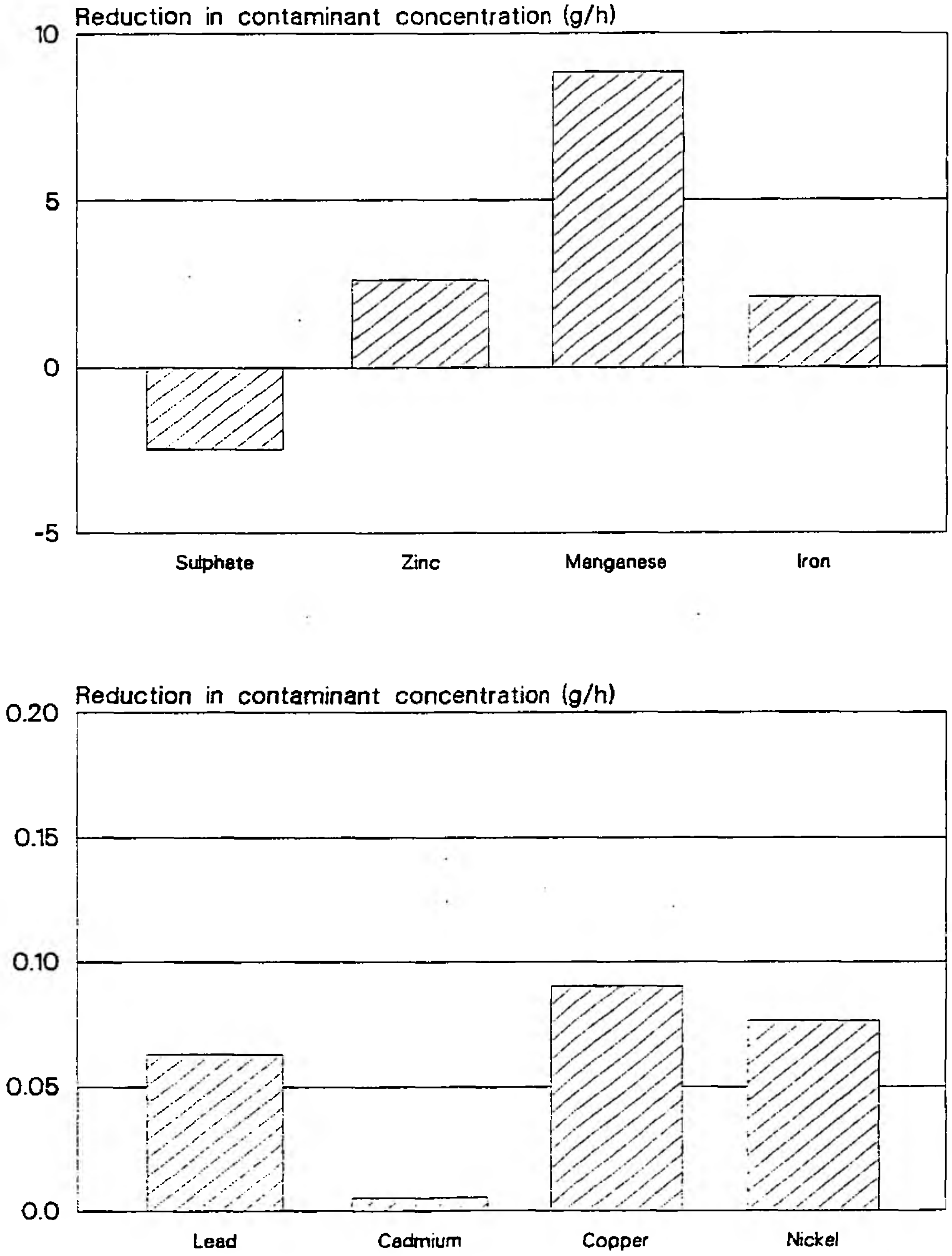

Figure 7.5 The Camdwrbach wetland area: contaminant removal

Internal return:

Information Services Unit
Rio House
Waterside Drive
Aztec West
Bristol
BS32 4UD

ISU Contact:
Int: 7-10-2856
Ext: 0117 914 2856
Email: Information centre

Please contact when/if:

- leaving Agency
- moving jobs
- moving location
- renewing item
- lending to another member of staff

7.5 Soil profile and soil chemical characteristics

The soil profile at points A1, A2 and A3 is shown in Figure 7.6. The organic layer seems to be some 0.2 - 0.3 m in depth and to lie directly on top of tailings.

Soil sample S1 was found to be slightly contaminated by lead, and heavily contaminated by cadmium, copper, zinc and nickel (see Table 7.7 and Table 3.2). S2 is less contaminated than S1 by all the metals investigation. S3 is less contaminated still.

Assuming exchange between water and sediment incurs to the same extent at points S1, S2 and S3 these results support the metal removal observed in water samples.

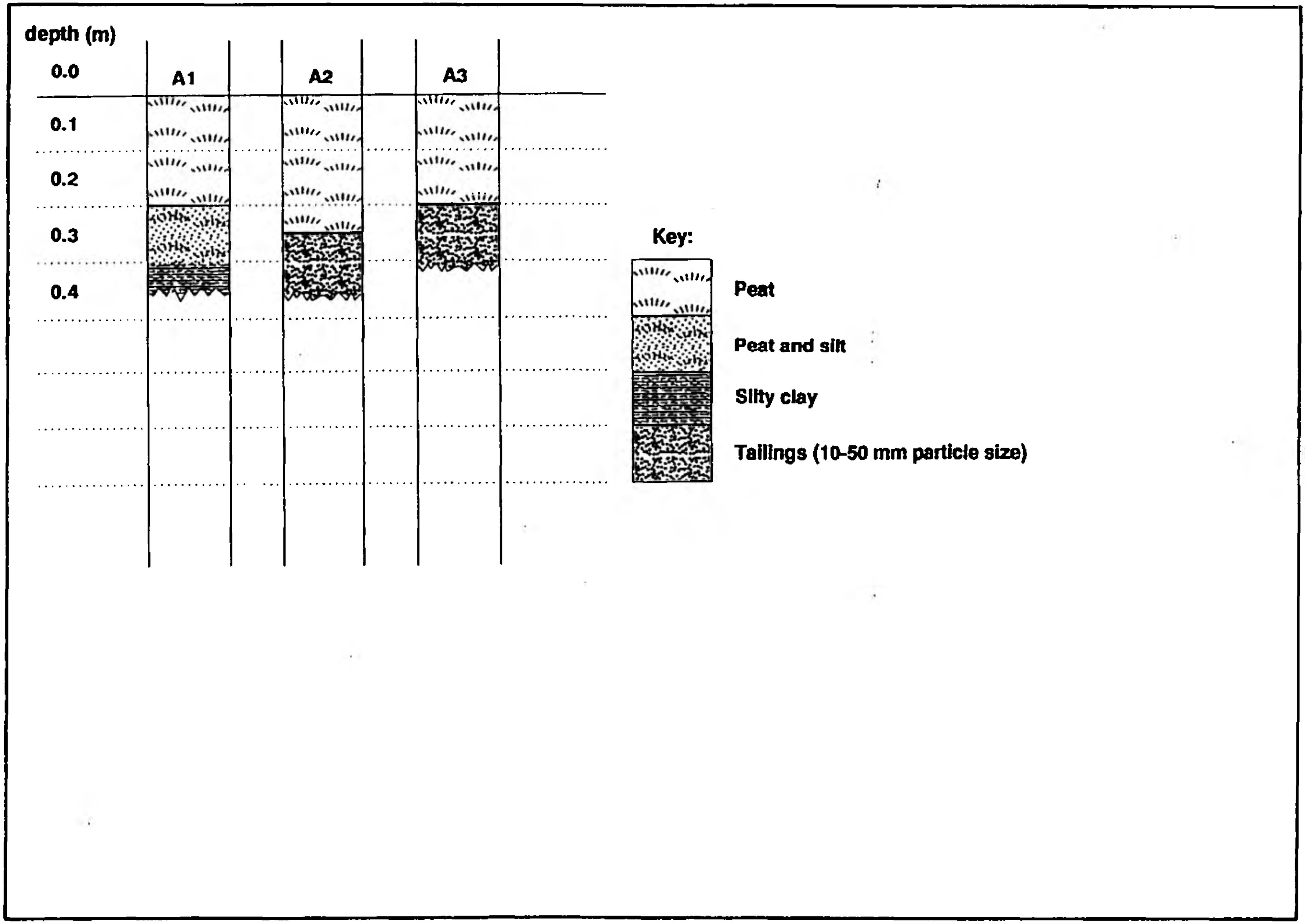

Figure 7.6 The Camdwrbach wetland area: hand auger profiles

Table 7.7 The Camdwrbach wetland area: soil contamination

Parameter	Units	S1	S2	S3	S4
pH		6.8	6.9	6.3	4.7
Organic solids	%	17.0	10.1	16.5	27.7
Lead	mg/kg	1152	573.8	288.7	95.8
Cadmium	mg/kg	170	65.1	< 0.6	< 0.4
Copper	mg/kg	1289	701	75.6	35.9
Zinc	mg/kg	35159	11988	943.8	52.7
Nickel	mg/kg	566.2	238.8	88.4	14.6

8. DISCUSSION

Table 8.1 summarizes various parameters of treatment performance for the four wetland areas studied.

Performance figures for a very large constructed wetland area in China receiving wastewater from a lead/zinc mine are included for comparison (Lan *et al* 1990). The wetland is divided into shallow 'aquatic treatment areas', which have been colonized by wetland plants, and deeper 'stabilization areas'. Mean depths of these areas are 0.1 m and 2.5 m respectively. Cattails (*Typha latifolia*) are the dominant vegetation. This particular constructed wetland was chosen for comparison since it is one of the few field-scale constructed wetlands for which performance data are available.

The results of this study indicate that there is metal uptake by the wetland areas although the degree of uptake varies from area to area and between sampling occasions.

The Afon Goch wetland area gave consistent metal removal between Point W2 and W3 although overall metal removal was poor. The Hafna wetland removed approximately 80% of influent lead loading. The Esgair Fraith wetland removed 30% of influent lead loading but lead contamination of the MCMD feeding this wetland area was low. The Camdwrbach wetland removed many metals including copper, zinc, cadmium and nickel.

Between W2 and W3, the Afon Goch wetland removed 30% of the sulphate loading at Point W2. None of the other wetlands removed sulphate ions.

None of the wetlands significantly affected the pH of the water.

The MCMD feeding these wetlands was chemically different in each case. These differences are summarized as follows:

The Afon Goch Wetland area
The MCMD contained higher concentrations of metals and was far more acid than the other wetland areas, at typically pH 2.8 compared to 6-7 at the other three wetlands.

The Hafna wetland area
The main pollutants were zinc, lead, iron and manganese. Typical zinc and lead concentrations, at 2600 μg/l and 160 μg/l respectively, exceed EEC standards for protection of salmonid fish and other freshwater life (excluding fish) (Gardiner and Mance 1984). Iron concentrations (typically 1500 μg/l) and manganese concentrations (typically 150 μg/l) exceed EEC drinking water standards. This MCMD is the second most polluted, after that flowing along the Afon Goch.

Table 8.1 Summary of natural wetland performance

Parameter	Afon Goch	Hafna	Esgair Fraith	Camdwrbach	Guangdong Region, China
Removal, %					
Sulphate	-30	-	-74	-8	-
Iron	30	-542	-	87	-
Copper	10	-	-19	96	-
Zinc	-10	-60	-52	92	80-95
Manganese	-20	8	-	85	-
Lead	-50	82	31	82	80-95
Cadmium	-15	-38	-26	98	80-95
Arsenic	65	-	-	-	-
Nickel	-30	-	-	97	-
Magnesium	-	-	-	-	-
Calcium	-	-	-	-	-
Aluminium	-	-	-	-21925	-
Removal, g/h					
Sulphate	-41430	-	-58.05	-2.49	-
Iron	5806	20.05	-	2.12	-
Copper	165	-	-0.03	0.09	-
Zinc	-340	-23.66	-3.66	2.64	2154.6
Manganese	-171	0.60	-	8.84	-
Lead	-7	2.32	0.04	0.06	1814.4
Cadmium	-1	-0.09	0.00	0.01	24.948
Arsenic	2	-	-	-	-
Nickel	-3	-	-	0.08	-
Magnesium	-	-	-	-	-
Calcium	-	-	-	-	-
Aluminium	-	-	-	-0.01	-

Note:
If the removal, in grams per day, is negative, the magnitude of this figure gives the amount of the contaminant released by the wetland per hour.

Table 8.1 Summary of natural wetland performance (continued)

Parameter	Afon Goch	Hafna	Esgair Fraith	Camdwrbach	Guangdong Region, China
Influent flow, l/min	2433	290	114	56	21000
Area, m²	310000	9500	170	150	87500
Water treatment efficiency, m²/l/min	127.4	32.8	1.5	2.7	4
Metal removal efficiency, mg/m²/day					
Sulphate	-3207.5	-	-8194.8	-398.0	-
Iron	449.5	50.6	-	338.8	-
Copper	12.8	-	-4.2	14.5	-
Zinc	-26.3	-59.8	-516.9	422.8	591.0
Manganese	-13.2	1.5	0.	1415.2	-
Lead	-0.5	5.9	5.4	10.0	497.7
Cadmium	-0.1	-0.2	-0.6	0.8	6.8
Arsenic	0.1	-	-	-	-
Nickel	-0.2	-	-	12.2	-
Magnesium	-	-	-	-	-
Calcium	-	-	-	-	-
Aluminium	-	-	-	-1.5	-

Note:
If the metal removal efficiency is negative, the magnitude of this figure gives the amount of the contaminant released by the wetland per square metre per day.

The Esgair Fraith wetland area
This was polluted with zinc to concentrations (typically 1000 $\mu g/l$) exceeding EEC standards for the protection of salmonid fish and other freshwater life (excluding fish), and aluminium to concentrations (50 $\mu g/l$) exceeding EEC drinking water standards. Zinc concentrations are approximately half those at the Hafna wetland.

The Camdwrbach wetland area
Zinc concentrations, at some 800 $\mu g/l$, exceeded standards for salmonid fish and other freshwater life. Iron (700 $\mu g/l$) and manganese (2200 $\mu g/l$) concentrations exceeded EEC drinking water standards.

The calculation of water treatment efficiency in $m^2/l/min$ and metal removal efficiency, in $mg/m^2/day$ enables comparisons of the performance of the wetlands that are independent of area and influent flow rate. These values are given in Table 8.1.

These treatment and metal removal efficiency figures show:

- The metal removal efficiency of the Camdwrbach wetland area is generally the greatest of the four natural wetlands. That of the Afon Goch is slightly greater than Camdwrbach for iron.

- The metal removal efficiencies of lead at Hafna and Esgair Fraith are about half that of Camdwrbach. The Afon Goch does not remove lead. All four natural wetlands are less efficient at removing lead than the Chinese constructed wetland, although influent lead concentrations are generally higher in the Chinese constructed wetland (1.6 mg/l).

- The Camdwrbach wetland removes cadmium, although this removal is far less efficient than the Chinese constructed wetland and, again, the influent to the wetland has higher concentrations of cadmium (0.022 mg/l).

- Influent zinc concentrations to the Camdwrbach wetland are some 50% of those to the Chinese wetland. Metal removal is comparable.

- The water treatment efficiency, a measure of the land requirement to treat a given flow rate, is lowest for the Esgair Fraith wetland area. This wetland is not successfully removing metals from the water. The water treatment efficiency of the Camdwrbach and Chinese wetlands is comparable. Both these wetlands are performing well. The water treatment efficiency of the Afon Goch Wetland is poor. Despite the large area of land available per unit flow rate the metal removal efficiency is low.

At all the natural wetlands, soil metal concentrations exceed those of the surrounding land. Soils may have become contaminated by metals through means other than metal removal from the water column by the wetland. Such means could include contamination by wind-blown particles or diffusion of metals upwards from more contaminated underlying material, especially where wetlands are underlain by spoil or tailings. All the wetlands in this study are underlain by spoil with the exception of the Afon Goch wetland.

The presence of elevated soil metal concentrations does, however, suggest that metal removal is taking place or has taken place at some time in the past.

Observation of the soil profile for the Afon Goch wetland at Point W3 suggests mechanisms of metal removal which may be operating. Metal oxidation will be taking place either in the water column or the suitable sediments close to the river itself. The Colour of the surface sediments indicate that metals, especially iron, are being precipitated. The presence of black, reducing sediments smelling faintly of hydrogen sulphide suggests that sulphate reducing bacteria are active. Metal removal, by precipitation within the substrate as sulphides is possible under these conditions.

The presence of oxidizing and reducing layers of substrate was only observed at Point W3 in the Afon Goch wetland, however, algae, encrusted with ferrous iron oxyhydroxides were also noted at the influent to the Camdwrbach wetland.

The organic substrate in all the wetlands except Afon Goch was quite thin, generally less than 0.4 m and often less than 0.2 m. In the Afon Goch wetland the depth of peat exceeded 0.6 m.

The conclusions reached should be considered in the light of the uncertainties which result from studying these hydrologically complex, natural systems. These uncertainties include the effects of

* evapotranspiration,
* contamination by underlying material,
* remobilization of material,
* the uncertain history of some of the areas,
* consideration of the wetland, to some extent, as a 'black box'.

These uncertainties are discussed below.

The effect of evapotranspiration

Little research has been done on evapotranspiration rates from wetland areas although they are considered to be reasonably similar for different species of wetland vegetation and approximate to that of open water.

Therefore, the effect of evapotranspiration has not been incorporated into the models of wetland performance in this study since the effect of evapotranspiration is dependant on wetland area and broadly independent of wetland morphology and vegetation.

The effect of remobilization of material
Some of these areas have been receiving MCMD for over a century. During periods of active mining, influent metal concentrations would have been higher than at present. The wetland may have removed metals historically but under lower metal concentrations, the position of chemical equilibrium between water column and sediment metals may have changed. This may have resulted in some sections of the wetland releasing metals, previously removed, into the water. In addition to this chemical dissolution, situations of high flow may result in the physical mobilization of metals previously precipitated.

The effect of contamination by underlying material
Where the wetlands overlie spoil or tailings, upward diffusion of metals from spoil to wetland may occur.

The uncertain history of some of the areas
Various changes in mining practice may have occurred that could have affected the wetland.

The consideration of the wetland as a black box
During this study, influent and effluent contaminant concentrations were taken from any discrete, identifiable surface water flows. In some instances, water samples were taken from intermediate points.

Owing to the hydrological complexity of the wetlands, attempts to quantify flow and water at many points within the wetland was considered very unlikely to repay the time and resources committed to such attempts.

The 'black box' approach with regard to water sampling was enhanced by qualitative observations of vegetation and soil profile, and by analysis of soil samples taken over the wetland area.

Remobilization of historically precipitated material may be of relevance to explain the poor performance of the Afon Goch wetland since there are a number of lagoons within the area studied. These lagoons are likely to have accumulated metal-rich sediments which, under high flow conditions, would be disturbed.

Additionally the poor performance of the Afon Goch wetland areas relative to the other areas studied may be due to poor contact between water and wetland plants and substrate. The river has been channelled along much of its length, possibly in order to drain the wetland area. The poor performance this may also be a consequence of the greater metal load and acidity of the MCMD at this site. Constructed wetland areas in the USA have, however, treated MCMD from coal mining of similar pH and iron and manganese concentrations.

The poor performance observed in the Hafna wetland may be a consequence of contamination from the underlying tailings. Alternatively, much of the flow may be bypassing the organic layer by flowing from the pool, along the buried concrete pipe, to Point W2. Performance of the wetland may improve in the summer when the general levels of plant and microbial metabolic activity increases. Aerial shoots of *Phragmites* were only just beginning to emerge at the end of the study period. A wetland must exhibit significant metal removal all year round to be a viable treatment method for MCMD.

It is worthy of note that a good vegetation cover has become established on highly contaminated tailings. For example, a soil sample from the *Carex* dominated area contained 1.8% zinc (18,000 mg/kg). The establishment of vegetation will have been aided by the calcareous nature of the tailings.

The single most important reason for the poor performance of the Esgair Fraith wetland is its short hydraulic retention time of eleven minutes. The volume of water in the wetland and the flow path observed during the 'tracing' experiment suggests that there is very little contact between water, plants and substrate.

Subject to the reservations mentioned in Section 7.4, the Camdwrbach wetland appears to be performing well. Its zinc removal efficiency is close to that observed in the Chinese constructed wetland.

There are several ways in which the metal-removal performance of a natural wetland could be improved:

(i) through measures that increase contact between water and substrate/vegetation such as preventing channelling and forcing water to enter the substrate.

(ii) by adding organic material; this would provide feed material for the sulphate-reducing bacteria responsible for immobilizing metals in the sediment as sulphides.

Some of these measures may be difficult to implement with the Afon Goch wetland area without causing other problems. The National Rivers Authority has an obligation, for flood defence reasons, to maintain an unimpeded flow along the river. Any proposals to impede the flow of the river, to provide better contact between water and wetland, would make this obligation difficult to meet. Many of the species of wetland vegetation occupying this area at present are deciduous, these return a large quantity of organic matter to the substrate annually. However, there may be limited potential to add a mulch of organic matter to the surface of some sections of the wetland to enhance sulphate-reduction processes.

Dredging the lagoons to reduce resuspension of contaminated sediment is unlikely to be of benefit. Such dredging may be extremely harmful if less-contaminated sediments overlie more-contaminated, older sediments as metals in the more-contaminated sediments may be liberated.

The establishment of hay bale islands in the lagoon, to provide a support matrix for the growth of emergent wetland vegetation, may be beneficial.

In the Hafna wetland area, blocking the concrete pipe would stop a quantity of water bypassing the wetland substrate and vegetation south of the pool. Circular holes are evident in the top of the exposed portion of the pipe; these can be assumed to be present in the top of the buried portion. These holes could be used to force water into the substrate but careful positioning of the blockage within the pipe would be necessary to avoid entry of water into the underlying tailings since this would result in further contamination of the water.

The performance of the Esgair Fraith wetland area could be improved by establishing a series of baffles to increase the retention time and hence contact of water and wetland. Hay bales would make suitable baffles; they are cheap, readily available and easy to install, they provide a matrix in which wetland plants and algae can grow. They may also provide for physical filtration of metal-rich suspended particles. Reducing the depth of the pools may allow for further colonization by emergent wetland plants such as *Juncus effusus*. Islands could be created using more hay bales.

No modifications of the Camdwrbach wetland are considered since the wetland is performing well.

9. CONCLUSIONS

- Only one of the natural wetlands studied, the Camdwrbach wetland, can be considered to be removing metals well.

- The Camdwrbach wetland demonstrates the potential effectiveness of *Juncus effusus* in wetlands removing metal contamination. *Juncus effusus* would be a good candidate for establishment in existing natural wetlands or for use in a constructed wetland, being especially suited to upland areas; it is prevalent in such areas and more resistant to wind than taller emergent plants.

- The performance of the wetland areas studied was variable, between the different wetlands, between parts of each and between sampling visits.

- It is very difficult to estimate metal-removal capacity of a wetland on the basis of a walk-over survey although the presence of bright orange deposits of iron oxyhydroxides or metal-encrusted algae would indicate that metal removal may be occurring. The type of study described here, involving the taking of water and soil samples, soil profile and investigation of the making of detailed on-site observations, is necessary to determine the effect a wetland is having on water quality.

- Several uncertainties are intrinsic to these hydrologically complex, natural systems. These include the effects of

    - evapotranspiration,
    - remobilization of historically precipitated contamination,
    - contamination from underlying materials,
    - the uncertain history of some of the sites

- The study of pilot-scale constructed wetlands would allow a greater degree of control over these uncertainties. Therefore, such constructed wetlands are better for detailed investigations of the metal-removal processes taking place.

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11. GLOSSARY AND ABBREVIATIONS

Background	In this study, background is used in the sense of background, *i.e.* historical, information.
Control sample	A sample taken to obtain a value, generally a concentration of a particular substance, that would occur in the absence of a process taking place or a situation occurring.
g/h	Unit of loading used in this study, grammes/hour
Loading	A measure of the amount of a given substance passing a particular point in a given time. The loading of a particular substance is calculated by multiplying its concentration by flow rate.
MCMD	Metal-contaminated mine drainage (MCMD) is generally formed when sulphide ores become exposed to oxygen and water, conditions favourable to their oxidation by bacteria such as *Thiobacillus ferrooxidans*. MCMD may be strongly acid and may contain high concentrations of a range of heavy metals. MCMD can be formed from waste underground or on the surface, so can emerge from underground or surface mine workings.
mg/kg	Units of concentration for soils, milligrams per kilogram, equivalent to parts per million by weight.
mg/l	Units of concentration, milligrams per litre, equivalent to parts per million.
μg/l	Units of concentration, micrograms per litre, 1 mg/l = 1000 μg/l, equivalent to parts per billion.
NGR	National Grid Reference
Retention time	The time taken for water to flow through a pool or channel. If a given parcel of water is considered to enter the pool at a certain time, it will leave after the retention time has elapsed.