NRA Wales 90

RICHARDS

MOOREHEAD & LAING LTD.

FEASIBILITY AND COSTING STUDY

for

A CONSTRUCTED WETLAND TREATMENT SYSTEM

for

NATIONAL RIVERS AUTHORITY
Welsh Region
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Final Report R&D Project 019W

Feasibility and costing study for a constructed wetland treatment system

Richards, Moorehead and Laing Ltd
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GLOSSARY

Acidity The sum of all the acidic chemical species in a sample of water. In addition to hydrogen ions, metal ions such as aluminium, iron and manganese have acidic or alkali-consuming properties. Acidity is expressed as mg/l $CaCO_3$ equivalent. Total acidity is determined by titrating the sample to pH 8.0 with a strong base. See also **Alkalinity**.

Adit A horizontal passage into a mine, often constructed for the purpose of draining water from the mine.

Alkaline addition A chemical means of treating AMD. The pH is raised by the addition of an alkali and, as a result, metals are precipitated.

Alkalinity The sum of all the chemical species in a sample of water that have acid-consuming properties. Alkalinity in water is generally caused by carbonate and bicarbonate ions and is expressed as mg/l $CaCO_3$ equivalent. The alkalinity of a sample of water gives a measure of its acid-buffering capacity.

ALD Anoxic Limestone Drain. A buried trench of limestone. Under anoxic conditions, the limestone can add alkalinity to the water and raise pH without the reactive surfaces becoming armoured by precipitated iron (III) oxides and losing their effectiveness.

AMD Acid Mine Drainage water. AMD results from the exposure of sulphide-containing minerals to water and oxygen. Sulphides are oxidized to sulphate, leading to an increased acidity and a solubilizing of metal ions. When a flow of water passes over oxidized sulphide-containing minerals it will become contaminated with acidity, sulphate and metal ions.

Attenuate To make or to become weak or thin. Attenuation in the context of this study refers to the property of structures to smooth out or buffer sudden increases in volume of flow.

EIFAC European Inland Fisheries Advisory Council. Sets water quality standards based on the toxicity of substances to fish.

Emergents Wetland plants which project leaves and stalks above the water surface, but are rooted in the substrate.

HDPE High-density polyethylene. A plastic commonly used to line structures for the purpose of water retention or exclusion.

Hydraulic short-circuiting	A situation where water takes a flow-path through a system that is far shorter than the designed flow-path. In constructed wetlands, hydraulic short-circuiting will lead to a reduced degree of treatment.
Liner	In wetland construction: any material used to isolate wetland components from groundwater. Materials that can be used include compacted clay soils, bentonite, asphalt, fibreglass, butyl rubber, and plastics.
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.
Pyrite	Iron sulphide (FeS_2).
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.
Rhizome	An underground stem producing roots and leafy shoots.
Rip-rap	Loose, broken stones, used to form a foundation on soft ground or under water or in the construction of embankments or revetments.
Subsurface flow wetland	A wetland designed such that there is no surface water and flow is confined to the substrate.
Surface flow wetland	A wetland designed such that flow is not confined to the substrate, and flow over the surface of the substrate can also occur.
Wetland	"Land in which the water table is at or above the ground surface for long enough each year to maintain saturated soil conditions and the related vegetation" (Reed *et al.* 1988).

EXECUTIVE SUMMARY

1. INTRODUCTION

The aim of the study is to assess the feasibility of constructing a wetland based coal mine effluent treatment system at sites in the Afon Pelenna catchment in West Glamorgan and in particular:

1. to provide design, construction, commissioning and aftercare details for the wetland-based treatment system,
2. to provide budget costs for each aspect of the construction of the treatment system,
3. to provide a basis for a submission for joint European/UK funding to construct, commission and operate the system as a Demonstration Project under the LIFE programme,
4. to disseminate useful information on this innovative treatment system to interested parties.

The treatment system proposed will have a wide application in other coal mining areas of Europe.

Previous studies of the Afon Pelenna catchment have shown that downstream of mine effluent discharges the upper Afon Pelenna and its tributary, the Nant Gwenffrwd, are fishless and fail European Inland Fisheries Advisory Council (EIFAC) water quality standards for salmonid fisheries with respect to iron concentrations. These studies have also indicated that a 95% reduction in concentration of iron in the Whitworth Lagoon discharge and a 50% reduction in the concentration of iron in the Garth Tonmawr discharge would result in the EIFAC standard being achieved.

2. THE NANT GWENFFRWD

The Nant Gwenffrwd joins the Afon Pelenna just downstream of the village of Ton-Mawr. The Gwenffrwd valley contains extensive disused coal workings, extraction of coal having ceased in the early 1960s. Some areas of the valley were reclaimed in the late 1970s in a reclamation scheme undertaken by West Glamorgan County Council.

As part of the scheme, a colliery spoil heap east of the position of the Whitworth Lagoon was regraded and the Whitworth Lagoon constructed, by enlarging an existing impoundment, to capture the flow from two adits below the spoil heap.

The Nant Gwenffrwd is essentially unpolluted upstream of the Whitworth Lagoon; on the basis of its chemical quality, it merits a National Waters Council classification of 1a (good quality).

The Gwenffrwd valley is underlain by the Carboniferous upper coal measures of the Pennant sandstones. In the southern, downstream part of the valley, the soil is of the Hirwaun or Wilcocks association. Much disturbed ground is expected in the upper part of the valley. The original soils are of the Gelligaer association. The valley sides are vegetated with acid grassland, bracken and Sessile Oak woodland and the valley with marsh.

Proposals for treating the mine discharges include:

* The pre-treatment of the water entering the Whitworth Lagoon from the north using an Anoxic Limestone Drain (ALD)
* The construction of a wetland treatment system to treat the flow from the Whitworth Lagoon.
* The diversion of the flow from the Gwenffrwd discharge, via an Anoxic Limestone Drain, to enter the wetland treatment system.
* The diversion of the flow from the Whitworth No.1 adit to enter a separate wetland or, alternatively, to pipe the flow to enter the main wetland treatment system.

The effluent from the ALDs will be anoxic but with an increased pH and alkalinity over the influent mine water. Oxidation/hydrolysis reactions can occur in this effluent to cause metal ions to precipitate. Settling lagoons are proposed to allow this precipitated material to be retained.

Wetlands would be clay lined with a substrate thickness of 700 mm and a maximum standing water level of 300 mm. Wetlands would be divided into cells and subcells to facilitate their efficient function and management. Mushroom compost is recommended as a substrate with vegetation derived from Reedmace, Bulrush, Yellow Flag or Common Reed. Groundwater and surface water runoff would be controlled by land drains.

A mean iron removal of 80% is considered likely.

3. GARTH TONMAWR

The upper Pelenna valley (Cwm Blaenpelenna) is a narrow upland valley, partially forested with conifers. Coal extraction in the valley centred around the Garth Colliery, which closed in the early 1960s.

At Garth Tonmawr, and downstream for some four hundred metres, the valley floor contains large, low heaps of spoil. Some of this spoil is being eroded into the Blaenpelenna. Upstream of Garth Tonmawr, around Middle Mine, there are significant heaps of colliery spoil. Gully erosion is evident on these, and water can be observed percolating through the spoil. At Garth Tonmawr, water issues from a disused level and flows through a small area of natural wetland on colliery spoil and dominated by Soft Rush before entering the Blaenpelenna.

Cwm Blaenpelenna is underlain by Carboniferous upper coal measures consisting of the Pennant sandstones. Soil type is very similar to Cwm Gwenffrwd, the soils of the lower valley being of the Hirwaun association, those of the upper valley being of the Gelligaer association. Spoil in the valley bottom is vegetated with poor acid-tolerant vegetation with some self-sown Larch and Spruce.

The use of an Anoxic Limestone Drain has been considered but rejected because minewater dissolved oxygen is in excess of the maximum suggested by Nairn, Hedin and Watzlaf (1990).

A wetland of 7000 m^2 is required on the basis of iron removal efficiency guidelines. The following general arrangement is proposed:

* The minewater discharges into attenuation lagoon which serves to buffer variation in flow rates.
* Flow from the attenuation lagoon crosses the Blaenpelenna on a channel/bridge to flow into the wetland area on the opposite bank.
* Discharge returns to the Blaenpelenna.

Subcells would be necessary, such as those proposed for wetland cells in Cwm Gwenffrwd. Vegetation and substrate specification would be as the Cwm Gwenffrwd wetland. The attenuation lagoon and wetland would be clay-lined.

Mean iron removal is expected to be in excess of 50%.

4. DETAILED DESIGN AND CONSTRUCTION

In order to design the treatment system in detail, information must be gathered on a wide variety of site-specific factors. Investigations should include:

* A full topographical survey.
* A wildlife survey.
* The collection of data on water quality and flow for all flows to be treated by the wetlands.
* The biological and chemical monitoring of the catchment downstream of the proposed discharge points to establish the 'baseline' biological and chemical quality of the water.
* The location of all services on or near the area of interest.
* A hydrological survey to locate and characterise all flows of surface and groundwater likely to affect the wetland.

* A detailed site investigation to characterize surface materials and soils, bedrock depth, available construction materials or any other geological or geotechnical aspects.
* The following will need to be determined on available substrate materials: hydraulic conductivity, pH, buffering capacity, plant nutrient concentrations and microbial activity.
* Landscape assessment.
* Assessment of the safety of casual users of the site.

A staged construction is advocated. Construction would take place over five years, from 1994, provided further information on water quality and flow can be obtained during 1993. The discharges would be treated in the following order, construction beginning in the second quarter of the years shown:

1.	Whitworth No.1	(1994)
2.	Garth Tonmawr	(1995)
3.	Gwenffrwd discharge	(1996)
4.	Whitworth A	(1997)
5.	Whitworth B	(1997).

The following programme details works to be carried out for a discharge which is to be pre-treated by an ALD, passed through a settling tank and then discharged to a wetland (*e.g.* Whitworth A). Where wetland-only treatment is proposed, items 3 and 4 will not apply and the final connection (item 8) is direct to the wetland.

1. The wetland and outlet to watercourse should be constructed.

2. The wetland vegetation should be allowed to become established, which may take between 3 months and a year after the planting season.

3. The settling lagoon and connection to wetland should be constructed.

4. The ALD, bypass and connection to settling lagoon should be constructed.

5. A temporary bypass for mine water, to a temporary lagoon, should be constructed. This bypass would consist of a limestone-filled, lined sump excavated adjacent to the existing discharge and overland pipework to a lagoon.

6. When the bypass has been completed and tested, mine water should be diverted into it.

7. Excavation to establish headwall structures should take place along the line of existing discharge, testing the water for dissolved oxygen at appropriate stages. When an acceptable level of dissolved oxygen is reached (where an ALD is to be constructed) a pipe to take the discharge should be sealed into the adit.

8. The final connection to the ALD should be made once the wetland has become established.

9. All contaminated material excavated during the course of the works should be taken to a licensed tip.

Actual programming will be governed by the amounts of excavation and filling required, and on the time to establish the wetland.

Pollution prevention measures will be needed during construction to deal with the disposal and treatment of excavated and disturbed materials.

5. COMMISSIONING

Commissioning of each wetland will take the following general steps:

1. Interception of acid mine water flows as described in Section 4.
2. Removal of any temporary flow diversions.
3. Control of water level to aid plant establishment.

6. AFTERCARE AND OPERATIONAL MAINTENANCE

The feasibility study identifies the principle maintenance measures to be:

* monitoring of wetland performance
* periodic removal of iron oxides and hydroxides from the settling lagoons
* periodic replacement of limestone in ALDs
* periodic replacement of wetland substrate
* process optimisation
* aftercare of wetland plants
* maintenance of structures.

7. COSTINGS

The estimated total cost including detailed design, construction and supervision is £954,300. The annual monitoring and maintenance cost is £29,500. The cost of replacing wetland substrate, once it has become exhausted, is estimated at between £30,000 (Whitworth No.1 System) and £138,000 (Garth Tonmawr), or 30-45% of the construction costs. Lifespan of substrate is expected to be of the order of twenty years. The Anoxic Limestone Drains will cost £9,000 and £23,500 to renew, after their twenty-year lifespan.

Items specifically excluded from these costs are:

* The cost of permissions, licences and any investigations of the environmental impact of the construction of the system.
* Long-term supervision of maintenance works.

8. REPORTING OF PROJECT RESULTS

Project results will be collated and disseminated through NRA R&D Notes and appropriate publications. Presentations at relevant conferences and the organisation of specific seminars are also proposed.

9. CONCLUSIONS

It is concluded from the data available that constructed wetland treatment of the discharges at Gwenffrwd and Tonmawr will result in the required improvements to the Pelenna catchment water quality.

1 INTRODUCTION

1.1 Aims

Richards, Moorehead and Laing Ltd has been appointed by the National Rivers Authority (NRA) Welsh Region to undertake a study of the feasibility of constructing a wetland-based coal mine effluent treatment system at sites in the Afon Pelenna catchment in West Glamorgan.

The study area is shown in Figure 1.1 and, schematically, in Figure 1.2.

The aims of the study are:

1) to provide design, construction, commissioning and aftercare details for the wetland-based treatment system.
2) to provide budget costs for each aspect of the construction of the treatment systems.
3) to provide a basis for a submission for joint European/UK funding to construct, commission and operate the system as a Demonstration Project under the LIFE programme.
4) to disseminate useful information on this innovative treatment system to interested parties.

A treatment system based on constructed wetlands is suitable for these sites because:

* Such systems require little or no day-to-day process control
* Operational and maintenance costs are low when compared to alternative systems
* Capital costs are relatively low
* Systems can provide additional environmental benefits, such as wildlife habitat.

A considerable body of literature documents the success of such systems in treating coal mine drainage in the United States of America.

1.2 Acid mine drainage in Europe

The generation and environmental impact of acidic mine drainage and associated acidic and metal-bearing waters is not confined to the United Kingdom.

Many other regions of the European Community encounter large-scale problems of acid drainage waters from coal and iron mines.

In the rich iron and coal fields of eastern France (Lorraine), Luxembourg and southern Belgium, the oxidation of iron deposits from previous mining activities has given rise to the pollution of water courses, and continues to be a problem to this day.

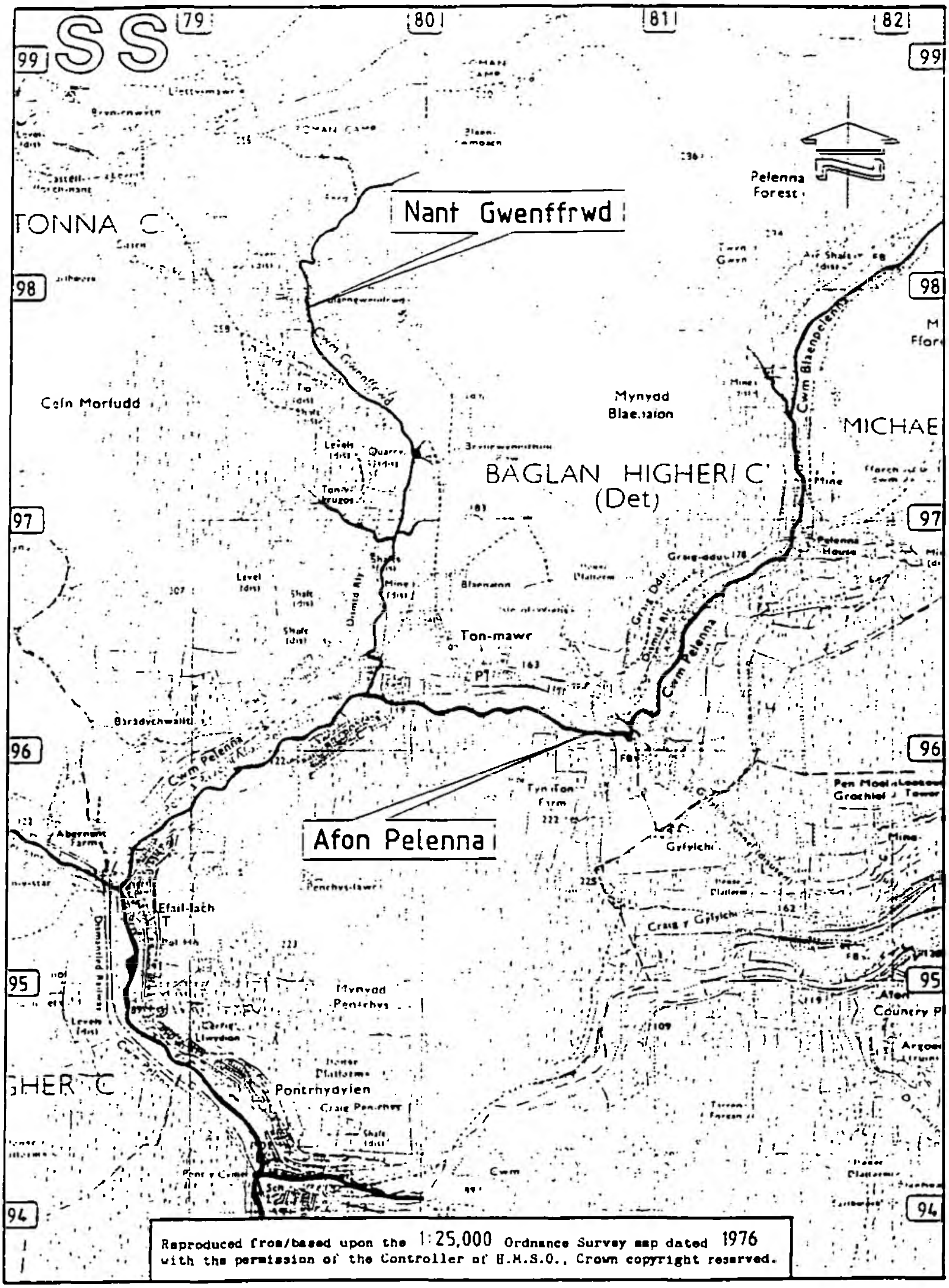


Figure 1.1 The study area

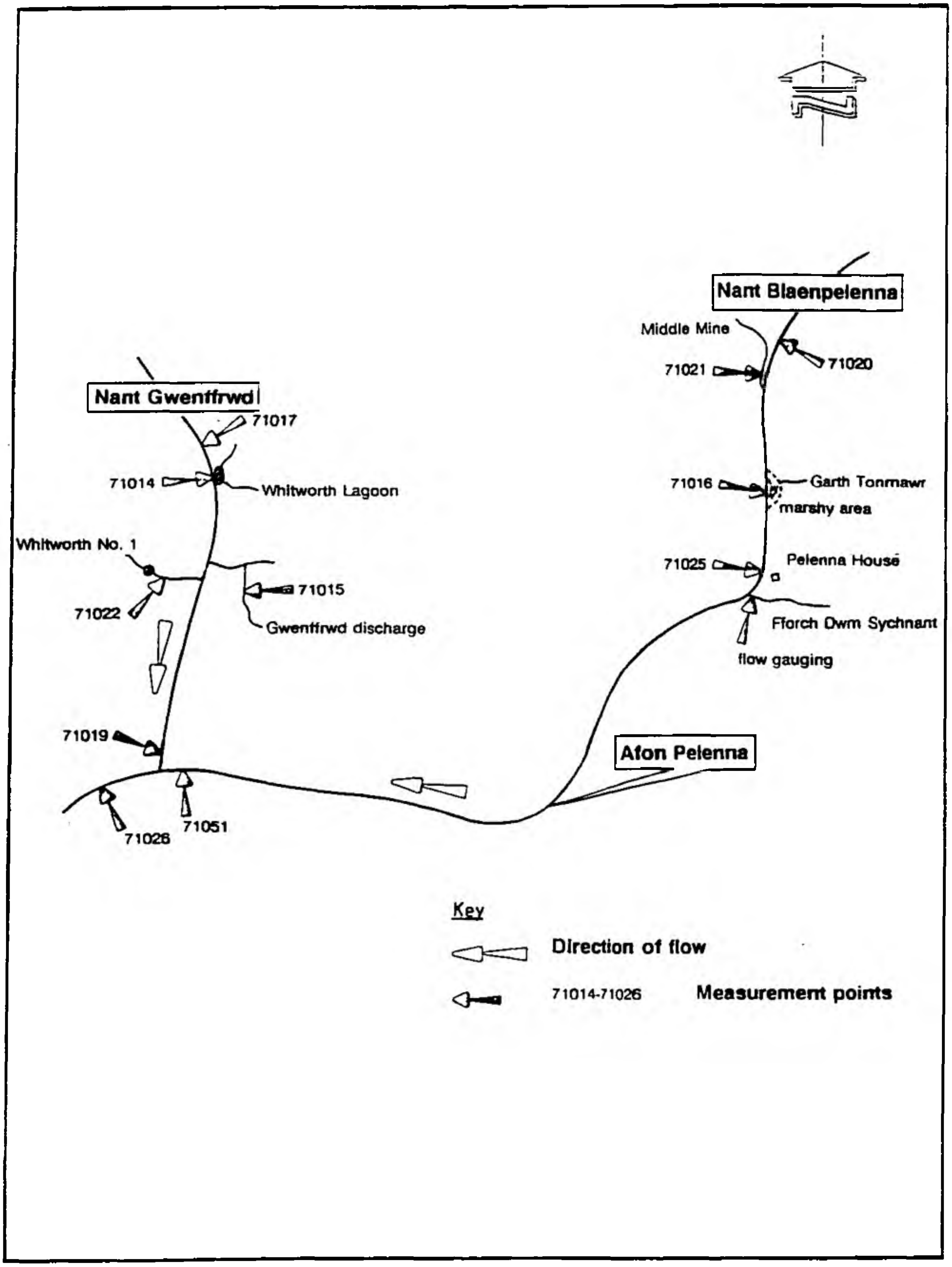


Figure 1.2 Schematic of the study area, from Ishemo and Whitehead (1992)

Similarly, in Spain, areas such as Bilbao also renown for their history of iron mining, generate large volumes of acid waters from flooded shafts.

The pollution of ground and surface waters in the Ruhr region of Germany also occurs as a consequence of previous mining. In the east of Germany, where lignite is mined by open cast methods, the situation is even worse. Rising water levels and acid deposition from the heavily polluted air, combined with the naturally high sulphur content of these brown coal basins has given rise to highly acidic surface waters, devoid of life and with little opportunity for ecological regeneration as they stand.

Wetland-based treatment systems offer the potential to ameliorate the effects of acid mine waters in all these areas.

1.3 Background

The upper Afon Pelenna (Blaenpelenna) and its tributary (the Nant Gwenffrwd) are largely fishless. The waters currently fail the European Inland Fisheries Advisory Council (EIFAC) water quality standards for salmonid fisheries with respect to iron concentrations, which is set at 1.0 mg/l dissolved iron. This failure to meet EIFAC standards is due to the discharge of acid mine drainage (AMD) from disused coal workings in the area. The iron gives the water an orange coloration and the subsequent precipitation of metal oxides and hydroxides on to the river bed further affects its quality and appearance.

Manganese, aluminium and ionic hydrogen also give cause for concern. The presence of coniferous plantations is causing the catchment to become acidified; the toxicity of aluminum is strongly linked to acidity and the metal becomes more toxic as pH falls.

The EIFAC standard for pH in salmonid fisheries is between pH 6 and pH 9. Upstream of the mine discharges, pH of the water courses drop below this range occasionally although the means of 6.3 in the Gwenffrwd and 6.7 in the Blaenpelenna referred to in Ishemo and Whitehead (1992) are acceptable. Downstream of the discharges, mean pHs of 5.3 (Gwenffrwd) and 5.9 (Blaenpelenna) are observed.

There are three major mine water discharges entering the Gwenffrwd and a further two entering the Blaenpelenna. These are detailed in Table 1.1 and shown on Figure 1.2.

Ishemo and Whitehead (1992) modelled various treatment possibilities for the catchment and concluded that EIFAC standards for iron would be satisfied by a 95% reduction in the concentration of iron in the Whitworth Lagoon outfall (NRA sampling location 71014), together with an increase in pH to 6.0, and a 50% reduction in the concentration of dissolved iron in the Garth Tonmawr discharge (NRA sampling location 71016).

	NRA sampling location point
Mine water discharges entering the Gwenffrwd	
- Effluent from Whitworth Lagoon †	71014
- Gwenffrwd discharge	71015
- Whitworth no. 1	71022
Mine water discharges entering the Blaenpelenna	
- Middle Mine discharge	71021
- Garth Tonmawr minewater †	71016

† Identified by Ishemo and Whitehead (1992) as being most significant AMD inputs to the catchment.

Table 1.1 Major mine water discharges entering the section of the catchment under study

This feasibility study considers the catchment in two sections:

1) the Nant Gwenffrwd
2) the Garth Tonmawr discharge on the Blaenpelenna.

1.4 Qualifications

The outline design is, of necessity, made on the basis of limited information. Available volume of flow information is especially limiting, comprising five readings for each location, taken during the winter of 1991 and spring of 1992. This period is when high flows are expected and it is envisaged that, where a component of the treatment system has been designed on the basis of mean averages of available flow information, the size of such components could be reduced were further information on flow available.

2 THE NANT GWENFFRWD

2.1 Description

Figure 2.1 shows the Nant Gwenffrwd and the area of interest.

2.1.1 Introduction

The Nant Gwenffrwd joins the Afon Pelenna just downstream of the village of Ton-Mawr. The Gwenffrwd valley contains extensive disused coal workings, extraction of coal having ceased in the early 1960s. Some areas of the valley were reclaimed in the late 1970s in a reclamation scheme undertaken by West Glamorgan County Council.

As part of the scheme, a colliery spoil heap east of the position of the Whitworth Lagoon was regraded and the Whitworth Lagoon constructed, by enlarging an existing impoundment, to capture the flow from two adits below the spoil heap. Further down the valley, at approximately NGR SS 799969 and 799968, two shafts 300–400 m deep were filled using waste material and capped. The buildings surrounding these shafts were demolished, and the area landscaped.

2.1.2 Surface water flows

The Nant Gwenffrwd is essentially unpolluted upstream of the Whitworth Lagoon; on the basis of its chemical quality, it merits a National Waters Council classification of 1a (good quality).

The Whitworth Lagoon receives drainage from an adit at about NGR SS 79980 27300 (the northernmost flow, subsequently known as Whitworth A) and from an adit at about NGR SS 79990 97260 (the southernmost flow, subsequently known as Whitworth B). The lagoon also receives a small amount of uncontaminated surface water runoff along a drainage channel down the slope from the track to the east of the lagoon. The flow of groundwater into the lagoon does not exhibit significant seasonal variation. The lagoon discharges over a sill, directly into the Nant Gwenffrwd.

The Nant Gwenffrwd is culverted for a short section immediately downstream of the discharge from the Whitworth Lagoon. Emerging from these culverts, which serve to convey the river through the bund retaining the Whitworth Lagoon, the river falls a few metres and then resumes its course down Cwm Gwenffrwd. There are two further discharges of AMD-contaminated water into the river.

* The Gwenffrwd discharge (71015) rises at an adit (NGR SS 801969, marked as level (disused) on Figure 2.1) then flows north along a recently constructed channel to enter a tributary of the Gwenffrwd which up to this point is of good

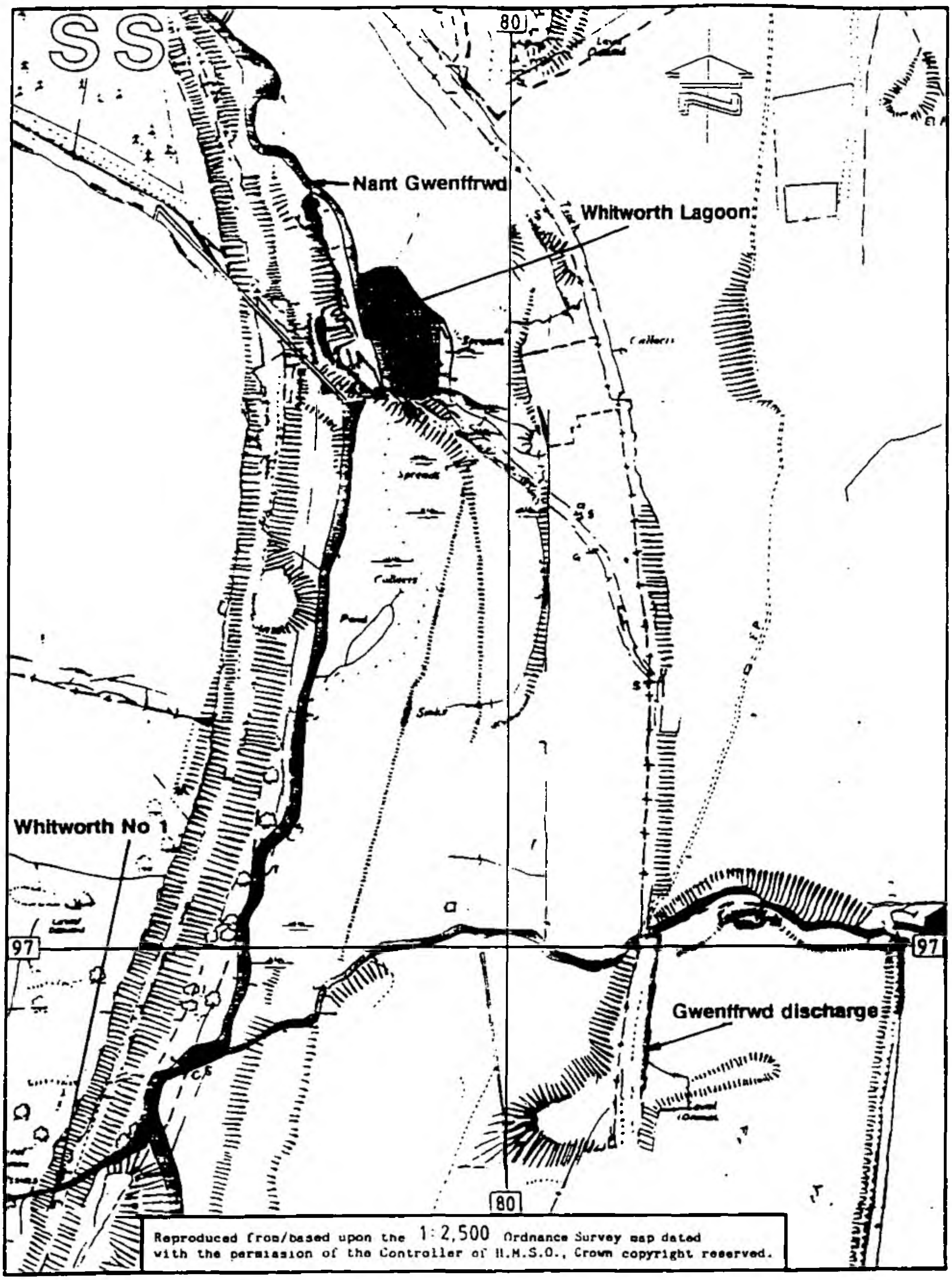


Figure 2.1 Cwm Gwenffrwd: area of interest.

water quality.

* The Whitworth No.1 discharge flows through a small area of natural wetland (shaded on Figure 1.2) and enters the Gwenffrwd immediately downstream of the confluence with the stream carrying the Gwenffrwd discharge.

2.1.3 Geology and soils

The Gwenffrwd valley is underlain by the Carboniferous upper coal measures of the Pennant sandstones. The beds are close to the horizontal, showing a very slight degree of dip to the north-north east. A major fault, the Ton-y-Grugos fault, runs north-south, and lies to the west of the valley.

In the southern, downstream part of the valley, the soil is of the Hirwaun or Wilcocks association characterised in Rudeforth *et al.* (1984) as having the following typical profile:

0-0.2m	Black, stoneless humidified peat or humose clay loam.
0.2-0.5m	Light brownish grey, mottled, slightly stony clay loam or sandy clay loam; weak subangular blocky structure.
0.5-1.0m	Grey with many ochreous mottles, moderately stony clay loam; weak medium blocky or prismatic structure; high packing density.

Considerable amounts of colliery spoil are also likely to be present in this area.

Much disturbed ground is expected in the upper part of the valley. The original soils are of the Gelligaer association, with typical profile (Rudeforth *et al.*, 1984):

0 - 0.1m	Black, humidified peat or humose sandy loam; weak fine subangular blocky structure.
0.1-0.25m	Greyish brown, slightly stony sandy loam; weak fine subangular blocky structure.
0.25 - 0.65m	Brown, moderately stony sandy loam; weak fine subangular blocky structure.
0.65m	Hard sandstone.

Any further subsidence due to the coal workings is considered unlikely, in view of the length of time since extraction ceased and the depth of the workings, estimated from the depth of the two shafts.

As far as our research has been able to determine, the soil of the valley floor south of the Whitworth Lagoon and north of northing 97 is original ground but the area south of northing 97 was reclaimed so original ground will be overlain by colliery spoil and other fill material.

2.1.4 Vegetation

The sides of the valley are vegetated by acid grassland, Bracken and Gorse with patches of Sessile Oak woodland in sheltered areas. Conifers have been planted on the west side of the valley.

Reclaimed areas around the Whitworth lagoon have been sown to grassland dominated by Fescue and Bents with some White Clover. Acid-loving species such as Sheeps Sorrel are found in places and the high rainfall has favoured colonisation by mosses. Spoil from an unvegetated area near the Whitworth Lagoon was found to have a pH of around 4.0.

The lagoon itself is bordered by clumps of Soft Rush which also dominate the channels into it. Toad Rush is also found here and the discharge from Whitworth B is surrounded by floating Pondweed.

South of the Whitworth lagoon the wettest parts of the valley floor and the terraces on the western side contain a Purple Moor Grass-dominated bog with patches of Sessile Oak. The bog also contains Soft Rush and *Sphagnum* species. Drier parts are vegetated by acid Bent/Fescue grassland and Bracken with some colonisation by Heather. Wet flushes dominated by Soft Rush are common within the grassland

2.1.5 Land ownership

Much of the land in the study area is in the ownership of West Glamorgan County Council. The extent of this ownership is shown on Figure 2.2.

Two footpaths cross the area of interest to this study. The routes of these are shown on Figure 2.2 also.

The only development likely to influence the area under study is a proposed cycle track. The route of this track is shown on Figure 2.2.

2.1.6 Objectives

Ishemo and Whitehead (1992) consider that a 95% reduction in the dissolved iron concentration of water leaving the Whitworth Lagoon would make the Gwenffrwd suitable for salmonid fish, in EIFAC terms.

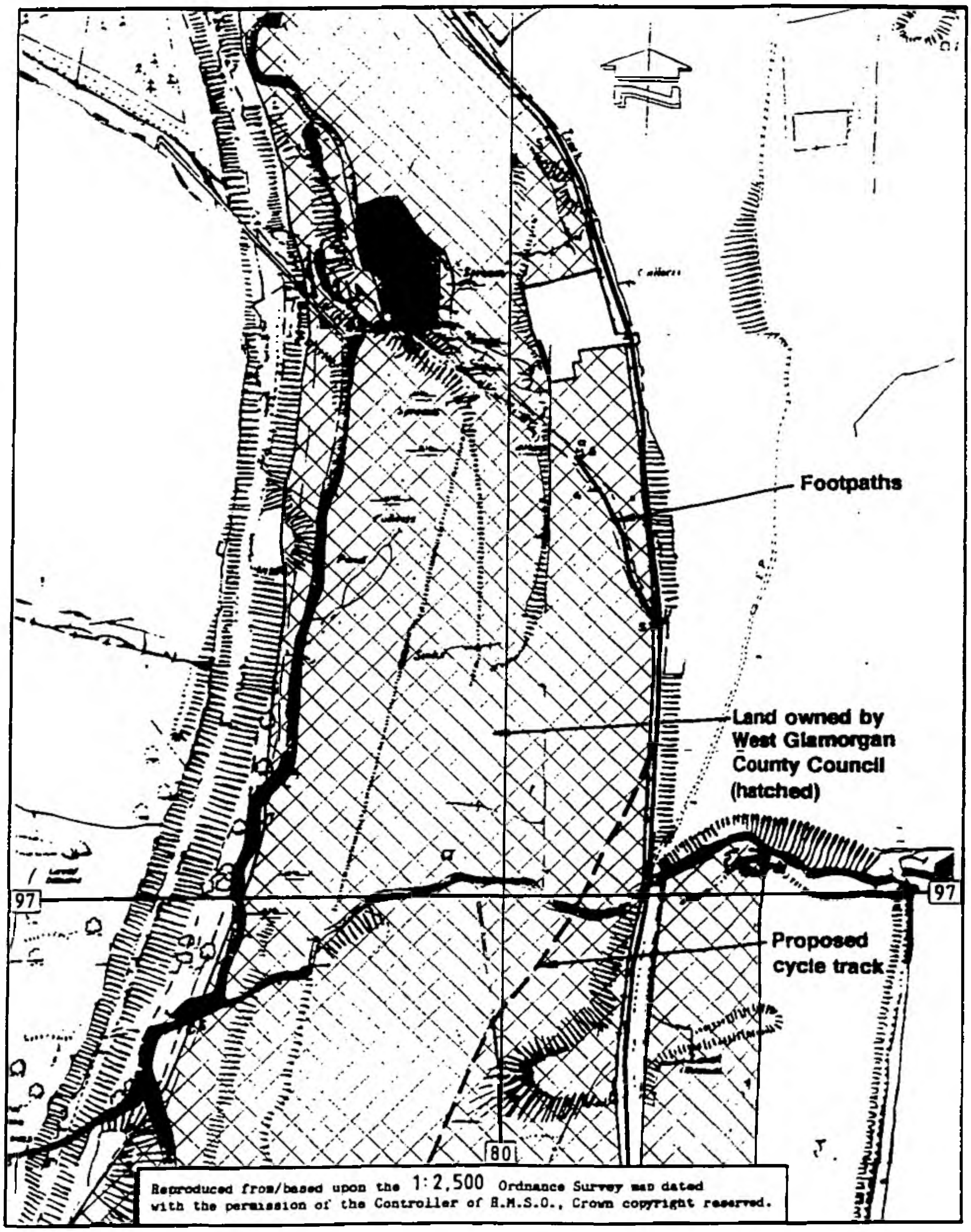


Figure 2.2 Landownership and footpaths in Cwm Gwenffrwd.

Proposals outlined in this section include

* The treatment of water entering the Whitworth Lagoon from the north using an Anoxic Limestone Drain.
* The construction of a wetland treatment system to treat the flow from the Whitworth Lagoon.
* The diversion of the flow from the Gwenffrwd discharge, via an Anoxic Limestone Drain, to enter the wetland treatment system.
* The diversion of the flow from the Whitworth No.1 adit to enter a separate wetland or, alternatively, to pipe the flow to enter the main wetland treatment system.

The relief of the site, together with the positions of the flows that require treating suggest the treatment system shown on Figure 2.3 and, diagrammatically in Figure 2.4. The main treatment system is on three terraces, the top terrace, receiving flow from the Gwenffrwd discharge, the middle receiving flow from Whitworth A and the bottom receiving flow from Whitworth B.

There are two alternatives for the treatment of the Whitworth No.1 flow: treatment *in situ* in a local wetland or piping of the flow into the wetland in the bottom terrace. We favour the former, for reasons discussed fully in Section 2.4.

In addition to the wetland treatment system, liming of the reclaimed area of land near the Whitworth Lagoon will significantly improve the quality of the vegetation, and reduce the risk of contamination of surface water runoff by colliery spoil.

2.2 Anoxic Limestone Drains

2.2.1 Introduction

Anoxic Limestone Drains (ALDs) are buried trenches filled with limestone. Acid mine water, when diverted through these trenches, reacts with the limestone and, thus, its pH and alkalinity is increased.

An increase in pH and alkalinity is especially desirable in the Gwenffrwd catchment, for the following reasons:

1) to attempt to counter the gradual catchment acidification
2) in order to meet the criteria suggested by Ishemo and Whitehead (1992) that a 90-95% reduction in dissolved iron concentrations will be sufficient to meet EIFAC standards in the Gwenffrwd provided pH can be raised to 6.0.

To construct an ALD, a HDPE-lined trench is filled with graded limestone, then the limestone covered with further plastic and a soil overburden. Skousen (1990) suggests

Treatment units are shown schematically only. Areas and locations are correct, but shape will be varied to blend with the existing landscape.

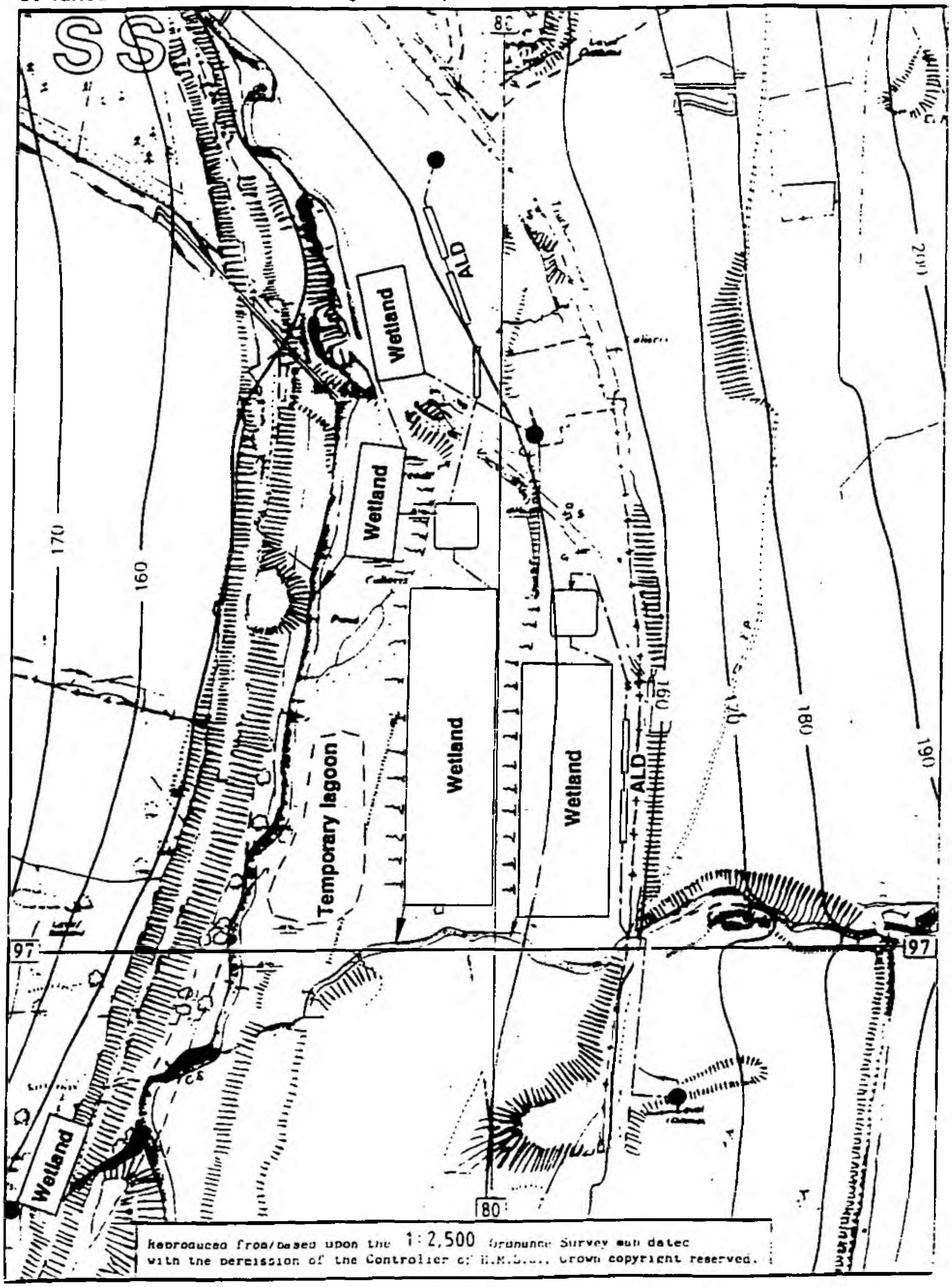


Figure 2.3 Cwm Gwenffrwd treatment system.

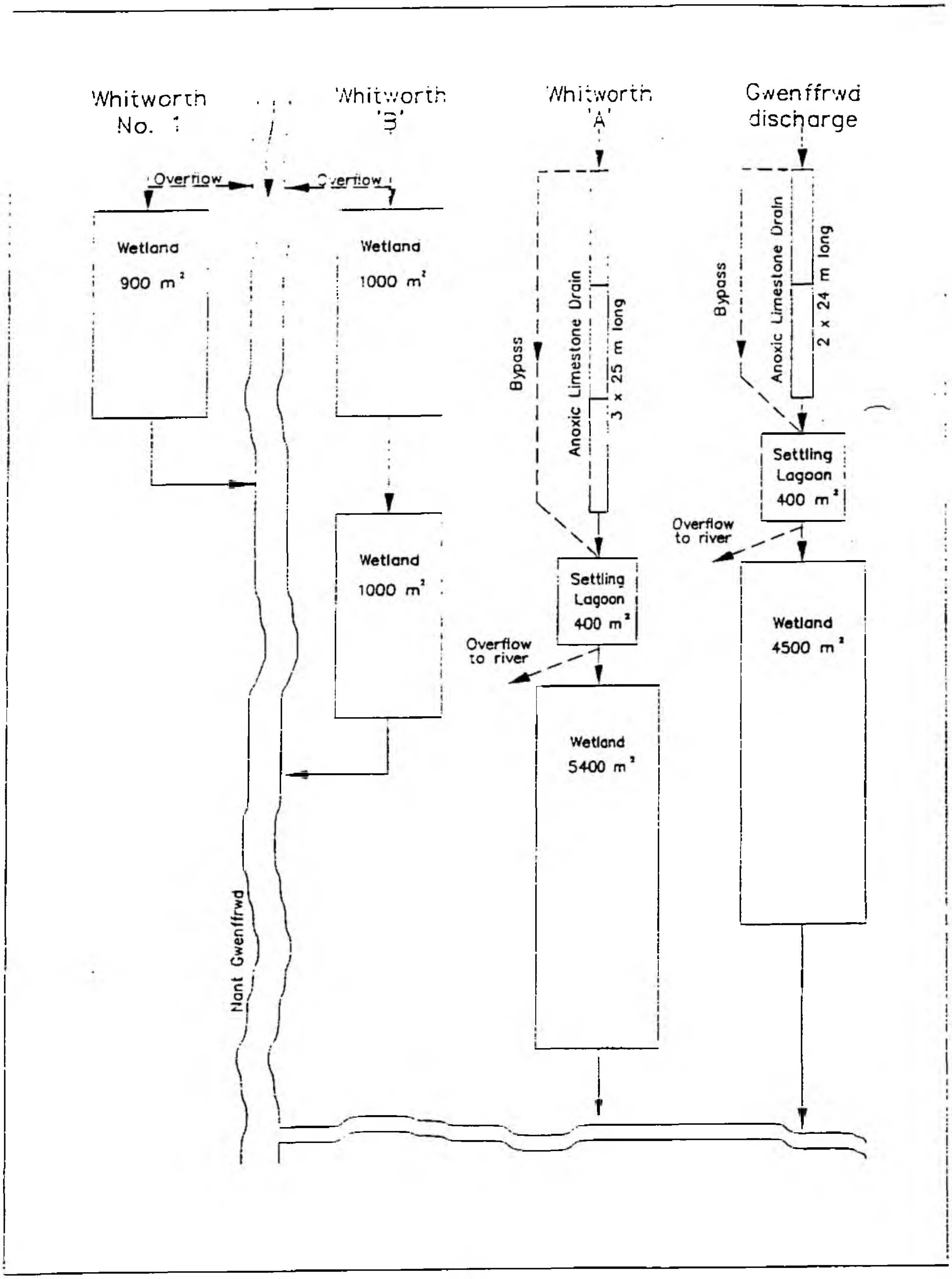


Figure 2.4 Diagram of Cwm Gwenffrwd treatment system.

that anoxic conditions may be enhanced by placing hay bales on top of a filter fabric above the limestone, inside the plastic envelope.

Under oxic conditions, armouring of limestone occurs following the oxidation of iron (II) species (Fe^{2+}) to iron (III). Such armouring inhibits further reaction and the limestone only generates a limited amount of alkalinity. In an anoxic limestone drain oxidation is inhibited by the conditions within the drain and the limestone does not become armoured with the precipitated iron (III) hydroxide.

ALDs do not directly remove metals from the AMD, although effluent from the drain will have a higher pH and so metal oxidation hydrolysis and precipitation as oxides/hydroxides will be promoted.

2.2.2 Design

ALDS are not recommended for treatment of groundwater with more than 2-3 mg/l dissolved oxygen, where aluminium concentrations exceed 25 mg/l, where pH is greater than 6.0 or when a significant proportion of the dissolved iron is in the Fe(III) oxidation state (Nairn, Hedin and Watzlaf, 1990, Skousen, 1990).

Given these criteria and the water quality information available (Appendix A), the northern of the two flows into the Whitworth Lagoon (Whitworth A) and the Gwenffrwd discharge would appear to be suitable for pre-treatment using ALDs, prior to the wetland-based water treatment system.

The water from the southern of the two flows entering the Whitworth Lagoon (Whitworth B) has an unexpectedly high dissolved oxygen content, at 11.3 mg/l, which renders it unsuitable for pre-treatment using an ALD. It is possible that this high dissolved oxygen content results from surface water infiltration close to the discharge and that this infiltration could be prevented, resulting in a discharge suitable for pre-treatment using an ALD. Further hydrological investigation, during the detailed design stage, would be necessary to confirm whether this is the case.

For the purpose of outline design, the Whitworth B discharge is not considered suitable for the installation of an ALD.

Appendix B details the calculations to determine the appropriate size for an ALD to treat the Gwenffrwd discharge and one to treat the Whitworth A flow, for a 20 year lifespan, using high quality (90% pure limestone, 300 and 840 tonnes respectively are required, or 200 and 560 m^3). Hydraulic considerations result in a trench 48m long, 2 m deep and 2.1 m wide for the Gwenffrwd discharge and one 75 m long, 2 m deep and 3.2 m wide for Whitworth A.

Figure 2.5 gives typical sections of an ALD.

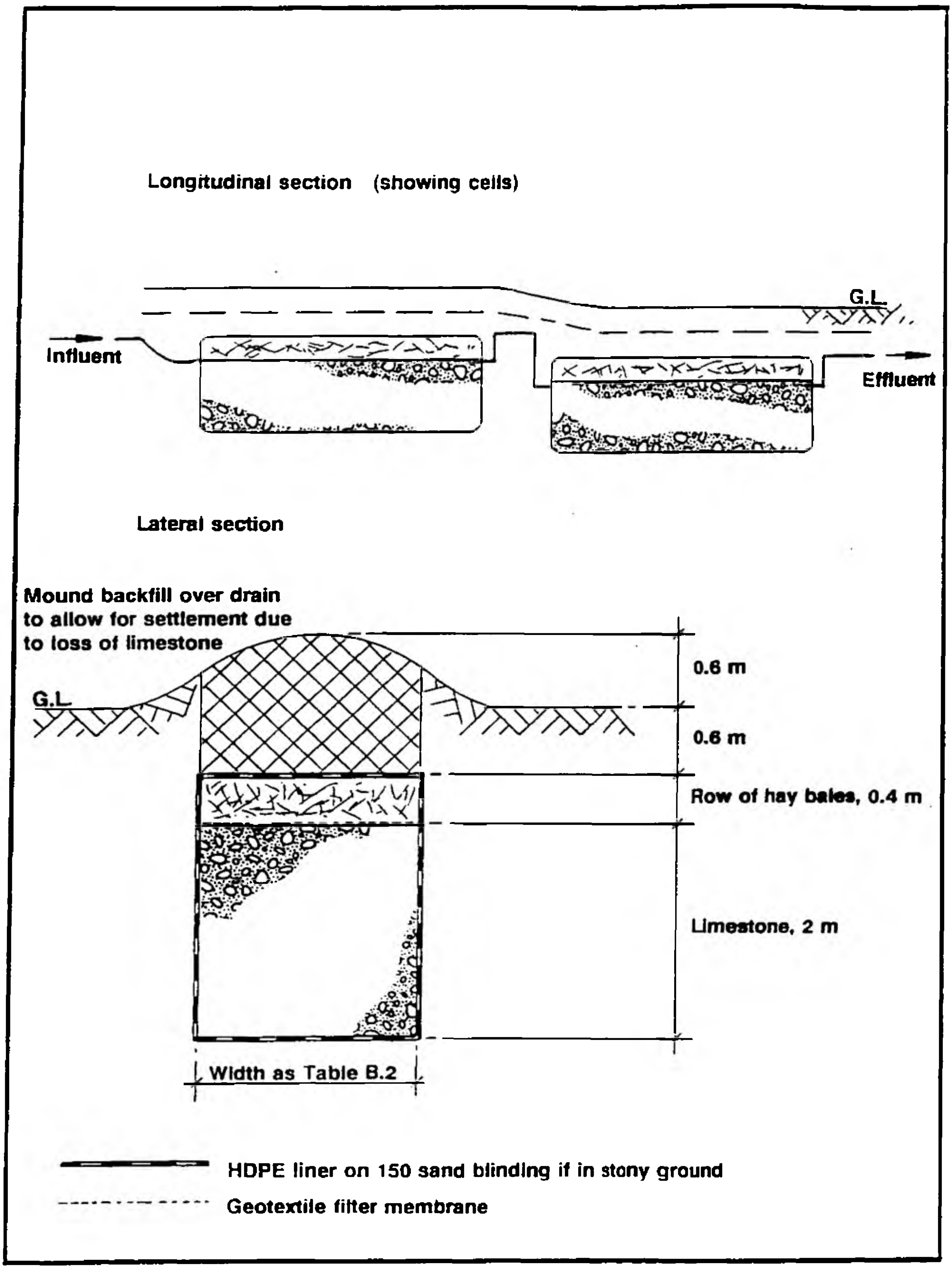


Figure 2.5 Typical sections of Anoxic Limestone Drain.

Constructing the ALDs as a series of cells, each with a flat base and outlets and inlets at the top of the cell, will maximise the amount of limestone that is submerged under conditions of low flow. The construction method will also enable the renewal of cells in turn, with the retention of some treatment capacity during the renewal of a particular cell. The installation of a temporary pipe or hose will enable diversion of the flow past a particular cell whilst it is being renewed.

The hay bales serve several purposes (Nairn, Hedin and Watzlaf, 1992). Degradation of the organic matter provides a sink for oxygen, maintaining the anoxic conditions, and generates carbon dioxide. Dissolved carbon dioxide is in itself a weak acid, and can further dissolve the limestone, thus generating alkalinity.

There are two alternatives to cope with high flow conditions through the ALDs (which have been designed on the basis of the mean flows):

1) Allow the flow to backup into the adit
2) Installation of an emergency bypass.

The former will simplify construction and enable attenuation of the flow within the adit. However, investigation must be carried out to determine whether the adit will accommodate such backing up.

A typical bypass would consist of a pipe which would only be used during higher flows. The operation of this bypass would be governed by the hydraulic head in the inlet pipe to the ALD, but a chamber and weir could not be used as this would tend to oxygenate the water and consequently lead to deposition of metal hydroxides within the ALD. An improved arrangement would use a branch in the inlet pipe leading to an inverted 'U' pipe which could be made adjustable to control the head at which the overflow would come into operation. Such a bypass would discharge into the settling lagoons.

It is necessary to intercept the flow from the adit in such a way that the flow remains anoxic. A typical headwall structure to perform this interception is shown in Figure 2.6.

Once intercepted, the flow from the Gwenffrwd discharge will be piped along the existing trench, cross under the bridge beneath the track and along to the start of the ALD, as shown in Figure 2.3.

2.3 Settling lagoons

The effluent from the ALDs will be anoxic but with an increased pH and alkalinity over the influent mine water. Oxidation/hydrolysis reactions can occur in this effluent to cause metal ions to precipitate. Settling lagoons are proposed to allow this precipitated material to be retained. The channels leading from the ALDs to the

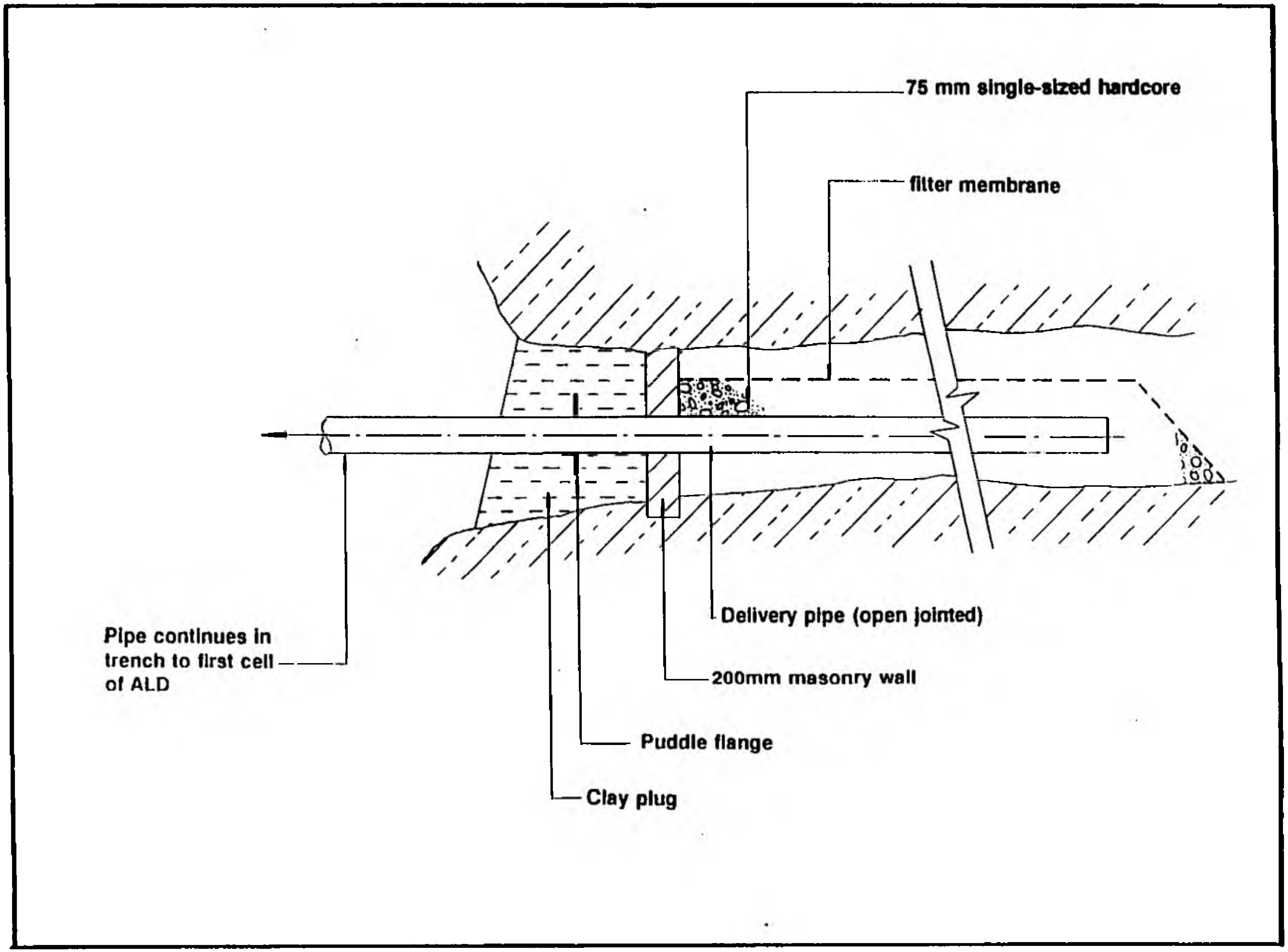


Figure 2.6 Typical headwall structure to intercept AMD at adit.

settling lagoons could be of concrete construction with large rocks set into the base to cause turbulent flow and enhance aeration of the water, which will enhance precipitation. The channel should be splayed, to dissipate flow velocity before flow enters the settling lagoons.

Two settling lagoons are proposed; their locations are shown in Figure 2.3. A typical plan is shown on Figure 2.7 and details of inlet structures on Figure 2.8. Calculations to specify dimensions of these lagoons are detailed in Appendix D. A lagoon 20 x 20 m is needed at the end of each ALD, with depths 0.65 m (Whitworth A) and 0.55 m (Gwenffrwd discharge). The locations should be prepared by excavating down to suitable firm ground. A clay lining, with sloping sides of nominal slope 1 in 3, would be suitable.

In order to discourage casual access to the lagoons and to soften their outlines the fringes of the lagoons should be planted with clumps of wetland vegetation salvaged during excavation of the site.

Removal of the precipitated metals could be facilitated by laying a concrete sump into the base of the lagoon and grading the base accordingly. A concrete trench set into the base of the lagoon would guide the end of a hose into the sump, and facilitate the removal of the precipitate by pump and tanker.

Adjustable overflows should be installed and excess flow discharged along a channel to the river. Overflows should be calibrated so as to prevent damage to the wetland through the application of greater than design flow rate.

2.4 Constructed wetland

2.4.1 Introduction

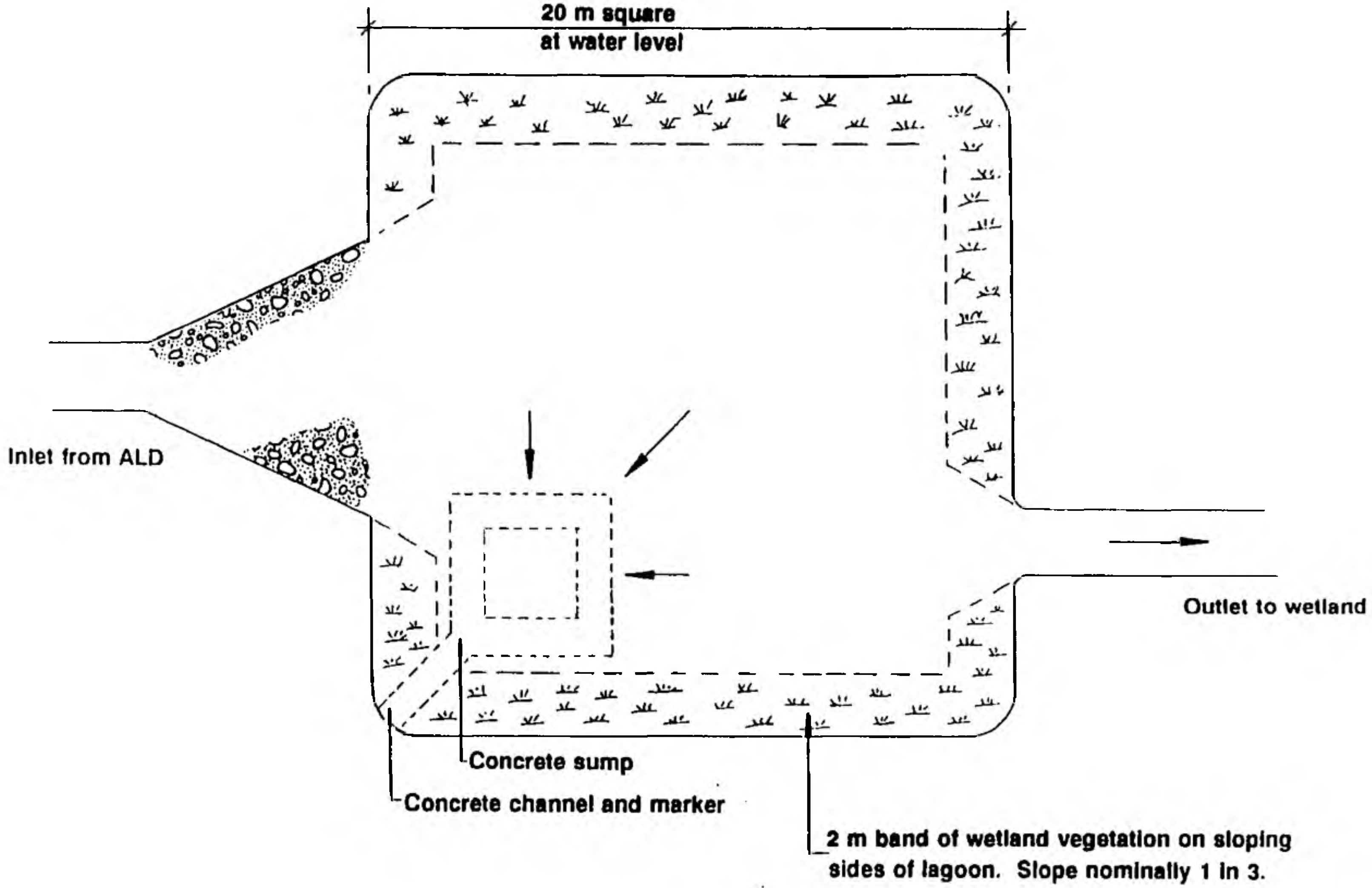
The use of constructed wetlands to remove metals from contaminated water is a relatively new field and the various removal mechanisms are not fully understood.

Two main mechanisms are considered to occur.

1) Metal oxidation and hydrolysis, within the surface water and oxic regions of the substrate, resulting in the precipitation of metals as oxides and hydroxides.

2) Sulphate-reduction, mediated by sulphate-reducing bacteria which reside in anoxic regions of the substrate. This results in the immobilization of metal sulphides within the substrate.

The latter mechanism represents a better long-term sink for removed metals than the former since precipitated hydroxides and oxides may be vulnerable to resuspension in storm events or redissolution by a pulse of highly acid ($pH < 3$) water. Also, the



- Lagoon to be lined with 300 mm - thick clay liner
- Base graded to allow sludge to settle into sump under gravity

Figure 2.7 Typical plan of settling lagoon.

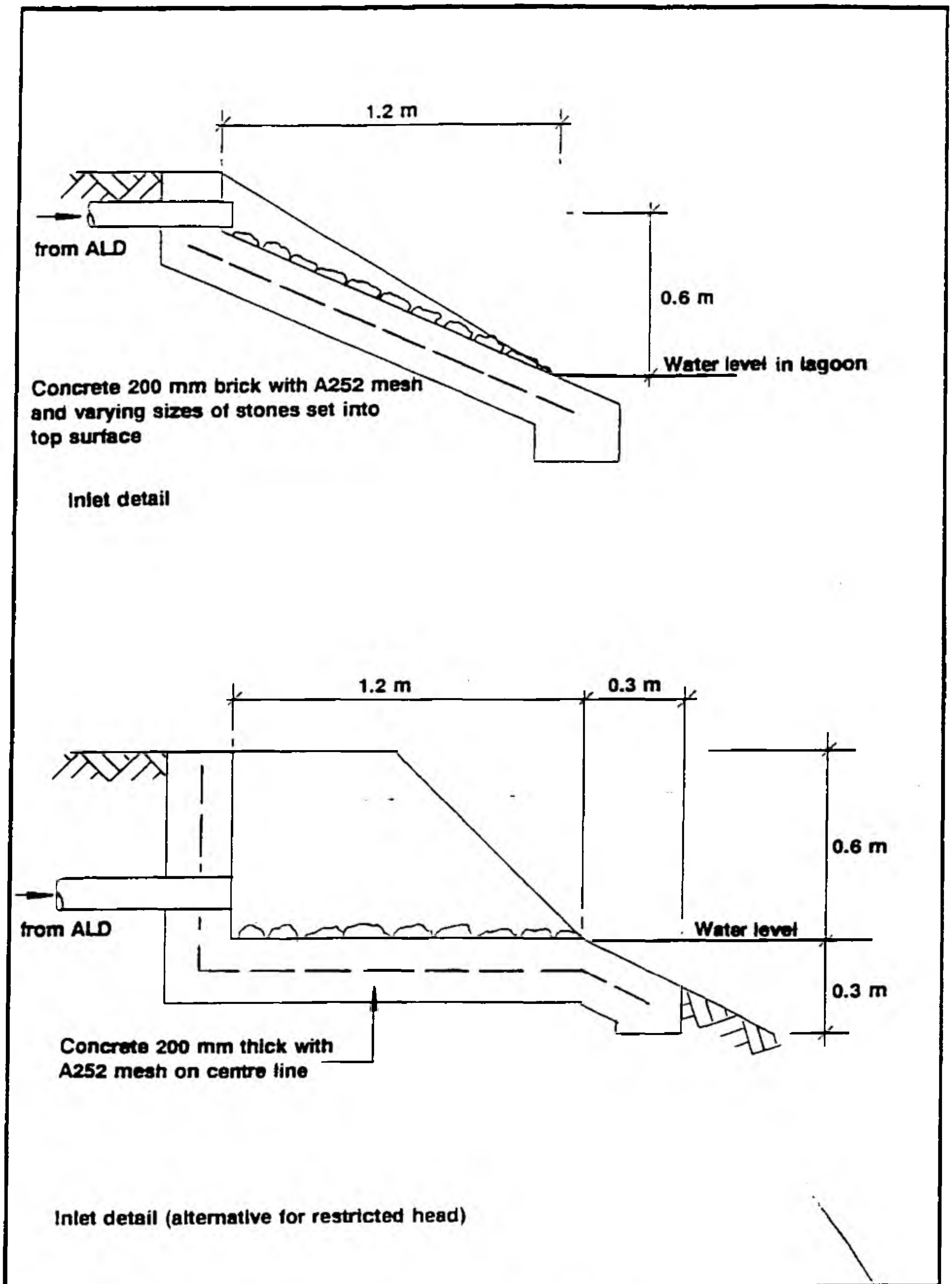


Figure 2.8 Settling lagoon - detail of inlet structures.

former mechanism can result in a lowering of pH whilst the latter consumes hydrogen ions.

The outline design of the constructed wetland described below favours sulphate-reduction.

For more information on removal mechanisms in constructed wetlands, see Richards, Moorehead and Laing Ltd (1992).

Constructed wetlands are of two main types: 'subsurface flow' and 'surface flow'. Subsurface flow wetlands are designed to confine most of the water flow to the substrate whereas in surface flow wetlands most of the flow occurs across the top of the substrate.

Of the two types, surface flow wetlands are simpler to design and construct and require simpler inlet systems. However, subsurface flow systems allow greater contact between wastewater and substrate but are more challenging to design. The sulphate-reduction rate will be far greater with subsurface flow. For more information, see Richards, Moorehead and Laing Ltd (1992).

The outline design of the constructed wetland aims to maximise subsurface flow.

2.4.2 Size and general arrangement

The sizing of wetland areas to treat each flow is detailed in Appendix E. The relief of the site and the treatment requirements suggest the use of cells of the sizes indicated on Figure 2.4 and shown in Table E.1.

Wetland cells with a substrate thickness of 700 mm and a maximum standing water level of 300 mm are proposed. The surface of the substrate should be undulating to give a minimum water depth (under low flow conditions) of 100 mm. The topography of the substrate would need to be finalized or adjusted after commissioning to improve water flow through the wetland.

Flow from the Gwenffrwd discharge should enter a wetland cell of 4500 m^2, having passed through the ALD and settling lagoon. This cell would be on the top terrace of the site. Flow from Whitworth A should enter a wetland cell of 5400 m^2 on the middle terrace of the site once it has passed through the second ALD and settling lagoon. Both these cells would discharge into the tributary of the Gwenffrwd. It is proposed that flow from Whitworth B should enter a wetland cell of some 1000 m^2, constructed within the Whitworth Lagoon, retaining the existing structure as much as possible. Overflow from this cell in high flow conditions could take place utilizing the existing sill of the lagoon. A new exit from the Whitworth Lagoon would be needed, through the bank to the south of the lagoon. Flow will then pass into a further cell of some 1000 m^2.

Whitworth No.1 flow could be treated locally using a wetland cell of some 900 m^2. Treating this flow locally has the following advantages:

* In a phased construction programme, successful operation of this cell can be demonstrated before proceeding with the construction of the larger cells.

* Local treatment eliminates the need to pipe the flow to enter the bottom terrace of the main wetland treatment systems, a pipe run of some 600 m.

* Local treatment means that the size of the southernmost cell on the bottom terrace of the main system need not be increased above 1000 m^2 and the existing pond south of this cell can be retained as a wildlife enclave.

The sizes derived are cautious, deliberately over-estimated and for the purpose of outline design only. Sizes should be refined on the basis of information gathered on flow volume and water chemistry at the detailed design stage.

2.4.3 The Whitworth Lagoon

Modification of the Whitworth Lagoon will entail diversion of flows entering the lagoon, the removal of the precipitated metal sludge by pump and tanker and its disposal to a licensed tip in an approved manner. Tipping costs are an estimated £15-20/tonne.

Once the lagoon is cleared, substrate and plants should be installed as detailed in Sections 2.4.7 and 2.4.8. The lagoon should be subdivided into subcells as detailed in Section 2.4.4.

2.4.4 Cells and subcells

Cells should be divided into subcells for the purpose of increasing the retention time, reducing hydraulic short-circuiting and enabling the uniform distribution of the influent. The general arrangement of a cell into subcells is shown in Figure 2.9, typical Sections in Figure 2.10.

Wetland cells have been shown as rectangular in plan, but during detailed design the shape will be refined to reduce visual impact so that the treatment system will blend with the surrounding landscape.

2.4.5 Inlet and outlet structures

Inlet to each cell should be via a channel with an adjustable weir, from which water will be fed to a rock-filled gabion. A filter membrane should be installed to separate

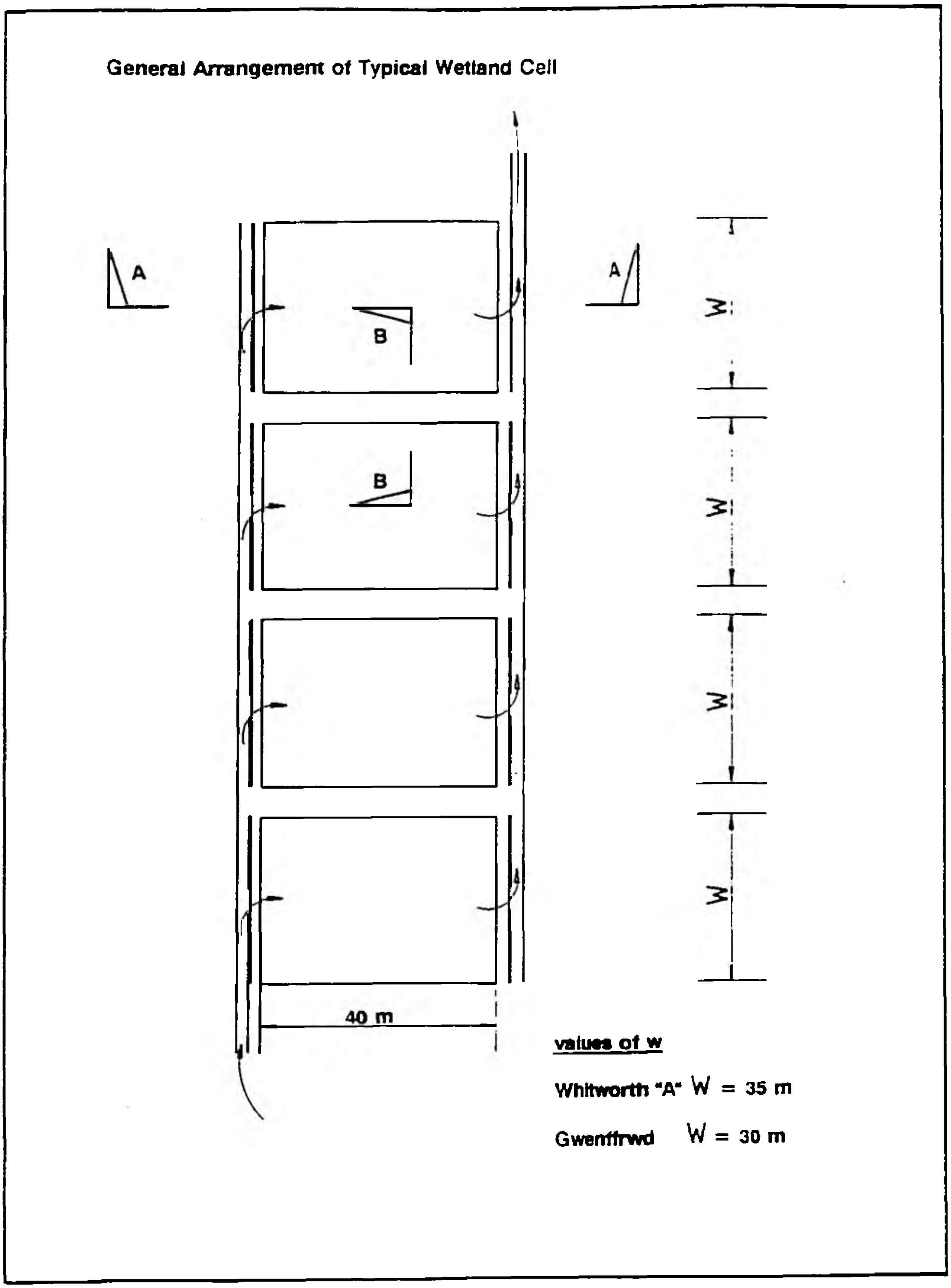


Figure 2.9 General arrangement of wetland cell (schematic).

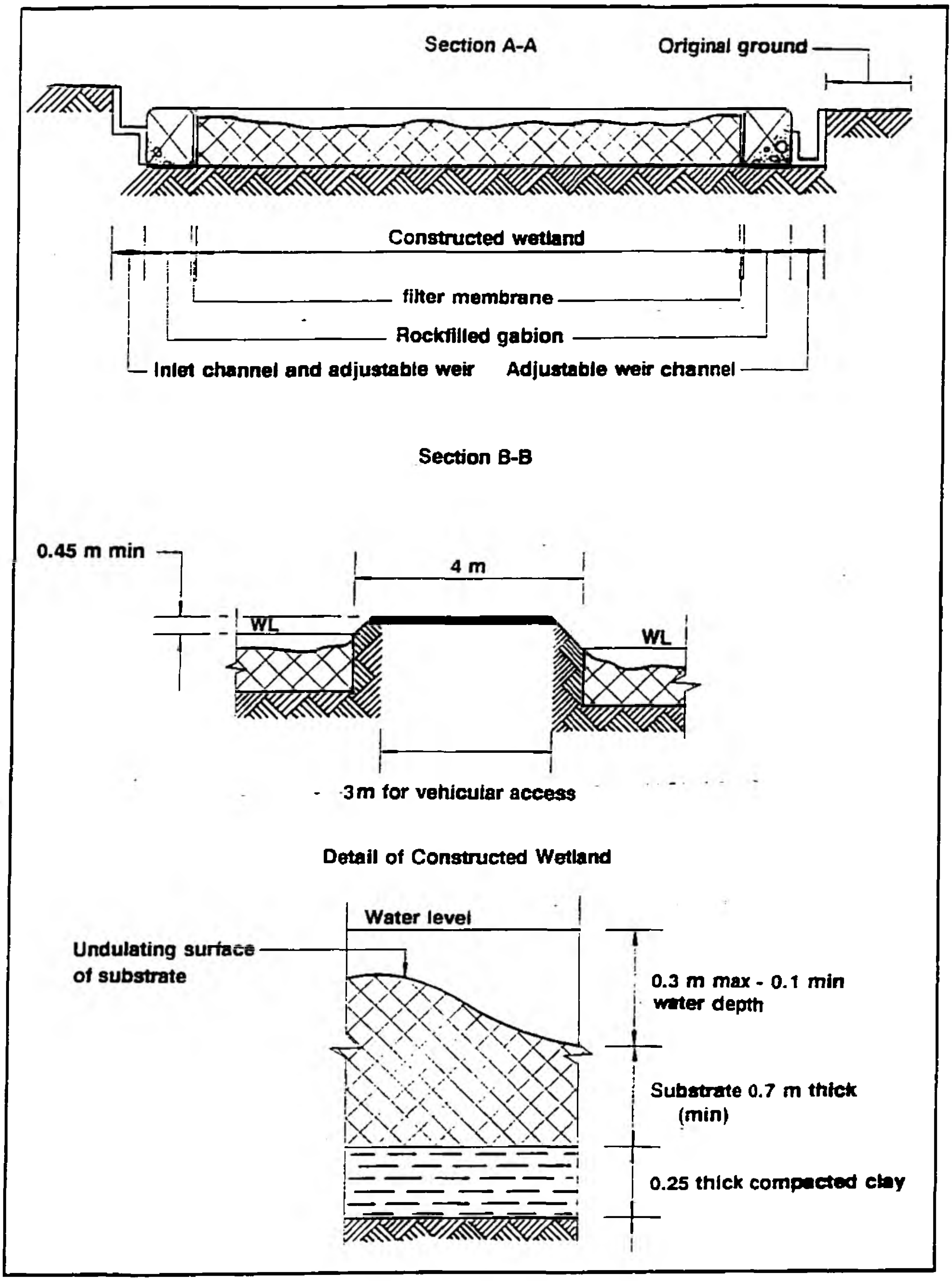


Figure 2·10 Typical sections of wetland cells.

the gabion from wetland substrate and through which water will pass to all levels of the substrate.

The adjustable weirs used to measure flows and regulate water levels between elements should be triangular profile "Crump" weirs, and in accordance with BS 3680:Part 4B:1969. The triangular profile and channel edges can be constructed in precast concrete sections and assembled on site.

The outlet structures should be the reverse of the inlet with water from all levels of the substrate percolating through the filter fabric, then collecting in the gabion and discharging through a channel into the receiving watercourse.

Should it prove necessary, it is possible to force water to enter the substrate at the base by blanking off some of the gabion.

2.4.6 Liners

Wetland cells should be lined to isolate them from groundwater. A material with a hydraulic conductivity of less than 10^{-8} m/sec is desired. Materials that could be used include compacted clay soils (0.15-0.25 m depth), bentonite, asphalt, fibreglass, butyl rubber and plastics. Bentonitic clays may not function correctly in AMD. Synthetic liners are expensive and should be assessed for resistance to aqueous hydrogen sulphide (H_2S). Recommended liner for the wetland cells is compacted clay, which is considered the most appropriate in this instance.

Suitable material may be present on site.

2.4.7 Substrate

The wetland cells should be filled with a substrate of mushroom compost to a depth of 0.7 m. This depth, together with the influent distribution structures describes in Section 2.4.5, serves to enhance the potential activity of sulphate-reducing bacteria. Mushroom compost is generally considered to be the optimum substrate for wetlands constructed to treat AMD. It is readily available and a rich source of plant nutrients and organic matter, which is required for growth of sulphate-reducing bacteria. Mushroom compost frequently has lime or chalk added during its manufacture to counter the natural acidity of other components. The compost contains less than 1% peat (supplier's information).

Alternative substrates include composted bark (more expensive than mushroom compost) or a mixture of straw and animal manure.

2.4.8 Vegetation

Most of the case studies in the literature of constructed wetlands treating coal mine drainage are planted with *Typha latifolia* (Reedmace). These plants tolerate high metal levels and are known to oxygenate the substrate very effectively. They are also cosmopolitan in distribution occurring anywhere from the Arctic Circle to 39°S and easy to obtain from commercial nurseries. *Typha* plants are tall and may be vulnerable to being blown over in exposed windy sites, although they have been grown successfully in upland areas such as the North Yorkshire Moors. It may be advantageous to construct windbreaks of banks of soil, east and west of each wetland cell.

The predominance of the use of *Typha latifolia* in the literature is mainly for geographical reasons - these plants are prevalent in the north east of the United States of America, the location of many of the case study sites.

The planting of a range of species is likely to be beneficial by:

* increasing the number of microhabitats within the wetland treatment and therefore increasing the variety of treatment processes possible.

* increasing the wildlife habitat potential

* increasing the visual interest of the site and reducing the visual intrusion.

Other plants that could be used in addition to *Typha* include *Scirpus lacustrum* (Bulrush), used to great success in Germany, *Iris pseudocorus* (Yellow Flag), which has a good root structure and is very hardy and *Phragmites communis* (Common Reed), used extensively in sewage treatment wetlands.

Any differences in effectiveness of these plants in coal mine drainage treatment are not fully understood. The phased construction, with Whitworth No.1 being treated locally first, could enable the differences to be investigated.

Suggested planting densities vary from one to four plants per square metre. Although rhizome cuttings have been extensively used, bare rooted plants are readily available and may become more quickly established than rhizome cuttings. Bare root plants can be quickly and easily planted in a slit made in the substrate.

A planting density of four plants per square metre is advocated, with bare rooted plants being planted into slits in the substrate, in staggered rows.

Planting should take place in Spring. The substrate should be saturated with water but not flooded. Mine drainage water should be introduced to the wetland gradually and only once plants have become established (see Commissioning, Section 5.2).

2.4.9 Drainage

Land drains will be required within the site to control groundwater and to intercept surface water runoff. This will be best achieved by the use of interceptor drains upslope of the new structures and agricultural land drains in various areas of the site.

2.4.10 Alternative process options

Several process options are considered here. These will need further investigation during the detailed design.

The first two of these are concerned with blending a low alkalinity discharge with a high alkalinity discharge. The nature of these works are such that they are unlikely to significantly affect the cost of the system.

1) The flow emerging from Whitworth B can be combined with that emerging from the ALD pre-treating Whitworth A, into a larger settling lagoon than that proposed in Section 2.4, and then to treat these flows together in a single wetland of some 7400m^2 on the middle terrace. The Whitworth Lagoon would be infilled.

2) The effluent from the systems treating Whitworth A and Whitworth B could be blended in a 'polishing pond' on the site of the temporary lagoon. This would require the construction of a channel carrying the effluent from the Whitworth B system to the polishing pond (see Figure 2.3). This channel is likely to disrupt the existing pond, which it would be advantageous to retain for its likely ecological value.

3) As described in Section 2.2.2, it may be possible to install an ALD for the discharge from Whitworth B provided the hydrological investigation during the detailed design shows that the dissolved oxygen content of this discharge can be reduced. The installation of a further ALD, which would require a further settling lagoon, would increase the cost of the project by some £25,000 but may increase the overall quality of treatment.

2.5 Performance expectation

The treatment system has been sized on the basis of guidelines on iron removal and flow rate to be of such a size that it should remove 100% of the influent iron from the Gwenffrwd discharge, Whitworth A and B and Whitworth No.1. It also incorporates many measures designed to increase the removal of metals by sulphate-reduction, to produce sulphide minerals locked within the substrate matrix.

The use of Anoxic Limestone Drains will further enhance iron removal by adding alkalinity and raising pH.

On the basis of information available at present, a mean iron removal performance of over 80% is considered likely.

The phased construction recommended, with Whitworth No. 1 being treated locally in wetland cell of 900 m^2 in the first instance, would enable more detailed predictions of the performance of larger cells and the entire system to be made.

3 GARTH TONMAWR

3.1 Description

The area of interest is detailed in Figure 3.1.

3.1.1 Introduction

The upper Pelenna valley (Cwm Blaenpelenna) is a narrow upland valley, partially forested with conifers. Coal extraction in the valley centred around the Garth Colliery, which closed in the early 1960s. The buildings of the Garth Colliery were located around the Garth Tonmawr minewater discharge (measurement point 71016 on Figure 1.2).

Historical maps show a mineral railway entering a level at this point. They also show the area to be surrounded by buildings. The railway has been removed and the buildings demolished, although some heavy foundations remain.

At Garth Tonmawr and downstream for some four hundred metres, the valley floor contains large, low heaps of spoil. Some of this spoil is being eroded into the Blaenpelenna.

Upstream of Garth Tonmawr, around Middle Mine, there are significant heaps of colliery spoil. Gully erosion is evident on these, and water can be observed percolating through the spoil. It is evident that the Middle Mine discharge (measurement point 71021 on Figure 1.2) has, from time to time, flowed over the top of these heaps although at the majority of the flow presently bypasses the heaps, running immediately to the south. The pH of the spoil at Garth Tonmawr and Middle Mine is acid, with pH between 4 and 4.5.

3.1.2 Surface water flows

At Garth Tonmawr, water issues from a disused level and flows through a small area of natural wetland on colliery spoil and dominated by Soft Rush before entering the Blaenpelenna.

3.1.3 Geology and soils

Cwm Blaenpelenna is underlain by Carboniferous upper coal measures consisting of the Pennant sandstones. The beds are close to horizontal or dip gently to the southwest. Minor northwest-southeast trending faults are present.

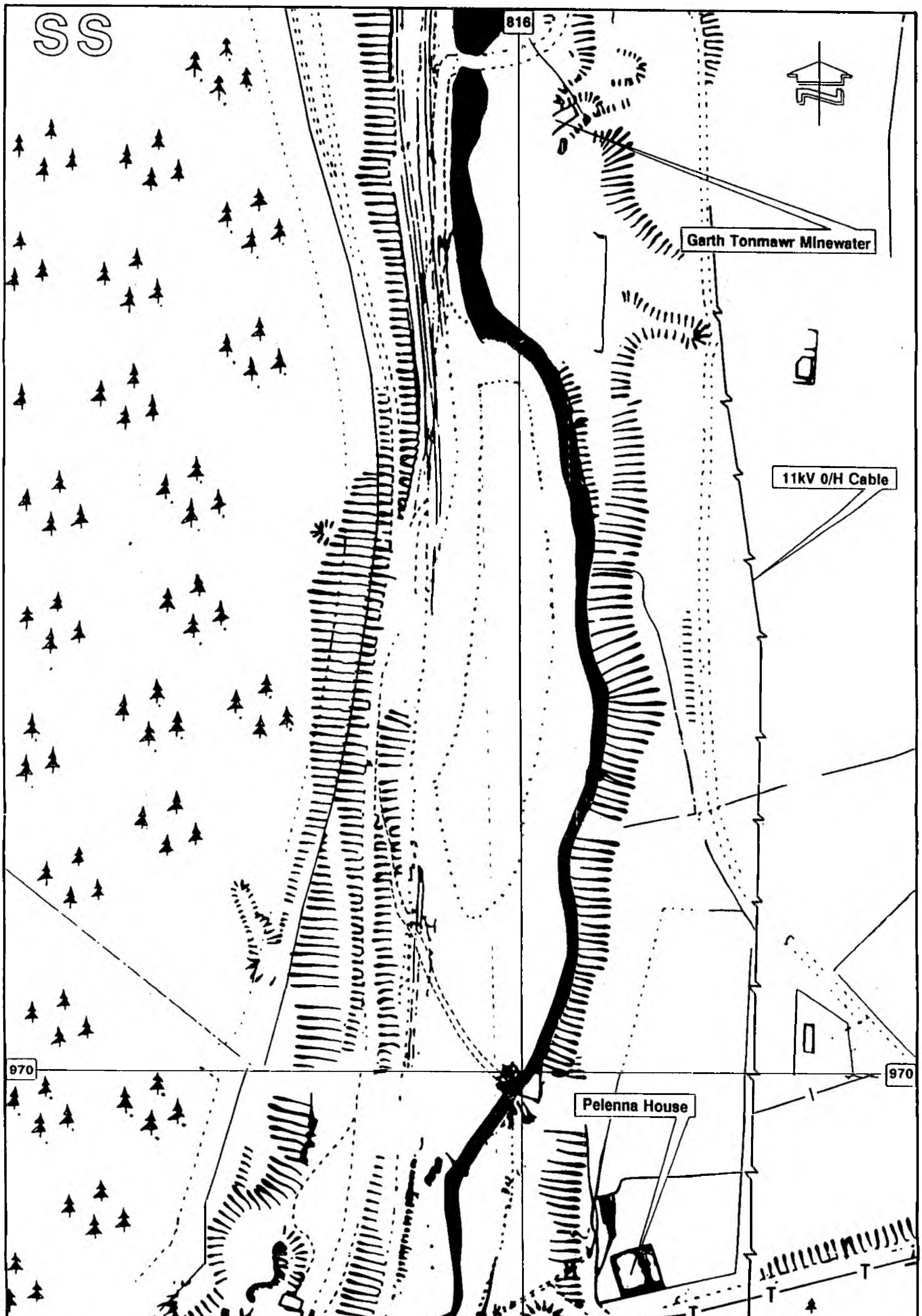


Figure 3.1 Garth Tonmawr: area of interest.

Surface deposits comprise Pleistocene glacial boulder clay and cover much of the valley sides with alluvium and colliery spoil covering the valley floor.

Soil type is very similar to Cwm Gwenffrwd, the soils of the lower valley being of the Hirwaun association, those of the upper valley being of the Gelligaer association.

3.1.4 Vegetation

The natural wetland adjacent to the discharge is dominated by Soft Rush. Drier parts of the colliery spoil heap on the east bank of the Blaenpelenna are vegetated by Spruce and Larch which have self seeded from a plantation on the west side of Cwm Blaenpelenna. Ground vegetation is principally of mosses and lichens with some Bents and Fescues and acid-tolerant wayside plants such as Foxglove and Sheeps Sorrel. The spoil heap on the west bank, downstream of the discharge, is again poorly vegetated. Some Larch and Spruce have become established on its fringes and on the plateau. Similar ground vegetation to that of the east bank spoil heap has become established away from areas traversed by vehicles.

3.1.5 Land ownership

The ownership of the land surrounding and immediately downstream of, the Garth Tonmawr mine discharge is uncertain. Representatives of West Glamorgan County Council understand it to be in the ownership of either a Mr Pughe or a Mr Miles, the owners of adjacent farms, and are currently making further enquiries.

3.1.6 Objectives

The Institute of Hydrology report (Ishemo and Whitehead, 1992) identifies the Garth Tonmawr minewater discharge as the most significant entry of iron to the Blaenpelenna and suggest that a treatment method resulting in a 50% reduction in dissolved iron would be sufficient to achieve the EIFAC standard for this part of the catchment.

3.2 Constructed wetland

The use of an Anoxic Limestone Drain has been considered but rejected because minewater dissolved oxygen is in excess of the maximum suggested by Nairn, Hedin and Watzlaf (1990) (see Section 2.2.2).

The sizing of the wetland to treat the Garth Tonmawr Minewater is detailed in Appendix F.

A wetland of 7000 m^2 is required on the basis of iron removal efficiency guidelines. The relief of the site is restrictive. The following general arrangement is proposed (see Figure 3.2).

The minewater discharges into attenuation lagoon (1800 m^2, not included in the 7000 m^2 wetland area) which serves to buffer variation in flow rates. A high flow bypass structure discharges from this lagoon directly into the Blaenpelenna. Flow from the attenuation lagoon crosses the Blaenpelenna on a channel/bridge to flow into the wetland area (7000 m^2) on the opposite bank. The wetland area is constructed on the low colliery heap spoil on this bank. Discharge returns to the Blaenpelenna.

Subcells would be necessary, such as those proposed for wetland cells in Cwm Gwenffrwd, detailed in Section 2.4.4 and on Figures 2.9 and 2.10. Vegetation and substrate specification would be as the Cwm Gwenffrwd wetland. The attenuation lagoon and wetland would be clay-lined.

Flow control and measurement structures would be installed on the entrance to the attenuation lagoon, on the channel/bridge and on the discharge from the wetland. Such structures would be similar to those detailed in Section 2.4.5.

3.3 Performance expectation

The wetland was sized using a 10 mg Fe/m^2/day iron removal rate. It is of such a size that it should remove 100% of the influent iron. However, for reasons including the high flow rate, the possible need to divert some of the minewater flow past the wetland and possible problems with maintaining uniform flow through the substrate, a lower treatment efficiency may be expected. On the basis of information available at present, mean iron removal performance is expected to be in excess of the 50% required for this discharge.

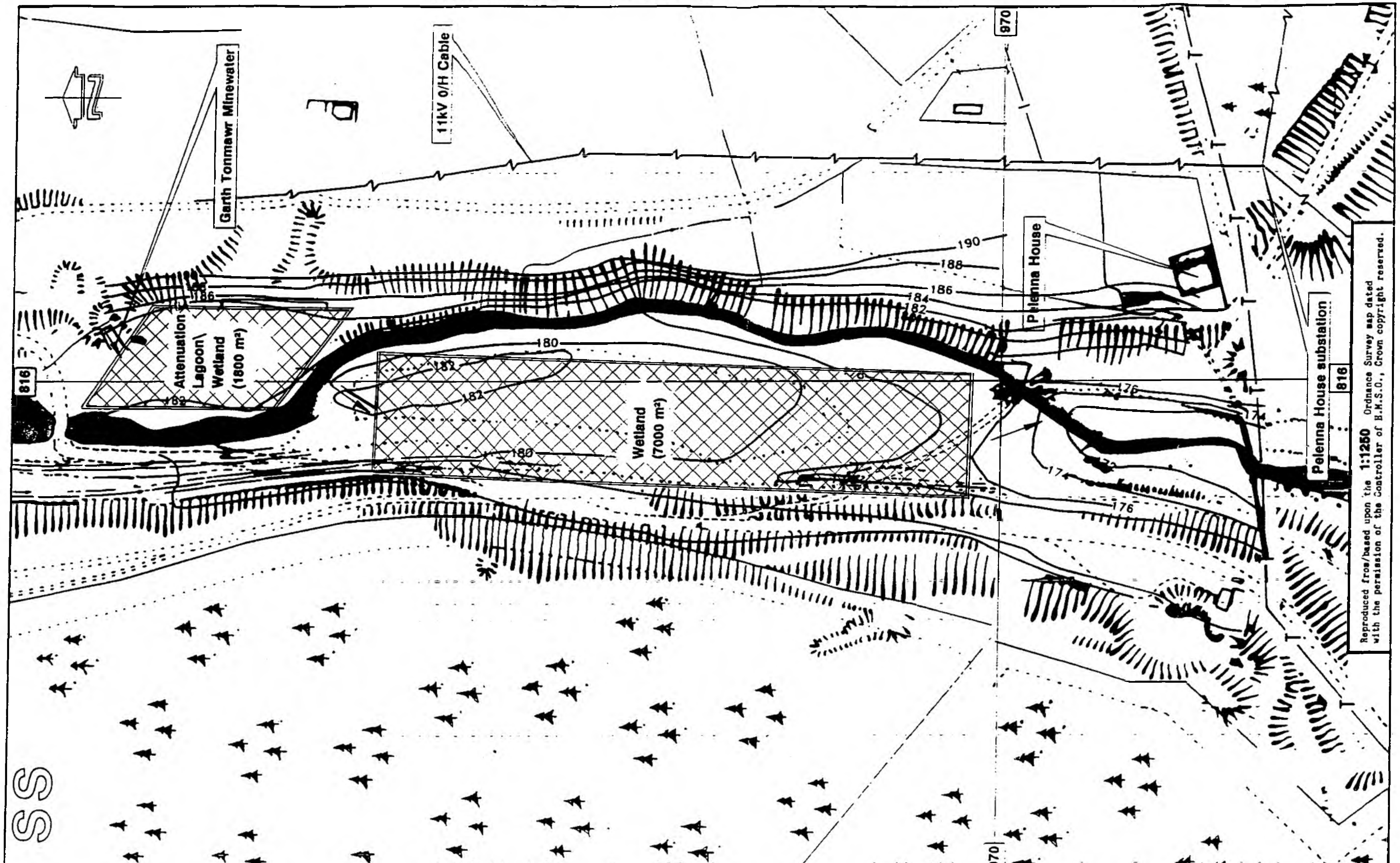


Figure 3.2 General arrangement of Garth Tonmawr wetland. Treatment units are shown schematically only. Areas and locations are correct, but shape will be varied to blend with the existing landscape.

4 DETAILED DESIGN AND CONSTRUCTION

4.1 Information gathering

In order to design the treatment system in detail, information must be gathered on a wide variety of site-specific factors. Investigations should include:

* A full topographical survey.
* A wildlife survey.
* The collection of data on water quality and flow for all flows to be treated by the wetlands.
* The biological and chemical monitoring of the catchment downstream of the proposed discharge points to establish the 'baseline' biological and chemical quality of the water.
* The location of all services on or near the area of interest.
* A hydrological survey to locate and characterise all flows of surface and groundwater likely to affect the wetland.
* A detailed site investigation to characterize surface materials and soils, bedrock depth, available construction materials or any other pertinent geological or geotechnical aspects.
* Excavations of each of the discharges to aid design of headwall structures and to confirm suitability for treatment using ALDs.
* The following will need to be determined on available substrate materials: hydraulic conductivity, pH, buffering capacity, plant nutrient concentrations and microbial activity. The outline design selects a substrate with a hydraulic conductivity of 10^{-4} m/s; it may prove necessary to mix the mushroom compost with crushed rock to attain this hydraulic conductivity value.
* A landscape assessment to evaluate the likely visual impact of the treatment system.

4.2 Detailed design

Minimum contents of a detailed design for large wetlands for municipal wastewater treatment are given by Tomljanovich and Perez (1989). These may be used as the basis of a detailed design for an AMD treatment wetland. The minimum contents are:

* access roads,
* utilities (overhead and underground),
* erosion control measures,
* location and boundaries of borrow areas,
* trees and existing vegetation to be left undisturbed,
* dikes (location, crest width, length, elevations, upstream and downstream slopes),
* spillway location, elevation and type,
* size, location, elevation, and type of water control structures,

* permeability requirements of substrate and dikes,
* liners (type, location, specification),
* placement of substrate materials,
* wetland base slope and tolerances,
* species and spacing of vegetation to be planted,
* liming and/or fertilizer requirements,
* seeding, mulching, fertilizing, and liming of dikes and disturbed land,
* inlet and outlet distribution piping (type, location, elevation).

In addition, the detailed design requires investigation of measures to minimise the visual impact of the treatment systems, and of measures to ensure the safety of casual users of the area.

4.3 Design and construction programme

A phased design and construction programme is advocated with the discharges being treated in the following order:

1. Whitworth No.1
2. Garth Tonmawr
3. Gwenffrwd discharge
4. Whitworth A
5. Whitworth B.

The benefits of treating Whitworth No.1 first are detailed in Section 2.4. The next discharge to be treated should be Garth Tonmawr since the proposed wetland is simpler than the main wetland in Cwm Gwenffrwd and has less stringent performance requirements. Lessons can be learnt during the construction of the Garth Tonmawr wetland and applied during the construction of the more complicated system.

A notional programme for the installation of the constructed wetland treatment systems for the catchment is given in Figure 4.1.

Construction will take place over five years, starting in 1994 (year 1). Some investigations will be needed in 1993 (year 0). These can be restricted to the assembly of water quality and flow data for the discharges and assembly of suitable 'baseline' water quality information for the catchment downstream of the proposed discharge points for the constructed wetland systems.

The following items detail works to be carried out for a discharge which is to be pre-treated by an ALD, passed through a settling lagoon and then discharged to a wetland

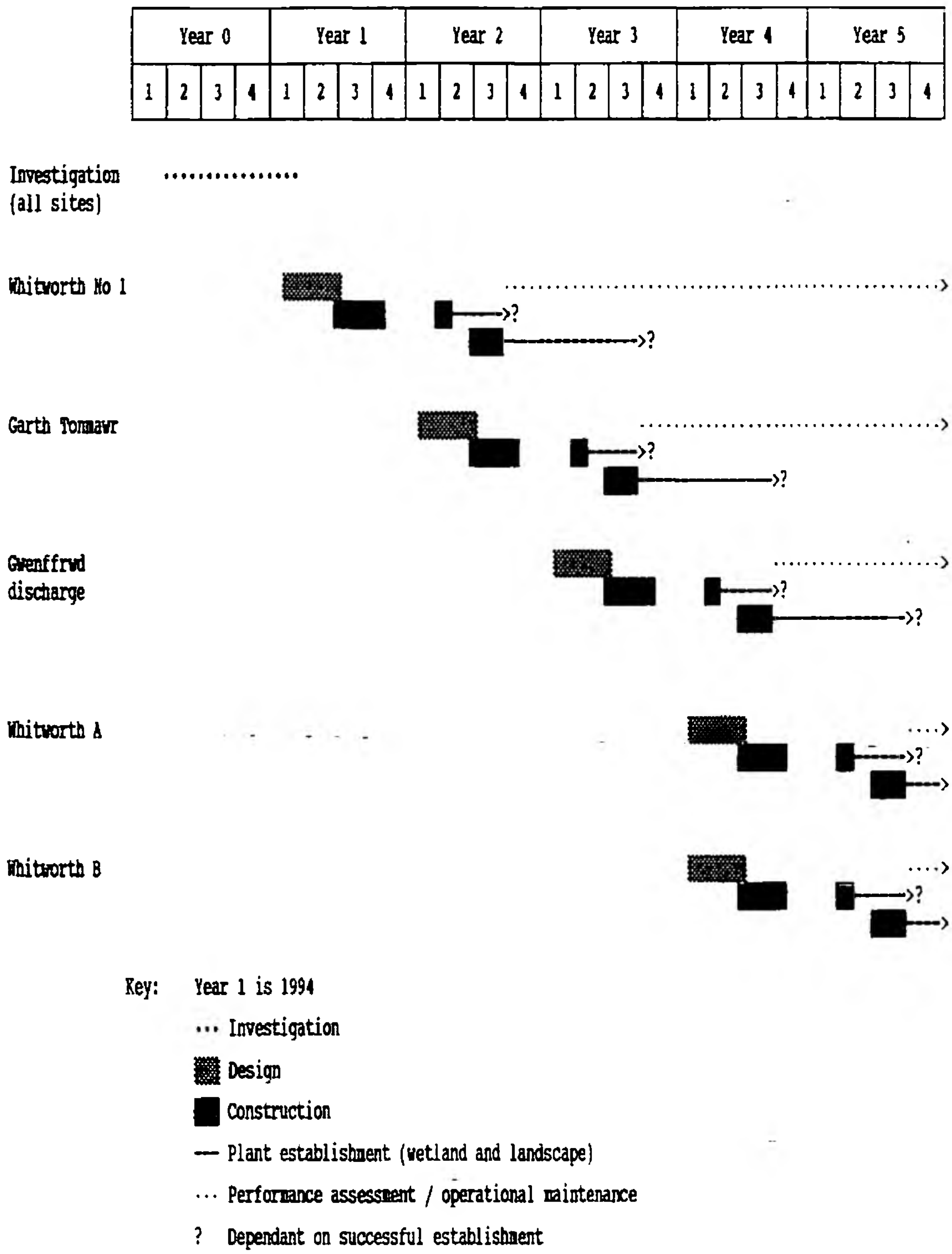


Figure 4.1 **Notional programme for design and construction of wetland treatment systems.**

(*e.g.* Whitworth A). Where wetland-only treatment is proposed, items 3 and 4 will not apply and the final connection (item 8) is direct to the wetland.

1. The wetland and outlet to watercourse should be constructed.

2. The wetland vegetation should be allowed to become established, which may take between 3 months and a year after the planting season.

3. The settling lagoon and connection to wetland should be constructed.

4. The ALD, bypass and connection to settling lagoon should be constructed.

5. A temporary bypass for mine water, to a temporary lagoon, should be constructed. This bypass would consist of a limestone-filled, lined sump excavated adjacent to the existing discharge and overland pipework to a lagoon. In Cwm Gwenffrwd, the temporary lagoon could be sited on the bottom terrace downstream of the existing pond. At Garth Tonmawr, the attenuation lagoon should serve this purpose.

6. When the bypass has been completed and tested, mine water should be diverted into it.

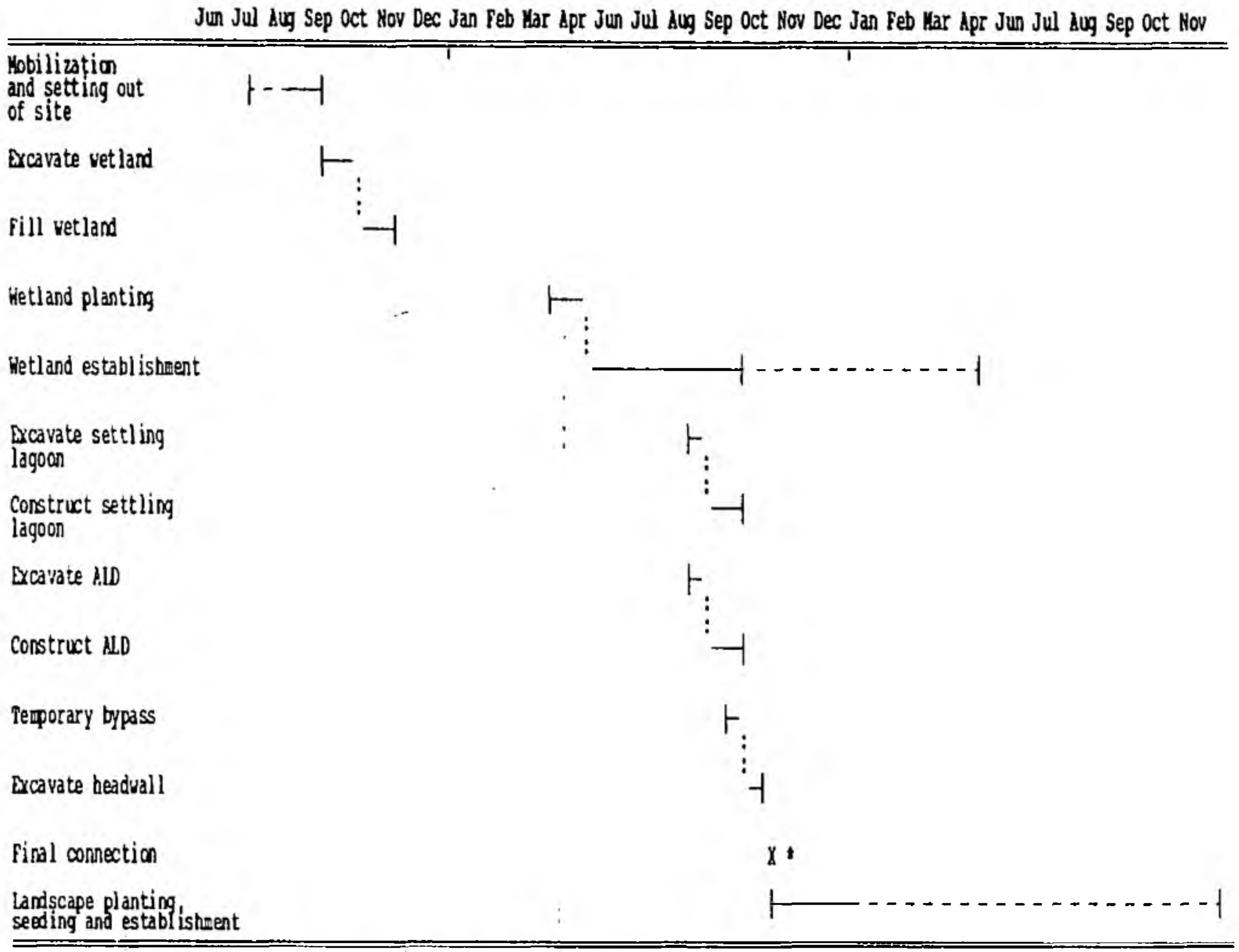
7. Excavation to establish headwall structures should take place along the line of existing discharge, testing the water for dissolved oxygen at appropriate stages. When an acceptable level of dissolved oxygen is reached (where an ALD is to be constructed) a pipe to take the discharge should be sealed into the adit. The detail of the seal will have to be finalised on site, but a typical arrangement is shown on Figure 2.7. All excavated material should be taken to a licensed tip.

8. The final connection to the ALD should be made once the wetland has become established.

9. All contaminated material excavated during the course of the works should be taken to a licensed tip.

Actual programming will be governed by the amounts of excavation and filling required, and on the time to establish the wetland.

Typical timing of construction of a wetland treatment system is given in Figure 4.2.



* Delay this date to March of following year if wetland not established

Figure 4.2 Typical timing for construction of a wetland treatment system.

4.4 Pollution prevention during construction

The following measures should be adopted:

* All new structures and wetland to be established before mine water is diverted through the system.

* Ground water arising during construction to be discharged to the temporary lagoon.

* Mine water to be diverted to the temporary lagoon when excavating into the adit when constructing the headwall.

* All contaminated material found in the lagoon and abandoned watercourses to be removed to a licensed tip as soon as it is excavated.

* A detailed programme to be submitted to, and agreed with, all interested parties before commencement of work on site.

* An employer's representative/clerk of works to be engaged for the duration of the contract.

* If required by the National Rivers Authority, continuous monitoring of turbidity and/or conductivity to be established downstream of the site to trigger alarm to indicate a pollution incident.

5 COMMISSIONING

5.1 Introduction

Commissioning of each wetland will take the following general steps:

1. Interception of acid mine water flows as described in Section 4.3.
2. Removal of any temporary flow diversions.
3. Control of water level to aid plant establishment.

This last point is described below.

5.2 Water level

The water level regime requires careful control following planting to ensure the plants survive.

Allen, Pierce and Van Wormer (1989) consider that too much water is liable to cause greater problems than too little. Plants should be introduced into a saturated, but not flooded, substrate and allowed to grow until the new shoots protrude above the design water level. The mushroom compose substrate would be installed wet but may require watering if it shows signs of drying out over the summer of the first year of establishment.

After the plants have become established, acid mine water should be gradually introduced, up to the final standing water depth and the design flow rate. The establishment of weeds in the substrate whilst the substrate is saturated but not flooded is unlikely to be of concern since weeds will not survive a standing water depth of 0.2-0.3m.

For more information on plant establishment, see Richards, Moorehead and Laing (1992).

5.3 Fertilizer requirements

Mushroom compost has the following typical nutrient concentration (supplier's information):

Nitrogen	2.6-2.8% of dry solids
Phosphorus	0.2-1.6% of dry solids
Potassium	0.9-2.4%
Organic matter	70-95%
pH	6.6

Compost is also likely to have a considerable amount of plant-available calcium, since chalk or lime is frequently added during its production, to counter the components' natural acidity. The compost will generally have a near-neutral pH. Given these nutrient levels, it is not considered that fertilizing of the wetland will be necessary during its commissioning.

6 AFTERCARE AND OPERATIONAL MAINTENANCE

6.1 Introduction

In a survey of some twenty constructed wetlands treating AMD from coal mining (Kleinmann and Girts, 1987) maintenance was generally considered inexpensive and not time-consuming.

Maintenance measures included the replacement of limestone rip-rap, grading to the limit the inflow of surface water runoff and the placing of hay bale dikes to limit channelization.

The feasibility study identifies the principle maintenance measures to be:

* monitoring of wetland performance
* periodic removal of iron oxides and hydroxides from the settling lagoons
* periodic replacement of limestone in ALDs
* periodic replacement of wetland substrate
* process optimisation
* aftercare of wetland plants
* maintenance of structures.

These measures are dealt with in detail below.

6.2 Monitoring of wetland performance

In order to monitor wetland performance, it is necessary to compile information on water quality and flow rates for flows entering and leaving each component of the treatment system.

The minimum analysis suite for samples entering or leaving wetland treatment cells is as follows:

pH
Iron, dissolved and total
Manganese, dissolved and total
Aluminium, dissolved and total
Acidity
Alkalinity
Sulphate

Flows leaving anoxic limestone drains should be analyzed to determine

pH
Dissolved oxygen and temperature
Alkalinity
Acidity.

At the Cwm Gwenffrwd site, water should be sampled leaving both ALDs, leaving the settling lagoons and, at minimum, leaving each wetland cell. At the Garth Tonmawr site, water should be sampled as it leaves the adit, as it passes between the two cells and as it leaves the treatment system after the second cell.

In addition to this minimum sampling programme, a detailed investigation of water quality within a particular cell can be justified on the basis of information gathering for process optimisation and for dissemination to interested parties.

Monitoring wells (vertically mounted tubes, running the whole depth of the substrate, with slots cut into the walls at a particular depth) could be placed within cells. To sample from these, they should be pumped to clear them of any water that has been standing (continuous monitoring of pH or conductivity would determine when this has been done) before being sampled.

Such monitoring wells would determine how treatment efficiency varies with depth within the substrate. For greatest efficiency, flow of water through the entire substrate should be monitored.

For reasons of economy, one cell at each site should be chosen to be fitted with such monitoring wells.

The construction of "Crumps" weirs at positions throughout the treatment system will aid the measurement of flow volume. Flow measurement points should include flows leaving both ALDs at the Cwm Gwenffrwd wetland and flows entering each wetland cell on both sites.

Detailed monitoring is essential to enable process optimisation and the early detection of any decline in performance which may indicate exhaustion of substrate or limestone.

A benthic macroinvertebrate survey of the catchment will serve to monitor the improvement in water quality once wetlands are operational.

6.3 Removal of iron oxides/hydroxides from the settling lagoons

Precipitated metal oxides and hydroxides will build up in the settling lagoons and need periodic removal. Several design features of the lagoons facilitate the removal of the sludge.

* the lagoons are sited close to the track, to allow easy access by road tanker
* concrete sumps will collect the sludge in a defined area
* the concrete channel leading to the sump provides a guide for the hose of the pump, to enable easy removal by pump and tanker (see Figure 2.9).

Sludge will need to be disposed of to a licensed tip in an approved manner.

Tipping costs are estimated at £15-20/tonne.

6.4 Periodic removal of limestone in ALDs

The Anoxic Limestone Drains have a design lifespan of twenty years. After this time, the limestone will be exhausted and need replacing.

This will entail the diversion of flow, the removal of soil overburden, limestone and hay bales, the checking of the integrity of the plastic liner and then the reconstruction of the ALD using fresh materials.

The multiple-cell design of the ALDs will allow renewal in sections, with easy diversion of the flow using a flexible hose or irrigation pipe.

A typical sequence for replenishment of ALDs is as follows:

1. Replenish the full length of the ALD.

2. Excavate overburden, part by machine, part by hand, so that liner is not damaged unnecessarily. Deposit spoil alongside ALD.

3. Fold back top of liner and remove any remaining hay/straw and filter membrane.

4. Repair liner as necessary.

5. Replenish limestone, filter membrane and straw/hay bales.

6. Reinstate ALD as originally specified.

6.5 Periodic replacement of wetland substrate

The literature has revealed only one constructed wetland case study in which the substrate was extensively renewed: a constructed wetland treating waste water from a synthetic rutile plant with an area of 2 hectares, had vegetation and 0.2m of substrate removed and replaced over some 10% of its area (Masters, 1989). This took place three years after the construction of the wetland and cost 12,000 Australian dollars (1989). It is not clear whether this replacement was required by a reduced treatment efficiency or whether it was a process modification.

Large constructed wetlands have been treating coal mine drainage in the United States for up to ten years and during this timescale replacement of wetland substrate has not come to light as a major concern.

Researchers in the United States Bureau of Mines estimated the lifespan of a wetland substrate at the Friendship Hill site (Kleinmann, R., personal communication). This wetland receives very acid water (pH 2-3). Around 50% of the alkalinity generated by the wetland was found to arise through dissolution of limestone within the substrate, 50% through sulphate reduction. Calculations on the basis of the amount of limestone and organic matter present initially result in an estimated 12 year lifespan for the substrate.

On the basis of a comparative examination of water quality data, a lifespan of 20 years or more is considered likely for the proposed wetland treatment system.

A typical sequence for replacement of wetland substrate is as follows:

1. Determine cell to be replenished.
2. Isolate cell from inlet channel and drain surface water into outlet channel.
3. Carefully excavate spent substrate so as not to unnecessarily damage the liner.
4. Repair liner where necessary.
5. Refill wetland and replant as originally constructed.

Spent substrate is not a hazardous material and the iron contained can generally be considered stable. Remobilization of iron oxide precipitates will only occur in the presence of water with $pH < 3$, or by physical resuspension. As long as the material remains anoxic, metal sulphides incorporated into the substrate will be stable.

Disposal on-site is, therefore advocated. The material would be encapsulated and buried. Drainage would be provided, to run into the wetland treatment system.

Alternatively, the material could be disposed of to a licensed tip. Placement in a temporary lagoon to allow drainage of excess water (back into the treatment system) would be of benefit in this case.

6.6 Process optimisation

These measures are generally concerned with:

1) Preventing channelization/or hydraulic short circuiting at the wetland surface.

2) Optimising flow through the entire wetland substrate.

The former can be accomplished through the use of hay bales or other surface flow barriers, or by utilizing the control weirs between sections of the treatment system.

The latter can be accomplished through small modifications of the inflow and outflow structures of the wetland cell and by the control of standing water level.

6.7 Aftercare of wetland plants

As noted in Commissioning (Section 5), the application of fertilizer to the wetlands is not considered necessary, due to the high nutrient content of the substrate.

Weeding is also not considered to be a requirement, since the standing water depth will prohibit the establishment of weeds.

It may prove advantageous to cut the above-ground parts of the *Typha* plants and some other species in the winter and leave the cut stems lying on the surface of the substrate. Although *Typha* does not die back in the winter, the above-ground parts of the plant become dormant so this cutting will not harm the plants and may promote vigorous growth.

The cut stems on the surface of the substrate represent a supply of fresh organic matter to the substrate which will increase the activity of sulphate-reducing bacteria and, possibly, increase the lifespan of the substrate.

6.8 Maintenance of structures

Measures to maintain the structures of the wetland treatment system include:

* checking the physical integrity of dikes and bunds between cells and repairing these where necessary.

* maintenance of safety measures such as signs warning of deep water in the settlement lagoons and the wetland fringe around these lagoons (serving to discourage pedestrian access).

* maintenance of windbreak structures.

* prevention of the establishment of trees or dikes and bunds on-site, or on vehicle access routes.

* maintenance and periodic cleaning (if necessary) of channels/flowpaths between sections of the wetland treatment system.

* maintenance of flow control and measurement structures ("Crump" weirs and sluices).

Damage due to freezing is considered unlikely since the wetland is treating groundwater which is unlikely to freeze.

7 COSTING

A provisional budget for the proposed treatment system is given below.

Table 7.1 details fixed costs for design, construction and establishment. Table 7.2 gives an estimate of annual costs of maintenance and performance assessment. Table 7.3 gives costs for replacement of wetland substrate and vegetation and for reinstatement of Anoxic Limestone Drains.

Figures 7.1 and 7.2 break down fixed and annual costs on a year-by-year basis, using the notional five-year-long design and construction programme given in Figure 4.1.

The estimated total cost including design, construction and supervision is £954,300. Annual maintenance and performance assessment costs of £29,500 are estimated.

The cost of complete replacement of wetland substrate, once it has become exhausted, varies from £30,000 to £138,000 depending on the discharge. These costs are 30-45% of the construction costs. The substrate has an expected lifespan in the order of 20 years.

The cost of renewing the ALDs, after their twenty-year lifespans, is estimated at £9,000 and £23,500 for that treating the Gwenffrwd discharge and that treating Whitworth A respectively.

Items specifically excluded from these costs are:

* The cost of permissions, licences and any investigations of the environmental impact of the construction of the system.
* Long-term supervision of maintenance works.

Item	Whitworth No. 1	Garth Tonmawr	Gwenffrwd discharge	Whitworth A	Whitworth B	Totals
Civil Engineering						
Haul road	32,000	27,000	5,000	5,000	5,000	74,000
Excavation	6,000	59,000	33,000	41,000	14,000	153,000
Clay liner	3,400	26,000	18,000	22,000	7,400	76,800
Landform & drainage	1,000	5,000	5,000	6,000	2,000	19,000
ALDs	-	-	7,500	20,000	-	27,500
Settling lagoons	-	-	1,000	1,000	-	2,000
Connections, channels etc.	18,000	66,000	31,000	32,000	21,000	168,000
Temporary works	30,000	30,000	10,000	10,000	10,000	90,000
SUBTOTAL	90,400	213,000	110,500	137,000	59,400	608,200
Wetland						
Substrate	5,000	40,000	22,000	27,000	10,000	104,000
Plants & planting	1,000	8,000	5,000	6,000	2,500	22,500
Establishment	3,000	6,000	5,000	5,000	5,000	24,000
SUBTOTAL	9,000	54,000	32,000	38,000	17,500	150,500
TOTAL	99,400	267,000	142,500	175,000	76,900	758,700
Preliminaries	10,000	26,000	14,000	17,000	8,000	75,000
TOTAL COST OF WORKS	109,400	293,000	156,500	192,000	84,900	835,800
Design						
Site investigation	3,000	4,000	4,000	4,000	4,000	19,000
Design & supervision	13,000	34,500	19,000	22,500	10,500	99,500
TOTAL COST OF DESIGN	16,000	38,500	23,000	26,500	14,500	118,500

Table 7.1 Fixed costs

See notes overleaf

Notes to Table 7.1:

* All costs are based on present day rates, and are budget costs only.

* Haul road costs are included under Whitworth No.1 contract but this haul road will serve other sites in Cwm Gwenffrwd.

* Repair costs of this haul road are added for each subsequent contract.

* Cost of temporary lagoon is also on Whitworth No.1 contract with no maintenance under subsequent contracts.

* Costs of permissions, licences and any investigations of the environmental impact of the scheme have not been included.

Item	Whitworth No. 1	Garth Tonmawr	Gwenffrwd discharge	Whitworth A	Whitworth B	Totals
Post Commissioning						
Aftercare	2,000	5,000	4,000	4,000	4,000	19,000
Performance assessment	1,000	2,500	2,000	2,000	2,000	9,500
Reporting of project results	200	200	200	200	200	1,000
TOTAL ANNUAL COSTS	3,200	7,700	6,200	6,200	6,200	29,500

Table 7.2 Annual costs

Notes to Table 7.2:

* All costs are based on present day rates, and are budget costs only.

* Analyses of samples at in-house NRA rates would significantly lower the cost of performance assessment.

Item	Whitworth No. 1	Garth Tonmawr	Gwenffrwd discharge	Whitworth A	Whitworth B
Wetland substrate replacement					
Excavation & disposal	4,000	30,000	190,000	23,000	9,000
Repairs to liner	1,000	6,000	4,000	5,000	2,000
Substrate	5,000	40,000	22,000	27,000	10,000
Plants & Planting	1,000	8,000	5,000	6,000	2,500
Establishment	3,000	6,000	5,000	5,000	5,000
SUB TOTAL	14,000	90,000	55,000	66,000	28,500
Number of subcells	2	6	4	4	2
Replacement cost per subcell	7,000	15,000	14,000	17,000	15,000
Encapsulation	8,000	8,000	8,000	8,000	8,000
TOTAL COST PER SUBCELL	15,000	23,000	22,000	25,000	23,000
Anoxic Limestone Drains					
Excavation/preparation			1,500	3,500	
Refill with limestone and repair			7,500	20,000	
TOTAL			9,000	23,500	

Table 7.3 Costs of replacement of wetland substrate and renewal of anoxic limestone drains

Notes to Table 7.3:

* All costs are based on present day rates, and are budget costs only.

* The cost of encapsulation provides a 'state of the art' solution with filter materials to collect gas and leachate, with this latter being treated using disposable canister filters prior to being returned to the treatment system. Further investigations may show a more modest encapsulation system to be appropriate.

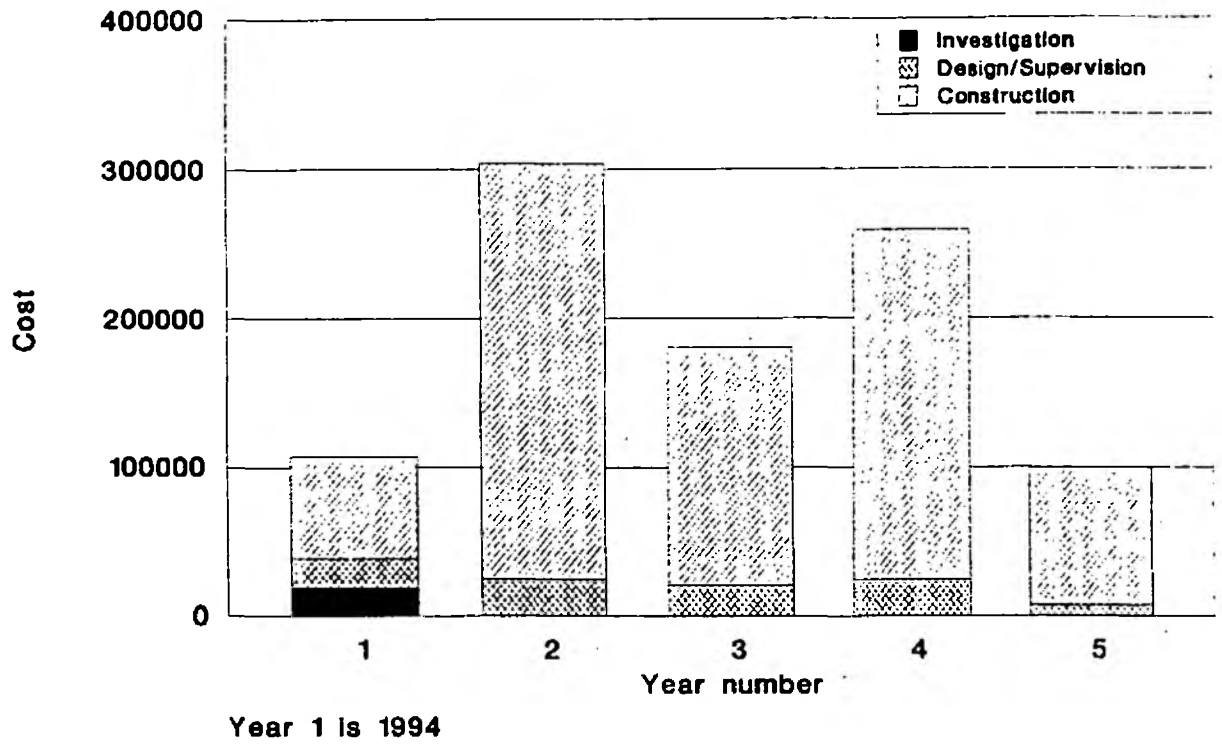


Figure 7.1 Breakdown of fixed costs by year.

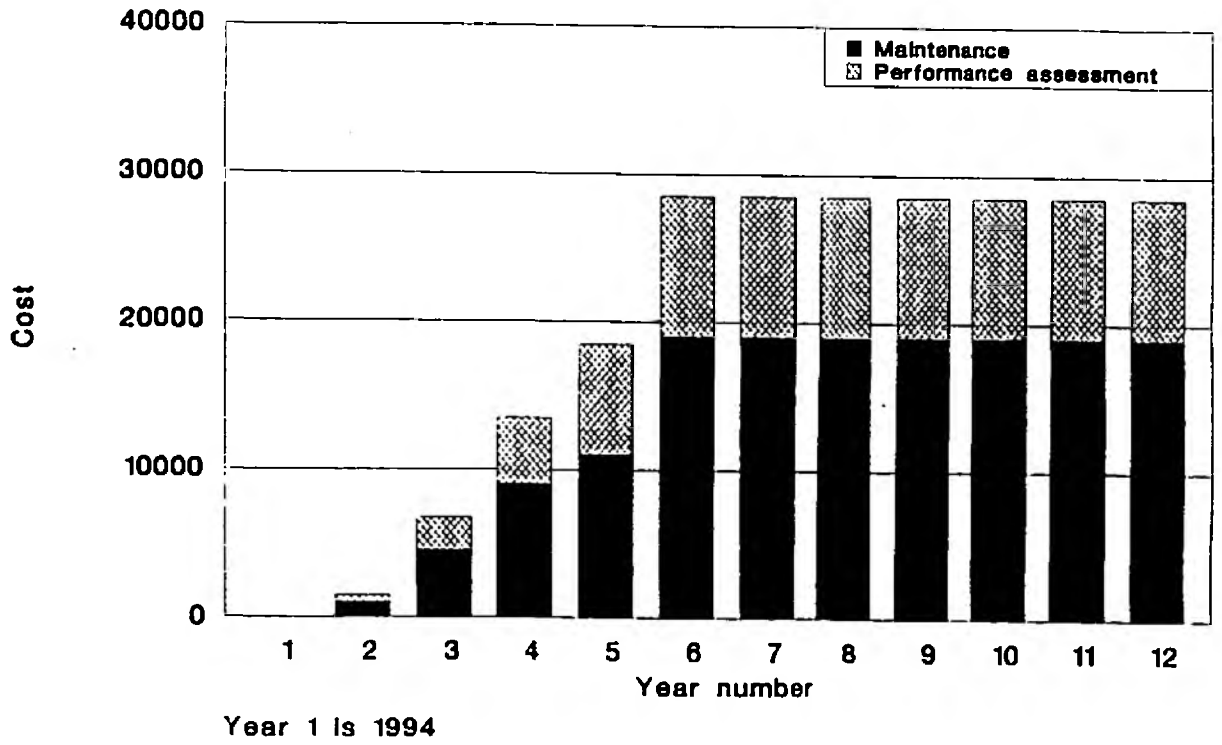


Figure 7.2 Breakdown of maintenance costs by year.

8 REPORTING OF PROJECT RESULTS

The design of the wetlands would incorporate facilities for both the monitoring and study of the performance of the wetlands. We suggest that the results of monitoring are compiled on an annual basis for the purposes of reporting. Results may then be disseminated through NRA R&D notes and through papers in appropriate publications.

We propose that self-funding seminars are held, to disseminate the results. In addition, papers describing the project would be presented at relevant conferences.

An annual cost of £1000 has been included in the Costing in Section 7 to cover reporting of project results.

9 CONCLUSIONS

Data from the study areas and design parameters based on existing wetlands elsewhere indicate that treatment of acid mine drainage by constructed wetlands is feasible at both Gwenffrwd and Garth Tonmawr. Within Cwm Gwenffrwd four separate wetlands systems are proposed, one at the Whitworth No.1 discharge and three on terraces downstream of the Whitworth Lagoon. Each wetland would treat a separate discharge. At Garth Tonmawr it is proposed that one wetland should treat the discharge. At both sites it is expected from the data available that EIFAC water quality standards would be achieved.

Phasing of wetland construction would allow experience to be gained on the simpler wetland systems before constructing the more complex ones.

Total design and construction costs are estimated to be £954,300 for all the wetlands proposed. Annual monitoring and maintenance costs in the order of £29,500 are expected.

Monitoring of the wetlands will allow performance data to be accumulated and disseminated which will be invaluable both for the management of these sites and the design and construction of wetlands elsewhere in Europe.

10 REFERENCES

Allen, H.H., Pierce, G.J., Van Wormer, R. (1989) Considerations and techniques for vegetation establishment in constructed wetlands. In Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural (Chattanooga, TN. 1988), edited by D.A. Hammer, 405-415, Chelsea, MI.:Lewis.

Ishemo, C.A.L., Whitehead, P.G. (1992) Acid mine drainage in the River Pelenna: modelling and pollution control. Wallingford:Institute of Hydrology.

Kleinmann, R.L.P., Girts, M.A. (1987) Acid mine water treatment in wetlands: an overview of an emergent technology. In Aquatic Plants for Water Treatment and Resource Recovery (Orlando, FL. 1986), edited by K.R. Reddy and W.H. Smith, 255-261, Orlando, FL.:Magnolia Publishing Inc.

Masters, B.K. (1989) Biological filtration of mine and industrial effluent waters. In Proceedings of the 1989 Australian Mining Industry Council Environmental Workshop (Ballarat, Australia 1989), 111-121, Dickson, ACT, Australia:Australian Mining Industry Council.

Nairn, R.W., Hedin, R.S. and Watzlaf, G.R. (1990) A preliminary review of the use of anoxic limestone drains in the passive treatment of acid mine drainage. In Proceedings, Twelfth Annual West Virginia Surface Mine Drainage Task Force Symposium (Morgantown, WV. 1991).

Nairn, R.W., Hedin, R.S. and Watzlaf, G.R. (1992) Generation of alkalinity in an anoxic limestone. In Proceedings, 1992 National Meeting of the American Society for Surface Mining and Reclamation (Duluth, Minnesota, 1992).

Reed, S.C., Middlebrooks, E.J., Crites, R.W. (1988) Natural systems for waste management and treatment. New York:McGraw-Hill.

Richards, Moorehead and Laing Ltd (1992) Constructed wetlands to ameliorate metal-rich mine waters. Review of existing literature. R&D Note 102 to National Rivers Authority

Rudeforth, C.C., Hartnup, R., Lea, J.W., Thompson, T.R.E., Wright, P.S. (1984) Soils and their use in Wales. Harpenden: Soil Survey of England and Wales.

Skousen, J. (1990) Anoxic limestone drains for acid mine drainage treatment, Green Lands, 21, No.4, 30-35.

Tomljanovich, D.A., Perez, O. (1989) Constructing the wastewater treatment wetland - some factors to consider. In Constructed Wetlands for Wastewater Treatment: Municipal, Industrial and Agricultural (Chattanooga, TN. 1988), edited by D.A. Hammer, 399-404, Chelsea, MI.:Lewis.

APPENDIX A - WATER QUALITY INFORMATION

Date	pH	DO mg/l	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
15-Oct-91	5.9			.130		.180			.942
05-Dec-91	5.7			84.050	71.260	.247	.247		1.228
08-Jan-92	5.1			68.548		.233			1.334
09-Jan-92	5.2			38.430	* 0.004	.176	* 0.926		.942
14-Jan-92	6.0			62.500	50.900	.149	.119		.337
03-Feb-92	5.7			81.990	79.270	.148	.048		1.300
12-Feb-92	4.8			71.400	79.590	.252	.183		1.624
13-Feb-92	4.6			50.821		.256	.128		1.221
09-Mar-92	5.9			14.752		.075			.547
10-Mar-92	5.4			22.891	29.600	.147	.081		.690
15-Apr-92	5.7			48.990	48.280	.032	.005		1.180
01-Jun-92	6.0			58.760		.179	.046		1.292
02-Oct-92	5.6			48.400	48.400	.006	.004		.980
16-Oct-92	5.7		4.6	61.000	60.300	.004	.004		1.120
05-Nov-92	6.8			.867	.747	.065	.020		.135
15-Jan-93	6.0		6.8	8.100	8.000	.024	.006		.135
23-Jan-93 #		4.7	16.7						
23-Jan-93 @		11.3	11.1						
avg	5.6		5.7	45.102	43.304	.136	.069		.938
max	6.8		6.8	84.050	79.590	.256	.247		1.624
min	4.6		4.6	.130	.747	.004	.004		.135
S.D.	.5		1.1	27.073	28.460	.087	.076		.448

* Suspect results, ignored.
\# Whitworth A
@ Whitworth B

Table A.1 Effluent from Whitworth Lagoon (NRA sample point 71014)

Table A.2 Gwenffrwd discharge (NRA sample point 71015)

Date	pH	DO mg/l	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
15-Oct-91	4.6			4.640		.771			.442
05-Dec-91	4.0			16.660		4.571	4.263		2.019
08-Jan-92	3.9			13.542		2.382			1.213
09-Jan-92	3.9			11.348	* 0.088	2.162	* 0.056		.963
14-Jan-92	4.2			15.500	11.000	1.910	1.858		.391
03-Feb-92	3.8			13.480	12.720	2.380	2.380		1.200
12-Feb-92	3.7			11.201	11.030	2.248	2.218		1.299
13-Feb-92	3.7			11.652		2.311			1.326
09-Mar-92	3.7			8.485		1.456			.885
10-Mar-92	3.6			8.943	9.910	1.613	1.609		.967
15-Apr-92	4.0			9.200	9.200	1.700	1.700		1.000
01-Jun-92	4.0			8.654	8.651	1.870	1.870		1.164
03-Sep-92	3.8			12.800	12.800	.900	.900		.800
02-Oct-92	3.9			16.400	16.400	2.200	.190		1.320
16-Oct-92	4.6			12.200	12.200	1.670	1.670		1.080
05-Nov-92	6.8			8.740	8.740	.877			.829
15-Jan-93	4.9		1.9	9.700	9.600	1.200	1.200		
22-Jan-93	6.8	1.1	6.6						
avg	4.3		4.3	11.361	10.188	1.895	1.655		.939
max	6.8		6.6	16.660	16.400	4.571	4.263		2.019
min	3.6		1.9	4.640	8.651	.771	.190		.391
S.D.	.9		2.4	3.103	3.729	.848	1.057		.480

* Supsect result, ignored.

Date	pH	DO mg/l	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
15-Oct-91	5.6			26.200		0.521			0.719
05-Dec-91	5.9			26.000	23.960	0.485	0.251		0.990
08-Jan-92	5.6			40.972		0.495			0.906
09-Jan-92	5.5			29.116	* 0.004	0.513	* 0.004		0.795
14-Jan-92	5.9			12.900	12.600	0.374	0.226		0.292
03-Feb-92	5.9			28.680	28.040	0.248	0.197		0.810
12-Feb-92	5.6			31.357	31.270	0.368	0.165		0.920
13-Feb-92	4.5			20.800		0.211	0.184		0.840
09-Mar-92	5.2			25.577		0.289			0.751
10-Mar-92	5.2			26.797	27.300	0.380	0.275		0.789
01-Jun-92	5.8			28.935	28.101	0.162	0.134		0.867
02-Oct-92	6.0			24.800	24.800	0.150	0.140		0.810
16-Oct-92	6.0		12.9	30.100	30.000	0.105	0.870		0.820
05-Nov-92	6.0			16.630	16.200	0.261	0.218		0.637
01-Dec-92	4.4			0.820	0.558	1.750	1.700		0.420
15-Jan-93	5.5		5.5	12.500	12.500	0.300	0.270		
22-Jan-93		7.5	9.8						
avg	5.5	7.5	9.4	23.886	19.611	0.413	0.356		0.758
max	6.0	7.5	12.9	40.972	31.270	1.750	1.700		0.990
min	4.4	7.5	5.5	0.820	0.558	0.105	0.134		0.292
S.D.	0.5	0	3.0	9.113	10.610	0.368	0.434		0.179

* Suspect, results ignored.

Table A.3 Garth Tonmawr minewater (NRA sample point 71016)

Table A.4 Gwenffrwd upstream of Whitworth minewater (NRA sample point 71017)

Date	pH	DO (% satn)	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
25-Jan-90	4.9	96.4						110	
28-Mar-90	6.7	100.0						73	
09-Apr-90	7.6	98.6						37	
17-Jul-90	7.6	104.0						36	
09-Oct-90	5.8	90.0						71	
23-Jan-91	7.1	94.1		0.138		0.672		79	
04-Apr-91	4.5	82.9		0.338		0.852		82	
23-Jul-91	6.8	93.0		0.098		0.366		52	
15-Oct-91	6.2			0.125		0.410			
05-Dec-91	6.6	96.4		0.076		0.594		160	
08-Jan-92	5.2			1.055		1.023			
09-Jan-92	4.5			1.180		1.410			
14-Jan-92	6.1	92.5		0.136		0.556		52	
03-Feb-92	7.0	93.2		0.135		0.326		31	
12-Feb-92	5.8			3.392		2.614			
13-Feb-92	4.9			0.276		0.826			
09-Mar-92	6.2			0.138		0.515			
10-Mar-92	5.5			0.202		0.611			
16-Mar-92	6.0	101.0		0.155		0.534		56	
15-Apr-92	6.0	84.6		0.180		0.550		63	
01-Jun-92	6.5	95.4		1.347		1.782		61	
05-Aug-92	6.6	93.4		0.175		0.253		32	
03-Sep-92	5.3	94.9		0.120		0.520		76	
02-Oct-92	7.2	93.6		0.170		0.360			
16-Oct-92	7.1	89.6		0.064		0.160		32	
05-Nov-92	5.9	91.9		0.090		0.320		46	
16-Dec-92	5.5	94.0		0.150		0.470		59	
avg	6.1	94.0		0.443		0.715		64	
max	7.6	104.0		3.392		2.614		160	
min	4.5	82.9		0.064		0.160		31	
S.D.	0.9	4.9		0.739		0.555		30	

Date	pH	DO (% satn)	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
25-Jan-90	4.5	94.7		0.482		0.742		68	
28-Mar-90	6.9	99.7		0.176		0.329		33	
09-Apr-90	7.8	95.8		0.218		0.379		23	
17-Jul-90	7.8	106.0		0.135		0.324		20	
09-Oct-90	6.9	96.3		0.153		0.873		42	
23-Jan-91	7.1	96.4		0.167		0.485		49	
04-Apr-91	4.7	85.5		0.368		0.542		45	
23-Jul-91	6.9	92.1		0.150		1.361		24	
15-Oct-91	6.5			0.204		0.398			
05-Dec-91	6.7	101.0		0.090		0.511		19	
08-Jan-92	5.2			1.077		0.695			
09-Jan-92	4.5			0.981		0.789			
14-Jan-92	7.2	96.4		0.086		0.309		27	
03-Feb-92	7.1	97.3		0.105		0.271		2	
12-Feb-92	5.3			1.384		0.862			
13-Feb-92	5.2			0.581		0.548			
09-Mar-92	6.5			0.135		0.286			
10-Mar-92	5.4			0.279		0.451			
16-Mar-92	6.2	97.9		0.093		0.309		31	
01-Jun-92	6.8	91.4		1.449		3.386		27	
05-Aug-92	6.5	94.5		0.808		0.277		20	
03-Sep-92	6.4	93.0		0.078		0.280		42	
02-Oct-92	7.1	93.6		0.350		0.300		19	
16-Oct-92	7.4	97.3		0.200		0.260		20	
05-Nov-92	6.0	95.3		0.117		0.364		32	
01-Dec-92	4.5	92.3		0.220		0.600		37	
09-Dec-92	6.8	95.7		0.136		0.466		42	
16-Dec-92	6.2	97.3		0.220		0.370		37	
avg	6.3	95.7		0.373		0.599		31	
max	7.8	106.0		1.449		3.386		68	
min	4.5	85.5		0.078		0.260		2	
S.D.	1.0	3.9		0.389		0.590		14	

Table A.5 Blaenpelenna upstream of Middle Mine discharge (NRA sample point 70120)

Date	pH	DO mg/l	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
15-Oct-91	7.1			0.970		0.130			0.375
05-Dec-91	7.5			0.498	0.338	1.142	0.064		0.492
08-Jan-92	7.5			1.389		1.198			0.397
09-Jan-92	7.5			1.644	* 0.025	1.448	* 0.056		0.460
14-Jan-92	6.2			0.779	0.388	1.011	0.041		0.155
03-Feb-92	7.6			0.875	0.369	0.759	0.025		0.430
12-Feb-92	7.7			1.105	0.418	0.681			0.413
13-Feb-92	7.7			1.178	0.155	0.747	0.356		0.440
09-Mar-92	7.5			0.802	0.387	0.769			0.320
01-Jun-92	7.5			0.549		0.638	0.038		0.441
02-Oct-92	7.7			0.580	0.580	0.550	0.063		0.440
16-Oct-92	7.8		47.7	0.270	0.270	0.220	0.033		0.460
05-Nov-92	7.4			0.658	0.461	0.912	0.043		0.402
01-Dec-92	6.9			1.030	1.010	0.790	0.049		0.440
15-Jan-93	7.2		21.2	0.390	0.390	0.580	0.065		
22-Jan-93		7.3	17.4						
avg	7.4		28.8	0.848	0.397	0.772	0.071		0.407
max	7.8		47.7	1.644	1.010	1.448	0.356		0.492
min	6.2		17.4	0.270	0.155	0.130	0.025		0.155
S.D.	0.4		13.5	0.367	0.233	0.335	0.092		0.083

* Suspect, results ignored.

Table A.6 Middle Mine discharge (NRA sample point 70121)

Date	pH	DO (% satn)	Alkalinity mg/l CaCO3	Fe (total) mg/l	Fe (diss) mg/l	Al (total) mg/l	Al (diss) mg/l	Zn (total) µg/l	Mn (total) mg/l
15-Oct-91	6.1			28.200		0.275			1.801
05-Dec-91	6.3			10.363	10.321	0.069	0.061		1.979
08-Jan-92	6.2			24.860		0.251			1.981
09-Jan-92	6.2			85.483	* 0.122	1.803	* 0.025		1.475
14-Jan-92	6.3			18.200	13.400	0.083	0.068		0.632
03-Feb-92	6.3			20.590	20.350	0.079	0.056		1.900
12-Feb-92	6.5			20.124	22.120	0.120	0.075		2.101
13-Feb-92	6.7			22.099	20.500	0.147			2.330
09-Mar-92	6.3			13.261		0.064			1.689
10-Mar-92	6.3			13.963	21.400	0.122	0.095		1.748
01-Jun-92	6.3			26.502	20.876	0.722	0.082		1.733
02-Oct-92	7.0			10.800	10.800	0.024	0.011		2.460
16-Oct-92	6.5		19.9	9.900	9.900	0.007	0.004		1.800
05-Nov-92	6.5			7.560	7.560	0.004	0.004		1.044
15-Jan-93	6.2		13.4	8.800	8.800	0.017	0.016		1.044
avg	6.4		16.65	21.380	13.836	0.252	0.043		1.714
max	7.0		19.9	85.483	22.120	1.803	0.095		2.460
min	6.1		13.4	7.560	7.560	0.004	0.004		0.632
S.D.	0.2		3.25	18.334	6.805	0.449	0.034		0.476

* Suspect, results ignored.

Table A.7 Whitworth No. 1 (NRA sample point 70122)

Date	71014	71015	71016	71017	71020	71021	71022
05-Dec-91	0.0144	0.0128	0.0145	0.0628	0.0685	0.0272	0.0006
09-Jan-92	0.0213	0.0114	0.075	0.8342	1.2561	0.0446	0.0031
12-Feb-92	0.0095	0.0063	0.0223	0.1553	0.2671	0.0176	0.0014
13-Feb-92	0.0095	0.0063	0.0223	0.1553	0.2671	0.0176	0.0014
10-Mar-92	0.0244	0.0145	0.0395	0.3081	0.5548	0.0286	0.0024
avg	0.016	0.010	0.035	0.303	0.483	0.027	0.002
max	0.024	0.015	0.075	0.834	1.256	0.045	0.003
min	0.010	0.006	0.015	0.063	0.069	0.018	0.001
S.D.	0.006	0.003	0.022	0.277	0.417	0.010	0.001

flows are in m3/sec

Table A.8 Available flow volume information

APPENDIX B - CALCULATIONS: ANOXIC LIMESTONE DRAINS

Sizing (after Skousen, 1990)

The most important parameter in sizing an ALD is the total acidity; this has been estimated from concentrations of acid species in water, using the method detailed in Appendix C.

The sizes of ALDs to treat the Gwenffrwd discharge and the flow from the Whitworth Lagoon are calculated in Table B.1. Note that the flow from Whitworth B will not be treated, and so the size of an ALD to treat only the flow from Whitworth A will be less than the size of one to treat the flow from the Whitworth Lagoon (840 m^3). For the purpose of outline design, in the absence of detailed information of the water quality of Whitworth A and Whitworth B, it is appropriate to reduce the size of the ALD for Whitworth A to 70% of 840 m^3. This 70:30 ratio is based on observations on-site of the relative flow in Whitworth A and Whitworth B.

Therefore, two drains of 300 and 840 tonnes are proposed, or 200 and 560 m^3 respectively.

	Gwenffrwd discharge	Discharge from Whitworth Lagoon
Calculated total acidity, mg/l $CaCO_3$	32.6	82.1
Mean flow, l/s	10	16
Acid loading, tonnes $CaCO_3$ per year	10.28	41.4
Tonnes $CaCO_3$ required (based on 20 year lifespan)	205	830
Tonnes limestone required (based on 90% $CaCO_3$ content)	230	920
Tonnes limestone required (based on 75% dissolution)	300	1230
Volume of limestone required, m^3 (based on density of 1.5 tonnes/m^3)	200	840

Table B.1 Sizing of Anoxic Limestone Drains

Hydraulic design

Flow through the ALD will be governed by Darcy's law, which applies for fine-grained soils, sands and gravels:

$$Q=K_sAS$$

where

Q = throughput of the drain in m^3/day
K_s = saturated hydraulic conductivity in m/day
A = saturated cross sectional area in m^2
S = hydraulic gradient as a decimal fraction

For the outline design, the following assumptions have been made:

K_s = 2500 m/day, assuming 40 mm single-sized, uncompacted limestone
S = 4/L, *i.e.* a 4 m head loss over the length of the drain
Q = mean flow in m^3/day
V = A.L, volume required for the drain in m^3.

Therefore

$$\frac{A}{L}=\frac{Q}{10{,}000}$$

and, since L = V/A:

$$A=\sqrt{\frac{QV}{100}}$$

Table B.2 summarizes the hydraulic design of the ALDs.

A depth of limestone of two metres gives an overall depth for the drain of 3-3.5 m, since limestone is covered by a layer of hay bales and then by up to 1 m of soil cover.

The need for construction in cells is discussed in the main text.

		Whitworth A	Gwenffrwd discharge
Flow, mean,	l/s	12	10
	m^3/day	1040	870
Volume of limestone required	m^3	560	200
Cross sectional area, A	m^2	7.6	4.2
Depth	m	2	2
Width	m	3.8	2.1
Length, L	m	75	48
Number of cells		3 (each 25 m long)	2 (each 24 m long)

Table B.2 Hydraulic design of Anoxic Limestone Drains

APPENDIX C - CALCULATION: ESTIMATION OF TOTAL ACIDITY

Total acidity is determined by titrating a sample of water to pH 8.0 with a strong base, then converting the titre to a value in mg/l $CaCO_3$ equivalent.

In this feasibility study, the total acidity is estimated where required using the method outlined in below.

Assumptions:

1) The following reactions are presumed to occur, with acidic species consuming 'alkali' with the stated equivalence to H^+:

Aluminium	$\longrightarrow$	$Al(OH)_3$	Equivalence = 3
Iron	$\longrightarrow$	$Fe(OH)_2$	Equivalence = 2
Manganese	$\longrightarrow$	$Mn(OH)_2$	Equivalence = 2

2) It follows from 1) that all iron is in the iron (II) oxidation state, *i.e.* reduced.

3) Above pH 5.0, aluminium will have an equivalence of 0, having been precipitated.

4) A factor of 100/2 converts equivalent hydrogen ion concentration in mmoles to mg/l $CaCO_3$ since:

$$CaCO_3 + 2\,H^+ \longrightarrow Ca^{2+} + CO_2 + H_2O$$

Method: example for Gwenffrwd discharge (pH 4.3, total iron 11.3 mg/l, total aluminium 1.895 mg/l, total manganese 1.056 mg/l).

Iron concentration $[Fe^{2+}]$, mmoles	= 11.3 / 56	
	= 0.202	
Therefore equivalent $[H^+]$, mmoles	= 0.202 x 2	
	= 0.404	(1)
Aluminium concentration $[Al^{3+}]$, mmoles	= 1.895 / 27	
	= 0.070	
Therefore equivalent $[H^+]$, mmoles	= 0.070 x 3	
	= 0.210	(2)
Manganese concentration $[Mn^{2+}]$, mmoles	= 1.056 / 55	
	= 0.019	
Therefore equivalent $[H^+]$, mmoles	= 0.019 x 2	
	= 0.038	(3)

continued...

Hydrogen ion concentration at pH 4.3, mmoles	= 5.01×10^{-5}	
Therefore $[H^+]$, mmoles, for titration to pH 8.0	= 1.85×10^{-5}	(4)
Total acidity as $[H^+]$, mmoles (Sum of (1) to (4))	= 0.652	
TOTAL ACIDITY AS $CaCO_3$, mg/l	**= 0.652 x 100/2**	
	= **<u>32.6</u>**	

APPENDIX D - CALCULATION: DIMENSIONS OF SETTLING LAGOONS

These are basically horizontal flow settling tanks.

Theoretical limiting falling speed (m/s) = Q/A
where Q = throughput of tanks m^3/s
A = surface area, m^2

However, in practice a tank will not work as effectively as the theory suggests. For the outline design, we will assume an efficiency of 30% which will account for the fact that the flow will not be uniform throughout the tank. Hence:

Limiting falling speed = Q / A / 0.3

All particles with a higher falling speed will settle out completely in the lagoon. Particles with a lower falling speed will be removed from the water in a proportion given by the ratio of their falling speed to the limiting falling speed.

The depth of the lagoon does not effect the falling speed of particles. The depth must be such that bed velocities do not become too high.

A maximum horizontal flow velocity of 0.015 m/sec is generally taken.

A starting point for the outline design can be as follows:

Surface area, A $\geq$ 0.07 m^2/m^3/day
Retention time $\geq$ 4 hours

Therefore,
depth of water, d $\geq$ Q / 6A
where Q = maximum flow in m^3/day
A = actual area in m^2

The calculations are summarized in Table D.1. Maximum flow is considered to allow the lagoon accommodate the maximum design flow through the ALD (the mean flow of the minewater) and additional flow through the bypass. The effects of surface precipitation will be minimal.

		Whitworth A	Gwenffrwd discharge
Flow, Q, maximum	l/s	18	15
	m^3/day	1500	1300
Theoretical area, A (at ≥ 0.07 m^2/m^3/day)	m^2	110	91
Actual area	m^2	400 (20 x 20 m)	400 (20 x 20 m)
Theoretical depth, d (at ≥ Q/6A, to give 4 hour retention time)	m	0.65	0.55
Actual depth	m	0.65	0.55
Limiting falling speed (assuming 30% efficient)	m^3/sec	0.00015	0.00013
Horizontal speed	m/sec	0.0014	0.0014

Table D.1 Dimensions of settlement lagoons

APPENDIX E - CALCULATION: SIZING OF CWM GWENFFRWD WETLAND

Wetland sizing has been undertaken on the basis of empirical guidelines from the literature. Two approaches are used and the larger resulting area taken in each case.

The first approach is based on throughput of the wetland. Between 5 and 15 m^2 of wetland per litre/min flow has been suggested (Richards, Moorehead and Laing Ltd, 1992). Case studies of constructed wetlands treating metal mine drainage suggest 4-27 m^2/L/min.

The second approach is based on iron loading. Hedin and Nairn (1990) suggest an iron removal rate of 10g Fe/m^2day at pH4 or 5 g Fe/m^2/day at pH3.

The Cwm Gwenffrwd wetland is designed on the basis of 5 m^2/L/min of maximum flow, and on the basis of 10 g Fe/m^2/day, taking the mean iron loading. Table 6.1 summarizes the sizing calculations. The higher of the two values for wetland area required, shown in bold, is the one adopted for sizing purposes.

		Gwenffrwd discharge	Whitworth A	Whitworth B	Whitworth No. 1
Flow, l/s,	mean	10	12	4	2
-	maximum	15	18	6	3
-	minimum	6	7.5	2.5	1
pH, mean		4.0	5.6	5.6	6.0
Iron loading, kg Fe / day		9.8	44	20	3.6
Limestone required,	tonnes	300	840	-	-
-	m^3	200	560	-	-
Wetland area required, m^3					
- (based on 5m^2/l/min flow)		**4500**	**5400**	1800	**900**
- (based on 10g Fe/m^2/day)		1000	4400	**2000**	400
Treatment area		Top terrace	Middle terrace	Bottom terrace	Local

APPENDIX F - CALCULATION: SIZING OF GARTH TONMAWR WETLAND

The sizing calculations use the two approaches detailed in Appendix E:

Volume of flow based:	$5m^2$ of wetland/L/min of flow
Iron removal based:	10g Fe/m^2/day.

As is evident from Table F.1, the former of these gives a much larger area requirement than the latter.

However, at this site, a 50% treatment would be sufficient, so the wetland is designed on the basis of the latter. Some of the minewater can be allowed to bypass the wetland should the high flow cause damage to the wetland structure, or be implicated in a low performance.

		Garth Tonmawr minewater
Flow, l/s,	mean	35
-	maximum	75
-	minimum	15
pH, mean		5.5
Iron loading, kg Fe / day		70
Limestone required,	tonnes	-
-	m^3	-
Wetland area required, m^3 - (based on $5m^2$/l/min flow)		22500
- (based on 10g Fe/m^2/day)		7000

APPENDIX G - COMMON AND BOTANICAL NAMES FOR PLANTS

The table gives common names in use in the United Kingdom for plants referred to in the feasibility study, together with the botanical names.

Agrostis capillaris	Bent Grass
Calluna vulgaris	Heather
Digitalis purpurea	Foxglove
Festuca rubra or festuca ovina	Fescue
Juncus bufonius	Toad Rush
Juncus effusus	Soft Rush
Larix decidua	Larch
Molinia caerulea	Purple Moor Grass
Picea spp.	Spruce
Potamogeton spp.	Pondweed
Rumex acetosella	Sheeps Sorrel
Typha latifolia	Reedmace

APPENDIX H - PHOTOGRAPHS

Cwm Blaenpelenna. View of the terraced marshes downstream of the Whitworth Lagoon

The Whitworth Lagoon. Whitworth A enters from the left, Whitworth B from the right. The drainage ditch from the road is clearly visible in the centre.

Gwenffrwd discharge (orange) entering tributary of Nant Gwenffrwd.

View from the west of terraced marshes downstream of the Whitworth Lagoon - proposed site of wetland based treatment system.

Gwenffrwd discharge entering recently constructed channel.

The Blaenpelenna at Garth Tonmawr

Discharge from natural wetland at Garth Tonmawr

Colliery spoil heaps at Middle Mine

Colliery spoil heap below Garth Tonmawr, the site of part of the proposed wetland treatment system