WHEAL JANE MINEWATER STUDY

ENVIRONMENTAL APPRAISAL AND TREATMENT STRATEGY

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Environmental Appraisal and Treatment Strategy

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EXECUTIVE SUMMARY

INTRODUCTION

Wheal Jane is an abandoned underground tin mine in Cornwall. After mine closure in 1991, underground pumping ceased, allowing groundwater levels to recover, releasing acidic metal laden minewater into the Carnon River. The result was a highly visible and widely reported pollution incident extending into the Fal Estuary.

In 1992 the NRA set up a project with the following objectives:-

- Amelioration of the effects of the metal rich minewater from Wheal Jane on the Carnon River and Fal Estuary.
- Development of water quality objectives for the Carnon River.
- Research into the most appropriate and cost effective long term treatment strategies for achieving various water quality objectives.

This report provides the basis for the NRA's recommendations, to the DoE, on the long-term options for treating the Wheal Jane minewater.

BACKGROUND

The mines in the Carnon Valley have been worked as far back as 2000 BC, although extensive mining only began in the 17th Century. By the 1850s the mines in the Carnon Valley were the largest group of copper producers in the world.

The effect of this industrial activity on the valley has been:

- The deposition of metal-rich silt in the Carnon River, Restronguet Creek and Carrick Roads.
- Dewatering and lowering of the groundwater table by both pumping and the construction of drainage tunnels (adits).
- Elevated metal concentrations in the local watercourses and the Fal Estuary.

THE RELEASE OF MINEWATER FROM WHEAL JANE

Following mine closure and the cessation of dewatering, it became apparent that a release of minewater into the Carnon River was inevitable. As minewater rose to the level of drainage adits, the NRA exercised its statutory powers to instigate an emergency treatment system. Despite attempts at treatment, there was an uncontrolled release of minewater on January 13, 1992 after an adit plug failed.

Water quality in the Carnon River and the estuary was greatly affected, with concentrations of many metals exceeding Environmental Quality Standards (EQS) by up to two orders of magnitude. The release of high iron loadings also caused short-term discolouration of Restronguet Creek and the Carrick Roads.

The treatment system, instigated by the NRA, has since been progressively upgraded and comprises:

- pumping of minewater from underground;
- the addition of hydrated lime to neutralise the acidic water, resulting in the formation of a metal hydroxide precipitate (metalliferous sludge);
- flocculation, to promote rapid settlement of the metalliferous sludge;
- sedimentation and storage of the resultant metalliferous sludge in the Clemows Valley Tailings Dam.

The existing treatment system is located on the Wheal Jane mine site and is operated on behalf of the NRA by South Crofty plc.

The system currently treats on average 155 l/s but now has sufficient capacity to handle up to 300 l/s. Monitoring has indicated that on average 97.5% of the metals are recovered from the treated minewater. By the end of 1994, the system had removed some 12 500 t of metal from the outflowing minewater and has been responsible for minimising the environmental impact on the Fal Estuary. Monitoring has demonstrated that the effects of the minewater release on both water quality and discolouration were short-lived. There appears to have been no major adverse effects from the incident on the biota of the estuary.

THE CURRENT SITUATION

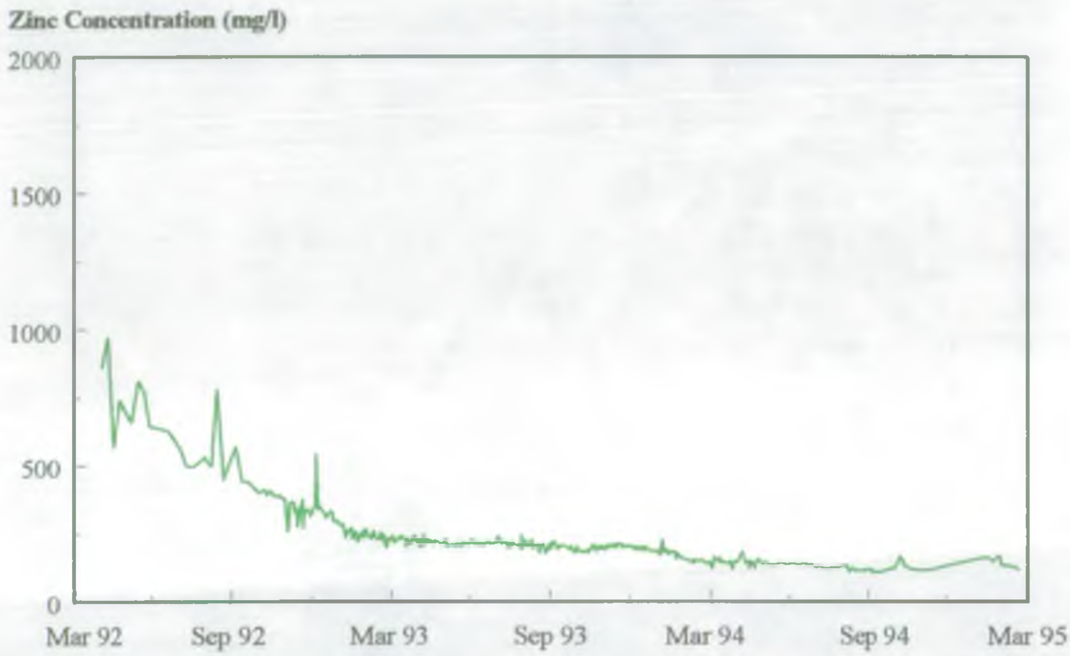
Although the existing treatment strategy has significantly reduced the release of untreated minewater to the Carnon River, an overflow of untreated minewater still occurs during the winter and spring from Nangiles Adit. Metal concentrations in the Wheal Jane mine have declined since 1992 and are typically one order of magnitude lower, as can be seen on Figure EX.1. Metal concentrations in the Carnon River have also declined rapidly and are now at pre-incident levels.

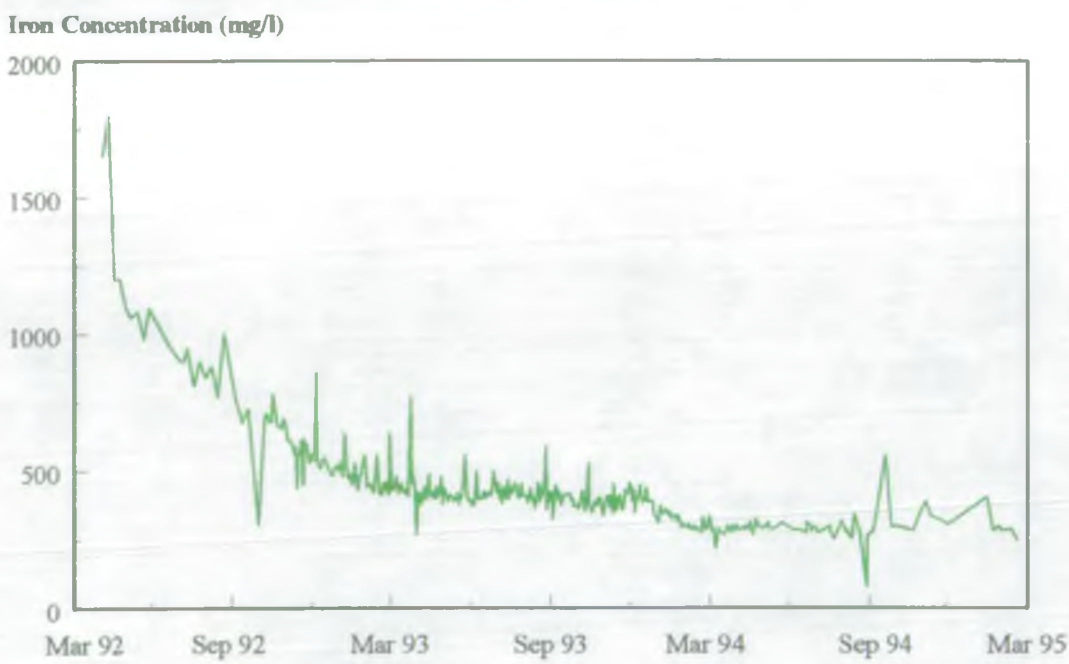
However, due to other sources of contamination, the concentrations of a number of metals in both the Carnon River and Restronguet Creek still exceed EQS under the European Community (EC) Dangerous Substances Directive. Zinc levels in part of the Fal Estuary also exceed the EC Shellfish Waters Directive.

The Wheal Jane complex, together with County Adit, are the major sources of contamination in the Carnon River. However, significant amounts of metals also are contributed from other tributaries and non-point sources. For this reason there would still be a significant metal loading in the Carnon River even if the two major point sources (Wheal Jane and County Adit) were treated.

Photograph Ex.1 Carnon River – Catchment above Grenna Bridge

Figure EX 1 **Measured Total Zinc and Iron Concentrations in No.2 Shaft**





WATER QUALITY OBJECTIVES FOR THE CARNON RIVER

Based on statutory and other requirements, the following water quality objectives have been adopted for the Carnon River:

- The "No Deterioration" objective : to maintain water quality at 1993-1994 levels.
- The "North Sea Commitments" objective : to achieve a reduction in the zinc loading in line with UK commitments made at the 1985 North Sea Conference.
- The "EC Directive" objective : to achieve full compliance with the EC Dangerous Substances Directives.

In addition a "No Treatment" scenario (do nothing option) has been considered.

The maximum permissible metal concentrations allowable for each of water quality objectives are summarised in Table EX-1, together with the predicted metal concentrations for the "No Treatment" scenario.

Table EX-1 : Water Quality Objectives for the Carnon River

Substance		Predicted "No Treatment" Water Quality	Water Quality Objectives		
			No Deterioration	North Sea Commitments	EC Directive
Cadmium	95 %ile		11 (T)	-	-
as μg Cd/l	AA	21 (T)	6 (T)	-	1.0 (T)
Copper	95 %ile		0.9 (T)	-	-
as mg Cu/l	AA	0.8 (T)	0.6 (T)	-	0.028 (D)
Zinc	95 %ile		13 (T)	-	-
as mg Zn/l	AA	26 (T)	6 (T)	3 (T)	0.5 (T)
Arsenic	95 %ile		0.3 (T)	-	-
as mg As/l	AA	n/a	0.1 (T)	-	0.050 (T)
Iron	95 %ile		17 (T)	-	-
as mg Fe/l	AA	52 (T)	8 (T)	-	1.0 (D)
Manganese	95 %ile		1.0 (T)	-	-
as mg Mg/l	AA	1.7 (T)	0.7 (T)	-	-
Aluminium	95 %ile		4.0 (T)	-	-
as mg Al/l	AA	6.2 (T)	2.1 (T)	-	-
pH	95 %ile		4.2	-	6.0
as pH units	5 %ile	n/a	7.1	-	9.0

Notes : EC Directive EQS values based on hardness > 250 mg/l $CaCO_3$/l.
AA ... Annual Average
(T) ... Total metal; (D) ... Dissolved metal.
n/a ... not available

Where a particular objective does not contain targets for every parameter, the values ascribed in the preceding objective have been applied.

An assessment was made of how much minewater from Wheal Jane would need to be treated in order for the river to meet the various water quality objectives. The treatment requirements necessary to achieve the "No Deterioration" and "North Sea Commitments" water quality objectives are summarised in Table EX-2.

Table EX-2 : Minewater Treatment Capacity to meet each Water Quality Objective

Annual probability of non-compliance	50%		5%	
	Maximum capacity (l/s)	Average flow (l/s)	Maximum capacity (l/s)	Average flow (l/s)
No Deterioration				
Annual Average	190	160	270	180
95%ile	210	170	300	190
North Sea Commitments				
Annual Average	230	175	300	190
EC Directive	Unable to meet all EC Directive Requirements			

Modelling of water quality in the Carnon River has indicated that the EC Directive Objective cannot be achieved, even if all the waters from both Wheal Jane and County Adit were treated. This is due to the presence of unidentified diffuse sources of contamination associated with other abandoned mineworkings.

THE LONG TERM STRATEGY

As part of the development of a long-term treatment strategy, studies have been undertaken to assess the potential for minimising the environmental impact of the minewater by:

- Passive treatment.
- Active treatment.
- Prevention and control.

PASSIVE TREATMENT TECHNOLOGY

The treatment of acidic metal-rich minewaters using passive systems is well established, with the design of each passive system dependent upon site specific criteria.

A pilot treatment plant has been constructed in the Carnon Valley and has been designed to treat up to 1.7 l/s of minewater (1% of the average outflow). A series of treatment cells promote the removal of iron, arsenic and manganese by aerobic processes, and cadmium, copper and zinc by anaerobic processes. The pilot plant also incorporates alternative methods of pre-treatment using an anoxic limestone drain and a small lime-dose plant which are intended to enhance the efficiency of metal removal in the aerobic and anaerobic cells.

Passive treatment is based upon "natural" biological systems which must be allowed to reach maturity before performance can be evaluated. Definitive results from the pilot plant will therefore not be available for a period of 2 to 3 years.

The preliminary passive treatment plant sizing and costings have revealed that, based on the current metal loadings:

- There is insufficient space available on the Carnon Valley Tailings Deposits to construct a passive treatment plant to achieve either the "No Deterioration" or "North Sea Commitments" objectives with a 5% annual probability of non-compliance.
- The Indicative capital cost of a passive treatment to meet the "No Deterioration" and "North Sea Commitments" Objectives with a 5% annual probability of non-compliance would be £15 - 28 million.

Passive treatment within the Carnon Valley may offer a technically feasible long term solution for treating either diffuse sources of contamination, or Wheal Jane minewater, should the metal loadings decay significantly.

ACTIVE TREATMENT TECHNOLOGY

Active treatment systems involve the continuous mixing of reagents with the minewater. An active system is typically cheaper to build than an equivalent passive scheme but the annual running costs are greater.

(a) *Existing Treatment*

The existing treatment strategy is one form of active treatment. The existing treatment system has sufficient capacity to meet the "No Deterioration" and "North Sea Commitments" objectives with a 5% annual probability of non-compliance. However the capacity of the dam restricts the life of the existing treatment system to between 5 and 14 years (ie. until the end of 2000 and 2010 respectively).

Table EX-3 : Existing Treatment Facility - Projected Costs

Average annual flow treated (l/s)	155[1]	190[2]
Annual operating costs (£)	748 000	810 000
Discounted Cost (£) :		
5 years	3 150 000	3 410 000
10 years	5 510 000	5 960 000

[1] Existing average treatment rate
[2] Average treatment rate to achieve 5% non compliance with "No Deterioration" and "North Sea Commitments" objectives.

Whilst the Clemows Valley Tailings Dam remains available for both effluent clarification and sludge storage, the existing treatment system offers the most cost effective method of treatment.

(b) *Active Treatment*

The applicability of various active treatment options has been appraised together with an assessment of possible sites for the storage of the metalliferous sludge produced by an active treatment system. The main conclusions from these studies are:

- Active treatment can be most effectively achieved using techniques to maximise the density of the resultant metalliferous sludge.
- The most cost effective location for an active plant is at the Wheal Jane Mine site.

The capital and annual operating costs for an active system, discounted to net present values, are summarised in Table EX-4.

Table EX-4 : Predicted Discounted Costs for the Preferred Active Treatment System

Installed Capacity Average Flow Rate	300 l/s 190 l/s		
Treatment Plant Location	Mine Site	Mine Site	Carnon Valley
Sludge Disposal[1]	Mine Site	Off Site	Off Site
Capital Cost	£ 5 440 000	£ 5 440 000	£ 7 440 000
Annual Operating Cost	£ 640 000	£ 830 000	£ 774 000
Net Present Value of Costs[2]			
5 yr	£ 7 990 000	£ 8 610 000	£ 10 315 000
10 yr	£ 10 000 000	£ 11 220 000	£ 12 750 000
25 yr	£ 13 475 000	£ 15 725 000	£ 16 950 000
50 yr	£ 15 380 000	£ 18 200 000	£ 19 250 000

[1] High density sludge product dewatered using frame and plate filters.
[2] Assumptions: Continued existing treatment for 1 year whilst plant is built.
Mine site sludge disposal into the Clemows Valley Tailings Dam.
Off site sludge disposal to a licenced landfill site.

PREVENTION AND CONTROL OF DISCHARGES

A number of potential options for reducing the quantity of contaminated water released from the mine have been considered but are not appropriate at Wheal Jane. The only potentially viable method of amelioration is the control of stream/groundwater interaction. The mining company has carried out stream works in the past to control this interaction. Consequently the potential for further flow reduction is considered to be small, although this remains to be confirmed.

SLUDGE DISPOSAL

The cost of sludge disposal currently represents about 30% of the costs associated with the existing treatment system. The sludge is deposited into the Clemows Valley Tailings Dam under a contract with South Crofty plc.

The following long term options have been considered:

- disposal in the Clemows Valley Tailings Dam;
- disposal to land within the mine site;
- disposal at new sites in the Carnon Valley;
- disposal off-site at a licensed landfill site
- commercial recovery and refining of the metals.

It has been concluded that:

- The Clemows Valley Tailings Dam is the preferred location for metalliferous sludge disposal.

- The installation of an active treatment plant would, unlike the existing treatment system, enable long-term disposal of sludge into the tailings dam.

- Disposal to land within the mine site is probably the next cheapest alternative.

- Alternative locations exist within the vicinity of the mine for sludge disposal, but development costs and planning restrictions could be severe.

- Waste products arising from full scale passive operations should be contained within the treatment cells where possible.

LOCATION OF LONG TERM TREATMENT PLANT

Three possible sites within the Carnon Valley have been considered for the location of a long term minewater treatment plant, namely the Carnon Valley Tailings Deposits, Wheal Jane Mine site and Point Mills. It has been concluded that:

- The Wheal Jane Mine site is the preferred location for an active treatment plant.

- The Carnon Valley Tailings Deposits are the most suitable site for a passive treatment plant.

- The most secure method of recovering minewater for treatment is by pumping from the Wheal Jane No. 2 Shaft.

- Should gravity drainage of minewater be preferable the most secure method of collection would be by upgrading the Jane's Adit at an estimated cost of £1 400 000.

ECONOMIC BENEFITS OF IMPROVEMENTS IN WATER QUALITY

The economic appraisal has assessed the costs and economic benefits associated with achieving each of the water quality objectives. Economic benefits have been appraised relative to the "No Treatment" option.

The approach taken towards the assessment of costs and benefits has been based on the use of social cost-benefit analysis techniques, including the valuation of environmental costs and benefits. It should be noted that it has not been possible to place monetary values on all predicted environmental effects.

Discounted benefit estimates for each of the water quality objectives have been calculated on the following basis:

- 10 years, 25 years and 50 years time horizons;
- a 6% discount rate (the Treasury rate for the NRA); and
- base, low and high benefit value cases.

The discounted benefit estimates for the base case assumptions are presented in Table EX-5, which shows that there is no difference in the level of benefits accrued under the "North Sea Commitments" and "EC Directive" objectives. It is, however, important to note that the improved water quality associated with the "EC Directive" is likely to provide greater protection of the conservation status of the area.

Table EX-5 : Present Value Benefit Estimates

Objective	Activity	10 Years	25 Years	50 Years
No Deterioration	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 206 000	3 637 000	4 424 000
	Maerl extraction	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	277 000	456 000	555 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 162 000**	**27 805 000**	**32 003 000**
North Sea Commitments	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 517 000	4 150 000	5 047 000
	Maerl Extraction	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	553 000	912 000	1 109 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 749 000**	**28 774 000**	**33 181 000**
EC Directive	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 517 000	4 150 000	5 047 000
	Maerl Extraction	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	553 000	912 000	1 109 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 749 000**	**28 774 000**	**33 181 000**

A sensitivity analysis was carried out by the development of low and high benefit estimates for each of the impact categories. The greatest sensitivity related to impacts on the maerl industry and property values under the lower benefit case and impacts on the sea bass fishery, oyster fishery and maerl industry under the higher benefit case.

Other predicted impacts which were considered to be significant, but for which it was not possible to derive a monetary valuation, include the effect on:

- the conservation value of the area, including the marine biota and bird populations;
- the smaller commercial fisheries (such as crabs) and recreational fisheries other than that for sea bass;
- land based recreational users of the area; and
- the tourist industry.

The costs derived from the economic benefit appraisal have been used together with the estimated treatment costs to calculate the net present value (NPV) and Benefit Cost Ratio (B/C ratio) for project lives of 5,10, 25 and 50 years. As the same average predicted treatment rate (190 l/s) is required to achieve both the "No Deterioration" and "North Sea Commitments", water quality objectives, with an annual probability of failure, of not greater than 5%, a detailed cost/benefit analysis has only been undertaken for the "North Sea Commitments" objectives.

TREATMENT OPTIONS

The cost estimates have confirmed that the existing treatment system is the most cost-effective method of treating the Wheal Jane minewater. However, the system relies on the availability of Clemows Valley Tailings Dam which has a remaining life of between 5 and 14 years.

(a) *Short Term Strategy 1996-99*

The short-term strategy is the continued operation of the existing treatment facility. This will enable:

- Further monitoring and the more certain prediction of the decline in Wheal Jane metal concentrations. These concentrations determine the size of the required long-term treatment plant and therefore any further reduction will result in a more cost-effective long-term solution.
- The development of an integrated water quality model for the Carnon Valley.
- The identification and assessment of treatment options for the major areas of diffuse contamination.

The cost benefit analysis for the existing treatment system (Table EX-6) indicates a benefit-cost ratio of over 4 and a net present value in excess of £10 million for a five year project timescale.

Table EX-6 : Cost Benefit Analysis - Existing Treatment System

	No Deterioration and North Sea Commitments (5% Non-compliance)	
	5 years	10 years[1]
PV costs	3.41	8.96
PV Benefits	14.99	20.75
NPV	11.58	14.79
B/C Ratio	4.40	3.48

PV - Present Value
NPV - Net Present Value
B/C - Benefit/Cost

[1] Assumes that the Clemows Valley tailings dam is used solely for minewater sludge deposition from 1996 onwards.

(b) *The Long Term Strategy*

The recommended future long-term strategy is likely to be the construction of the preferred active treatment system.

- Active treatment is the only technically proven method of achieving both the "No Deterioration" and "North Sea Commitments" objectives with an annual probability of non-compliance of not greater than 5%.

- An active treatment system can be constructed either on the mine site or on NRA owned property.

- For a 50 year project life, the discounted cost of active treatment with sludge disposal on site is £15 million, which is less than the upper bound cost of building a passive treatment plant to achieve the "No Deterioration" objective with a 50% annual probability of non-compliance.

The cost-benefit analysis for the continued use of the existing treatment system followed by implementation of the recommended long-term system in 2000 is summarised in Table EX-7, and indicates that:

- Benefit-cost ratios of approximately 2 exist for meeting the "North Sea Commitments" water quality objectives.

- On-site sludge disposal is preferable to disposal to landfill sites.

Table EX-7 : Proposed Future Treatment Strategy - Base Case Benefit Analysis

	Sludge Disposal On Site (preferred option)				Sludge Disposal Off-Site			
	5 years	10 years	25 years	50 years	5 years	10 years	25 years	50 years
PV costs	7.48	9.49	12.96	14.87	7.48	10.09	14.59	17.06
PV benefits	14.99	20.75	28.77	33.18	14.99	20.75	28.77	33.18
NPV	7.51	11.26	15.81	18.31	7.51	10.66	14.18	16.12
B/C Ratio	2.00	2.19	2.22	2.23	2.00	2.06	1.97	1.94

Assumptions: 5 years operation of the existing treatment plant followed by the commissioning of an Active treatment facility.
Compliance with the "No Deterioration" and "North Sea Commitments" water quality objectives with a less than 8% annual probability of non-compliance.

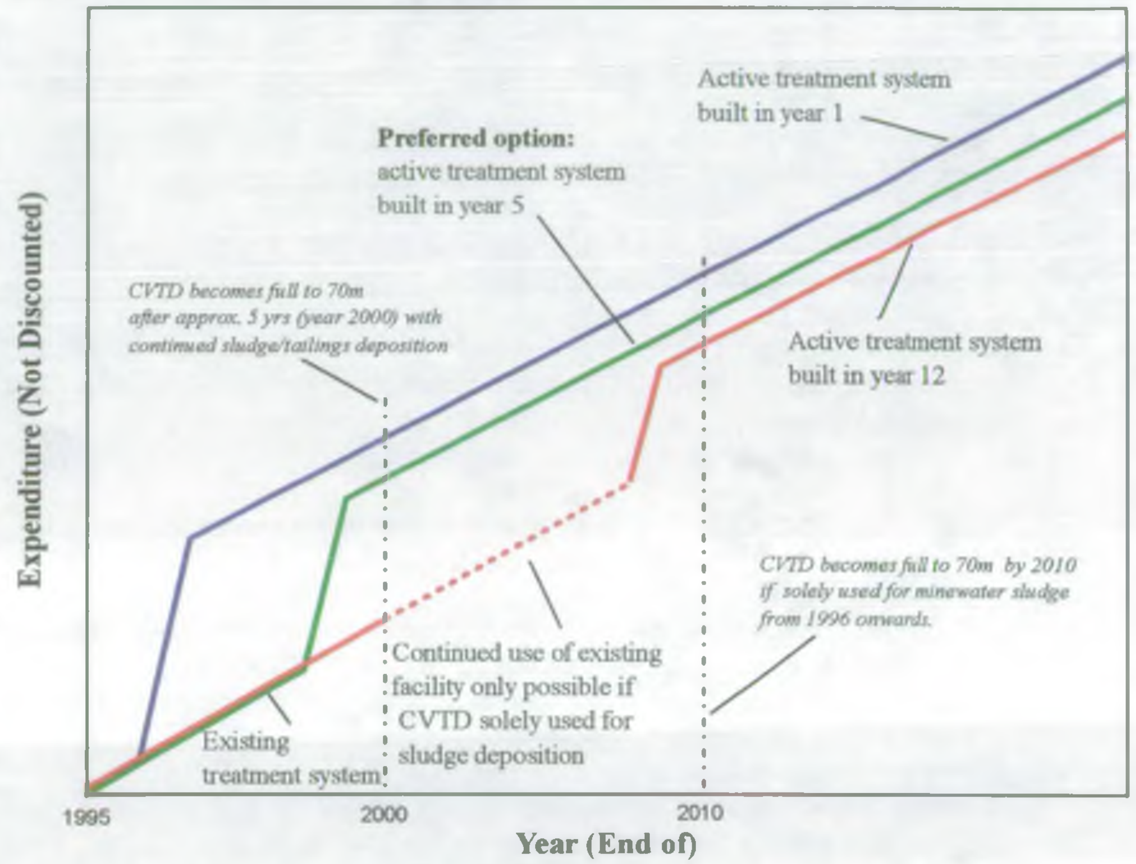
The effect on the present value project cost of delaying the implementation of the long term treatment system has been established on the assumption that the existing system is operated for either an additional 1, 5 or 12 years and replaced after this period with an active system. The projected cash flow and present value of the costs for these options are summarised in Figure EX.2. Figure EX.2 indicates that, on the assumption that the tailings dam is solely for the use of sludge deposition from January 1996 onwards, the lowest present value cost is achieved by deferring plant construction for as long as practicable.

Delaying the construction of an active treatment system is, however, dependent on both successful negotiations with South Crofty Plc, to secure long term use of the tailings dam, and the relocation of South Crofty's milling operations off site. The practicalities and possible timing of the mill relocation remain uncertain and therefore the assumption has been made that tailings deposition into the Clemows Valley Tailings Dam is likely to continue for the next 5 years. On this basis, the Treatment Strategy detailed in Table EX-8 has been developed for the next 5 years.

Table EX-8 : Recommended Future Treatment Strategy

Period	Activity
1996-2000	Continued operation of the existing treatment system.
1996-1999	On-going data collection, planning studies, etc.
1999	Reappraisal of the treatment requirements and detailed design of the long term treatment system.
2000	Construction and commissioning of the long term treatment system at the mine site.
2001-onwards	Active treatment with sludge disposal to the Clemows Valley Tailings Dam.

Figure EX 2 Schematic Cost Distribution for Delayed Active Treatment Implementation



Present Value Costs for Different Operating Scenarios (sludge disposal on site)

Year	Continued Existing Treatment (£ millions)	Existing Treatment Plant Replaced by Full Active Plant after: (Total capital and operating costs in £ millions)		
		1 year	5 Years	12 Years
1	0.81	5.89	0.81	0.81
5	3.41	7.99	7.48	3.41
10	5.96	10.00	9.49	5.96
12	6.79	10.66	10.15	9.49
25	N/F	13.47	12.96	12.31
50	N/F	15.38	14.87	14.22

CVTD - Clemows Valley Tailings Dam N/F - Not Feasible

Costs based on treating an average of 190 l/s to achieve "No Deterioration" and "North Sea Committments" objectives with a 5% annual probability of non compliance

CONCLUSIONS AND RECOMMENDATIONS

Detailed studies have been undertaken to establish possible long term treatment options for the Carnon River and in particular the Wheal Jane minewater problem. The main conclusions from these studies are:

(i) Wheal Jane and County Adit are the two major sources of contaminated water entering the Carnon River.

(ii) Unidentified diffuse sources of contamination exist within the Carnon Valley from other abandoned mine workings.

(iii) The metal concentrations in the Wheal Jane minewater are reducing with time. The total metal concentrations have decayed exponentially from in excess of 3000 mg/l in 1992 to approximately 500 mg/l in 1994. However, the rate of decline has reduced and a longer data set is required before a reliable trend can be established.

(iv) Water quality modelling using the average minewater metal concentrations measured during the period October 1993 to September 1994, indicates:

  (a) Under the "No Treatment" option the metal concentrations in the Carnon River would be an order of magnitude higher than current levels and there would be widespread and prolonged iron discolouration in the Fal Estuary.

  (b) The current average treatment rate of 155 l/s will achieve the "No Deterioration" water quality objective with less than a 50% annual probability of non-compliance for all metals other than iron.

  (c) An average treatment rate of 190 l/s is required to achieve the "No Deterioration" water quality objective with a 5% annual probability of non-compliance. This treatment rate will also achieve the "North Sea Commitments" water quality objective with a 5% annual probability of non-compliance.

  (d) The "EC Directive" water quality objective cannot be achieved by treating only the Wheal Jane and County Adit waters because of high contamination from other diffuse sources.

SHORT TERM TREATMENT STRATEGY

(v) The existing treatment system can be operated to achieve (b) and (c) in (iv) above. The system offers the most cost effective method of treatment. The life of the system is governed by the Tailings Dam which has available storage until, at least, the year 2000.

(vi) The benefit-cost ratios for scenarios (b) and (c) in (iv) above are in excess of 4 over the next five years.

LONG TERM TREATMENT STRATEGY

(vii) Treatment beyond 2000 can be most cost effectively provided using active technology.

(viii) The preferred location for an active treatment facility is on the Wheal Jane mine site with disposal of sludge to the Clemows Valley Tailings Dam. The benefit-cost ratio for long-term treatment in this way is approximately 2.

(ix) The life of the Clemows Valley Tailings Dam can be extended beyond the year 2000 by the use of an active treatment system designed to minimise the volume of sludge produced.

(x) The passive treatment trials are, to date, inconclusive and further testing is required to confirm the efficacy of this type of system for long term use at Wheal Jane.

RECOMMENDATIONS

The main recommendations from the study are:

(i) The existing treatment system should continue for at least three years from April 1996 to March 1999.

(ii) The treatment plant should be operated to achieve the "No Deterioration" Water Quality Objective with a 5% annual probability of non-compliance.

(iii) The pilot passive treatment trials should continue for at least three years from April 1996 to March 1999.

(iv) The following studies should be carried out to determine future treatment needs:

- Collection and appraisal of water quality and flow data.
- Develop a model to simulate the decay in the Wheal Jane metal concentrations.
- Identify the diffuse sources of contamination.
- Further develop an integrated water quality model for the Carnon River.
- Assess the long term impact of minewater on the estuary biota.

1

1. INTRODUCTION

Wheal Jane is an abandoned underground mine in Cornwall and prior to closure was one of the last operating tin mines in the UK.

The Wheal Jane workings were dewatered by continuous pumping during the mining operations. After mine closure in March 1991, underground pumping ceased, and the groundwater level within the mine was allowed to recover.

Following formal notice of closure from the then mine owners (Carnon Consolidated Ltd), it became apparent to the NRA that a release of minewater into the Carnon River was inevitable. The NRA monitored the rate of recovery and the quality of the minewater, as well as collecting baseline environmental data from the Carnon River and Fal Estuary.

Despite the efforts of Carnon Consolidated Ltd and the NRA, once groundwater levels in the mine reached adit level, acidic metal laden minewater was released into the Carnon River. The result was a highly visible and widely reported pollution incident, the effects of which extended into the Fal Estuary.

To minimise environmental damage and alleviate public concern, the NRA exercised its statutory powers under Section 161 of the Water Resources Act (1991) and instigated an emergency treatment system.

In 1992, the Department of the Environment (DoE) approved an £8.3 million project with the following principal objectives:-

- Amelioration of the effects of the metal-rich minewater from Wheal Jane on the Carnon River and Fal Estuary.
- Development of appropriate intermediate water quality objectives for the Carnon River in addition to the NRA's routine water quality assessments.
- Research into the most appropriate and cost-effective long-term treatment strategies for achieving the various water quality objectives.

This report provides the basis for the NRA's recommendations to the DoE on the long-term options for dealing with the Wheal Jane minewater. The report has been produced jointly by NRA South Western Region and consultants Knight Piésold. Specialist economic and benefit appraisal has been provided by consultants Risk and Policy Analysts Ltd and the report has been externally reviewed by Dr P Younger from the University of Newcastle upon Tyne.

2

2. BACKGROUND

CONTENTS

2.1 LOCATION

The Wheal Jane mineworkings are located near the village of Baldhu in the Carnon Valley, which lies between Falmouth and Truro in south west Cornwall (see Figure 2.1). The Carnon River, which drains an area of some 45 km^2, discharges via Restronguet Creek into Carrick Roads, part of the Fal Estuary.

2.2 GEOLOGY

2.2.1 Regional Context

The western part of Cornwall is composed primarily of intensely faulted and folded non-calcareous sedimentary rocks of the Devonian age (see Figure 2.2). These were formed from mud and sand deposited in a deep marine environment, into which basic and ultrabasic rocks, collectively known as greenstones, were intruded. Subsequently, the strata were faulted and fractured before finally being uplifted by a major igneous intrusion. A period of hydrothermal activity ensued, during which the pre-existing fractures and fissures of the country rock were injected with mineral-bearing fluids.

The resultant mineralisation, which comprises primarily tin and copper deposits, follow the trend of the fractures and fissures and are orientated approximately east-west. However, subsequent mineralisation, principally including lead and zinc, with some silver, was formed at right angles to the tin and copper lodes and are known as "caunter" lodes. The final phase of intrusion involved the deposition of barren quartz veins and the subsequent development of clay-filled faults also at right angles to the major tin and copper lodes. The metalliferous deposits of the region, therefore, are primarily tin and copper but with subsidiary lead, silver, zinc and other associated minerals.

It is believed that during the Permian age the mineralised zones were exposed and subjected to progressive erosion. Erosion led to a cycle of deposition and reworking of the materials and the eventual development of alluvial deposits in the lower reaches of the rivers. Sea level changes resulted in the flooding of the valley systems and consequently the metal rich alluvial deposits, in part, now lie in estuarine environments, including Restronguet Creek and the Fal Estuary.

2.2.2 The Carnon Valley

The country rock in much of the Carnon Valley comprises the Devonian strata of the Mylor series (see Figure 2.3). This is known locally as killas, a Cornish mining term denoting the local barren rocks. The killas has been extensively intruded by east-west trending mineral-bearing veins. These metalliferous lodes extend throughout the Carnon Valley and contain high concentrations of tin and copper. Many deposits are also rich in pyrite and arsenic (Ref. 2).

The alluvial deposits in the lower reaches of the Carnon River and in Restronguet Creek have been covered by the silt and sand-sized waste (tailings) discarded

Figure 2.1 Location Plan

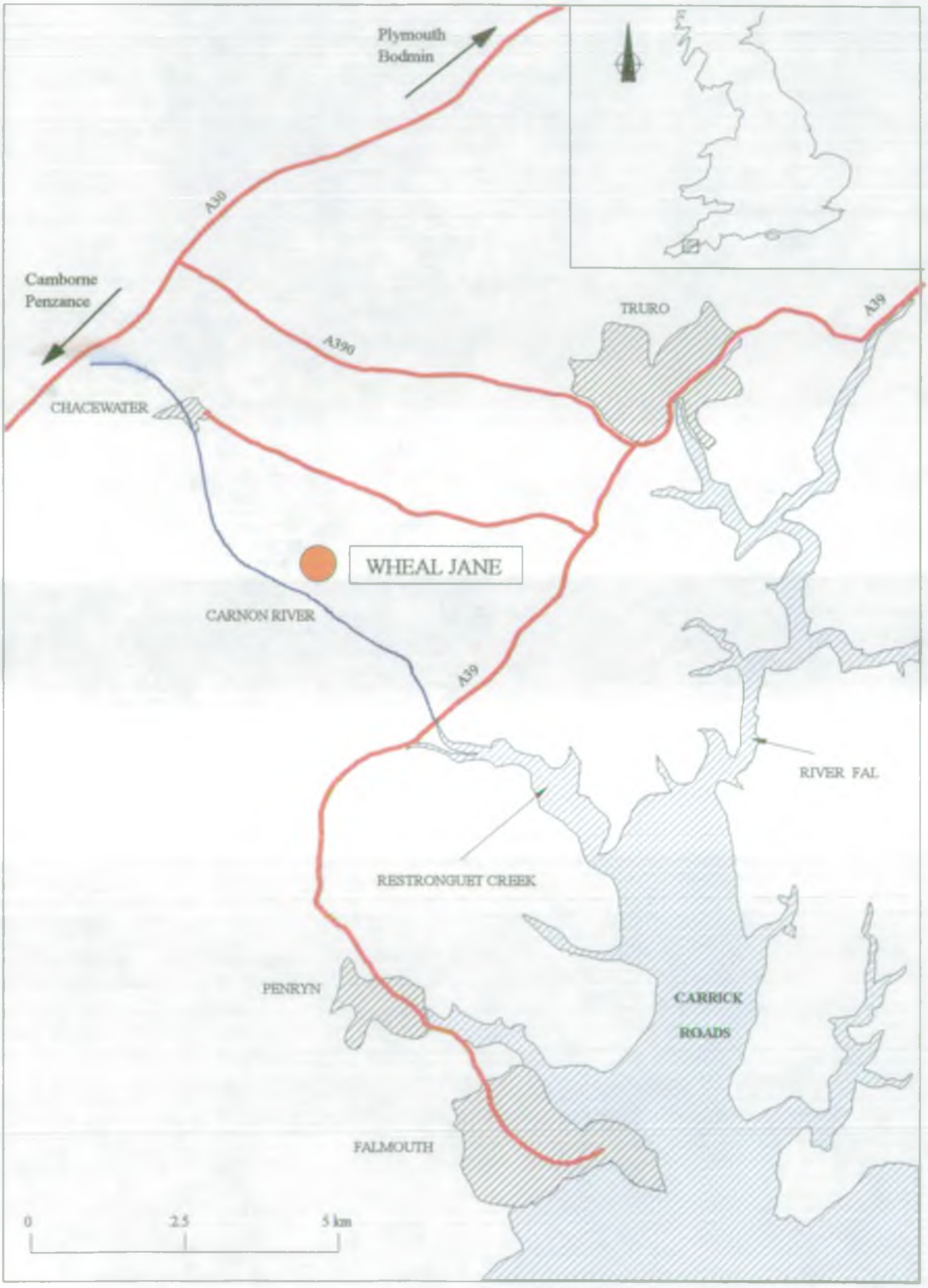


Figure 2.2 General Geological Plan of West Cornwall (Ref 1)

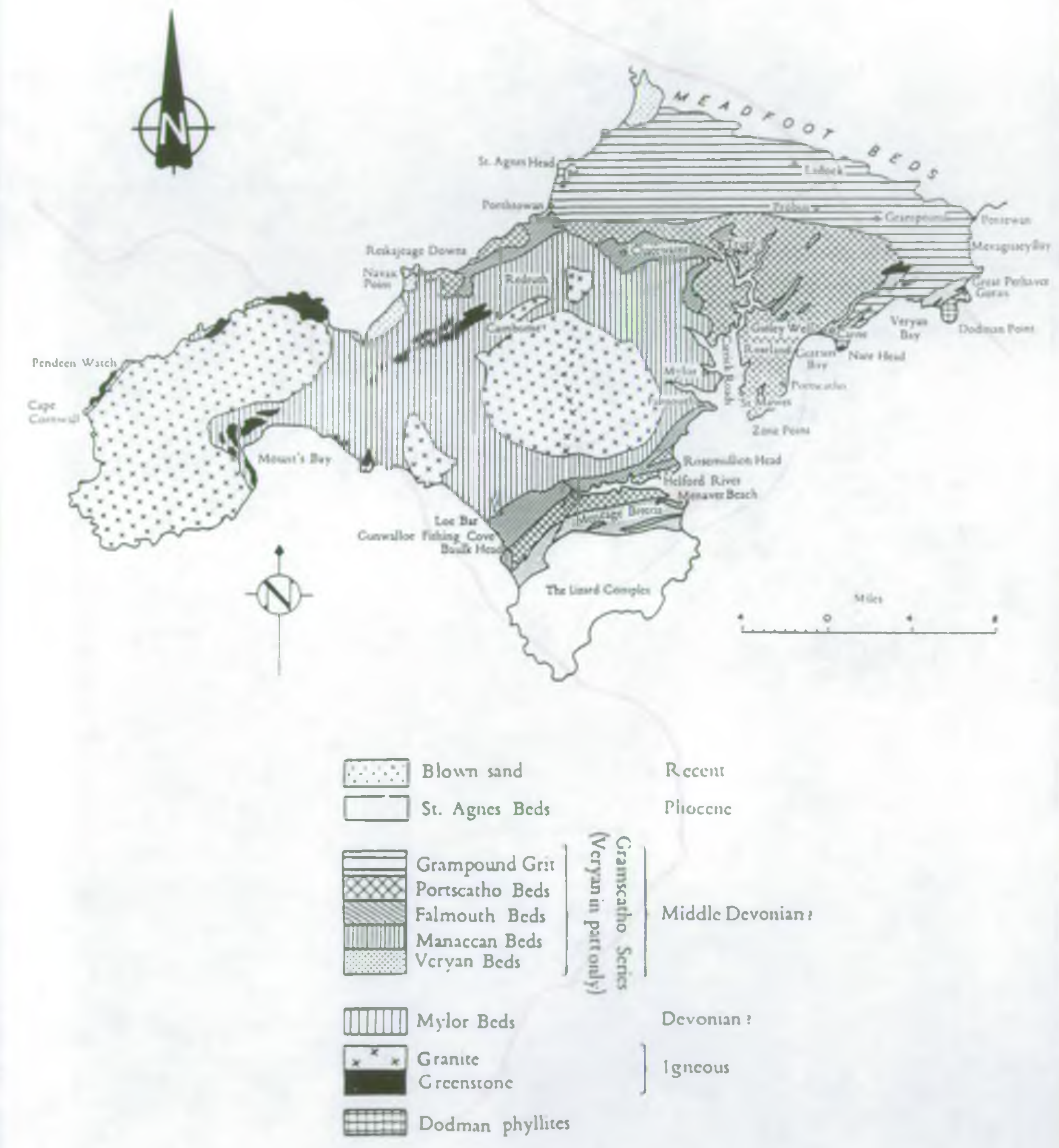
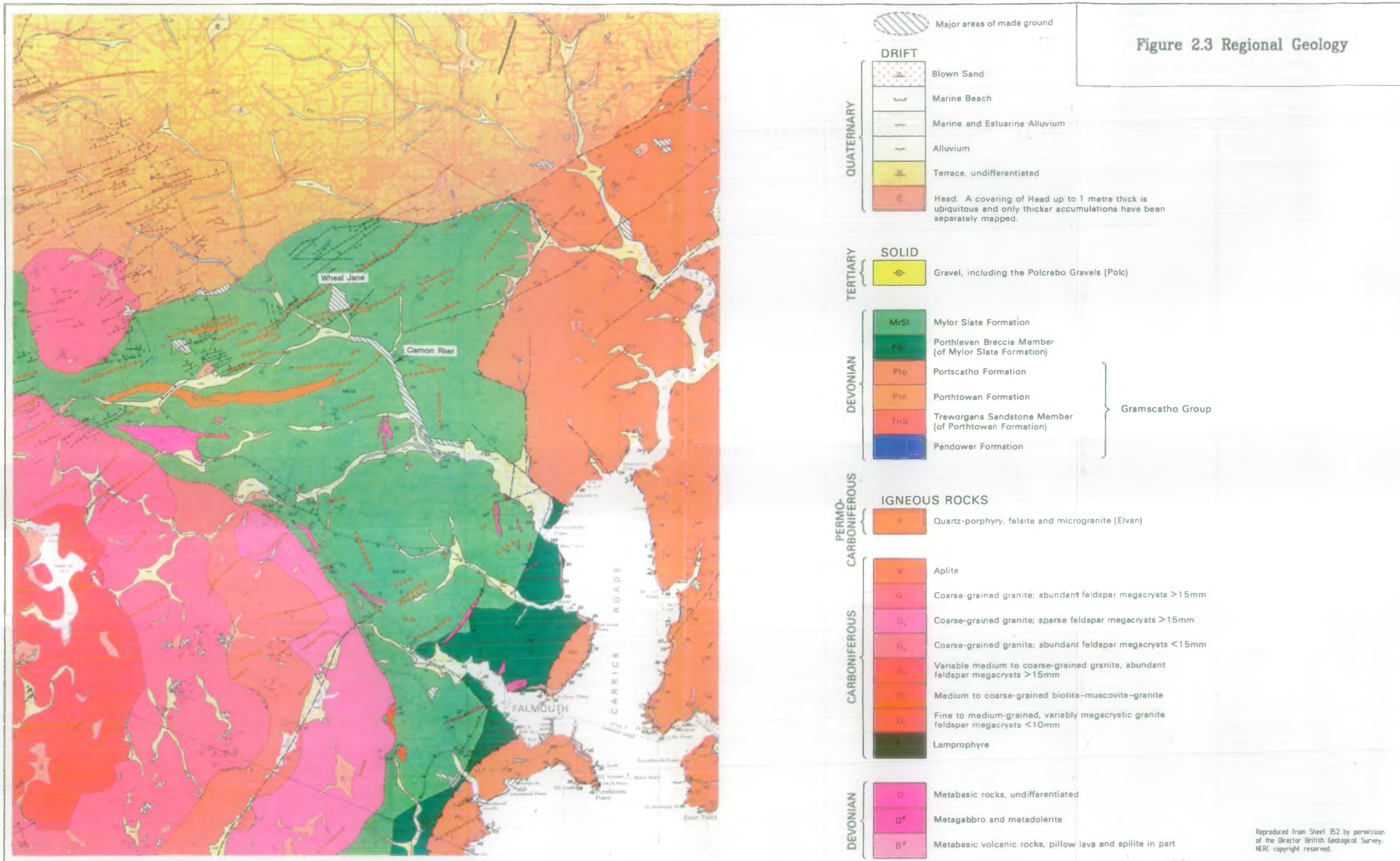


Figure 2.3 Regional Geology



from mineral workings in the valley. Writers in the 19th century suggested that some 700 000 m^3/yr of material was deposited annually into the navigable channel of the Carnon River and "lodged primarily where the backwater meets the tide regularly encroaching on the creek" (Ref. 3). The fine particles within this material often passed into Carrick Roads, but most of the material was either deposited in Restronguet Creek to form the mudbanks visible at low tide or within the Carnon Valley itself.

2.3 MINING HISTORY

2.3.1 Historical Perspective

Earliest mining activity in the Carnon Valley may date from 2000 BC, and there are reports of tin mining by the Romans in the area (Ref. 3). However, extensive mining activity probably dates from the 17th century. By 1678, the Poldice mine in the upper Carnon Valley was a profitable tin producer and by the early 19th century the mining area of Gwennap, part of which lies within the Carnon catchment, was reported as supplying more than a third of the world's copper output. By the 1850s the Consolidated Mines were the largest copper producers in the world (Ref. 4). The output from these mines was shipped through the port of Devoran which, for a short period, was the largest mineral port in Cornwall.

The mining operations supported a wide range of associated industries in the Carnon Valley during the early to mid-19th century. The 1878/1880 Ordnance Survey maps (see Figures 2.4, a and b) identifies the presence of active or recently closed works in the valley associated with copper smelting, tin streaming (the recovery of tin from sediments), sulphuric acid production (from pyrite), tin smelting, arsenic recovery and ochre works (producing pigment).

The quantity of mining wastes deposited over the years into the Carnon River and entering Restronguet Creek has caused considerable migration of the tidal limit. In 1620, Bissoe was a tidal port capable of receiving boats of up to 200 tons. An 1827 report indicates that the creek formerly extended much further up the Carnon Valley, but gravel and silt from the mining industry had choked the upper navigation channel, filling the valley with alluvial matter up to 12 m deep. Nevertheless, Restronguet Creek was still navigable in 1889 for vessels of 300 tons as far as the village of Devoran (Ref. 3).

The creek has been worked in the past to recover metals. The first reports of this relate to the extraction of tin and date back to 1778. The year of 1824 marked the start of a 20-year period when extensive volumes of tin were mined from estuarine muds in the creek.

The metalliferous mining industry in Cornwall, as in other parts of the UK, declined in the late 19th and early 20th centuries. The 1907/1908 Ordnance Survey maps (see Figures 2.4, c and d) indicates that, by this time, virtually all large-scale mining and associated industries in the valley had ceased production, with only small scale reworking of old mine dumps and alluvial deposits taking place. The reworking of old tailings deposits continued sporadically until the late 1970s.

2.3.2 Wheal Jane

The Wheal Jane complex includes some workings of great antiquity but few detailed records of the earliest mining activities are available. By the 18th century the Wheal Jane workings, together with West Wheal Jane, were a major producer of tin with lesser quantities of copper and arsenic (Ref. 4) and later became a major producer of pyrite (Ref. 6). Nevertheless, working ceased temporarily in about 1875. Nangiles and Wheal Widden worked the same lode structure as Wheal Jane and all these mines were subsequently amalgamated into the Falmouth Consolidated Group, which was dissolved in 1915.

The amalgamation of numerous individual mines is of considerable importance, since it extended the interconnection of the workings (see Figure 2.5). Many of the earlier workings are poorly documented and the extent of the interconnections is not always known. Nevertheless, it is acknowledged, for example, that there is a direct connection between Nangiles and Wheal Jane either through the adit system or shallow underground workings. These workings may also have been connected to other, more distant, operations of the same group, such as Wheal Widden and, more tenuously, Wheal Baddern and Wheal Hope.

The modern workings began in 1970 when, after four years of development work, Consolidated Goldfields Ltd reopened Wheal Jane. During the 1970s, there were only four working underground mines in Cornwall two of which, Wheal Jane and Mount Wellington, were in the Carnon Valley. Wheal Jane was the first new major tin mine to be opened in 50 years and one of the largest metal mines ever worked in the UK.

The development work included dewatering of the old workings, the sinking of a new shaft (Wheal Jane No. 2 Shaft) to 366 m, with deepening and widening of the adjacent Clemows Shaft. The mill constructed on the site included innovative refining techniques to process 600 t/day of ore. The concentrates (tin and copper/zinc) were shipped via Truro harbour to both UK and Swedish smelters, and the waste product from the refining process, comprising 95% of the mill throughput, was discharged into the Clemows Valley Tailings Dam. At start-up the mine employed some 440 people. Water pumped from underground was lime dosed and discharged via the tailings dam into the Clemows Stream.

Over the next 21 years, the mine had a chequered history, which involved :

- Two changes of ownership - from Consolidated Goldfields Ltd to RTZ Corporation in 1979 and subsequently to Carnon Consolidated Ltd in 1988 (now trading as South Crofty plc).
- The cessation of all underground operations for some six months during protracted negotiations over the transfer of ownership to RTZ.

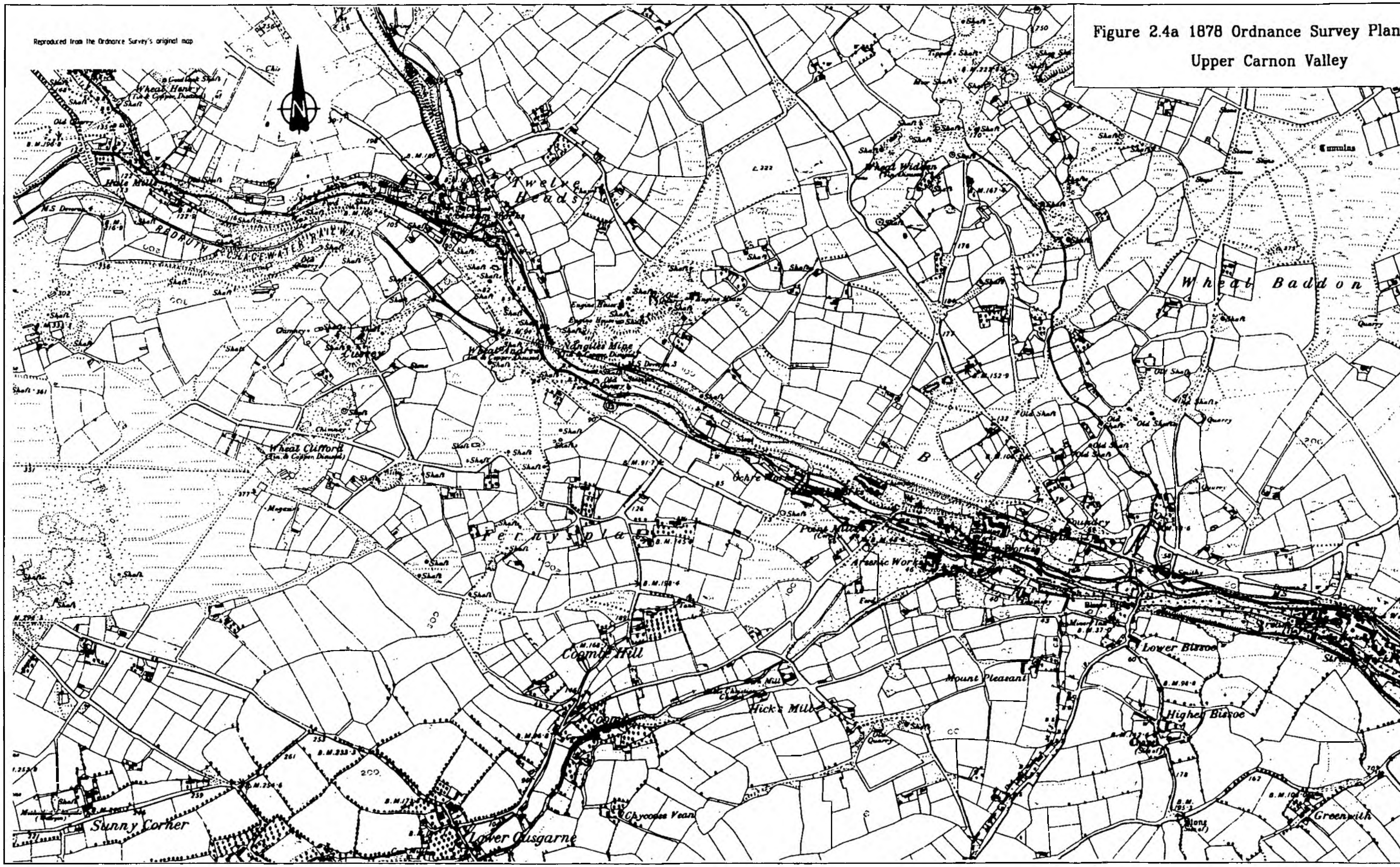
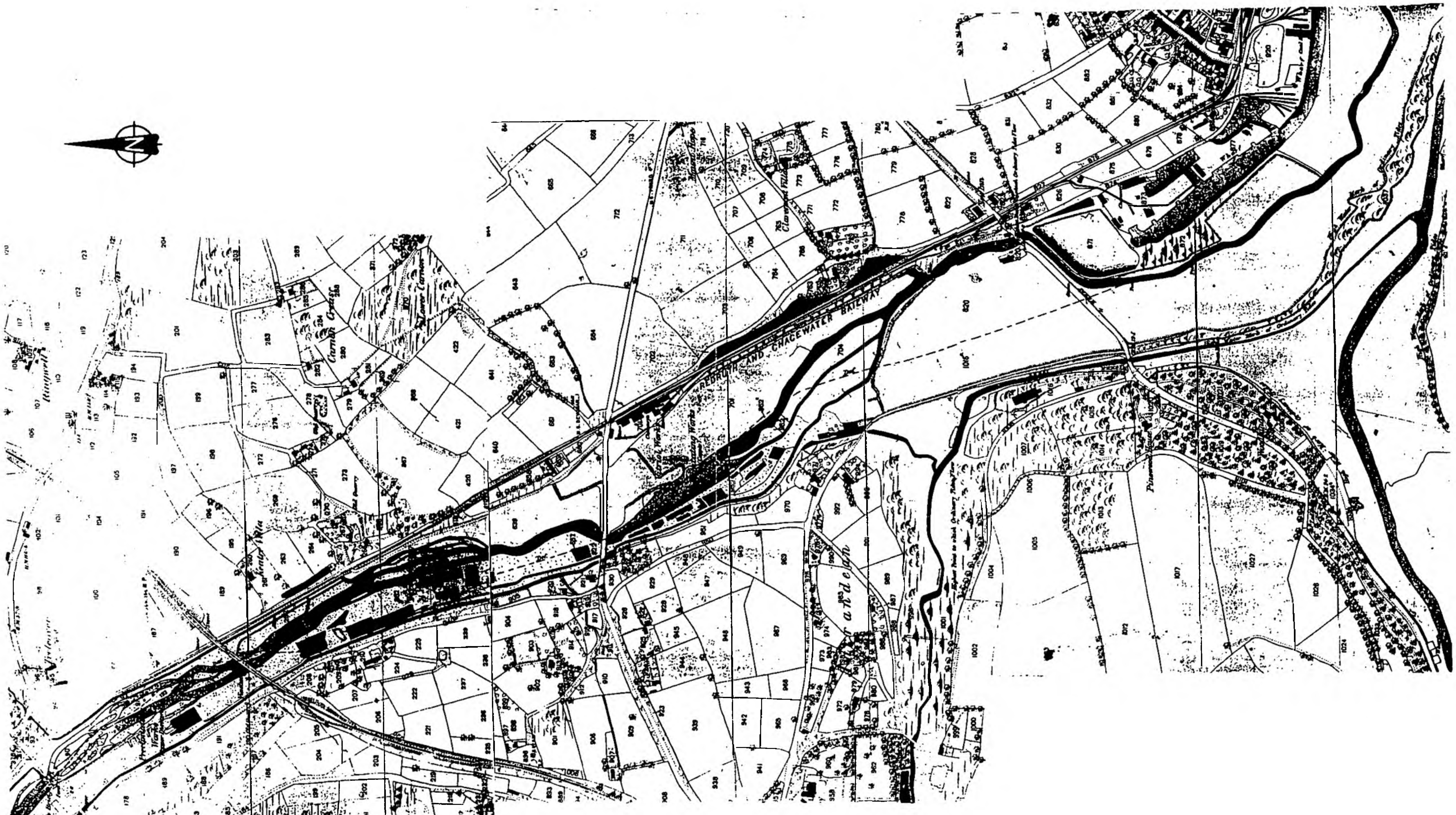


Figure 2.4a 1878 Ordnance Survey Plan
Upper Carnon Valley

Reproduced from the Ordnance Survey's original map

Figure 2.4b 1880 Ordnance Survey Plan

Lower Carnon Valley



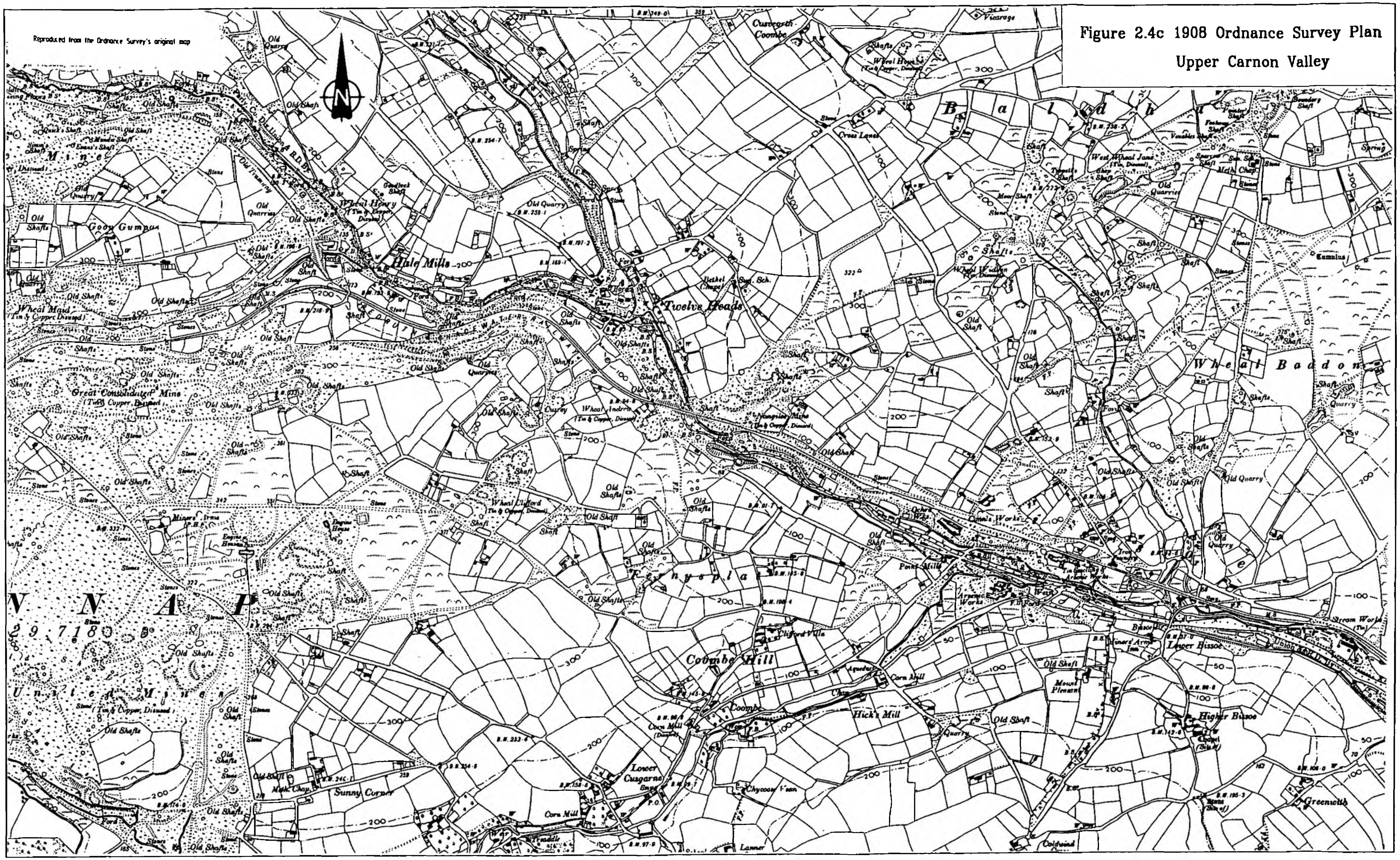


Figure 2.4c 1908 Ordnance Survey Plan
Upper Carnon Valley

Figure 2.4d 1907 Ordnance Survey Plan

Lower Carnon Valley

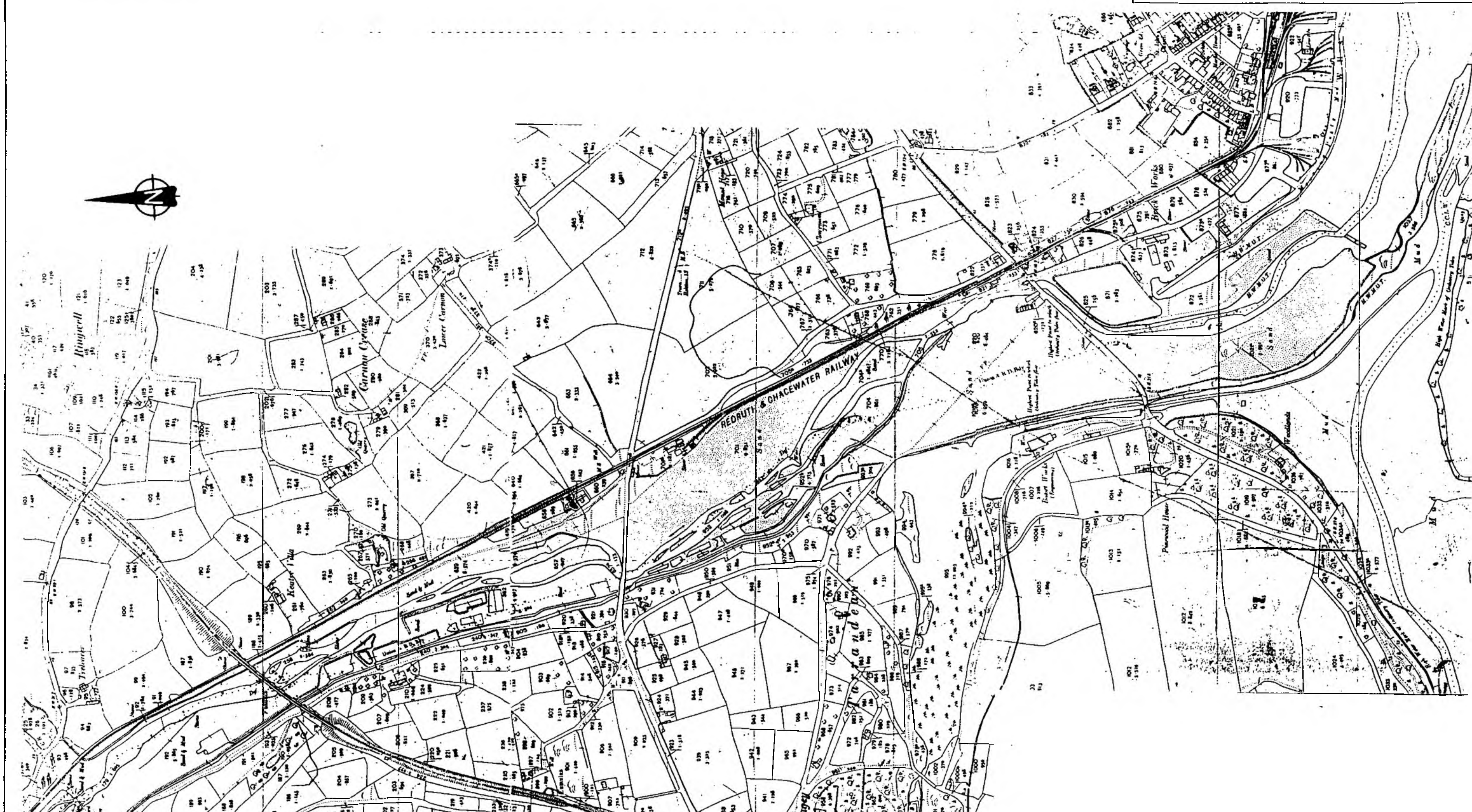
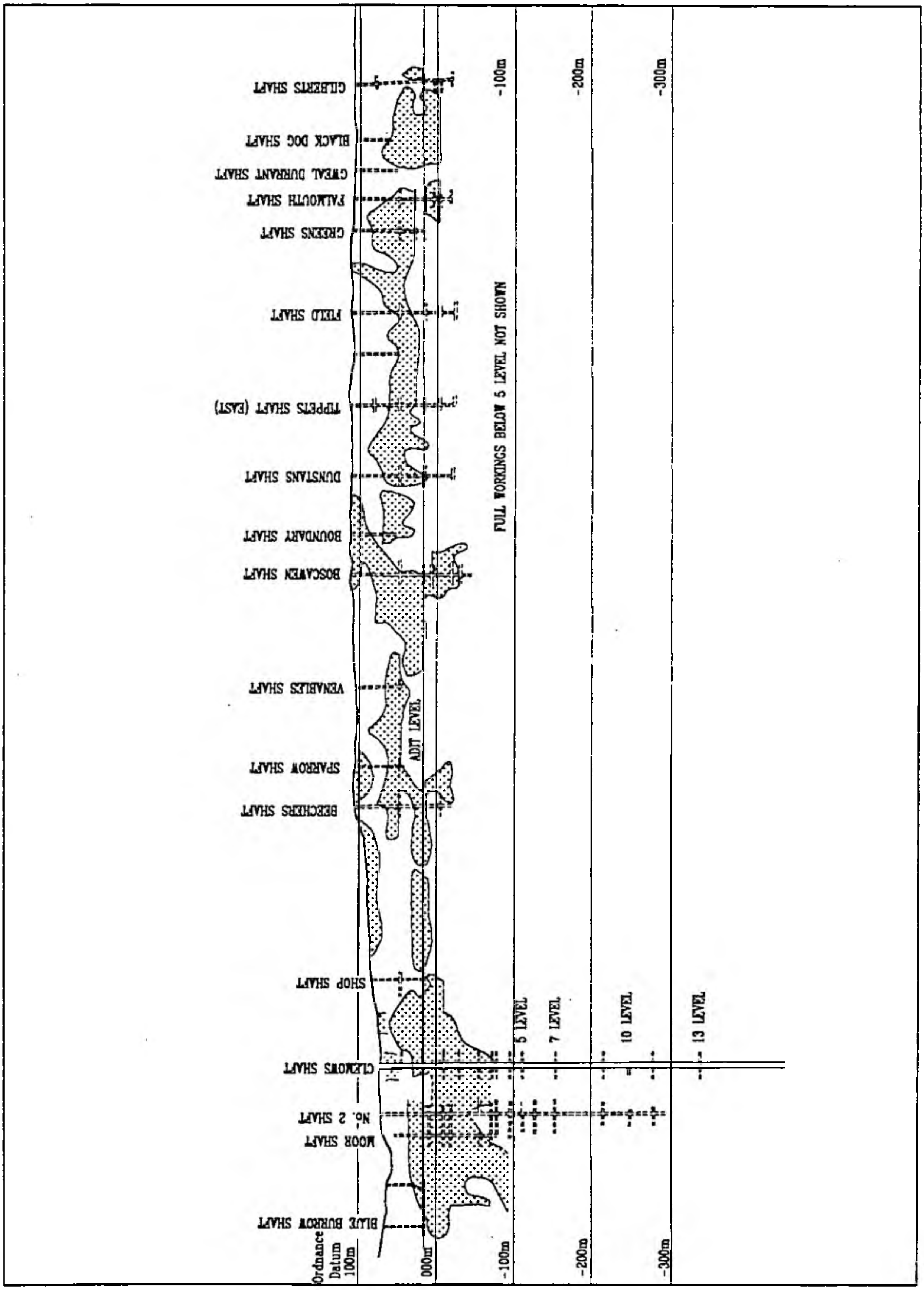


Figure 2.5 Schematic Section of Wheal Jane Workings



- A merger with the adjacent Mount Wellington mine in 1981, where the workings had been re-opened in 1975 to exploit the western end of the same orebody worked at Wheal Jane.
- A merger with South Crofty mine and, in 1988, the reorganisation of mining operations, which resulted in the cessation of mineral processing at South Crofty and the use of the Wheal Jane mill to process ore from both underground operations.

Despite the changes in circumstances, the mine workings were progressively extended both vertically to a depth of more than 500 m below ground level, and horizontally, primarily to the west below the Old Mount Wellington workings. Ore production increased to some 900 t/day and the mill continued to produce both tin and copper/zinc concentrates.

In 1991, the mine management decided to end underground working at Wheal Jane, leading to the cessation of all operations underground including dewatering. The mine was formally abandoned by the owners, Carnon Consolidated Ltd, on 9th September 1991. However, ore extraction from South Crofty mine continues and the Wheal Jane mill still processes this ore and discharges residue into the Clemows Valley Tailings Dam.

The history of Wheal Jane is summarised in Table 2-1.

Table 2-1 : Synoptic History of Wheal Jane

1740	First record of mining at Wheal Jane
1847	Commencement of period of production record
1875	Cessation of underground operation
1875 - 1893	Extraction by tributers above adit level
1905	Amalgamation to form Falmouth Consolidated
1915	Dissolution of Falmouth Consolidated
1915 - 1919	Extraction by tributers
1939	Taken over by Mount Wellington but development not completed
1966	Initial prospecting by Consolidated Goldfields Ltd
1966 - 1970	Planning and mine development by Consolidated Goldfields Ltd
1970	Production commenced at 600 t/d
1978	Mine closure, pumps continue to dewater during negotiations
1979	RTZ purchase Wheal Jane and recommence production
1981	RTZ purchase Mount Wellington underground workings
1988	Carnon Consolidated Ltd purchase mining operations from RTZ
1988	Processing of South Crofty ore moved to Wheal Jane
1991	Cessation of underground operation at Wheal Jane. Pumps switched off

2.4 HYDROGEOLOGY

2.4.1 Pre-Mining Hydrogeology

Although there is no hydrogeological information from the Carnon Valley prior to mining activity, it is probable that the water table would have been a subdued profile of the local topography. Groundwater levels and flow in the valley would have been controlled primarily by the Carnon River and the hydrogeological characteristics of the country rock.

The country rock (killas) exhibits relatively low primary permeability and hence groundwater flow would have been through secondary permeability (i.e. through the extensive faults and fractures which exist in this stratum). The dominant groundwater flow direction in areas of mineralisation, therefore, is along these features, which in the Carnon Valley run predominantly east-west (i.e. generally perpendicular to the river).

2.4.2 The Impact of Historic Mineworkings on Hydrogeology

Early mining activity was predominantly based around small scale open-pit or near-surface workings and resulted in the formation of extensive shallow voids above groundwater level.

As surface deposits were fully exploited it was necessary to follow the veins of ore deeper underground. By the 17th century the workings had begun to extend below the groundwater table and, consequently, some means of dewatering was necessary. Water levels in mines were traditionally lowered by means of near horizontal tunnels, known as adits, capable of draining water by gravity. Most of the early shallow workings at Wheal Jane, for example, were drained by the Jane's Adit which discharged into the Carnon River above Bissoe Bridge.

As workings extended to greater depths, extensive pumping operations were required. By the 19th century steam-operated pumps at mines in the Carnon Valley were capable of lowering the groundwater table by up to 700 m (2000 ft) (Ref. 4). Nevertheless, adits continued to be an integral part of mine dewatering by intercepting infiltration, so minimising inflow to mine workings, and reducing the pumping head required, often by more than 30 m. Consequently, the adits were often extended to improve the overall efficiency of dewatering operations. The County Adit which drains most of the mine workings on the west side of the valley, for example, was constructed over a period of 150 years from 1730 onwards. The adit consists of a number of branch tunnels which have a total length of 50 km (Figure 2.6). The maximum distance of any branch from the portal is approximately 8 km. County Adit, which currently discharges some 200 l/s of poor quality water into the Carnon River, continues to influence groundwater levels in the area.

2.4.3 Impact of Recent Mineworkings on Hydrogeology

Recent underground operations at Wheal Jane mostly involved workings more than 120 m below adit level. During these operations the workings were extended some 520 m below ground level and dewatering operations increased accordingly.

Following the acquisition of Mount Wellington by the owners of Wheal Jane, a deep connection was made between the two mines and the workings were extended to the west under the existing Mount Wellington workings. As a consequence of the connection, pumping from the combined workings peaked in 1981 but declined subsequently following restoration of the County Adit. This reduced the inflow into Mount Wellington from adjacent abandoned workings which are also drained by the adit.

The large-scale extraction of ore from these workings created a substantial series of inter-connected linear voids in the vicinity of Wheal Jane, generally orientated in an east west direction. These voids extend beneath the Carnon River and across both sides of the valley floor (see Figure 2.6). The dewatering operations resulted in an east-west elongated cone of depression around the workings.

The piezometric surface during mining was found to be flat on the line of the workings but very steep when monitored perpendicular to the workings, due to the generally low primary permeability of the killas. However, where the workings intersected strata with a locally increased permeability, high inflows from the killas were experienced. One such inflow, which occurred at around 160 m below Wheal Jane No. 2 Shaft surface level, resulted in an inflow of sufficient magnitude to merit the construction of a watertight door on a redundant drive.

Dewatering beneath the bed of the Carnon River also induced large volumes of river water to flow into the mine. In 1975, there was a major inflow following collapse of the old surface workings. As a result the river was permanently diverted through an 80 m long canalised section.

2.5 HYDROLOGY AND WATER QUALITY

2.5.1 The Carnon Catchment

The Carnon Catchment, which drains an area of 45.5 km^2, has been greatly modified by the mining activity. In general, tributaries to the west of the Carnon River are fed from the granite uplands whilst those to the east rise on killas. Many streams flow over areas of previous mining activity which may profoundly influence the flow regime.

The Carnon River flows into Restronguet Creek, part of the Fal Estuary, near the village of Devoran.

Figure 2.6 Adits and Mineworkings

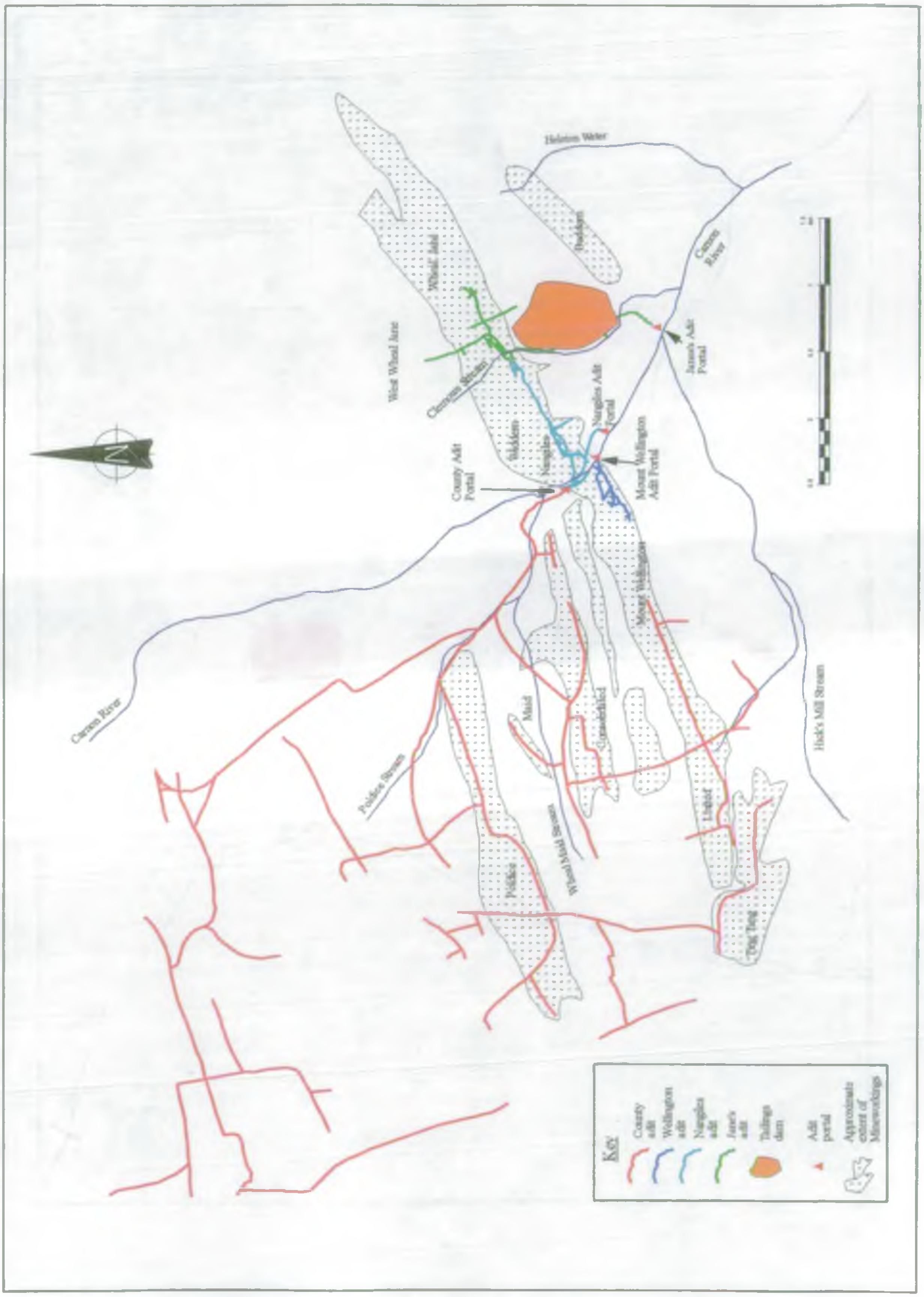
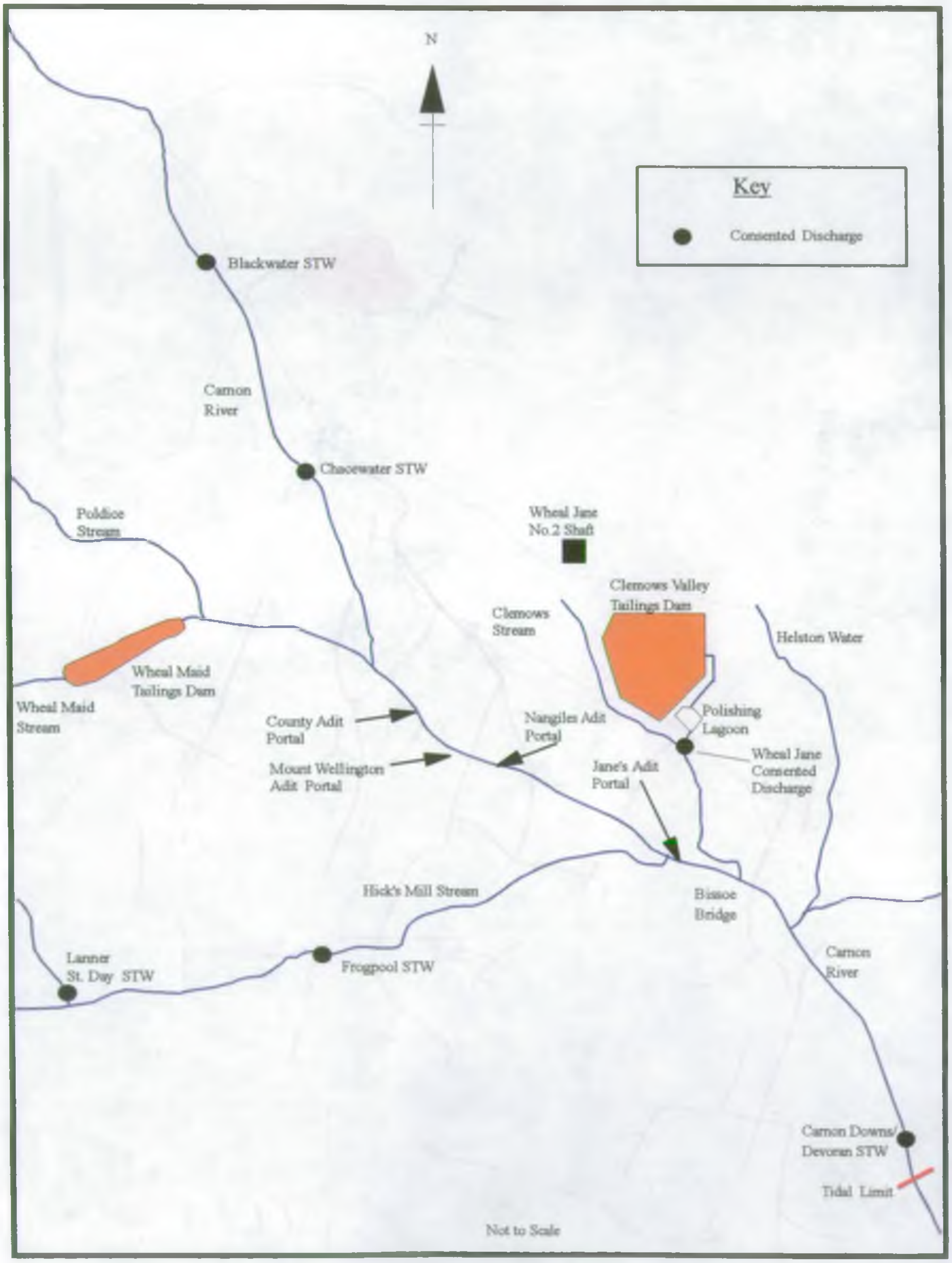


Figure 2.7 Locations of Major Discharges to The Carnon River



2.5.2 Water Quality in the Carnon River

It is likely that mineralisation within the catchment would have had an influence on water quality prior to the development of mining activities. Elevated background concentrations of trace metals in soils and river bed sediments are characteristic of many areas with extensive mineralisation. However, the mineral workings and the associated processing industry which developed from the 17th century onwards would have had a profound effect on water quality. For example, concern was raised in 1876, following mine closure, that deposits of ochre (iron hydroxide) might block the County Adit. Indeed, at one time, ochre was collected commercially in the area and supported a local pigment industry.

In recent years the NRA and its predecessors have undertaken routine water quality monitoring at Devoran Bridge (see Table 2-2). When the data for 1990 are compared with Environmental Quality Standards (EQS) given in DoE Circular 7/89 introduced in accordance with the EC Dangerous Substances Directive (EC 76/464), it is apparent that the EQSs were exceeded at Devoran Bridge for cadmium, copper, zinc, iron and arsenic. It is almost certain, therefore, that the Carnon catchment has had a long history of significantly elevated concentrations of trace metals.

Biological monitoring was carried out at some locations as part of the NRA's 1990 National Biology Survey. This confirmed the poor macro-vertebrate status of the river.

In recent years the major sources of metal inputs into the Carnon River have been the adits, although the inputs from non-point sources such as run-off from mine dumps, the sites of former metal processing works and, indeed, from the accumulated sediments in the valley floor are likely to have made a significant contribution.

In addition to the sources of metal associated with the former mining industry, the Carnon River catchment also receives inputs from a number of Consented Discharges, principally including :

- Treated domestic sewage arising from small dwellings or groups of dwellings (i.e. discharges of less than 5 m^3/day).
- The discharge from the ongoing milling operations at Wheal Jane.
- The discharge from five water company sewage treatment works, at Carnon Down/Devoran, Lanner St. Day, Frogpool, Blackwater and Chacewater.

The locations of the major inputs into the Carnon River are indicated on Figure 2.7.

Table 2-2 : Annual Average Metal Concentrations in the Carnon River at Devoran Bridge.

Year	Annual Mean Concentration (μg/l total metal)								
	Cadmium	Lead	Chromium	Zinc	Copper	Nickel	Arsenic	Iron	Manganese
1969				3 241	712		147	1 608	
1970				3 627	712		241	3 867	
1971				8 790	945		296	10 269	
1972				5 626	874		425	11 355	
1973				3 135	644		164	3 725	
1974	7.8	48.4	4.0	3 812	508	93.7	292	6 123	896
1975	6.1	41.6	3.1	3 693	465	91.2	199	5 350	806
1976	13.1	53.3	8.0	5 693	445	112.0	166	7 959	1 347
1977	11.0	63.7	13.3	6 533	634	139.0	225	11 341	1 201
1978	14.9	38.9	13.2	8 182	639	94.1		13 051	1 911
1979	11.7	36.0	13.5	8 871	723	96.7		21 045	1 894
1980	29.9	32.7	9.4	11 520	652	96.1		14 427	1 797
1981	8.0	26.1	11.0	5 367	517	74.9		8 555	1 058
1982	18.8	76.6	11.8	12 572	1 059	112.0		29 178	1 963
1983	22.6	154.0	9.7	15 415	676	155.0		31 031	2 176
1984	15.9	60.0	7.2	11 811	790	108.0		19 600	1 952
1985	11.6	19.3	10.5	15 591	638	94.5		8 920	1 692
1986	9.5	14.2	6.8	6 595	534	87.0		9 337	1 584
1987	8.7	12.7	1.4	6 474	516	81.1	131	8 695	1 647
1988	12.7	11.6	2.7	8 981	519	89.5	133	9 478	1 951
1989	10.3	6.0	1.0	8 310	405	87.7	44.2	6 937	2 455
1990	13.1	13.1	1.1	8 615	451	84.5	39	5 124	1 891
EQS	1.0	250 (D)	250 (D)	500	28 (D)	200 (D)	50 (D)	1000 (D)	-

Note : Those metals for which the EQS is set as a concentration of dissolved metal are indicated by (D)
EQS taken from DoE circular 7/89.

2.5.3 Restronguet Creek and the Fal Estuary

The Fal is a typical ria (flooded valley), formed after the last glaciation about 8000 years ago. The main feature within the Fal Estuary is the deep central channel, the old river valley, which runs along its entire length. The sides of the channel rise steeply from a depth of 25-30 m to extensive shallow banks on both sides, which may be the floodplain of the original river. Although the majority of creeks are dry at low water, dredging around Falmouth Docks and Penryn River maintains the depth in these areas to around 6 m.

Restronguet Creek, into which the Carnon River discharges, is situated at the north western end of the Carrick Roads within the Fal Estuary (see Figure 2.8).

The major fluvial inputs to the estuary are :

- River Fal at Turnaware Point . . . . . . 5.65 m^3/s
- Restronguet Creek 1.95
- Penryn 0.4
- Percuil 0.3
- Mylor 0.15
- St. Just 0.04

The input from Restronguet Creek is composed principally of the Carnon River (average flow of 0.8 m^3/s) and the River Kennal (average flow of 1.1 m^3/s).

Tidal currents are generally weak throughout the Fal Estuary. However, where constrictions in water flow occur, such as at the entrance to Restronguet Creek, stronger currents occur.

2.5.4 Water Quality in the Fal Estuary

The Restronguet Creek has long received both acidic metal-rich minewater and high suspended solid loadings from the mining areas to the north and west. The impact of these inputs has extended well into Carrick Roads. However, in addition to the metal mine waste from Restronguet Creek, Carrick Roads has also received historically large influxes of china clay waste from the rivers in the east of the region.

Streams still carry material which, since the tidal creeks such as Restronguet are well protected from the processes of marine erosion, tends to remain within the estuarine system. The Fal Estuary also receives in excess of 12 000 m^3 of treated sewage per day.

2.6 BIOLOGY AND NATURAL RESOURCES

2.6.1 Landscape

The landscape of the Carnon Valley owes much to the widespread disturbance of the area by mining. The upper valley around Twelveheads shows varied landform, irregular slopes and mature plant regeneration (mostly heathland) on areas previously affected by mining activity. The stretch of valley from Twelveheads to Bissoe Bridge has a relatively high quality landscape value.

Below Bissoe Bridge, the valley floor has been subjected to restructuring as a result of the deposition and reworking of tailings and other wastes generated by the mining industry. Much of the valley floor comprises bare ground or is poorly revegetated, with some unimproved grassland and scrub. Elsewhere, to the west of the catchment, there are areas of broadleaf woodland.

The Carnon Valley contrasts sharply with the Fal Estuary, which is designated as an Area of Outstanding Natural Beauty (AONB) as well as an Area of Great Scientific Value (AGSV) (see Figure 2.9). The eastern side of the estuary is also designated as part of the Heritage Coast. St. Mawes, Falmouth and Penryn are designated as Historic Settlements.

2.6.2 Conservation Value of the Carnon Valley

Despite many years of mining activity, the Carnon Valley has some sites (see Figure 2.10), which are of local conservation value. Of particular value are:

- *Wheal Gorland* (NGR SW 732 429)

  The Wheal Gorland SSSI, which covers approximately 0.6 ha, is centred around an abandoned copper mine of considerable geological interest. The mining dumps comprise a wide variety and quality of secondary lead and copper minerals.

- *Bissoe Valley Educational Nature Reserve* (NGR SW 773 413)

  The Bissoe Valley Educational Nature Reserve covers 3 ha to the west of Bissoe Bridge. The site was created under a restoration project which included a fencing programme, tree planting and landscaping to create wetland habitats, three pools and grassland and meadow habitats. The site has been adopted by the Cornwall Trust for Nature Conservation as a small nature reserve with the hope that suitable habitats will attract the wide variety of dragonflies previously recorded in the area.

Figure 2.8 Estuary Plan

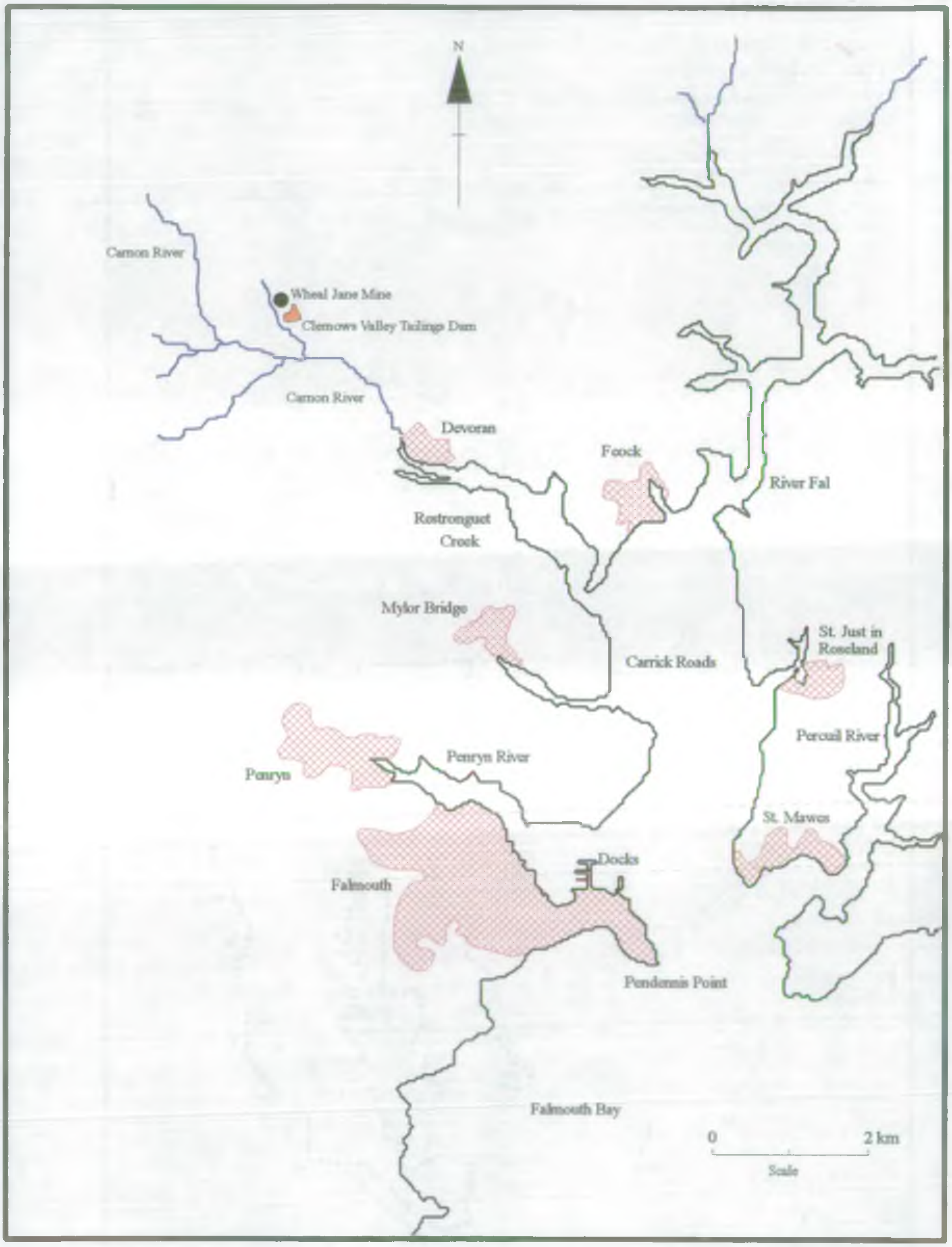
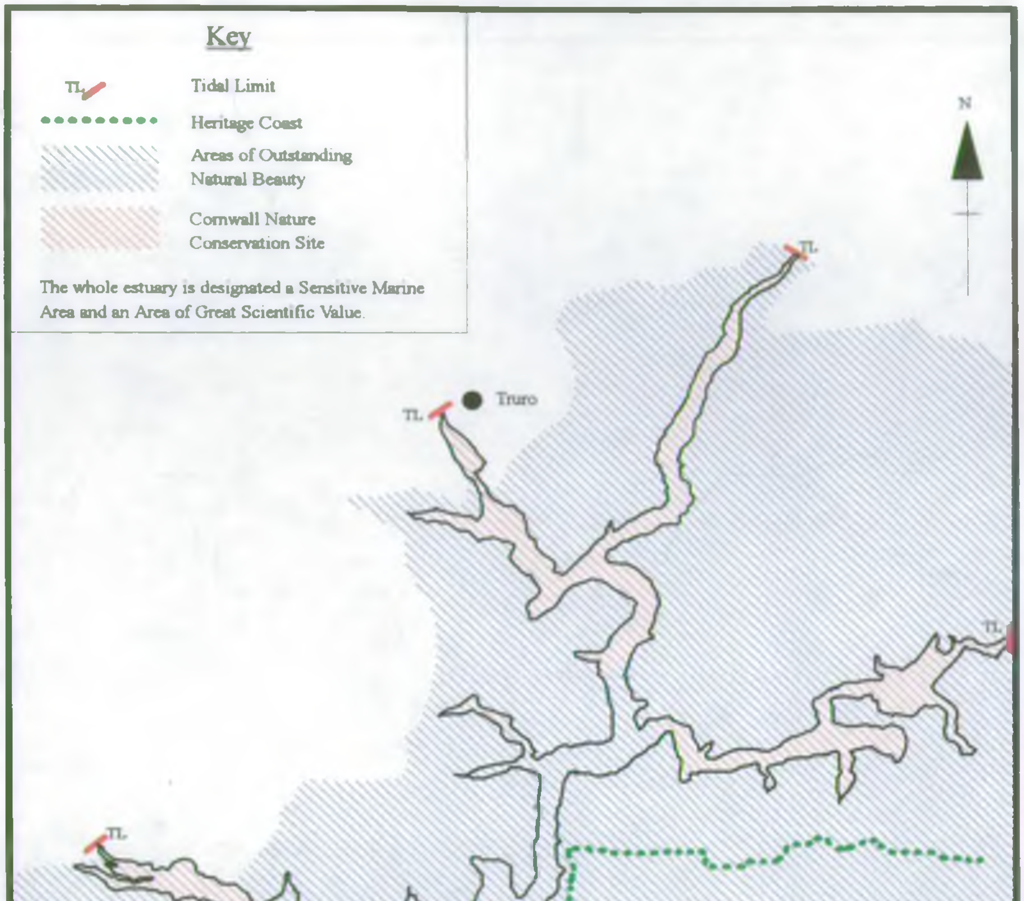


Figure 2.9 Fal Estuary Conservation Designations



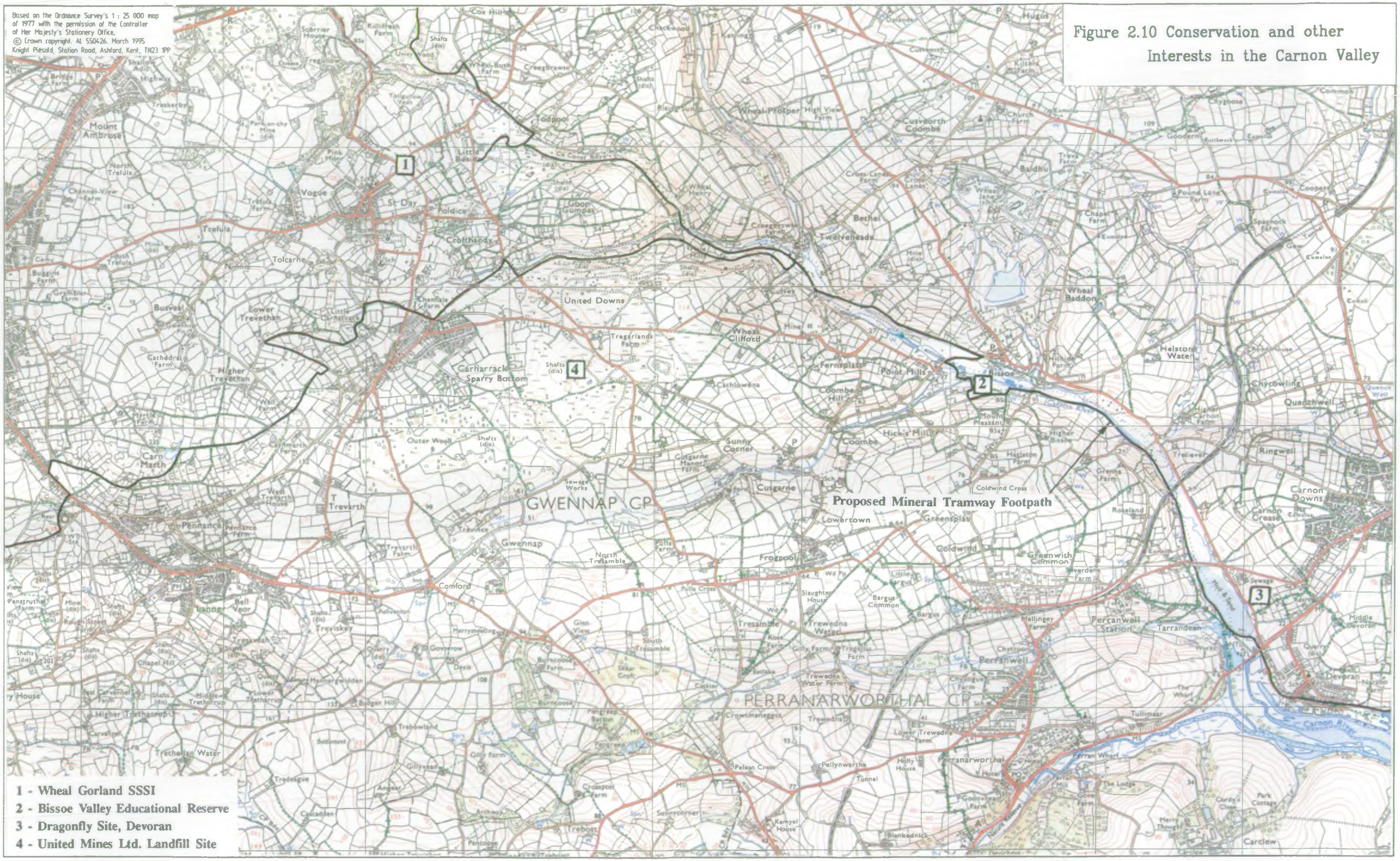


Figure 2.10 Conservation and other Interests in the Carnon Valley

- *Devoran Dragonfly Site* (NGR SW 790 397)

  This site, which includes both woodland and open water, is primarily of interest for its dragonfly and damselfly population, including a breeding species of damselfly that is nationally rare. Buzzards hunt widely across this and adjoining areas and a colony of sand martins, an uncommon species in Cornwall with only 150-200 pairs countywide, has been recorded.

Elsewhere the fragmented and secondary nature of most of the other habitats within the catchment limit their conservation value.

2.6.3 Conservation Value of the Fal Estuary

The Fal Estuary has a very high conservation value. It is considered by English Nature to be of national importance as one of the richest estuaries in Britain, with a high habitat diversity and community type. Major habitat types within the estuary include subtidal habitats, saltmarsh, mudflats and lagoons. The estuary is one of the most southwesterly estuaries in the UK, which makes it an essential feeding station and stopping point during spring and autumn migrations of wild fowl and other birds, as well as an overwintering haven during cold winters. Of particular interest are (see Figure 2.11) :

- *Sensitive Marine Area*

  The Fal Estuary is part of a region, stretching from Dodman Point to Lizard Point, designated by English Nature as a Sensitive Marine Area. Sites carrying this designation are recognised as being of national importance for marine wildlife.

- *Sea Bass Nursery Areas*

  Although the estuary supports more than 100 species of fish, it is most notable as a nursery for sea bass (*Dicentrarchus labrax*). The Fal Estuary sea bass nursery is of national importance in the Ministry of Agriculture, Fisheries and Food (MAFF) long-term strategy for the conservation and management of the bass fishery in the coastal waters of England and Wales. Two areas in the estuary have been designated bass nursery areas, namely :

  - The area encompassing all tidal waters enclosed by a line drawn 270 degrees true from Weir Point to Turnaware Point.

  - The Percuil River, including all tidal waters enclosed by a line drawn 151 degrees true from St. Mawes Castle to Carricknath Point.

- *Roseland Voluntary Marine Conservation Area*

  The Roseland District on the eastern side of the Carrick Roads is a Voluntary Marine Conservation Area. The seabed in this area is covered by rare coralline algae known as maerl and beds of the uncommon eel grass *(Zostera)*.

  St. Mawes Bank hosts the only significant sized beds of living maerl in southern Britain. Maerl is listed as a "threatened community" in the Invertebrate Red Data Book and is of international importance. The two species that compose the maerl, *Phymatolithon calcareum*, and *Lithothamnion corallioides* are both listed in Annex V of EC Directive 92/93 "On the conservation of natural habitats and of wild fauna and flora. Maerl beds form an important, extremely diverse habitat for a host of other plants and animals. More than 120 species of seaweed are associated with these beds, many of which have not yet been found elsewhere in the British Isles. The maerl also provides habitat for the rare Couch's goby (Gobius couchi) which has not yet been found elsewhere in Britain.

  Zostera is considered as "nationally scarce" by English Nature, with only 74 areas recorded nationally.

- *Cornwall Nature Conservation Site*

  Restronguet Creek is designated a Cornwall Nature Conservation site as part of a broader designation encompassing the whole Fal Estuary intertidal zone. In addition, the Devoran Quay Preservation Society owns and manages a 9 ha site for recreation/wildlife situated near the tidal limit of Restronguet Creek. The area contains patches of tidal saltmarsh.

  The mudflats in Restronguet Creek are an important feeding ground for waders, wildfowl and gulls and have been estimated to support between 25% and 30% of the total Fal Estuary populations (Ref. 5).

2.7 ECONOMIC PERSPECTIVE

2.7.1 Agriculture

Although there is no Grade 1 agricultural land within the Carnon Valley, some Grade 2 land does occur in sheltered areas with well-drained loam soils. Notable crops include early potatoes and broccoli. Elsewhere, small dairy farms are typical.

2.7.2 Fisheries

The Fal Estuary supports a commercial native class B oyster fishery (see Figure 2.11). The fishery has unique cultural heritage value - it has the last remaining sail-powered fleet in the UK. Fishery production has increased in recent years. MAFF estimate that 400 000 oysters were produced for human

- *Devoran Dragonfly Site* (NGR SW 790 397)

  This site, which includes both woodland and open water, is primarily of interest for its dragonfly and damselfly population, including a breeding species of damselfly that is nationally rare. Buzzards hunt widely across this and adjoining areas and a colony of sand martins, an uncommon species in Cornwall with only 150-200 pairs countywide, has been recorded.

Elsewhere the fragmented and secondary nature of most of the other habitats within the catchment limit their conservation value.

2.6.3 Conservation Value of the Fal Estuary

The Fal Estuary has a very high conservation value. It is considered by English Nature to be of national importance as one of the richest estuaries in Britain, with a high habitat diversity and community type. Major habitat types within the estuary include subtidal habitats, saltmarsh, mudflats and lagoons. The estuary is one of the most southwesterly estuaries in the UK, which makes it an essential feeding station and stopping point during spring and autumn migrations of wild fowl and other birds, as well as an overwintering haven during cold winters. Of particular interest are (see Figure 2.11) :

- *Sensitive Marine Area*

  The Fal Estuary is part of a region, stretching from Dodman Point to Lizard Point, designated by English Nature as a Sensitive Marine Area. Sites carrying this designation are recognised as being of national importance for marine wildlife.

- *Sea Bass Nursery Areas*

  Although the estuary supports more than 100 species of fish, it is most notable as a nursery for sea bass (*Dicentrarchus labrax*). The Fal Estuary sea bass nursery is of national importance in the Ministry of Agriculture, Fisheries and Food (MAFF) long-term strategy for the conservation and management of the bass fishery in the coastal waters of England and Wales. Two areas in the estuary have been designated bass nursery areas, namely :

  - The area encompassing all tidal waters enclosed by a line drawn 270 degrees true from Weir Point to Turnaware Point.

  - The Percuil River, including all tidal waters enclosed by a line drawn 151 degrees true from St. Mawes Castle to Carricknath Point.

- *Roseland Voluntary Marine Conservation Area*

  The Roseland District on the eastern side of the Carrick Roads is a Voluntary Marine Conservation Area. The seabed in this area is covered by rare coralline algae known as maerl and beds of the uncommon eel grass *(Zostera).*

  St. Mawes Bank hosts the only significant sized beds of living maerl in southern Britain. Maerl is listed as a "threatened community" in the Invertebrate Red Data Book and is of international importance. The two species that compose the maerl, *Phymatolithon calcareum*, and *Lithothamnion corallioides* are both listed in Annex V of EC Directive 92/93 "On the conservation of natural habitats and of wild fauna and flora. Maerl beds form an important, extremely diverse habitat for a host of other plants and animals. More than 120 species of seaweed are associated with these beds, many of which have not yet been found elsewhere in the British Isles. The maerl also provides habitat for the rare Couch's goby (Gobius couchi) which has not yet been found elsewhere in Britain.

  Zostera is considered as "nationally scarce" by English Nature, with only 74 areas recorded nationally.

- *Cornwall Nature Conservation Site*

  Restronguet Creek is designated a Cornwall Nature Conservation site as part of a broader designation encompassing the whole Fal Estuary intertidal zone. In addition, the Devoran Quay Preservation Society owns and manages a 9 ha site for recreation/wildlife situated near the tidal limit of Restronguet Creek. The area contains patches of tidal saltmarsh.

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Figure 2.11a Fal Estuary Maerl Beds, Zostera Beds and Bass Nursery Area

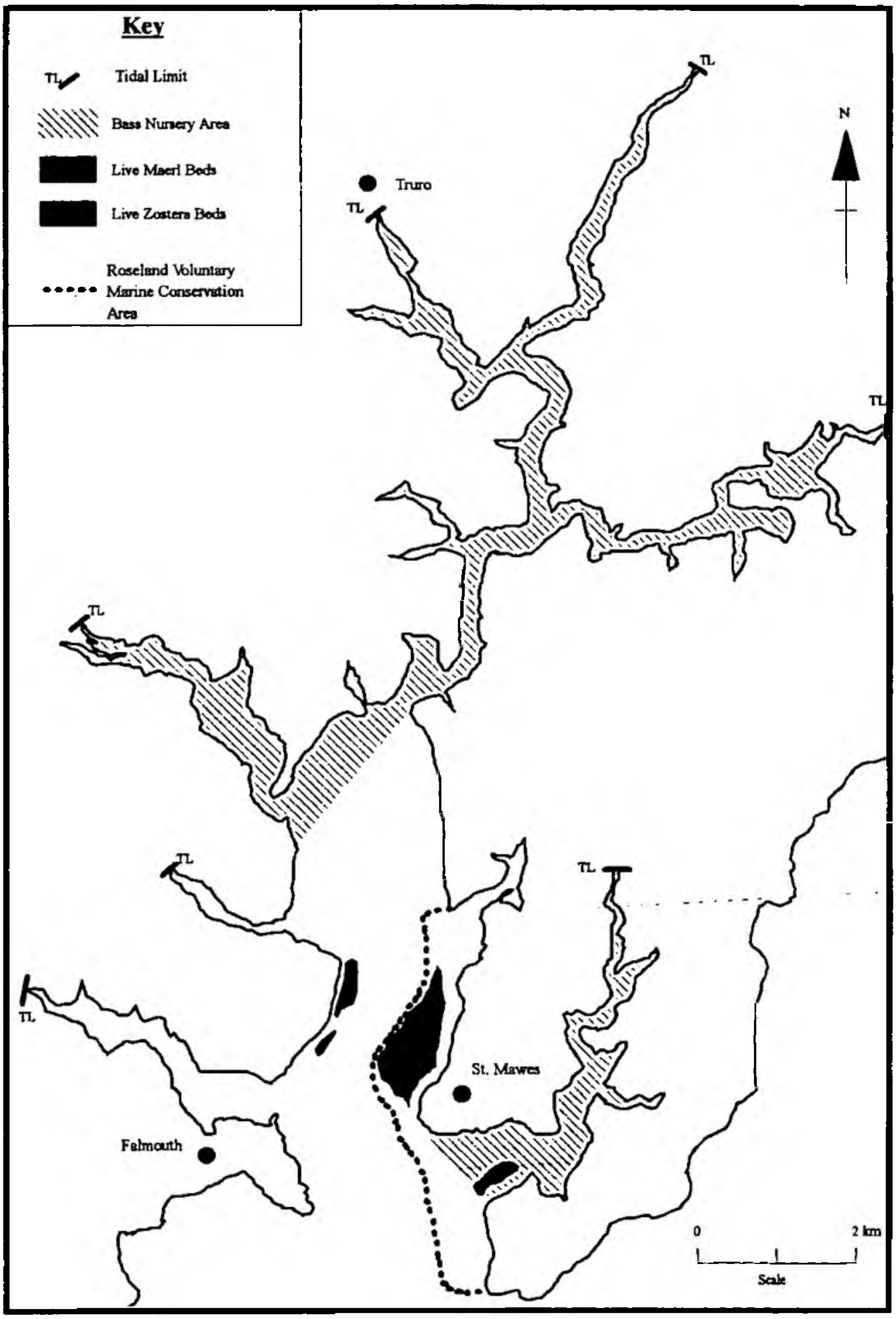
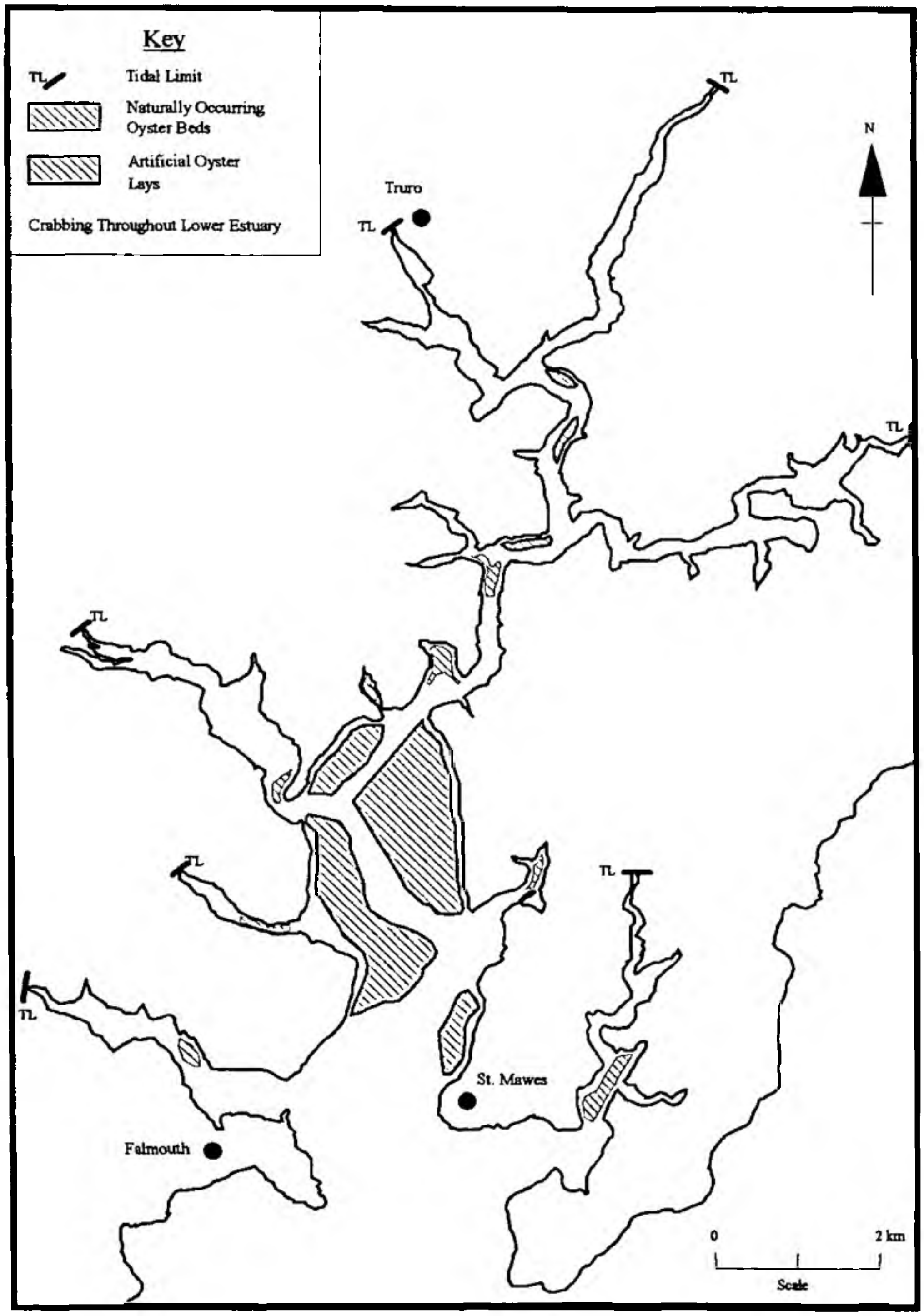


Figure. 2.11b Fal Estuary Oyster Fishery



consumption in the 1993/94 season. Oysters occur naturally throughout the estuary, but are dredged and relayed according to size by the fisherman in particular areas.

There are no other major commercial fisheries in the estuary, but bass and both velvet and green shore crab are also commercially exploited.

2.7.3 Maerl Exploitation

The maerl beds at St. Mawes Bank have had an economic value since the 18th century as a calcium-rich soil additive. The extensive, dead unattached maerl is collected by means of a suction dredge by Cornwall Calcified Seaweed Company in a restricted area under licence from MAFF. Maerl is dried, crushed and used as a soil conditioner, as animal food additive, for water filter construction and in pharmaceutical and cosmetic products.

2.7.4 Mineral Processing

Mining activity in the immediate area has ceased, although ore from the South Crofty mine is still milled at Wheal Jane and waste is deposited in the Clemows Valley Tailings Dam. South Crofty plc holds a water abstraction licence to supply the mill with up to 2 Mm^3/yr from the Carnon River and a Consent to Discharge excess water from the tailings dam to the Clemows Stream.

2.7.5 Waste Disposal

County Environmental Services (CES), the local authority waste disposal company, operate the United Mines Landfill (UML) site, which is licensed to receive up to 1000 tonnes of Category A to F waste per day subject to a maximum limit of 260 000 tonnes per year (see Figure 2.10).

2.7.6 Housing

A large percentage of the coastline of the Fal Estuary, particularly at the northern extreme and down the western side, is developed for housing, much of which is highly valuable, commanding prime sea views across the estuary.

2.7.7 Tourism

Cornwall is one of the most popular tourist destinations in the country, with more than three million visitors per year. Estimates put tourist spending in Cornwall at £620 million for 1990, with tourism accounting for 20% of the total employment in the county. The Fal Estuary and surrounding towns rely heavily on tourism, with almost 20% (£113 million) of the total 1990 tourist expenditure in Cornwall being attributed to the Carrick District.

2.7.8 Recreation and Amenity

The Carnon Valley itself is of limited recreation and amenity value with only informal recreation, including horse riding, walking, dog exercising, bird watching and mountain biking occurring to any significant extent. However, the Kerrier Groundwork Trust is involved in the Mineral Tramways Project which plans a footpath between the north and south Cornwall coasts that will take in the old mineral tramways and numerous industrial heritage sites (see Figure 2.10). The Trust also plans to revitalise a number of old industrial sites along the walk, several of which are in the Carnon Valley.

In contrast, the Fal Estuary is used extensively for watersports which sustains many small businesses. Within Carrick District alone, there are an estimated 161 firms directly involved in recreation-based maritime industries employing some 2000 people, 7% of the total employment in the area. Several companies operate ferries and pleasure boat trips along the Fal Estuary.

2.8 SUMMARY

The Carnon Valley and Restronguet Creek contain valuable deposits of tin and copper, which have been worked extensively from the 17th century. Mining activity reached a peak in the mid-19th century, when the mines in the area were among the largest producers of copper in the world, and the valley also supported a wide range of mineral processing and associated industries, including smelting, acid production, ochre (pigment) works and arsenic recovery.

The mining activities within the Carnon Valley and the Restronguet Creek would have had a deleterious effect on water quality in both the Carnon River and the Fal Estuary. In particular, the disposal of millions of tons of tailings into the river and estuary over many years has resulted in the accumulation of metal-rich sediments throughout much of the Carnon Valley and Restronguet Creek.

Despite the historical impacts of mining, the Fal Estuary, including Restronguet Creek, is of great environmental importance. The estuary:

- is designated as both an Area of Outstanding Natural Beauty and an Area of Great Scientific Value
- is nationally important as a sea bass nursery
- supports large numbers of wild fowl and other birds
- supports the only significant beds of maerl (a rare coralline algae) in Southern Britain, which is listed in Annex v of the EC Directive 92/93. Directive
- supports beds of the nationally scarce eel grass

- is designated, on the eastern side of the Fal Estuary, as part of the Heritage Coast

- supports a commercial native oyster fishery.

The local communities rely heavily on tourism, for which the Fal Estuary acts as a focus for extensive water-based recreations.

2.9 REFERENCES

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3. THE RELEASE OF MINEWATER FROM WHEAL JANE

CONTENTS

3.1 INTRODUCTION

Following the decision by Carnon Consolidated Ltd to end underground working, dewatering of the Wheal Jane mine was terminated on March 6, 1991. As a consequence, the water level within the mine workings began to rise. In the absence of mine dewatering, the water level within abandoned mine workings can be expected to recover to a level at which it can drain under gravity through adits or surface workings.

The NRA and Carnon Consolidated Ltd were aware of the potential pollution risk posed by such drainage and initiated an enhanced water quality monitoring programme in an attempt to predict the location, time, quantity and quality of the eventual release of mine water from the workings.

At the same time, the NRA intensified its monitoring of groundwaters, in conjunction with the District Councils, and in the receiving waters of the Carnon River and the Fal Estuary to include surveys and analyses of sediments and biota in Restronguet Creek.

3.2 THE EFFECT OF CLOSURE OF WHEAL JANE ON GROUNDWATER

The monitoring programmes of both the mine operator and the NRA revealed that, following the cessation of dewatering, water levels were rising in the abandoned mine workings. In addition to detecting a rise in shafts at Wheal Jane, monitoring revealed a consistent rise in water levels in shafts at a number of other locations within the Carnon Valley, including Mount Wellington, United Downs and The Consolidated mine workings. This confirmed the presence of hydraulic connections between the mine workings and suggested that groundwater recovery was taking place over an area of some 8 km^2.

Four major adits potentially drain the workings in the Carnon Valley (see Table 3-1). Drainage would be expected to occur from the adit with the lowest decant level, which for the Wheal Jane workings, is Jane's Adit. Subject to the extent of the hydraulic connections between the workings, the adit with the lowest decant level has the potential to control drainage from the flooded mine workings.

Table 3-1 : Adit Decant and Portal Levels

Adit	Decant Level (m AOD)	Portal Floor Level (m AOD)
Jane's	14.75	approx. 10
Nangiles	15.86	13.0
Mount Wellington	19.6	approx 17
County	unknown	17.11

As the level of minewater approached the decant level of Jane's Adit, pumping from No. 9 Adit shaft commenced on November 16, 1991 in an attempt to prevent minewater release through the adit.

The minewater was treated with lime and pumped to the Clemows Valley Tailings Dam, to allow precipitation of metals, prior to discharge to the Carnon River via the Clemows Stream. In addition an emergency settlement pond was constructed at the Portal of Jane's Adit by Carnon Consolidated. However, the pumping was unable to stem the rise in water level in the workings and minewater commenced issuing from the adit on November 17, 1991. Flow from the adit increased to at least 5 000 m^3/day (1 million gallons/day) of untreated minewater, quickly overwhelmed the emergency settlement pond and entered the Carnon River.

A plug was subsequently constructed at the Jane's Adit portal and, on November 20, 1991 the valves were closed to prevent any further release of minewater to the river. The pumping from No. 9 Adit Shaft continued in an attempt to prevent a further rise in the level of groundwater.

However in December 1991, high winds hindered settlement of the precipitate in the tailings dam and caused the re-suspension of some of the previously deposited hydroxides. As a result the quality of the water decanted from the tailings dam deteriorated. To help alleviate this problem the water level within the dam was progressively raised to the maximum level, consistent with the freeboard requirement necessary to ensure the safe operation of the dam. Further raising of the water level would have encroached on the emergency storm water storage capacity provided by the freeboard requirement and in the event of an abnormal storm may have compromised the safety of the dam.

On January 4, 1992, the decision was made to suspend treatment operations and temporarily store the groundwater within the underground mine complex. At that stage it was believed that adequate voidage was available underground to store the minewater until the weather conditions improved sufficiently to allow treatment to recommence. Water levels within the mine progressively rose.

The portal of Nangiles Adit is only just above the level of the Carnon River and, consequently, had been plugged during the working of Wheal Jane to prevent the flow of water into the workings during periods of high river flow. However, the head of water behind the plug caused it to fail on January 13, 1992. Within 24 hours, an estimated 25 - 50 000 m^3 (5-10 million gallons) of untreated minewater had been released directly into the Carnon River carrying with it an estimated 100 tonnes of metal. The flow declined over the succeeding days, but remained above 6 000 m^3/d (1.2 million gallons per day) for several weeks.

Immediately after the release from Nangiles Adit, the pumping and treatment of minewater at Wheal Jane was re-started, and were subsequently transferred to Wheal Jane No. 2 Shaft (see Section 4). This effectively lowered the water level in the mine and significantly reduced the amount of untreated minewater flowing from Nangiles Adit.

3.3 THE CHEMISTRY OF WHEAL JANE MINEWATER

During the dewatering of mine workings, sulphide minerals (principally pyrite) are exposed to air and water, conditions which promote the oxidation of sulphides and the resultant generation of acidity. It is not necessary in this context to address in detail the complex chemical reactions which are involved in the production of acidic minewaters and which may vary depending upon the specific geochemical environment present in different environments. Excellent reviews of this topic are given elsewhere (Refs. 1 & 2). However, it is appropriate to consider the basic reactions involved, which can be summarised as (Ref. 3):

$$FeS_2 + 3\tfrac{1}{2}O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad \text{(Reaction 1)}$$

$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \tfrac{1}{2}H_2O \qquad \text{(Reaction 2)}$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \qquad \text{(Reaction 3)}$$

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad \text{(Reaction 4)}$$

At a pH of below 4.5 the rate of Reactions 1, 2 and 4 is primarily a function of the activity of the bacteria, *Thiobacillus ferrooxidans*, which accelerate the pyrite oxidation process.

The most important consequences of these reactions are:

- The generation of acidity by the oxidation of pyrite (Reactions 1 and 4).
- The generation of additional acidity following the hydrolysis of ferric (and aluminium and manganese) ions (Reaction 3); it is for this reason that presence of these dissolved ions imparts mineral acidity to the minewater.
- The generation of elevated concentrations of other dissolved metal ions following the dissolution of metalliferous minerals (principally cadmium, zinc, copper, manganese and arsenic) and aluminium silicates in the acidic minewater.

The recovery of groundwater levels within the abandoned workings leads to the accumulated products of pyrite oxidation being flushed from the system. The resultant mine drainage is typically highly acidic and contains high concentrations of dissolved metals and sulphates.

Both the initial release from Jane's Adit in November 1991, and the subsequent much larger release of minewater from Nangiles Adit in January 1992, were characterised by low pH and high concentrations of dissolved metals (see Table 3-2).

Table 3-2 : The Quality of Minewater Releases from Jane's and Nangiles Adits (Ref. 4)

	Jane's Adit (November, 1991)	Nangiles Adit (January, 1992)
pH	2.8	2.6 - 3.1
Aluminium	no data	170 - 197
Arsenic	no data	26 - 29
Cadmium	0.8 - 1.6	1.4 - 1.9
Copper	15 - 19	14 - 18
Iron	232 - 975	1 720 - 1 900
Lead	no data	0.2 - 0.3
Manganese	no data	11 - 25
Nickel	no data	4.2 - 5.1
Zinc	346 - 819	1 260 - 1 700

All data, except pH, expressed as mg/l dissolved metal.

3.4 LEGAL CONSIDERATIONS

The historic difficulty in achieving the EQS specified under EC Directives in the Carnon River and parts of the estuary have long been recognised by the NRA. The release of minewater in January 1992 served to highlight this long standing problem. The deterioration in the quality of the Carnon River was of particular concern because of the potential implications for the Fal Estuary.

In order to minimise the short-term impacts of the release of minewater, and to alleviate public concern, the NRA decided to exercise its statutory powers under Section 161 of the Water Resources Act 1991. This entailed resuming and progressively improving a temporary treatment system (see Section 4) and evaluating the options for long-term treatment (see Section 14).

Legal advice was sought on whether or not a prosecution could be sustained against the mine owners under Section 85(1) of the Water Resources Act 1991. It was accepted that the Wheal Jane workings were only a part of a whole series of interconnected mines which contributed to the inflows into Wheal Jane. Consequently, it would be difficult, if not impossible, to identify the extent to which the contaminated minewater might have arisen from the workings under the control of Carnon Consolidated Ltd (now South Crofty plc). As such, the mine owner could not be said to have "caused" the pollution.

The Company also had the benefit of the defence offered by Section 89(3) of the Act relating to water flowing from an abandoned mine to the offence of "knowingly permitting" the release of the untreated water. Likewise, the NRA could not claim reimbursement of expenses incurred by exercising its antipollution powers under Section 161 because of a similar defence offered by Section 161(4).

As a consequence of this legal advice, the NRA decided to approach the problem of the release of untreated minewater in cooperation with the mine owners. In this respect, South Crofty plc have proved to be both cooperative and helpful in attempting to minimise the impact of the minewater release.

3.5 POST-INCIDENT MONITORING

Following the initial release of minewater from Nangiles Adit on January 13, 1992, the NRA reviewed the water quality and biological monitoring programmes to facilitate:

- An assessment of the impact of the release of minewater on the Carnon River and the Fal Estuary.
- The management of the existing treatment system.
- The consideration of appropriate Water Quality Objectives for any long-term treatment strategy.

Details of the monitoring arrangements are summarised in the following paragraphs.

3.5.1 Meteorological Data

Rainfall data is available from four locations (see Figure 3.1):

- Trevince, comprising daily records collected by the Meteorological Office since 1952.
- Wheal Jane, comprising daily records (except for Sundays and Public Holidays which are included in the succeeding day's total) collected by South Crofty plc since 1971.
- Bissoe Bridge, comprising daily records collected automatically by the National Rivers Authority since 1992.
- United Mines Landfill, comprising limited data from September 1992 collected by County Environmental Services Ltd.

Data on evaporation losses in the area are available from The Meteorological Office Rainfall and Evaporation Calculating System (MORECS).

3.5.2 Groundwater Monitoring

Groundwater levels have been monitored at a series of wells, shafts and boreholes. The use of the numerous old mine shafts in the area to monitor and sample groundwater has been constrained by the past necessity to cap these shafts for safety reasons.

3.5.3 Hydrological Monitoring in the Carnon River

A network of hydrological monitoring stations has been developed by the NRA (see Figure 3.1).

This network comprises:

- A series of four principal sites on the Carnon River system - at Twelveheads, Trehaddle (on Hick's Mill Stream), Bissoe Bridge and Devoran Bridge. Each station is equipped with an automatic water level recorder providing 15-minute interval flow data. The Devoran Bridge and Bissoe Bridge stations have recently been improved, by the construction of new gauging facilities, to overcome problems resulting from the effects of high tides and complex channel profiles.

- A series of secondary sites used for intermittent flow recording.

- Stations at the portals of the two major adit systems currently contributing flow to the Carnon River - Nangiles and County Adits (Jane's Adit is plugged at present and Wellington Adit has negligible flow).

3.5.4 Water Quality Monitoring in the Carnon River

Twenty five locations within the Carnon catchment are monitored for a wide range of parameters, including metals, major anions and pH (see Figure 3.2). These locations include seven routine sampling points, four consented discharges and 14 non-routine sampling points.

3.5.5 Estuarine Water Quality Monitoring

Estuarine water quality is monitored at 10 routine locations and nine investigational sites within the Fal Estuary, comprising four sites in Restronguet Creek, one in Mylor Creek, two in the Penryn River, three in the Percuil River, one in the Fal River and eight in Carrick Roads (see Figure 3.3).

3.5.6 Sediment and Biological Monitoring

Biological monitoring of the Carnon Catchment is routinely undertaken at the seven routine sampling points (see Figure 3.2).

Figure 3.1 Hydrological and Meteorlogical Monitoring Locations in the Carnon Catchment

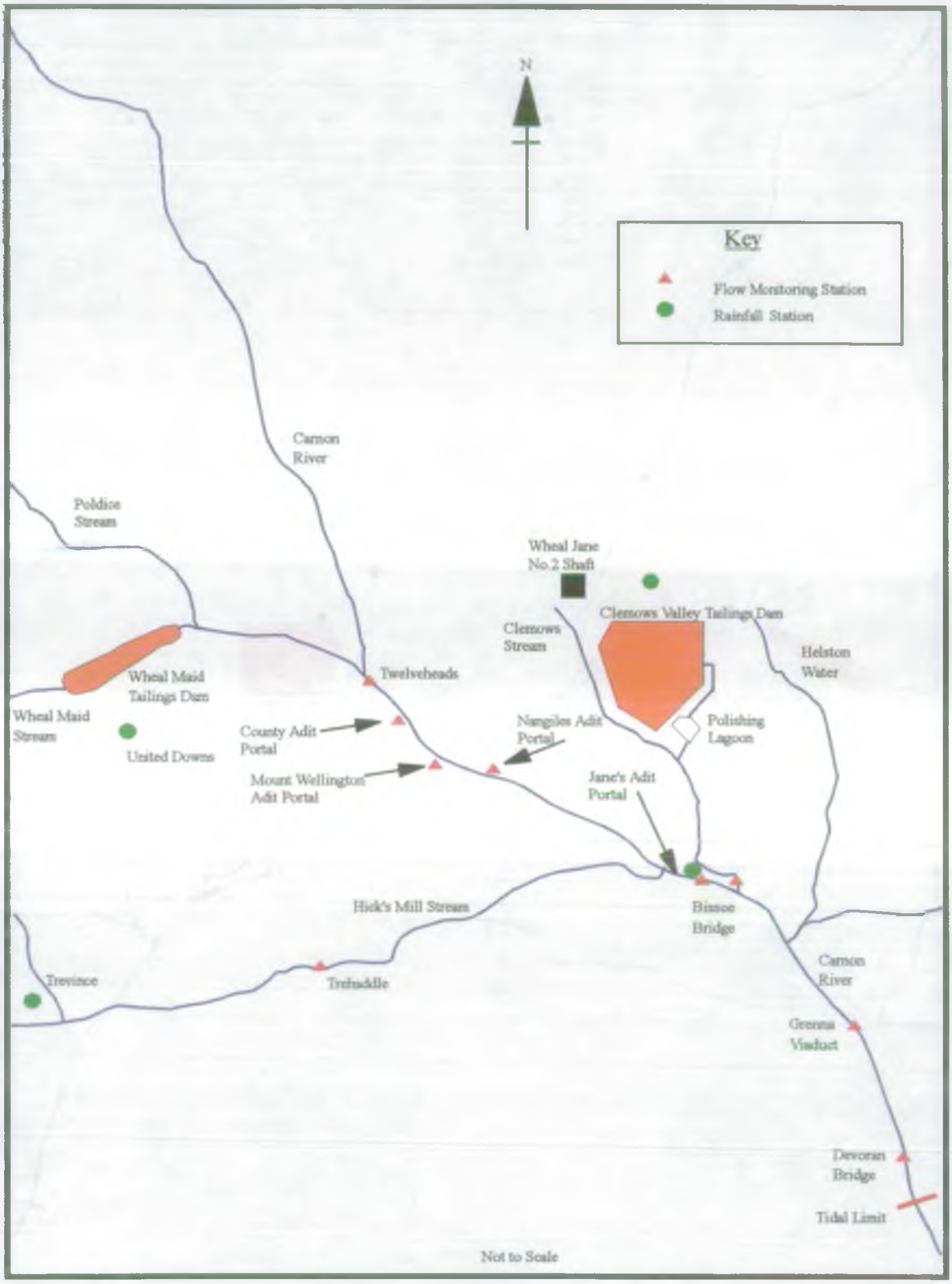


Figure 3.2 Water Quality Monitoring Locations in the Carnon Catchment

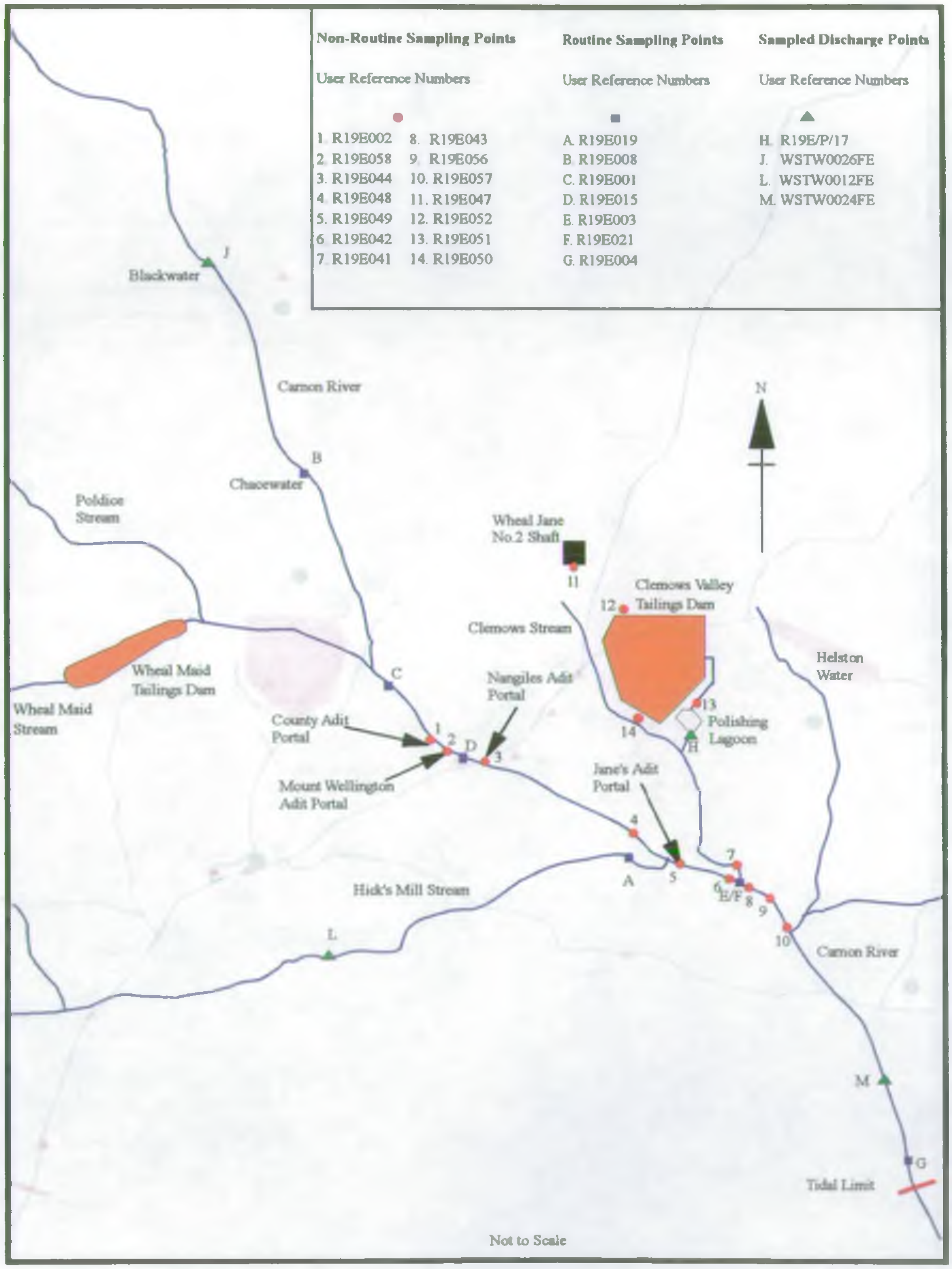
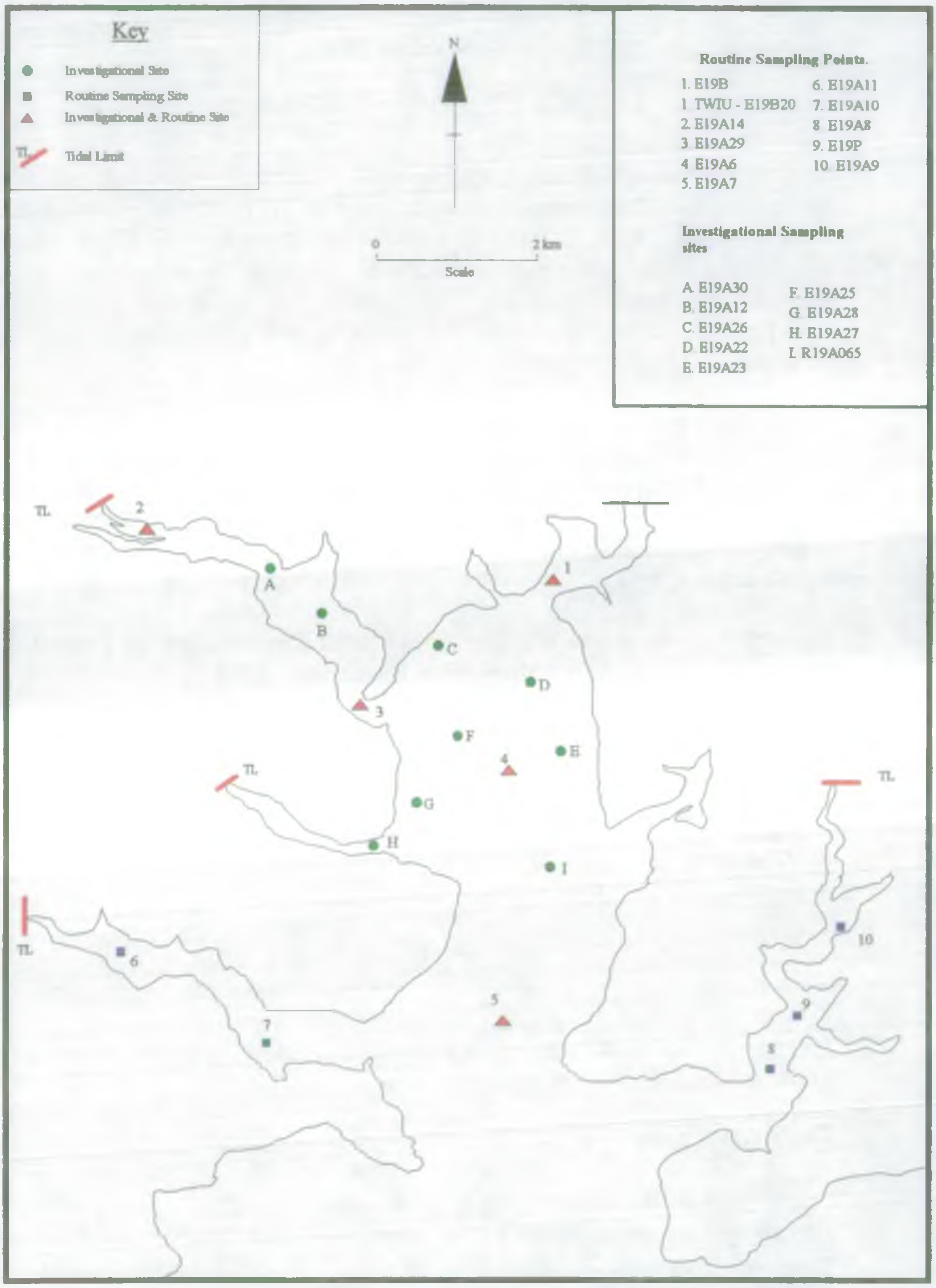


Figure 3.3 Estuarine Water Quality Monitoring Locations



In the Fal Estuary, surveys of metal concentrations in sediments were undertaken in January, February and May, 1992. Brown algae were sampled for metal analysis and biological sampling was carried out in Restronguet Creek by visual inspection and core sample analysis in March, May and July, 1992.

3.6 THE IMPACT ON THE CARNON RIVER

3.6.1 Water Quality

Water quality in the Carnon River has been affected adversely by mining activity for many years and, even prior to the release of minewater from Jane's and Nangiles Adits, the river failed to meet Environmental Quality Standards (EQS) at Devoran Bridge for a number of metals, namely arsenic, cadmium, copper, iron and zinc (see Section 2). Nevertheless, the release of minewater from Nangiles Adit, in particular, had an immediate and significant deleterious impact on water quality in the river.

Metal concentrations in the Carnon River at Devoran Bridge showed a rapid and substantial increase followed by a more gradual decline as the initial flow rate subsided and treatment of the minewater was resumed (see Figure 3.4). At their peak, concentrations of several metals in the Carnon River were an order of magnitude greater than had been recorded previously and EQS at Devoran Bridge were exceeded typically by several orders of magnitude (see Table 3-3).

Table 3-3 : Peak Metal Concentrations at Devoran Bridge following the Release of Minewater from Nangiles Adit

	Peak Metal Concentration (January 14, 1992)	Environmental Quality Standards
pH	3	6 - 9
Arsenic	6 000	50
Cadmium	600	1
Copper	7 000	28 (D)
Iron	600 000	1 000 (D)
Nickel	1 200	200
Zinc	440 000	500

All data, except pH, expressed as $\mu g/l$ total metal.
All EQS values for metals expressed as annual average total concentrations unless indicated by (D) for dissolved.

3.6.2 Flora and Fauna

The impact of the release of untreated minewater from Nangiles Adit on an already greatly impoverished river ecosystem (see Section 2) is difficult to quantify. Although concentrations of many metals in the Carnon River were increased dramatically, the long term impact on the river itself was probably minimal. The most significant consequence of the release was the greatly increased metal loading which entered the Fal Estuary from the Carnon River.

3.7 THE IMPACT ON THE FAL ESTUARY

3.7.1 Water Quality

The release of untreated minewater into the Carnon River had a significant effect on water quality in the Fal Estuary. The pH in Restronguet Creek was temporarily lowered to 4.5 from approximately 6.5; metal inputs into the estuary from the Carnon River rose to 30 kg/day cadmium, 20 tonnes/day zinc and 30 tonnes/day iron. On January 15th, two days after the release from Nangiles Adit, concentrations of arsenic, cadmium, copper, iron, nickel and zinc exceeded EQS specified under both EC Directive 79/923 (the "Shellfish Waters Directive") and EC Directive 76/464 (the "Dangerous Substances Directive") at Turnaware Bar and throughout the western side of Carrick Roads, often by several orders of magnitude (see Figures 3.5, 3.6 and 3.7).

Despite the relatively rapid decline in the flow of minewater from Nangiles Adit and a consequent reduction in the metal loadings entering the estuary, cadmium and zinc concentrations remained above EQS in the Carrick Roads throughout January 1992. Water quality improved steadily during February, March and April but it was not until October 1992 that concentrations had returned to the pre-incident level throughout the estuary (Ref. 5).

3.7.2 Discolouration of the Estuary

The most visible consequence of the release of untreated minewater was the widespread occurrence of a vivid orange brown discolouration in Restronguet Creek and the Carrick Roads (see Plate 1). This was caused by the formation of substantial quantities of an iron hydroxide precipitate (ochre) which was dispersed throughout the estuary.

Discolouration was first recorded in Restronguet Creek in early January, probably as a consequence of the earlier release of minewater from Jane's Adit. However, the much larger release from Nangiles Adit resulted in discolouration which extended throughout Restronguet Creek, the western side of Carrick Roads and out into Falmouth Bay. By January 16, the sea area off Pendennis Point had become a distinctive orange brown colour which, at its extreme, almost reached the Helford Estuary to the south-west (see Figure 3.8). The discolouration persisted throughout the remainder of January and into February. However, by mid-February the discolouration was absent from Carrick Roads, except at low tide, and by mid-March improvements were noted in Restronguet Creek.

The discolouration had a serious and detrimental effect on the aesthetic quality of the whole estuary and became the focus of intense public and media attention.

Photograph 3.1 Pollution Plume in Carrick Roads

Figure 3.4a Water Quality at Devoran Bridge

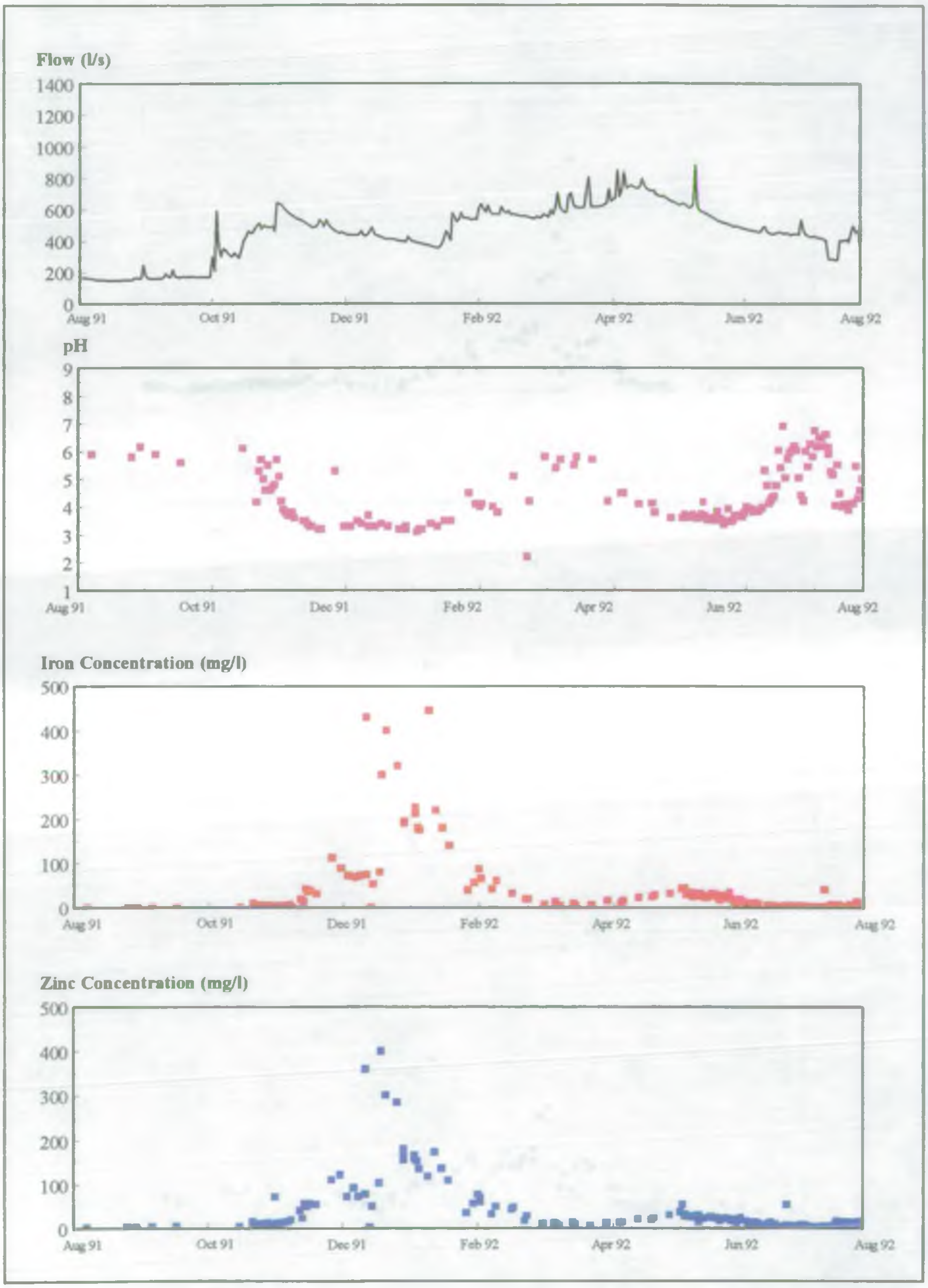


Figure 3.4b Water Quality at Devoran Bridge

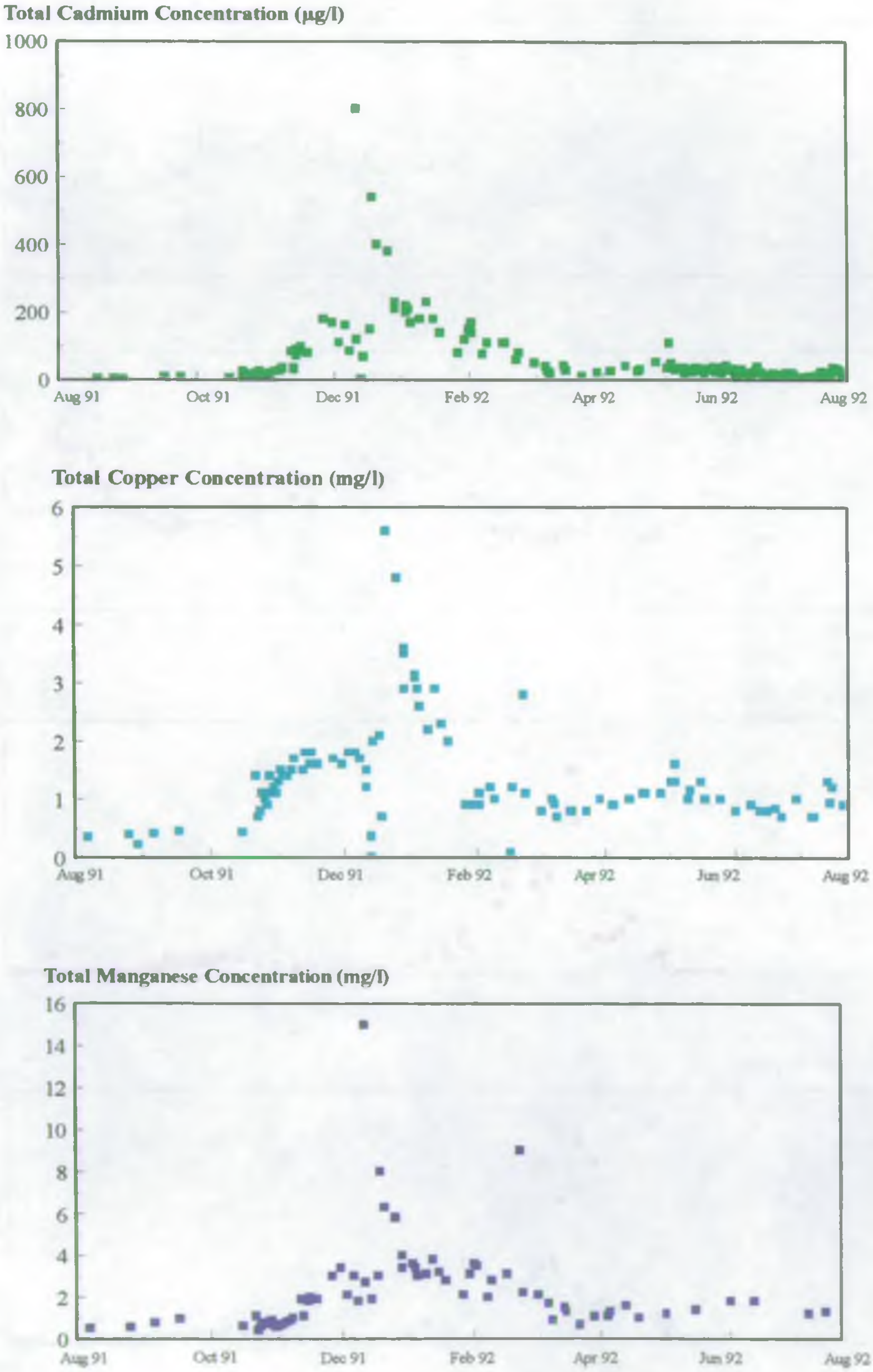


Figure 3.5 **Dissolved Zinc Concentrations (µg/l) in Restronguet Creek and Carrick Roads. Tidally Averaged, Surface Data.**

EQS = 40 µg/l under the Dangerous Substances Directive

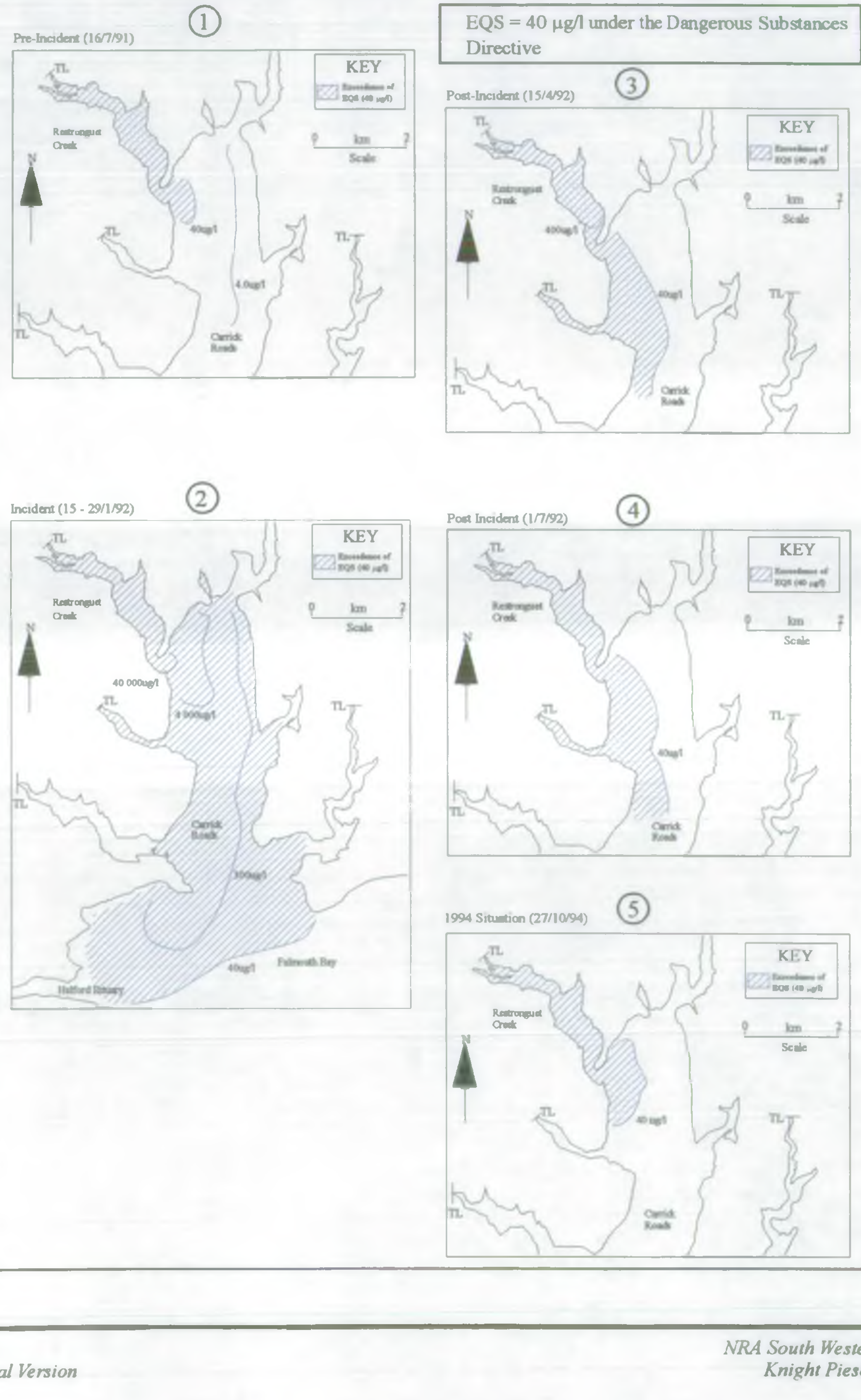


Figure 3.6 **Dissolved Copper Concentrations (µg/l) in Restronguet Creek and Carrick Roads. Tidally Averaged, Surface Data.**

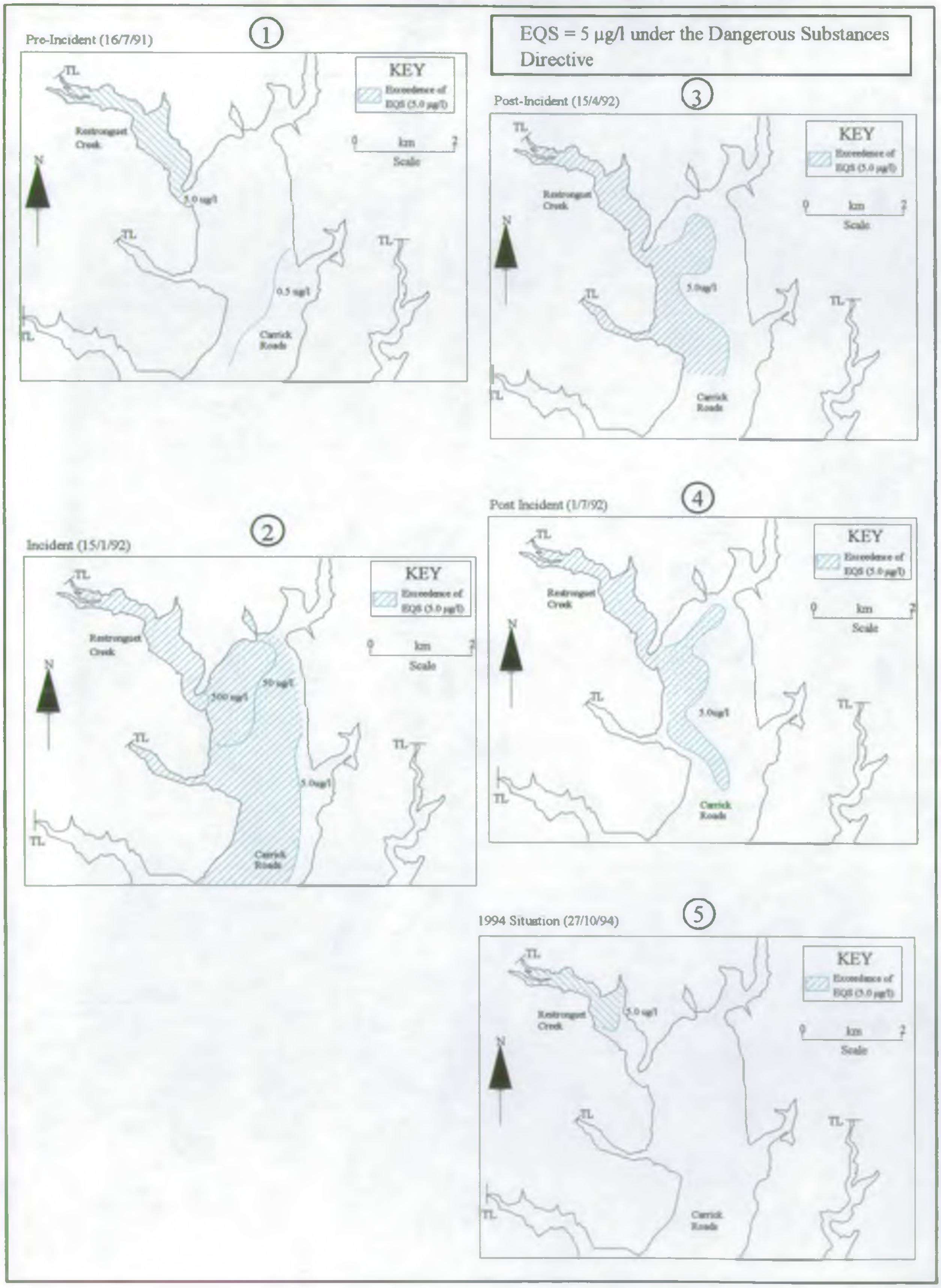


Figure 3.7 **Dissolved Cadmium Concentrations (μg/l) in Restronguet Creek and Carrick Roads. Tidally Averaged, Surface Data.**

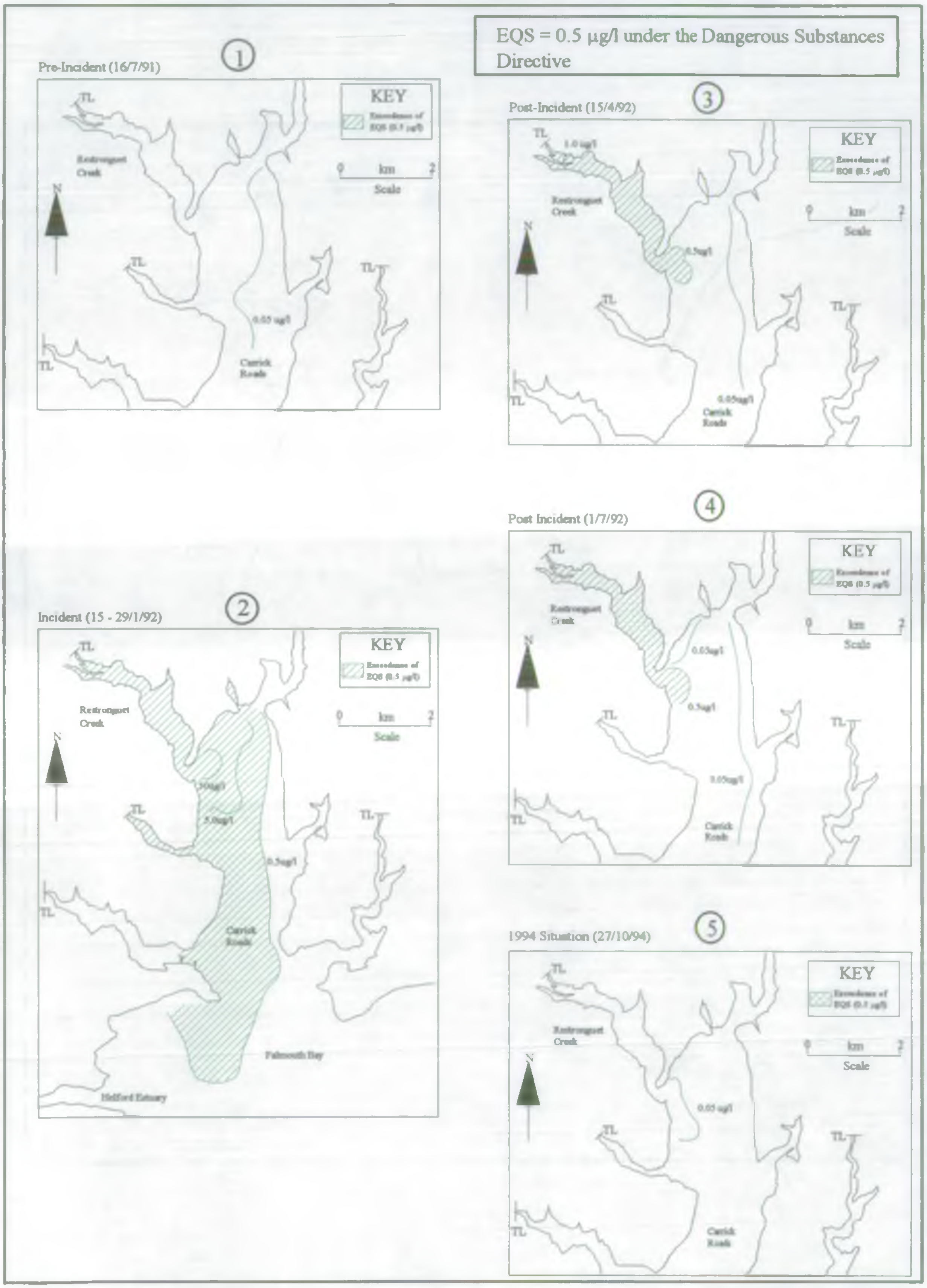
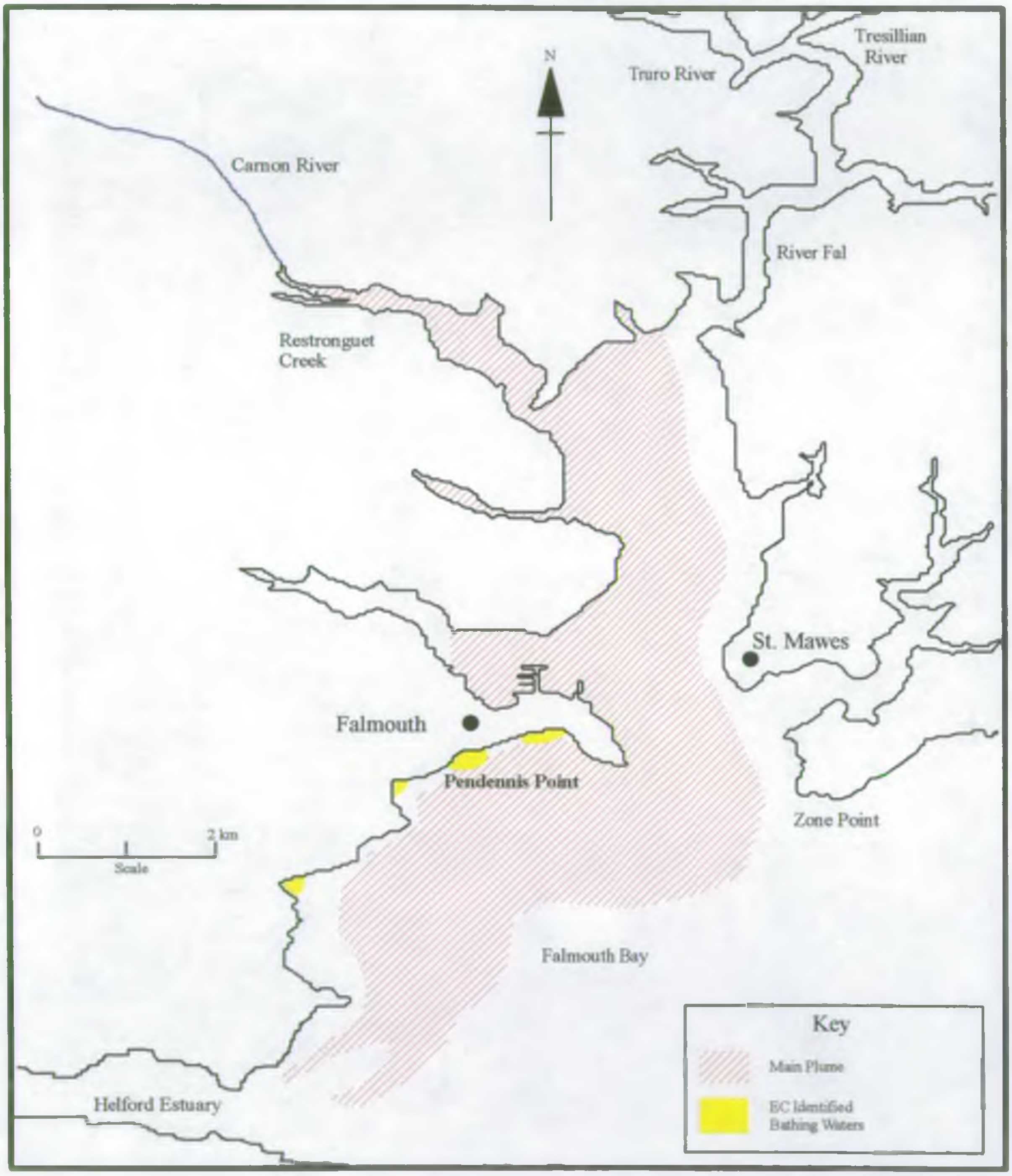


Figure 3.8 **Maximum Extent of Iron Discolouration. 16/1/92**



3.7.3 Effects on Sediment Metal Concentrations

The metal concentration in sediments in Restronguet Creek and much of Carrick Roads has been elevated as a consequence of both the geological conditions and mining activity over many years. In addition, sediment metal concentrations tend to be highly variable, reflecting local conditions of deposition and remobilisation of sediments and precipitates. A brief survey of sediment metal concentrations did not reveal any consistent trend in metal concentrations in response to the release of minewater. However, there was limited evidence of temporary localised increases in some samples from Restronguet Creek.

3.7.4 Flora and Fauna

- *Restronguet Creek*

Even prior to the release of minewater, the flora and fauna of Restronguet Creek was impoverished due to both the high sediment loading and metal inputs which resulted from many years of mining activity. The head of Restronguet Creek supports only two species of benthic macro-invertebrates (*Nereis diversicolor and Scrobicularia plana*), both of which have been shown to develop metal tolerance (Ref. 6) and hence are unlikely to have been affected by the increase in estuarine metal concentrations.

In contrast, the mouth of the creek supports 24 species of macro-invertebrate. Some of these species were adversely affected by the incident, with a high proportion of the Northern Barnacle population (*Balanus balanoides*) around Restronguet Creek being killed (Ref. 7), probably as a consequence of being smothered by the iron precipitate rather than the direct toxic effect of copper and zinc.

However, recruitment of the Australian Barnacle (*Elminius modestus*) was rapid and a barnacle population was soon re-established. An increase in mortality among juvenile cockles was also observed in January, 1992, although this was only temporary.

The saltmarsh flora were unaffected by the incident.

- *Carrick Roads*

In general, the flora and fauna of the Carrick Roads do not appear to have been significantly affected by the temporary increase in estuarine metal concentrations (Ref. 8). There were no adverse effects on the health of subtidal beds of the rare Eel Grass *(Zostera)*.

3.7.5 Long-term Effects

Although the acute affects of the incident on the flora and fauna of the estuary appear to have been minimal, concern has been raised over the potential effects of chronic (long-term) exposure to certain metals. A number of issues have received particular attention, including:

- *Zinc Accumulation in Oysters*

  Routine monitoring of metal levels in the oysters (*Ostrea edulis)* from near the entrance to Restronguet Creek has been undertaken by the Ministry of Agriculture, Fisheries and Food. The data suggest that concentrations of zinc in the oysters have not changed as a consequence of the release of untreated minewater and the reproductive capacity of the oyster community does not appear to have been adversely effected. At no time has MAFF advised that the recorded zinc concentrations in oysters would render them unfit for consumption.

- *Metal Accumulation in Brown Algae*

  Copper and zinc concentrations in the brown alga *Fucus vesiculosus* have been widely used as an indicator of long-term exposure to elevated metal concentrations in the Fal Estuary (Ref. 9).

  Samples of algae taken from Restronguet Creek during July, 1991 (i.e. pre-incident) were found to contain metal concentrations elevated above "normal" background, as might be expected given the historically elevated metal loadings entering the creek. However, repeat sampling in the spring and summer of 1992 (i.e. post-incident) revealed a further increase above the already elevated concentrations (see Table 3-4). Concentrations have since declined, but more recent data are incomplete.

Table 3-4 : Metal Concentrations in Samples of Brown Algae from Restronguet Creek

	Cadmium	Copper	Iron	Zinc
Control Site:				
Falmouth Beach	0.6	9	no data	244
Pre-incident:				
July 1991	3.2	150	222	774
Post-incident:				
March 1992	1.0	270	2958	869
May 1992	1.5	259	5117	2226
July 1992	1.4	204	1706	2020

All data expressed as mg/kg dry weight

- *Mortality in Swans*

  Post mortem analysis of swan tissue from birds which died during the winters of 1993 and 1994 revealed the presence of elevated levels of lead and zinc in the pancreas and liver.

  Although there is no direct evidence to link the swan deaths with elevated metal concentrations (irrespective of the possible source), research is continuing into the possible causes of the deaths and any relationship with the temporary increase in estuarine metal concentrations.

- *Changes in Species Composition*

  The observation that increased mortality in populations of the Northern Barnacle was followed by rapid recruitment of the Australian Barnacle has raised the possibility that the species composition of the barnacle population may have been fundamentally altered.

3.8 SUMMARY

Wheal Jane was the last of the operational mines in the Carnon Valley and its closure in 1991 resulted in the recovery of groundwater levels throughout the valley as the interconnected mine workings gradually flooded. The acidic metal contaminated minewaters finally reached adit level in late 1991 and, following the failure of the plug in the Nangiles Adit in January, 1992, there was a major release on minewater into the Carnon River.

Despite the poor quality of the Carnon River, the release of minewater had an immediate deleterious impact on water quality in the river. Environmental Quality Standards for a range of metals, including principally arsenic, cadmium, copper, iron and zinc were exceeded, typically by several orders of magnitude.

The effect on the Fal Estuary was similarly dramatic. Environmental Quality Standards were exceeded in Restronguet Creek and throughout the western side of Carrick Roads. The most visible impact was the widespread discolouration of the estuary caused by the precipitation of iron hydroxides. The contamination was perceived to be a threat to the ecology of the estuary, the commercial oyster fishery and to the tourist trade.

Mindful of the environmental and economic importance of the Fal Estuary, the NRA decided to exercise its statutory powers under Section 161 of the Waters Resources Act and implement a treatment strategy designed to reduce the flow of untreated minewater from Wheal Jane. This treatment system has successfully restored water quality to pre-incident levels and effectively prevented the long-term deterioration in water quality. As a result, the impact of the incident on the biota of the Fal Estuary appears to have been minimal and the deterioration in the water quality short-lived.

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4

4. EXISTING TREATMENT SYSTEM

CONTENTS

Photograph 4.1 Wheal Jane No. 2 Shaft and Lime Dosing Plant

Photograph 4.2 Discharge of Treated Minewater into the Clemows Valley Tailings Dam

4.1 EXISTING TREATMENT SYSTEM OBJECTIVES

The existing treatment system was implemented by the NRA, with the cooperation of the mine owners, as an emergency response to the release of contaminated minewater into the Carnon River. The primary objective was to minimise the environmental impact on the Carnon River by treating as much minewater as possible.

As the treatment system developed, operating guidelines were put in place by the NRA to enable the operatives to manage the system. In essence, these comprised:

- The treatment of the maximum quantity of minewater practicable.
- Compliance with the target pH values set for key locations throughout the system.

Details of the target pH values are summarised in Table 4-1 and the location of the monitoring probes are shown on Figures 4.1 and 4.2.

Table 4-1 : Existing Treatment System Target pHs

Location	Probe No.*	Target pH		Notes
		Objective	Acceptable Range	
Inlet to dam	2	9	8.5 - 9.5	When mill operating.
		9.5	9.0 - 10.0	May be required when the mill is not operating.
		-	10.0 - 11.0	When mill is closed and toe drain volume is high.
Dam decant	5	>8	8.5 - 9.0	
		-	10.0 - 11.0	When mill is closed and toe drain volume is high
Polishing lagoon	6	7.5 - 8.0	<9	Consented discharge into Clemows stream

*Location of probes shown on Figures 4.1 to 4.2.

Figure 4.1 Temporary Treatment System Layout

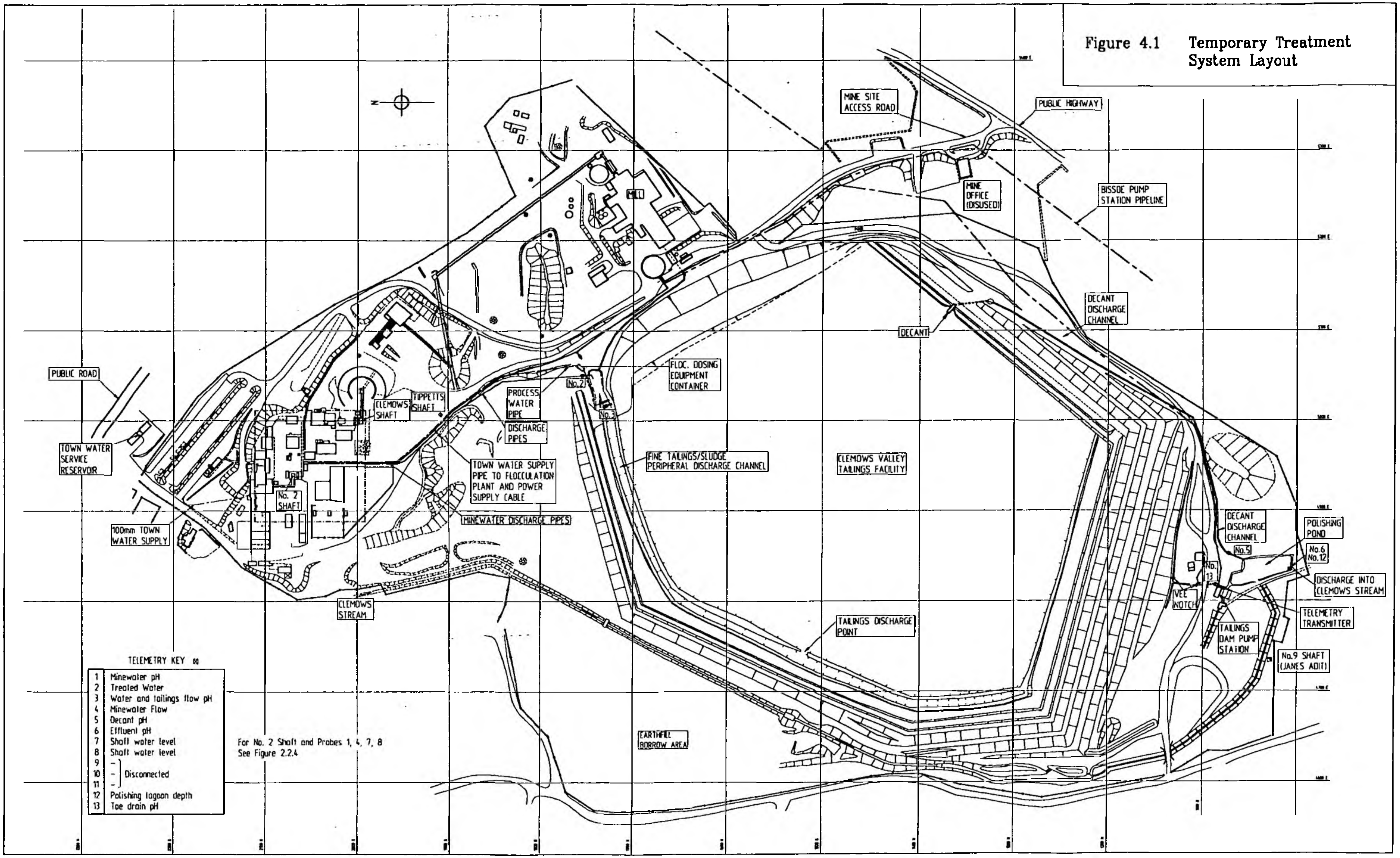
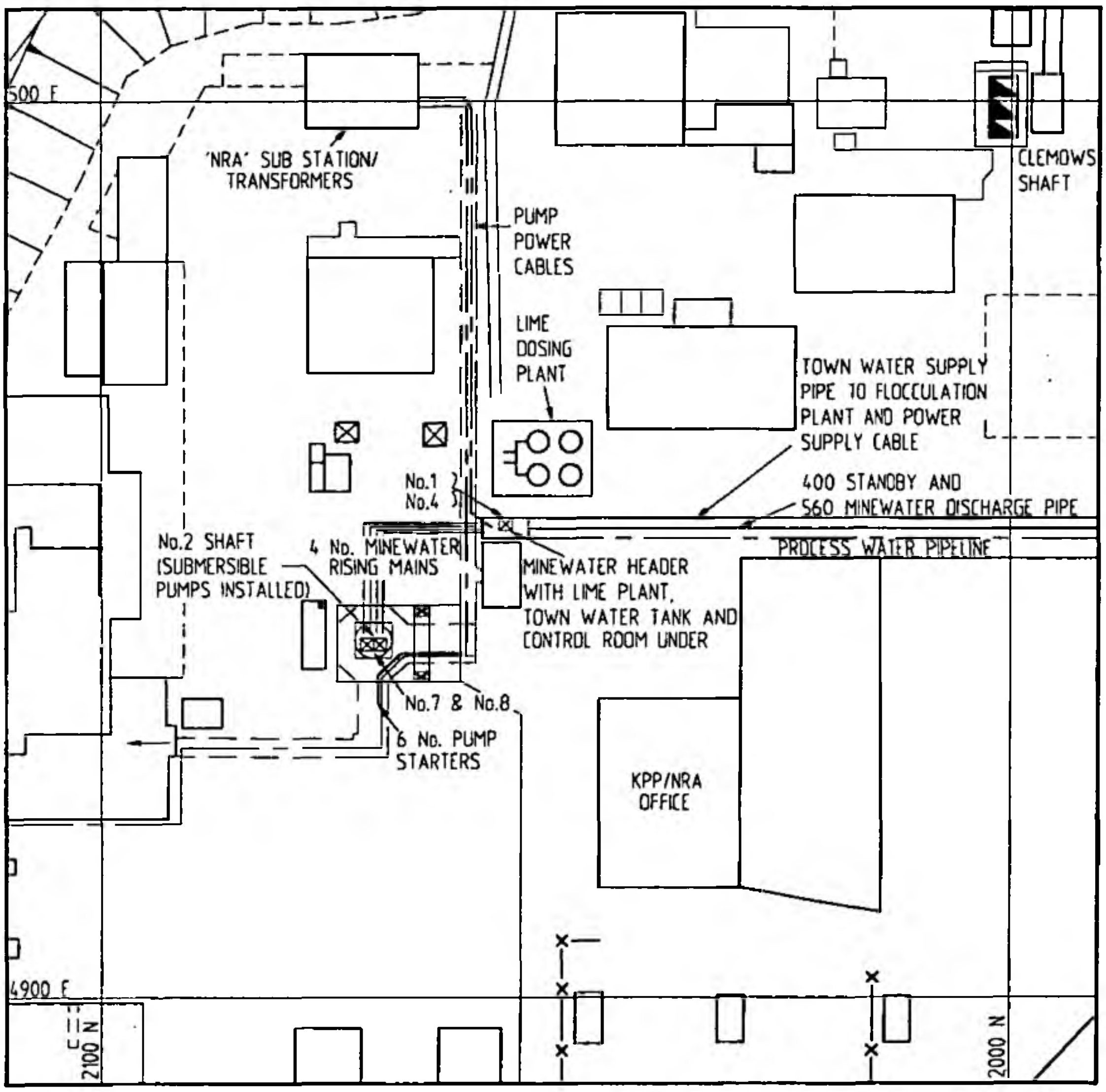


Figure 4.2 No. 2 Shaft – Site Plan



FOR TELEMETRY KEY REFER TO Figure 2.2.3

Table 4-2 : Existing Treatment System Key Dates

Period	Pump Installation	Operating Installed Capacity l/s			Average Flow Treated l/s	Notes
		No. 9 Adit Shaft	No. 2 Wheal Jane	Total Installed		
16/11/91 - 4/1/92	Submersible Pump operating in No. 9 Adit Shaft	58	-	58	58	16/11/91 Lime dosing commenced into the adit
4/1/92 - 13/1/92	Pumping Stopped	-	-	-		13/1/92 Nangiles Adit plug burst
13/1/92 - 14/2/92	Submersible Pump operating in No. 9 Adit Shaft	58	-	58	58	
14/2/92 - 28/2/92	Submersible Pumping from both adit and Wheal Jane	58	58	116	116	14/2/92 Mine site lime dosing commenced
28/2/92 - 23/10/92	2 Pumps operating at Wheal Jane. Adit pump removed	-	116	116	116	
23/10/92 - 6/94	3 Submersible Pumps operating at Wheal Jane	-	174	174	156	18/2/94 New lime dosing plant commissioned
6/94 - onwards	6 Borehole pumps installed in Wheal Jane. Total Capacity 300 l/s	-	300*	300*	155	average 1993-94

* Could be increased to 315 l/s by reconfiguring the discharge pipework

4.2 TREATMENT METHOD

The treatment process developed at Wheal Jane was relatively simple, and involved the following processes:

- Pumping of minewater from underground.
- The addition of slaked lime to neutralise the acidic water, resulting in the precipitation of metal hydroxides (sludge).
- Flocculation to promote rapid settlement of the metalliferous precipitate.
- Sedimentation and storage of the resultant metal hydroxide sludge.

Crucial to the implementation of the emergency treatment system was the availability of the Clemows Valley Tailings Dam for metalliferous sludge storage. The treatment system, therefore, has been developed to ensure both efficient removal of the metals precipitated from the minewater and the effective operation of the tailings dam.

In addition to allowing the use of the tailings dam for sludge deposition, the mine owners, South Crofty plc, provided staff and technical assistance in implementing the treatment system.

4.3 TREATMENT SYSTEM DEVELOPMENT

The development of the emergency minewater treatment system was started by the mine owner and the NRA in early November 1991. Details of the principal dates in the implementation of the system are summarised on Table 4-2. Subsequently the system has been subjected to continuous appraisal and, where appropriate, upgraded to provide cost-effective treatment, as outlined in the following subsections.

4.3.1 Phase 1 Treatment

The initial treatment scheme involved the addition of lime to the adit and the recovery of some 58 l/s of treated water using a submersible pump installed in No. 9 Adit shaft. Water recovered from the adit was pumped into the Clemows Valley Tailings Dam where the precipitated metalliferous sludge settled out of suspension.

This treatment system, albeit rapidly implemented, suffered a number of significant disadvantages, namely:

- The pumping capacity was insufficient to control the water level within the mine.
- The pH of the treated water was difficult to control.

- The addition of lime to raise the pH increased the risk of blocking the adit with precipitated metalliferous sludge.
- The discharge pipe from the pump ran up the face of the dam and, in the event of a pipe burst, could have seriously eroded the dam wall.
- Pumping the treated minewater into the dam tended to break up the hydroxide particles making sedimentation in the tailings dam difficult.

4.3.2 Phase 2 Treatment

Following the failure of the Nangiles Adit plug, treatment recommenced and additional funding was made available to upgrade the system. Treatment operations were transferred from the adit to Wheal Jane No. 2 Shaft (one of the two shafts that previously served the mine) as this offered the following advantages:

- Sufficient space to allow the installation of additional pumps. A second pump was installed and commissioned on February 14, 1992, thereby increasing the pumping capacity to 116 l/s.
- Use of the mine lime storage and slurry preparation facility for dosing purposes.
- Complete mixing of the treated water with the fine tailings effluent stream to enhance sedimentation.
- The addition of a long chain anionic polymer flocculant to the tailings/minewater mixture to further aid sedimentation.
- Dosing of the water at surface rather than underground, thereby avoiding the break-up of the naturally flocculated metal precipitates by the pump impellers.
- Reduced risk of obstructing the adit with sediments.

4.3.3 Phase 3 Treatment

In common with most tailings dams, the Clemows Valley Tailings Dam is stage constructed with the dam raised annually to provide sufficient storage for the next 12 months. Neither the need for minewater treatment nor the volume required for the storage of the metalliferous sludge had been foreseen when the 1991 dam raising works were carried out. Consequently only sufficient capacity had been made available to store the tailings produced from ore processing during 1991/1992.

The introduction of the low density metalliferous sludge from minewater treatment resulted in a significant increase in the rate of filling and raised the possibility of the dam running out of storage. South Crofty plc commissioned a report (Ref. 1) on the effect of sludge deposition on the operation and capacity of the dam. This report was submitted in April, 1992 and recommended both modification of the operating regime and the provision of additional storage to accommodate the anticipated volume of sludge. As a result of the work carried out during the summer of 1992, sufficient additional storage was created to allow the pumping rate to be increased to at least 174 l/s.

4.3.4 Phase 4 Treatment

Following the initial development of the existing treatment system, the technical performance of each component was assessed. Where necessary system components were either modified or replaced. In particular the following modifications were made:

Pumping system	-	Installed capacity increased from 174 l/s to 300 l/s.
Lime dosing	-	New plant installed and lime purchase price reduced by competitive tender.
Discharge to dam	-	Installation of a standby discharge pipe to the tailings dam.
Flocculant	-	An alternative flocculant selected following performance testing and the submission of tenders.
Clemows Valley Tailings Dam	-	Deposition and construction techniques modified to ensure the safe, efficient deposition of both tailings and metalliferous sludge.

As a result of both the reducing metal concentrations and the modifications made to the treatment system the annual operating costs reduced from approximately £1 500 000/yr in 1992 to an estimated £750 000/yr in 1995.

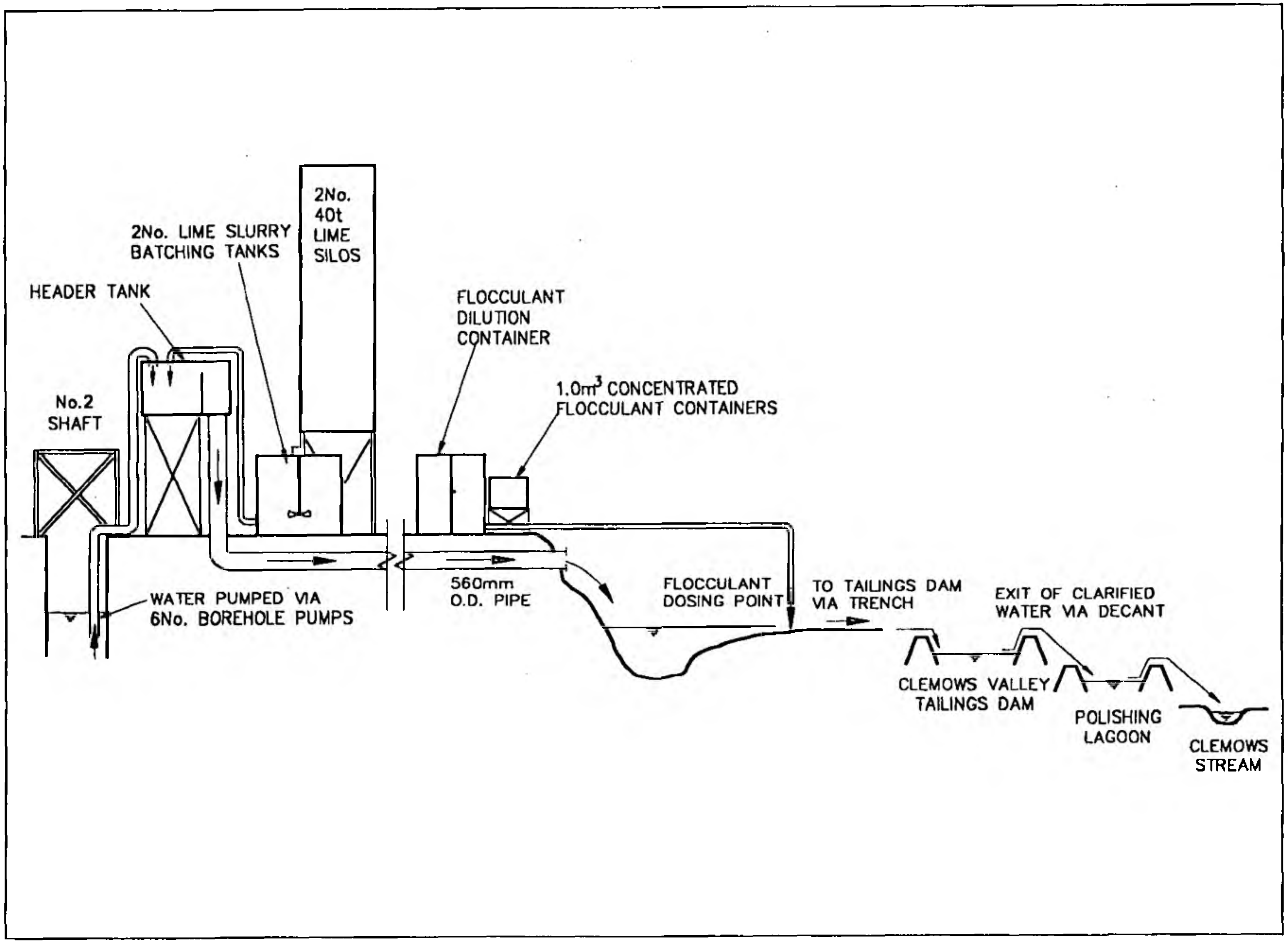
4.4 PLANT DESCRIPTION, OPTIMISATION AND PERFORMANCE

The layout of the existing treatment plant is shown in Figures 4.1 to 4.3.

The modified treatment system comprises the following principal components:

- Six submersible pumps installed in Wheal Jane No. 2 Shaft.
- Two 40 t capacity lime silos, two slurry conditioning tanks and a pH controlled automatic dosing system.
- 20 m^3 capacity header tank/reaction vessel.
- Duty and standby discharge pipes to the Tailings Dam.
- Flocculant dosing station.
- Clemows Valley Tailings Dam.
- Polishing lagoon.

Figure 4.3 Temporary Minewater Treatment System



A detailed description of the design, selection, optimisation and performance of each system component is presented in the following subsections.

4.4.1 No. 2 Shaft Pump Installation

The initial treatment strategy for minimising the impact on the Carnon River required a pumping regime which, whenever feasible, prevented the release of untreated water via Nangiles Adit. In an attempt to achieve this objective, the pumping capacity was increased from 58 l/s in February 1992 to 174 l/s in October, 1992, by the installation of a futher two heavy duty submersible pumps in No. 2 Shaft. Further uprating of the pumping capacity was initially prevented by:

- Spatial constraints within the shaft, which prevented the installation of additional heavy duty submersible pumps.
- The apparent inability of other pump manufacturers to supply an alternative unit capable of operating in acidic, heavy-metal laden ground water.

Although the installed submersible pumps were fitted with special acid resistant stainless steel impellers, the units initially tended to fail after approximately three months service and consequently, on average, one pump change took place every month.

To minimise pump corrosion, a small volume of lime slurry was discharged into the shaft to maintain a pH of at least 3.5 in the vicinity of the pumps. Shaft lime addition was achieved by a manually set dosing valve and was monitored by a pH probe linked to the telemetry system.

Groundwater inflows during the winter of 1992/93 demonstrated that the maximum pumping capacity of 174 l/s was unable to cope with all the water entering the mine. Flows in excess of the maximum pumping capacity drained via the Nangiles Adit, which at times of peak flow discharge up to 270 l/s of untreated water into the Carnon River. Untreated minewater continued to flow from the Nangiles Adit for a period of approximately six months in 1992 and eight months in 1993.

Further reduction in the volume of minewater released from the Nangiles Adit required an increase in the capacity of the pumping system installed in Wheal Jane No. 2 Shaft. Preliminary hydrogeological studies indicated that a pumping capacity of approximately 300 l/s would be required to minimise the discharge of excess minewater from Nangiles Adit. In addition to controlling the discharge from Nangiles Adit, upgrading the pumping arrangements proved advantageous in:

- Allowing the installation of more efficient pumps, thereby reducing the unit pumping cost.
- Enabling the quantity of water pumped to be varied in response to mine inflow.

Based on these objectives, tenders were issued in November, 1993, for the purchase of submersible pumps that:

- Could be installed in Wheal Jane No. 2 Shaft at a depth of some 50 m below ground level.

- Were resistant to corrosion by acidic water.

- Would enable up to approximately 300 l/s to be pumped.

After a full technical and financial adjudication of the returned tenders, a contract was awarded for the supply of seven stainless steel borehole pumps and associated electronic controllers. Six pumps were installed in No. 2 Shaft to provide the required pumping capacity, whilst the seventh was kept on site ready for immediate installation in the event of pump failure.

Installation of six borehole pumps in place of the existing units required the replacement of the shaft capping steelwork and construction of a new pump lifting frame. Steelwork erection was carefully programmed to ensure that existing treatment operations were not interrupted and, together with the installation of the new pumps, was completed in June, 1994. Since then, the pumps have operated without failure.

The pump installation arrangements are shown schematically in Figure 4.4. Each pump is suspended in the shaft by means of a collapsible 150 mm diameter plastic delivery pipe which terminates at the shaft access platform, some 3 m below surface. Water from the six pump delivery lines is transferred into 4 x 180 mm diameter HDPE pipes which discharge into a 20 m^3 elevated header tank.

The approximate discharge capacity of the system, together with details of the pump installation levels are shown on Figure 4.5. Although the capacity of the new pumps is slightly less than the previous units (55 l/s compared to 58 l/s), adoption of the pumping regime shown in Table 4-3 will maintain an average annual treatment capacity of approximately 155 l/s, which is slightly greater than the 151 l/s average achieved during 1993.

Table 4-3 : Proposed Outline Pumping Regime

Period	Months	No. Pumps Operational	Total flow (l/s)
Winter	4	3	165
Spring	2	3	165
Summer	4	3	165
Autumn	2	2	110
		Approximate Annual Average Flow	155

Figure 4.4 Schematic Diagram of Wheal Jane No.2 Shaft Pumping System

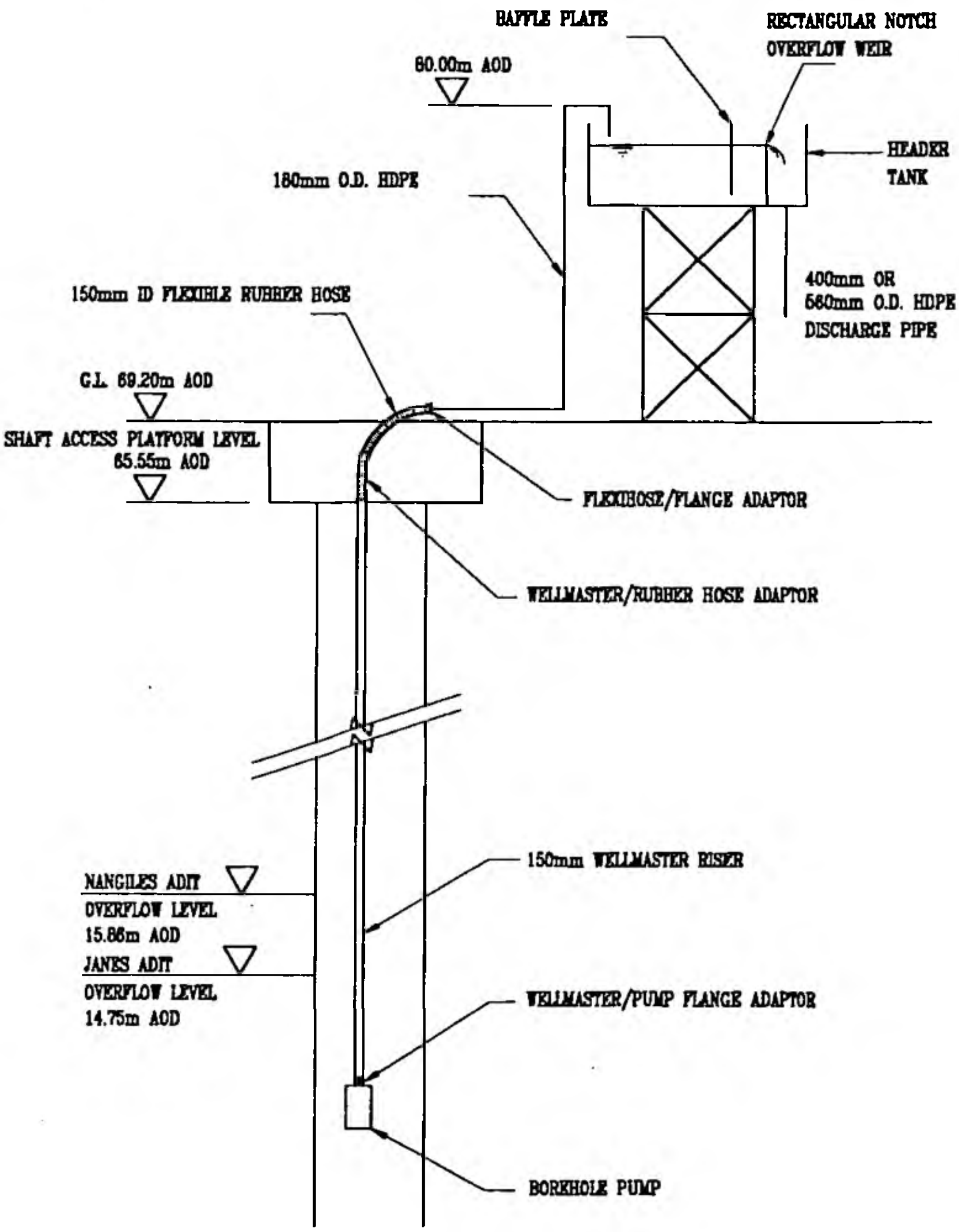
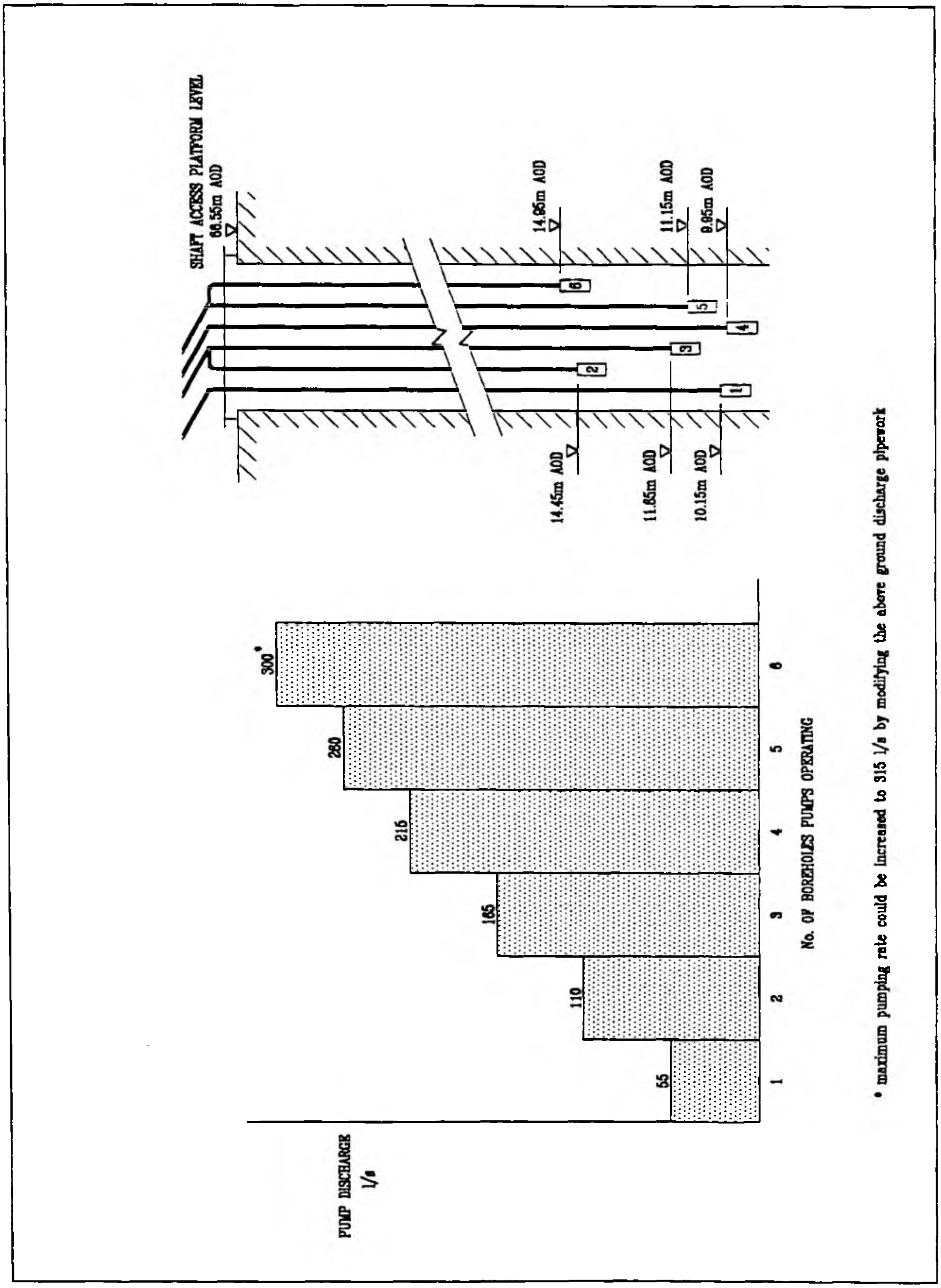


Figure 4.5 Wheal Jane No. 2 Shaft Pumping System. Capacity and Pump Installation Levels



The water level within the abandoned Wheal Jane Mine complex, over the last three years, has been maintained within a range of between 13 and 18 m above ordnance datum (AOD). This range has been dictated by:

- The lowest water level at which the pumps can be safely operated (10.5 m AOD).
- The level required for gravity drainage of excess flow out of Nangiles Adit.
- The water level necessary to drain Jane's Adit for inspection.

The lowest operating water levels occur during the late summer/early autumn when the quantity of flow into the mine is at a minimum. During this period the water level within the mine can be controlled satisfactorily by pumping at a rate of approximately 110 l/s.

The maximum water level occurs during late winter/early spring, when the inflow into the Wheal Jane/Nangiles mine complex peaks. The actual water level is dependent upon the number of pumps operating and the head required to drain any excess flow via Nangiles Adit and, therefore, varies with the preceding weather conditions.

4.4.2 Lime Dosing System

Lime was originally added in powder form into Jane's Adit. When pumping from the adit ceased, lime dosing began into the elevated header tank, located adjacent to Wheal Jane No. 2 Shaft.

Aqueous lime slurry is added to the minewater discharged into the header tank to raise the pH from approximately 3.5 to 9.5. The added lime neutralises the acidic minewater and reacts with the dissolved metals to form insoluble hydroxides, in accordance with the chemical reactions given in Appendix 4A.

The pH of the treated minewater is measured immediately prior to discharge into the dam and the recorded value used to adjust the quantity of lime slurry added.

The lime slurry introduced into the header tank was originally prepared using the old storage silo and mixer arrangement previously operated by the mine. This system, although offering significant benefits in comparison with the direct introduction of powdered lime into the adit, had the following disadvantages:

- The silo capacity was inadequate to ensure continuity of supply in the event of a delivery vehicle breakdown or inclement weather.
- The silo and mixer tank were of considerable age and, consequently, the system was prone to breakdown.

- The prepared lime slurry had to be pumped 100 m from the batching plant to the dosing point. Frequent restrictions and blockages of the pipework occurred due to the build-up of limescale.

- For operational reasons, it was necessary to stop lime dosing whilst the storage silo was refilled. This resulted in the cessation of dosing for up to an hour per day.

- The slurry concentration varied throughout the lime batching and mixing cycle, making it impossible to add lime to the minewater at a constant rate.

As a consequence of the limitations of the existing lime dosing system it was impossible to control accurately the pH of either the treated water released into the dam or the supernatant water removed from the decant. Consequently lime dosing was relatively inefficient with significantly more lime being added to the treated water than theoretically required.

To allow more efficient use of the lime, construction of a new lime dosing facility was instigated in July, 1993. The facility was commissioned on February 18, 1994.

The conceptual arrangement of the new lime dosing facility is shown in Figure 4.6, and comprises:

- Two 40 t capacity silos.

- Two 12 m^3 capacity mixer/conditioner tanks.

- Duty and standby dosing pumps to deliver the lime slurry from the mixer tanks to the header tank.

- Duty and standby pneumatically operated splitter valves to control the rate of slurry addition.

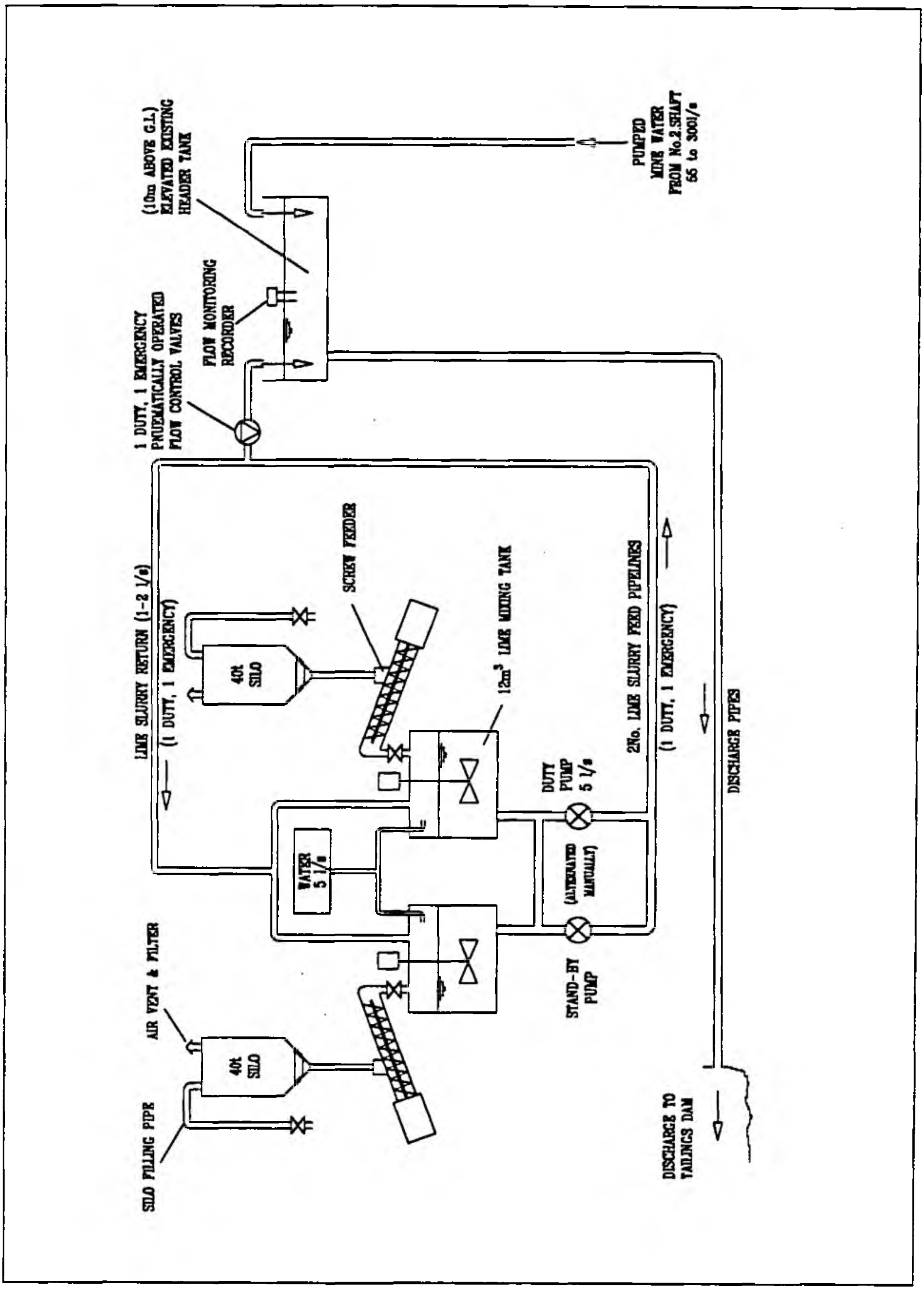
- pH control system providing automatic control of the pneumatic valves and hence the treated water pH.

- Central computerised console which operates the batching sequence.

- Back-up controls to allow manual operation in the event of a computer failure.

The introduction of a system using two mixer/conditioner units allows one unit to prepare a new batch of lime slurry whilst the other unit is delivering slurry to treat the minewater. When nearly empty, probes within the mixer tanks switch slurry delivery to the full tank, whilst the emptied unit is refilled with lime and water. This system allows continuous dosing with lime slurry of a constant concentration and, in combination with the automated dosing valve, maintained a more stable treated water pH.

Figure 4.6 Lime Dosing Plant Schematic Layout



The quantity of lime added to each batch is controlled by varying the operating time of the screw feeder transferring lime from the silo to the mixer tanks and is designed to allow the slurry strength to be varied between 7% and 13%. This enables up to approximately 1.5 t of lime to be used to prepare each 12 m³ batch of lime slurry.

Lime consumption is dependent not only on the efficiency of the dosing plant but also is a function of both the dissolved metal content and, to a lesser extent, the pH of the minewater, as illustrated in Table 4-4 (details of the chemical reactions involved are summarised in Appendix 4A).

Table 4-4 : Theoretical Lime Consumption

Dissolved Iron and Zinc Concentration	Lime Consumption (kg/m³ of minewater)		
	pH Raising	Metal Removal	Total Lime Consumption
1000 mg/l	0.04	1.25	1.29
500 mg/l	0.04	0.62	0.66
250 mg/l	0.04	0.31	0.35

(assuming an Fe^{2+}/Zn^{2+} ratio of 3:2 and a pH increase from 3 to 10)

The actual quantity of lime used is greater than indicated in Table 4-4 due to the presence of other metals. Table 4-4 indicates that theoretically a dosing rate of 0.66 kg/m³ is required to neutralise a sample of acidic water containing a total of 500 mg/l of iron and zinc. However, laboratory testing of a minewater sample containing 365 mg/l of metals revealed that 0.714 kg/m³ of lime was actually required to precipitate the metals. The actual average lime addition rate achieved by the lime dosing plant during 1994 was 0.87 kg/m³. This is some 22% greater than the laboratory measured value and reflects a combination of both the variation in the minewater chemistry and the efficiency of the plant.

The effectiveness of the new lime dosing plant in controlling pH is illustrated in Figure 4.7, which shows the variation in pH of the supernatant water discharged from the tailings dam. Figures 4.7(a) and 4.7(b) reveal that the old mine lime dosing plant controlled the pH within a range of ± 3 pH units. The new plant reduced this range to ± 1 pH unit as shown in Figure 4.7(c).

4.4.3 Treated Water Discharge

The water pumped from underground is neutralised by the addition of lime and conveyed the 360 m to the Clemows Valley Tailings Dam by either a 400 mm or 560 mm outside diameter HDPE pipe.

Both pipes are connected to the discharge chamber from the 20 m³ header tank within which the pumped minewater is mixed with the lime slurry. Full mixing of the lime slurry and minewater is achieved by the turbulence within the header

Figure 4.7 Decant pH Record April 1992, 1993 and 1994

tank. The lime-dosed minewater flows into either discharge pipe via a rectangular notch weir which is used in combination with an ultrasonic depth transducer to record the flow.

The retention time in the header tank and discharge pipe varies between three and eight minutes depending on which pipe is in use and the quantity of flow treated. The maximum retention time is just sufficient to ensure the minewater is substantially neutralised prior to discharge into the tailings dam. The minimum retention time, which occurs when the maximum quantity of minewater is being treated, is inadequate to ensure that the minewater is fully neutralised prior to discharge into the dam. Under these conditions the chemical reactions reach completion within the tailings dam.

4.4.4 Flocculant Dosing System

Treated water is discharged into an open channel at the Northern corner of the tailings dam (Figure 4.8). Here the water is mixed with the fine tailings product from the mill and flocculated with an anionic polymer flocculant prior to discharge into the Clemows Valley Tailings Dam.

Mixing the treated water with the fine tailings was found to be beneficial, as the relatively dense sand and silt sized tailings particles enhance the settlement rate and improve the settled density of the metalliferous sludge.

The settling rate is further improved by the addition of a long chain anionic flocculant at a dose rate of 3 mg/l. The choice of flocculant was made on both technical and financial criteria, with suppliers asked to tender for the provision of a flocculant capable of complying with the specification detailed in Table 4-5.

Table 4-5 : Flocculant Performance Specification

	Settling Rate (cm/min)	Initial Settled Density after 30 min (g/l)
Metalliferous Sludge Only	>10	>30
Fine Tailings/Sludge Mixture	>50	>300

Flocculant assessment was made using standardised laboratory testing procedure, as secondary effects such as excessive turbulence and high winds made field testing unreliable.

To ensure the flocculant continues to comply with the specification, routine weekly laboratory and field settling tests are carried out by the site operator.

4.4.5 Clemows Valley Tailings Dam

The Clemows Valley Tailings Dam is owned and operated by South Crofty plc for the deposition of waste produced from the Company's ore milling operations at Wheal Jane.

Historically, the dam has been used to store tailings arising from mining the Wheal Jane ore body. However since November, 1991, the dam has been used for the co-deposition of the metalliferous sludge produced by the NRA's existing minewater treatment operations and tailings arising from processing the South Crofty orebody.

The dam acts as a large settling lagoon and storage facility for the tailings which are discharged into the depository as an aqueous slurry. Tailings are introduced into the dam as a 10% aqueous slurry (measured weight by weight) at a rate of approximately 7 800 m^3/day. Typically milling is carried out continuously for a 10-day period every fortnight. No discharges from the mill occur into the tailings dam during the four days per fortnight shut-down period. Approximately 80 to 90% of the water in the slurry discharged from the mill is recovered as clarified supernatant which is discharged from the tailings dam into a final effluent polishing lagoon. Water from the polishing lagoon is either returned to the mill for re-use or released via a licensed discharge into the Clemows Stream.

The tailings dam (Figures 4.8 and 4.9) comprises a structural outer wall zone confining a centrally located supernatant pond. Wall construction is undertaken using a combination of locally won earthfill and the coarse fraction of the tailings, which is separated within the mill, from the fine (slimes) fraction by means of hydrocyclone. The fine tailings and, more recently, the metalliferous sludge, are discharged into the supernatant pond to form a low strength, subaqueous deposit.

Prior to the introduction of metalliferous sludge into the depository during 1991, the coarse tailings fraction was discharged from a number of open end points to form a subaerially deposited tailings beach. This beach formed a dense fully drained deposit which possessed sufficient shear strength to allow the material to be used as the foundation for subsequent wall raises and therefore formed part of the retaining embankment.

The supernatant pond effectively acted as a settling lagoon and, consequently, the control of pond area was critical to the efficient operation of the depository. Normally the pond was maintained at a size consistent with the settling requirements of the finer tailings particles, thereby ensuring the quality of the supernatant water, whilst allowing the remainder of the depository to be used for subaerial deposition. Tailings deposition continuously reduces the area and volume of the pond and, therefore, the pond level is periodically raised to maintain the minimum pond size.

Fig. 4.8 Clemows Valley Tailings Dam - Plan of Depository

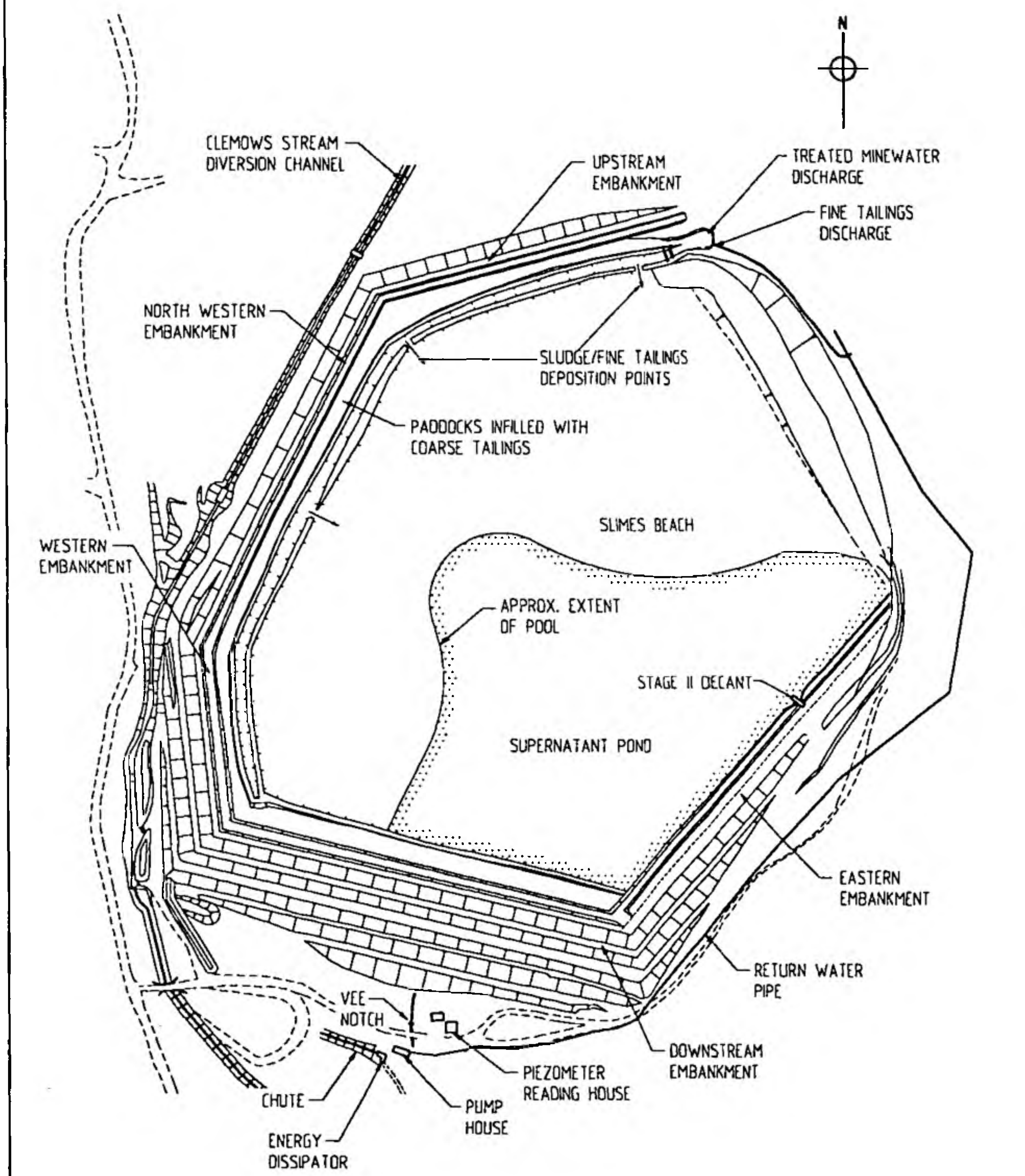
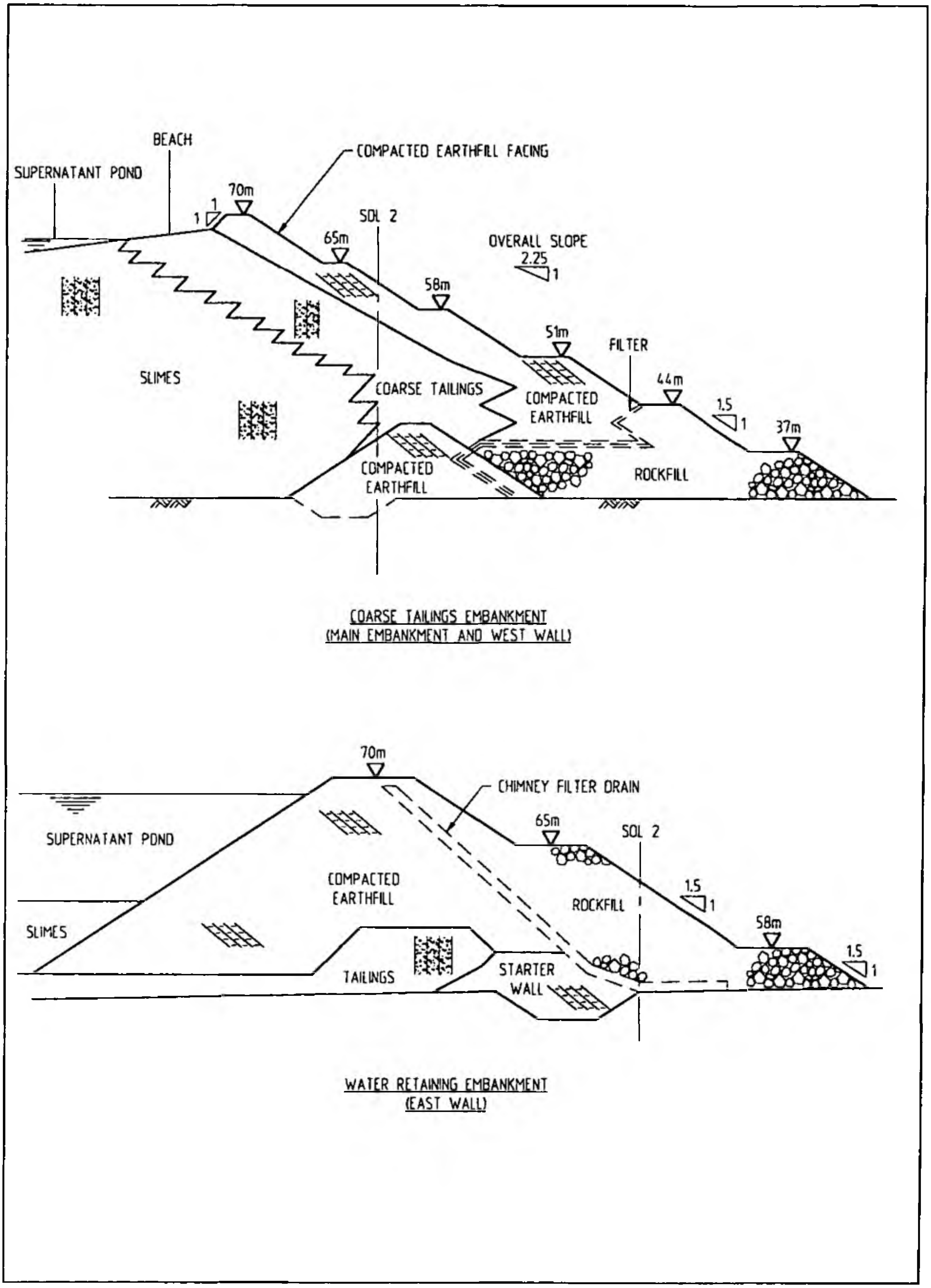


Figure 4.9 Clemows Valley Tailings Dam - Typical Embankment Sections



Prior to mine closure, sufficient coarse tailings was available to ensure that the peripheral beach rose at a rate consistent with the rise in pond level. Depending on tailings production, both the beach and pond level rose at a rate of between 0.75 and 1.25 m/year.

Studies undertaken early in 1992 (Ref. 1) revealed that the continued treatment of some 116 l/s mine water, with a metal loading of in excess of 3 000 mg/l, would have required the pond level to rise by up to 3 m/yr. Metalliferous sludge deposition into the pond would have resulted in the pond level rising faster than the maximum feasible rate of beach construction. The size of the supernatant pond would have increased, inundating the tailings beach and rapidly consuming the available storage. Unless the operating regime was substantially revised, the dam would have run out of storage. Inundation of the coarse tailings beach would also lead to the deposition of the sludge/fine tailings mixture within the structural zone of the dam, possibly compromising the future stability of the retaining embankments.

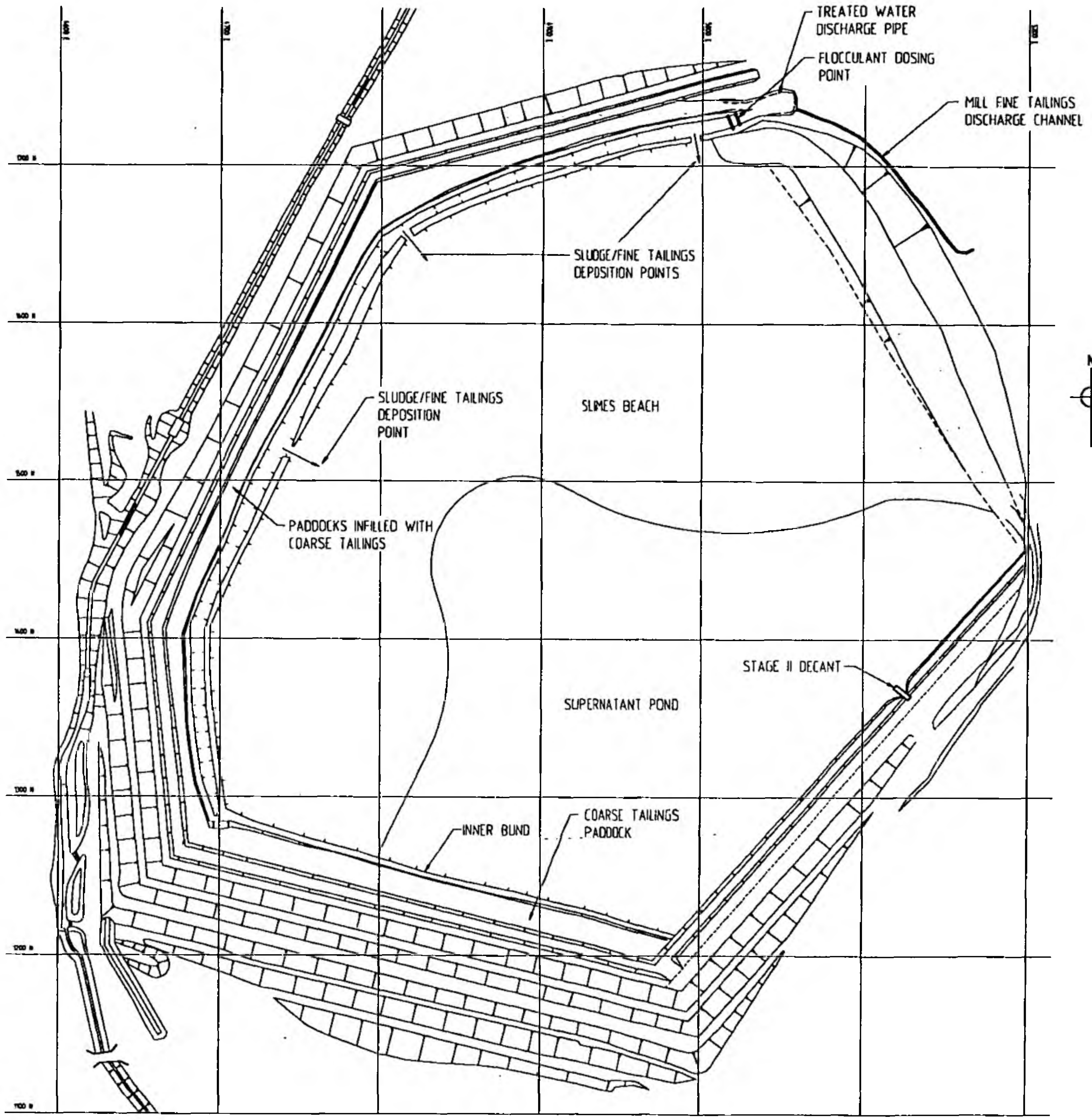
To prevent the deposition of either sludge or fine tailings within the areas critical to the stability of the dam, the method of embankment construction was amended as shown in Figure 4.10. The revised construction sequence involved:

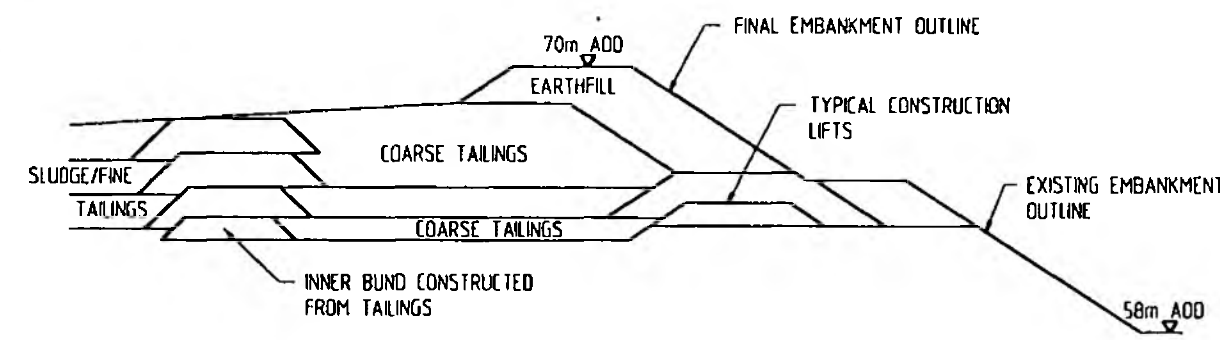
- The construction of an inner bund from tailings to form a paddock into which the coarse tailings could be deposited without being contaminated by slimes.
- Excavation of a distribution channel, along the western side of the depository to allow fine tailings/sludge deposition from a number of discrete locations.
- Systematic operation of each deposition point both to form a subaerial fine tailings/sludge deposit and to control the size and shape of the supernatant pond.

The performance of the depository has been monitored by means of topographical and geotechnical surveys undertaken in November, 1992, April, 1993 and February, 1994. Data derived from these surveys has:

- Been used to establish the volume of additional storage used as a result of metalliferous sludge deposition.
- Demonstrated that subaerial deposition of the fine tailings/sludge mixture improves the deposited density (the average subaerial and subaqueous tailings/sludge mixture densities from the February, 1994, survey were 0.8 and 0.15 t/m^3 respectively).
- Confirmed that the average density of the mixture deposited between February, 1992 and February, 1994 was of the order of 0.7 t/m^3, primarily due to the beneficial effects of subaerial deposition.

Figure 4.10 Clemows Valley Tailings Dam Amended Deposition Arrangement





REVISED EMBANKMENT CONSTRUCTION DETAIL
(NOT TO SCALE)

4.4.6 Polishing Lagoon

Final effluent clarification is undertaken in a 1000 m^2 x 4 m deep polishing lagoon located at the toe of the tailings dam.

The lagoon performs a number of functions which include:

- Final clarification of the water decanted from the tailings dam (this is especially important during periods of inclement weather).
- Neutralisation of acidic water from both the tailings dam toe drain and surface runoff.
- Balancing lagoon from which water can be drawn to feed the mill make-up water pump station.

Excess water is released from the polishing lagoon into the Clemows Stream via a consented discharge held by South Crofty plc.

4.5 EXISTING TREATMENT SYSTEM MANAGEMENT AND OPERATION

The existing treatment system is operated in accordance with a contract made between the NRA and Carnon Consolidated Ltd. Daily site management of the existing treatment operations was transferred in December, 1993 to Knight Piésold, Consulting Engineers. However, the overall management and responsibility for the operation of existing treatment system remains with the NRA.

In June, 1994, Carnon Consolidated Ltd was registered as a Public Limited Company and changed its name to South Crofty plc. A Certificate of Incorporation was sent to the NRA and confirmation was received that the change of name did not affect the rights or obligations of either the company or the NRA under the terms of the contract.

In essence, the contract requires South Crofty plc both to operate the existing treatment system efficiently and to store within the Clemows Valley Tailings Dam the metalliferous sludge produced from the existing treatment system. Under the contract, payment is made by the NRA to South Crofty plc for:

- Manhours worked in operating and maintaining of the existing treatment facilities.
- The additional storage utilised within the dam as a result of the deposition of metalliferous sludge.

- Consumables required for the operation of the plant, together with an agreed ordering and handling charge.

Supervision of South Crofty plc is carried out by Knight Piesold who effectively act as "Engineer under the Contract". Knight Piesold's duties include:

- Supervision of the operation and maintenance works carried out by South Crofty plc.
- Coordination of additional works required to ensure the satisfactory operation of the treatment system.
- Response to system alarms and instigation of emergency repair work.
- Certification of the monthly invoices submitted by South Crofty plc.
- Certification of the bi-monthly interim invoices for the estimated additional volume of storage utilised within the Clemows Valley Tailings Dam as a result of metalliferous sludge deposition.
- Annual reconciliation of the volume of actual additional storage utilised within the Clemows Valley Tailings Dam with the estimated volume authorised on the interim invoices.

Full details of the responsibilities and procedures followed are set out in the Operations Manual (Ref. 2).

4.6 PERFORMANCE MONITORING

The performance of the existing treatment system is monitored by the NRA on a continuous basis and by means of regular water quality sampling.

Continuous monitoring is achieved by seven pH probes and four flow depth probes installed at the locations shown on Figures 4.1 and 4.2. Each probe is connected to a data capture and telemetry system which is used to trigger an alarm at the NRA's Regional Communications Centre in Exeter. Depending on the relative significance of the alarm signal, either an immediate response is instigated or the fault investigated during the next working day. Details of the alarm settings and agreed responses are summarised in Table 4-6.

Table 4-6 : Existing Treatment System Alarms

DISCRETE ALARM		
Monitor Number	Description	Action
D1	Disconnected	None
D2	Mains Failure	Inform Knight Piésold immediately
D3	Floc Plant Failure	Working hours otherwise next day
D4	Pump Station Telemetry Line Failure	Working hours otherwise next day
D5	New Lime Plant Failure	Inform Knight Piésold immediately
ANALOGUE OR LEVEL ALARM		
Monitor Number	Description	Action
A1	Minewater pH > 5	Advise Knight Piésold during working hours otherwise next day
A2	Treated water pH < 6	Advise Knight Piésold immediately
A3	Water and tailings flow pH < 6	Working hours otherwise next day
A4	Combined pump flow pressure transducer water level < 135 mm	Advise Knight Piésold immediately
A5	Decant pH < 8	Working hours otherwise next day
A6	Effluent pH < 6	Advise Knight Piésold during working hours otherwise next day
A7	Shaft water level	No alarm triggered
A8	Shaft water level	Advise Knight Piésold during working hours otherwise next day if level exceeds 15.86 m
A9	---	---
A10	---	---
A11	---	---
A12	Polishing Lagoon depth	No alarm triggered
A13	Toe drain pH	No alarm triggered

4.7 PLANT PERFORMANCE

Comparison of the minewater and decant metal loadings for the period between October 1, 1993 and September 31, 1994, (Table 4.7), demonstrates that on average 97.5% of the metals were recovered from the treated minewater. The mass of metal deposited within the Clemows Valley Tailings Dam during this period amounts to approximately 3000 t.

Table 4-7 : Existing Treatment Metal Recovery October, 1993 - September, 1994

Element	Metal Loading kg/day		% Recovery	Tonnage Recovered
	Minewater	Decant		
Iron	5096	104	97.9	1822.1
Zinc	2497	59	97.6	889.9
Aluminium	539	18	96.7	190.2
Arsenic	158	1	99.3	57.3
Manganese	157	22	85.6	49.3
Cadmium	2	0.1	95	0.7
Overall recovery			97.5%	3009.5 t

The average minewater and polishing lagoon metal concentrations measured during the October, 1993 to September, 1994 study period are summarised in Table 4-8, together with the corresponding average concentrations in the Carnon River upstream of Bissoe Bridge.

Table 4-8 : Average Measured Metal Concentrations for Minewater and the Carnon River Upstream of Bissoe Bridge

Element		Average Concentrations Oct '93 - Sept '94		
		Minewater	Polishing Lagoon	Carnon River Upstream of Bissoe
Iron	mg/l	298.0	4.06	13.17
Zinc	mg/l	143.0	2.24	8.51
Aluminium	mg/l	34.6	1.65	2.48
Arsenic	mg/l	8.4	0.06	0.12
Manganese	mg/l	-	1.24	0.71
Cadmium	(μg/l)	132.0	6.04	7.4
Copper	mg/l	1.3	0.02	N/A

N/A - not available

With the exception of manganese, the water discharged from the polishing lagoon was of better quality than the measured quality in the Carnon River upstream of the confluence with the Clemows Stream. The existing treatment system, therefore, is effective not only in removing metals from the treated water but also in improving the quality of the Carnon River by dilution.

In terms of mass of metal recovered, between February 1992 and December 1994 in excess of 12 500 t have been removed by the existing treatment operations and stored in the Clemows Valley Tailings Dam - metal that otherwise would have been discharged into the Carnon River and probably deposited in the Fal Estuary.

4.8 TREATMENT SYSTEM COSTS

Details of both the capital expenditure on the existing treatment system and operating costs are summarised in the following subsections.

4.8.1 Capital Expenditure

The following major capital equipment purchases have been made since February, 1992:

	£
Submersible Pumps	70 000
Pump-lifting frame	15 000
Lime Dosing Equipment	120 000
Dam Discharge Pipe	35 000
TOTAL	240 000

4.8.2 Operating Costs

The unit operating costs for the existing treatment system, excluding sludge disposal, are summarised in Table 4-9. These costs are inclusive of:

- Electrical power purchased via South Crofty plc.
- Lime purchase.
- Flocculant purchase.
- Plant operation and maintenance by South Crofty plc.
- Flocculant preparation water purchased from South Crofty plc.

Table 4-9 indicates that the cost of operating the existing treatment system at an average flow rate of 155 l/s is approximately 11.2 p/m^3 exclusive of sludge disposal. This unit rate includes fixed costs such as plant maintenance which are relatively independent of the quantity of flow treated, the unit cost for treating other flows will therefore be slightly different.

Table 4-9 : Existing Treatment System Operating Costs (Excluding Sludge Disposal)

Commodity	Consumption Rate	Unit Price p/m^3	Annual Operating Cost £/year
Installed capacity l/s			300
Average treatment rate l/s			155
Electricity	0.38 kWh/m^3	1.8	88 000
Lime purchase	0.87 kg/m^3	5.8	285 000
Flocculant	3 g/m^3	0.6	27 000
Town water and sundries	-	1.8	90 000
Maintenance	-	1.2	60 000
TOTAL OPERATING COST		11.2p/m^3	550 000

Electrical power is purchased at an average rate of 4.57 p/kWh from South Crofty plc. This is slightly cheaper than the budget price of 4.64 p/kWh offered by the local power company. The arrangement not only represents a marginal saving of £1000 in operating cost, but also avoids the need to install an independent power supply at a cost of £30 000.

Hydrated lime and flocculant are supplied by separate fixed price contracts of up to four years duration.

4.8.3 Sludge Disposal

Sludge disposal into the Clemows Valley Tailings Dam is paid for at the rate stated in the NRA's maintenance contract with South Crofty plc. The calculation and payment mechanism take into account both the volume occupied by the sludge and the effect of sludge deposition on the settled tailings density.

Reconciled payments made between February 14, 1992 and March 31, 1994 amounted to £1 312 630 for the deposition of some 30 000 t of dry solids (Ref. 3). This represents a unit disposal rate of £43.75 per tonne of dry solids. The additional volume of storage occupied was approximately 131 000 m^3 which is equivalent to an average sludge density of 0.23 t/m^3.

Sludge disposal costs during the 1992/1994 period represented approximately 50% of the total cost of operating the existing treatment system. The mass of sludge produced during this period was equivalent to 15% of the tailings mass deposited within the pond and, consequently had a significant effect on the deposited density.

The decline in the minewater metal concentrations, combined with improvements in the treatment plant, have resulted in the quantity of sludge produced reducing from an average of 14 000 t/yr during the 1992/94 period to approximately 5000 t/yr for the existing treatment rate of 155 l/s. The sludge to tailings mass ratio therefore has reduced from 15% to 5% and, consequently, the effect of sludge deposition on the densities attained within the dam has substantially reduced.

As a result of both the reduction in the mass of sludge produced and increased tailings production by South Crofty plc, the equivalent sludge density achieved within the tailings dam should be similar, if not greater than, that previously attained. The cost of future sludge deposition into the Clemows Valley Tailings Dam therefore is unlikely to exceed £43.75/t of dry solids.

The maintenance agreement between the NRA and South Crofty plc includes provision for increasing the sludge disposal costs based on published indices. The unit disposal rate therefore has been inflated to £48/t to account for the revised disposal cost applicable from April 1, 1995. Based on both the current treatment rate and minewater metal concentrations, the annual cost of sludge disposal will be of the order of £200 000/yr for a treated flow of 155 l/s.

OK
SCP
(IGNORE).

4.8.4 Total Annual Treatment Costs

The total future annual treatment costs for continued use of the existing treatment system are summarised in Table 4-10 which indicates that continued operation of the existing treatment system to treat an average flow of 155 l/s will incur an annual operating cost of £748 000/yr.

Table 4-10 : Existing Treatment Annual Operating Costs

Installed capacity	l/s	300
Average treatment rate	l/s	155
Operating Costs	£	550 000
Sludge Disposal	£	198 000
TOTAL ANNUAL COST	£	748 000
Unit Treatment Cost	£/m³ (of water)	0.152

4.9 CONTINGENCY ARRANGEMENTS

The continued success of the existing treatment system is based both on the cooperation of South Crofty plc and the continued availability of the Clemows Valley Tailings Dam for sludge disposal. Guideline procedures to be adopted in the unlikely event of a major operational difficulty or South Crofty plc ceasing to trade have been developed and are contained in Part B of the Operation Manual (Ref. 2). In particular, guidance is provided to cover such eventualities as:

- Major electrical failure.
- Emergency procedures for the tailings dam.
- Termination of the maintenance contract by either South Crofty plc or the NRA.

The document also contains outline details of the contingency plans developed to cover the possibility of the tailings dam being unavailable. The contingency arrangements adopted are dependent on the particular circumstances, but include:

- Development of a treatment plant and emergency sludge storage facility on the lower pilot plant site. Such a scheme would take approximately six months to implement and would have an operational life of about 12 months.
- Fast-track construction of a long-term active treatment facility on NRA land. Design and construction would be subject to planning approval and would take about 12 months to complete. Dewatered sludge from the process would either be temporarily stored on site or transferred to a licensed tip.

Implementation of the contingency arrangements should the Clemows Valley Tailings Dam be unavailable for sludge disposal requires a period of at least six months. Operation of the existing treatment system during this period therefore requires the use of the Clemows Valley Tailings Dam.

A preliminary assessment has shown that the risk associated with the failure of the Clemows Valley Tailings Dam is relatively small. The possibility of the dam not being available for sludge deposition, as a result of failure, has therefore not been considered in any further detail.

The contractual arrangements between the NRA and South Crofty plc stipulate that South Crofty plc are required to give 12 month's notice of their intent to terminate the contract. Under this scenario therefore sufficient time is available to implement alternative treatment arrangements. The legal status of the 12-month termination period is, in the event of the mine going into Receivership or

Liquidation, less certain and, therefore, the legal implications of this and its effect on the NRA have been carefully considered.

4.10 EXISTING TREATMENT SYSTEM UPGRADE

The performance of the existing treatment system has been monitored throughout 1992/94 and, where appropriate, the system has been upgraded. Limited opportunity exists for further upgrading the treatment process without significant capital investment to minimise the sludge disposal costs by means of dewatering prior to deposition in the tailings dam. The potential for such an upgrade is detailed in Section 11.

4.11 OPERATIONAL LIFE

The potential operating life of the existing treatment system is limited by the available storage capacity remaining within the Clemows Valley Tailings Dam (Section 12 Sludge Disposal). The tailings dam has planning permission for a final crest level of 70 m AOD although, subject to planning permission, it would be feasible to raise the dam to 76 m AOD.

The time taken to use the storage remaining up to 70 m AOD is dependent on both the quantity of minewater treated and the amount of tailings deposited within the dam by South Crofty plc.

Table 4-11 : Estimated Existing Treatment System Life from January, 1996

Operating Scenario	Minewater Treated (Installed Capacity) l/s	Approximate Storage Life[1]
Continued ore processing at Wheal Jane	155 (300)	5 years
Ore processing stops in 1996, dam used only for sludge disposal	155 (300)	14 years

[1] assumes co-deposition density of 0.23 t/m^3 and 0.1 t/m^3 for deposition of sludge only.

Table 4-11 indicates that the remaining life of the Clemows Valley Tailings Dam is approximately five years (ie. until the end of 2000) assuming continued deposition of the metalliferous sludge and tailings. However should South Crofty plc relocate its milling operations off-site by 1996, then sufficient storage would remain within the dam to allow sludge deposition until 2010.

4.12 LEGISLATION

The operation of the existing treatment system is required to comply with the legislative framework set out by the Health and Safety at Work Act 1974 and the Water Resources Act 1991.

4.12.1 Health and Safety

All site operations are subject to the requirements of the Health and Safety at Work Act 1974 and associated regulations. In addition the site is covered by the Mines and Quarries Act 1954.

A site specific Health and Safety Policy has been prepared to cover the operation of the existing treatment plant.

4.12.2 Water Resources Act

4.12.2.1 Groundwater Abstraction

South Crofty plc, as occupier of the site, has made an application for the abstraction of groundwater from the Wheal Jane No. 2 Shaft for the existing treatment operations. This application has been advertised and subject to the resolution of any objections, an abstraction licence will be granted to the company.

4.12.2.2 Discharge Consent

The discharge of water from the Clemows Valley Tailings Dam into the Clemows Stream is covered by a consent to discharge set in the 1970s.

The existing discharge consent was set for the ore processing operations undertaken by the original mine owners and, therefore, does not take into account the recent changes in the type of ore being processed or the existing treatment operations being carried out by the NRA. A detailed review of the discharge consent considering the implications of both changes in the type of ore processed by South Crofty plc and the NRA's activities, therefore is required. This review is underway.

As the NRA's existing treatment system and South Crofty plc's ore processing both rely on the use of the Clemows Valley Tailings Dam for effluent clarification purposes, the two processes are inseparably linked and cannot, for consenting purposes, be considered in isolation.

In addition although the existing minewater treatment facility is operated under contract by South Crofty plc, the operating criteria have been developed and stated by the NRA.

4.13 SUMMARY

The existing treatment system was rapidly implemented by the NRA in 1991 as an emergency response to the impact of acid mine drainage from Wheal Jane on the Carnon River. The temporary treatment operations have removed approximately 12 500 tonnes of metals from the river system since 1992; this compared with an estimated 100 tonnes released in the incident of January 13, 1992.

The system has subsequently been upgraded with the installation of:

- New pumps
- New lime dosing facility
- New flocculant dosing system

The system now installed has sufficient capacity to treat a flow rate of up to 300 l/s although it is currently treating 155 l/s of minewater.

The estimated operating costs for the existing treatment system based on an average treatment rate of 155 l/s is £748 000/yr, which represents a unit operating cost of 15.2 p/m^3 of treated minewater. These costs are inclusive of power, consumables and maintenance, but are exclusive of contract supervision, etc.

Continued operation of the facility is dependent on the ongoing availability of storage within the Clemows Valley Tailings Dam. Based on the current rate of tailings production and predicted sludge quantities, sufficient storage is available within the depository for co-deposition of tailings and sludge until the end of year 2000. Dam life, however, could be extended to 2010 if ore processing on the site were to cease by January 1996.

There is limited scope for further upgrading the existing system, which is considered to be both relatively efficient and cost effective.

4.14 REFERENCES

(1) Knight Piésold & Partners. Clemows Valley Tailings Dam. Implications of Minewater Sludge Storage on the operation of the Depository. R7027. April, 1992.

(2) Knight Piésold and Partners. Wheal Jane Minewater Treatment Study. R7798. June 1995. Operations Manual.

(3) Knight Piésold & Partners. Wheal Jane Minewater Treatment Project. Clemows Valley Tailings Dam. Storage Reconciliation 14.02.92 - 31.03.94. R8423. February, 1995.

APPENDIX 4A
Precipitation Reactions

APPENDIX 4A
PRECIPITATION REACTIONS

All reactions assume that solid lime is added to a solution of metal salts. Calcium Sulphate will only precipitate when the product of molar concentrations of calcium and sulphate is greater than 2×10^{-4} (barely reached when Wheal Jane minewater is neutralised). Therefore, calcium and sulphate are shown as ions in the equations.

(i) Zinc

$$Zn^{2+} + SO_4^{2-} + Ca(OH)_2 \rightarrow Zn(OH)_2 + Ca^{2+} + SO_4^{2-}$$

(ii) Iron

$$Fe^{2+} + SO_4^{2-} + Ca(OH)_2 \rightarrow Fe(OH)_2 + Ca^{2+} + SO_4^{2-}$$

Now in the presence of atmospheric oxygen and water then:

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$$

(iii) Aluminium

$$2Al^{3+} + 3SO_4^{2-} + 3Ca(OH)_2 \rightarrow 2Al(OH)_3 + 3Ca^{2+} + 3SO_4^{2-}$$

(iv) Manganese

$$Mn^{2+} + SO_4^{2-} + Ca(OH)_2 \rightarrow Mn(OH)_2 + Ca^{2+} + SO_4^{2-}$$

Now in the presence of atmospheric oxygen then:

$$4Mn(OH)_2 + O_2 \rightarrow 4MnO(OH) + 2H_2O$$

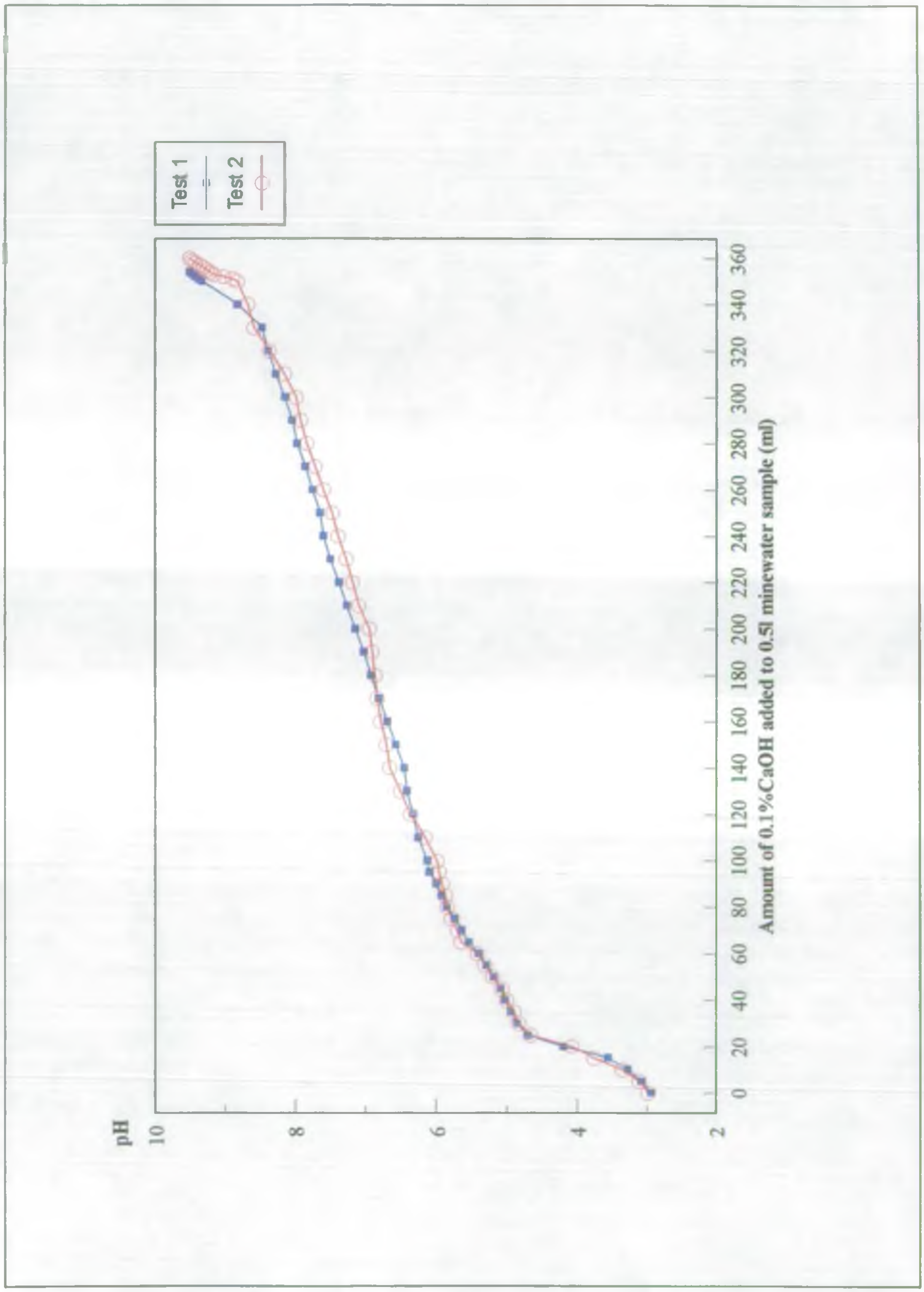
(v) Cadmium

$$Cd^{2+} + SO_4^{2-} + Ca(OH)_2 \rightarrow Cd(OH)_2 + Ca^{2+} + SO_4^{2-}$$

(vi) Arsenic

Arsenic occurs as soluble arsenate (AsO_4^{3-}) or arsenite (AsO_3^{3-}) in acid minewater. When iron is present and the pH is raised, the arsenic is precipitated; if oxygen is present, ferric arsenate ($FeAsO_4$) is produced.

Figure 4A.1 **No. 2 Shaft Minewater Neutralisation Curve**



5

5. THE CURRENT SITUATION

CONTENTS

5.1 INTRODUCTION

The existing treatment system initiated by the National Rivers Authority has been operating for some three years (see Section 4). Under this system, a maximum of some 174 l/s of minewater has been treated and discharged, through the Clemows Valley Tailings Dam, to the Clemows Stream. This strategy has significantly reduced, but not completely eliminated, the discharge of untreated minewater to the Carnon River. Flow from Nangiles Adit still occurs when the water level within the mine rises above adit level despite the operation of the pumps.

This section of the report summarises the hydrological and water quality information collected since the release of minewater in January 1992.

5.2 METEOROLOGICAL DATA

Rainfall has been monitored at four locations (see Section 3.5 and Figure 5.1). The most reliable and longest record is for Trevince in the south-west of the catchment.

Data from the Trevince and Wheal Jane rainfall gauges were compared for the period 1992 - 1994 and showed close agreement (a difference of 1% over each year). The station at Trevince therefore has been used to provide long term rainfall figures.

The long-term rainfall data from Trevince were used to calculated return periods for recent years. For example, 1993, with an annual rainfall of 1475 mm, had a return period of between 10 and 20 years. The wettest three month period between abandonment of Wheal Jane mine and October, 1994 was from December, 1993 to February, 1994 when 644 mm of rain were recorded. This was close to the wettest three month period on record, which occurred between October and December, 1960, when 666 mm of rain fell.

By contrast, the driest three-month period on record was between May and July, 1976 when only 50.9 mm of rain fell. The driest recent period was from May to July, 1992 when 118 mm were recorded at Trevince.

Weekly actual evapotranspiration data were obtained from MORECS weekly bulletin sheets for square 186 for 1992 to 1994. Monthly data were also obtained for 1972 to 1984 and used to estimate average weekly evaporation (see Table 5-1). Actual values ranged from a minimum of 3.4 mm/week in the winter to 21 mm/week in the summer. Annual totals ranged from 429 mm to 600 mm between 1972 and 1984.

Table 5-1: Average Weekly Actual Evapotranspiration (based on 1972 to 1984 figures)

Month	Average Weekly AE during month (mm)
January	4.78
February	5.21
March	8.93
April	13.39
May	17.81
June	15.10
July	15.79
August	13.23
September	11.83
October	8.72
November	6.01
December	4.50

Actual evapotranspiration figures were used in combination with rainfall at Trevince to estimate effective rainfall where:

effective rainfall = rainfall - actual evapotranspiration

5.3 SURFACE WATER AND GROUNDWATER LEVELS

River levels have been recorded at each of the NRA's water quality stations either:

- at 15 minute intervals using dataloggers, or
- at least weekly by means of a gauging board.

These data primarily have been used in conjunction with manual flow gaugings to derive a stage discharge relationship for each monitoring site. In addition, river water levels were measured in the Carnon River between Twelveheads and the Hick's Mill Stream confluence as part of the river survey in February, 1995. River bed levels and local topography were surveyed, as were adit portal locations and levels.

Groundwater levels have been monitored at a series of existing wells, shafts and boreholes to provide information on relative river/groundwater levels (see Figures 5.1 to 5.3 and Tables 5-2a and b). An additional six boreholes (95/1 to 95/6) were drilled in February 1995 to monitor groundwater levels within the vicinity of the Carnon River. Selected groundwater levels for February 1995 have been used to derive conjectured groundwater contours (see Figure 5.4).

Figure 5.1 Groundwater Monitoring Sites and Rainfall Gauges

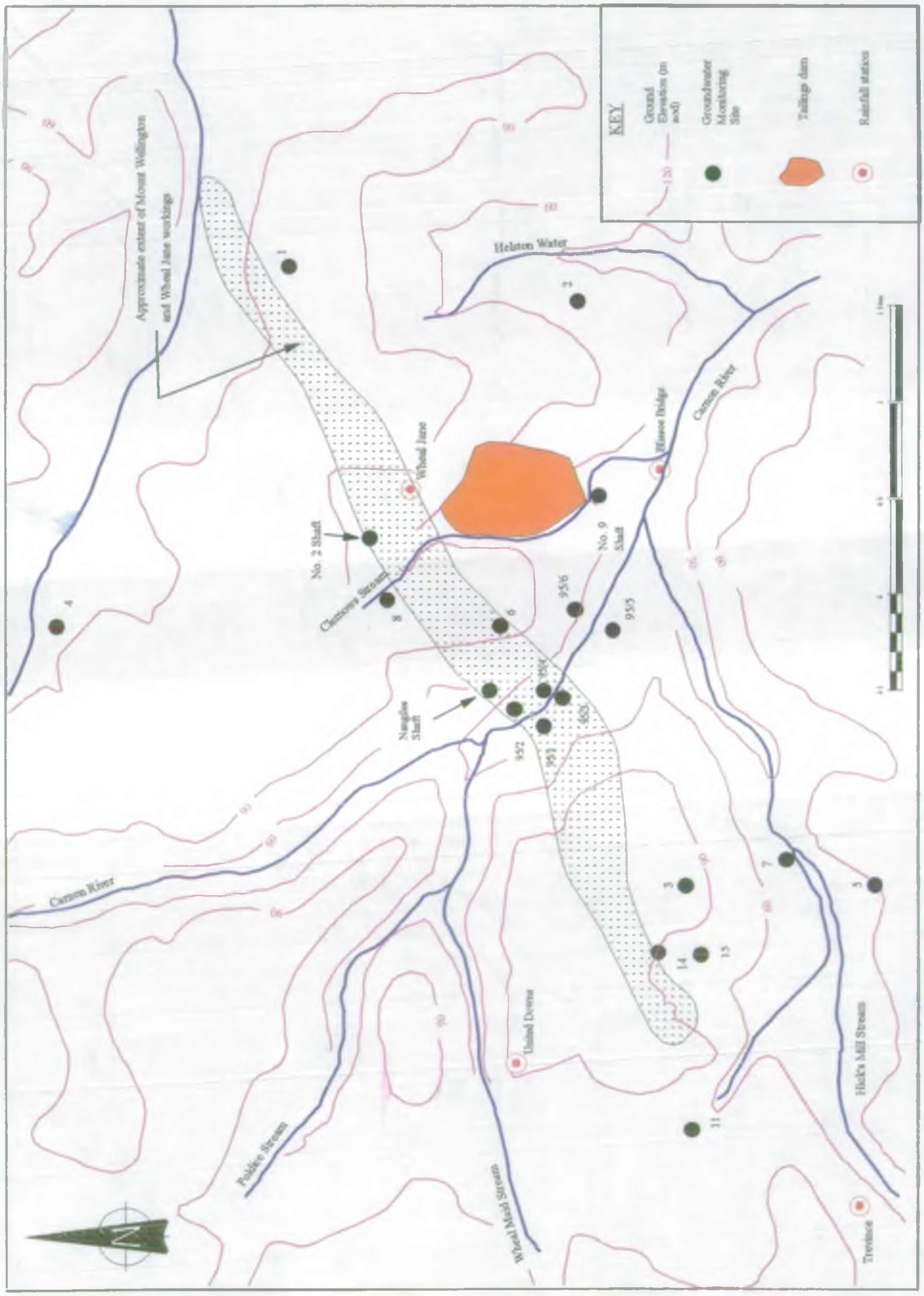


Figure 5.2 Relative Groundwater and River Levels February 1995

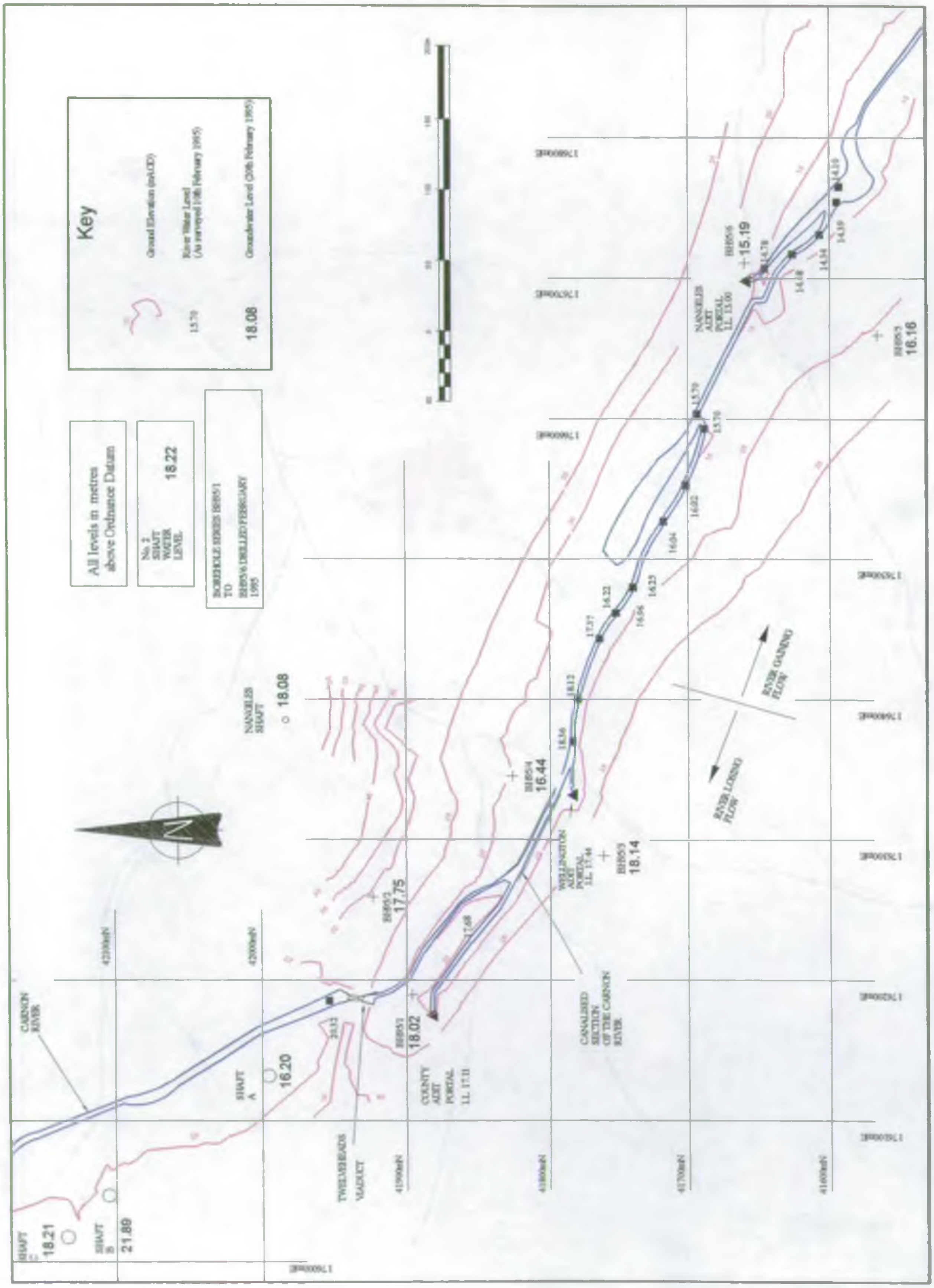


Figure 5.3 Relative Groundwater and River Levels March 1995

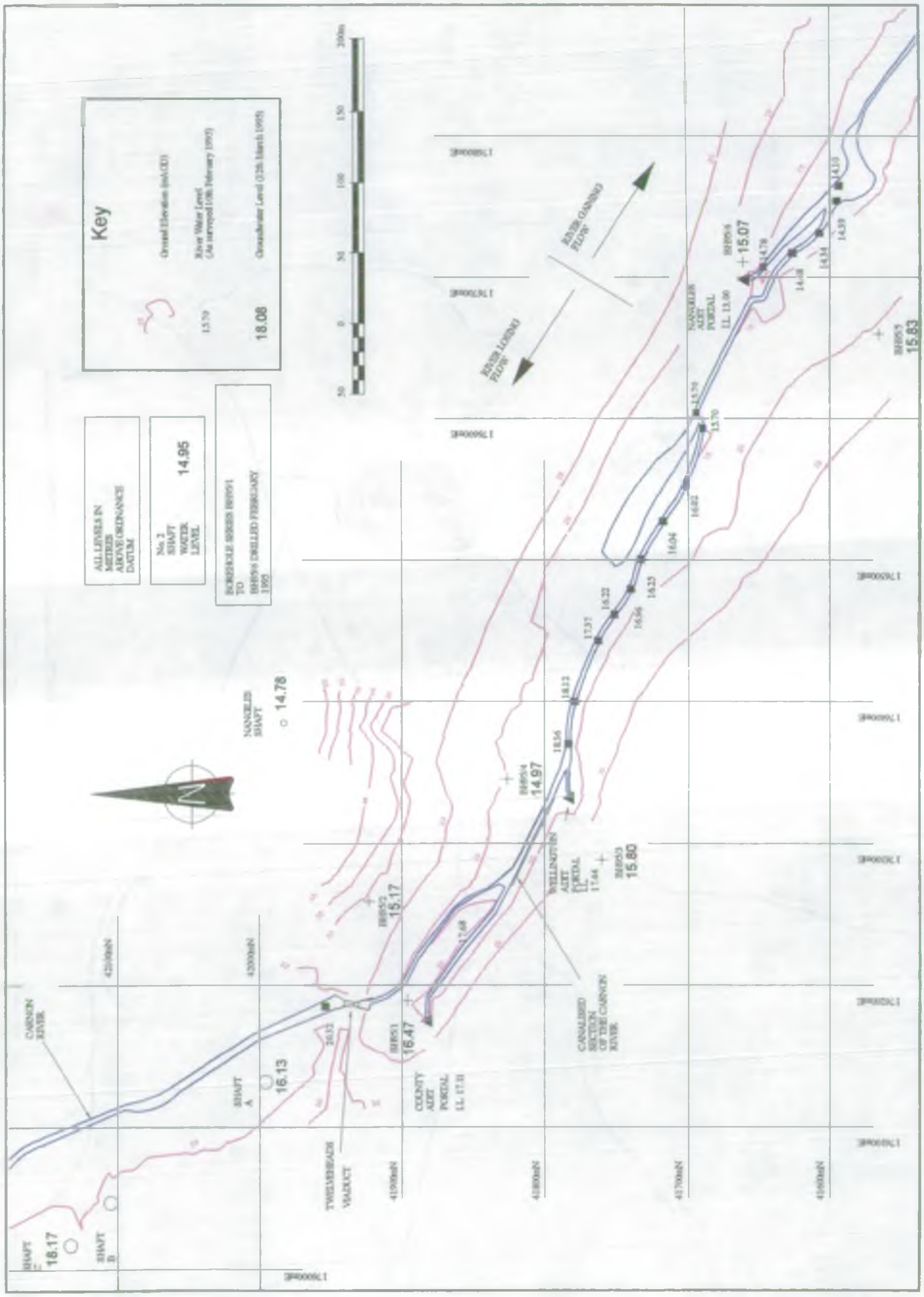


Figure 5.4 **Groundwater Contours February 1995**

Table 5-2a : Water Level Monitoring

Well	Datum (mAOD)	Dipped level (metres below datum)									
		10/10/94	13/10/94	25/10/94	04/11/94	09/11/94	15/11/94	24/11/94	01/12/94	13/12/94	20/12/94
1	105.888	50.69		43.75	35.5	18.77	15.28	15.22	17.05	15.6	
2	42.366	5.8		3.2	1.5	1.58	1.47	1.72	1.84	1.67	
3	86.734	70.1		DRY	24	40.04	24.1	36.59	48.27	40.9	
4	78.386	4.19		3.3	2	2.14	2.13	3.02	3.59	2.86	
5	61.948	4.23		3.62	1	0.9	0.75	0.99	0.98	1.11	
6	69.51			13.95	14	13.92	13.93	13.98	13.98	13.98	
7	35.613	0.69		0.46	0.45	0.36	0.36	0.36	0.36	0.36	
8	75.077			0.6	0.45	0.4	0.4	0.4	0.4	0.4	
11	67.6		54.9		45.46	40.88			48.6		38.43
14	90.0		-		-	-			71.4		70.62
15	80.0		59.17		37.12	40.2			35.28		35.29

Well	Datum (mAOD)	Level (m AOD)									
		10/10/94	13/10/94	25/10/94	04/11/94	09/11/94	15/11/94	24/11/94	01/12/94	13/12/94	20/12/94
1	105.888	55.178		62.118	70.368	87.098	90.588	90.648	88.818	90.268	
2	42.366	36.566		39.166	40.866	40.786	40.896	40.646	40.526	40.696	
3	86.734	16.634			62.734	46.704	62.634	50.144	38.464	45.834	
4	76.386	74.196		75.086	76.386	76.246	76.256	75.366	74.796	75.526	
5	61.948	57.718		58.328	40.948	61.048	61.198	60.958	40.968	60.838	
6	69.51			55.56	55.51	55.59	55.58	55.53	55.53	55.53	
7	35.613	34.923		35.153	35.163	35.253	35.253	35.253	35.253	35.253	
8	75.077			74.477	74.627	74.677	74.677	74.677	74.677	74.677	
11	67.6		12.7		22.14	26.72			19.0		29.17
14	90.0		-		-	-			18.6		19.38
15	80.0		30.83		42.8	39.8			44.72		44.71

Notes:

For locations see Figure 5.1.

1. Goodern Manor Farm: deep, unobstructed borehole. Good datum, easily accessed.
2. Rose Villa, Helston water: potable supply shallow well with submersible, approximate datum.
3. United Farm, Cusgarne: deep borehole/well with aged submersible may be obstructed. Data on 4/11 and 15/11/94 considered unreliable, perched water.
4. Saveock Farm, Saveock: shallow well, historically dry during mining as with 3, datum satisfactory.
5. Pulla Farm, Cusgarne: ex potable supply well, good datum.
6. Lilac Cottage: poor datum (±50 mm).
7. Cusgarne Manor Farm: disused well, difficult access and barbed wire, data of dubious value.
8. Crosslanes Farm, Twelveheads: abandoned well at bottom of hill, very poor datum ±100 mm, difficult access.
11. United Mines Landfill Site: Borehole W11
14. United Mines Landfill Site: Borehole W14
15. United Mines Landfill Site: Borehole W15

Table 5-2b : Water Level Monitoring

Borehole/ Shaft	Datum (m AOD)	20/2/95		12/3/95	
		Dipped Level (mbd)	Level (m AOD)	Dipped Level (mbd)	Level (m AOD)
Borehole 95/1	21.28	3.26	18.02	4.81	16.47
Borehole 95/2	28.56	10.80	17.76	13.39	15.17
Borehole 95/3	26.84	8.70	18.14	11.04	15.8
Borehole 95/4	20.04	3.60	16.44	5.07	14.97
Borehole 95/5	21.21	5.05	16.16	5.38	15.83
Borehole 95/6	18.54	3.35	15.19	3.47	15.07
Shaft A	24.25	8.05	16.2	8.12	16.13
Shaft B	26.24	4.35*	21.89*	4.30*	21.94*
Shaft C	26.91	8.70	18.21	8.74	18.17
Nangiles Shaft	60.06	41.98	18.08	45.28	14.78
Wheal Jane No. 2 Shaft	66.55		18.22		14.95

* Perched Water Level

For locations see Figures 5.1 and 5.2

Since recovery of mine water levels, pumping from Wheal Jane No. 2 Shaft has maintained water levels in the shaft between 13 and 18 m AOD.

Nearer to the Carnon River (i.e. further from the effects of pumping) the high hydraulic conductivity of the mineworkings ensures a shallow water table gradient and levels in mine workings near the river are similar to those in Wheal Jane No. 2 Shaft. This was illustrated in February and March 1995 when minewater levels were reduced from around 18 to 15 m AOD over a few weeks. Groundwater levels, recorded in boreholes 95/1 to 95/4, exhibited a similar response (see Figures 5.2 and 5.3).

Examination of the river water levels and groundwater levels between Twelveheads and Point Mills shows that:

- in the upstream section, groundwater levels are lower than river levels (i.e. possible flow loss from the river)
- in the downstream section, groundwater levels are higher than river levels (i.e. possible flow gain by the river)

The potential therefore exists for both infiltration of river water (river flow losses) and river flow gains (baseflow).

As water levels in the mine fell between February and March 1995, the position at which these river flow losses became gains moved downstream and there was a greater distance over which losses could occur. The canalised section (see Figure 5.2) reduces the distance over which the river flows over old mineworkings, thus reducing losses in this section.

5.4 MINEWATER FLOW AND CHEMISTRY

Peak concentrations of most metals recorded in Wheal Jane No. 2 Shaft had been reached by March, 1992 (see Table 5-3). Peak copper concentrations, however, were not observed until December, 1992. The differences between the pattern of copper and other metal concentrations is unclear, but is likely, in part at least, to be a consequence of differences in the distribution of copper and other minerals within the mine workings.

Since the peak concentrations were recorded, there has been an almost exponential decline in the concentrations of most metals (see Figures 5.5a and b). Metal concentrations recorded in September, 1994 are typically one to two orders of magnitude less than the peak values (see Table 5-3).

The pumping arrangements in Wheal Jane No. 2 Shaft are described in detail in Section 4.4.1 and flow is shown in Figure 5.5a.

Table 5-3 : Water Quality in Wheal Jane No. 2 Shaft

	Peak Concentration (with date)		Mean Concentration during September, 1994
pH	2.8	(minimum)	3.5
Arsenic	162	(09.07.92)	9
Aluminium	190	(15.03.92)	27
Cadmium	1.7	(05.03.92)	0.08
Copper	23	(08.12.92)	1.2
Iron	5070	(05.03.92)	345
Lead	2.4	(03.11.92)	n/a
Manganese	27	(05.03.92)	8
Nickel	5	(12.03.92)	0.7
Zinc	2130	(03.09.91)	132
Sulphate (as SO_4)	6100	(05.03.92)	476
All data, except pH, expressed as mg/l total metal concentration.			

Quality of the water pumped from Wheal Jane No. 2 Shaft does not necessarily indicate the quality of water present throughout the mineworkings. Variations may be expected to arise as a consequence of the interaction of local geology, groundwater flow and the presence of shafts or adits.

An indication of the variation in quality with depth has been obtained by lowering a monitoring probe to a depth of 200 metres below surface (see Figure 5.6). The results show clear evidence of variations with depth. Of particular significance is:

- A rapid increase in dissolved oxygen concentrations close to the surface.
- A clear distinction between the water quality above 150 m below ground level (bgl) and that below 180 m bgl, with the deeper water being characterised by a higher pH, temperature and concentration of total dissolved solids.

The depth at which the water quality changes coincides with the Level 5 mineworkings. During operation, the workings at Level 5 and below experienced significant inflows of high temperature groundwater.

5.5 SURFACE WATER AND ADIT FLOWS

Twelve flow gauging stations were established in the Carnon River catchment in 1980, consisting of either temporary or permanent weir structures, and flows were recorded over a 10 month period.

The present hydrological network consists of four principal river flow monitoring stations and two adit flow stations where data are collected at 15 minute intervals (see Figures 5.8a, 5.9a, 5.11a, 5.12a, 5.14a and Table 5-4).

Figure 5.5a **No.2 Shaft Water Quality**

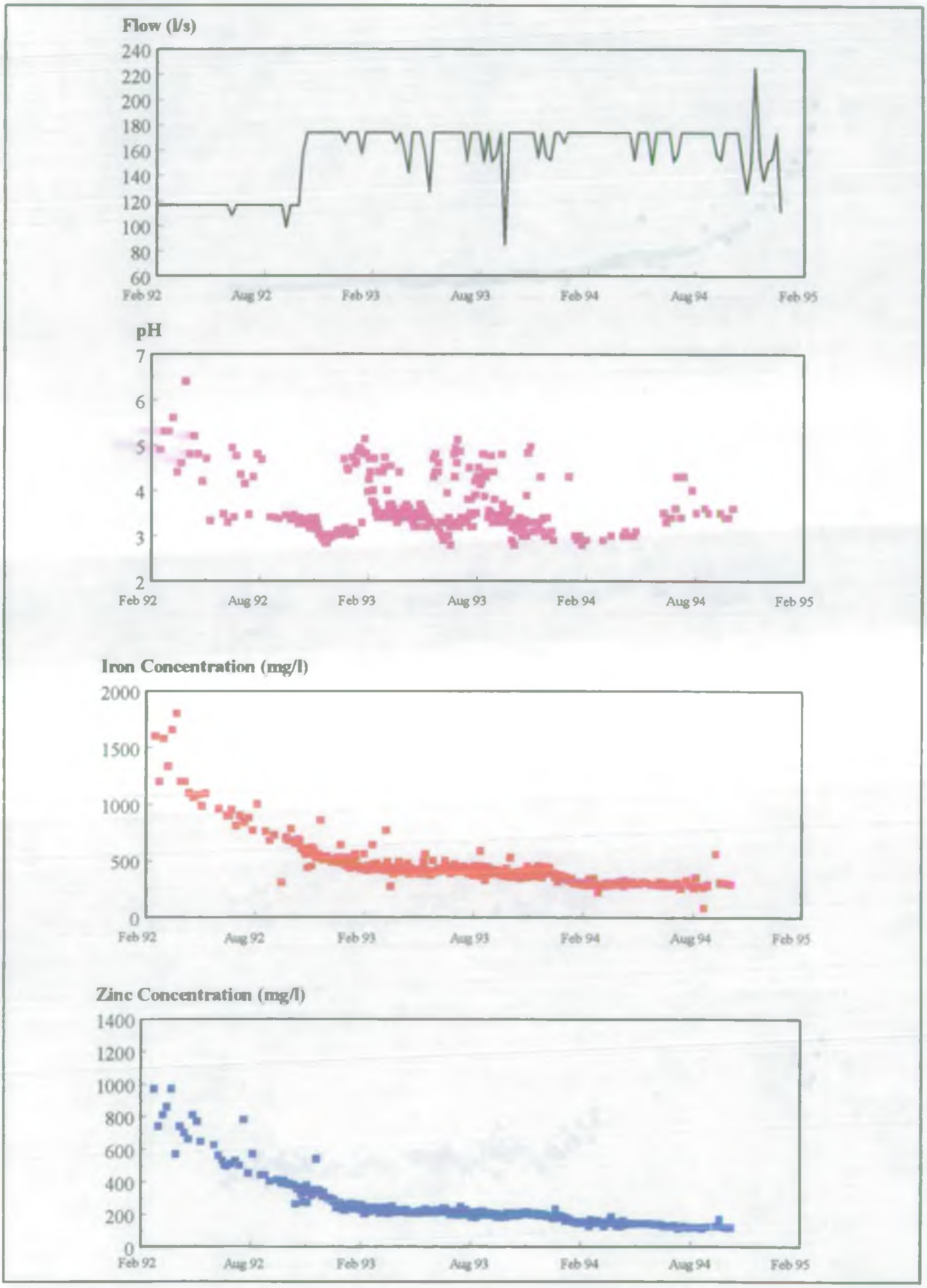


Figure 5.5b **No.2 Shaft Water Quality**

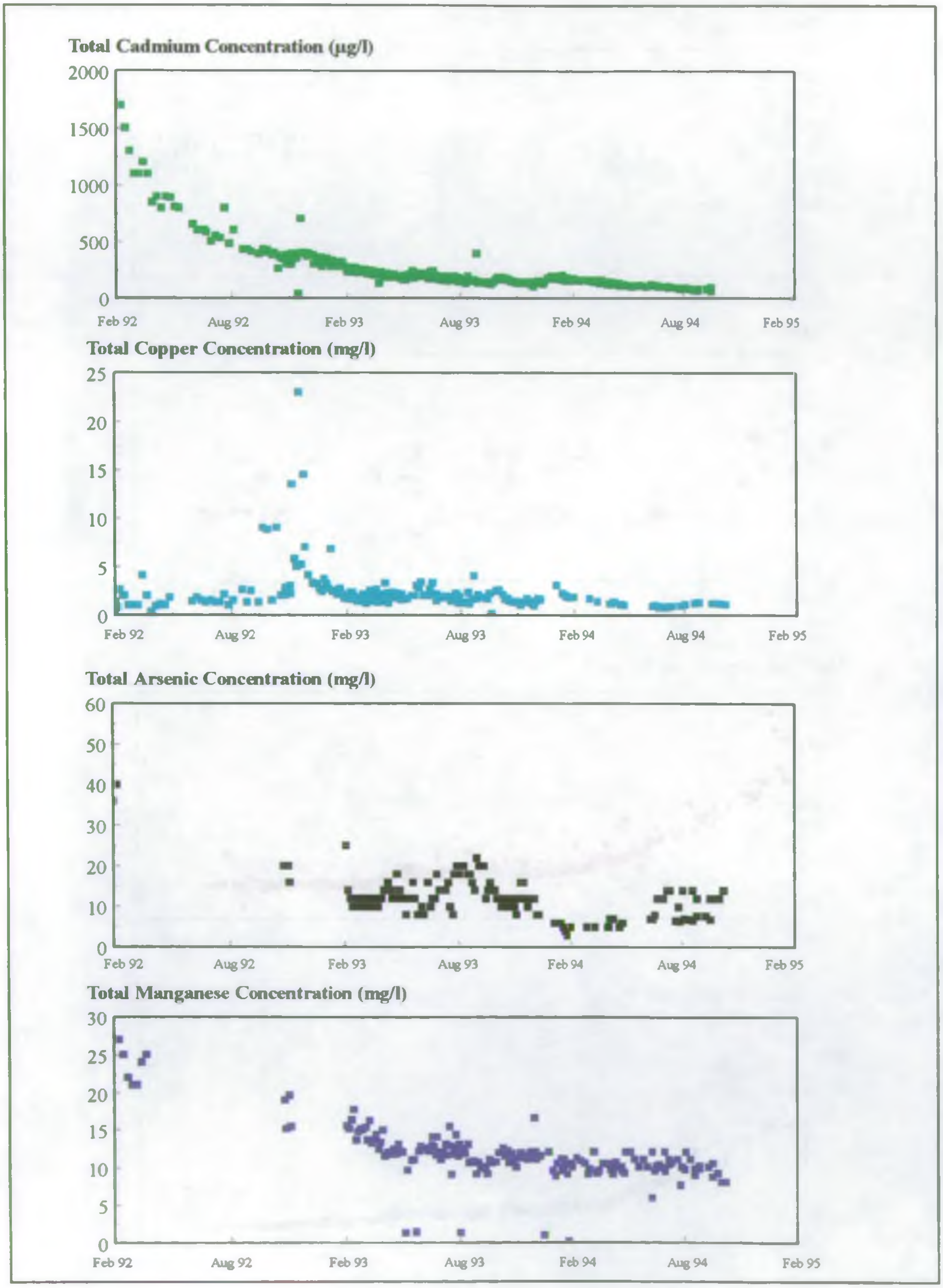


Figure 5.6 Variations in Water Quality with Depth in Number 2 Shaft - May 1994

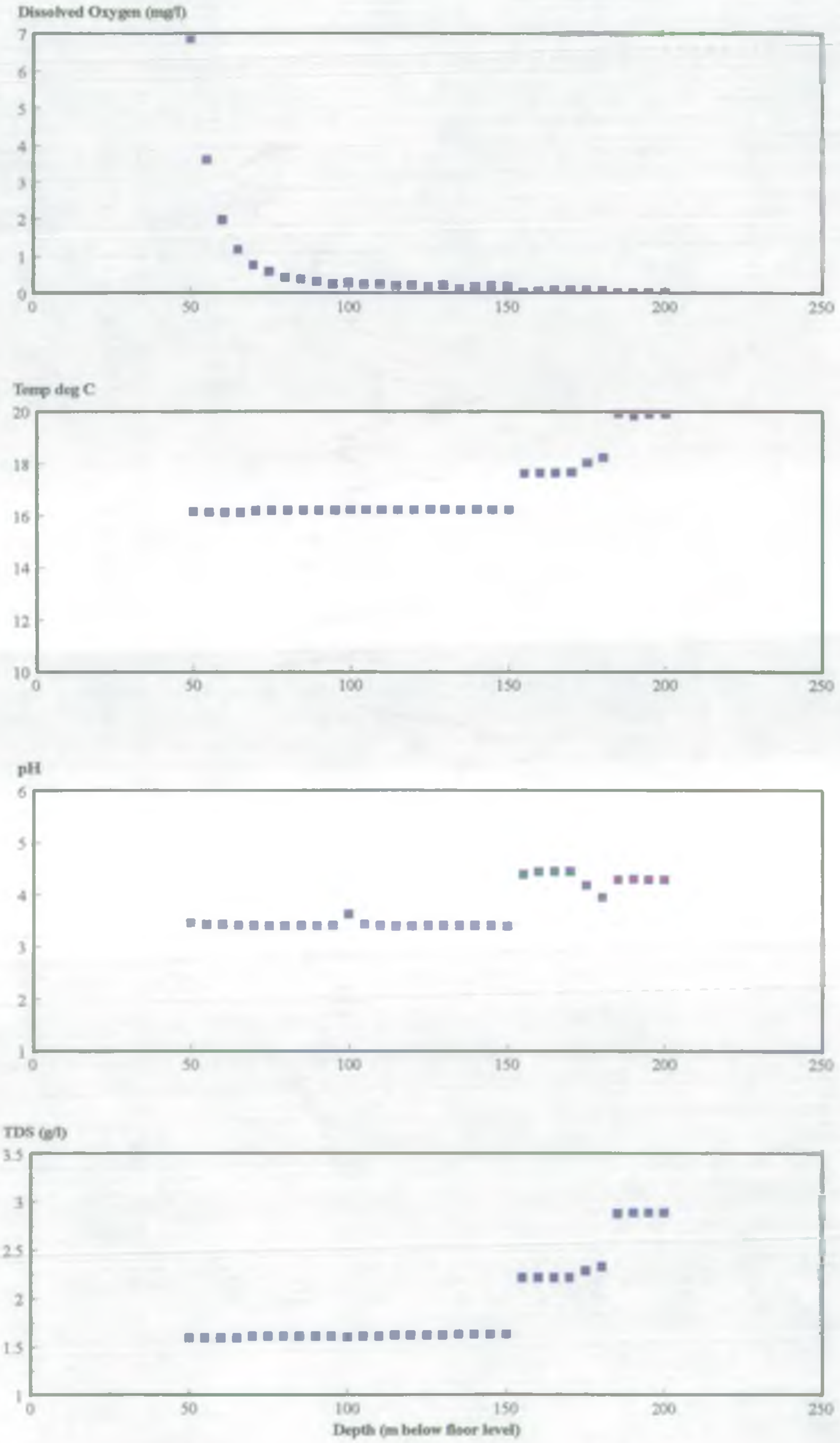


Figure 5.7 Baseflow Separation - Hick's Mill Stream at Trehaddle

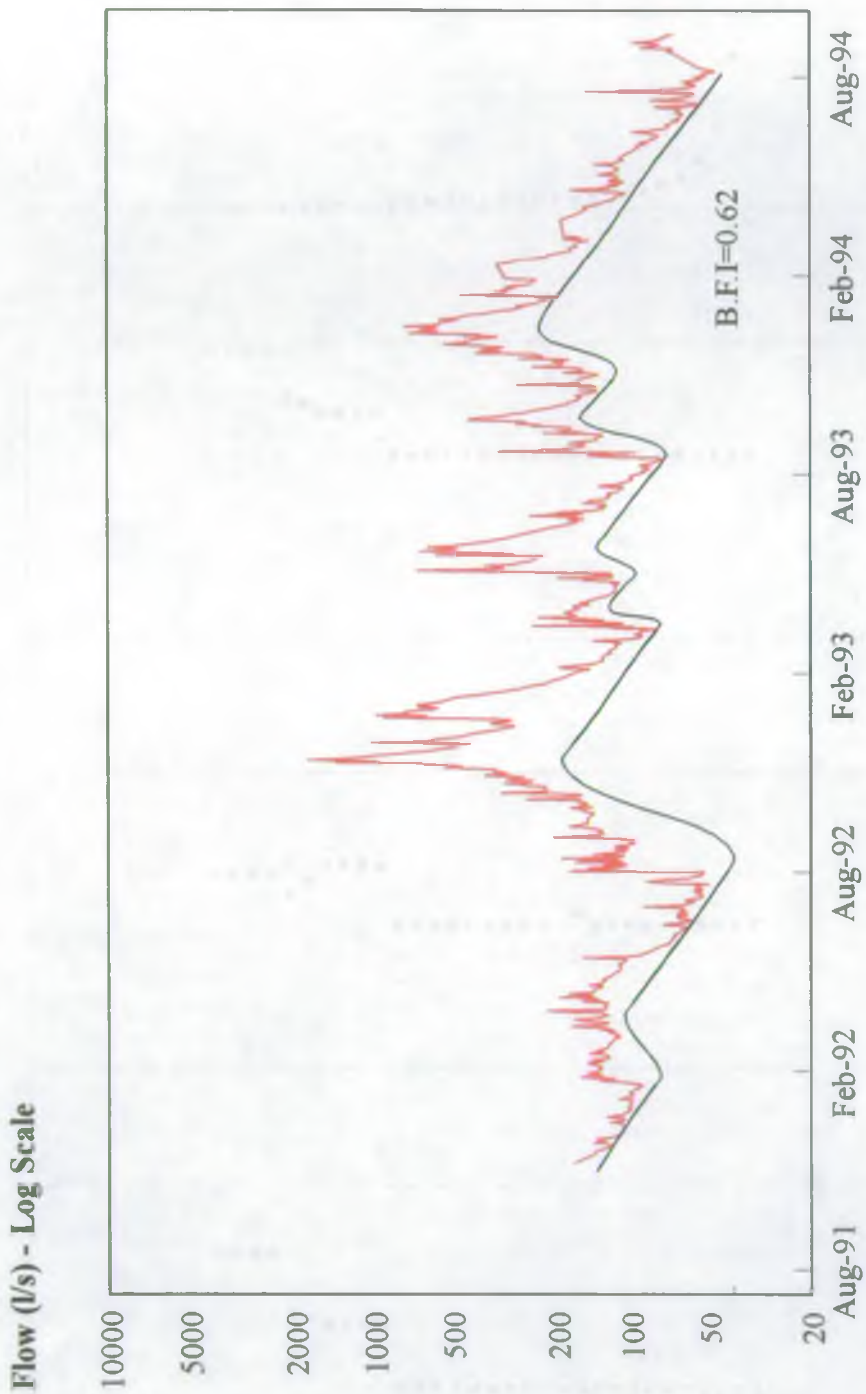


Table 5-4 : Carnon Valley Flows and Stage/Discharge Ranges

Site	Period of Record (1)	Flow (l/s)			Stage/Discharge Range (l/s)	
		Mean	Min	Max	Min	Max
Twelveheads	Nov 91- Oct 94	175	17	1590	0	398
Hick's Mill Stream	Sept 91 - Oct 94	191	47	1750	49	1186
Bissoe(2)	Sept 91 - Oct 94	803	127	5103	0	639
Nangiles Adit	Apr 92 - Oct 94	54	0	318	0	435
County Adit	Apr 92 - Oct 94	320	109	1558	108	1358

(1) October 1994 cut-off date; measurements are ongoing.

(2) Combination of flow at Twelveheads, Trehaddle, County Adit and Nangiles Adit. Devoran Bridge not included because of unreliable record.

Flow in the Carnon River is measured at Twelveheads, Bissoe and Devoran Bridge. At both Bissoe and Devoran Bridge, difficulties in obtaining stage/discharge relationships resulted in unreliable flow measurements, particularly at high flow. New gauging structures have now been installed at both sites.

Contributory flows to the Carnon River are measured at Trehaddle on the Hick's Mill Stream, and at the portals of the County Adit and Nangiles Adit.

Less regular flow measurements have been taken at Clemows Stream, Wellington Adit and Jane's Adit.

Nangiles Adit is in effect the Wheal Jane mine overflow, so the sum of Wheal Jane No. 2 Shaft flow and Nangiles adit flow is the total point discharge from the mine. On average this mine discharge makes up around 21% of the Carnon River flow at Bissoe (see Table 5-5).

Flow measurements taken in 1980 were used to assign proportions of flow in a similar manner whilst dewatering was taking place. The results are shown in Table 5-5 and indicate that the proportion of flow in Hick's Mill Stream, for example has remained approximately the same at 22% during mining and rebound. At Twelveheads and in the County Adit, flow in 1980 was less than at present, accounted for by a higher flow from Wheal Jane (at that time taken to be the sum of pumped flow from Wellington and Jane).

Table 5-5 : Carnon Valley Flow Contributions above Bissoe

Source	% Flow	
	1992-1994	1980
Carnon River at Twelveheads	20	14
Hick's Mill Stream	22	22
County Adit	37	27
Wheal Jane	21	37

5.6 SURFACE/GROUNDWATER INTERACTION

There is evidence of flow moving between the rivers and groundwater as shown by the relative levels of groundwater and river water (Figures 5.2 and 5.3). This flow has been quantified by examining change in flow along the Carnon River and by baseflow analysis.

(1) *Change in Flow*

Comparison of estimated flow at Bissoe Bridge (when it is within the stage/discharge calibrated range) with the combined flows from all adits and tributaries upstream, gives the amount of flow gained by the Carnon River from surface runoff and baseflow contributions. The gauged flow at Bissoe is upstream of the Clemows Stream confluence which is not included therefore in these calculations.

It was possible to quantify baseflow in this way only for periods when flow gaugings at Bissoe were known to be accurate. At high flows, when gaugings are inaccurate, baseflow could not be quantified, but is likely to represent a smaller proportion of total flow.

Three example periods are shown in Table 5-6 for which effective rainfall has been estimated as zero so the contribution from surface runoff is negligible. For each period, there is a net baseflow to the river between Twelveheads and Bissoe. The magnitude of baseflow (25 l/s to 179 l/s) represents between 6% and 46% of the upstream flow. Even if flow gaugings are assumed to have an accuracy of 5% there is still a significant net baseflow.

Table 5-6 also includes estimated baseflow for 1980, using flow measurements taken at that time (Ref. 1). Despite the significant dewatering beneath the river, there did not appear to be a measurable loss of flow. In fact the estimated baseflow contribution entering the river at 113 l/s was similar to that calculated using the recent data.

It would appear that, contrary to the hydraulic gradient in the vicinity of the mineworkings, there is a net gain in river flow between Twelveheads and Bissoe. It can be inferred that canalisation of the river bed where it crosses the mine workings has effectively isolated the river from underlying minewater.

Table 5-6 : Carnon River/Groundwater Interaction between Twelveheads and Bissoe over Dry Periods

Period	29/4 - 30/6/92	4/8 - 7/9/93	8/6 - 26/7/94	Apr - Jul 1980
Days	63	35	49	122
Rain (mm)	53.5	62.0	48.7	209.8
Effective rainfall (mm)	0	0	0	7.8
Flow (l/s)				
Twelveheads	71	89	98	58
Trehaddle	105	99	82	154
County Adit	238	200	171	175
Nangiles Adit	20	4	71	0
Sum	434	392	422	387
Bissoe	459	571	543	500
Difference [1]	-25	-179	-121	-113
% of Sum	6	46	29	29
No. 2 water level (m AOD)				
Start	16.00	15.97	16.30	-
End	15.92	13.58	13.13	-

[1] Positive difference is flow from river to groundwater
Negative difference is baseflow to river

A fuller interpretation of change in flow, including seasonal and spatial variations will be possible once reliable flow measurements at strategic sites, including Bissoe and Devoran Bridge, are available.

(2) *Baseflow Analysis*

Baseflow separation was also used to quantify river/groundwater interaction (Ref. 4). By plotting log flow against time (see Figure 5.7), baseflow recession approximates to a straight line where the baseflow component is the area under the line. Flow data from Twelveheads and Trehaddle were used to estimate baseflow in the Carnon catchment. A long flow recession from April to July 1994 was used to define the slope of the recession line. Between recessions the separation is more uncertain, but it was assumed that groundwater levels respond rapidly to rainfall and that baseflow contributions are still significant at high flow.

A baseflow index (BFI) of 0.62 was estimated at Trehaddle on the Hick's Mill Stream which compares well with the baseflow index of 0.66 calculated by the NRA for the nearby Kenwyn River which also drains a killas catchment. A baseflow index of 0.62 was also estimated at Twelveheads.

From a water quality perspective, the magnitude of baseflow is of significance since, even with no discharge from the Nangiles Adit untreated mine waters may still be reaching the Carnon River through the river bed. It will be possible to refine baseflow calculations as reliable flows at Bissoe and Devoran Bridge become available from the new gauging stations. However, there is little indication from the water quality data that this baseflow contains significant concentrations of metals.

5.7 UNTREATED MINEWATER FLOWS

Between 1992 and 1994 the water level in Wheal Jane No. 2 Shaft was held between 13 and 18 m AOD (see Figure 5.13). The flows and quality of the treated minewater are discussed in Section 5.4.

Prior to the winter of 1993, untreated minewater flows occurred from Nangiles Adit when the water level within the mine workings exceeded 15.86 m AOD. However, there was an apparent change in the relationship during the winter of 1993 resulting in flow occurring when a higher level of approximately 16.4 m AOD was reached in Wheal Jane No. 2 Shaft. This may be a consequence of a blockage in the adit system, and illustrates the dependency of the system on adit integrity.

Peak flows from the adit, which are rainfall dependent, occur in December or January of each year (see Figure 5.8a). Mean summer flow from Nangiles Adit, over the period April, 1992 to October, 1994, is 19 l/s compared to a mean flow of 145 l/s during winter.

The quality of the water from Nangiles Adit is closely related to the flow rate. At low flows, the adit discharges only localised groundwater which has relatively low metal concentrations. However, at higher flow rates, the concentrations of most metals approaches that of Wheal Jane No. 2 Shaft water, with the exception of arsenic. This remains low, probably due to precipitation within the adit system (see Figures 5.8a & b).

5.8 WATER QUALITY AT DEVORAN BRIDGE

The concentrations of metals in the Carnon River at Devoran Bridge reached a peak following the uncontrolled release from Nangiles Adit in January, 1992 (see Figures 5.9a & b). At this time, recorded concentrations of iron, zinc and cadmium exceeded 450 mg/l, 400 mg/l and 800 μg/l respectively. Since January 1992, concentrations in the Carnon River decreased to pre-incident level. However, close examination of the more recent data (see Figure 5.10) suggests that, on some occasions at least, metal concentrations increased as flow increased. These increases in concentration reflect the incidence of significant flow from Nangiles Adit following periods of heavy rainfall.

Figure 5.8a **Nangiles Adit Water Quality**

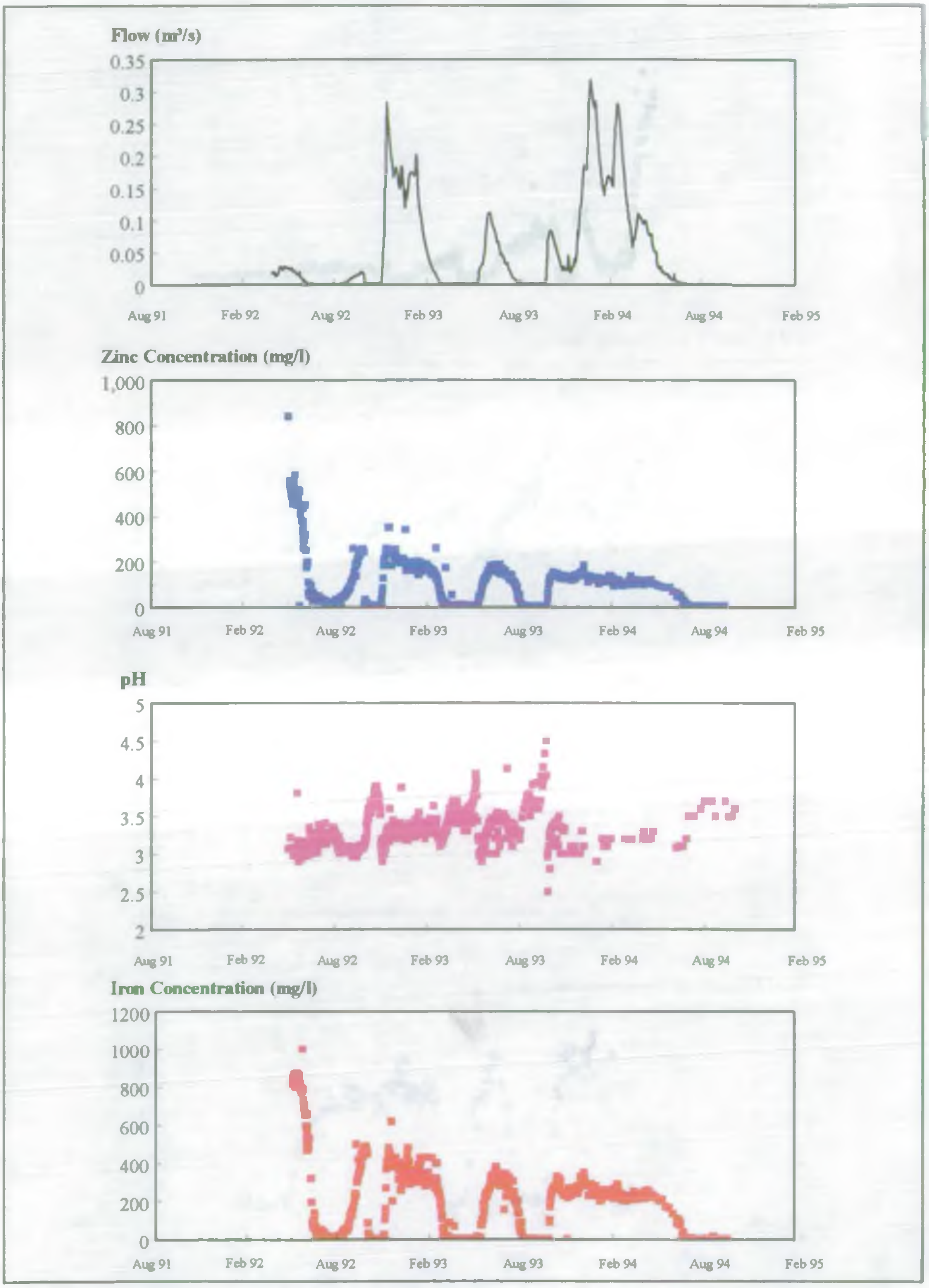


Figure 5.8b **Nangiles Adit Water Quality**

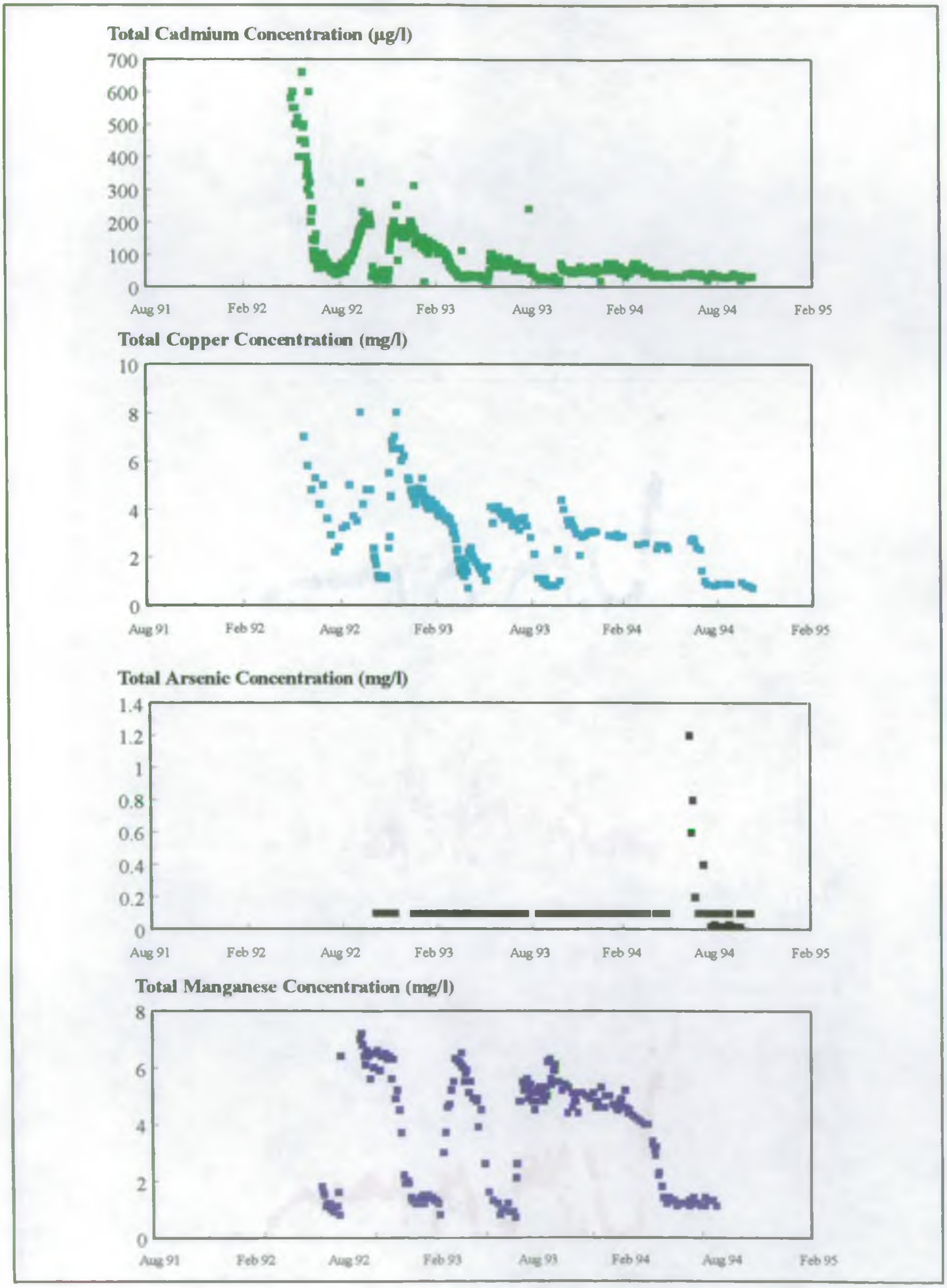


Figure 5.9a **Water Quality at Devoran Bridge**

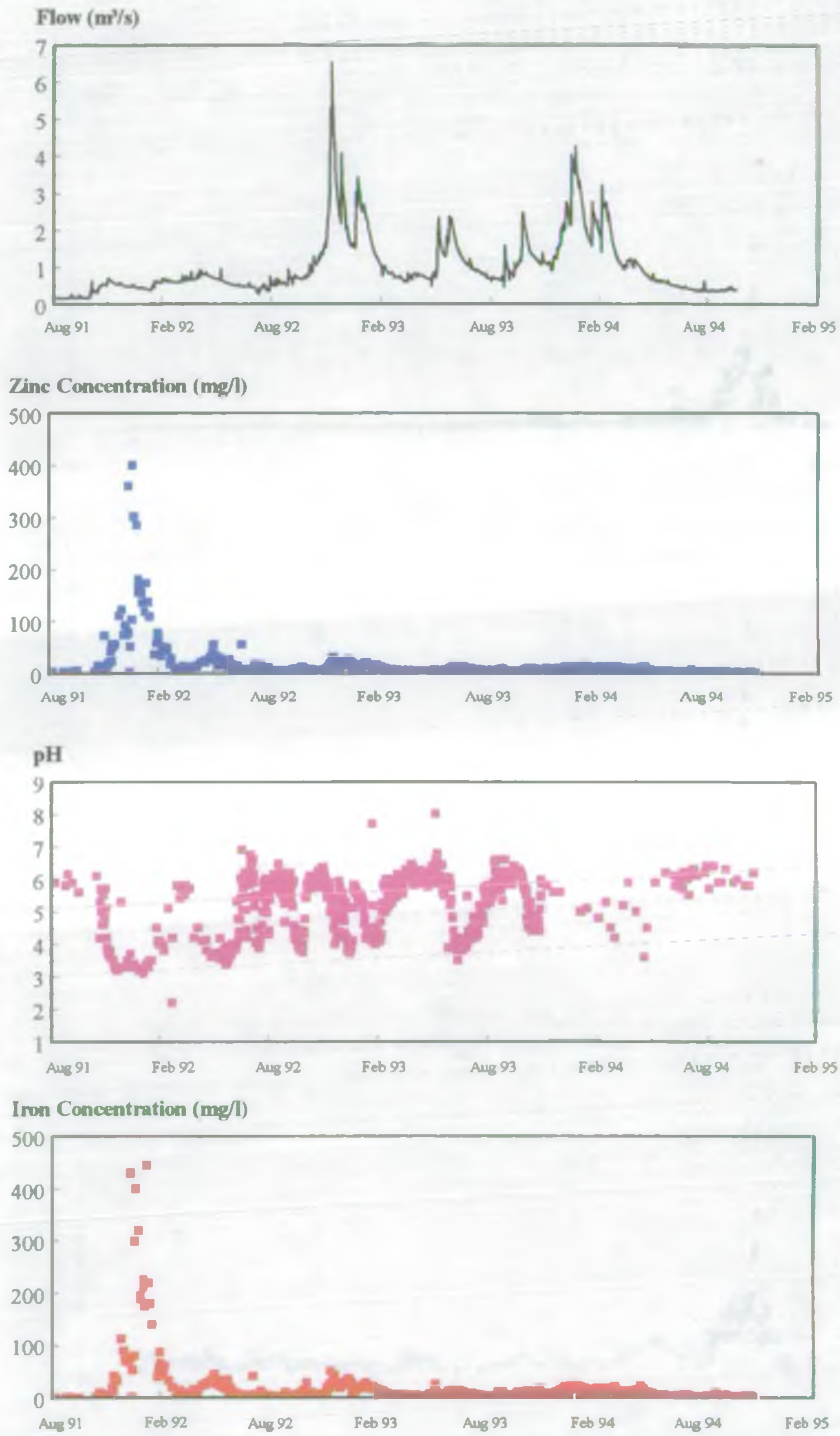


Figure 5.9b **Water Quality at Devoran Bridge**

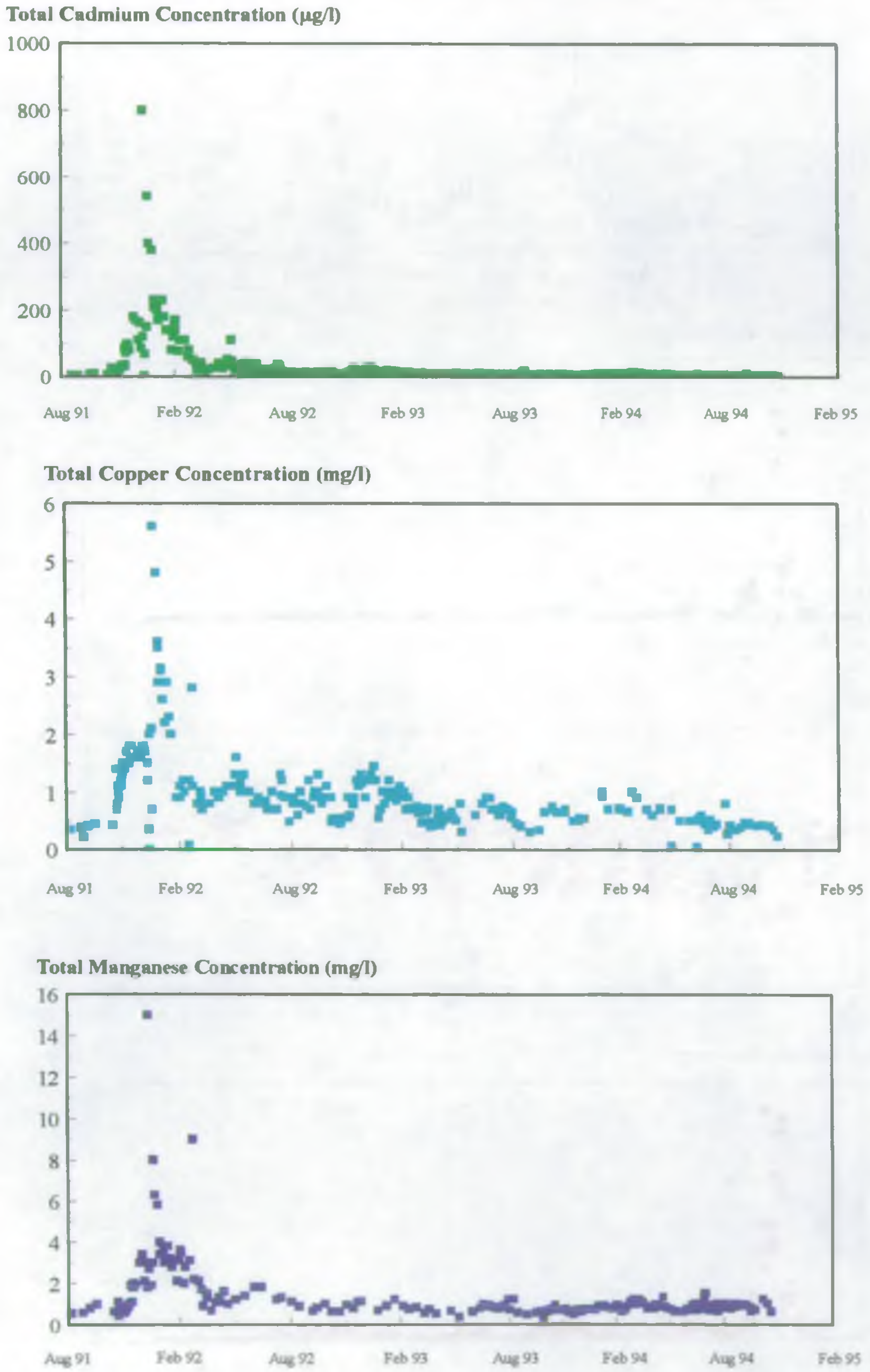
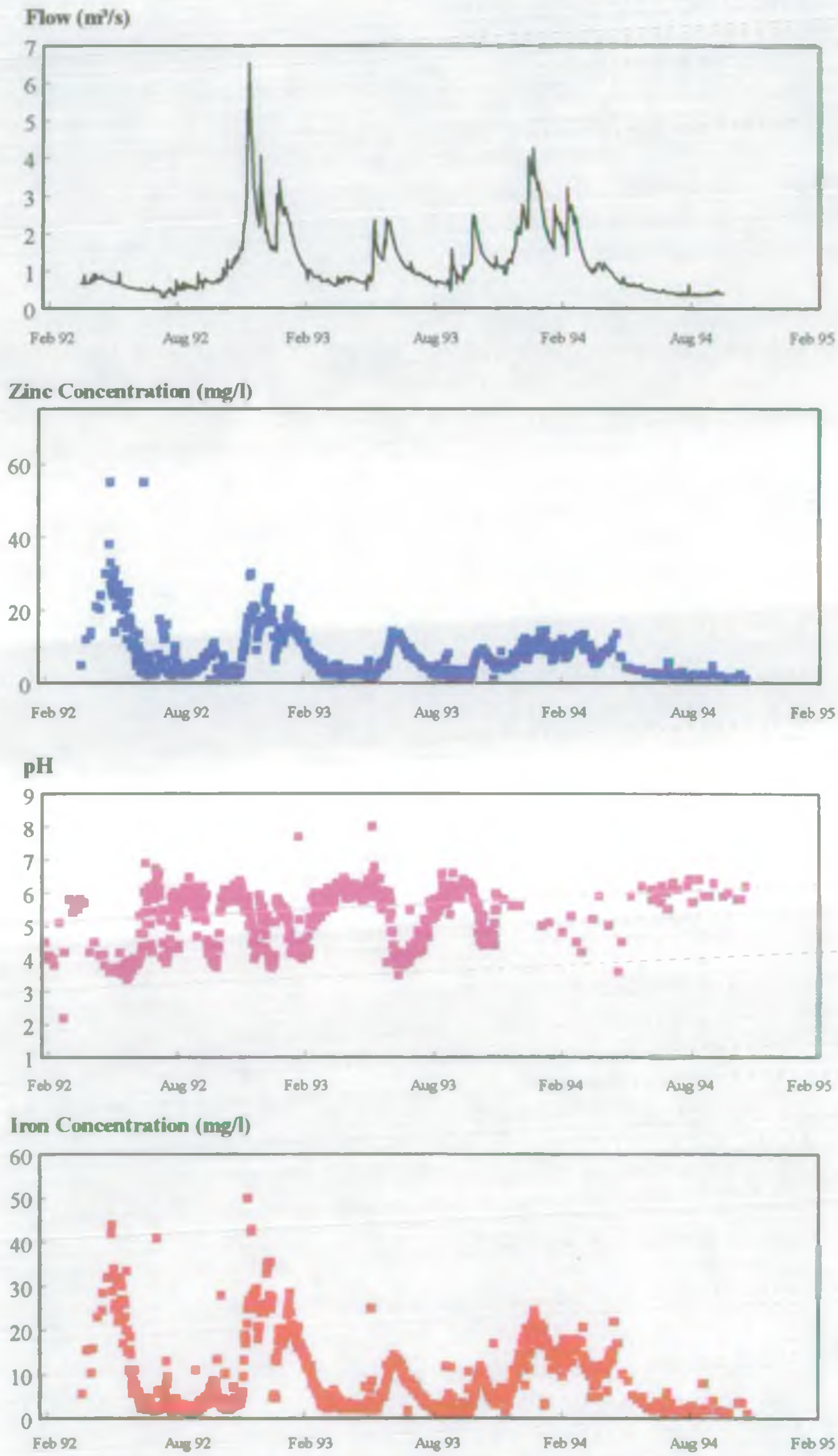


Figure 5.10 **Recent Water Quality at Devoran Bridge**



5.9 OTHER SOURCES OF CONTAMINATION IN THE CARNON VALLEY

5.9.1 County Adit

The flow hydrograph from County Adit (see Figure 5.11a) indicates a variation pattern similar to that shown in the Nangiles hydrograph with the characteristic winter peaks. However, discharge from County Adit is consistently higher than from Nangiles Adit, reflecting its larger catchment area and the influence of pumping at Wheal Jane which is designed to control the flow in Nangiles Adit. Mean summer and winter discharges from the County Adit are 234 l/s and 544 l/s respectively, between April, 1992 and October, 1994.

The quality of the discharge from County Adit appears to be improving slowly, although there is some evidence of an increase in iron concentration during periods of high flow (see Figures 5.11a & b). There is evidence also of an increase in the concentrations of iron, zinc and copper, and a small increase in flow, towards the end of 1991, coinciding with the final stages of the re-watering of the Wheal Jane mineworkings. This provides further evidence of the link between the two mines.

5.9.2 Wellington Adit

Flow from Wellington Adit is only gauged on a weekly basis. Inspection of the limited data for 1993 indicated that flow was occurring in the adit but was minor at between 0.5 and 1 l/s. Limited sampling of the discharge from 1993 to 1994 revealed the water quality to be highly variable (see Table 5-7).

Table 5-7 : Water Quality in the Wellington Adit

pH	Al	Cd	Cu	Fe	Mn	Zn	SO_4
2.8 - 6.5	3 - 34	0.02 - 0.13	<1	2 - 168	0.7 - 4.4	<1 - 30	32 - 712
All data expressed as a range in mg/l, except pH.							

5.9.3 Jane's Adit

Jane's Adit has been plugged since November, 1991 and the outlet valve opened only to allow a discharge to meet the requirements of the Pilot Passive Treatment Plant (a maximum of approximately 1.7 l/s) (see Section 10). There is also believed to be a leakage of similar magnitude around the plug which currently issues into the Carnon River.

5.9.4 Carnon River upstream of Twelveheads

Upstream of the gauging station at Twelveheads, the Carnon River drains a total area of 21.36 km^2. The Wheal Maid and Poldice Streams rise in the granite uplands and combine to form the Hale Mills Stream which flows into the Carnon

Figure 5.11a **County Adit Water Quality**

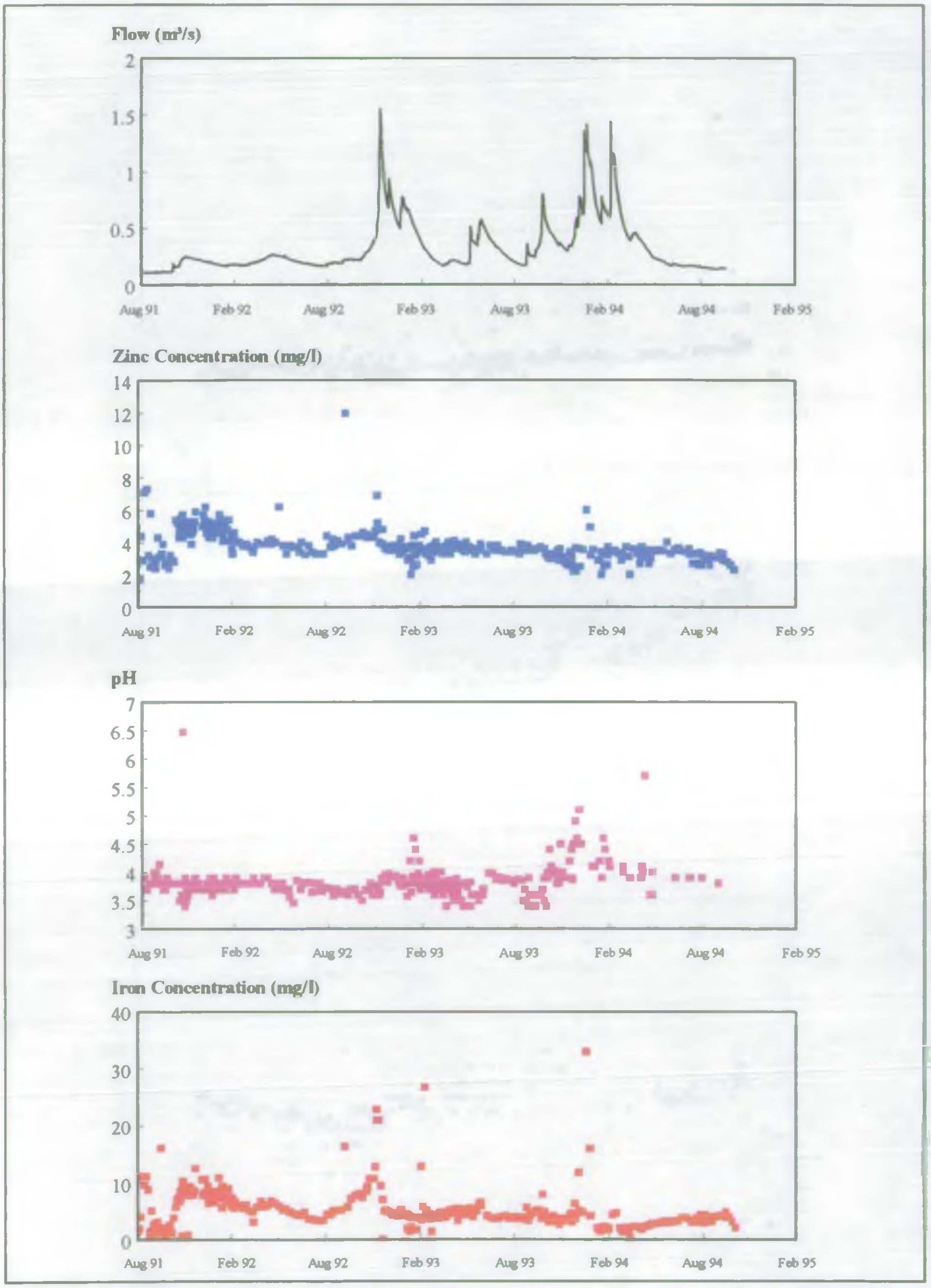


Figure 5.11b **County Adit Water Quality**

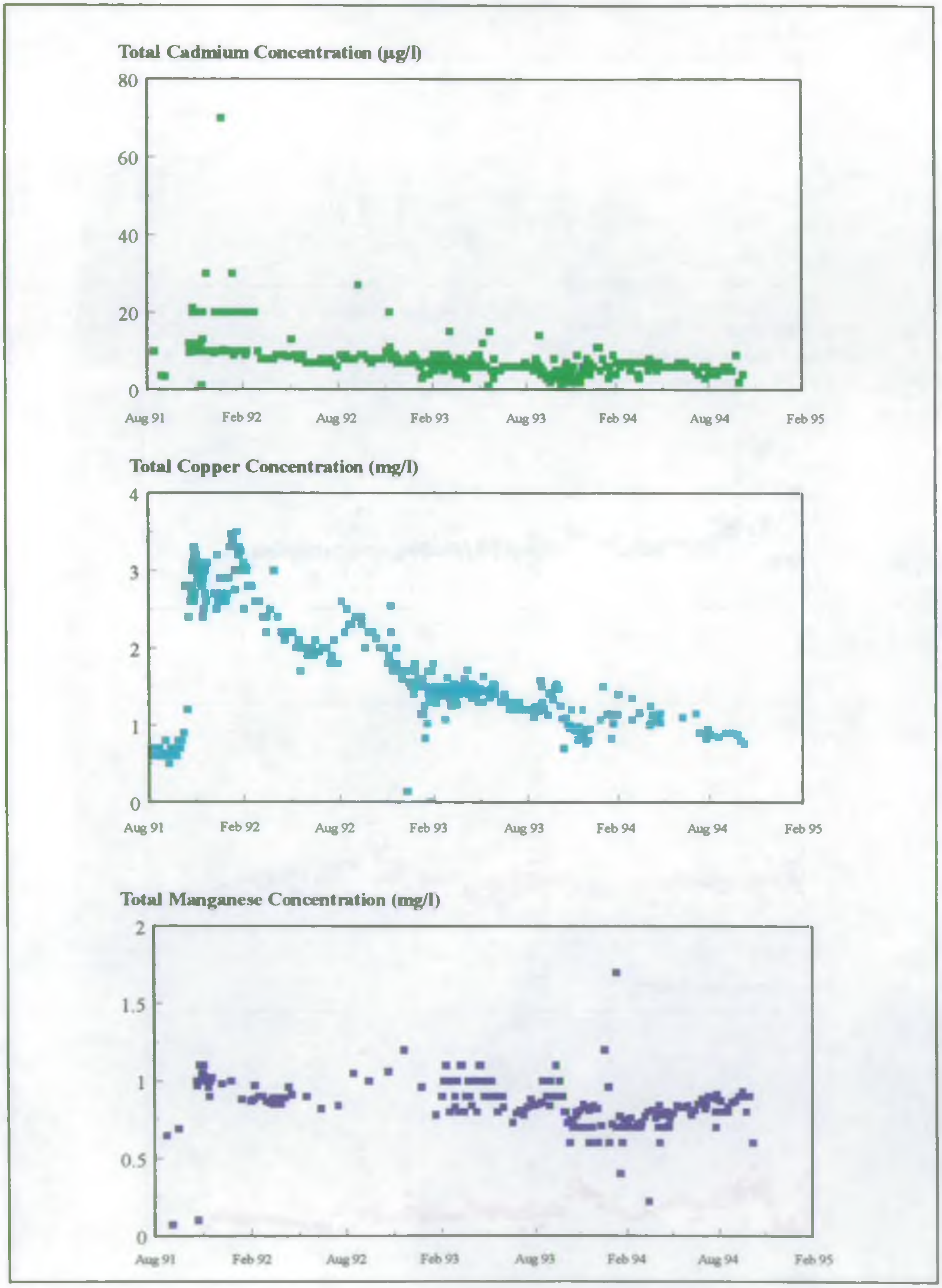


Figure 5.12a **Water Quality at Twelveheads**

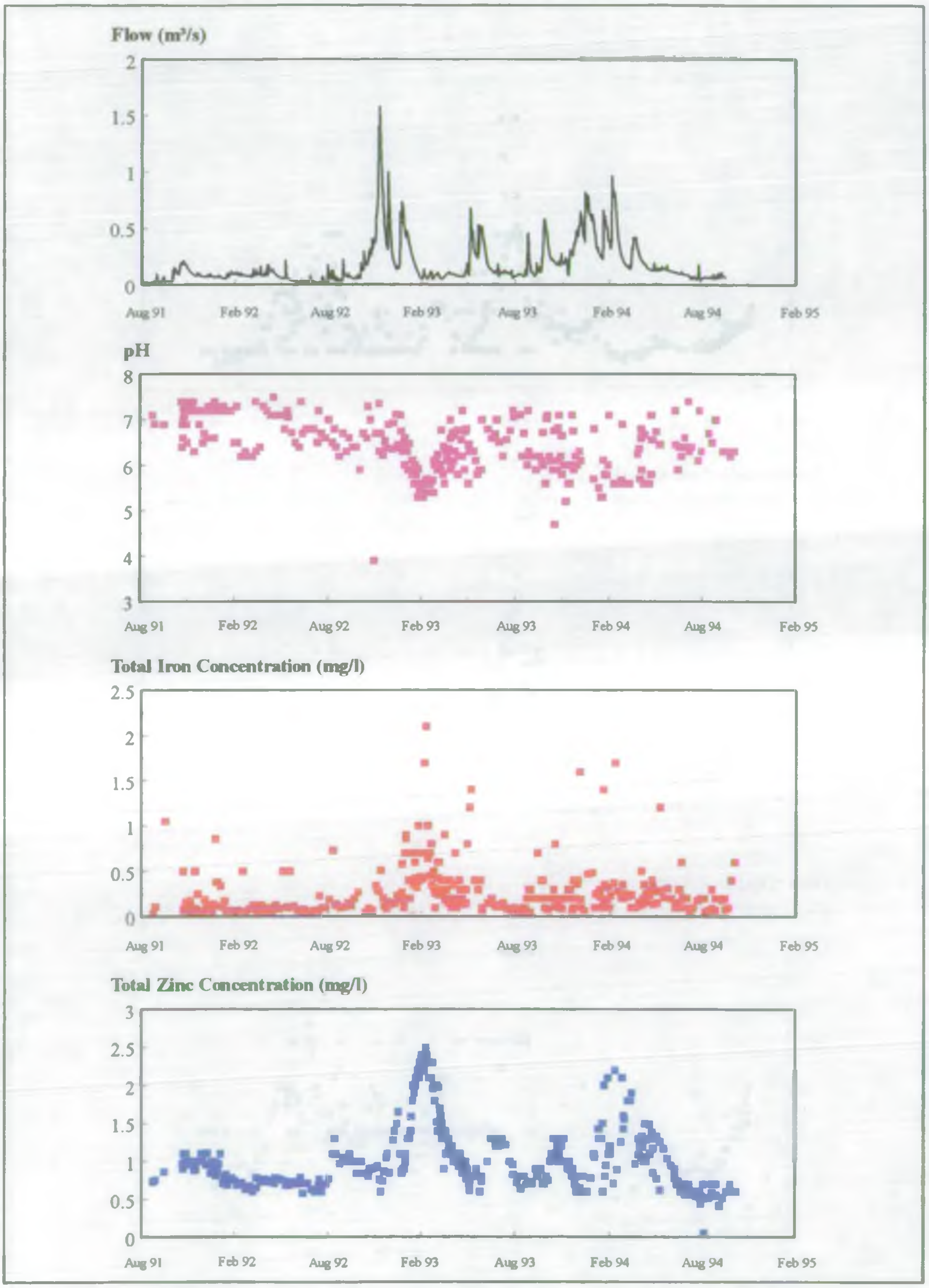


Figure 5.12b **Water Quality at Twelveheads**

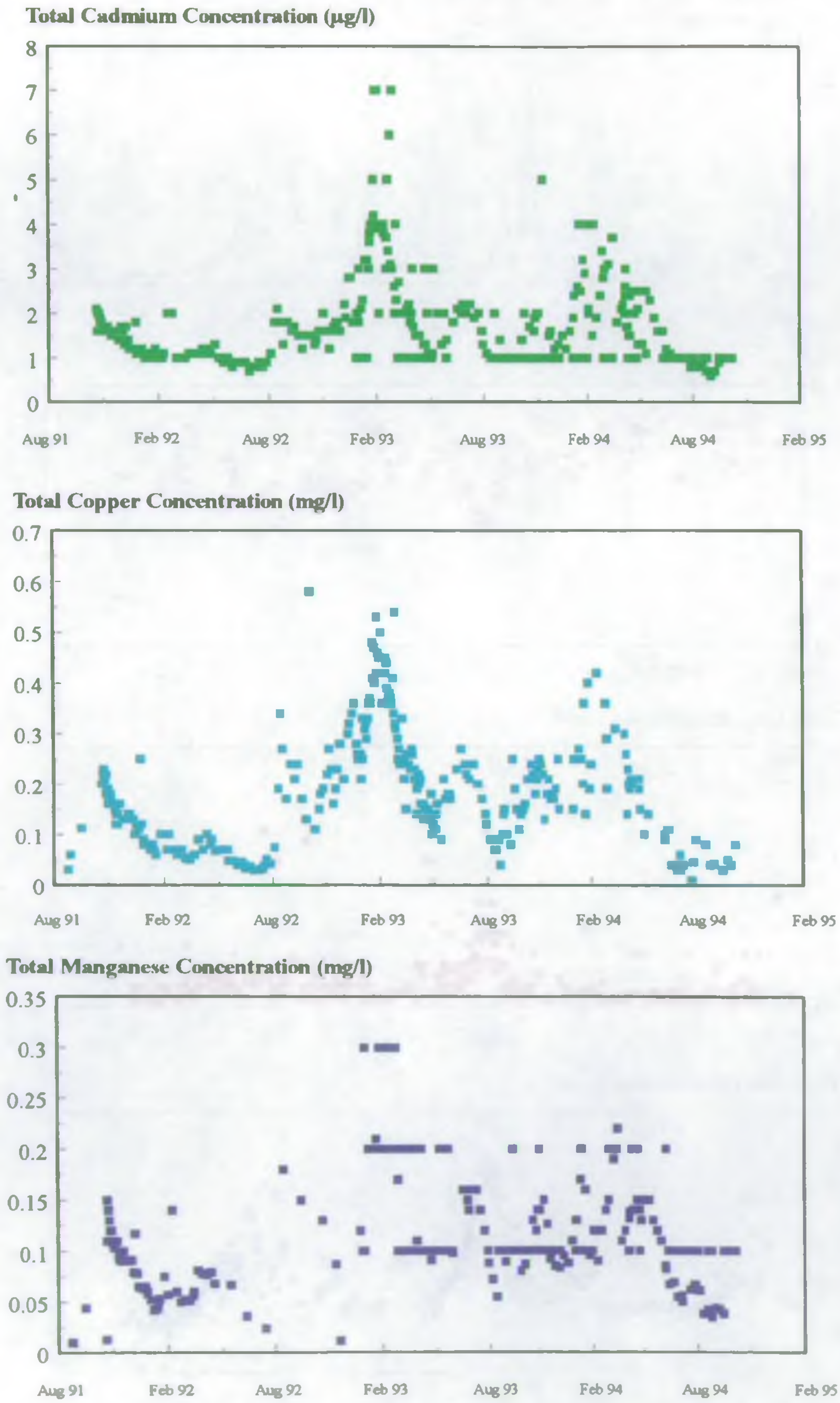
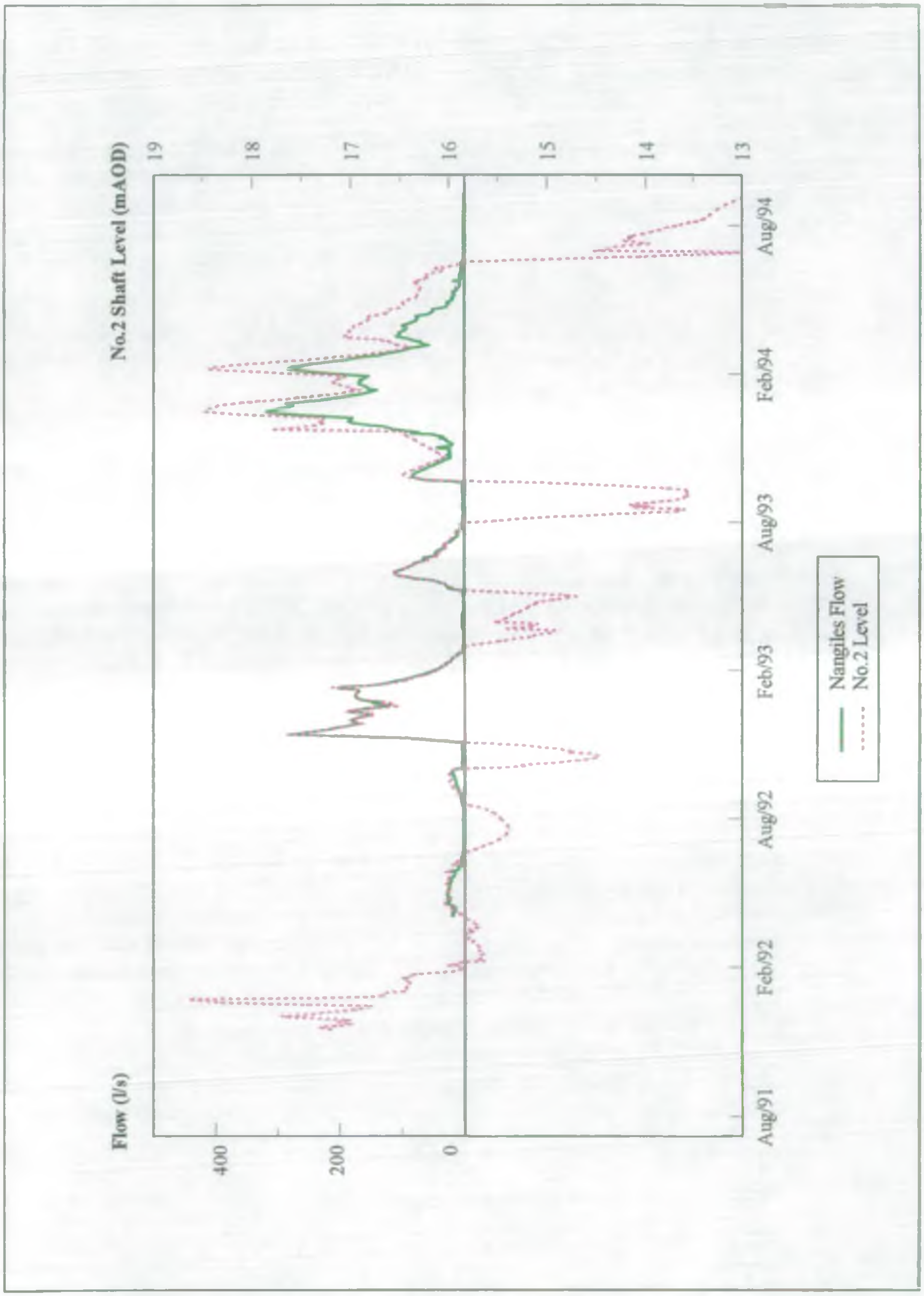


Figure 5.13 **Flow from Nangiles Adit with No.2 Shaft Levels**



River above Twelveheads gauging station. This whole area is considerably disturbed by old mine workings.

Mean flow for the period November 1991 to October 1994 was 175 l/s with a maximum flow of 1590 l/s on December 2, 1992; minimum flow at Twelveheads was 17 l/s.

Water quality in the Carnon River at Twelveheads is highly variable with peak concentrations occurring shortly after peak flow (see Figures 5.12a & b). Water quality in the upper Carnon catchment is influenced principally by two sources:

- Run-off from numerous spoil heaps immediately upstream of Twelveheads.
- Run-off and seepage from the Wheal Maid and Poldice Streams which drain an area which includes mineworkings and a disused tailings dam.

5.9.5 Clemows Stream

Clemows Stream drains a small catchment area of 2.39 km^2. The Clemows Valley Tailings Dam is situated in the catchment and flow in the stream is augmented by treated minewater from Wheal Jane.

Flow in the Clemows Stream has been recorded since July 1994. Between July 21 and October 1, 1994 the mean flow was 147 l/s which was similar to the mean pumped discharge from Wheal Jane No. 2 Shaft. Maximum and minimum discharge was 230 and 32 l/s respectively. In the absence of long term flow data it has been assumed that outflow from the Clemows catchment and tailings pond via the polishing lagoon is equal to Wheal Jane No. 2 pumped flow.

The potential error in Clemows Stream flow resulting from this assumption has been estimated as $\pm 15\%$, leading to errors in loadings at Devoran Bridge ranging from $\pm 0.2\%$ to 2.8% (depending upon the metal being evaluated.) Significant errors were not produced because the flow in Clemows Stream was of relatively good quality.

The water quality in the Clemows Stream is influenced primarily by the quality of the discharge from the polishing lagoon downstream of the Clemows Valley Tailings Dam. The polishing lagoon receives the outfall from the tailings dam, which includes both treated Wheal Jane No. 2 Shaft minewater and mill discharge, and the seepage through the dam intercepted by the toe drain. The quality of the Clemows Stream was monitored immediately prior to its confluence with the Carnon River between May and September 1994 (see Table 5-8).

Table 5-8 : Clemows Stream Water Quality

Al	As	Cd	Fe	Mn	Zn
0.6 - 7.0	0.01 - 0.05	0.002 - 0.023	1 - 23	0.6 - 3.6	0.2 - 19.6
All data as range in mg/l.					

Figure 5.14a **Water Quality of Hick's Mill Stream at Trehaddle**

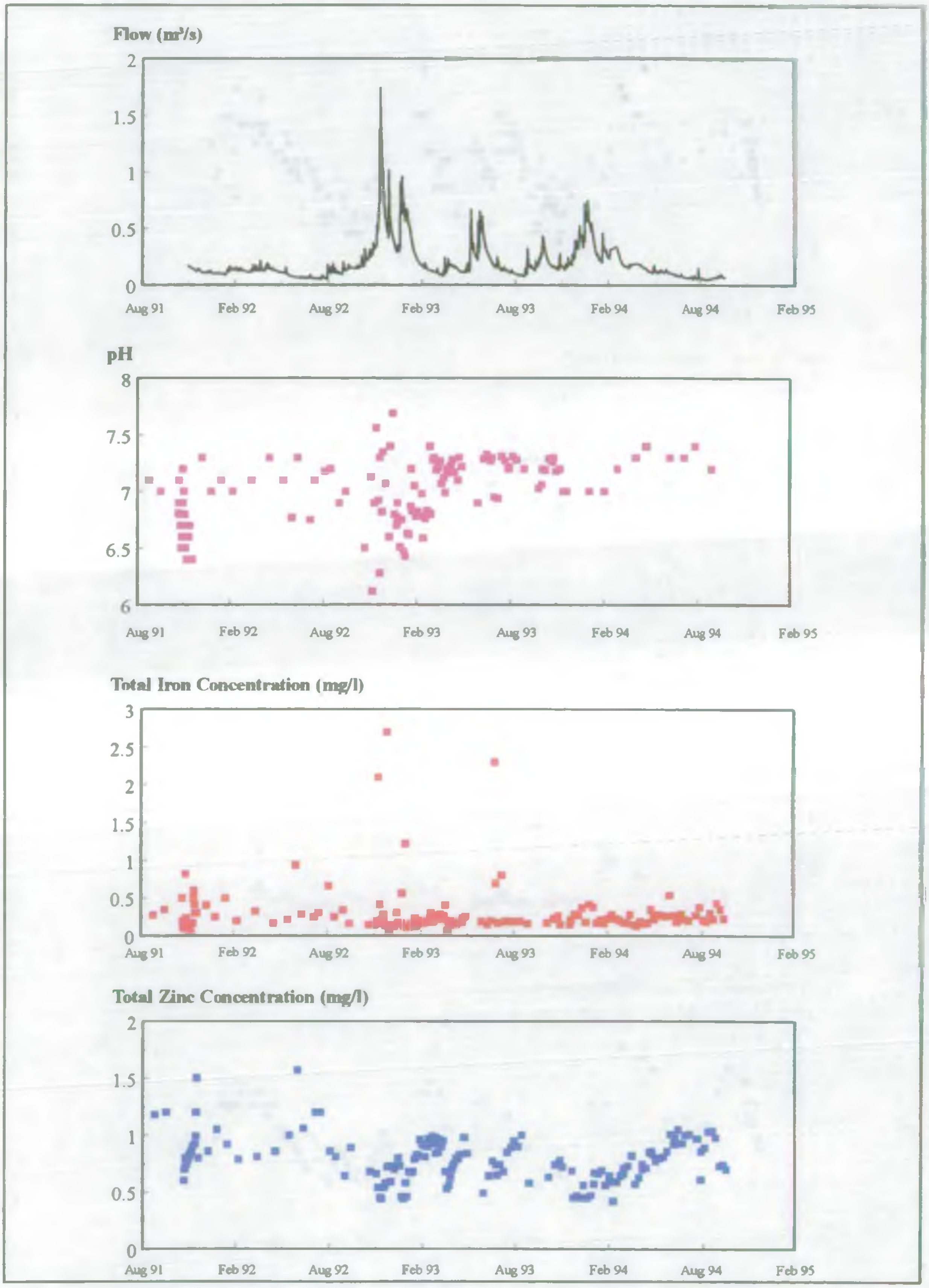
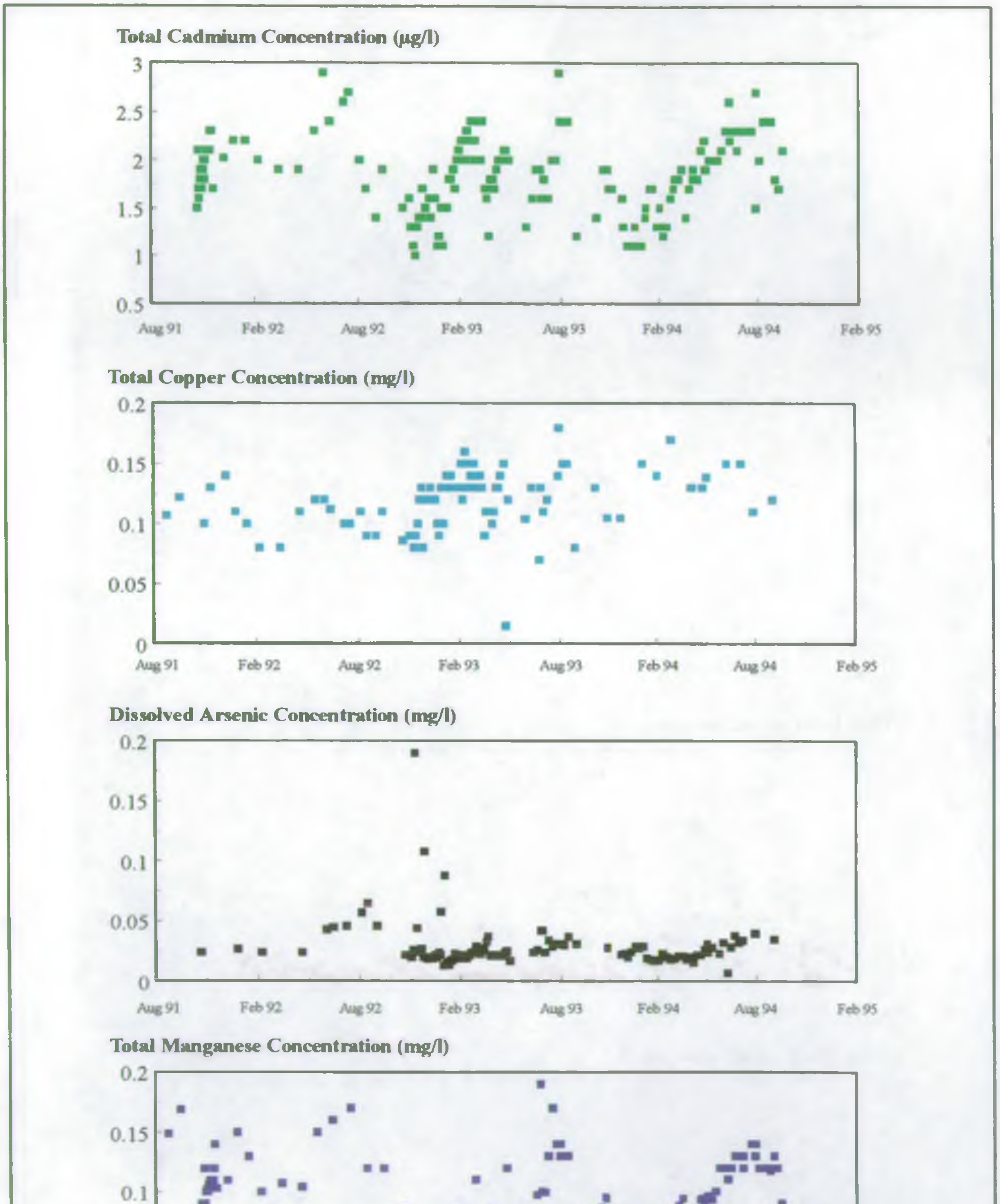


Figure 5.14b **Water Quality of Hick's Mill Stream at Trehaddle**



5.9.6 Hick's Mill Stream

Hick's Mill Stream rises in the west of the region on the granite upland and drains a catchment area of 12.46 km^2 above the gauging station at Trehaddle. Mean flow for the period 1992 - 1994 has been 191 l/s with maximum and minimum flows of 1750 l/s and 47 l/s respectively.

Water quality in Hick's Mill Stream is generally of a higher quality than is found elsewhere in the Carnon catchment upstream of Bissoe Bridge (see Figures 5.14a and b). Nevertheless, the water does contain concentrations of metals which are above normal UK background values, principally cadmium, copper and zinc. These elevated values are principally a consequence of a small part of the catchment which drains abandoned mineworkings.

5.9.7 Relative Importance of Contaminant Sources

An estimate of the relative importance of the contaminant loadings at the various monitoring locations on the water quality at Devoran Bridge has been undertaken using data from October, 1993 - September, 1994 (see Table 5-9). It is apparent that, even allowing for the success of the existing treatment strategy, the Wheal Jane complex remains a significant source of metal contamination. However, it is also apparent that other sources within the catchment, principally County Adit, also have a significant effect on metal loadings at Devoran Bridge. Of particular significance is the relative importance of the non-point sources, both those above Twelveheads and Trehaddle which are included in measurements taken at these sites and the non-measured "other" sources. This suggests that significant metal loadings would be experienced at Devoran Bridge even if the two major point sources were treated.

Table 5-9 : The Relative Importance of Sources of Contamination Recorded at Devoran Bridge

Monitoring Location	Al	As	Cd	Cu	Fe	Mn	Zn
• Twelveheads	7%	18%	4%	5%	<1%	3%	2%
• County Adit	33%	41%	28%	54%	8%	35%	13%
• Hick's Mill	1%	9%	4%	4%	<1%	2%	1%
• Wheal Jane[1]	52%	20%	56%	23%	85%	53%	77%
• Others[2]	7%	12%	8%	14%	5%	7%	7%

All data expressed as % of the loading at Devoran Bridge based on calculated mean daily loadings for 4 monitored locations and estimated loadings for other sources based on October, 1993 - September, 1994 data.

[1] Wheal Jane complex includes Nangiles Adit and Wheal Jane No. 2 Shaft water only.
[2] Other sources includes small non-measured point sources (eg. Wellington Adit) plus diffuse sources. The contributions from these sources has been estimated by mass balance.

5.10 CONCLUSIONS

A considerable volume of hydrological and water quality data has been collected from the Carnon River catchment since the release of minewater in January 1992. The major sources of flow and metal loadings have been identified which contribute to concentrations at Devoran Bridge.

Since 1992 metal concentrations have decreased at Devoran Bridge to pre-incident levels, although there are occasions, notably when flow occurs from Nangiles Adit, when metal concentrations increase temporarily.

Nangiles Adit acts as an overflow for the Wheal Jane complex. The Wheal Jane No. 2 Shaft metal concentrations have also decreased from a peak of 6850 mg/l to an average of 550 mg/l in September, 1994.

It is apparent that the Wheal Jane complex still remains a significant source of metal contamination in the Carnon River. Other sources also have an impact on the metal loadings at Devoran Bridge and monitoring is continuing, so that contributions from both point and non-point sources may be evaluated.

6. HYDROLOGICAL MODELLING

CONTENTS

6.1 INTRODUCTION

The existing treatment system at Wheal Jane is achieving the NRA objective of preventing further deterioration of the Carnon River. Nevertheless at some stage a long-term strategy for the Carnon River, and for the treatment of Wheal Jane minewater in particular, will be required. The successful implementation of such a strategy relies upon identifying the principal sources of contamination within the catchment, understanding their flow and quality characteristics and evaluating potential methods of treating these sources so that the water quality objectives of the Carnon River can be met.

Minewater and surface water models have been developed to assess the effectiveness of each treatment option in meeting water quality objectives. These models include the:

Wheal Jane flow model
Carnon River flow model
Carnon River quality model

A water quality model for Wheal Jane was also developed but is not considered to be sufficiently reliable for the purposes of designing and costing a treatment strategy.

This section describes the development, use and reliability of the models and the conceptual model of the Carnon River catchment upon which they are based.

6.2 CONCEPTUAL HYDROLOGICAL MODELS

6.2.1 Carnon River

The characteristics of the Carnon catchment were described in Section 5 using the data collected during the current study. The catchment down to the tidal limit at Devoran Bridge covers an area of 45.5 km^2 (see Figure 6.1) and contains several gauged and ungauged sub-catchments (Figure 6.2).

Measured flows in the upstream catchment are given in Table 6-1 which includes average flows for the Hick's Mill Stream at Trehaddle and the Carnon River at Twelveheads for 1992 to 1994. These flows have been expressed as unit runoff (flow/catchment area) and show that, on average, unit runoff is 37% over the Twelveheads catchment area whereas unit runoff at Trehaddle is between 46% and 80%.

Table 6-1 : Unit Runoff Upstream of Bissoe Bridge

	1992		1993		Oct 93 - Sep 94	
Rain (mm)	1133.5		1420.4		1593.4	
Effective Rainfall (mm)	572.5		864.7		994.5	
Days	366		365		371	
Flow	l/s	%	l/s	%	l/s	%
Twelveheads	143	19	206	21	247	23
Trehaddle	181	24	229	24	178	17
County Adit	276	36	364	37	412	39
Nangiles Adit	35	5	48	5	75	7
Wheal Jane No. 2 Shaft	120	16	127	13	151	14
Total (l/s)	755		974		1063	
Unit runoff	(mm)[1]	% eff rain	(mm)[1]	% eff rain	(mm)[1]	% eff rain
Twelveheads	211	37%	304	35%	371	37%
Trehaddle	459	80%	580	67%	458	46%
Total	659	115%	848	98%	941	95%

[1] Calculated from flow/catchment area
where Twelvehead catchment = 21.36 km^2
Trehaddle catchment = 12.46 km^2
Total gauged catchment
upstream of the Clemows Stream = 36.21 km^2 (see Figure 6.2)

Unit runoff for the total flow in the Carnon River at the confluence with the Clemows Stream (a gauged area of 36.21 km^2) is approximately 100%. Average annual data are not ideal for describing hydrological processes but the lag in the system (see Section 6.3.1) means that shorter time intervals produce inconsistent results.

These observations lead to the following conceptual catchment flow balance for gauged flows upstream of Bissoe Bridge and Clemows Stream:

- A significant proportion (approximately two-thirds) of effective rainfall on the Twelveheads catchment appears to infiltrate and pass subsurface to adjoining sub-catchments, reappearing either in adits and mineworkings or as base flow further down the catchment. The remaining one-third (i.e. the measured flow at Twelveheads) consists of a direct runoff component (approximately 38%) and an estimated baseflow component of 62% (see Section 5.6)

- Approximately one-third of the effective rainfall on the Hick's Mill Stream catchment also appears to pass subsurface to adjoining sub-catchments. The remaining two-thirds (ie. the measured flow at Trehaddle) again have a baseflow component of around 62% (see Section 5.6).

Figure 6.1 Hydrological Catchments and Gauging Sites

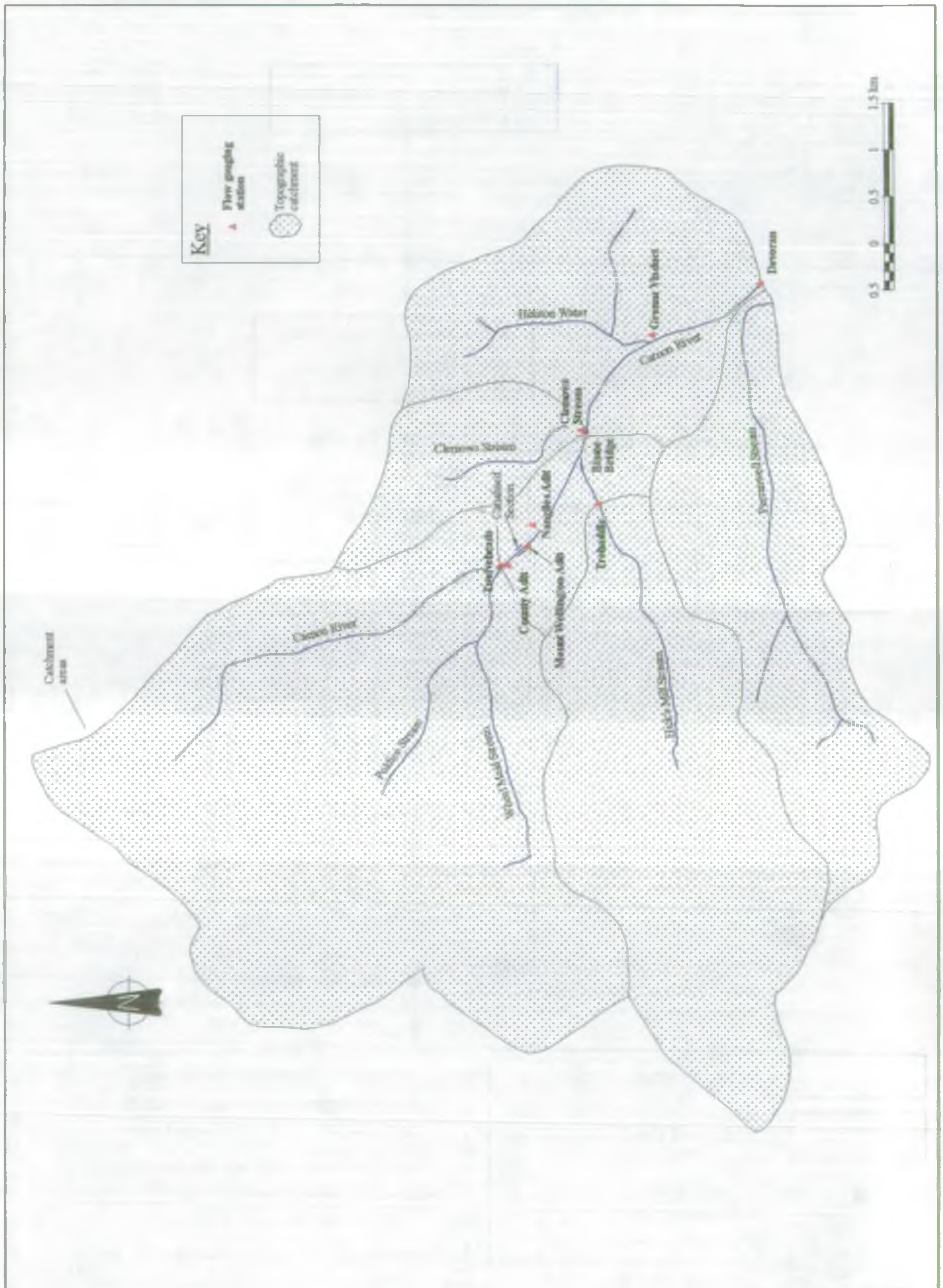
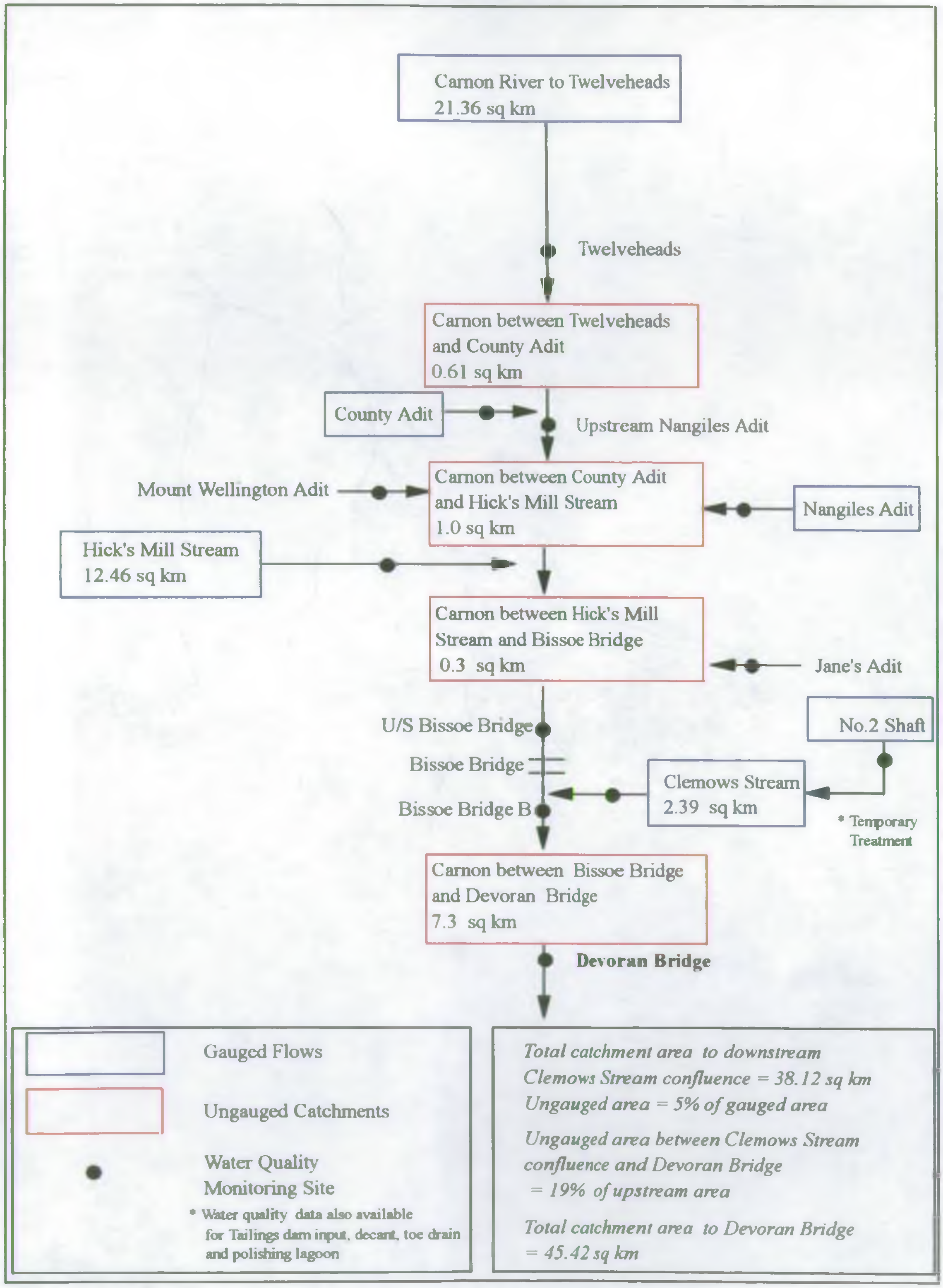


Figure 6.2 Carnon Valley Sub-Catchment Areas Showing Gauged and Ungauged Catchments and Monitoring Sites



- Gauged flow upstream of Bissoe Bridge and Clemows Stream is roughly equivalent to effective rainfall over the gauged catchment implying that the infiltration noted above has reappeared as adit flow, minewater flow or base flow in the intervening catchment.

For the downstream, ungauged catchment, the following assumption is made:

- Flow from ungauged catchment areas is proportional to flow from the gauged catchment area upstream of Bissoe Bridge and Clemows Stream.

This is acknowledged to be an oversimplification and is based on limited data and the observation that unit runoff upstream of Bissoe is approximately 100%. There are indications from measured changes in flow between Twelveheads and Bissoe (see Section 5.6) that under low flow conditions there is a significant baseflow contribution along this stretch of the Carnon River (catchment area 1.9 km^2), possibly derived from the upstream catchment, leading to unit runoff in excess of 100%. Water quality data indicate that this baseflow does not contain significant concentrations of metals so the contribution in terms of loading at Bissoe Bridge and hence Devoran Bridge, is not considered to be significant. The use of gauged flows over these ungauged catchments will improve confidence in the results however.

For the purposes of flow modelling it has been assumed therefore that:

(i) the inflow to the Carnon River between Twelveheads and Bissoe Bridge is 5% of the gauged flows upstream and;

(ii) the inflow to the Carnon River between Bissoe and Devoran Bridge is 19% of the upstream flow.

As more flow data are collected it will be possible to improve the conceptual and hydrological models of the Carnon River.

6.2.2 Wheal Jane Mine

The following conceptual model is used as the basis for the empirical Wheal Jane flow model (Section 6.3).

The Wheal Jane mineworkings pass beneath the Carnon River (see Fig 5.1) and have a high hydraulic conductivity resulting from mine workings and interconnections. Minewater inflow is derived from rainfall, and minewater outflows occur into the Carnon River from controlled pumping at Wheal Jane No. 2 shaft (and ultimate discharge into the Clemows Stream) and as untreated flow from Nangiles adit. Flow from Jane's Adit into the Carnon River is also possible but this is restricted to a minor seepage by the downstream plug in the Adit.

Flow from Nangiles Adit is dependent upon the water level in Wheal Jane No.2 Shaft, with flow only occurring when the water level in the shaft reaches the overflow level (see Section 5.7). The quantity of untreated flow from Nangiles Adit is therefore a function of effective rainfall, pumping rate and the water level in the shaft. If the water level is below overflow level, inflow to the mine can be accommodated as a change in storage, whereas if the water level is close to overflow level, any additional inflow will result in a discharge from Nangiles Adit.

This conceptual model can also be refined as long term flow, level and quality data are collected.

Ultimately an integrated catchment model should be developed, based on physical and chemical processes within the catchment.

For the purposes of the current study the hydrological models (described in the following sections) are useful and sufficiently accurate for assessing the effects of treating the major sources of contamination.

6.3 WHEAL JANE FLOW MODEL

6.3.1 Derivation and Validation

A relationship between inflow and outflow at Wheal Jane was developed so that an estimate of probable future outflows and the treatment required could be made.

Rather than attempt to simulate all the complexities of the system, an empirical model was established which related mine inflow to outflow using the period of intense monitoring from 1992 to 1994 for calibration. It was assumed that inflow was a function of effective rainfall, and outflow was the sum of flows from Wheal Jane No. 2 Shaft and Nangiles Adit, with an allowance made for change in storage.

Inflow = Wheal Jane No. 2 + Nangiles - change in storage   Equation 6.1

where Nangiles Adit flow is a function of level in Wheal Jane No. 2 Shaft.

The real situation is more complex than this due to contributions from and losses to rivers. Even without these variables, there are two unknown quantities in the relationship: storage coefficient and catchment area.

Initially, the relationship between the inflows and outflows was examined for a range of combinations of area and storage. Typically the relationship looked like the upper graph in Figure 6.3 and it was apparent that some form of lag and smoothing function was needed for effective rainfall.

Figure 6.3 **Wheal Jane Water Balance Model**
Comparison of Inflows and Outflows

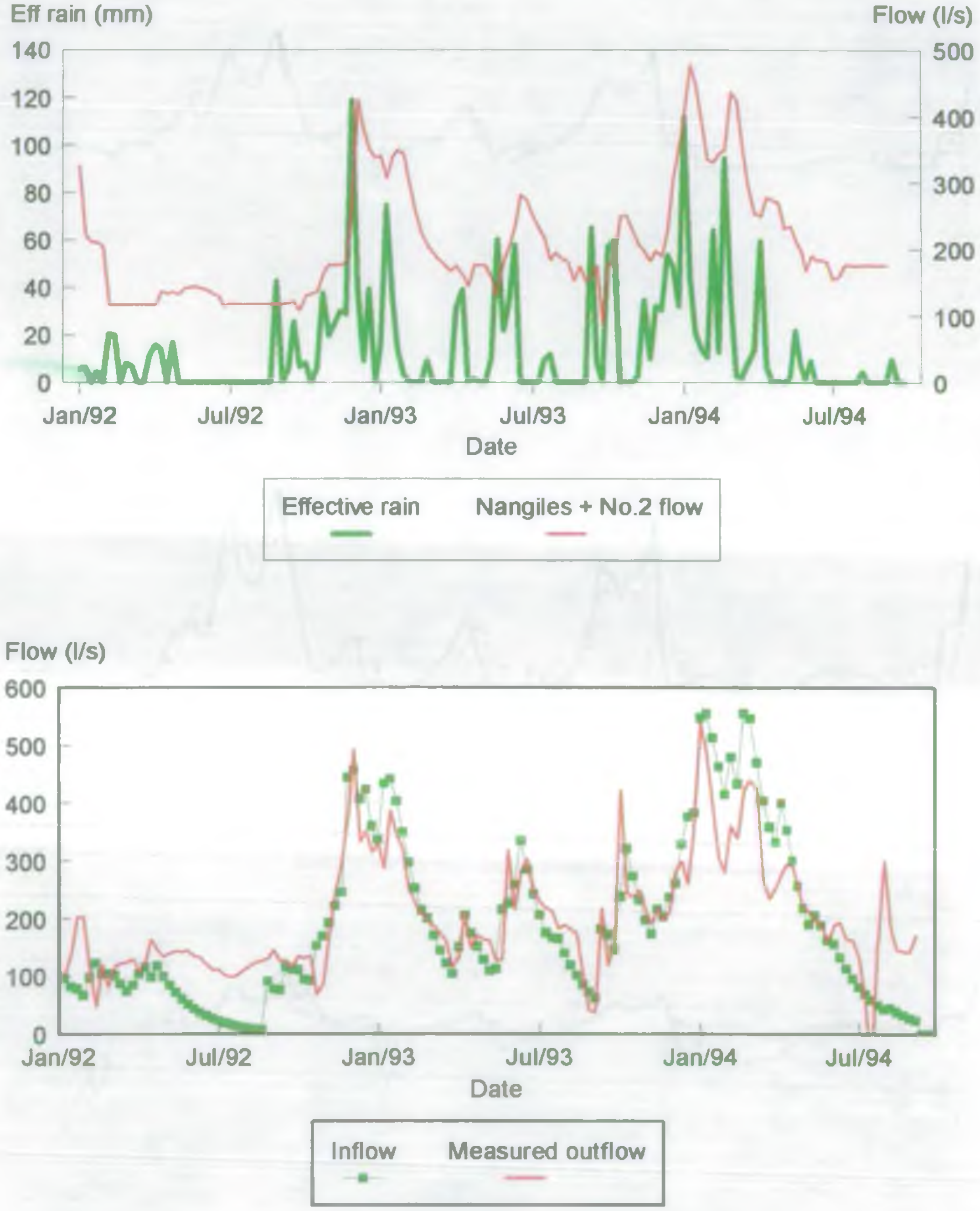
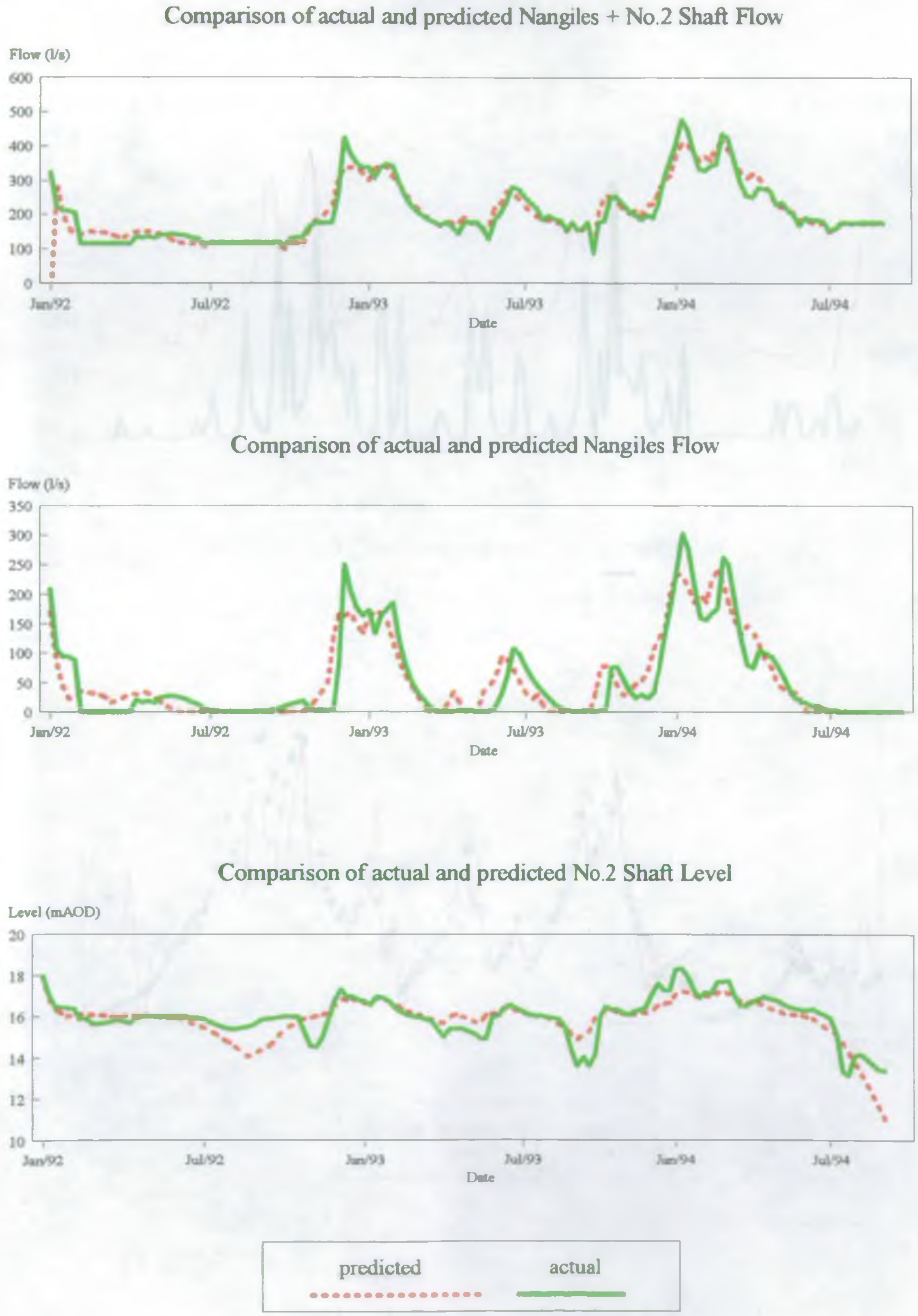


Figure 6.4 **Wheal Jane Water Balance Model**
Comparison of Predicted and Actual Flows and Water Levels



The relationship used was:

$$Q_2 = KQ_1 + R(1-K) \qquad \text{Equation 6.2}$$

where Q_2 is inflow at time t
Q_1 is inflow at time t-timestep
K is the recession constant for the time interval
R is effective rainfall

A weekly timestep was selected initially.

Therefore there were three unknowns in the relationship; storage coefficient, area and the recession constant.

A best fit approach was used, therefore, and the variables altered until inflows approximated outflows. The actual data used for the calibration included Wheal Jane No. 2 Shaft level and flow, Nangiles flow and effective rainfall, weekly from January, 1992 to September, 1994. The final fit between inflow and outflow is shown in the lower graph in Figure 6.3. The variables used were:

- storage coefficient — 0.01
- area — 8 km^2
- recession constant — 0.85 for weekly time interval

The model was then used to predict outflow in the form of Nangiles flow and Wheal Jane No. 2 Shaft water level for given rainfall and pumping scenarios. The predicted outflow parameters for the calibration period are compared with actual values in Figure 6.4. There is seen to be good agreement with the flows from Nangiles. Water levels in Wheal Jane No. 2 Shaft also show a generally good fit except at the extremes.

The accuracy of the model was quantified by a numerical comparison of the model results with measured field results (see Table 6-2) for a selection of wet and dry periods of varying length. The errors in predicting flow ranged from 14 to -18% but, in most instances, were less than 5%. The worst cases were associated with large variations in water level (i.e. change in storage). These periods were examined more closely and changes were made to the variables until a best fit was achieved. The fit at other times was then found to be very poor. This may be due to relationships between storage and level or river/ groundwater flow and level which have not been accounted for in the model.

The model is a valuable tool for estimating mine outflows for given rainfall events, particularly when changes in storage are small, for example over yearly periods. Under these conditions and within the range of calibration, the accuracy of the predicted outflow is estimated to be within ±5%.

The adequacy of the weekly timestep used in the model was assessed by examining the rate of response of the system to rainfall events. It was found that, after a heavy rainfall event, there was an initial outflow response which gradually

Table 6-2 : Wheal Jane Flow Model Calibration

Historical		29/4/92 to 30/6/92	4/8/93 to 7/9/93	8/6/94 to 26/7/94	1992	1993	Sept 1993-94	21/10/92 to 22/12/92	10/11/93 to 11/1/94	Week ending 4/1/94	Week ending 18/8/92	Week ending 11/1/94	Week ending 28/9/93	Week ending 1/12/92
Rain	(mm)	53.5	62	48.7	1133.5	1420.4	1593.4	407.7	447.9	116.2	33.3	49.3	6.9	125
Effective rain	(mm)	0	0	0	572.5	864.7	994.5	347.3	398.6	111.9	0	44.9	0	118.8
No. of days														
Actual														
No.2 flow	(l/s)	115	165	168	126	167	168	172	166	166	116	174	85	174
Nangiles	(l/s)	20	4	4	35	48	71	81	116	240	1	303	1	82
No.2 + Nangiles	(l/s)	135	169	172	161	214	244	253	282	406	117	477	86	256
Mean No.2 level	(m AOD)	15.99	15.21	15.30	15.96	15.93	16.05	15.93	17.10	17.77	15.41	18.31	13.86	16.35
Predicted														
Inflow	(l/s)	117	137	135	155	217	231	270	297	424	87	428	173	359
Nangiles	(l/s)	9	0	0	380	51	76	82	114	207	0	234	5	128
No.2 + Nangiles	(l/s)	124	165	168	154	217	244	254	280	373	116	408	90	302
Mean No.2 level	(m AOD)	15.90	15.47	15.31	15.79	16.10	15.49	16.30	16.49	16.87	14.39	17.13	15.62	16.40
Change in storage	(l/s)	7	280	330	-1	0	14	-16	-17	-50	29	-20	-83	-58
No.2 + Nangiles error	(l/s)	11	4	4	7	-3	0	-1	2	33	1	69	-4	-46
%		8	2	2	4	-2	0	0	1	8	1	14	-5	-18

decreased over a period of months. In view of the length of lag, a weekly timestep is considered adequate.

6.3.2 Long-Term Predictions

The Wheal Jane flow model produces estimates of mine inflow and outflow for given effective rainfall. Weekly estimates of effective rainfall were made for the period 1952 to 1994 using daily rainfall data and average weekly actual evapotranspiration data (see Section 5.2). Effective rainfall was converted to inflow using Equation 6.2 and mine outflow estimated using Equation 6.1. The model was used to predict average weekly mine outflows for the rainfall events recorded between 1952 and 1994. These outflows were utilised as input to the Carnon River quality model.

The average annual inflows from 1952 to 1994 occurring as a result of rainfall are presented in Table 6-3 and are seen to range from a maximum of 250 l/s in 1960 to a minimum of 143 l/s in 1992 with an average of 192 l/s. These figures indicate that, on an annual average basis, four pumps in Wheal Jane No. 2 Shaft pumping at a combined rate of approximately 230 l/s (4.4 mgd) would be sufficient to control the inflow.

However there is a wide variation in inflow over each year, with peak inflows typically in the region of 400 l/s and minimum inflows around 100 l/s.

The maximum weekly inflow for the rainfall events from 1952 to 1994 was 501 l/s which occurred in February, 1988 as a result of a weekly effective rainfall of 171.1 mm. If an input of this magnitude occurred when the pumping rate was 232 l/s, there would be an excess inflow of 269 l/s. This excess could either be discharged from Nangiles adit or be taken up by storage, or a combination of the two. A flow of 269 l/s is equivalent to a rise in water level of approximately 2 m in a week, so if initial water levels were less than 2 m below the decant level of Nangiles Adit, there would not be a discharge from the adit.

Following on from this example, it is clear that the most likely time for discharge to occur from Nangiles Adit is after a period of prolonged high effective rainfall which has caused water levels to rise despite pumping.

The wettest and driest three month periods between 1952 and 1994, and the wettest cumulative periods are shown in Table 6-4. The estimated inflow to the mine (which is equal to outflow assuming no change in storage) is also shown.

Table 6-3 : Long Term Rainfall and Predicted Wheal Jane Mine Inflow

Year	Effective Rain (mm)	Rain (mm)	Inflow Mean (l/s)	Max. Mean weekly (l/s)	Min. Mean weekly (l/s)
1952	706.0	1252.1	161	333	85
1953	190.7	714.1	177	293	87
1954	839.9	1399.0	187	404	107
1955	617.4	1158.5	202	398	86
1956	629.8	1175.4	183	326	84
1957	608.1	1149.5	210	349	99
1958	936.3	1477.4	214	366	124
1959	717.9	1259.0	180	396	84
1960	1072.3	1613.4	250	407	96
1961	589.8	1127.6	202	412	85
1962	617.5	1166.7	170	334	85
1963	783.2	1324.3	203	343	113
1964	393.7	934.8	163	257	87
1965	718.3	1259.7	169	354	100
1966	883.0	1424.1	246	420	103
1967	616.3	1157.4	191	305	85
1968	601.7	1147.3	169	284	103
1969	719.9	1261.3	191	342	99
1970	493.1	1034.2	169	381	82
1971	294.5	835.6	156	269	82
1972	671.8	1241.0	169	358	86
1973	347.6	1039.5	191	340	82
1974	869.6	1500.5	234	430	94
1975	478.1	1042.1	182	319	89
1976	615.2	1043.2	170	339	84
1977	766.2	1365.2	203	397	86
1978	683.3	1192.8	188	396	83
1979	785.9	1346.4	211	407	85
1980	588.6	1153.6	192	384	84
1981	712.6	1235.5	187	320	89
1982	827.9	1407.8	214	380	87
1983	444.8	1010.3	173	366	83
1984	663.4	1149.9	185	362	84
1985	632.9	1173.6	191	311	104
1986	784.3	1325.4	195	359	103
1987	556.5	1097.6	186	317	84
1988	835.7	1376.8	238	501	108
1989	557.7	1099.1	160	309	83
1990	711.4	1257.0	205	466	83
1991	528.4	1066.9	197	351	84
1992	571.6	1133.5	143	360	87
1993	868.2	1420.4	221	355	121
1994	599.3	1027.4	218	424	99
Mean	654.2	1199.5	192	361	92

Table 6-4 : Predicted Wheal Jane Inflow over Wet and Dry Periods

Period Start	Period End	Rain (mm)	Effective rain (mm)	Inflow (l/s)	No. of days
23-Nov-54	15-Feb-55	629.9	565.8	358	91
13-Sep-60	06-Dec-60	669.2	566.0	328	91
21-Nov-78	13-Feb-79	637.2	460.6	233	91
28-Sep-82	21-Dec-82	638.7	481.8	260	91
12-Dec-89	06-Mar-90	640.9	567.4	339	91
12-Jul-55	04-Oct-55	66.6	0.0	108	91
01-Jun-76	24-Aug-76	37.8	0.0	100	91
22-Aug-78	14-Nov-78	62.1	0.0	87	91
07-Jun-83	30-Aug-83	82.1	0.0	114	91
09-May-89	01-Aug-89	71.2	0.0	125	91
12-May-92	04-Aug-92	118.4	0.0	111	91
27-Oct-92	19-Jan-93	551.0	462.4	279	91
09-Feb-93	04-May-93	178.0	96.6	197	91
18-May-93	10-Aug-93	429.1	212.0	216	91
07-Dec-93	01-Mar-94	643.9	576.1	358	91
11-Oct-60	14-Feb-61	810.2	704.3	374	133
26-Jan-88	05-Apr-88	521.3	450.5	389	77
04-Jan-94	15-Mar-94	475.0	419.0	384	77

The ability of the pump installations at Wheal Jane No. 2 Shaft to deal with these events is discussed below and illustrates how the model can be used to optimise pumping and minimise mine discharges.

The maximum pumping rate at Wheal Jane No. 2 Shaft is approximately 300 l/s but could be increased to 315 l/s by modifying the discharge pipework. The lowest pump switch-off level is currently 10 m AOD, which is approximately 5.9 m below the Nangiles Adit decant level. All the cumulative inflows were analysed from 1952 to 1994 and revealed that there would have been 14 occasions on which, even with pumping at some 315 l/s, water levels would have risen by more than 1.5 m. On six of these occasions a rise of more than 3 m would have resulted and, out of these, three would have resulted in a rise of more than 4.5 m.

There was only one instance of a rise in water level of more than 5.9 m which would have resulted in flow from Nangiles even if the initial water level had been 10 m AOD. This was between October, 1960 and February, 1961, when a total of 810 mm of rain fell in four months.

It is of interest to note that one of the wettest cumulative periods on record occurred between January and March, 1994. If Wheal Jane No. 2 Shaft had been pumping at 315 l/s at this time, a rise in water level of 5.7 m would still have resulted. If the initial water level had been 10 m AOD, the final water level would have been just below the Nangiles Adit decant level of 15.9 m AOD and, according to the results of the model, adit discharge would have been prevented.

A pump switch-off level of 10 m AOD has been shown, by modelling, to be effective in controlling overflow from Nangiles Adit. This level could be modified, as necessary to suit operating conditions.

The figures quoted above are based on model results. The error between modelled and measured outflow for the high inflow January to March, 1994 period was 2%. Beyond the calibration range (i.e. below 13 m AOD), the model may be less accurate. Long term test pumping at these lower levels would be recommended before any significant changes are made to Wheal Jane No. 2 Shaft operating conditions.

The flow model was also used to investigate changes to the overall flow regime during dewatering and rebound. The measured flow during dewatering between January and July, 1980 was compared with the flow that would have occurred under current operating conditions at Wheal Jane. The results show that the total flow predicted is within 7% of the historical measured flow.

Assuming that such a short record is representative, it can be concluded that the total inflow to the system was similar during mine dewatering and rebound (i.e. the catchment area and hydrogeological boundaries were virtually unchanged) but the outflows are distributed in different proportions, with flows in County Adit and the Carnon River at Twelveheads increasing by the same amount as the reduction in pumped flow from the mine.

The increase in flow in County Adit and at Twelveheads since mine abandonment can be almost certainly attributed to higher groundwater levels in the region.

6.4 WHEAL JANE WATER QUALITY

Based on the recorded concentrations of iron and zinc in water pumped from Wheal Jane No. 2 Shaft since January, 1992 (see Figure 5.5a) there is evidence of a decline in metal concentrations in Wheal Jane No. 2 Shaft water. If this is so, there are repercussions for the treatment strategy as minewater quality improves with time.

The variation in the data is substantial. Nevertheless, an effort was made to model the variation of concentration with time with a view to predicting concentrations. Two different approaches were used. The first used mathematical equations and linear regression to identify the formula which most closely fitted the available data. The second approach started with a conceptual mixing model and appropriate equations were derived. Again, the existing data were used to solve the equation.

In both cases a good fit with measured iron and zinc concentrations at Wheal Jane No. 2 Shaft was achieved (see Figure 6.5a and 6.5b). Predictions, however, ranged from decay to a constant value within three years, to a gradual decay resulting in half the existing metal load after 10 years. The extrapolation values of decay curves of this nature is generally accepted to be unreliable and

Figure 6.5a **Measured and Predicted Total Zinc and Iron Concentrations in No.2 Shaft**

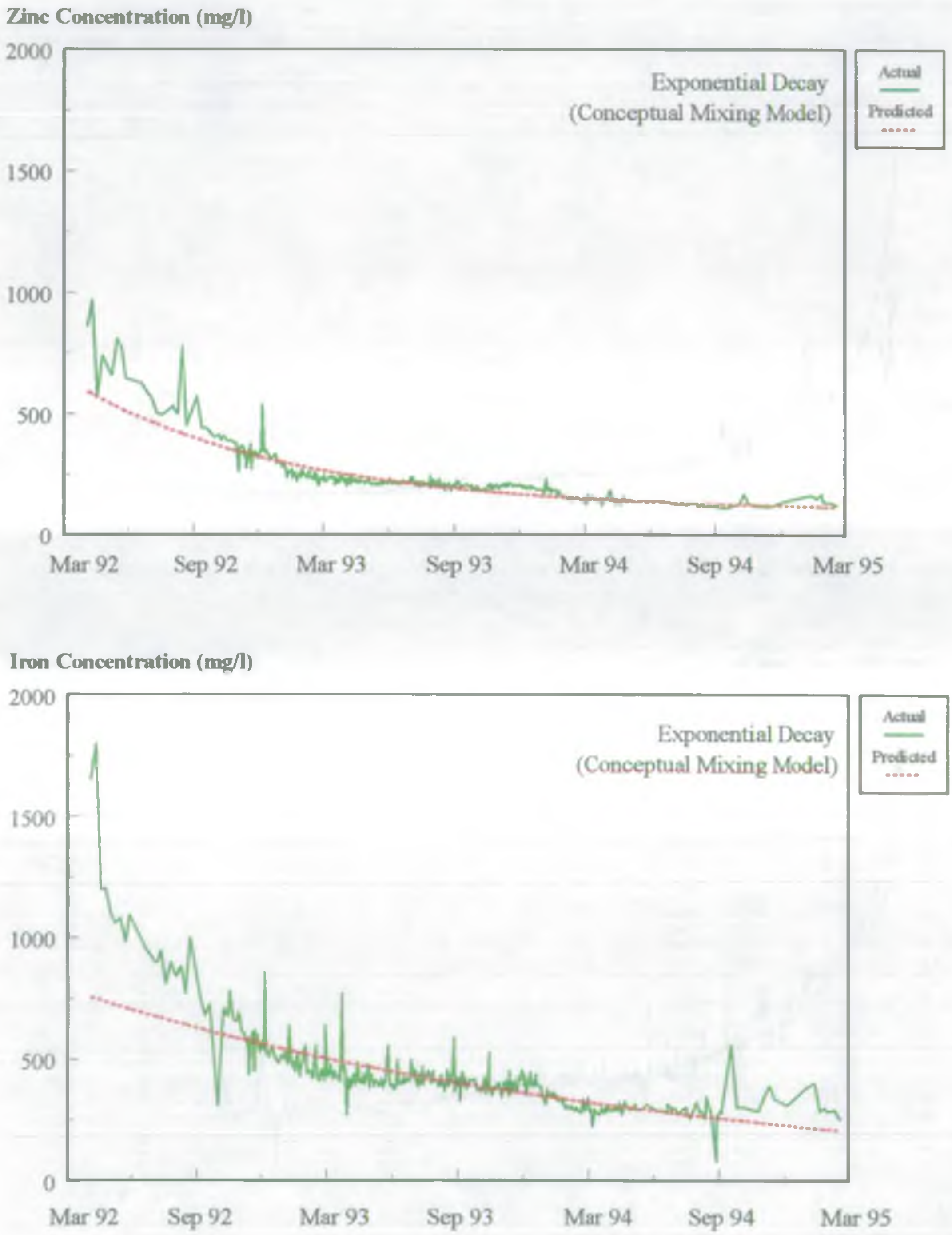
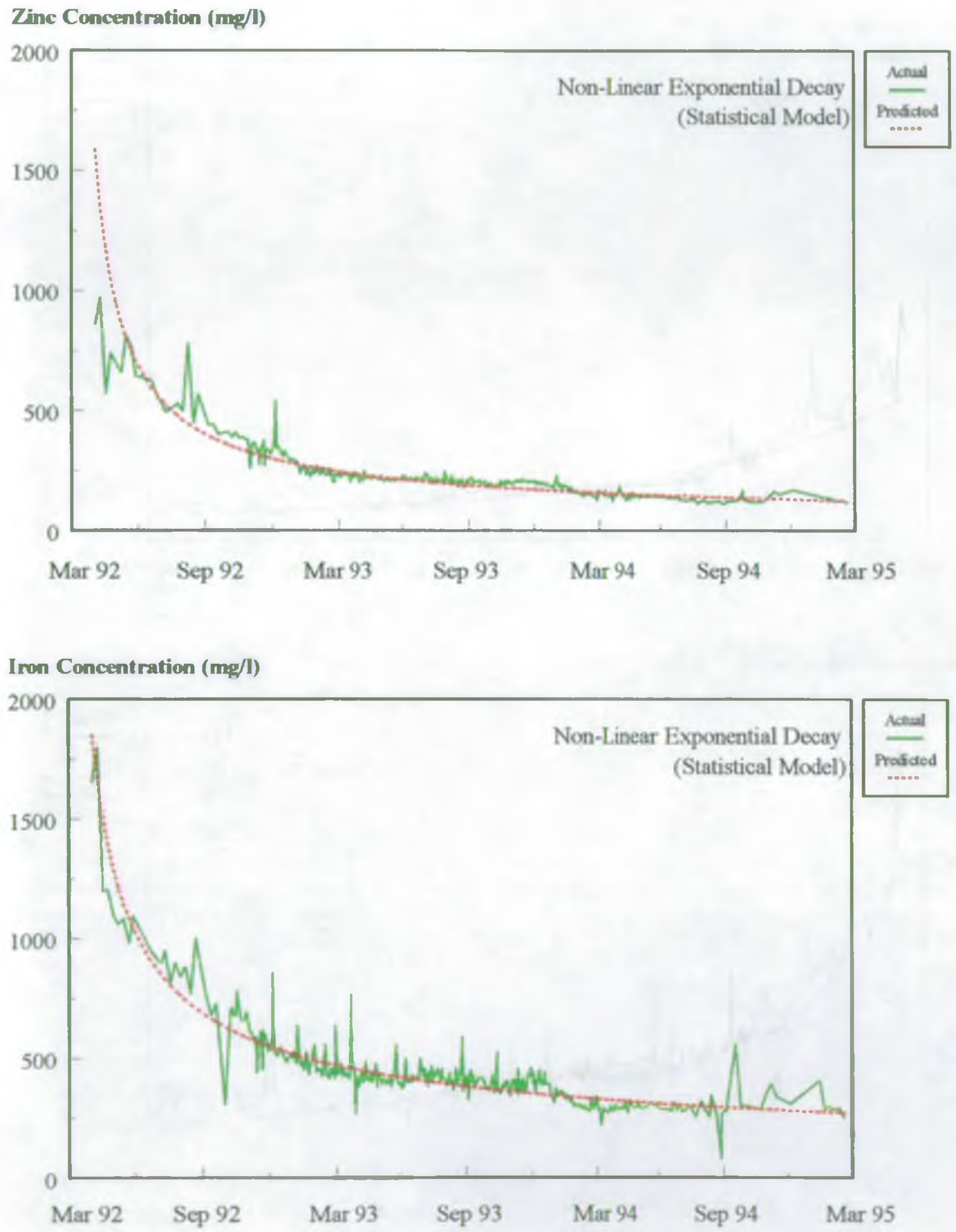


Figure 6.5b Measured and Predicted Total Zinc and Iron Concentrations in No.2 Shaft



inadvisable. For the purposes of designing and costing a treatment strategy, the concentrations measured between October, 1993 and September, 1994 have been used. Nevertheless it appears likely the quality of water discharged from the mine will continue to improve slowly over time.

6.5 CARNON RIVER FLOW MODEL

6.5.1 Derivation and Validation

An empirical model was also developed which related effective rainfall to flow between September 1991 and June 1994 in the:

Carnon at Twelveheads
Hick's Mill Stream at Trehaddle
County Adit

The 34 month flow record for the Carnon Valley was used to validate the model which could then be used to predict flows for the period of record for which rainfall was available (1952 to present).

A modified version of the Pitman monthly rainfall/runoff model (Ref. 3) was used. The Pitman model was originally developed in South Africa but has since been modified by KP and others to allow its use in a wider range of conditions, including those in the UK. Principal inputs to the model are time series rainfall and evapotranspiration data, plus a number of other parameters which govern the hydrological behaviour of the various runoff components.

The original model included evaporation from interception storage, direct runoff (overland flow), evapotranspiration and runoff from soil storage. Modifications include additional deep moisture storage to represent groundwater runoff or delayed interflow, depending upon the choice of parameter values and interpretation, which contributes to baseflow and an improved infiltration function, giving a more realistic relationship between rainfall and direct runoff.

Each component of runoff (direct runoff and interflow from the upper and lower soil storages) are separately lagged by the Muskingum method to give total runoff in each month of the rainfall record.

Parameter values and lags are determined by trial and error, carrying out successive runs of the model until the "best fit" is obtained between observed and simulated monthly flows. The "fit" is judged against a graphical display of monthly means and standard deviations, flow duration curves, a time plot of observed and simulated flows and selected leading statistics (eg correlation coefficient, mean and standard deviation of the logarithms of annual flows).

The data used in the analysis (complete months only, based on daily data from NRA) is summarised in the Table 6-5.

Table 6-5 : Pitman Model Data

Location	From	To
Carnon at Twelveheads	Sep 1991	Jun 1994
Carnon at Trehaddle	Dec 1991	Jun 1994
County Adit	Sep 1991	Jun 1994
Rainfall at Trevince	Jan 1952	Oct 1994
Evaporation for MORECS square 186	Jan 1972	Oct 1994

The Pitman model requires that all rainfall data years are complete, to allow continuous variation in soil and groundwater storages from month to month. Thus final two months of the Trevince record (November and December, 1994) were taken to be the average observed values. Actual evapotranspiration data were averaged over the available record to give a series of 12 monthly values which then were used in each year of the rainfall record, 1952 to 1994. The model does not require that observed flow records are complete. The use of concurrent pairs of observed and simulated values ensures consistency between observed and simulated statistics.

The data available allowed calibration of the model from 1991 to 1994. Graphical comparisons of observed and estimated flows are given in Figure 6.6. Overall, the "fit" is reasonable, given the short periods of observed flow records although relatively large anomalies occur in December, 1993 to February, 1994 for Hick's Mill Stream and the Carnon River at Twelveheads.

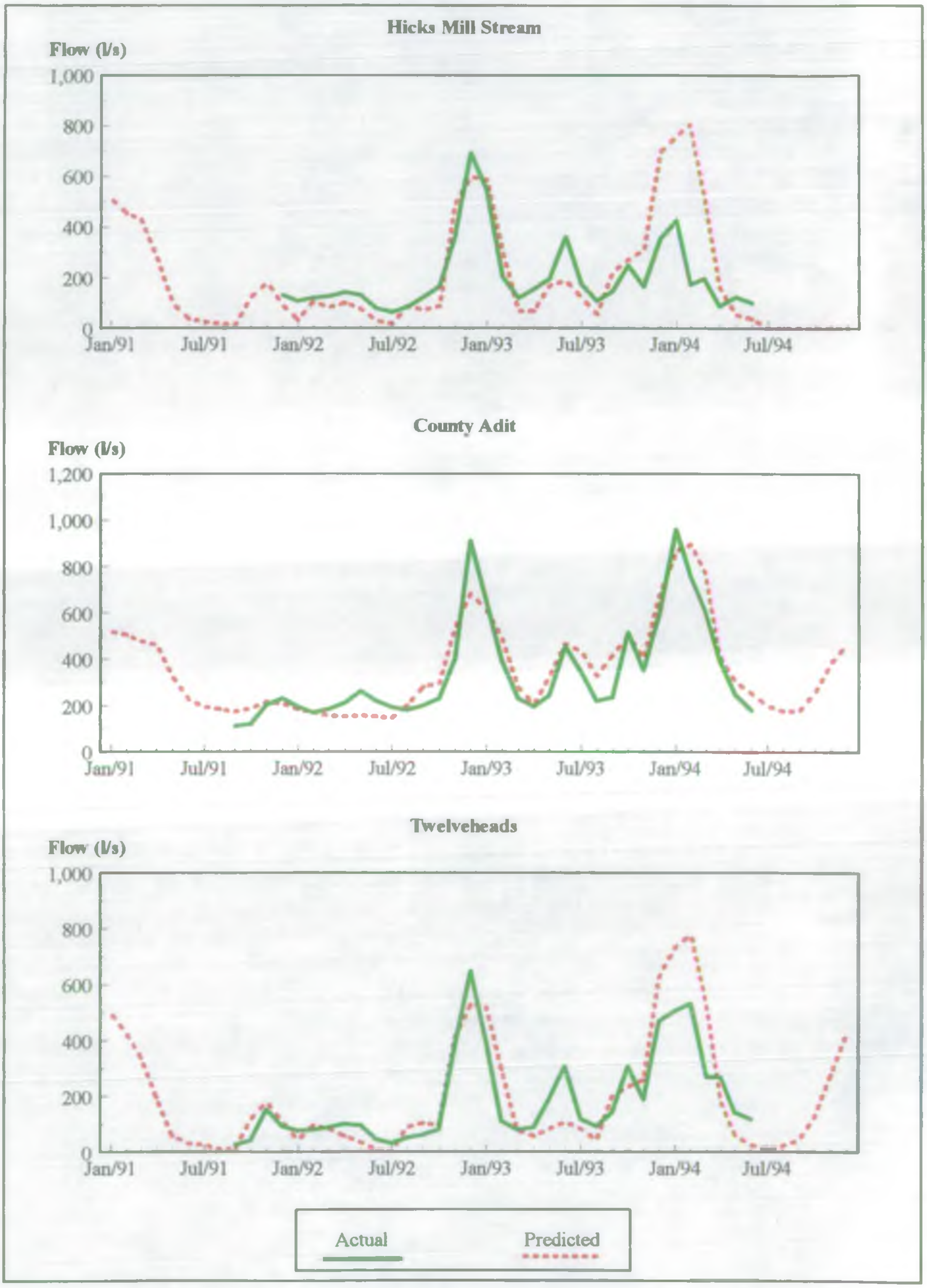
A comparison of rainfall at Trevince with recorded flows at the three sites also shows anomalous behaviour over this period, with higher rainfall resulting in lower flows in December, 1993 to February, 1994 than in December, 1992 to February, 1993. There are insufficient data to establish the cause of the anomalies and the Pitman models were assumed to give a sufficiently realistic estimate of flows for the purposes of the present study.

6.5.2 Long-Term Predictions

The model was then extended to cover the period from January, 1952. The predicted annual average flows at Twelveheads, Trehaddle and County Adit are given in Table 6-6.

The extended flow data were subsequently utilised with chemical data to provide estimates of future chemical loadings in downstream reaches of the Carnon river, as described in the next section.

Figure 6.6 **Carnon Valley Modified Pitman Model - Comparison of Actual and Modelled Flows**



6.6 CARNON RIVER QUALITY MODEL

6.6.1 Modei Development and Validation

The final water quality of the Carnon River depends upon the flow and concentration of the various inputs from surface runoff, groundwater inflow, adits and pumped minewater. The main inputs and their relative contributions to the Carnon River at Devoran Bridge are summarised in Table 5-9. The aim of the Carnon River quality model is to include the flow and concentration of each input so that the impact of each, with or without treatment, can be quantified. Thus treatment strategies can be proposed for the Carnon River to achieve various quality objectives.

The Carnon River quality model is a flow and mass balance mixing model which extends to Devoran Bridge and includes iron, zinc, copper, cadmium, manganese, aluminium and arsenic. Flow and concentration are entered for each of the following inputs sources:

Carnon River at Twelveheads
Hick's Mill Stream
County Adit
Nangiles Adit
Ungauged area between Twelveheads and Bissoe
Clemows Stream
Ungauged area between Bissoe and Devoran Bridge

and the resultant concentration of each metal at Devoran Bridge calculated.

The model was calibrated using weekly average data from October, 1993 to September, 1994. Over this period, flow and concentration were measured accurately and continuously at most of the sites with the exception of flows in the Clemows Stream and in the Carnon River at Bissoe and Devoran Bridge. Flow in the Clemows Stream was taken to be Wheal Jane No. 2 Shaft flow and the Carnon River flows were estimated as 105% and 119% of upstream flows respectively (see Section 6.2.1).

The concentration of these additional 5% and 19% inflows also had to be estimated. The 5% inflow between Twelveheads and Bissoe was assumed to have concentrations equal to those recorded in the Carnon River at Points Mill. The 19% inflow concentration was derived by relating weekly average measured concentration at Bissoe with measured concentration at Devoran Bridge and assuming a 19% increase in flow (see Table 6-7). The negative iron inflow concentration corresponds to a loss of iron between Bissoe and Devoran Bridge, probably as a result of iron hydroxide precipitation.

Table 6-6 : Long Term Predicted Flows in the Carnon Catchment

Year	1 Carnon at Twelveheads l/s	2 County Adit l/s	3 Hicks Mill Stream l/s	4 Wheal Jane (Nangiles Adit + No. 2 Shaft) l/s	5 Ungauged Carnon Catchment above Clemows Confluence l/s	6 Ungauged Catchment between Clemows Confluence and Devoran l/s	7 Estimated Devoran Flow l/s
1952	182	73	179	161	30	237	861
1953	63	160	64	177	23	185	673
1954	169	306	183	187	42	337	1224
1955	118	216	105	202	32	255	928
1956	107	214	94	183	30	238	865
1957	66	190	57	210	26	209	758
1958	103	254	104	214	34	269	978
1959	150	256	133	180	36	287	1041
1960	194	422	237	250	55	440	1599
1961	178	291	185	202	43	342	1241
1962	303	356	327	170	58	461	1676
1963	404	476	460	203	77	615	2235
1964	114	212	124	163	31	245	888
1965	201	311	185	169	43	346	1255
1966	259	467	285	246	63	501	1821
1967	166	279	182	191	41	327	1186
1968	141	240	141	169	35	276	1001
1969	219	342	229	191	49	391	1421
1970	174	298	192	169	42	332	1207
1971	94	180	102	156	27	212	769
1972	186	265	172	169	40	316	1147
1973	154	280	167	191	40	316	1147
1974	264	464	300	234	63	503	1828
1975	152	289	161	182	39	312	1135
1976	168	259	190	170	39	314	1140
1977	235	366	239	203	52	416	1512
1978	267	367	255	188	54	430	1560
1979	258	375	248	211	55	436	1583
1980	202	328	222	192	47	377	1370
1981	193	321	194	187	45	357	1295
1982	251	404	270	214	57	454	1649
1983	156	272	159	173	38	304	1102
1984	202	310	212	185	45	363	1318
1985	169	284	161	191	40	321	1166
1986	226	356	228	195	50	401	1456
1987	168	314	192	186	43	343	1246
1988	228	440	255	238	58	464	1684
1989	181	231	186	160	38	302	1098
1990	231	88	214	205	37	294	1069
1991	150	275	188	197	41	323	1174
1992	163	276	181	143	38	304	1106
1993	227	364	229	221	52	415	1508
1994	239	398	172	218	51	409	1487
Mean	188	299	194	192	44	348	1265

1 2 3 derived from Pitman model
4 derived from Wheal Jane Flow model
5 = 0.05 x (1 + 2 + 3 +4)
6 = 0.19 x 5
7 = 1 + 2 + 3 + 4 + 5 + 6

Table 6-7 : Estimated Average Inflow Concentration Between Bissoe and Devoran Bridge (October, 1993 - September, 1994)

	Loading at Bissoe (mg/s)	Loading at Devoran Bridge (mg/s)	Inflow concentration (mg/l)
Cadmium	8.8	9.0	0.001
Copper	707	751	0.21
Iron	13 620	13 610	-0.05
Zinc	9 530	9 630	0.45
Arsenic	137	150	0.06
Manganese	1 080	1 100	0.11
Aluminium	2 730	2 760	0.16

The validity of the model was confirmed by simulating the water quality at Bissoe between October, 1993 and September, 1994 (see Figure 6.7).

As the Devoran Bridge water quality data was used to estimate the average annual metal concentrations of the additional flow, independent calibration of the model was not feasible. However, an indication of the response of the model is shown on Table 6-8, which compares the predicted and actual annual average metal concentrations for the 1993/94 study period. This correlation will improve as reliable flows at Bissoe and Devoran Bridge become available.

Table 6-8 : Comparison Between Actual and Predicted Annual Average Metal Concentrations at Devoran Bridge (mg/l)

Metal	Actual 1993-1994	Predicted 1993-1994	Actual 1993	Predicted 1993
Cadmium	0.007	0.005	0.007	0.004
Copper	0.54	0.53	0.69	0.5
Iron	11.6	11.0	7.8	9.3
Zinc	7.8	6.2	6.5	5.4
Arsenic	0.11	0.06	0.17	0.06
Manganese	0.86	0.58	0.7	0.52
Aluminium	2.04	1.75	2.4	1.58

6.6.2 Long-Term Predictions

The model was extrapolated to include flows that would have arisen as a result of rainfall events between 1952 and 1994. Thus the probability of a range of resultant concentrations at Devoran Bridge was estimated. Details of the model input data are summarised in the following subsections:

Figure 6.7 **Carnon Valley Water Quality Model**
A Comparison of Predicted and Actual Metal Concentrations at Bissoe

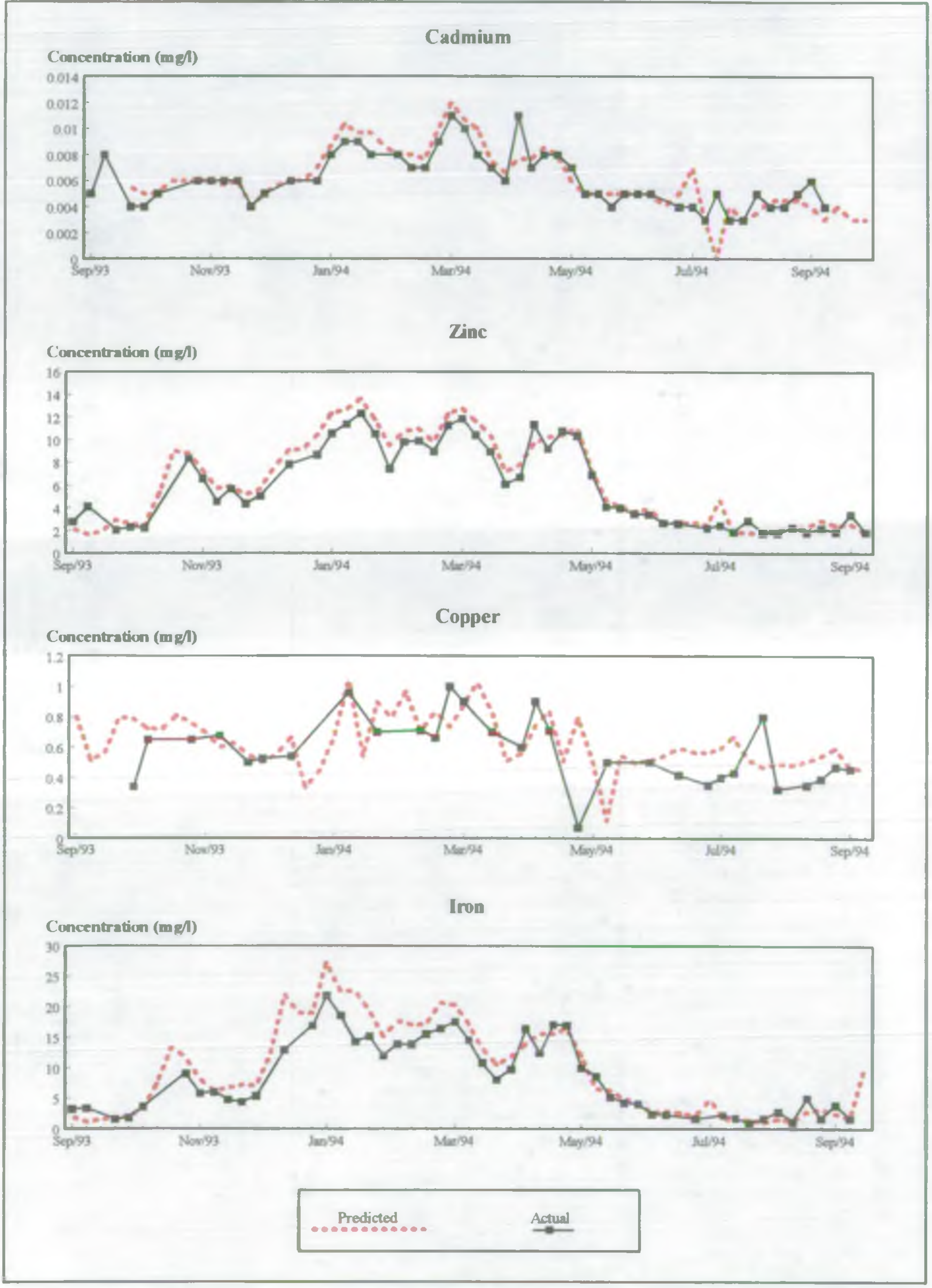
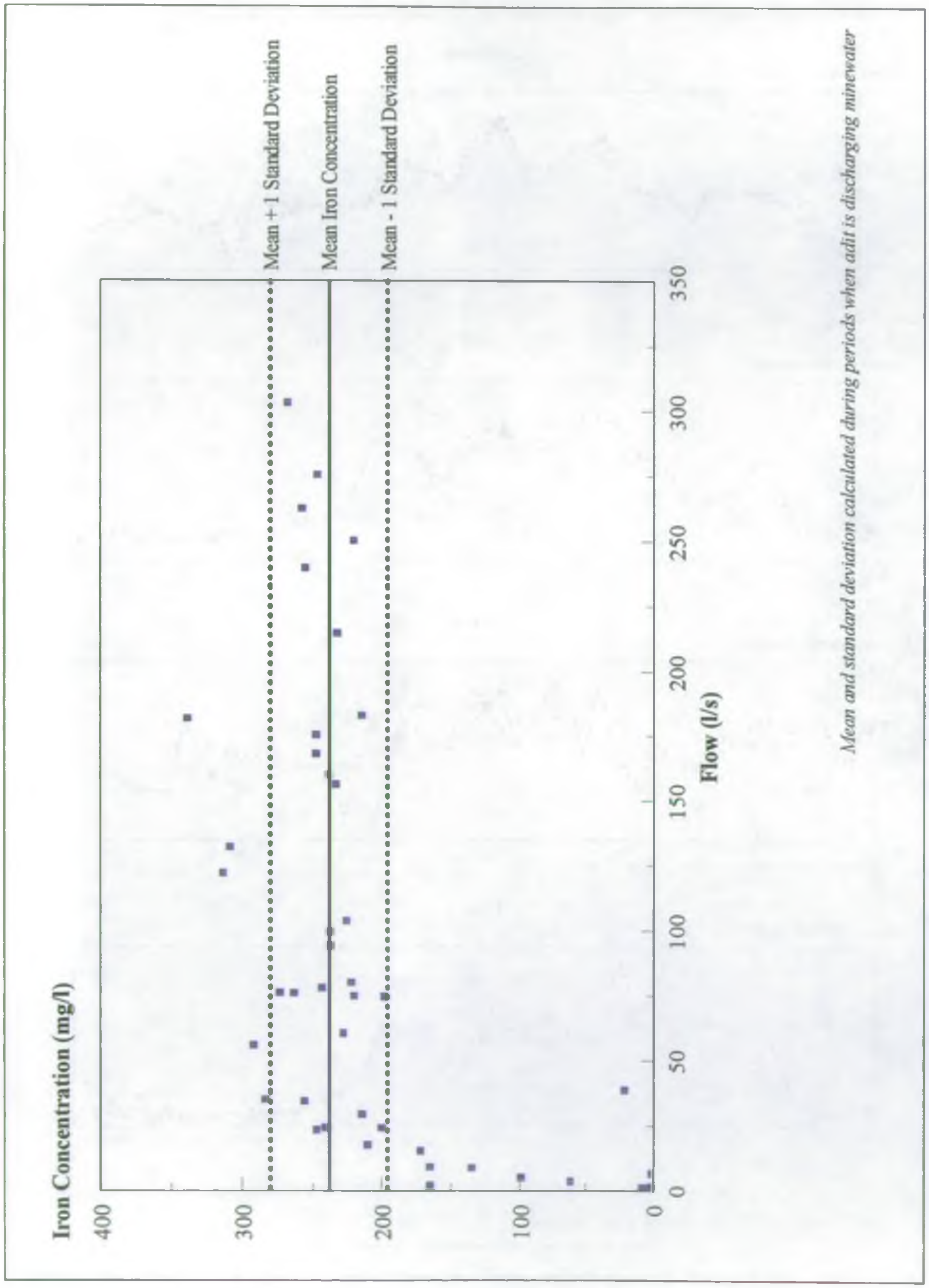


Figure 6.8 **Variation of Nangiles Adit Concentrations with Flow October 1993 to September 1994**



Flow Data

Rainfall records for Trevince were used to calculate effective rainfall and to generate average monthly flows:

- For the Carnon River at Twelveheads, County-Adit and Hick Mills Stream using the Carnon River flow model (Section 6.5).

- From the Wheal Jane/Nangiles Mine complex using the Wheal Jane flow model (Section 6.3).

Metal Concentrations

Measured metal concentrations for the 1993/1994 study period were used for both calibration and simulation purposes. Use of data collected prior to 1993 was considered inappropriate due to the high metal concentrations associated with the initial flows from the mine.

Average annual metal loadings were used for each site since there was no evidence of a consistent variation in water quality with flow as shown, for the example, at Nangiles Adit in Figure 6.8.

The water quality scenarios set by the NRA are based on annual average and 95 percentile water quality standards at Devoran Bridge. The output from the model over the 43-year simulation period therefore has been analysed to establish:

- The mean annual average concentrations limits.

- The mean annual 95 percentile concentrations.

Given that the minewater flow requiring treatment is dependent upon rainfall, it is unrealistic to design a treatment system to ensure 100% compliance with the objectives. Consequently, the model has been used to estimate treatment flows which relate to mean (50%) and 5% confidence limits.

Figure 6.9 illustrates the concept used in deriving the annual average and 95 percentile values. These values were then analysed statistically to give the 5, 50 and 95% confidence limits (i.e. the 95, 50 and 5% risk of failure).

The sensitivity of the model has been assessed by examining the effect of varying the input data. Nangiles Adit constitutes a major source of metals so the sensitivity of the simulation to potential variations in the quality of the water discharged via the adit was assessed by varying the Nangiles metal concentrations by ± one standard deviation (see Figure 6.8).

Annual average and annual 95 percentile concentrations have been predicted for the combination of conditions shown on Table 6-9. The mean and two extremes for each case are presented graphically in Figure 6.10, which shows the iron concentration at Devoran Bridge for various treated flows. The effectiveness of treatment is discussed in a later section.

Table 6-9 : Devoran Bridge Water Quality Simulation - Conditions included in Sensitivity Analysis

Nangiles Adit Concentration	Confidence Limit		
Mean - 1 StDev.	5%	50%	95%
Mean	5%	50%	95%
Mean + 1 StDev.	5%	50%	95%

6.6.3 Modelling Treatment Options

To assess the benefits to be gained by treatment, the model was used to predict the effect of not treating Wheal Jane No. 2 Shaft water during 1993/94. The metal loading in the flow from the shaft was assumed to equal the average untreated concentration measured in Wheal Jane No. 2 Shaft between October 1993 and September 1994.

The results are shown in Table 6-10 which indicates a significant increase in concentration at Devoran Bridge with no treatment. These are the predicted long term equilibrium concentrations, and it is probable that concentrations immediately following the initial release would be higher than shown.

The impact of additional water treatment on the quality of the Carnon River has been simulated (Section 7.4) by assuming that the water is treated to the residual concentrations shown in Table 6-11. These concentrations are based on the supernatant water produced from lime dosing trials, undertaken on site, and should therefore provide a reasonable approximation of the performance of a lime dosing system. The residual concentrations are not critical for the simulation so have been assumed to be typical for all the potential treatment techniques considered.

Figure 6.9 **Carnon Valley Water Quality Model**
Relationship Between Monthly Concentrations, Annual Averages and 95 Percentiles, 1990 to 1994

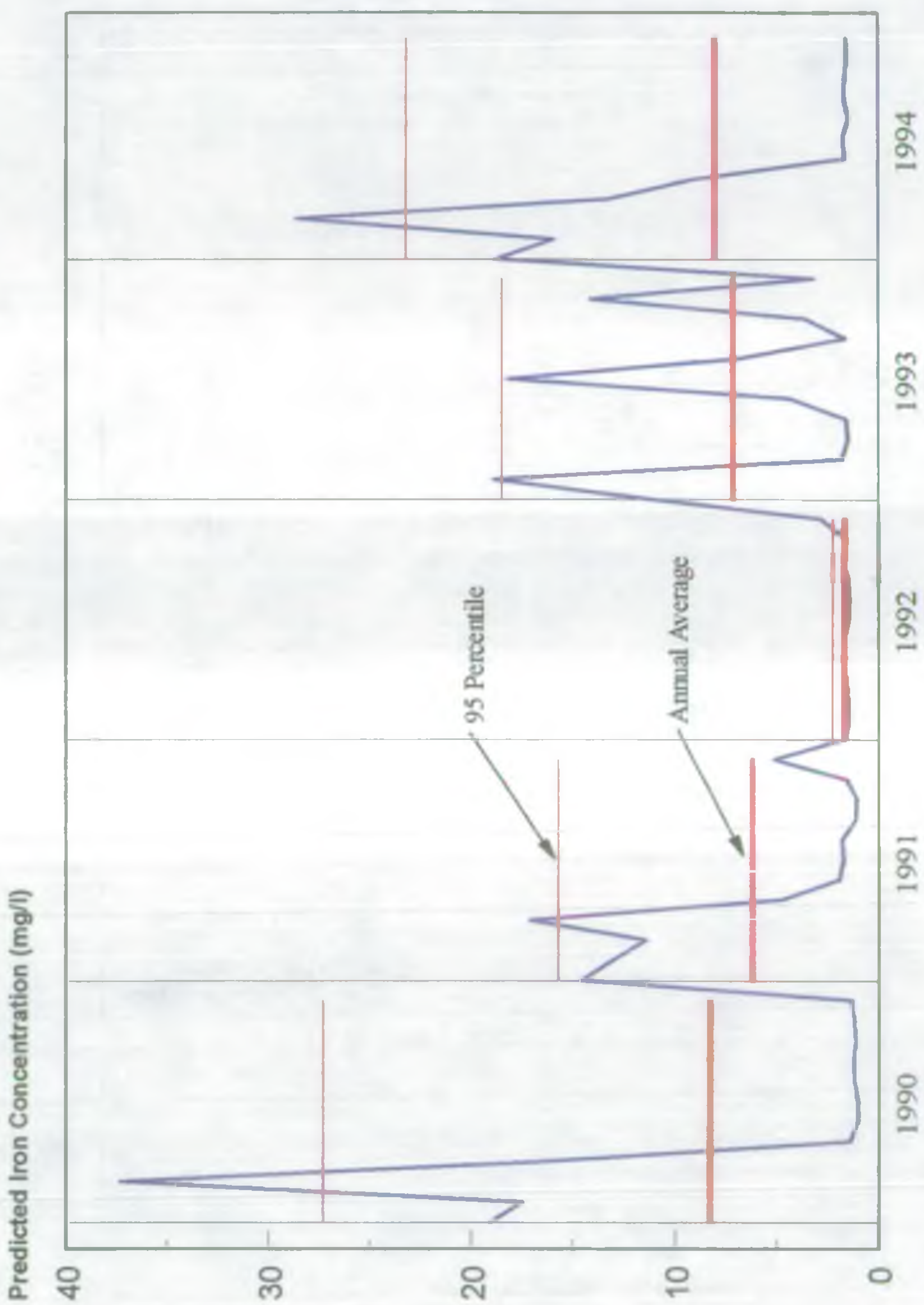


Figure 6.10 **Carnon Valley Water Quality Model**
Iron Concentration at Devoran vs Design Flow of Treatment Plant

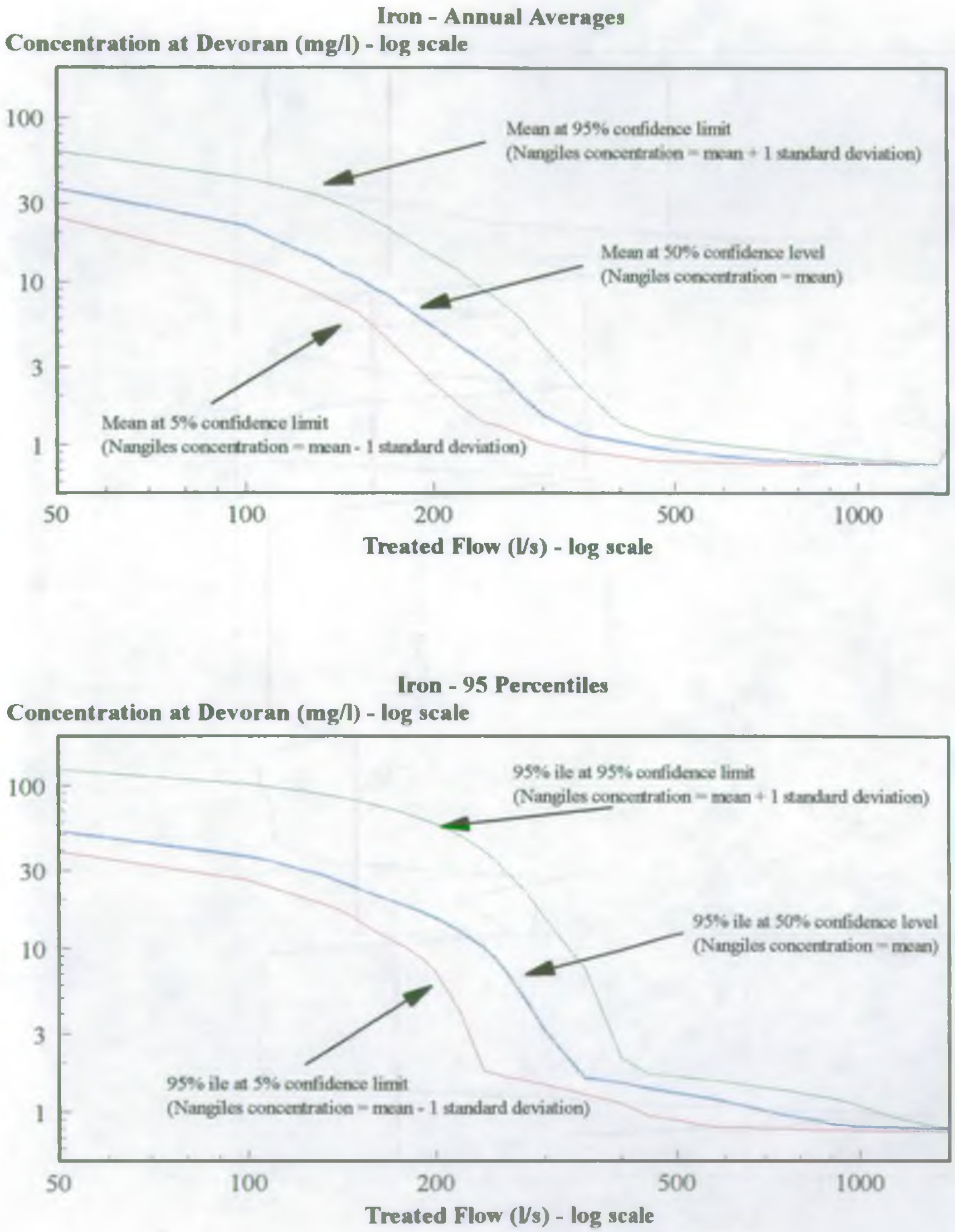


Table 6-10 : The Influence of Existing Treatment System on Sources of Contamination Recorded at Devoran Bridge

Monitoring Location	Al	As	Cd	Cu	Fe	Mn	Zn
i) With implementation of existing treatment system (measured):							
• Twelveheads	7%	18%	5%	5%	<1%	3%	2%
• County Adit	33%	41%	28%	54%	8%	35%	13%
• Trehaddle	1%	9%	4%	4%	<1%	2%	1%
• Wheal Jane No. 2 Shaft[1]	9%	10%	12%	<1%	3%	19%	5%
• Nangiles Adit	43%	10%	44%	23%	83%	34%	72%
• Others[2]	7%	12%	7%	14%	5%	7%	7%
Load at Devoran (mg/s)	2760	150	9	750	13 610	1 100	9 630
Concentration at Devoran (mg/l)	2.1	0.11	0.007	0.57	10.3	0.83	7.2
ii) Without implementation of existing treatment system (modelled):							
• Twelveheads	3%	<1%	1%	4%	<1%	1%	<1%
• County Adit	12%	2%	8%	43%	2%	14%	4%
• Trehaddle	<1%	<1%	1%	3%	<1%	<1%	<1%
• Wheal Jane No. 2 Shaft[3]	66%	95%	74%	21%	73%	68%	71%
• Nangiles Adit	16%	<1%	13%	18%	23%	13%	22%
• Others[2]	3%	<1%	2%	12%	1%	3%	2%
Load at Devoran (mg/s)	8 200	1 510	28	1 020	69 090	2 310	34 680
Concentration at Devoran (mg/l)	6.2	1.14	0.021	0.77	52.0	1.74	26.1

All data expressed at % of the loading at Devoran Bridge based on annual average loadings October 1993 - September 1994.

[1] Treated Wheal Jane No. 2 Shaft water quality as measured from polishing lagoon.
[2] Other sources includes small non-measured point sources (e.g. Wellington Adit) plus diffuse sources.
[3] Untreated Wheal Jane No. 2 Shaft water quality as measured from No. 2 Shaft.

Table 6-11 : Treated Water Residual Metal Concentrations

	Residual Concentration for Lime Dosing mg/l
Cadmium	0.0005
Copper	0.027
Iron	0.110
Zinc	0.15
Arsenic	0.015
Manganese	0.496
Aluminium	0.329

6.7 THE USES AND LIMITATIONS OF THE MODEL FOR THE DEVELOPMENT OF WATER QUALITY OBJECTIVES

The water quality model was set up and calibrated, where feasible, using the data collected for the October, 1993/September, 1994 study year. On this basis, the model provides a reasonably accurate aid for assessing the effects of treating the major sources of contamination within the Carnon River. In particular, the model provides an indicative means of:

- Assessing the effects of changing the existing treatment system pumping rate.
- Estimating the treatment capacity required to achieve particular quality objectives for the Carnon River.

However at the low metal concentrations, such as those associated with EQS, the validity of the model is somewhat uncertain, for the following reasons:

- The hydrological data has been generated by fitting a relationship to the stream flow and rainfall data available for the last three years. Correlation over a longer duration is required to improve the reliability of the relationship.
- The relationship between flow and metal concentrations for each source cannot be fully established without collection over a longer period.
- The metal concentrations attributable to the diffuse flow sources, the effects of attenuation and the relationship between total and dissolved metal concentrations have not been accurately assessed.
- The effect of continued decline in the Wheal Jane metal loading has not been simulated as insufficient data are available to predict an accurate decline curve.

Nevertheless, the model is particularly useful in its ability to estimate water quality at Devoran Bridge for a range of climatological conditions and treatment options.

As more data are collected and the conceptual models are refined it should be possible to link these models together to create an integrated catchment model embracing flow and quality.

6.8 CONCLUSIONS

Although the existing treatment system at Wheal Jane is achieving its objectives, a long-term strategy for the Carnon River and the Wheal Jane minewater in particular will be required. The successful implementation of such a strategy relies upon identifying and treating the main sources of contamination within the catchment.

Hydrological models have been developed which provide reasonably accurate aids for assessing the effects of treating major sources of contamination in the Carnon River catchment. These models include empirical models of flow from Wheal Jane mine and in the Carnon River.

A model of water quality in the Carnon River was also developed which included flow and concentration from each of the major contributors. The model was calibrated using existing data and then used to predict the probable metal concentrations at Devoran Bridge given the rainfall events recorded between 1952 and 1994. The model relied upon predicted flow and concentration input data over the 43-year period, generated by the flow models and from measured values.

The models were used to assess the effects of changing existing treatment pumping rates, and to estimate the treatment capacity required to achieve particular quality objectives for the Carnon River. Further refinement of the conceptual models and the development of an integrated catchment model will be necessary if treatment of all point and diffuse sources of contamination is to be assessed.

6.9 REFERENCES

(1) Knight Piésold Final Report on the Investigation of Water Infiltration into the Mine, December, 1980 (for Carnon Consolidated Ltd).

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(3) Pitman, W.V., 1973. A Mathematical Model for generating monthly river flows from meteorological data in South Africa. HRU Report 2/73.

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7

7. DEVELOPMENT OF WATER QUALITY OBJECTIVES

CONTENTS

7.1 INTRODUCTION

The existing treatment strategy has been developed on the basis of reducing, as far as has been practical, the flow of untreated minewater into the Carnon River. Operating on this basis, treatment has resulted in the water quality in the Carnon River improving to a level comparable with that which existed prior to the release of minewater in January, 1992. However, the instigation and management of a long-term treatment strategy requires the setting of carefully considered objectives against which technical feasibility, costs and benefits of the treatment options can be evaluated.

Given the presence of more than one source of metal contamination in the Carnon Valley (see Sections 2 and 3), it is not appropriate to set objectives for the treatment of Wheal Jane minewater in isolation. Consequently, objectives have been set for the Carnon River at Devoran Bridge, the monitoring location nearest the tidal limit and which represents the sum of all inputs to the Carnon River and directly affects the water quality of Restronguet Creek and for Fal Estuary.

For the purposes of the Wheal Jane Minewater Study, Water Quality Objectives have been set only for those parameters directly affected by inputs from the abandoned mine workings.

7.2 STATUTORY CONSIDERATIONS

The NRA seeks to maintain and where necessary improve the quality of controlled waters. This is achieved by setting objectives for the catchment based on Water Quality Objectives to protect recognised uses and by ensuring compliance with the standards specified in both UK statute and EC Directives. The standards relevant to the Carnon River and the Fal Estuary are principally those specified under :

(i) *The EC Dangerous Substances Directives*

The Dangerous Substances Directive "on pollution caused by certain substances discharged in the aquatic environment of the community", 76/464/EEC, established two lists of substances for which controls are required. EC Directive 76/464 requires member states to take steps to eliminate pollution by List I substances and reduce pollution by List II substances. List I substances are regarded as particularly important because of their toxicity, persistence and bioaccumulation :

- The concentrations of List I substances in discharges and receiving waters are regulated by specified Environmental Quality Standards (EQS) issued through daughter Directives. Concentrations of cadmium, for example, are specified in EC Directive 83/513. The requirements of the daughter Directives have been transcribed into UK law via the Surface Water (Dangerous Substances) (Classification) Regulations of 1989 and 1992 (SI 2286 of 1989 and SI 237 of 1992), the Annexes of which set out

EQSs for "inland surface" and "estuary" waters. The NRA are required to monitor receiving waters in the vicinity of discharges, background levels of List I substances and the levels in sediments or biota near the discharge.

List II contains substances which are considered to be less dangerous but which still can have a deleterious effect on the aquatic environment. There are currently no statutory regulations relating to List II substances. Responsibility for the implementation of this Directive in the U.K. lies primarily with the NRA and follows guidance from the Department of the Environment set out in DoE Circular 7/89 (Ref. 1). Appendix 1 of DoE 7/89 sets out quality objectives for List I substances in "inland surface waters" and "estuary waters". Appendix II sets out a series of National Environmental Quality Standards for List II substances.

(ii) *The EC Bathing Waters Directive*

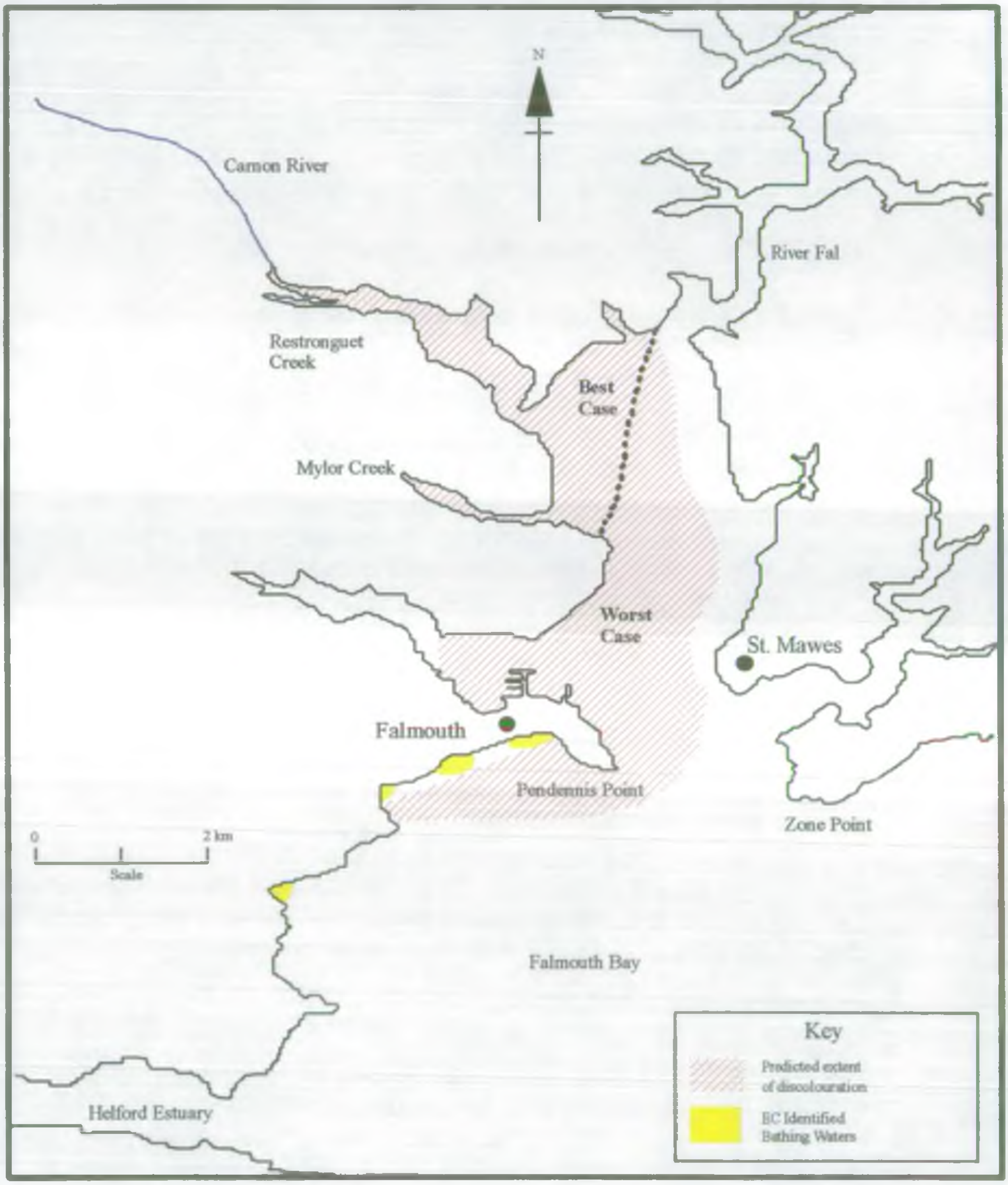
The Bathing Waters Directive "concerning the quality of bathing water" (76/160/EEC) aims to protect the environment and public health of bathing water, by reducing pollution entering identified bathing areas. The Directive lays down 19 physical, chemical and microbiological parameters for assessing the quality of bathing waters which include total and faecal coliforms, salmonellae, enteroviruses, pH, transparency, colour, mineral oils, surface-active substances and phenols. The mandatory requirements of the Directive were transcribed into UK law via the Bathing Water (Classification) Regulations of 1991. Sites identified as bathing waters (see Figure 7.1) by the DoE must be monitored between 1 May and 30 September.

As the competent authority for implementing this directive, the NRA has a two-fold obligation. The first is to monitor the quality of popular bathing waters and to provide the results to the DoE which assesses compliance. The second is to maintain and improve where necessary bathing water quality so that it complies with the standards laid down in the Directive. To achieve this, the NRA has to identify the sources of pollution, quantify the effects and ensure that improvements take place.

(iii) *The EC Shellfish Waters Directive*

The Directive "on the quality required of shellfish waters" (79/923/EEC) is concerned with the protection of shellfish (defined as bivalve and gastropod molluscs) populations and lays down the requirements for the quality of designated waters. The Directive aims to safeguard shellfish populations from harmful consequences resulting from the discharges of polluting substances into associated waters. The requirements of the Directive were implemented in accordance with DoE advice notes of January 1980 and November 1980 on the implementation of the Shellfish Waters Directive. Designated shellfish water in the Fal Estuary are discussed in Section 2.7.2.

Figure 7.1 Predicted Maximum Extent of Iron Discolouration



(iv) *The Second and Third Ministerial North Sea Conferences*

The UK Government, at the second and third Ministerial North Sea Conferences, made a commitment to reduce the loadings of certain substances ("Annex 1" substances) entering tidal waters, from both rivers and direct discharges, by 50% by 1995 compared to a 1985 baseline. In England and Wales, the NRA is responsible for identifying inputs where reductions must be made in order to meet this commitment. The NRA's methodology, which is considered to be the most cost-effective means of compliance with the commitment, for selecting sites has been to attempt to achieve an 80% reduction in load at a small number of sites so as to affect an overall 50% reduction nationally. The NRA has identified those significant sources where 80% reductions will be sought. The Carnon River has been identified as a significant source of zinc inputs into tidal waters.

7.3 OBJECTIVES FOR CARNON CATCHMENT

Based on statutory and other requirements, the following objectives have been adopted as the basis for the evaluation of a long-term minewater treatment strategy for the Carnon River:

- The "No Deterioration" objective : to maintain water quality at 1993-1994 levels.

- The "Pre-incident" objective : to restore the Carnon River to the pre-incident water quality, defined as the quality which existed between 1980 and 1990.

- The "North Sea Commitments" objective : to achieve an 80% reduction from the 1985 loadings of zinc in line with commitments made to the North Sea Conference.

- The "EC Directive" objective : to achieve compliance with the EC Dangerous Substances Directives.

In addition, a "No Treatment" objective has been defined and evaluated, principally to act as a baseline against which improvements brought about by the possible adoption of the other objectives can be measured.

7.3.1 The "No Treatment" Objective

The Carnon Water Quality Model (see Section 6.6) has been used to predict the annual average concentrations of key parameters at Devoran Bridge which would have been experienced during the period October, 1994 - September, 1995 if no water treatment had been undertaken (see Table 7-1). These predicted values give an indication of the likely water quality that would be experienced were the "No Treatment" objective adopted in future.

7.3.2 The "No Deterioration" Objective

An assessment of current water quality in the Carnon River has been undertaken based on water quality data collected between January 1, 1993 and December 31, 1994 (see Table 7-1). The values for the mean and "face value" 95 percentile have been used as the water quality targets to maintain no deterioration in current water quality.

Table 7-1 : Water Quality Objectives for Devoran Bridge

Substance		No Treatment	No Deterioration	Pre-incident Quality	North Sea Commitments	EC Directive
Cadmium	95 %ile		11 (T)	49 (T)	-	-
as μg Cd/l	AA	21 (T)	6 (T)	15 (T)	-	1.0 (T)
Copper	95 %ile		0.9 (T)	3.1 (T)	-	-
as mg Cu/l	AA	0.8 (T)	0.6 (T)	0.8 (T)	-	0.028 (D)
Zinc	95 %ile		13 (T)	22 (T)	-	-
as mg Zn/l	AA	26 (T)	6 (T)	10 (T)	3 (T)	0.5 (T)
Arsenic	95 %ile		0.3 (T)	0.7 (T)	-	-
as mg As/l	AA	n/a	0.1 (T)	0.2 (T)	-	0.050 (T)
Iron	95 %ile		17 (T)	39 (T)	-	-
as mg Fe/l	AA	52 (T)	8 (T)	14 (T)	-	1.0 (D)
Manganese	95 %ile		1.0 (T)	3.6 (T)	-	-
as mg Mg/l	AA	1.7 (T)	0.7 (T)	1.8 (T)	-	-
Aluminium	95 %ile		4.0 (T)	-	-	-
as mg Al/l	AA	6.2 (T)	2.1 (T)	-	-	-
pH	95 %ile		4.2	3.4	-	6.0
as pH units	5 %ile		7.1	6.3	-	9.0

Notes : EQS based on hardness > 250 mg/l $CaCO_3$/l.

(T) ... Total metal; (D) ... Dissolved metal.

Where a particular objective does not contain targets for every parameter, the values ascribed in the preceding objective have been assumed.

7.3.3 The "Pre-incident Water Quality" Objective

Information on the water quality in the Carnon River between 1980 and 1990 is available from routine monitoring programmes (see Section 2). The average concentrations of relevant parameters has been taken to represent the pre-incident water quality (see Table 7-1). It is apparent that the pre-incident water quality objective would accommodate a deterioration in current water quality, target concentrations being somewhat higher than those required to comply with the no deterioration objective. For this reason, the "Pre-incident Water Quality" objective has been omitted from the evaluation of a potential long-term treatment strategy.

7.3.4 The "North Sea Commitments" Objective

An evaluation of historic data indicates that, in 1985, the total annual zinc loading of the Carnon River at Devoran Bridge was 309 000 kg, representing an annual average concentration of 15.6 mg/l. An 80% reduction in this loading, to 61 800 kg/year, corresponds to a target annual average zinc concentration of 3.1 mg/l.

7.3.5 The "EC Directive" Objective

Concentrations of relevant parameters to ensure full compliance with the EC Dangerous Substances Directives at Devoran Bridge have been adopted from DoE Circular 7/89 (Ref. 1) (see Table 7-1).

Under the EC Dangerous Substances Directives, EQS for copper, arsenic and iron are specified as dissolved concentrations. However, there is insufficient data for dissolved metal concentrations in the Carnon River to develop water quality targets. For this reason, all objectives have been specified as total metal concentrations.

7.4 DETERMINATION OF TREATMENT REQUIREMENTS

Using the hydrological model developed for the Carnon River (see Section 6), estimates have been made of the flow of minewater which would require treatment in order to meet the stated objectives for metals (see Table 7-2). It is apparent that the "EC Directive" objective at Devoran Bridge cannot be achieved by treating releases of minewater from adits alone. Contamination arising from diffuse or non-point sources ensures that EQS will not be met even if both the major adit sources (Nangile's Adit and County Adit) were treated.

Table 7-2 : Flows of Wheal Jane Minewater Requiring Treatment to Satisfy Water Quality Objectives at Devoran Bridge

	50% Annual Risk of Failure		5% Annual Risk of Failure	
	Maximum Treated Flow (l/s)	Average Treated Flow (l/s)	Maximum Treated Flow (l/s)	Average Treated Flow (l/s)
No Deterioration :				
• Annual average	190	160	270	180
• 95%ile	210	170	300	190
North Sea Commitments:				
• Annual average	230	175	300	190
EC Directive :				
• Annual average	NA	NA	NA	NA
• 95%ile	NA	NA	NA	NA

NA ... Modelling indicates that it is not possible to achieve full compliance with EQSs by treating either Wheal Jane or a combination of Wheal Jane and County Adit (the two major point sources).

The hydrological model proved to be unsuitable for predictions of the treatment requirements to meet target pH values. However, historical data suggest that pH is not expected to lie outside the objectives when targets for metals are achieved.

7.5 THE EFFECT OF ADOPTING WATER QUALITY OBJECTIVES FOR THE CARNON RIVER ON ESTUARY WATER QUALITY

7.5.1 The "No Treatment" Objective

The likely water quality in the Fal Estuary under the "No Treatment" objective was predicted using the Estuarine Contaminant Simulator Model (ECoS) (Ref. 2). This is a one-dimensional model which simulates tidally and sectionally averaged concentrations of dissolved cadmium and zinc for different freshwater inputs of total metal. The model incorporates established relationships for the partitioning of metals between sediment and water. The ECoS Model is considered to be of use particularly in situations where the inputs from freshwater form the major part of the total metal loading in the estuary (such as under the adoption of a "No Treatment" objective). The model also provides predictions of annual time series data for EQS assessment without excessive computing requirements.

The ECoS Model was used to predict dissolved cadmium and zinc concentrations at two sections across the Fal Estuary :

- Turnaware Bar, in the north of the estuary near the Fal River.
- Carrick Roads outside the mouth of Restronguet Creek.

Under the "No Treatment" objective, EQS for zinc under both the Dangerous Substances and Shellfish Directives would be exceeded in the Fal Estuary although cadmium concentrations would remain within EQS (see Table 7-3).

Table 7-3 : Predicted Water Quality in the Carrick Roads under the "No Treatment" Objective

		Turnaware Bar	Outside Mouth of Restronguet Creek
Cadmium :	Summer average	0.04 μg/l	0.06 μg/l
	Winter average	0.09 μg/l	0.12 μg/l
	Annual average	0.07 μg/l	0.09 μg/l
	EQS	1.0 μg/l	1.0 μg/l
Zinc :	Summer average	52 μg/l	65 μg/l
	Winter average	100 μg/l	132 μg/l
	Annual average	76 μg/l	99 μg/l
	EQS	40 μg/l*1	40 μg/l*2

*1 ... EQS (as MAC) under EC Shellfish Waters Directive
*2 ... EQS (as Annual Average) under EC Dangerous Substances Directive

7.5.2 The "No Deterioration" Objective

Metal inputs into Restronguet Creek from the Carnon River under the "No Deterioration" objective would remain broadly similar to current levels. Consequently, concentrations of cadmium, copper and zinc are likely to continue to exceed the EQS under the Dangerous Substances Directives for Restronguet Creek. Concentrations of zinc are likely to exceed the EQS under the Shellfish Waters Directive at Turnaware Bar.

7.5.3 The "North Sea Commitments" Objective

An estimation of the likely water quality in Restronguet Creek that would be experienced under the North Sea Commitments objective has been based upon a review of data for a short period between April and October, 1991 (see Table 7-4). During this period, when the water level within the mine workings was rising and there was no release of minewater into the Carnon River, the average concentration of zinc at Devoran Bridge was 2400 μg/l, below the target value of 3100 μg/l.

Table 7-4 : Zinc Concentrations in the Carnon River and Restronguet Creek for April/October 1991

Zinc Concentration	Average Concentration	Range	EQS
Carnon River (μg/l total zinc)	2 400	900 - 3 300	500
Restronguet Creek (μg/l dissolved zinc)	69	22 - 218	40*1
Turnaware Bar (μg/l dissolved zinc)	23	12 - 34	40*2

Note : *1 ... EQS under EC Dangerous Substances Directives
*2 ... EQS under EC Shellfish Waters Directive

It is apparent that, under a reduced zinc loading from the Carnon River, the EQS for zinc was still exceeded in Restronguet Creek.

7.5.4 The "EC Directive" Objective

There are no historical data which can be used to predict the likely water quality in Restronguet Creek and the Fal Estuary which might arise in the event that full compliance with EQS was achieved at Devoran Bridge.

An attempt was made to model the likely changes in water quality in Carrick Roads using the Estuarine Contaminant Simulator (ECoS) Model. However, under these circumstances the contribution to estuarine metal concentrations from the Carnon River is dramatically reduced. However, the accumulated metal contaminated sediments within the estuary and other minor freshwater inputs become the controlling factors in determining estuarine water quality. The ECoS Model cannot be used to make predictions with any degree of accuracy under these conditions. However, it is possible that the influence of the metal-rich sediments would be sufficient to ensure that EQS in both Restronguet Creek and the Fal Estuary would continue to be exceeded even if the Carnon River were to comply with EQS at Devoran Bridge.

7.6 ENVIRONMENTAL IMPLICATIONS FOR THE FAL ESTUARY OF ADOPTING WATER QUALITY OBJECTIVES FOR THE CARNON RIVER

7.6.1 Discolouration of Restronguet Creek and Carrick Roads

The appearance of discolouration due to iron hydroxide precipitation in estuarine waters is dependent upon the iron concentration and pH of the waters. The extent and intensity of the discolouration is dependent not only on the quality of the input from the Carnon River but also on the degree of mixing promoted by the tidal influences.

Under all the Water Quality Objectives except the "No Treatment" objective, the inputs of acidic iron-rich water would not be sufficient to promote discolouration of the estuary to any significant degree. A simple mass balance model, based on iron loadings entering the estuary from the Carnon River, suggests that, under all objectives except the "No Treatment" objective, discolouration might be experienced in no more than 0.2% of months (i.e. in the long-term, about one month every 40 years).

Under the "No Treatment" objective, however, the iron concentration in estuarine waters will be determined principally by the concentration and flow of the untreated minewater. Under these conditions, discolouration of the Restronguet Creek may be experienced in up to 56% of months (i.e. in the long-term, discolouration would be experienced once every two months). Furthermore, the discolouration on occasions may be intense, persistent and, depending on tidal influences, extend well into Carrick Roads.

The estimated extent of the discolouration over a 14 day period, under the "No Treatment" objective, was predicted using the simple mass balance model for both:

- Low flow summer conditions, when flow from the mine would amount to approximately 0.1 m^3/s, (the best case).
- High flow winter conditions, when flow from the mine can be up to 0.5 m^3/s (the worst case).

In both cases significant discolouration throughout Restronguet Creek and Mylor Creek and extending into Carrick Roads is expected. Under the worst case conditions, discolouration would extend beyond Pendennis Point (see Figure 7.1). Three designated Bathing Waters may experience increased colour and turbidity as a consequence.

7.6.2 Estuarine Ecology and Metal Toxicity

The toxicity of metals is dependent upon many factors including: chemical speciation, chemical transformations (such as methylation), rates of metal uptake, interactions between metals, and inter-specific and intra-specific variations, including metal tolerance in response to metal accumulation. Consequently, although it is not possible to predict accurately changes in estuarine ecology which might result from different concentrations of metals in estuarine waters, under the "No Treatment" objective, it is probable that :

- Concentrations of zinc in oysters would increase to a level at which they would be declared unfit for human consumption (even though the zinc concentrations might not be deleterious to the adult shellfish themselves).

- The elevated concentrations of zinc, combined with the smothering effect of iron precipitates, would have a deleterious effect on certain species within the benthic flora and fauna. Although difficult to predict, the consequent reduction in food supplies might be expected to impact upon wildfowl and waders using the estuary.

- The elevated concentrations of zinc, combined with the smothering effect of iron precipitates, would have a deleterious impact on the sea bass nursery and both commercial and recreational fisheries.

It is unlikely that any deleterious effects would be experienced under either the "No Deterioration" or the "North Sea Commitments" objectives.

The adoption of the "EC Directive" objective may lead to a long-term improvement in the diversity and abundance of benthic invertebrates in Restronguet Creek and parts of the Fal Estuary. However, no significant short-term improvements would be expected since the metal-rich sediments would continue to exert a significant influence on the ecology of the estuary for many years.

7.7 REFERENCES

(1) Water and the Environment. The implementation of European Community Directives on pollution caused by certain dangerous substances discharged into the aquatic environment. Department of the Environment Circular 7/89.

(2) The estuarine modelling shell ECoS; an evaluation for use by the National Rivers Authority. NRA R&D Note 111, 1992.

(3) Wheal Jane effluent Treatment Options; Implications for Environmental Quality in Carrick Roads and Restronguet Creek. J.R.W. Harris and P.J. Somerfield, Plymouth Marine Laboratory. Report to NRA South Western Region, 1994.

8. LOCATION OF LONG-TERM TREATMENT PLANT

CONTENTS

Photograph 8.1 Carnon Valley Tailings Deposits

Photograph 8.2 Wheal Jane Minesite and Clemows Valley Tailings Dam

8.1 INTRODUCTION

Amelioration of the acid mine drainage problems associated with the Carnon River potentially involves the construction of a long-term treatment system within the valley. Three sites have been considered as possible locations for such a treatment works, namely:

- The Carnon Valley Tailings Deposit between Bissoe and Devoran bridges.
- The Wheal Jane Mine site.
- The area of derelict land upstream of Point Mills bridge.

The location of these sites is shown on Figure 8.1.

The Carnon Valley site is suitable for the construction of either a passive or active treatment system. The Wheal Jane mine site is most suited to active treatment, however the possibility exists to use the surface of the Clemows Valley Tailings Dam as an additional area for passive treatment. The Point Mills site, because of land restrictions, is appropriate only for active treatment.

This section of the report is sub-divided into two main parts. The first deals with the valley in general and includes outline details of land ownership, planning and environmental issues and potential methods of recovering water from the mine.

The second part (Section 8.5 onwards) provides a more detailed assessment of the issues relevant to each specific site. In particular, this section comments on the engineering, planning and environmental factors associated with each site.

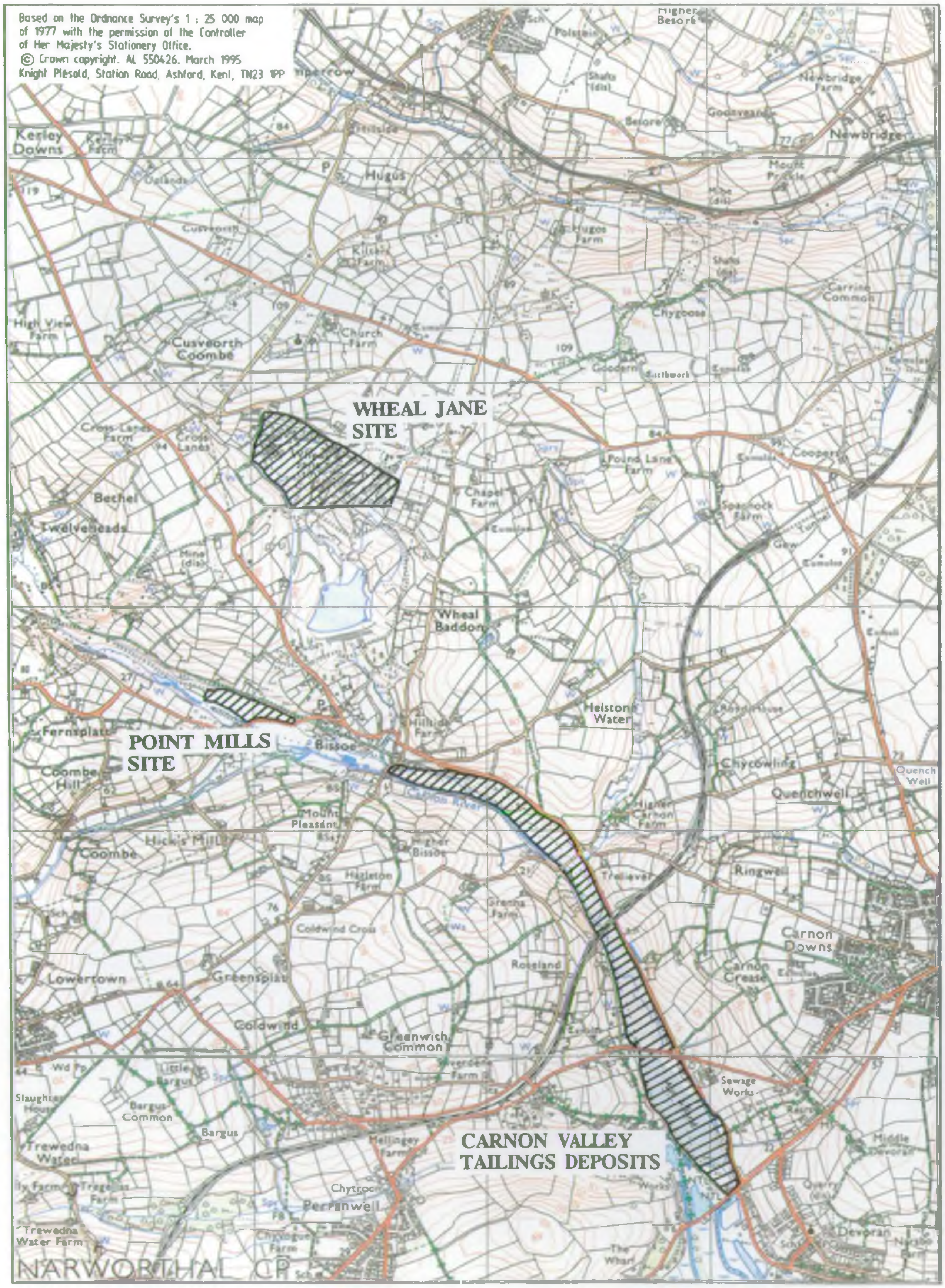
Cost estimates for the construction of a treatment facility on each site are detailed, as appropriate, in Section 10 Passive Treatment and Section 11 Active Treatment.

8.2 LAND OWNERSHIP

Although definitive land ownership searches have not been undertaken, ownership of the three potential treatment plant sites is understood to be as follows:

Carnon Valley Tailings Deposit	-	NRA
Wheal Jane Mine Site	-	South Crofty plc
Points Mills Site	-	Land and Marine Aggregates Ltd

Figure 8.1 Location Plan



8.3 PLANNING ISSUES

8.3.1 County Council and District Council Development Plans

8.3.1.1 Cornwall County Council

The September, 1994 draft Cornwall County Council Structural Plan (Ref. 1) provides a statement of the County Council's policy towards development within the county. Although the Carnon Valley is not referred to explicitly in the report, any development within the valley will need to be in line with the Council's objectives which include:

- Protection and enhancement of the natural environment.
- Wise use and stewardship of renewable and non-renewable resources.
- Minimisation of the production of waste and pollution of land, air and water, and the reversal of existing degradation.

In addition to these general objectives, the following policy statements are deemed to be particularly applicable to the Wheal Jane Minewater Study:

Policy ENV1 - The planning for and development of Cornwall will be based on land use change that conserves, enhances and sustains its environmental assets and resources.

Policy ENV3 - Proposals for development likely to have a material impact on the environment and character of Cornwall and/or make material demands on infrastructure, services and natural resources should be accompanied by an Environmental Statement. Unless it has been demonstrated that the environmental effects are acceptable within the context of other policies in this Plan, such development will not be supported.

Policy ENV4 - All developments must take full account of and respect the landscape characteristics ensuring that the inherent qualities of the whole of Cornwall are maintained and enhanced.

Policy ENV8 - Throughout Cornwall, the siting of development should avoid disturbance or damage to sites of archaeological or historic interest.

Policy ENV24 - In considering proposals for reclamation of derelict land, priority will be given to proposals which deal effectively with safety hazards and facilitate other approved development or will lead to the removal of features that detract from the character of the landscape. The proposed after uses of such a scheme will be dependent on the locality in which they are set and other priorities and policies of the plan.

Policy ENV25 - Development should not increase pollution (including disturbance of existing pollutant) in the water environment either directly or indirectly.

Policy ENV26 - Development, including that along the coast, should not lead to or add to the risk of flooding either in flood plains or on other land liable to flooding.

Policy ENV27 - Development should not lead to the contamination of land.

Policy W2 - All waste disposal proposals will be assessed against the need for the development, the environmental impact of the proposal and the protection of public health. Proposals will not be permitted where they could adversely effect areas recognised for their landscape, nature conservation, historic, archaeological or agricultural value.

Policy W4 - The high quality restoration of landfill or other landraising sites will be required where practicable on a progressive basis. Normally planning permission for landfill will be granted only if the proposal demonstrates a positive enhancement, both of the site and the landscape character of the area in which it is located.

Cornwall County Council Highways Department advised that proposals are under consideration to upgrade the A39 Truro to Falmouth Road at Devoran. One of these proposals involves the construction of a roundabout as shown on Figure 8.2.

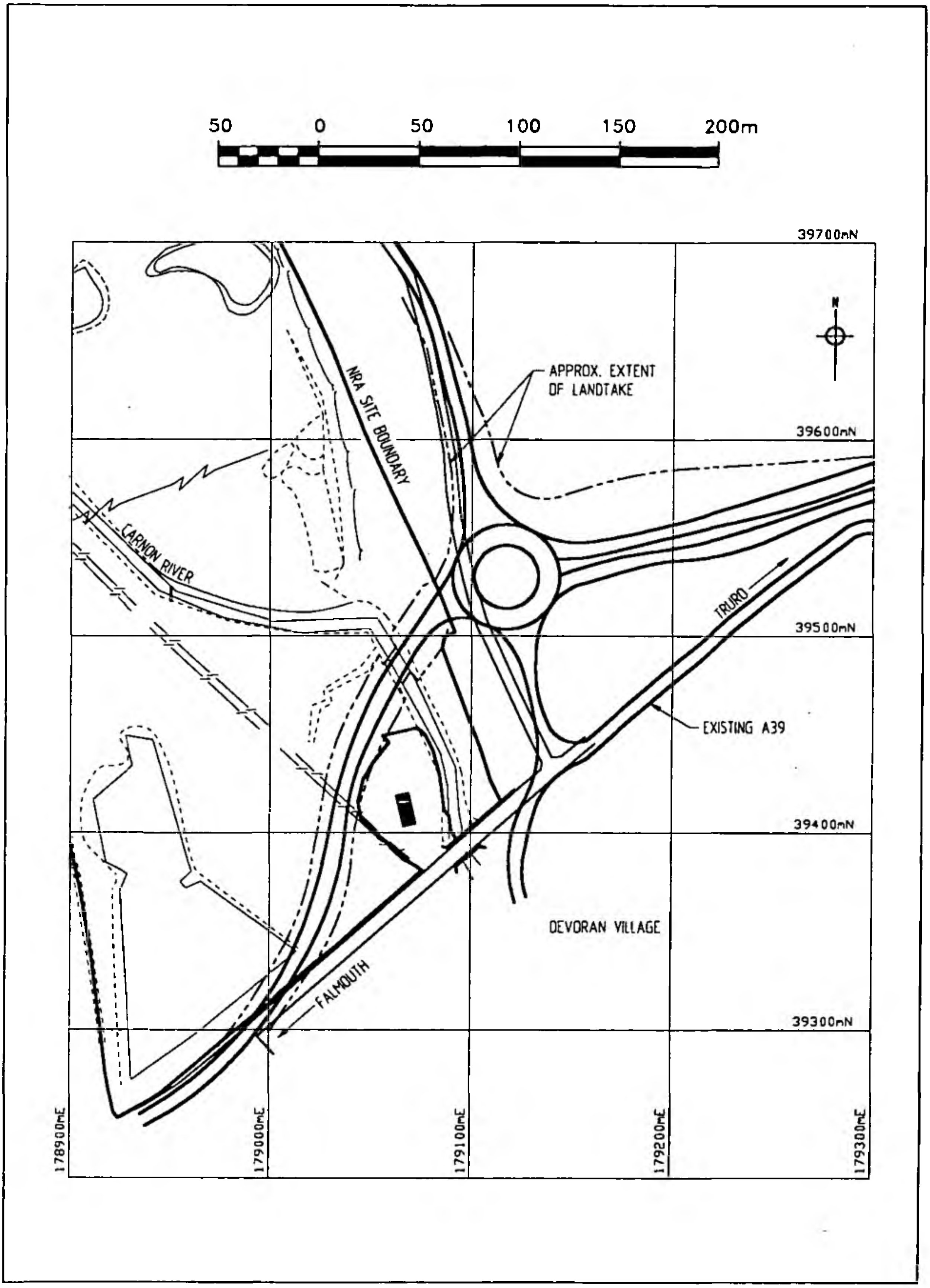
8.3.1.2 Carrick District Council

The Carnon Valley, in general, has not been identified within the Carrick District Structural Plan (Ref. 2) either as an area of preferred development or of special landscape value. However, there are parts of the valley which have been classified as Cornwall Nature Conservation Sites (see Section 2 Background).

The District Council's policies reiterate those of the County Council, with the addition of the following policy:

Policy 10H - The District Planning Authority will not grant planning permission for development proposals which would conflict with the implementation of the mineral tramway project in association with Kerrier Groundworks Trust.

Figure 8.2 Proposed A39 Roundabout at Devoran



8.3.2 Environmental Impact

The development of a scheme to treat the Wheal Jane minewater provides an opportunity not only to ameliorate the impact of acid minewater on the Fal Estuary but also to reinstate substantial parts of the Carnon Valley.

Depending on both the size of the treatment plant and local authority requirements an environmental impact statement would be prepared for the proposed and, in principle, would address:

- Noise and dust.
- Traffic.
- Archaeology.
- Existing ecology.
- Potential for ecological enhancement.
- Potential for enhanced public access.
- Visual impact.

8.3.3 Traffic

Although precise estimates of additional traffic cannot be generated until the proposed treatment system has been designed, it is considered that post construction traffic movements will be relatively low. Preliminary estimates of the additional traffic generated by the operating treatment plant are:

Treatment System	Estimated Number of Return Journeys Per Week
Active Treatment	
Lorries	10-35
Cars	50-100
Passive Treatment	
Lorries	<3
Cars	<15

Significantly more vehicle movements will be generated during plant construction and detailed arrangements for the routing of this traffic will need to be agreed as part of the planning process.

8.4 LEGAL CONSIDERATIONS

The following legislation will need to be considered in the selection of a long-term treatment site:

- Town and Country Planning Acts and Regulations.
- Mines and Quarries (Tips) Act 1969.
- Mines and Quarries Act 1954.
- Environmental Protection Act 1990.
- Water Resources Act 1991.
- Health and Safety Regulations.

~~subject to definitive survey~~ STET.

The Waste Regulatory Authority has indicated that any facility, within which the waste product would be stored indefinitely, would need to be both licensed and built to an approved standard.

Dealt with later

The above list, however, is not exhaustive and due regard will be taken of all other relevant legislation.

8.5 MINEWATER ABSTRACTION

A secure means of abstracting minewater is required as part of the development of the long-term minewater treatment system.

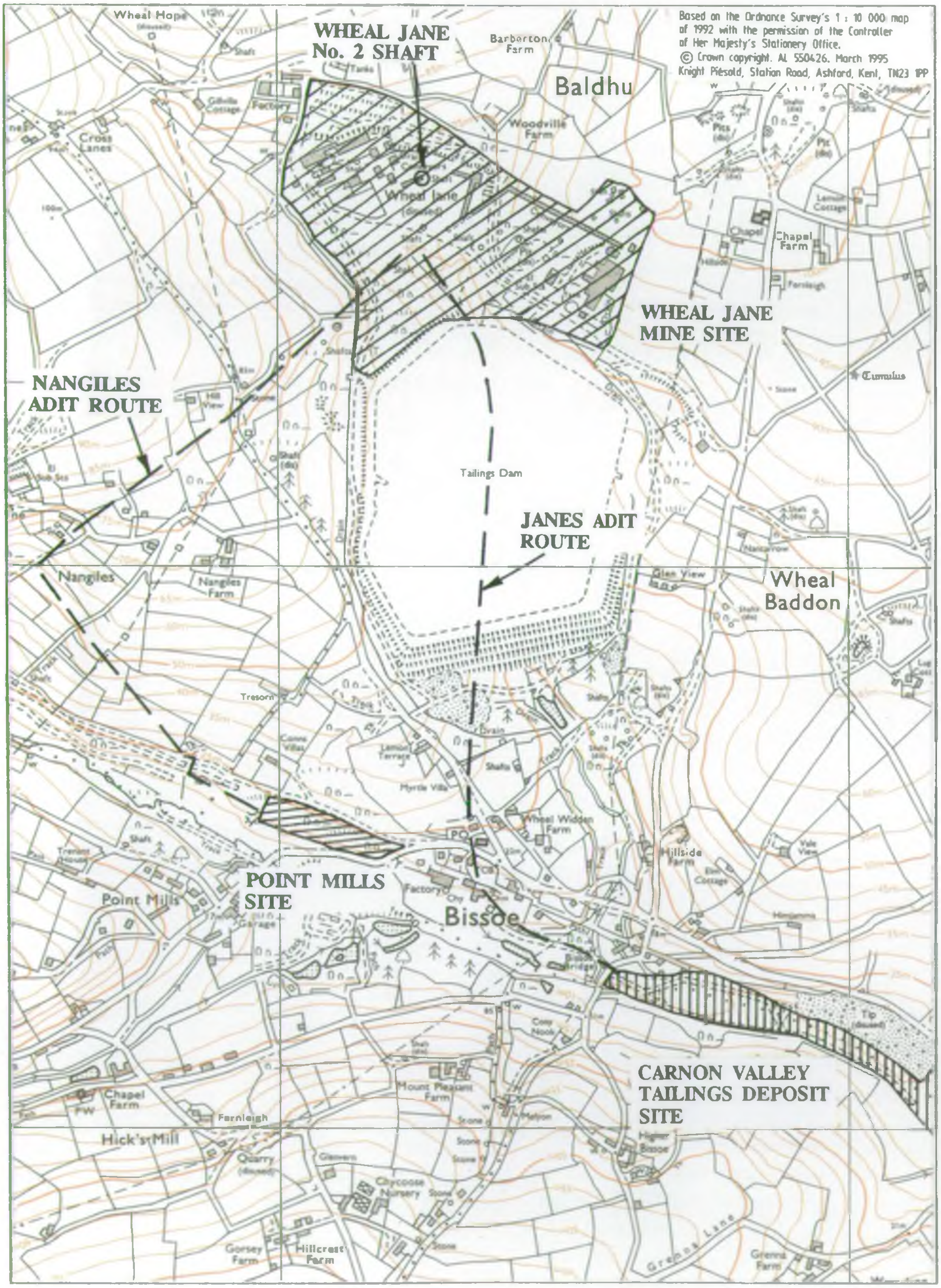
The provision of a suitable minewater abstraction system, therefore, forms an integral part in the appraisal of possible sites for the construction of a long-term treatment facility. The following possible abstraction routes have been considered:

- Wheal Jane No. 2 Shaft.
- Jane's Adit.
- Nangiles Adit.
- New Adit.
- Directional drilling.

The relative locations of the existing abstraction routes are shown in Figure 8.3.

Where feasible, parts of the Janes Adit have been inspected. The results from this inspection have been used, together with the available old plans and geological information, to estimate the possible extent and cost of the works required to enable the adits to be used for long-term abstraction.

Figure 8.3 Possible Minewater Abstraction Routes



8.5.1 Wheal Jane No. 2 Shaft

Wheal Jane No. 2 Shaft comprises a concrete-lined structure some 4.5 m diameter and approximately 340 m deep. The shaft was sunk in the late 1960s and was used to transport men and materials underground.

Six borehole pumps have been installed in the shaft, together with a new pump handling facility, as part of the NRA's existing operations.

Structurally the shaft is generally considered to be in good condition. However the skip guides and other shaft fittings were not removed following mine closure. As a result, the steelwork continues to be progressively attacked by acidic minewater. Consequently, in places, it is badly corroded and in the long-term may collapse. Should abstraction from Wheal Jane No. 2 Shaft form an integral part of the long-term treatment system, it is recommended that the shaft fittings and associated steel work are removed from the shaft between the surface and the standing water level.

Dismantling of shaft steelwork will not only remove the possibility of it collapsing on to the submersible pumps, but, if appropriate, would enable the installation of additional submersible pumps.

Part, if not all, of the shaft has been concrete-lined. The long-term durability of this lining should be checked by selective coring and analysis of the concrete.

8.5.2 Jane's Adit

Jane's Adit was driven to prevent the mine workings flooding with groundwater. The adit is approximately 1.5 m high x 0.9 m wide and was driven a distance of approximately 2.0 km from the portal at Bissoe to the Wheal Jane mine. To facilitate construction, a number of shafts were sunk along the line of the adit. Cross cut stopes and other drives also connect into the adit.

Water from the Wheal Jane mine starts flowing from the adit at an elevation of approximately 14.75 m AOD. Below this level the adit only intercepts infiltration and, therefore, the quality of this water is relatively good.

A concrete plug was installed at the adit portal in November, 1991 to prevent the uncontrolled release of water from Wheal Jane into the Carnon River. The plug incorporates a 300 mm diameter high level outlet and a 150 mm diameter low level outlet. Both outlets are fitted with stainless valves to control the flow from the adit. The high level outlet is connected to the passive pilot plant distribution main, whilst the low level outlet has been blanked off to prevent accidental release of minewater to the river.

A limited internal inspection of the adit was undertaken in October, 1993 and November, 1994. Full inspection of the whole adit was considered unsafe by the Mine Safety Officer due to:

- Significant water flow through the adit which had to be drained by pumping.
- Lack of at least two secure access/egress points (one at each end of the section under inspection).

Based on the limited inspections undertaken, it was concluded that:

- The majority of the adit was in a satisfactory condition.
- The upstream section of the adit, within the zone of influence of the recent Wheal Jane workings, has been affected by ground movement induced by mining and therefore was in a less satisfactory condition. A 30 m length is heavily timbered and much of this timbering is broken indicating that, locally, the surrounding rock has collapsed onto the timber work.
- Inspection of the adit immediately downstream of the Wheal Jane Mine was prevented by up to 1.2 m of water and precipitated iron hydroxide (ochre). The location and occurrence of this build-up suggests that the adit may be partially blocked by the remains of the former No. 2 Adit shaft plug, collapsed rock or by hydroxides precipitated during the early treatment operations.
- Some of the intersections between the adit and the adit shafts have been stopped up with timber boards and steel supports. These stopings were generally in a satisfactory condition, but represented a potential long-term liability.
- Access to the adit, for future inspections and/or repair, would be impossible unless long-term provision was made to maintain the Wheal Jane No. 2 Shaft pumping system for dewatering purposes.
- Due to the tortuosity of the adit and the small cross sectional area, mobilising men and materials to carry out any repairs would be extremely difficult.

Preliminary costings indicate that the adit could be enlarged and made secure for a cost of £1 400 000.

In conclusion, the adit in its present condition offers a relatively secure method of abstracting water to feed a plant located on the Carnon Valley Tailings Deposits. However, due to the size and tortuosity of the adit, internal inspection and repair would be difficult to achieve. Although the probability of a complete collapse is small, the resultant consequences would be significant.

8.5.3 Nangiles Adit

The original Nangiles Adit drained water from the upper levels of the Wheal Jane and Nangiles Mines into the Carnon River via County Adit. This discharge route was subsequently blocked and a cross cut driven from the northern bank of the Carnon River, at a location some 500 m upstream of Point Mills, to intersect the Nangiles Adit.

A secure means of abstracting minewater for treatment could be achieved by upgrading the length of the adit between the portal and Nangiles Engine Shaft. Nangiles Engine Shaft is connected to the mine complex on several different levels and provides sufficient built in redundancy to cope with collapse of one or more of the drives on each level. The security of this route, therefore, primarily relies on the integrity of both the adit and Nangiles Engine Shaft.

If Nangiles is adopted as a long-term abstraction route, the adit would need to be upgraded to provide a suitable minimum adit cross section to allow access for maintenance.

The geological plans indicate that part of the adit may be on lode and possibly has been subjected to ground movement associated with past mining activity. Therefore, it is anticipated that at least part of the adit will be in a poor condition.

Water removed from the adit would be transferred to the treatment works located either at Point Mills or the Carnon Valley Tailings Deposits. Construction of such a transfer system would require the negotiation of an easement with the landowners along the route.

8.5.4 New Adit

Installation of a new adit would provide the opportunity to recover minewater via the most direct route appropriate for the treatment works. However, construction would cost approximately £2 000 000 due to:

- The length of adit required (approximately 1250 m).
- The difficulty of constructing through open or collapsed workings.
- The risk of intercepting flooded workings.

As a consequence of the risk and potential costs, a more cost effective solution can be achieved by upgrading one of the existing adits.

8.5.5 Directional Drilling

Minewater could be abstracted for treatment by means of a series of holes put down using directional drilling techniques to intercept the old workings. Such holes could be drilled either vertically or at an inclination to suit the mine geometry.

Abstraction from depth within the mine is not considered beneficial as:

- The process of ongoing acid generation is believed to occur predominantly within the unsaturated zone above the water table and within the region subjected to seasonal groundwater level fluctuations. A significant proportion of this water is collected by the upper mine levels and associated drainage adits and may not be easily drained into the collection holes.

- Only limited flow occurs through the mine workings at depth due to the fact that the water table within the orebody is held nearly horizontal by drainage into the upper levels and adits. In effect, the voids below river level contain predominantly stagnant water.

- Shaft probing has indicated the conductivity and dissolved metal content of the minewater increases with depth and has confirmed the presence of stratification within the mine. The evidence of stratification suggests that only limited mixing of shallow and deep water is occurring within the mine.

- Abstraction of the more highly contaminated water from depth within the mine would result in an unnecessary increase in treatment costs due to the additional reagents necessary to precipitate the higher metal concentrations.

8.5.6 Preferred Abstraction Options

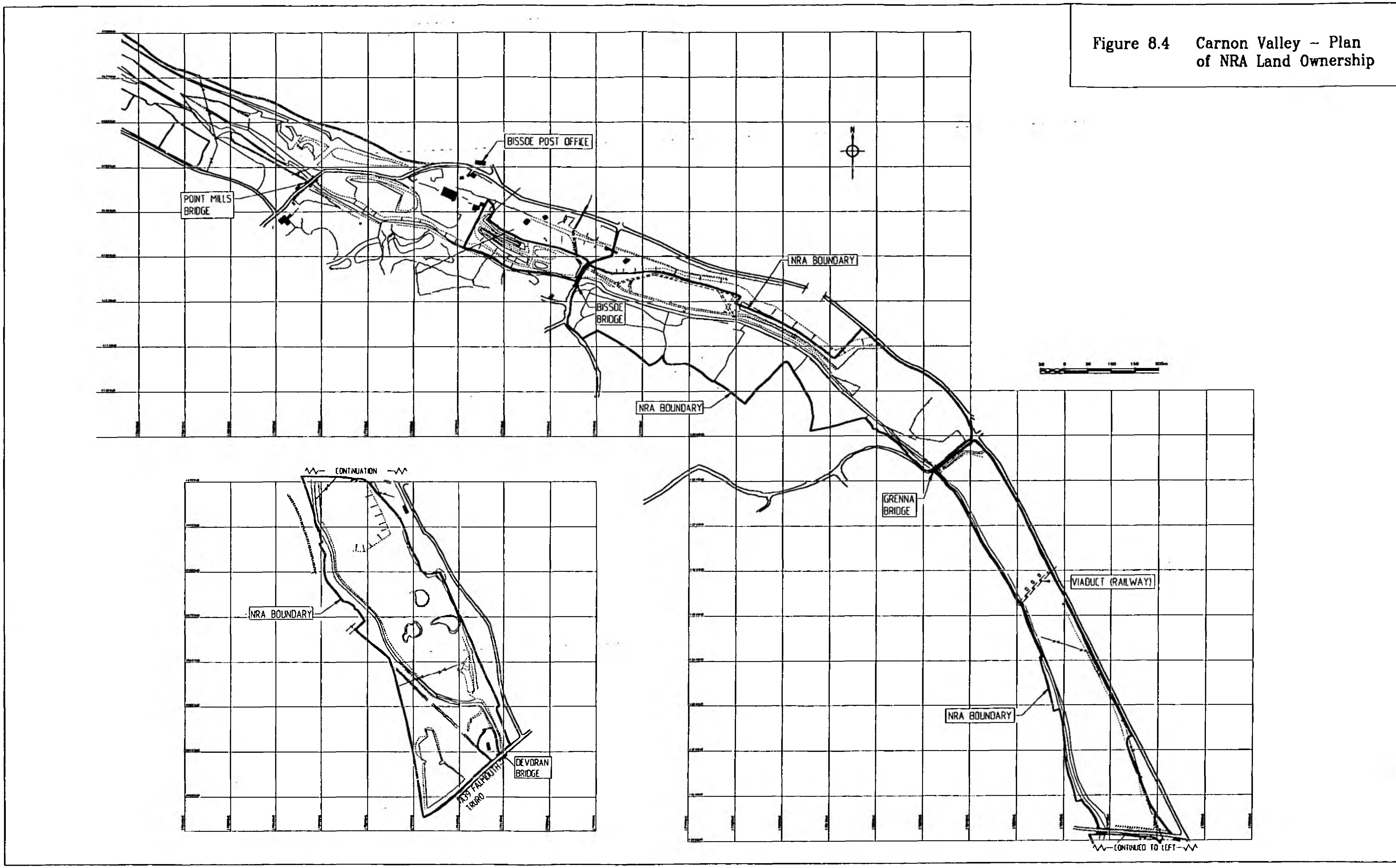
The desk studies and associated field inspections have indicated that the most cost effective and secure method of recovering water from the Wheal Jane Mine for treatment is from the Wheal Jane No. 2 Shaft.

8.6 CARNON VALLEY TAILINGS DEPOSITS

8.6.1 Site Description

An area of 40 ha located between Bissoe Bridge and Devoran Causeway (Figure 8.4) has been purchased by the NRA specifically to ensure that virtually all the suitable land within the valley is available for treatment purposes. Consequently, the site is potentially suited to the construction of either a passive

Figure 8.4 Carnon Valley – Plan of NRA Land Ownership



or active treatment system. The land purchased comprises the following approximate areas:

	ha
Old Tailings Deposits	29.9
Open Water (Ponds)	1.0
Carnon River	3.3
Agricultural Land	6.2
Total Area	40.4

8.6.2 Planning and Legal Aspects

Development of a treatment facility on the relatively flat area of land occupied by the former Carnon Valley Tailings Deposits would involve integration of the treatment scheme with:

- Reinstatement of the remainder of the tailings deposits in a manner in keeping with the rest of the valley.
- Provision of a permissive bridle path adjacent to the river between Devoran and Bissoe.

Legal responsibility for the security of the tailings depository is covered by the Mines and Quarries (Tips) Act 1969. Discussions with the Mines and Quarries Inspectorate have revealed that as the depositories are no longer in use or associated with an operating mine, the deposits can be re-classified as disused and therefore fall within Part II of the above Act.

Legal liability for the security of the tips on this basis lies with the landowner. Responsibility for ensuring that the landowner maintains the tips in a condition which does not endanger the public lies with the County Council.

Redevelopment of the Carnon Valley site for either passive treatment and/or metalliferous sludge disposal would require planning consent from Cornwall County Council.

8.6.3 Engineering

8.6.3.1 Ground Conditions

Exploratory drilling at the locations shown in Figure 8.5 have revealed that the superficial geology generally comprises:

Made ground - comprising a 1 to 2 m thick stiff crust underlain by 4 - 6 m of very soft to medium dense silt and sandy material (tailings).

Alluvium	-	thin (< 1 m) bands of either dense sands or organic rich alluvial silts and clay.
Mylor shale	-	weathered, increasingly intact with depth, blue grey slightly metamorphosed shale.

A typical borehole log is shown in Figure 8.6, whilst the full site investigation report is contained in Ref. 3.

Groundwater levels within the tailings deposits vary and within part of the passive treatment pilot plant site lie at ground level. An area at the south eastern end of the site is occupied by a number of shallow lakes.

The soft ground conditions present beneath the 1 to 2 m thick consolidated crust covering the whole of the tailings deposit represent potentially difficult conditions for the construction of any treatment facility. Structures built on the tailings, for example, would need to be supported on piles driven into the underlying rock, or founded on concrete raft structures.

Excavation to depths of approximately 1.5 m may be feasible without the use of specialist techniques. Excavations to greater depths, however, will require:

- The control of groundwater inflows.
- Measures to ensure the stability of excavated faces.
- The provision of a granular drainage blanket layer on the base of any cells or lagoons to both control long-term water levels and provide a running course upon which construction plant can operate.

To minimise construction costs, where feasible, deep excavations should be avoided.

The results from the 1994 chemical analyses of the groundwater and the superficial materials present within the valley are summarised in Table 8-1 and are similar to the data derived from previous investigations. These investigations have revealed that:

- The tailings samples were found to contain particularly high concentrations of arsenic and copper. The levels of nickel, zinc, tin and lead were also elevated above normal background levels. The underlying alluvium contained elevated concentrations of the same metals (except for nickel), although to a lesser degree.
- The principal contaminants present in the water sampled from the boreholes were arsenic, copper and zinc and, to a lesser degree, lead, nickel and chromium.

Figure 8.5 Carnon Valley Tailings Deposits and Location of 1994 Exploratory Boreholes

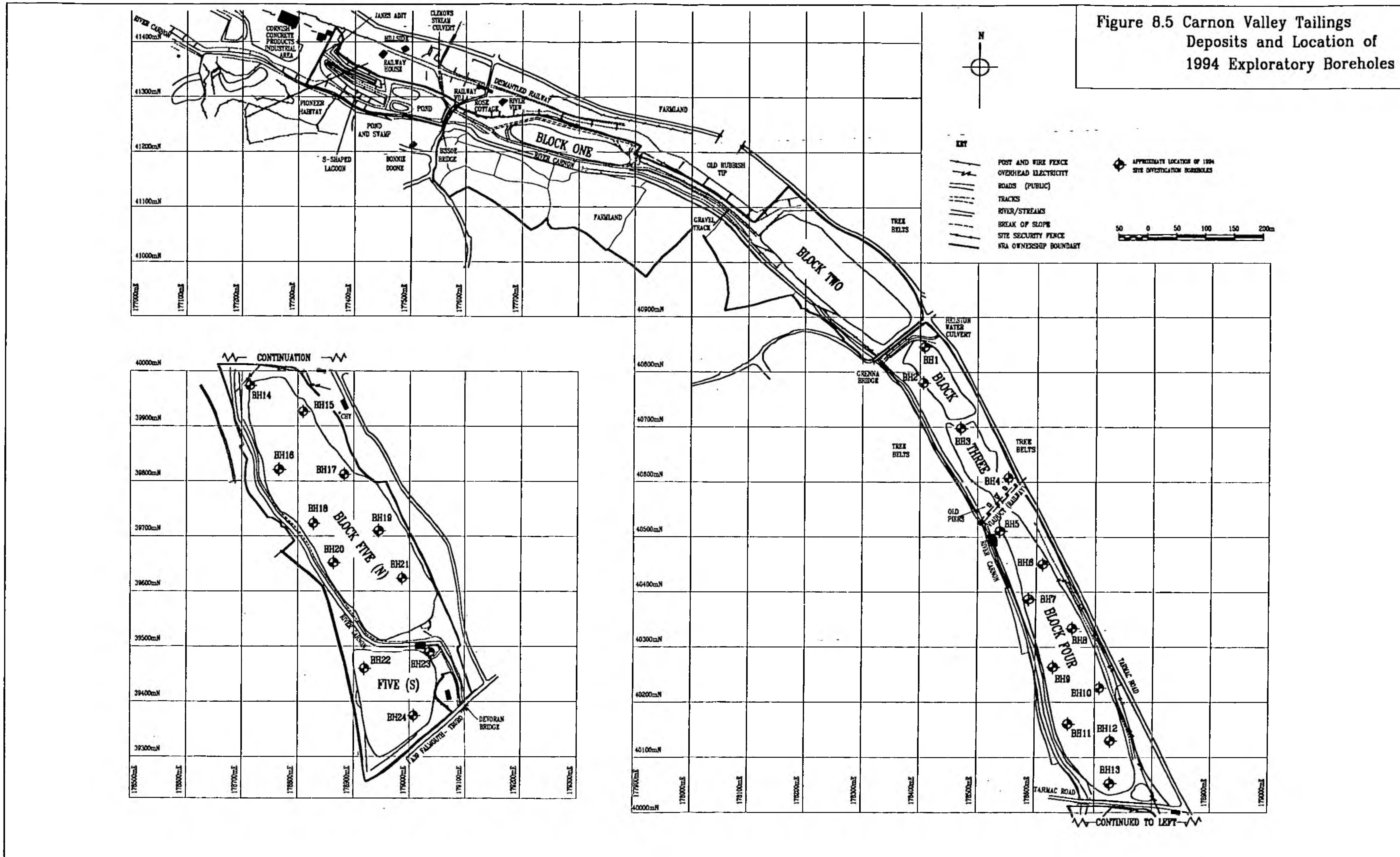


Figure 8.6 Carnon Valley Tailings Deposit – Typical Borehole Log

Sampling				Properties			Strata			
Depth	Sample Type	Depth Cased	Depth to Water	Strength kN/m²	W %	SPT N	Description	Depth	Legend	Level OD
								G.L.		5.21
0.20 - 1.00	B	0.00	DRY		37.0		MADE GROUND: Loose brown mottled red brown slightly sandy clayey silt with occasional relict rootlets (Tailings Material).			
1.00 - 1.45	U11	1.00		45	41.0		Becoming very loose below 1.00m.			
1.45 - 1.60	J						MADE GROUND: Very loose greyish brown mottled brown slightly sandy clayey silt with occasional small cobbles (Tailings Material).	1.50		3.71
2.00 - 2.45	SJ	2.00			45.0	2				
3.00 - 3.45	U10	3.00		23	40.0					
3.45 - 3.60	J									
4.00 - 4.45	SJ	4.00				2	MADE GROUND: Very loose dark brownish grey slightly sandy silt (Tailings Material).	4.00		1.21
4.50 - 4.90	B	4.50					MADE GROUND: Very loose black/dark brown/greenish brown clayey silt with occasional fine to medium gravel (Tailings Material).	4.50		0.71
5.00 - 5.45	U18	5.00	2.00	16	25.0					
6.50 - 6.95	SJ	6.50	3.60			3	Very loose silty fine to coarse SAND and GRAVEL (ALLUVIUM).	6.50		-1.29
7.00 - 8.00	B	7.00	4.00							
8.00 - 8.45	SJ	8.00	2.00			7	Very soft dark grey slightly sandy very silty CLAY with some fine to coarse gravel (ALLUVIUM).	8.00		-2.79
8.60 - 9.00	B	8.60	4.00							
9.00 - 9.45	U14	9.00	3.90				Loose pale grey clayey SILT with occasional fine to medium gravel and much decomposed organic material (ALLUVIUM).	9.00		-3
9.45 - 9.60	J									
10.40- 10.60	SJ	10.40	4.80			61/50	Pale grey mottled yellow highly decomposed very narrowly cleaved highly to moderately weathered SLATE, very weak, with some clay/silt matrix and infill. (MYLOR SERIES).	10.40 10.60		-5 -5
							End of Borehole 9 at 10.60m.			

- The results indicate that any construction on the site would need to take due regard of the risks to the health of the site workers and the general public. Appropriate precautions might include good standards of hygiene, designated clean areas, washing facilities, protective clothing and the provision of both dust monitoring and control measures.

- In addition, the removal of materials from the site would need to be undertaken in a controlled manner in accordance with the Duty of Care Regulations 1991. Off-site disposal would be a site licensed to accept contaminated materials.

- The sulphate concentrations in the tailings, alluvium and groundwater were elevated and, therefore, to ensure adequate durability, buried concrete structures would need to be designed in accordance with BRE Digest 363.

8.6.3.2 Carnon River

The Carnon River has been relocated from its original course, within the centre of the valley floor, to the south western side of the flood plain to allow the deposition of tailings.

Tailings deposition has been undertaken behind a bund constructed along the left hand bank of the river (looking downstream). In most places, these bunds are of sufficient height to contain the 1:100 year flood and, therefore, only a limited part of the available area now falls within the 1:100 year flood plain. Development of any treatment facility within the area of the Carnon Valley Tailings Deposits will need to:

- Prevent loss in flood storage capacity.

- Pay due regard to the need to maintain and protect the tailings confinement bund from erosion by the river.

In addition, the treatment works may need to be designed to withstand flooding from events in excess of the 1:100 year return period.

8.6.3.3 Services

The site is served only by low capacity domestic water and electricity supplies. Should an active treatment facility be constructed on this site, additional services would have to be installed.

8.6.4 **Minewater Abstraction**

A secure supply of minewater for a treatment located within the Carnon Valley could be achieved as outlined in Section 8.5, by means of a pipeline running from either the upgraded Jane's or Nangiles Adits.

8.6.5 Environmental Impact

The construction of a treatment scheme on the Carnon Valley Tailings Deposits provides an opportunity to positively improve the environment with the Carnon Valley. Such a scheme would be landscaped to minimise the visual impact of both the treatment plant and the Carnon Valley Tailings Deposits.

8.7 WHEAL JANE MINE SITE

Subject to the agreement of South Crofty plc, the existing Wheal Jane Mine site may provide a suitable location for an active treatment works. In particular, the site offers the following potential advantages:

- Established use for mining and process engineering.
- Availability of the Clemows Valley Tailings Dam and potentially other areas of the mine site for continued metalliferous sludge disposal.
- The development of an integrated strategy for both minewater treatment and site restoration.

Detailed negotiations would need to be carried out with South Crofty plc should this option be deemed the preferable solution. Preliminary discussions have revealed that South Crofty plc:

- Propose to relocate the existing ore processing plant to the South Crofty Mine, to avoid hauling ore from South Crofty Mine to Wheal Jane for processing.
- In principle, the company is amenable to the idea of the site being used for continued water treatment purposes.

In addition, it may be feasible to redevelop the surface of the Clemows Valley Tailings Dam to provide an additional 16 ha of land for passive treatment. Such redevelopment, however, would be difficult due to the unconsolidated nature of the near surface material stored within the dam.

8.7.1 Site Description

The Wheal Jane site itself comprises:

- The abandoned Wheal Jane shafts and associated mine buildings.
- The Wheal Jane Mill, which is used to process tin ore won from the South Crofty Mine.
- The Clemows Valley Tailings Dam.

8.7.2 Planning and Legal Aspects

8.7.2.1 Planning Aspects

The Wheal Jane Mine site already has planning consent for winning, processing and disposal of waste produced by mining operations. Construction of a long-term active treatment facility at this site is potentially advantageous in that:

- The need to develop additional land for industrial purposes would be avoided.
- The site is already adequately supplied with the necessary infrastructure to support such an operation.
- Use of the Clemows Valley Tailings Dam minimises the additional traffic generated, as the disposal of any resultant metalliferous sludges could be undertaken on site.

8.7.2.2 Legal Aspects

The operation of the Clemows Valley Tailings Dam is covered by the Mines and Quarries (Tips) Act 1969 and the associated regulations. The dam is currently defined as a classified active tip as the facility is still in use, is more than 4 m high and contains in excess of 10 000 m^3 of stored waste. Clarification of the status of the deposit if solely used for metalliferous sludge disposal has been sought from the Mines and Quarries Inspectorate. The Inspectorate's lawyers have advised that although the facility would still be in use, it would be legally classified as a disused tip.

Preliminary discussions have been held with the Waste Regulatory Authority (WRA) regarding the legal status of the tip under the Environmental Protection Act 1990. The WRA has advocated that, in the event of the dam being used solely for the storage of metalliferous sludge, the facility should be licensed in accordance with the Act.

8.7.3 Engineering

8.7.3.1 Construction

The site has already been used for heavy engineering purposes and a large flat platform has been previously constructed by means of a cut and fill operation upon which the mine complex has been founded. This platform should be suitable for the construction of an active treatment plant.

Construction of a passive treatment system on the surface of the tailings dam would be difficult to achieve unless the surface of the dam is first allowed to consolidate and then covered with a layer of free-draining material to form a suitable working platform upon which to found the subsequent works.

8.7.3.2 Services

The site is already well serviced by the existing electrical supply and is connected to mains water.

8.7.4 Minewater Abstraction

Minewater would be abstracted for treatment using pumps located in Wheal Jane No. 2 Shaft, which is the preferred abstraction point identified in Section 8.5. This system has been operational for approximately three years as part of the NRA's existing treatment system. The nearby Clemows Shaft also remains open and could be used to provide a secondary abstraction source, in the unlikely event of a blockage in Wheal Jane No. 2 Shaft.

8.7.5 Environmental Impact

Construction of a treatment facility on the Wheal Jane site should have minimal environmental impact on the valley. Indeed, the possibility exists to use the ongoing minewater treatment scheme to assist in the reinstatement of the Clemows Valley Tailings Dam, thereby producing a further benefit to the Carnon Valley environment.

8.8 POINT MILLS

The construction of an active treatment system is technically feasible on the area of open land located immediately to the north of Point Mills bridge. The potential treatment plant site comprises a gently inclined platform located on the left bank of the Carnon River. This area was previously occupied by the chemical works shown on the old ordnance survey plans but is now derelict.

8.8.1 Planning and Legal Considerations

This site is overlooked by the adjacent properties in Point Mills and would need to be carefully engineered to minimise the environmental impact.

The site is not owned by the NRA and, therefore, either a long-term lease or the freehold would need to be obtained before the site could be developed.

8.8.2 Engineering

The ground conditions on this site are unknown. However, the historical ordnance survey plans indicate that the site was previously used for industrial purposes and may, therefore, contain old foundations, contaminated fill and made-up ground.

The installation of new site services, including the upgrading of the road junction, would be required.

8.8.3 Minewater Abstraction

The main advantage of this site is its close proximity to Nangiles Adit and consequently would require the minewater to be piped only a short distance. The level of the site, however, is close to that of the adit portal and therefore low head pumps may be needed to feed minewater into the treatment system.

8.8.4 Environmental Impact

The site is sparsely vegetated and of limited environmental value. Development of an active treatment plant at this site would provide an opportunity to rehabilitate the area surrounding the proposed plant.

8.9 SUMMARY AND CONCLUSIONS

8.9.1 Summary

Three possible sites with the Carnon Valley have been considered for the location of a long-term minewater treatment plant, namely the Carnon Valley Tailings Deposits, Wheal Jane Mine site and Point Mills. The attributes of these sites are summarised below:

Carnon Valley Tailings Deposits

- This site is suitable for active and passive treatment systems.
- Minewater could be fed by gravity to the site either via the Nangiles or Jane's Adit.
- Development of the site would be integrated with the restoration and improvement of the amenity value of the valley floor.

Wheal Jane Mine Site

- The mine site is suitable for active treatment and the surface of the Clemows Valley Tailings Dam also could be used for passive treatment.
- Minewater would be transferred from underground using submersible pumps installed in Wheal Jane No. 2 Shaft.
- This site has established processing use and has adequate infrastructure.
- The opportunity exists to integrate minewater treatment with restoration of the site.
- The site is adjacent to Clemows Valley Tailings Dam which is the preferred location for waste solids disposal.

Point Mills

- The site is suitable only for the construction of an active treatment plant.
- Minewater would be fed to the plant from the nearby Nangiles Adit.
- The site is currently derelict.

8.9.2 Conclusions

The preferred location for the long-term treatment of Wheal Jane Minewater is dependent on the method of treatment adopted. From the review of the possible development sites outlined in the previous sub-sections, it can be concluded that based on planning and other non-technical aspects:

- The Wheal Jane Mine site is the preferred location for an active treatment plant.
- The Lower Carnon Valley Tailings Deposit is the most suitable site for a passive treatment plant.
- If necessary additional land for passive treatment could be made available by redeveloping the surface of the Clemows Valley Tailings Dam.
- The most secure method of recovering minewater for treatment is by pumping from the Wheal Jane No. 2 Shaft.
- Should gravity discharge of minewater be preferable, the most secure method of collection would be by upgrading the Jane's Adit at an estimated cost of £1 400 000.

8.10 REFERENCES

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9

9. PREVENTION & CONTROL OF DISCHARGES

CONTENTS

9.1 INTRODUCTION

The potential for prevention and control of minewater emanating from Wheal Jane has been addressed as part of the overall treatment strategy. The methods addressed include:-

- Physical control of recharge and hence discharge by sealing the river bed and other major points of recharge to the mine workings and/or controlling groundwater movement and flow.

- Control of acid generation by inhibiting oxidation and other mechanisms which contribute to acid mine drainage (see Table 9-1).

Table 9-1 : Potential Methods for Prevention and Control of Discharges from Wheal Jane

Physical Control of Recharge and Discharge			
Method	Technique	Access	Mapping
Reduce recharge	Seal river bed	-	-
	Seal catchment surface	-	-
	Seal surface features	-	-
Restrict groundwater flow	Underground barriers	✓	✓
Control of Acid Generation			
Method	Technique	Access	Mapping
Inhibit oxidation	Inundate with water	-	✓
	Backfill with slurry	-	✓
	Air sealing	✓	✓
Seal rock surfaces	Apply sealants	✓	✓
	Apply bactericides	✓	✓
Chemical and Bacteriological modification	Backfill with lime-based slurry	-	✓
	Inundate with seawater	-	✓
	Introduce organic substrate	✓	✓
	Introduce antibacterial agents	✓	✓

9.2 RECHARGE AND DISCHARGE CONTROL

Recharge and discharge control implies a reduction in the volume of water infiltrating into the mine system and thus a reduction in the volume of contaminated water emanating from the mine. Recharge into the mine is derived from direct infiltration of rainfall and seepage from water courses. Methods of controlling these processes at Wheal Jane are discussed below.

9.2.1 Seepage Control from the Carnon River

In 1975, following the collapse of old workings during a flood event, the Carnon River flowed into the workings rapidly overwhelming the mine pumps. For mine safety reasons a stretch of the river was confined within a concrete channel to prevent such a reoccurrence. This work resulted in some 80 m of the river being canalised over the most vulnerable stretch of the workings between the County Adit and Wellington Adit portals. It is believed that other potential inlet points were identified and sealed during this operation and a subsequent study of water infiltration to the mine identified no significant inflow via the river floor (Ref. 1).

Since recovery of water levels in the mine, the potential for flow from the river to the mine workings has been reduced further due to the reduced hydraulic gradient. Measurements of minewater levels have confirmed, however, the continuing potential for seepage from the river to occur. More detailed flow measurements at intervals along the Carnon River will be required if this seepage is to be quantified. Existing river flow measurements indicate a net base flow to the river at least in the summer months.

If water levels in the mine were to be lowered in the long-term then there may be significant infiltration from the river to the mine workings. Under these conditions there would be benefit in sealing those areas of the river bed where losses are identified.

9.2.2 Recharge Control through Catchment Treatment

Catchment treatment would involve sealing off the major points of ingress into the workings and preventing recharge into the system.

Since the main source of inflow to the workings is rainfall, the only identifiable method of reducing this inflow would be to install a low permeable cover across the majority of the catchment which would be impractical and unrealistic.

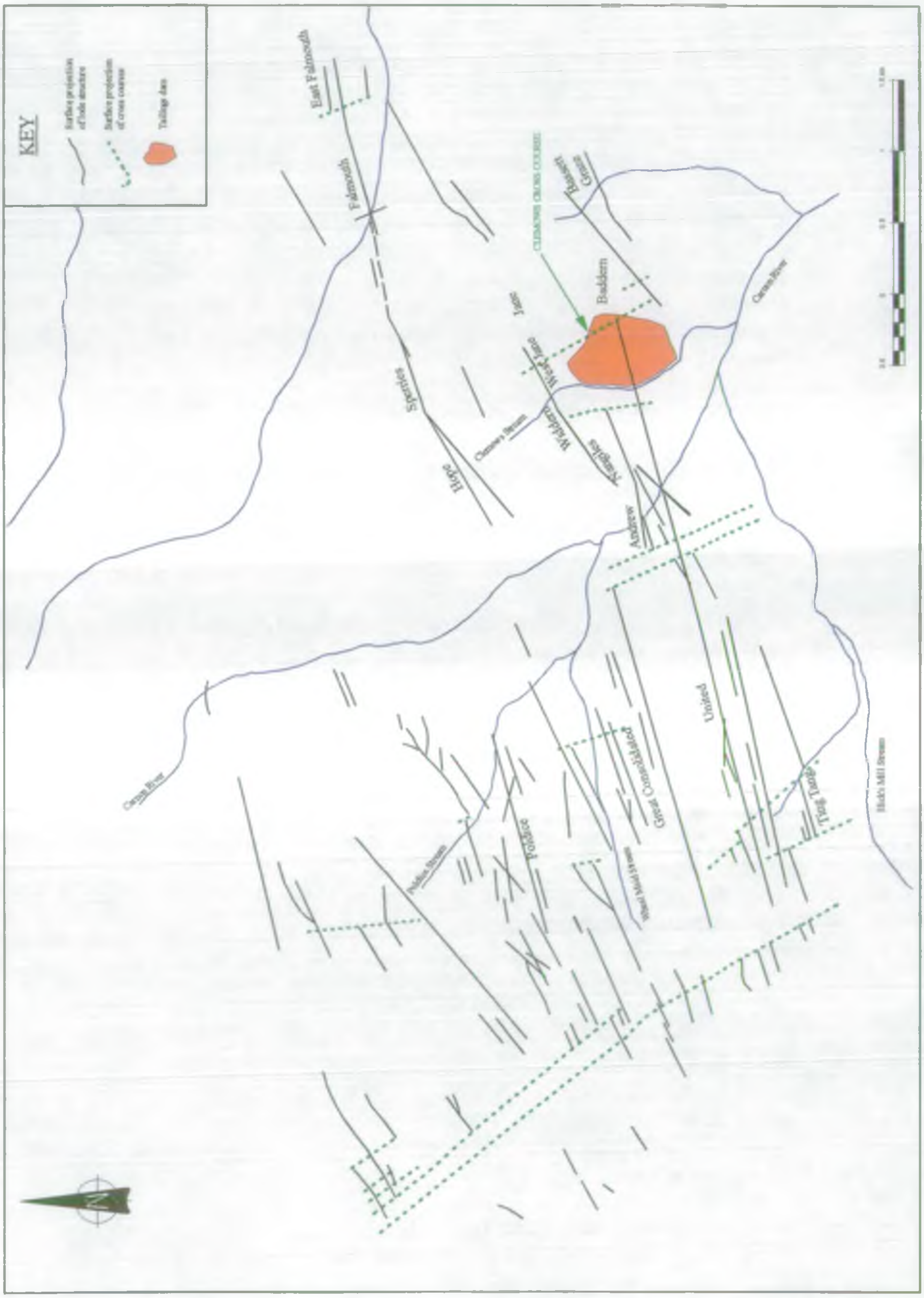
9.2.3 Seal Surface Mine Workings

There are also features on the mine site and in the surrounding area (see Figure 9.1) which may be net contributors to underground flow, including:

- Old shafts and surface expression of stopes.
- The open coffin on the Wheal Jane site.
- Any surface expression of the Clemows cross course (Ref. 2).
- Relaxed and open strata above old workings (Ref. 3).

The contribution from these features, based on areal extent alone, is considered negligible.

Figure 9.1 Plan of Surface Projection of Old Workings



9.2.4 Construction of Shallow Underground Barriers

The construction of barriers underground could limit the movement of groundwater and raise groundwater levels, thus marginally reducing inflow to the mine. On a seasonal basis, however, peak flows might increase due to loss of underground storage and attenuation.

Construction of barriers would rely on in-depth knowledge of mine workings and hydrology if uncontrolled seepage at dispersed locations in the catchment were to be prevented.

The practicalities and cost of sealing and controlling inundation above the present groundwater surface indicates that this method is of limited application at Wheal Jane unless it can be proved to be cost-effective in providing some mitigation of poor water quality (see Section 9.3).

9.3 CONTROL OF ACID GENERATION

The pre-requisites for acid generation at Wheal Jane are:

- Exposure of pyritic rock surfaces to oxidation.
- Supply of oxygen to exposed rock surfaces.
- The presence of catalysts, such as iron oxidising bacteria, to promote the oxidation processes.
- Supply of water to promote oxidation and dissolution of mineral salts.
- Drainage of waters to and from the area of oxidation.

Abatement measures need to target the above components to either isolate the rocks from the geochemical processes which result in the generation of acid mine drainage or to reduce or alter the strength of the resulting reactions. Experience indicates that such methods need to be targeted to the specific geology and hydrochemistry of the mine.

The following sections summarise those techniques which are available and which may have potential for use at Wheal Jane.

9.3.1 Inhibiting Oxidation

Exclusion of air from mine workings can have significant beneficial effects by preventing or retarding the oxidation process and acid generation. Exclusion of air can be achieved by:

- Inundation with water (Ref. 4).
- Backfilling voids using rock paste slurries (Ref. 5).
- Air sealing by means of air traps (Ref. 6).

At Wheal Jane the cessation of pumping led to the inundation of the majority of the workings and thus this method has been successful in eliminating the generation of acidity at depth. The potential for inundation of the upper zone of workings, by raising groundwater levels using underground barriers was discussed in Section 9.2 and is unlikely to be effective.

Were the upper levels of the mine to be flooded there still remains the potential for shallow groundwater flow and the exposure of mineral surfaces during periods of low groundwater levels. Some generation of acid and the leaching of metals would, therefore, still occur.

Exclusion of air by backfilling and sealing the mine relies upon detailed knowledge of the workings. At Wheal Jane data relating to the extent of the shallow workings above adit level is limited and the methods would be unlikely to prove successful.

9.3.2 Sealing Rock Surfaces

The application of sealants, such as epoxy paints or bitumen-based compounds, to the surface of the in situ minerals can be effective in excluding the oxidising and catalysing media. Sealants are available, the primary requirement being their stability, low permeability and longevity but need to be proved before application.

Rock surfaces may also be sealed with bactericides (Ref. 7). The rate of oxidation of pyrite in the presence of water and oxygen is relatively slow, but is accelerated by the presence of the bacteria thiobacillus ferrooxidans and ferrobacillus sulphooxidans. It has been shown that the catalysing activity of these bacteria may be inhibited by the application of anionic surfactants such as sodium lauryl sulphate, sodium dodecylbenzene sulphonate, potassium sorbate and sodium benzoate. To date, the principal use of bactericides has been in abating acid effects on surface mines enabling revegetation, which itself adds a degree of alkalinity to the system. Such examples have shown reasonable success but none have been in operation for longer than ten years and moreover, on the worse sites have required repeat applications to control acidity.

The logistics of application underground are currently the subject of much research and can therefore be considered to be unproven.

The application of sealants relies upon accessing the exposed mineral surfaces both within mine workings and along fissures which, at Wheal Jane, would be a difficult, dangerous and costly exercise. Therefore, this method is not recommended.

9.3.3 Chemical and Bacteriological Modification

The introduction of materials to the workings which would either reduce the rate of oxidation or at least inhibit it has the potential to improve the water quality. These materials include:

- Limestone or mineral salt compounds.
- Organic materials.
- Antibacterial agents.

Limestone

Limestone has the potential to neutralise the acidity, raise the pH and encourage precipitation. The most effective mode of introduction would be to pump lime-based slurry underground. This would reduce the void space and seal off or neutralise potentially acid producing rock surfaces, but would require a significant volume of lime to fill the void. In addition the two factors controlling the effectiveness of infilling the voids with limestone are:

- In the presence of dissolved oxygen, iron precipitates on the limestone causes armouring, rapidly rendering the neutralisation potential ineffective.

- Where dissolved oxygen is low the hardness of the water may be elevated by the lime addition but most metals will remain in solution resulting in oxidation and precipitation at surface.

To be cost-effective the method would need good mapping of the network of underground workings and an assessment of the long-term geotechnical and chemical characteristics of the slurry.

Mineral Salt Compounds

The alternative to lime is a saline solution which can be introduced by pumping seawater into the workings. This has a dual effect, it causes rapid precipitation of metal and inhibits further oxidation. The main drawbacks are the cost of pumping significant volumes of seawater into the workings and secondly the potential impact on groundwater quality in the area. The effectiveness and the impact are not quantifiable, research is currently being undertaken in the USA on this aspect.

Organic Materials

The use of organic materials to treat acidic minewater has been well described in the texts, particularly in the description of the passive treatment system. Bacteria are known to feed on sulphates and to catalyse the reduction of metal sulphates creating metal sulphides. It has been proposed that the construction of anaerobic conditions underground may assist in the reduction of acidity.

The method would require the creation of controlled flow through a system containing an organic substrate, preferably in the final outlet pathways from the minewater system, i.e. the adits. Providing the bacteria can survive the high acidity conditions existing within the underground anaerobic system, acid reduction would take place. The problems however of achieving a significant reduction in acid discharges relate to the following:

- Effective flow control through the anaerobic zone.
- Adequate permeability to cope with the design flow and retain anaerobic conditions.
- Replacement of the substrate on a regular basis dependent on the material used once the organic content has been depleted.
- The likely need to treat the water and overflow volumes on discharge from the adit.
- The size of adit and organic cell needed to treat the flow emanating from Wheal Jane.

This system has potential, but is limited by the volume of substrate required to achieve other than minor quality improvements. Much work would be required to prove the application at Wheal Jane. The cost of opening up the adit system to enable backstowing will also be of significance to enable maintenance and safe working conditions throughout its design life.

Antibacterial Agents

Research into the use of antibacterial agents to inhibit acid production in surface coal mines and spoil heaps has been undertaken (Refs. 8 & 9). Agents such as Caulobacter have been proved successful and have an advantage over bactericides in that they exhibit natural regeneration. Bactericides may require repeat application to overcome problems of depletion. Microbial agents are suggested to inhibit oxidation of pyrite by parasitism, antibiotic properties, competition and rapid regeneration. Success in the laboratory in reducing minewater acidity has been claimed, but the method remains very much a research subject with no known experience of underground application. Again similar costs and practical difficulties of access for application will arise.

9.4 APPRAISAL OF THE AVAILABLE OPTIONS

The methods available for prevention and control of discharges from Wheal Jane involve reduction of flow through the mine by physical means and control of acid generation by modification of subsurface conditions. Details of the potentially applicable techniques are summarised in Table 9.1.

The suitability of some of these methods is hampered by the requirement for access to the mine and knowledge of mine workings and detailed mapping. The cost of making safe the old workings to provide this access and enable mapping would be prohibitive.

The most promising methods involve sealing surface features to reduce recharge. Canalisation of a section of the Carnon River has already proved effective in reducing mine inflows. There may only be limited scope for further reduction however.

Research is continuing in the USA and elsewhere into techniques for the prevention and control of acid mine drainage. Although there is no single method which could be used at Wheal Jane, a number of small-scale techniques might provide limited amelioration and should be considered in an ongoing programme of monitoring and evaluation of treatment strategies at the site.

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10. PASSIVE TREATMENT TECHNOLOGY

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Photograph 10.2 "Lime-free" Pilot Passive Treatment Plant during Construction

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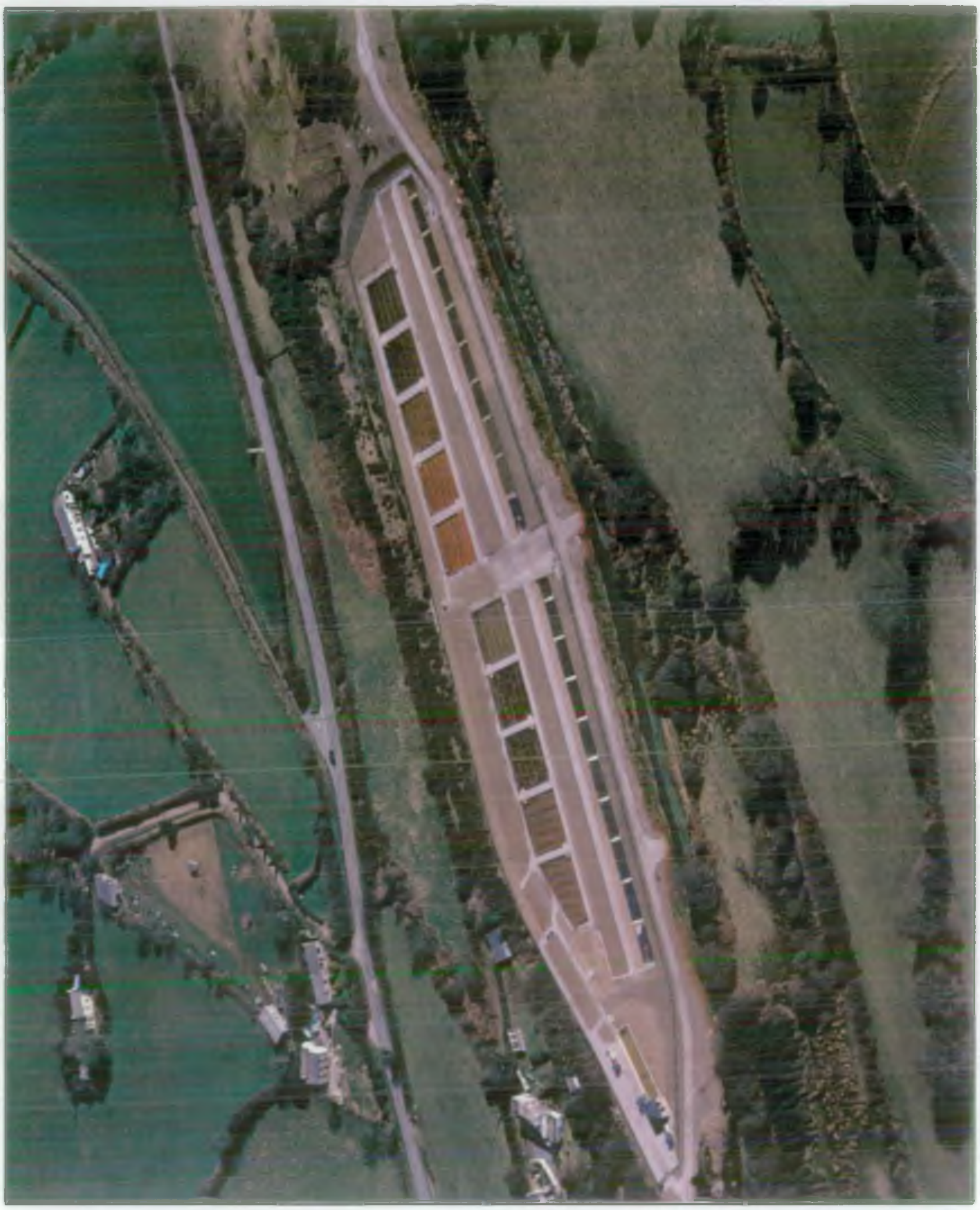
Photograph 10.4 Aerial View of the Pilot Passive Treatment Plant and the Clemows Valley Tailings Dam March 1995

Photograph 10.5 Completed "ALD" and "Lime-dosed" Pilot Passive Treatment Plants



Photograph 10.6 Completed "Lime-free" Pilot Passive Treatment Plant

10.1 INTRODUCTION

The likely benefits to be gained from developing a treatment strategy for Wheal Jane capable of operating for many years with the minimum of operating costs were recognised soon after the initial release of minewater. One of the options that was identified early in 1992 for consideration as part of a long term treatment strategy has been the use of low input or "passive" treatment technology (Refs. 1 & 2).

Passive treatment technology is based on designs that utilise systems which, once established, require a minimum of continued inputs (raw materials, energy and labour) to maintain their performance. This is in contrast to conventional "active" treatment technologies which rely to a much greater extent on continuing inputs, usually of raw materials, energy and labour.

Many of the passive treatment technologies are derived from observations of natural systems, such as reed beds or marshes, which have been exposed to inputs of contaminated waters. A detailed understanding of the complex physical, chemical and biological processes which operate in these systems has evolved only in recent years. Many aspects are still poorly understood and some apparently contradictory findings have yet to be resolved. Consequently, the construction of many types of passive treatment systems is based to a large extent on empirical design parameters often derived from experience under a wide range of operating conditions.

In such circumstances, where the degree to which design parameters used in one situation may be applied to others is uncertain, it is prudent to construct and operate small pilot plants to test the validity of these parameters. Accordingly, in November 1992, Knight Piésold were instructed by the NRA to undertake detailed design works and supervision of construction of a pilot passive treatment system in the Carnon Valley. The design parameters used in the Wheal Jane Pilot Passive Treatment Plant are derived principally from experience gained by Knight Piésold in the U.S.A. The succeeding sections discuss in some detail the basis upon which individual design parameters were adopted, the way in which the construction of the pilot plant has attempted to modify these parameters in response to the particular conditions at Wheal Jane and the results obtained from the operation of the pilot plant to date.

10.2 DESIGN CRITERIA FOR PASSIVE TREATMENT SYSTEMS

10.2.1 Background

Passive treatment systems can utilise a wide variety of processes, all of which are known to occur naturally, to achieve neutralisation of the acidity and removal of dissolved metals from minewater. In principle, some or all of the following processes can be applied:

(i) The precipitation of metal hydroxides in an aerobic environment, such as a reed bed.

(ii) The co-precipitation of metals and the adsorption of metals onto metal precipitates.

(iii) The reduction of sulphate and the consequent precipitation of metal sulphides in an anaerobic environment.

(iv) The adsorption of metals onto an organic-rich substrate.

(v) The uptake of metals by living plants.

The aim of a passive treatment plant is usually to encourage the formation and precipitation of inorganic metal compounds, such as hydroxides or sulphides, since these tend to be more stable than organo-metallic complexes (which are susceptible to the decomposition of the organic component). For this reason, whilst processes (iv) and (v) may be an inevitable (and in some cases beneficial) consequence of the design considerations for the Wheal Jane pilot plant, only processes (i) - (iii) have been evaluated as an integral part of the design parameters.

The selection and enhancement of individual processes in a passive treatment plant is based upon the selection of the most appropriate technique to suit the particular conditions.

10.2.2 The Precipitation of Metal Hydroxides in an Aerobic Environment

10.2.2.1 Design Principles

The extent to which dissolved metals will be hydrolysed and precipitated as hydroxides is dependent principally on:

- The pH of the minewater in the treatment plant, since each metal hydroxide will only form above a certain pH.
- The availability of oxygen to promote the oxidation of those metals, such as iron, which tend to exist in a reduced state (which is not readily hydrolysed) in anoxic minewater.

Sufficient oxygen is normally provided principally by diffusion from the atmosphere. This may be supplemented by oxygen generated by the photosynthesis of aquatic plants (algae and submerged macrophytes) and the diffusion of oxygen from the root zones of certain plants, principally reeds.

The pH above which this reaction occurs is itself dependent upon on the Eh (reduction-oxidation potential or redox) of the environment. In an aerobic environment such as a reed bed, the redox potential is normally in the range 300-500 mV. Under these conditions the approximate pH above which the metals tend to hydrolyse varies between 3.5 for iron and aluminium and 9.5 for cadmium and manganese (see Table 10-1).

Table 10-1 : Approximate pH values required for hydrolysis and precipitation of hydroxides, oxides or carbonates (Ref. 3)

Metal	Approximate pH
Iron (Fe^{3+})	3.5 - 5.0
Aluminium	3.5 - 5.0
Arsenic	no hydroxide formed
Copper	6.0 - 7.0
Cadmium	8.5 - 9.5
Zinc	7.5 - 8.5
Manganese	8.5 - 9.5
Note:	The actual pH above which metals hydrolyse is dependent upon a range of factors including temperature, pressure, redox and activity.

However, the hydrolysis of certain metals, notably iron, manganese and aluminium, tends to reduce the pH. For this reason, aerobic passive treatment systems must have some mechanism for controlling pH. In the absence of such a mechanism the pH would tend to drop below the minimum pH value required.

The pH in most aqueous aerobic environments is controlled by the carbonic acid-bicarbonate-carbonate buffer system in which carbon dioxide dissolves in water and forms an equilibrium with carbonic acid, bicarbonate and carbonate ions according to the following series of reactions (Ref. 4):

$$CO_{2(gas)} \leftrightarrow CO_{2(aq)} \qquad \text{(Reaction 1)}$$

$$H_2O + CO_2(aq) \leftrightarrow H_2CO_3 \qquad \text{(Reaction 2)}$$

$$H_2CO_3 \leftrightarrow H^+ + HCO_3^- \qquad \text{(Reaction 3)}$$

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \qquad \text{(Reaction 4)}$$

$$HCO_3^- \leftrightarrow CO_{2(aq)} + OH^- \qquad \text{(Reaction 5)}$$

$$CO_3^{2-} + H_2O \leftrightarrow HCO_3^- + OH^- \qquad \text{(Reaction 6)}$$

In this way, the dissolution of carbon dioxide, which can be derived from the respiration of plant roots, bacterial decomposition of organic matter or diffusion from the atmosphere will tend to increase the bicarbonate alkalinity and thus enhance the buffering capacity of the system. For this reason, aerobic treatment systems function most efficiently when a mature vegetation cover has been established. This vegetation may include species of reeds (which are particularly well adapted to this type of environment), rushes, some trees and algae.

Where the initial pH of the system is below about 5.5, however, the buffer system tends not to function particularly well and at a pH of below around 4 does not operate at all, since at a low pH there is tendency for carbon dioxide to exsolve (i.e. Reactions 1 and 2 move to the left).

Consequently, in passive systems treating minewater at a pH of below 5 some other mechanism is required by which the pH can be raised to, and maintained at, the appropriate level. This can be achieved in two ways:

- By the use of a pre-treatment system, such as a lime-dose plant which raises the pH of the influent minewater to a level at which the bicarbonate buffer system will function, or an anoxic limestone drain, which both raises the pH and adds buffering capacity through the release of carbonate ions.

- By the buffering action of the wetland substrate itself, the efficiency of which is dependent upon the geochemistry and mass of the substrate.

Despite the operation of the various buffer systems and the use of pre-treatment it is not usually feasible in a passive aerobic system to raise the pH to a level sufficient to promote the widespread precipitation of copper, cadmium, zinc and manganese. However, aerobic systems normally contain a flourishing algal community. During photosynthesis algae remove carbon dioxide from the water and generate significant amounts of oxygen. The diffusion of these gases in water is relatively slow, which results in the creation of a micro-environment around the algal filaments. This micro-environment, which persists through the normal diel and seasonal variations in light intensity, is presumed to exist around all species of green and blue-green algae, although limited experimental evidence suggests that the filamentous green alga *Cladophora* is amongst the most effective in generating a high pH micro-environment (Ref. 5).

The algal micro-environment may have a pH in excess of 10, even though the pH of the water body as a whole may be near neutral. In alkaline environments such as these, metals such as manganese may precipitate initially either as an oxide or as a carbonate, which may be subsequently oxidised to an oxide. The deposited metal oxides then function as autocatalytic nuclei further enhancing the formation of metal precipitates. These reactions can be utilised to remove small amounts of metals which would not normally form hydroxides in an aerobic environment.

Consequently, aerobic systems have the potential to remove dissolved iron and aluminium from the minewater, by promoting hydrolysis and the precipitation of hydroxides, and mitigate against the resultant fall in pH by the action of the buffer systems. They also have the potential to remove much smaller amounts of other metals in the micro-environment which exists within the algal mats.

10.2.2.2 Design Parameters

The operation of an aerobic passive treatment system is dependant principally upon a supply of oxygen and the ability of the system to maintain a pH sufficient to promote the hydrolysis of the "target metals", namely iron and aluminium. The operation of a system which utilises the algal micro-environment is dependent upon maximising the contact between the minewater and the algae.

- *The Availability of Oxygen*

  Oxygen in the atmosphere will diffuse into the surface film of a water body relatively easily (particularly where there is a positive gradient maintained by the use of that oxygen in oxidation of ferrous iron Fe^{2+} to ferric iron Fe^{3+}). However, the diffusion of oxygen through the deeper parts of a water body is relatively slow (even where there is a positive gradient), although this may be enhanced by the ability of some plants (principally reeds) to transport oxygen directly to the root zone.

  For this reason shallow aerobic systems function better than deeper ones. However, the continual mixing of the water body will enhance the dispersal of oxygenated water (by replacing oxygen-rich water from the surface with oxygen-poor water drawn from depth). In passive treatment systems this mixing is achieved in two ways:

  - By the "landscaping" of the substrate into a series of ridges at 90° to the flow and channels with a maximum water depth of 300 mm.

  - By the division of the aerobic treatment system into a number of discrete cells each separated by weirs and/or cascades.

- *The maintenance of pH*

  The sizing of aerobic cells to ensure the maintenance of an adequate pH is based upon a consideration of two factors:

  - The loading of the target metals in the discharge - principally iron since in most instances this is the dominant target metal.

  - The influent pH - since this will determine the effectiveness of the bicarbonate buffer system.

  Experience, based largely upon field observations, in the U.S.A. suggest the following loading factors:

  For an influent pH of < approximately 5.5 ... 2 - 4 g $Fe/m^2/day$.

  For an influent pH of > approximately 5.5 ... 5 - 11 g $Fe/m^2/day$.

The increased efficiency of systems receiving an influent of pH above 5 (regardless of whether this is the "natural" pH of the minewater or whether there is some form of pre-treatment) is due both to the more effective neutralisation by the bicarbonate buffer system of the acidity generated by the precipitation of hydroxides and to the increased rate of oxidation of ferrous to ferric iron.

These loading factors can be used to calculate the surface area of a treatment system required using the formula:

$$A = Fe.Q.C.\frac{1}{L}$$

where: A is the surface area required (m^2)
Fe is the influent dissolved iron concentration (mg/l)
Q is the influent flow (l/min)
C is the conversion factor 1.44
L is the pH dependent loading factor (i.e. either 2 - 4g or 5 - 11g).

- *The utilisation of the algal micro-environment*

  The efficiency of precipitation of metals within the algal micro-environment is dependant primarily upon:

  - Providing a suitable environment for algae to develop.
  - Maximising the passage of minewater through the micro-environment surrounding the algal filaments.

  Both of these requirements are optimised within a system which provides a substrate, such as a "rock filter", for algal growth through which the minewater flows. The depth of the rock filter is constrained by the need to ensure adequate light penetration.

  Experimental data relating the efficiency of manganese removal to different flow regimes has provided a means for calculating the surface area of a rock filter necessary to achieve the removal of a given amount of manganese; this information suggests that up to 2 g of manganese can be removed per m^2/day.

10.2.2.3 Pre-treatment Systems

Pre-treatment systems of the type discussed in Section 10.2.2.1 which are used to raise the influent pH of minewater, and under certain circumstances to add buffering capacity, prior to passive treatment usually depend upon either:

- *The addition of lime using a small lime-dosing plant to raise the pH*

  The objective of a lime-dose plant as a pre-treatment for passive systems is to raise the pH without promoting the active precipitation of metal hydroxides (which would negate many of the benefits of a passive system). The level to which the pH can be raised depends upon the particular metals present in the minewater, the pH at which hydroxides are formed (see Table 10-1) and the concentration of dissolved oxygen (see Section 10.2.2.1). For most minewaters, the presence of dissolved iron limits the level to which the pH can be raised to a maximum of between 4 and 5.

  Lime neutralises the minewater in accordance with the following reaction:

  $Ca(OH)_2 + 2H^+ \rightarrow 2H_2O + Ca^{2+}$ (Reaction 7)

  The quantity of lime required to achieve the optimum pH, therefore, is calculated on the basis that 1 mole of lime reacts with 2 moles of hydrogen ions.

- *The use of anoxic limestone drains (ALDs)*

  The ALD raises the pH of the influent minewater and adds alkalinity by the dissolution of calcium carbonate to generate carbonate and bicarbonate ions:

  $CaCO_3 \rightarrow Ca^{2+} + CO_3^{2-}$ (Reaction 8)

  $CaCO_3 + H^+ \rightarrow Ca^{2+} + HCO_3^-$ (Reaction 9)

  $CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$ (Reaction 10)

  $CaCO_3 + H_2O + CO_2 (g) \rightarrow Ca^{2+} + HCO_3^-$ (Reaction 11)

  Empirical evidence suggests that ALDs containing limestone can add up to 300 mg/l alkalinity, being limited principally by the rate of limestone dissolution in water. The sizing of the ALD is dependent, therefore, principally upon the influent pH (and the required effluent pH) and the required life expectancy of the system. However, the performance of an ALD is dependent upon:

  - The influent flow rate - the mineral acidity imparted by the presence of certain metal ions may limit the maximum flow rate (Ref. 6).

  - The dissolved oxygen concentration - the presence of dissolved oxygen in concentrations above approximately 1 mg/l will promote the oxidation of ferrous iron and the subsequent formation of ferric hydroxide causing significant armouring of the limestone and the prevention of further dissolution (Ref. 6).

- The presence of dissolved aluminium or ferric ions - aluminium and ferric ions will hydrolyse within the ALD promoting the formation of hydroxides. Ferric hydroxide will cause armouring of the limestone and aluminium hydroxide, although believed to have little affinity for limestone, may cause clogging of the ALD or associated pipework (Ref. 6).

Within these constraints, the design of efficient ALDs is dependent upon:

- Maintaining a suitable retention time (between 1-2 days) within the system to maximise alkalinity generation.
- The use of limestone with a high level of purity, preferably at least 90% $CaCO_3$ (Ref. 7).
- Optimising the particle size of the limestone to maximise the surface area available for dissolution whilst maintaining the required permeability, particularly where there is a risk of clogging. Particle sizes in the range 20-70 mm are normally preferred.
- The maintenance of an impermeable cover to the system to prevent the ingress of air or rainwater.
- The possible incorporation of an anoxic pond immediately prior to the ALD which, operating in a similar manner to an anaerobic cell but at a higher surface loading factor, would tend to remove dissolved oxygen, reduce ferric iron to ferrous iron and promote the precipitation of aluminium hydroxides.

10.2.3 The Co-precipitation of Metals and the Adsorption of Metals onto Metal Precipitates

The hydroxides formed by the precipitation of ferric iron and aluminium are capable of scavenging other metal ions thus enhancing their removal from solution by co-precipitation into the lattice of the solid phase as that phase itself is precipitated. The affinity of a trace ion for a particular lattice is determined by the relative sizes, ionic charges and electronegativities of the major element and the trace ion concerned. This process is the basis of a commonly used method in the active treatment of both potable and wastewaters (Ref. 8).

Furthermore, the hydroxides formed initially during the precipitation of certain metals, notably iron, manganese and aluminium, may be gradually transformed into oxyhydroxides or oxides. For iron the possible reactions are:

$Fe^{3+} + 3OH^- \leftrightarrow Fe(OH)_3$ (amorphous) (Reaction 12)

$Fe(OH)_3 \leftrightarrow FeOOH + H_2O$ (goethite) (Reaction 13)

$2Fe(OH)_3 \leftrightarrow Fe_2O_3 + 3H_2O$ (hematite) (Reaction 14)

The hydroxides and particularly the oxyhydroxides and oxides of these metals have a strong capability of adsorbing other metal ions onto their surface. The mechanism of adsorption essentially involves the surface acting as a weak acid, which attracts hydroxide ions, creating a negative surface. This negative surface then attracts and adsorbs positive ions (both of the same and other metals).

These two processes may significantly enhance the efficiency of metal removal within an aerobic treatment system. Arsenic, in particular, is readily removed from solution by co-precipitation with iron as ferric arsenate. However, the contribution that these processes make to the overall efficiency of metal removal in a passive treatment system is difficult to quantify. For this reason they are usually disregarded in the design of such systems. Empirical design criteria by their very nature will, of course, take account of these processes.

10.2.4 The Reduction of Sulphate and the Consequent Precipitation of Metal Sulphides in an Anaerobic Environment

10.2.4.1 Design Principles

The precipitation of metal sulphides in an anaerobic environment is dependent upon the generation of hydrogen sulphide, by bacterial reduction of sulphate, and the subsequent reaction of the hydrogen sulphide with dissolved metal ions to form insoluble metal sulphides. The simplified series of reactions is (Ref. 9) :

$$2CH_2O + SO_4^{2-} \rightarrow H_2S + 2HCO_3^- \qquad \text{(Reaction 15)}$$

$$M^{2+} + H_2S + 2HCO_3^- \rightarrow MS + 2H_2O + 2CO_2 \qquad \text{(Reaction 16)}$$

where: CH_2O denotes organic matter
M represents the metal ion

The formation of metal sulphides is influenced by pH, the solubility product of the metal sulphides, and the concentration of the metal. Metal sulphides usually form in the following sequence:

CuS - PbS - ZnS - CdS - NiS - FeS

Manganese sulphide is relatively soluble under the conditions normally found in an anaerobic environment and would only be expected to form when the concentrations of all other metals are extremely low. Aluminium does not form any sulphide compounds in an anaerobic environment (Ref. 9).

The extent to which dissolved metals will be precipitated as sulphides is dependent on the activity of sulphate-reducing bacteria, principally the *Desulfovibrio* family. In order to function efficiently, these sulphate-reducing bacteria require certain conditions:

- *A carbon source in a readily useable form*

  Passive treatment systems normally utilise a diverse bacterial community to produce low molecular weight carbon compounds (such as lactate or acetate) from the decomposition of plant material.

- *A pH ideally in the range pH 5 to 9*

  The bacteria themselves are capable of significant adjustments to the pH, thus modifying their own environment, through two reactions (Ref. 10):

  $SO_4^{2-} + 2CH_2O + 2H^+ \rightarrow H_2S + 2H_2O + 2CO_2$ (Reaction 17)

  $SO_4^{2-} + 2CH_2O \rightarrow HS^- + HCO_3^- + H^+$ (Reaction 18)

  In acidic water, Reaction 17 predominates, consuming H^+ ions and causing the pH to rise; in alkaline waters Reaction 18 will predominate generating H^+ ions. Consequently, where the minewater influent has a pH of less than 5 bacterial activity will tend to raise the pH to the optimum of between 5 and 9. However, where, for example, the flow of acid minewater exceeds the neutralising capability of the bacteria, and the pH remains below 5, then the activity of the sulphate-reducing bacteria may be severely depressed. This may in part at least be due to the reduced activity of the other bacteria producing the carbon source which is in turn utilised by the sulphate reducers.

- *A sulphate source*

  The generation of hydrogen sulphide and maintenance of a suitable pH are both dependent upon a continued supply of sulphate (Reaction 15). Fortunately, most metal-rich minewaters also contain elevated concentrations of sulphate as a consequence of the initial oxidation of sulphide minerals (Reactions 1 and 4 - sulphate reduction in an anaerobic system being essentially the reverse of these reactions). However, a continuous supply of sulphate-rich minewater is required to prevent wide fluctuations in the activity of the sulphate-reducing bacteria.

- *The absence of strong oxidising agents*

  Sulphate reduction requires an environment with a low reduction-oxidation potential (redox). Negative redox, ideally around -100 mV provides the optimum environment. The presence of strong oxidising agents (such as O_2, Fe^{3+}, Mn^{4+}) in the influent minewater is detrimental to the maintenance of negative redox. For this reason that part of an anaerobic system which receives oxygenated minewater is dominated by the reduction of these strong oxidising agents. The activity of sulphate-reducers in this part of the system is low. However, the formation of certain sulphide minerals, such as pyrite, is enhanced by the availability of slightly oxidised elemental sulphur (Ref. 9). Consequently, the rate of pyrite formation is optimised near the oxic - anoxic interface in an anaerobic system.

10.2.4.2 Design Parameters

The selection of a suitable substrate for an anaerobic treatment system is based principally on two criteria:

- The need for a suitable primary carbon source.

- The presence of an initial inoculum of sulphate-reducing bacteria.

An anaerobic passive treatment system requires the provision of a primary carbon source which can be utilised by anaerobic bacteria to generate a suitable low molecular weight carbon source for use by sulphate reducers throughout the design life of the system. Some potential carbon sources are readily decomposed (hay, for example). These carbon sources would tend to be consumed rapidly and result in an early senescence of the system. Alternatively, more slowly degraded sources (wood, for example) would ensure longevity of the system but in such a system bacterial activity tends to be low in the first few months following commissioning. Consequently, most anaerobic treatment systems utilise a substrate which comprises a range of "short-term" and "long-term" carbon sources. The preferred substrate must also satisfy the required permeability to ensure the maintenance of the design flow through the system.

Sulphate-reducing bacteria are ubiquitous in natural environments. However, the rate at which an anaerobic treatment system can be commissioned is enhanced greatly by the presence of an initial inoculum containing a high population of "active" bacteria. Suitable inocula can be derived from most natural sulphate-rich anaerobic environments such as animal manures.

The size of anaerobic treatment systems is determined by two factors - a volumetric loading factor and a surface area loading factor.

The stoichiometry of the metal sulphide precipitation reactions is typically 1 mole of sulphide will precipitate 1 mole of metal. In general, it has been found that 1 cubic centimetre of anaerobic substrate can produce 300 nanomoles of sulphide per day. Thus, the volumetric loading factor for an anaerobic cell is approximately 300 nanomoles of dissolved metal per cubic centimetre of anaerobic substrate per day (0.3 moles/m^3). Under this loading, sulphide production requirements are satisfied and virtually all metals should be precipitated as sulphides.

The surface area loading factor is determined by the need to moderate the pH of the influent minewater. Sulphate-reducing bacteria can exert a degree of control over the pH of their environment (Reactions 17 and 18), although this capability can be exceeded depending on the magnitude of the stress imposed by the influent pH and flow rate. The flow rate is controlled by the surface loading factor. Empirical observations suggest that at a pH of below around 5 the appropriate surface loading factor is approximately 800 ft^2/USgall/min, i.e. 20 m^2/l/min. At higher pH values, the stress is correspondingly reduced and a very much lower surface loading factor, down to <5 m^2/l/min may be acceptable.

The activity of the sulphate-reducing bacteria may be reduced by the infiltration of oxygen-rich, sulphate-poor rainwater. Consequently, it is recommended that all anaerobic cells are capped with impermeable material.

10.2.5 Miscellaneous Processes

10.2.5.1 The Uptake of Metals by Plants in the Aerobic System

Uptake of metals by some plants can be significant. Metal accumulation may reach a toxic level in some plant species and, unless harvested, the metals may be returned to solution upon decomposition of the dead plant material. However, many of the plant species, such as reeds, which are most suited to an aerobic treatment system do not readily accumulate metals. For these reasons this process is not considered significant in a passive treatment system.

10.2.5.2 The Adsorption of Metals onto an Organic-Rich Substrate

Organic material in both aerobic and anaerobic environments has the potential to adsorb certain metal ions. Copper ions in particular are readily adsorbed onto organic material such as partially decomposed plant matter. However, the capacity of the organic matter to adsorb metals is finite and the metals may be released during the further decomposition of the organic material.

The adsorption of metals onto organic substrate is a feature in the early stages of the commissioning of anaerobic cells and commonly gives rise to a "honeymoon" period during which exceptionally high rates of metal removal are experienced. As the organic substrate becomes saturated with metals, however, the apparent efficiency of the system declines, with further metal removal dependent solely on the activity of sulphate-reducing bacteria.

For these reasons this process is not considered in the design of passive treatment systems.

10.2.6 Pilot Plant Design Statement

10.2.6.1 Introduction

The design criteria for passive treatment plants are based largely on empirical observations from a large number of minewater treatment projects. The experience gained from these projects suggests a series of design parameters, each of which has a wide operating range dependent upon site-specific considerations. The selection of the more precise design parameters required for a full-scale treatment plant can only be achieved through a series of laboratory tests and operation of a pilot plant.

The design of a suitable pilot plant is dependent principally upon the characterisation of the chemical composition of the effluent stream to be treated. The choice of methods for the removal of the metals can then be undertaken in the context of an understanding of the principles which underlie each of the methods available.

10.2.6.2 Characterisation of Minewater Chemistry

A characterisation of the minewater chemistry is fundamental to the selection of the most appropriate processes on which to base a passive treatment plant. The monitoring of minewater quality in Wheal Jane No. 2 Shaft is considered to provide the data which most accurately characterises the water within the Wheal Jane mineworkings. This data has provided the basis for the designs of both the active and passive pilot treatment plants. However, the concentration of metals in mine water typically declines exponentially during the first months after groundwater recovery before stabilising to a more consistent quality (see Section 6). As a consequence of this initial decline in metal concentrations, no consistent water quality data was available during the early stages of the design of the pilot plant. Therefore, it was necessary to make a (conservative) prediction of the likely water quality requiring long-term treatment based on the data then available (see Table 10-2).

Table 10-2 : Predicted Minewater Chemistry used in the Design of the Pilot Treatment Plant

pH	Al	As	Cd	Cu	Fe	Mn	Pb	Zn	D.O.	SO_4
3.0	40	15	0.1	5	250	20	0.3	250	3 - 5	1000
All units except pH expressed as mg/l total metal. DO - dissolved oxygen										

Sampling and analysis of Wheal Jane minewater from Wheal Jane No. 2 Shaft has been carried out regularly since February 1992. The most recent data, for the period June - September 1994 (see Table 10-3) indicates an iron concentration which is slightly higher than expected, although most other metals, especially zinc, are present at much lower concentrations than those used in the design of the pilot plant.

Table 10-3 : Recorded Wheal Jane No. 2 Shaft Minewater Chemistry

Date	pH	Al	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
June 1994	3.4	33	7	0.11	0.91	292	11	n/d	135	1179
July 1994	3.9	30	8	0.98	0.80	288	11	0.2	126	1130
August 1994	3.7	28	9	0.81	1.10	287	10	0.2	114	1096
September 1994	3.5	27	9	0.78	1.21	291	10	0.3	119	1171
All units except pH expressed as mg/l total metal and reported as monthly mean (range).										

Although the pilot treatment plant has been designed on the basis of a water quality predicted from Wheal Jane No. 2 Shaft data, since this is considered to be most representative of the chemistry of the minewater in the long-term, the plant itself will be fed with water taken from Jane's Adit. Jane's Adit has been plugged effectively since 1991. Consequently, few data are available to assess the actual quality of the influent to the pilot plant. However, a discharge was allowed for a short period of time at the beginning of 1994 to enable an assessment of the likely chemistry of the adit waters (see Table 10-4).

Table 10-4 : Recorded Average Minewater Chemistry from Samples Taken from Jane's Adit and Wheal Jane No. 2 Shaft (March - April 1994)

	pH	Al	As	Cd	Cu	Fe	Mn	Pb	Zn	SO_4
Jane's Adit	3.8	100[1](60)	1.8	0.23	1.5	202[1](150)	28	0.8	138	1530
Wheal Jane No. 2 Shaft	3.6	50	2.5	0.22	1.7	446	14	0.2	224	n/a

All units except pH expressed as mg/l total metal, except arsenic which is reported as dissolved.
n/a - no data available.

Note [1] The presence of suspended iron and aluminium hydroxides in some samples (apparently flushed from the adit system and easily removed in a settling pond) suggests that these values may not be representative of the long-term concentrations to be treated in a passive system; the average concentration of those samples not effected by suspended matter is given in parentheses.

The limited data available for Jane's Adit suggests a slightly different water chemistry from that recorded in Wheal Jane No. 2 Shaft. Of particular interest are the much lower iron, arsenic and zinc concentrations in the adit water compared with the corresponding values for Wheal Jane No. 2 Shaft.

The observed differences may be, at least in part, a consequence of the formation of iron hydroxides (with associated arsenic) within the adit system itself. This may have a long term influence on the quality of the adit discharge. However, conditions within the adit system are unlikely to favour the precipitation of zinc. It is likely, therefore, that the differences are also in part a function of the limited duration of flow from the adit, in which case the metal concentrations in the adit water will tend towards those of No 2 Shaft in the long term.

These interpretations are supported by data from Nangiles Adit (see Section 5) which indicate that the concentrations of zinc in the discharge from this adit does indeed resemble that in Wheal Jane No. 2 Shaft during periods of high discharge from the adit, whilst the concentration of arsenic in the adit water remains significantly lower than that in Wheal Jane No. 2 Shaft.

The differences between the metal concentrations in Wheal Jane No. 2 Shaft minewater, Jane's Adit discharge and the quality predicted for the purposes of pilot plant design are of significance in assessing the performance of the pilot plant. However, the apparent differences are not so great as to significantly change either the design or the operation of the pilot plant.

Similarly, the implications of any future changes in minewater quality (which are discussed in detail in Section 6) do not significantly affect the objectives of pilot plant operation. The configuration of the pilot plant remains suitable to assess the site-specific design criteria. The predictions of actual minewater quality requiring long-term treatment become relevant only in the design of a full scale treatment plant.

10.2.6.3 Selection of Appropriate Passive Treatment Technology

The Wheal Jane minewater is characterised primarily by low pH and significantly elevated concentrations of iron, zinc, cadmium, copper, arsenic, aluminium and manganese. There are several methods which are available for the passive treatment of minewater of this quality (see Table 10-5).

Table 10-5 : Options for Passive Treatment of Acidic Metal-rich Minewater

Treatment system	pH Control	Target Metal			
		Fe & As	Zn, Cu, Cd	Al	Mn
Aerobic system:					
• without pre-treatment	*[1]	**[1]	o	***	o
• ALD pre-treatment	***	***[2]	o	o[4]	o
• lime-dose pre-treatment	***	***	o	***	o
• "rock filter" utilising algal micro-environment	o	*	?	*	**[6]
Anaerobic system:	**	**[3]	***	?[5]	o

Key:
- * Can be effective subject to certain constraints
- ** Generally effective
- *** Generally the most effective option
- o Generally not suitable

[1] Can be effective but often requires substantial surface area.
[2] ALD's are vulnerable to armouring of the limestone if the minewater contains either ferric ions or aluminium in solution and/or dissolved oxygen at concentrations > 1-2 mg/l - some additional pre-treatment may be necessary.
[3] The effectiveness of anaerobic systems in arsenic removal is unproven.
[4] ALD's are vulnerable to clogging with aluminium hydroxide precipitates.
[5] Anaerobic systems may be vulnerable to clogging with aluminium hydroxide precipitates - some additional pre-treatment may be necessary.
[6] The precipitation of manganese in the algal micro-environment is the only proven passive technology for effective manganese removal.

It is apparent that in order to treat minewater with the characteristics of that which is discharged from Wheal Jane in a passive system, it is necessary to utilise more than one passive technology. In particular, whilst an aerobic system might be expected to remove iron and arsenic efficiently (and some aluminium), this type of system would not be expected to remove significant amounts of zinc or cadmium. Similarly, while an anaerobic system might be expected to remove iron, arsenic, zinc, copper and cadmium, this type of treatment may not remove aluminium without the risk of clogging and is unlikely to remove manganese at all. Consequently, the pilot passive treatment system was based upon a combination of:

- An aerobic wetland (designed principally to remove iron and, co-incidentally arsenic and possibly aluminium),
- An anaerobic system (designed to remove zinc, copper and cadmium).
- A rock filter utilising algal micro-environments (to remove manganese),

In order to evaluate the performance of the aerobic systems with and without pre-treatment, the pilot passive treatment plant comprised three separate combinations of treatment systems, namely:

- A "lime-free" system utilising an aerobic wetland, a rock filter utilising algal micro-environments, and an anaerobic system.

- A "lime-dose" system utilising an aerobic wetland with pre-treatment by lime-dosing, a rock filter utilising algal micro-environments, and an anaerobic system.

- An "ALD" system utilising an aerobic wetland with pre-treatment by anoxic limestone drain, a rock filter utilising algal micro-environments, and an anaerobic system.

The "lime-free" system was also configured to enable minewater to be fed directly into the anaerobic cell to evaluate the performance of this system at removing iron and arsenic.

10.2.6.4 Selection of Sequence of Treatment Systems

In a complex multi-system treatment plant, the efficiency with which individual systems function is dependent not only upon the characteristics of the minewater influent but also on the performance of the preceding stage in the treatment. In particular, optimum treatment performance is ensured by the aerobic wetland preceding the anaerobic system since:

- Treating minewater in an anaerobic system first would tend to remove some iron (which could more efficiently be removed in an aerobic wetland) and, as a consequence, would require a greater volume of substrate to remove the zinc, cadmium and copper (which can only be removed anaerobically).

- The performance of the anaerobic cell is enhanced by the increased pH of the discharge from the aerobic cell relative to the influent minewater.

- The risk of clogging of the anaerobic cell by aluminium hydroxides is reduced since they are likely to precipitate in an aerobic environment.

Similarly, a rock filter which utilises the algal micro-environment to remove manganese functions best when the other metals have been removed first and when it receives a higher pH discharge (such as from the anaerobic cell). Under these circumstances, the rock filter acts as a final "polishing" stage by, for example, reducing the elevated B.O.D. which is characteristic of the initial anaerobic cell discharge.

Consequently, the optimum treatment sequence is an aerobic wetland (with or without pre-treatment) followed by an anaerobic system followed by a final rock filter for each of the three pilot systems (see Figure 10.1).

10.2.6.5 Selection of Design Flows

The design flow of the pilot passive treatment plant is based upon two criteria:

- Ensuring that the pilot plant is of sufficient size to mimic adequately the performance of a full scale system, particularly with respect to the influence of rainfall and seasonal performance in aerobic wetlands.

- The confines of existing land availability and construction constraints.

As a consequence of these factors, the following flows were used in the design of the treatment systems:

- For the "lime-free" system .... 0.7 l/s (42 l/min).

- For the "lime-dose" and "ALD" systems .... 0.5 l/s (30 l/min).

However, in order to evaluate the pilot plant fully the supporting pipework and other infrastructure was designed to accommodate higher flows (of up to 150% of design flow). In this way, there is the potential to operate the system to "breaking point" to assess the limits of its performance capability, and to allow for a degree of siltation within the pipework.

10.2.7 The Design of the "Lime-free" System

10.2.7.1 Aerobic Wetland (see Figure 10.2)

- *Influent feed*

  The aerobic wetland is fed directly from a 2 m^3 GRP header tank incorporating a float valve, which ensures the maintenance of a constant inflow into the system. The header tank is itself fed by gravity from a valve chamber immediately adjacent to the Jane's Adit portal via a 160 mm OD MDPE pipe. The minimum operating head at the highest part of the system is some 2 m.

  The inlet and outlet pipes in the header tank are submerged so as to reduce aeration of minewater (and the consequent risk of metal precipitation) within the tank. Discharge from the header tanks is controlled by a pinch valve, with flow rate measured by V-notch weirs located in sealed chambers to reduce aeration.

- *Dimensions of Aerobic Cells*

  In accordance with the design criteria, and assuming a theoretical design life of approximately 7 years the depth of the aerobic cells was determined by the following requirements:

Figure 10.1 Schematic Layout of Pilot Passive Treatment Plant

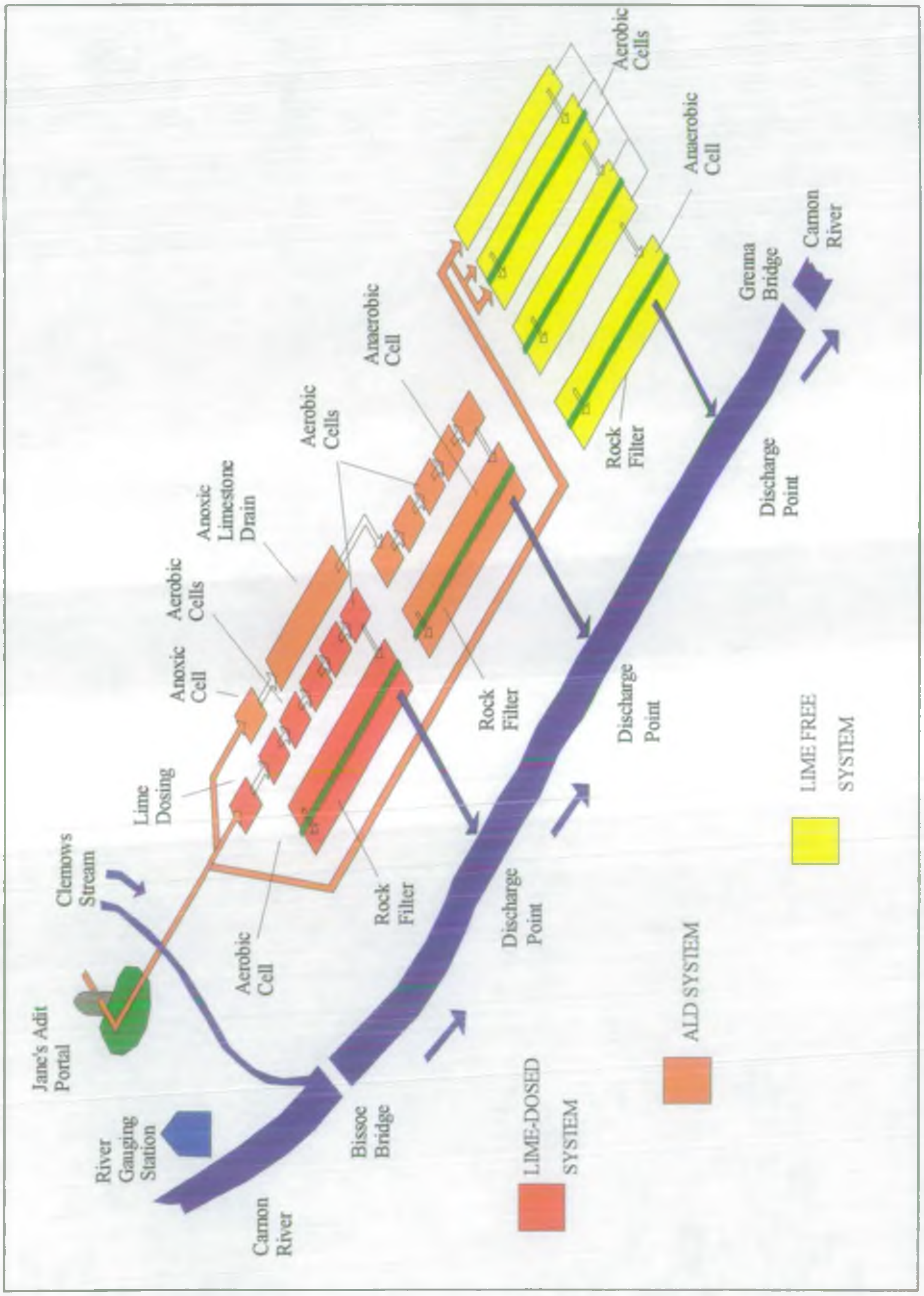
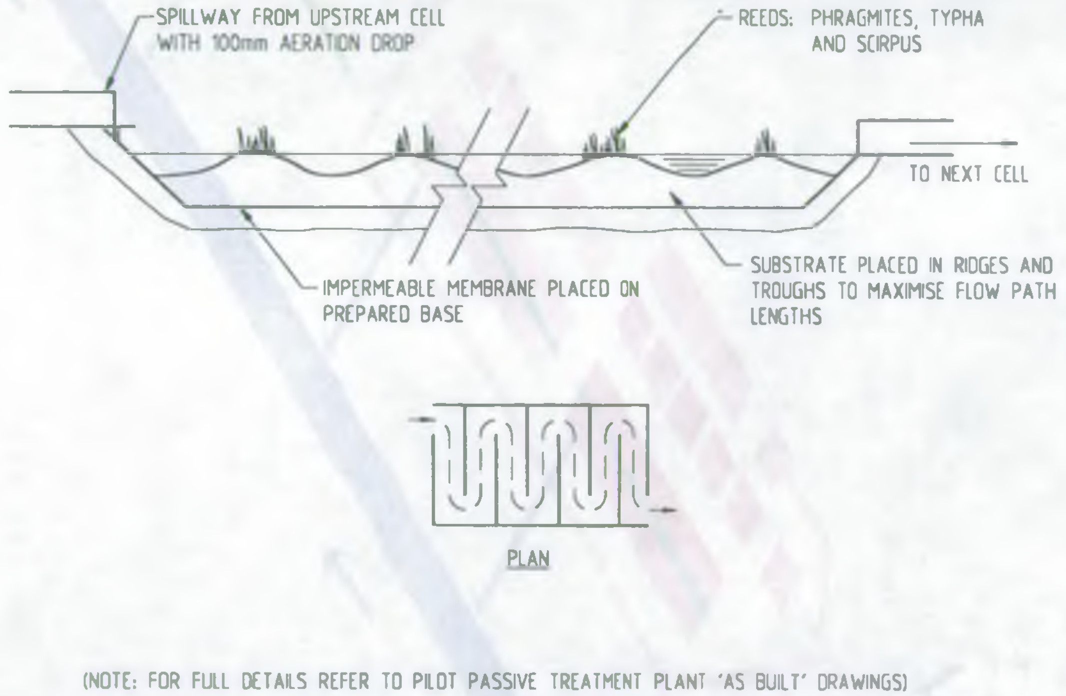


Figure 10.2 Schematic Longitudinal Section Through Aerobic Cell



- A maximum depth of water of 300 mm.
- A minimum rooting depth for reeds in the substrate of 300 mm.
- An operational freeboard of 150 mm.

The surface area of the "lime-free" aerobic cells was determined by the following formula:

$$A = \frac{1}{L} \text{ Fe Q C m}^2$$

where Fe is the influent dissolved iron concentration (i.e. 250 mg/l)
Q is the influent flow (i.e. 42 l/min)
C is the conversion factor 1.44
L is pH dependent loading factor (4 $g/m^2/day$)

Therefore: A = 3780 m^2 (as measured at the water level - the corresponding "top" and "bottom" surface areas of each 750 mm deep cell being determined by the need to accommodate a 1 in 2 side slope).

In practice, this overall value of 3780 m^2 was divided almost equally (subject to construction constraints) into five separate cells of:

- 1 x 750 m^2
- 4 x 760 m^2

The construction of a series of separate aerobic cells assists in the operation of the pilot plant by:

- Facilitating the monitoring of the system, by enabling the influent and effluent of each cell to be sampled separately.
- Facilitating the maintenance of the system, by enabling individual cells to be removed temporarily from the system without disrupting the entire flow.
- Ensuring that the residence time within the system is maintained, by reducing the risk of "short-circuiting".
- Enhancing oxygenation of the water as it flows over a small weir constructed between cells.

Each cell was formed by excavating in-situ material and importing fill to form embankments where the existing ground level was below embankment crest level. The cells were lined with an HDPE impermeable membrane. The crest width of the embankments was set at 2.6 m to allow access for small plant for maintenance works.

- *Substrate*

The excavated fill material was rejected as a substrate on the basis of potentially phytotoxic metal concentrations (for example, copper concentrations ranged up to 2700 mg/kg and zinc up to 820 mg/kg in the excavated material). Coarse tailings, which is principally crushed granite, was found to have an acceptable concentration of potentially phytotoxic metals (see Table 10-6).

Table 10-6 : Substrate Metal Concentrations

pH	Cu	Ni	Zn	Cd	Pb
4.5	99	21	69	0.8	7
All units, except pH, expressed as mg/kg dry weight; analysis presented as the mean value derived from 34 samples.					

- *Planting of Reeds*

Reeds were planted at an average density of 1 plant/m^2 in each of the first two cells and at a density of 4 plant/m^2 in the remaining three cells. The reduced planting density in the first two cells is a reflection of the possible poor performance of reeds in these cells which receive "raw" acidic minewater with no pre-treatment.

The reed species planted comprised a 50:50 mix of *Phragmites* (Common Reed) and *Typha* (Reedmace) within each cell. In addition, a total of 100 *Scirpus* (Bullrush) were also planted throughout the system. Within this overall mix, each species was distributed randomly throughout each cell. All plants were obtained as container grown nursery stock. After planting, cells were fertilized with a general purpose phosphorous-potassium mixture at a rate of about 400 kg/hectare to promote root growth.

Algae were encouraged to colonise the cells by the introduction of algal mats obtained from local waterbodies which receive acidic minewaters naturally.

10.2.7.2 Anaerobic System (see Figure 10.3).

- *Influent Feed*

Minewater exits the final aerobic cell through a vertically piped overflow structure and enters the anaerobic cell via a 90 mm diameter MDPE pipe. The influent passes into three equally spaced horizontal feeder pipes located centrally within a shallow gravel surround overlying the substrate. The feeder pipe is perforated over much of its length, with the last 5 m being solid so as to avoid short-circuiting of the water along the substrate/liner interface. The influent, therefore, permeates vertically down through the substrate material.

- *Dimensions of Anaerobic Cell*

The dimensions of the anaerobic cell were determined on the basis of the volumetric loading factor of 0.3 moles sulphide/m^3/day and the area loading factor of 19.7 m^2/l/min. With a design flow of 0.7 l/s and a predicted zinc concentration (zinc being the principal target metal) of 250 mg/l, the design dimensions of the anaerobic cell are, therefore, 775 m^3 substrate with an effective surface area of 827 m^2.

The top dimensions of the cell were increased to accommodate a 1:2 slope for construction purposes. The additional volume of substrate may contribute to metal removal but has not been included in the design since this additional substrate may not receive a significant flow.

The anaerobic cell was excavated in a similar way to the aerobic cells. However, a 150 mm minewater collection blanket comprising 40 mm gravel was placed at the base of the cell. This was overlain by a geomembrane to prevent migration of substrate into the underdrainage layer. The underdrainage feeds into a 90 mm diameter perforated MDPE collection pipe prior to discharging into the adjacent rock filter. The flow through the anaerobic cell is controlled by adjusting the height of a flexible rubber pipe at the discharge point.

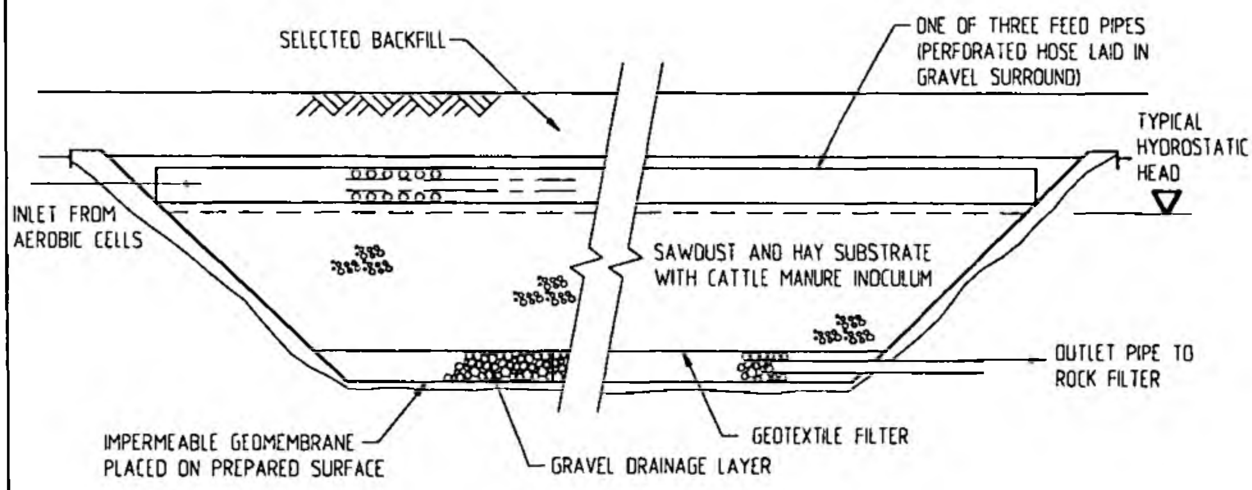
- *Substrate*

Laboratory tests were undertaken to identify a suitable organic substrate in accordance with the design principles. It was found that the requirements for a suitable primary carbon source, combining both readily available carbon and adequate longevity, was provided by a mixture of sawdust (95%) and hay (5%) (although local sources of hay were discounted because they were found to contain elevated concentrations of some metals). Fresh cow manure was found to provide a suitable inoculum of sulphate-reducing bacteria (although the manure was aged for eight weeks on site prior to commissioning of the cell to reduce the risk of pathogens being introduced into the final discharge).

The components were mixed to a homogenous consistency before placement in the cell. The substrate was placed in a manner which avoided excess compaction and allowed a minimum permeability of approximately 1 x 10^{-6} m/s.

An impermeable polythene cap was installed over the substrate to prevent the infiltration of rainfall, which would introduce oxygenated sulphate-

Figure 10.3 Schematic Longitudinal Section Through Anaerobic Cell



(NOTE: FOR FULL DETAILS REFER TO PILOT PASSIVE TREATMENT PLANT 'AS BUILT' DRAWINGS) poor water into the system. The cap was covered with excavated soil materials, with a 1:100 slope to assist run-off, prior to seeding with grasses. Two lengths of 100 mm diameter uPVC perforated pipe were installed beneath the capping layer to act as a vent should there be an accumulation of gases beneath the cap.

10.2.7.3 Rock Filter (see Figure 10.4)

- *Influent Feed*

  The outlet from the anaerobic cell (the flexible rubber pipe) discharges directly into the rock filter.

- *Dimensions of Rock Filter*

  The rock filters were designed on the basis of removing 2 g/m^2/day of manganese. Given a predicted manganese concentration of 20 mg/l and a design flow of 0.7 l/s, the area of the rock filter is 600 m^2. The depth of the rock filter is approximately 700 mm, allowing for 200 mm of rock, a maximum 100 mm of water depth and a 400 mm freeboard.

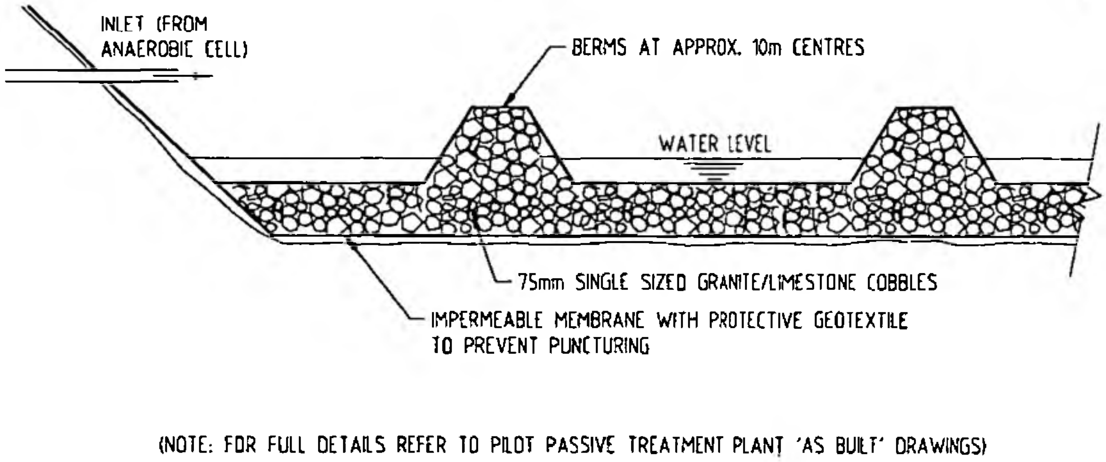
  The rock filter was excavated and lined in a similar way to the other aerobic and anaerobic cells.

- *Substrate*

  The most readily available material for the rock filter was granite. A 200 mm depth of 75 mm diameter granite cobbles was placed in the base of the cell. A series of 1 metre wide, 450 mm high berms were constructed at approximately 10 m intervals along the cell to aid mixing and provide access for sampling.

  The colonisation of the rock filter by green algae immediately after commissioning of the system is constrained by the temporary poor quality of the discharge from the anaerobic cells, which typically contains an elevated BOD (often exceeding 500 mg/l), low dissolved oxygen and negative redox. Conditions suitable for algal growth in the rock filter will only exist after the full commissioning of the anaerobic cells (some 2-3 months after start-up). At this time, algae will be encouraged to colonise the rock filter by the addition of algal "mats" obtained locally (possibly from the aerobic cells) and the application of a phosphate fertiliser.

Figure 10.4 Schematic Section Through Rock Filter



10.2.8 The Design of the "Lime-dose" System

10.2.8.1 Pre-treatment

- *Influent Feed*

  The lime-dose plant is fed from a header tank identical to that in the "lime-free" system.

- *Plant Design*

  In accordance with the design principles the lime-dose plant is designed to raise the pH of the influent minewater to a level just below that at which metals (principally iron) might precipitate as hydroxides. The amount of lime required is based on the neutralisation process, and, assuming an influent pH of 3.0 the design lime requirement has been calculated as 0.037 g/l. However, to accommodate a degree of flexibility (in, for example, influent pH and flow rate) the plant has been designed with the capacity to add between 0.01 g/l and 0.1 g/l lime to a flow of between 0.125 l/s and 1 l/s.

  Lime addition is achieved using an aqueous slurry solution prepared in a lime-batching plant. The plant, which is located adjacent to the header tank, comprises a cylindrical enclosed plastic tank fitted with a centrally mounted electronic agitator unit, a variable speed peristaltic pump with an operating range of 0.05 - 2.3 l/min, and a manually triggered mains water addition system. The mixing tank has a capacity of 6 m^3, sufficient to maintain a minimum 5 day discharge capability of lime solution at the maximum anticipated rate of lime addition.

  The lime slurry is injected into a 90 mm diameter MDPE pipe which discharges into a small reinforced concrete sludge channel of dimensions 21 m x 5 m x 600 mm deep. The sludge channel has a retention time sufficient to ensure precipitation of any hydroxides inadvertently formed by the addition of lime.

10.2.8.2 Aerobic Wetland

- *Influent Feed*

  The aerobic wetland is fed by a 90 mm MDPE pipe directly from the sludge channel.

- *Dimensions of Aerobic Cells*

  In accordance with the design criteria the depth of the "lime-dose" aerobic cells was identical to that determined for the "lime-free" system, namely 750 mm.

The surface area of the "lime-dose" aerobic cells was determined by the same formula used in the design of the "lime-free" system, namely:

$$A = \frac{1}{L} \; Fe \, Q \, C \; m^2$$

where Fe is the influent dissolved iron concentration (i.e. 250 mg/l)
Q is the influent flow (i.e. 30 l/min)
C is the conversion factor 1.44
L is pH dependent loading factor (10 $g/m^2/day$)

Therefore: A = 1080 m^2 (as measured at the water level - the "top" and "bottom" surface areas of each 750 mm deep cell being designed to accommodate a 1 in 2 side slope).

This overall value of 1080 m^2 was also divided almost equally (subject to construction constraints) into five separate cells of:

- 1 x 210 m^2
- 4 x 220 m^2

Individual cells were constructed in an identical manner to that used in the "lime-free" system.

- *Substrate*

The substrate used was identical to that used in the "lime-free" system.

- *Planting of Reeds*

Reeds were planted at an average density of 4 plant/m^2 in all five cells. The reed species planted were identical to that of the "lime-free" system, namely a 50:50 mix of *Phragmites* (Common Reed) and *Typha* (Reedmace) with 100 *Scirpus* (Bullrush). Cells were also fertilized with a general purpose phosphorous-potassium mixture at a rate of about 400 kg/hectare to promote root growth.

10.2.8.3 Anaerobic System

The anaerobic system is similar to that designed for the "lime-free" system. The effective surface dimensions have been reduced to accommodate the reduced design flow of 0.5 l/s. The substrate volume is 554 m^3, with an effective surface area of 591 m^2.

10.2.8.4 Rock Filter

The rock filter is similar to that designed for the "lime-free" system. The surface area has been reduced to 430 m^2 to accommodate the reduced design flow of 0.5 l/s.

10.2.9 The Design of the "ALD" System

10.2.9.1 Pre-treatment

The presence of dissolved oxygen and aluminium in the minewater indicates that the performance of the ALD may be constrained by the precipitation of ferric and aluminium hydroxides. In order to reduce the risk of ALD failure, attempts have been made to remove the dissolved oxygen and aluminium in a small anoxic cell prior to passage through the ALD.

- *Influent Feed*

  The anoxic cell is fed from a header tank identical to that in the other two systems.

- *Plant Design*

  - Anoxic cell

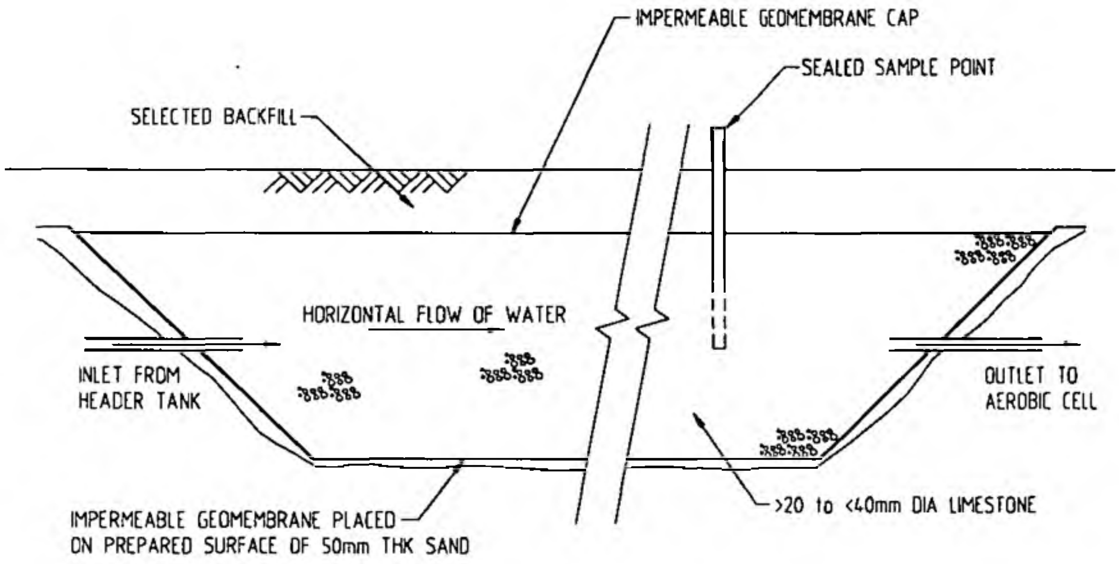
    The anoxic cell is based on similar design principles to the anaerobic cells, although operating at a much higher flow than could be sustained by the surface loading factor required for optimum sulphate-reducing conditions.

  - Anoxic limestone drain (see Figure 10.5)

    The efficiency of the anoxic pond at removing aluminium and maintaining iron in the ferrous form is uncertain. Consequently, two alternative ALD systems were constructed. In System I, 100% of the minewater passes through the anoxic cell and the ALD "senior"; in System II only 10% of the flow passes through the anoxic cell and a smaller ALD "junior" prior to mixing with the 90% of the flow which remains untreated. The reduced flow through the anoxic cell in System II facilitates an enhanced performance of both the anoxic cell and ALD and, in theory when combined with the remaining 90% of the flow, produces a similar water quality to System I.

    Both the ALD "senior" and the ALD "junior" are designed for a minimum two-day retention time for their respective design flows of 0.5 and 0.05 l/s. Both systems were filled with <40 mm to >20 mm limestone enclosed within a welded HDPE liner. A

Figure 10.5 Schematic Longitudinal Section Through Anoxic Limestone Drain



(NOTE: FOR FULL DETAILS REFER TO PILOT PASSIVE TREATMENT PLANT 'AS BUILT' DRAWINGS) void ratio of 20% was used for retention determination. The sizes of the ALD systems are:

- ALD "senior" : 67.5 m x 7.6 m, containing approximately 790 tonnes limestone.
- ALD "junior" : 11.2 m x 5.2 m, containing approximately 65 tonnes limestone.

Devonian Limestone was chosen for both ALD systems on the basis of cost and availability after laboratory tests revealed no significant difference in the performance of locally available limestones. Both limestones tested in the laboratory generated approximately 155 mg/l $CaCO_3$ and raised the pH of minewater to around pH 6.0.

10.2.9.2 Aerobic Wetland

- *Influent Feed*

  The aerobic wetland is fed directly from the combined outlets of the ALD system via a 90 mm diameter MDPE pipe.

- *Dimensions of Aerobic Cells*

  In accordance with the design criteria (see Section 2.5.2.2) the depth, surface area and construction of the "ALD" aerobic cells was identical to that determined for the "lime-dose" system, namely 1080 m^2 x 750 mm deep. However, because of construction constraints, the five separate cells had the following dimensions:

  - 1 x 210 m^2
  - 4 x 220 m^2

- *Substrate*

  The substrate used was identical to that used in both the "lime-free" and "lime-dose" systems.

- *Planting of Reeds*

  Reeds were planted at an identical density to that adopted for the "lime-dose" system, namely an average density of 4 plant/m^2 in all five cells. The reed species planted also comprised a 50:50 mix of *Phragmites* (Common Reed) and *Typha* (Reedmace) with 100 *Scirpus* (Bullrush). Cells were also fertilized with a general purpose phosphorous-potassium mixture at a rate of about 400 kg/hectare to promote root growth.

10.2.9.3 Anaerobic System

The anaerobic cell was identical to that designed for the "lime-dose" system.

10.2.9.4 Rock Filter

The rock filter was similar to that designed for the "lime-dose" system. However, the granite substrate was replaced over the middle third of the rock filter with limestone cobbles to enable an assessment of any potential for increased pH through limestone dissolution.

10.2.10 Miscellaneous Considerations

10.2.10.1 Underdrainage

An underdrainage system comprising a 150 mm depth of single sized 40 mm aggregate has been provided under each impermeable membrane lined structure to counteract the effects of a high groundwater table. The drainage layer is totally enclosed by a filter membrane (Terram T1000) to minimise the migration of fines and possible choking of the system. Each drainage layer is connected by continuous slotted pipes laid in trenches lined with Terram T1000 at approximately 10 m centres to produce efficient dewatering.

10.3 PILOT PLANT CONSTRUCTION

10.3.1 Introduction

Tenders for the construction of the pilot passive treatment plant, together with other works associated with the study, were issued to contractors in December 1993. The contract was awarded to local contractor E. Thomas Construction (Mowlem Ltd) in February 1994.

The location chosen for the construction of the pilot plant comprised an area of approximately 4 ha immediately downstream of Bissoe Bridge (Figure 10.6). The site was sub-divided into two parts by an area of raised ground comprising a former County Council refuse tip. The lime dosed and ALD systems were built on the upper site, with the lime free system located on the lower site.

The whole area has been subjected to mining activity which culminated in the diversion of the Carnon River to the western side of the valley. River diversion was achieved by means of an earth and rockfill bund, which enabled the valley floor to be infilled with tailings. The tailings deposits were eventually capped with locally won material to form a surface that gently sloped towards the Carnon River. Ground levels on the upper pilot plant site varied between 10 m and 8 m AOD, and between 10 m and 7 m AOD on the lower pilot plant site.

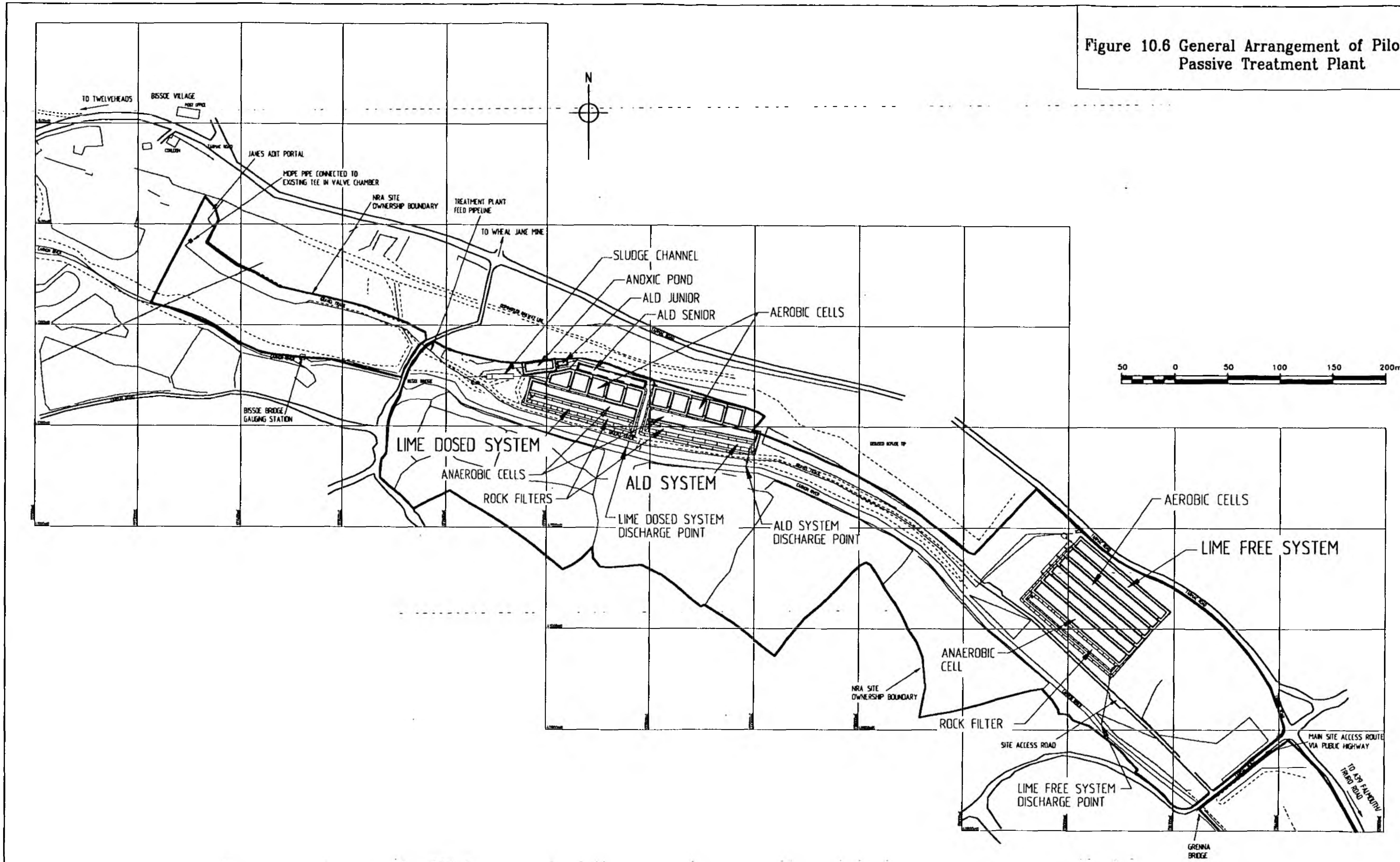


Figure 10.6 General Arrangement of Pilot Passive Treatment Plant

Limited revegetation of the capped tailings had occurred as a result of both natural recolonisation and restoration works. However, due to the lack of good quality topsoil and the presence of potentially phytotoxic metals within the capping material, the vegetative cover was generally sparse.

10.3.2 Ground Conditions

Ground conditions within the pilot plant area were investigated by means of four shell and auger percussion boreholes and some 12 test pits. The ground conditions encountered reflected the site history, with the superficial deposits comprising:

Thickness	Material
0 to 0.5 m	gravelly clay capping material (weathered killas)
3 to 4.5 m	tailings
1.4 to 8.5 m	alluvium

The consistency of the tailings varied spatially across the site but typically comprised silty sands and silty clays with occasional sandy gravel horizons. The upper 1 to 2 m of tailings tended to be firm to stiff probably due to a combination of consolidation and near surface desiccation. The undrained strength of the tailings, however, tended to decrease with depth and typically at depths of in excess of 2 m the material was very soft to soft.

Groundwater levels varied across the site reflecting both the proximity of the river and the heterogeneous nature of the tailings. For construction purposes the water table was assumed to be concurrent with the surface.

Chemical analyses of the tailings and groundwater samples were undertaken as part of both the 1992 and 1994 site investigations (see Section 8). These investigations revealed particularly high levels of iron, arsenic, copper, manganese, cadmium and zinc. Reference to the HSE guidance note "Protection of Workers and the General Public during the Development of Contaminated Land" (Ref. 10) indicated that the site was classified as moderately contaminated and consequently the contractor was instructed to take appropriate measures to minimise the risk to the site workforce.

The relatively fine grading of the tailings, combined with the reduction in undrained shear strength with depth, either required the use of ground improvement techniques to increase the strength sufficiently for construction purposes or necessitated shallow construction. As the use of dewatering or other ground improvement techniques was potentially both difficult and expensive, the depth of excavation was restricted.

10.3.3 Programme

Site construction work commenced on 14th March 1994 and was substantially complete by the end of November 1994. Key dates of the construction of each pilot plant are summarised in Table 10-7.

Table 10-7 : Pilot Passive Plant Key Construction Dates

Activity	Pilot Plant System		
	Lime-free	ALD	Lime-dosed
Construction commenced	14 March	28 April	25 April
Underdrainage commenced	28 March	28 April	25 April
Aerobic cells			
Excavation	11 April - 9 May	6 - 11 June	31 May - 3 June
Lining	26 April - 7 May	23 June	22 June
Substrate placed	12 May	28 - 29 June	23 - 24 June
Reeds planted	16 - 19 May	25 - 27 July	27 - 28 July
Anaerobic cells			
Excavation	23 April - 4 May	29 June - 4 July	7 - 14 July
Lining	7 - 8 June	20 July	22 - 27 July
Substrate placed	11 - 30 July	19 Aug - 2 Sept	11 - 21 August
Rockfilter			
Excavation	25 April - 9 May	4 - 8 July	13 - 18 July
Lining	25 June	21 July	28 July
Stone placed	18 - 20 July	19 Aug - 2 Sept	11 - 21 August
Pre-ALD			
Excavation		22 - 29 June	
Lining	N/A	28 July	N/A
Substrate placed		26 August	
ALD			
Excavation		27 May - 13 June	
Lining	N/A	24 June - 11 Aug	N/A
Limestone placed		28 June - 5 July	
Sealed		10 August	
Lime Dosing Plant Commissioned	N/A	N/A	31 January 1995

N/A - Not Applicable

10.3.3.1 Construction Details

A number of major modifications to the initial design were incorporated into the construction of the pilot plant to reflect:

- in situ ground conditions;
- the results from ongoing confirmatory testing;
- construction requirements.

10.3.3.2 Site Underdrainage

To control groundwater levels within the pilot plant area an extensive underdrainage system was installed as part of the initial construction works. The drainage system was designed to meet four primary purposes:

- Control of groundwater levels during construction, thereby allowing construction to take place in relatively dry stable ground conditions.
- To avoid the build-up of excessive uplift pressure beneath the cell liners.
- Underdrain each cell to prevent possible leakage of contaminated groundwater into the treatment system.
- Act as a possible leak detection system in the event of the failure of a cell liner.

The design of the underdrainage system was modified on site to comprise:

- 150 mm thick drainage blanket beneath each cell.
- A series of corrugated perforated plastic drainage pipes placed in a granular fill surround.

Both the drainage blanket and the granular perforated pipe surround were wrapped in a geofabric to prevent the migration of fines and the eventual clogging of the drainage system.

The perforated collection pipes were installed at 10 m centres beneath the "lime-free" system site and at 17.7 m beneath the "ALD" and "lime-dose" system site. On both the upper and lower pilot plant sites the underdrainage pipes were connected to an interceptor main which discharged the collected groundwater into the river.

Localised problems were experienced installing the underdrainage where the trenches intercepted either groundwater or soft material. In these circumstances the trenches tended to collapse and the contractor had to resort to either temporary support or cutting back the excavation until stable side slopes were achieved.

10.3.3.3 Minewater Distribution Pipework

Minewater for the pilot plant is drawn off from the downstream plug in Jane's Adit and transferred to each of the pilot schemes by a 160 mm diameter MDPE buried pipe. Air bleed valves and washout facilities have been incorporated to enable the pipe to be purged of both air and accumulated solids.

Minewater to each scheme is fed into a circular polypropylene holding tank. Each tank was designed to act as a constant head facility balancing out any short term variations in the inflow. The inlet to each tank was fitted with a mechanical float valve, complete with an integral downpipe designed to prevent air entrainment in the inflowing water.

The flow rate into each pilot plant is regulated by a manually adjusted pinch valve and is monitored by both manually and automatically recording the depth of flow over the inlet monitoring chamber v-notch weir.

No major problems were associated with installation of the minewater distribution pipe and associated components.

10.3.4 Treated Water Discharge Arrangements

The treated minewater discharge arrangements for each scheme comprise a separate monitoring chamber connected to a pipe discharging into either the river or the treated water collection sump. Each monitoring chamber is fitted with a v-notch weir and ultrasonic depth probe to record the flow and an automatically read pH probe. A manually operated valve was fitted to the discharge pipe to allow the system to be isolated from the river. In addition a flap valve was fitted to the pipe outlet to prevent flooding of each pilot plant with river water during periods of abnormally high flow.

To enable each pilot plant to operate without discharge to the Carnon River, a treated minewater return main was incorporated into the system to allow water to be returned to the Wheal Jane mine site for further treatment.

The treated minewater return system comprises:

- treated water collection sump constructed at the outlet from each pilot plant;
- a submersible pump located in each sump to transfer the treated water to South Crofty plc's Bissoe pump station;
- a booster pump located within the Bissoe pump station to convey the water back to the Wheal Jane mine site via South Crofty plc's emergency water supply pipeline.

Power for the pumps serving each of the three pilot plants is fed from the Pilot Plant Control Building.

No significant problems were experienced during the installation of the return main and associated works.

10.4 PRINCIPLES OF OPERATION

10.4.1 Introduction

Passive treatment is, by definition, designed to operate with a minimum of active control. However, because passive treatment is based, at least in part, on biological systems, there is an extended commissioning period during which the biological systems reach maturity. This commissioning period requires relatively intense management of the plant to optimise the flow through the system and promote rapid establishment of the reeds, algae and anaerobic bacterial communities. Thereafter, the pilot plant should function with minimum maintenance and the principal objective of "operation" becomes monitoring of performance, especially the response of the components of the system to changes in rainfall and temperature.

10.4.2 Commissioning

Full commissioning of any passive plant which incorporates aerobic reed bed systems is constrained by the time required for these systems to reach maturity (normally 1 - 2 growing seasons). The algal and anaerobic bacterial communities can reach maturity under optimum conditions within a matter of weeks or months.

During this commissioning period the plant is being managed by:

- The addition of fertiliser to reed bed and algal cells to assist in establishment.
- Incubating the anaerobic cells in sulphate-rich water to promote the development of a flourishing bacterial community.
- Running the plant at first 25% then 50% of design flow as the systems start to mature.

Extensive in-situ monitoring (often on a daily basis) has been undertaken to evaluate the early development of each component system. As individual components reach maturity, the intensity of monitoring is reduced to the level required to evaluate long-term performance.

10.4.3 Performance Assessment

10.4.3.1 Objectives

In order to assess the performance of each component of each of the three Pilot Passive Treatment Systems, a comprehensive programme of monitoring has been instigated. The programme comprises:

- Continuous monitoring of flow, pH, and/or dissolved oxygen at 15 selected locations.
- In situ monitoring of pH, dissolved oxygen, redox potential, conductivity and temperature using portable instruments at 46 locations.
- Laboratory analysis of water samples for a range of parameters on a routine basis from 46 locations.

The results of field and laboratory testing are being recorded and assessed regularly during the operation of the plant, and the testing programme reviewed as and when required.

10.5 OPERATIONAL RECORD

10.5.1 Influent Water Quality

The chemistry of the influent minewater has been monitored since immediately prior to the commissioning of each of the three pilot systems. The results (which are summarised in Table 10-8) indicate that:

- Aluminium, cadmium, and manganese concentrations are higher than predicted.
- Copper, iron and zinc concentrations are lower than predicted.

Of principal concern is the higher aluminium concentration, since this results in a greater risk of clogging of the anoxic pond and / or the ALD with a gelatinous aluminium hydroxide. The other differences will merely be reflected in the efficiency of the pilot system and can readily be incorporated into any future design work.

Table 10-8 : Comparison of Influent Minewater Chemistry and Design Values

	pH	Al	Cd	Cu	Fe	Mn	Zn
Design values	3.0	40	0.01	5	250	20	250
Influent to pilot plant							
average -	3.9	62	0.16	0.8	190	31	113
range -	(3.5 - 4.6)	(43 - 90)	(0.02 - 0.30)	(<0.1 - 1.2)	(93 - 284)	(22 - 46)	(85 - 156)

All units except pH expressed as mg/l total metal.

10.5.2 Commissioning

The three systems ("lime-free", "lime-dose" and "ALD") of the Pilot Passive Treatment Plant were commissioned on different dates (and different days of the week) to facilitate the implementation of the intensive monitoring requirements.

In accordance with the requirements for commissioning the initial flow through each system was set at approximately 25% of design flow (0.125 l/s for the "lime-dose" & "ALD" systems, and 0.175 l/s for the "lime-free" system). As the systems mature this has been increased to 50% of design flow (0.25 l/s for the "lime-dose" & "ALD" systems, and 0.35 l/s for the "lime-free" system), prior to the eventual increase to full design flow. The commissioning of each system is summarised in Table 10-9. None of the three systems will reach full maturity until the end of the 1995 growing season.

Table 10-9 : Summary of Commissioning Dates

	Lime-dose System A		ALD System B		Lime-free System C	
	Date	Flow	Date	Flow	Date	Flow
Pre-Treatment	31/1/95	0.25 l/s	1/12/94 9/12/94	0.125 l/s 0.25 l/s	-	-
Aerobic Cells	3/2/95	0.25 l/s	12/12/94	0.25 l/s	16/11/94 25/11/94	0.175 l/s 0.35 l/s
Anaerobic Cell	n/c		22/12/94- 3/1/95 3/2/95	0.125 l/s 0.125 l/s	21/12/94 18/1/95	0.175 l/s 0.35 l/s
Rock Filter	n/c		n/c		n/c	

Note: n/c ... not yet fully commissioned.

10.5.2.1 Preliminary Results

10.5.2.1.1 Introduction

The pilot passive treatment plant is still in the process of being commissioned. Consequently, sufficient data has been collected to date to undertake only a preliminary analysis of the performance of the anoxic pond / ALD and the aerobic cells in the "lime-free" and "ALD" systems. Insufficient data is available to evaluate the performance of the "lime-dose" plant, the aerobic cells of the "lime-dose" system or the anaerobic cells and rock filters of any of the three systems.

10.5.2.2 Dilution by Rainfall

An important part of the evaluation of the performance of the aerobic cells of the three systems will be an assessment of the diluting effect of rainfall. Estimates of the dilution effect of rainfall for the "lime-free" and "ALD" aerobic cells were made by two methods:

- Estimates based on inflow, outflow and rainfall data.

- Estimates based on the concentration of chloride ions in the influent and effluent from the aerobic cells (chloride is essentially a non-reactive ion and, therefore, changes in chloride ion concentration should reflect any rainfall inputs or evapotranspiration losses).

The results of these calculations for the "lime-free" aerobic cells, for the period 16.11.94 - 21.12.94, revealed that the composition of the water discharged from the lost aerobic cell was:

(i)	Flow balance	74% rainwater 26% minewater
(ii)	Chloride concentrations	68% rainwater 32% minewater

The correlation between the calculation methods i) and ii) was good, the difference being within the anticipated range for evapotranspiration during the period from November to January and the inherent errors in the chloride analysis and flow and rainfall measurement.

10.5.2.3 "Lime-free" System

Within five days of commissioning of the aerobic cells a thin layer of orange-brown ferric hydroxide precipitate was observed in Cell 1, spreading rapidly to Cell 2. No precipitate has yet been observed in Cells 3 to 5. An assessment of the changes in dissolved iron concentration between the influent and effluent indicates that, at an average influent flow rate of 0.27 l/s, approximately 95% of the iron has been removed by the aerobic cells (see Figure 10.7).

The change in pH (see Figure 10.7) indicates that the aerobic cells are currently unable to raise the pH sufficiently to promote the precipitation of the remaining iron or accommodate an increase in flow. This is to be expected given that the maintenance of a suitable pH depends upon the operation of the bicarbonate buffer system. The buffer system has yet to develop to a significant degree as the aerobic cells have not yet reached maturity.

The concentrations of arsenic in the influent and effluent reveal a 99% removal in the aerobic cells, with 95% removal in the first cell (see Figure 10.7). This reflects the efficiency of arsenic co-precipitation and adsorption which accompanies the formation of iron hydroxides.

Figure 10.7 Preliminary Results - 'Lime-Free' System

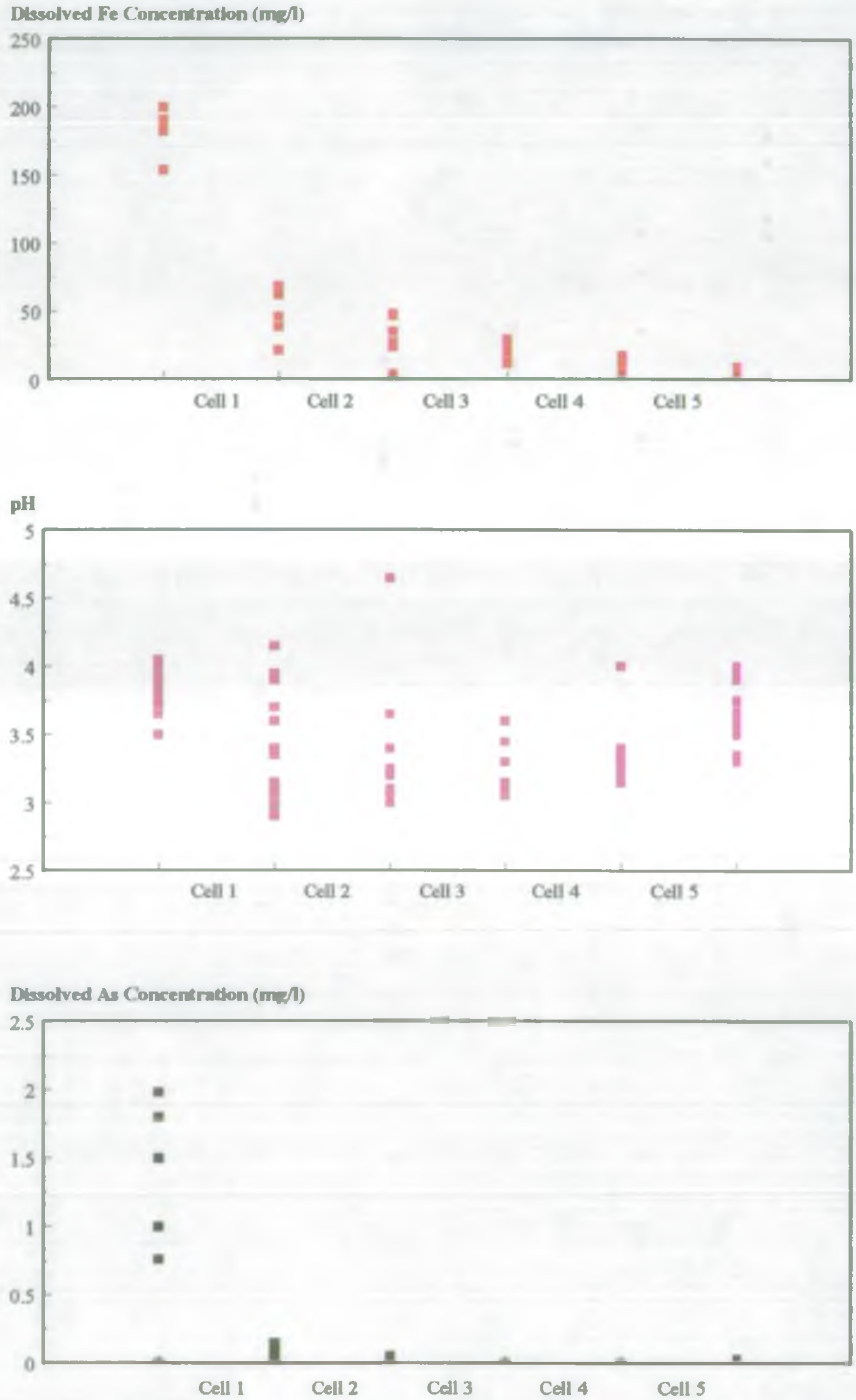
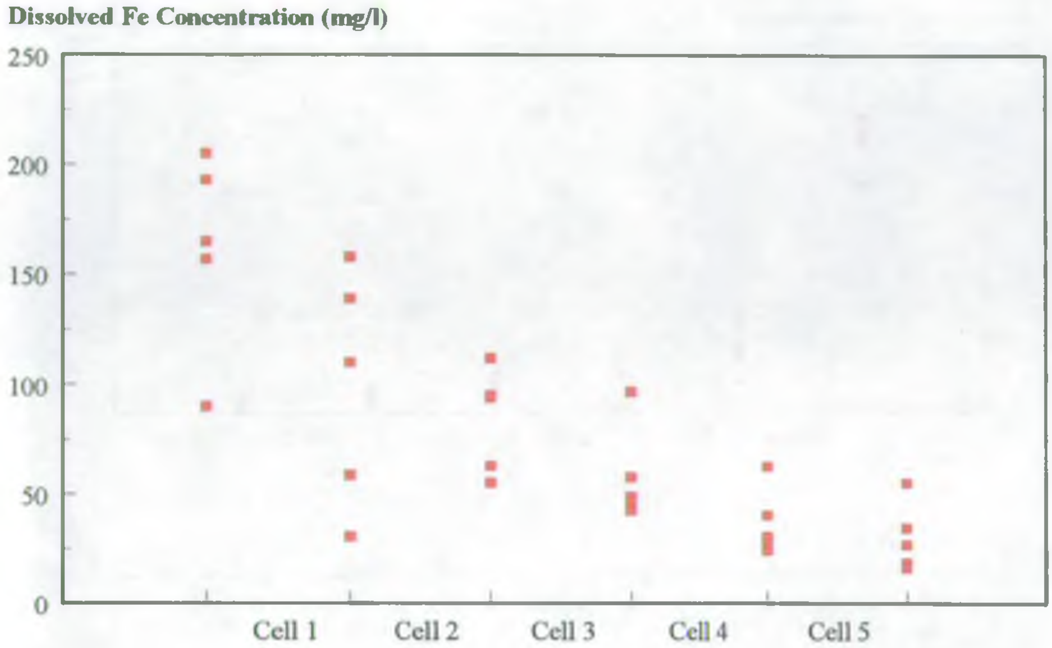
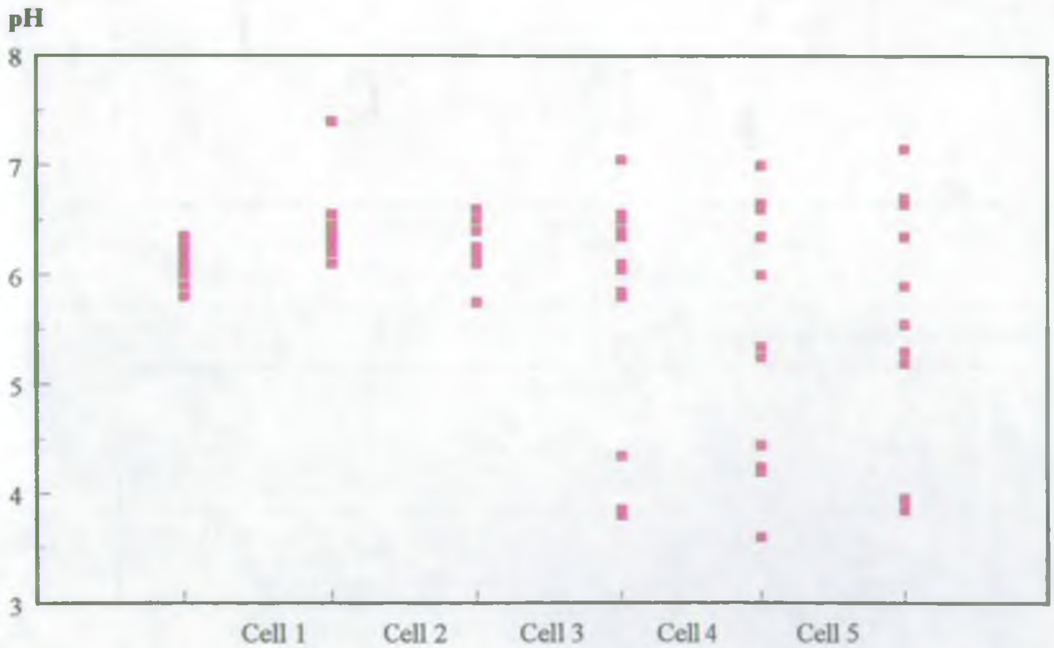


Figure 10.8 Preliminary Results - ALD System





10.5.2.4 "ALD" System

The anoxic pond has been commissioned to 50% design flow, with an effective reduction in the dissolved oxygen concentration by 40% to around 2 mg/l. This was accompanied by a rise in pH from 3.9 to 5.1 and a reduction in redox from +270 mV to +53 mV. A further improvement in the performance of this cell may be necessary to fully protect the ALD from the risk of armouring with iron hydroxide.

A translucent/white aluminium hydroxide precipitate (containing approximately 15% aluminium and 1% iron) has been noted in the sampling chamber at the discharge point from the anoxic pond. Whilst confirming the ability of the anoxic pond to remove aluminium from solution the potential for the precipitated hydroxide to clog the ALD is being closely monitored. A preliminary evaluation of the ALD itself indicates that the pH of the minewater is being increased to approximately pH 6.

An assessment of the changes in dissolved iron concentration between the influent and effluent of the aerobic cells indicates that, at an average influent flow rate of 0.163 l/s, approximately 75% of the iron has been removed by the aerobic cells (see Figure 10.8).

The change in pH indicates a wide fluctuation in the ability of the cells to maintain a sufficient pH to optimise the precipitation of iron. This is to be expected given that the aerobic cells have not yet reached maturity.

10.5.3 **Future Operation of the Pilot Plant**

The data available to date are insufficient to adequately evaluate the performance of the pilot plant. Nevertheless, the complex and lengthy process of commissioning a passive system has provided the basis for a realistic assessment of performance over the succeeding months. It is estimated that at least 2 further years of operation of the pilot plant will be required before final conclusions can be drawn. In the meantime it will be necessary to use the design parameters in any discussion of a long-term, full scale passive treatment facility.

Whilst site specific design criteria for a full scale passive treatment system should become available after a period of two years operation of the pilot plant, the pilot plant itself has a minimum design life of 5-7 years. This design life is constrained primarily by the freeboard within the aerobic cells and could easily be extended by appropriate maintenance work. The pilot plant therefore offers an excellent opportunity to act as a focus for long-term applied research into many aspects of the chemistry and treatment of acidic metal-rich minewaters. A number of U.K. research institutions and universities have expressed an interest in assisting in the long-term use of the pilot plant should this be deemed appropriate.

10.6 SUITABILITY OF PASSIVE TREATMENT TO MEET WATER QUALITY OBJECTIVES

10.6.1 Efficiency of Metal Removal

The pilot treatment plant has only recently been commissioned and insufficient data are available at this stage to undertake a detailed evaluation of the design criteria. However, experience of currently operating passive treatment systems elsewhere tends to confirm the validity of the original design parameters. There is no reason to suggest that the operation of the pilot plant will result in the need for a fundamental re-appraisal of design parameters.

Nevertheless, there remains some uncertainty in specific key design parameters required to optimise the performance of a passive treatment plant. Of principal interest are:

- The effectiveness of the pre-ALD in preventing armouring or clogging of the ALD.
- The optimisation of the area loading factor in the design of anaerobic cells.
- The suitability of the anaerobic cells in removing iron and arsenic in addition to zinc, cadmium and copper.
- The efficiency of manganese removal in the rock filter.

All four of these issues will be investigated thoroughly during the operation of the pilot plant. The uncertainty over the area loading factor for the anaerobic cells, which is essentially pH dependent, is of prime significance. Although the volume of substrate required is determined by the metal concentration of the influent, the area loading factor governs the surface area of substrate required (and hence is a principal determinant of land requirements and construction costs). Recent experience in the U.S.A. suggests that the design criteria of 800 ft^2/US gallon/min. (14 m^2/m^3/day) might be reduced to around 600 ft^2/US gallon/min. (10.5 m^2/m^3/day) without any deterioration in performance of the cell. If confirmed, this would significantly reduce both the area of land required and the costs of a full scale passive treatment system.

10.6.2 Requirements for Full Scale Passive Treatment System

The modelling of water quality parameters at Devoran Bridge (see Sections 6 and 7) indicates that a full scale treatment plant would require a capacity of approximately :

- 190 l/s ... to comply with the annual average metal concentrations of the "No deterioration" objective (assuming a 50% annual risk of failure).

- 210 l/s ... to comply with the 95 percentile metal concentrations of the "No deterioration" objective (assuming a 50% annual risk of failure).

- 230 l/s ... to comply with the annual average metal concentrations of the "North Sea Commitments" objective (assuming a 50% annual risk of failure).

- 270 l/s ... to comply with the annual average metal concentrations of the "No deterioration" objective (assuming a 5% annual risk of failure).

- 300 l/s ... to comply with both the 95 percentile metal concentrations of the "No deterioration" objective (assuming a 5% annual risk of failure) and the annual average metal concentrations of the "North Sea Commitments" objective (assuming the same 5% annual risk of failure).

For comparative purposes, preliminary design estimates for passive treatment plants required to treat either 190 or 300 l/s have been derived (see Table 10-10). All design estimates are based on a minewater quality comparable to that recorded most recently (autumn 1994) in Wheal Jane No. 2 Shaft (see Table 10-3).

Table 10-10 : Design Estimates for Full Scale Passive Treatment Systems

	Land Area Required (ha)		Budget Cost (£ million)	
	Design 1	Design 2	Design 1	Design 2
Passive system incorporating pre-treatment, aerobic cells, anaerobic cell and rock filter :				
• Capacity 190 l/s	77	71	19	17
• Capacity 300 l/s	124	115	30	27
Passive system incorporating pre-treatment with lime-dose plant, anaerobic cell and rock filter :				
• Capacity 190 l/s	26	22	11 - 18*	10 - 18*
• Capacity 300 l/s	41	32	17 - 28*	15 - 28*

Design 1 : Anaerobic cell based on area loading factor of 14 m^2/m^3/day.
Design 2 : Anaerobic cell based on area loading factor of 10.5 m^2/m^3/day.

Budget costs based on 1995 construction costs (including provision for upgrading Jane's Adit to ensure continuity of influent) but excluding operating costs estimated as £150 000 for years 1 - 3 and £50 000 per year thereafter. Costs also make provision for the installation of a liner and underdrainage system which is likely to be required by the Waste Regulation Authority.

* The principal uncertainty in the budget estimate is the cost of anaerobic cell substrate; the lower value given relates to the use of the cheapest but as yet unproven substrate (straw) whilst the upper cost estimate relates to the use of the proven substrate used in the pilot plant (sawdust).

The assessment of potential sites for the construction of a full scale treatment plant has identified two possible locations (see Section 8) :

- Approximately 40 ha of land owned by the NRA in the Carnon Valley.
- Clemows Valley Tailings Dam - 16 ha.

Site reconnaissance, desk study researches and site investigation (see Section 8) have identified only 22 ha of land (all in the Carnon Valley) that would be suitable, without undertaking excessive ground improvement works, for the construction of a passive treatment plant.

Consequently, whilst in principle passive treatment technology has the capability to treat the required flow, constraints on land availability indicate that a passive treatment system in the Carnon Valley could treat no more than 190 l/s. On this basis passive systems could improve the water quality at Devoran Bridge sufficient to comply with the annual average metal concentrations of the "No deterioration" objective (assuming a 50% annual risk of failure), but would appear not to be capable of treating sufficient water to meet any more demanding objectives.

The cost estimates summarised in Table 10-10 have been prepared based on the 1995 construction rates and a preliminary design developed using the experience gained from building the pilot plant. In order to show how the costs of a full-scale plant would be apportioned between the different components, a more detailed breakdown of the costs of building a plant to treat 190 l/s is presented on Table 10-11. In deriving these costs an allowance has been made for the following:

- The 1994 site investigation revealed that the Carnon Valley tailings deposits are very loose. Standard penetration tests indicated that the undrained strength of the tailings, at depths greater than 1 m below surface, is probably less than 20 kN/m^2 which is unlikely to support the weight of construction plant and may adversely effect the stability of any cut slopes. A granular blanket has therefore been incorporated beneath each cell to both allow vehicular access during construction and to assist in the control of ground water levels. In the unlikely event of the liner failing, the underdrainage system also beneficially acts as a leakage detection and collection system

- The organic substrate within the anaerobic cell will become contaminated with List I and List II metals including cadmium, arsenic and zinc. Eventually the substrate will either have to be removed to a suitably licensed landfill site or the cells used as a permanent depository for the precipitated metals. To account for the possibility of the metals being permanently stored in situ, it has been assumed that the cells will be lined in accordance with current UK landfill practice. As the existing tailings are contaminated with heavy metals and the Carnon Valley aquifer of low vulnerability, it has been assumed that lining with a single layer of HDPE will be adequate.

- Granular flow distribution and collection layers have been incorporated into the top and base of each cell to ensure uniform flow through the anaerobic cell substrate. Full utilisation of the substrate is especially important at Wheal Jane due to the limited land area available and the resultant need to maximise the flow treated per unit area.

- Table 10-11 indicates that the most significant single cost in the construction of an anaerobic cell is associated with the supply, mixing and placement of the substrate. The effect of substrate price on construction costs has been assessed by considering the use of straw in place of sawdust. Preliminary cost estimates indicate that the replacement of sawdust with straw would reduce the initial construction costs by approximately 40%, which potentially amounts to an initial saving of some £7 million. This saving would however be substantially reduced by the need to replace straw more frequently than sawdust, due to both the form and potentially lower organic carbon content of straw. Any short-term cost benefit may therefore be off set by the reduced cell life.

- The provision of a lime dosing plant to increase the pH of the water introduced into the anaerobic cell thereby allowing the potential reduction in the areal loading factor from 14 to 10.5 m^2/m^3/day.

Table 10-11 : Cost Estimate for Passive Plant to Treat 190 l/s

Item	Cost Estimate (£)			
	Design 1		Design 2	
Janes Adit Upgrade	1 400 000		1 400 000	
Delivery Pipeline	400 000		400 000	
ANAEROBIC CELL				
Substrate Type	Sawdust	Straw	Sawdust	Straw
Cell Loading Factor	14 m^2/m^3/day		10.5 m^2m^3/day	
Required area	26 (ha)		22 (ha)	
Excavation	1 155 000		897 000	
Underdrainage	626 000		509 000	
Liner	626 000		509 000	
Base Gravel Drain	574 000		445 000	
Substrate	8 948 000	3 014 000	9 483 000	3 219 000
Top Distribution Pipework	500 000		405 000	
Capping Layer	589 000		405 000	
Other Works	16 000		84 000	
SUB TOTAL	13 199 000	7 265 000	12 993 000	6 729 000
ROCK FILTER				
Excavation	112 000		112 000	
Underdrainage	210 000		210 000	
Liner	107 000		107 000	
Rock Layer	149 000		149 000	
Other works	2 000		2 000	
SUB TOTAL	580 000	580 000	580 000	580 000
LIME PLANT			100 000	100 000
SUB TOTAL	15 579 000	9 645 000	15 473 000	9 209 000
Planning and Engineering (15%)	2 337 000	1 446 000	2 321 000	1 382 000
TOTAL COST	**£17 916 000**	**£11 091 000**	**£17 794 000**	**£10 591 000**

The distribution of the anaerobic cell and rock filter construction costs are illustrated graphically on Figure 10.9 and are summarised in Table 10-12 and 10-13 respectively.

Table 10-12 : Anaerobic Cell Cost Distribution

Item	Cost Proportion (%)
Excavation	4 - 7
Underdrainage	8 - 15
Liner	4 - 8
Minewater distribution and collection system	8 - 14
Substrate	45 - 71
Capping layer	4 - 7

Based on treating 190 l/s through a plant built on the Carnon Valley Site.

Table 10-13 : Rock Filter Cost Distribution

Item	Cost Proportion (%)
Excavation	19
Underdrainage	36
Liner	18
Substrate	26

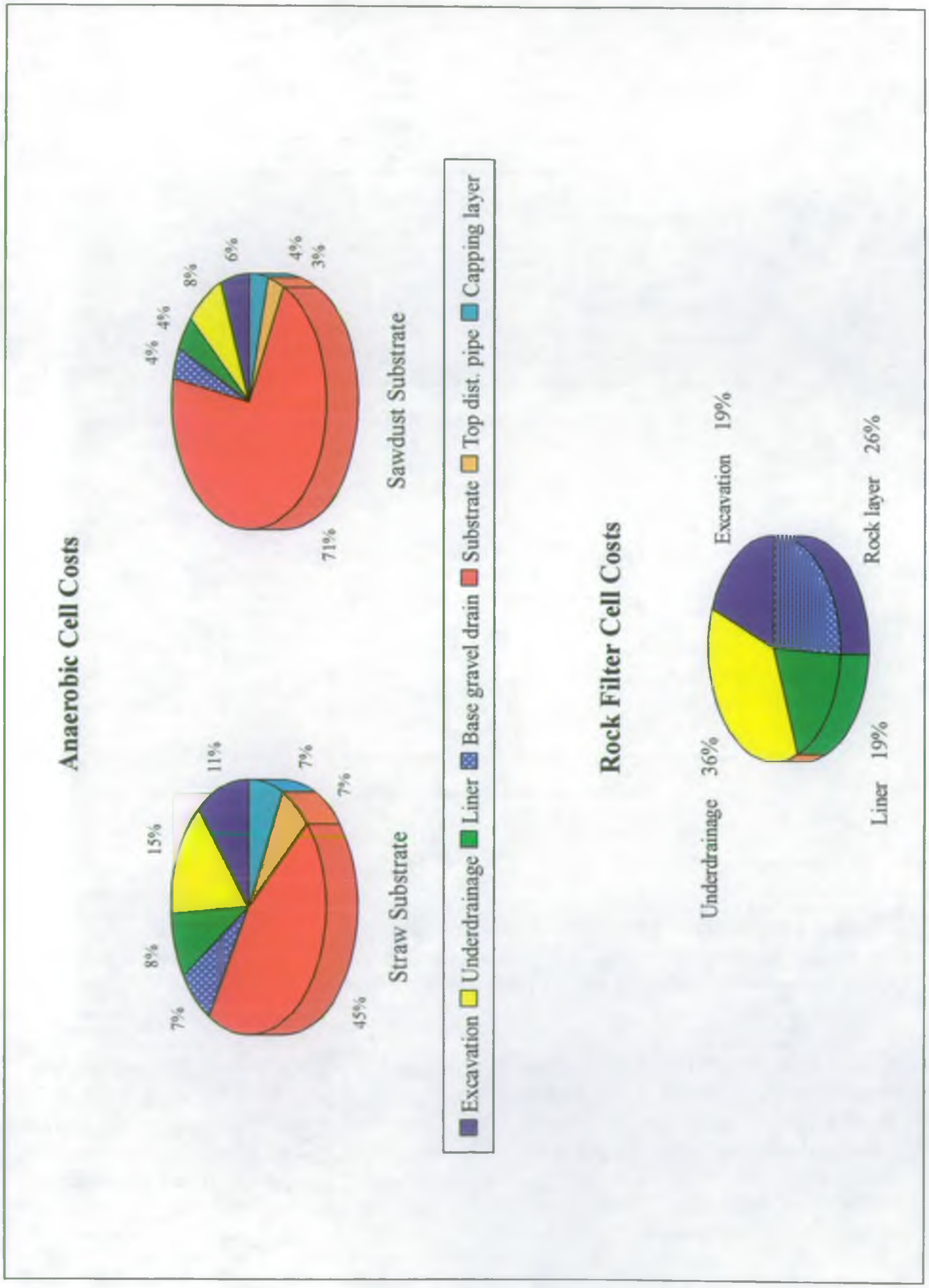
Based on treating 190 l/s through a plant built on the Carnon Valley Site.

10.7 SUMMARY

The treatment of acidic metal-rich minewaters using passive systems is well established. The design of passive systems is dependent upon site specific criteria and it is normal practice to develop detailed design parameters through the operation of a pilot scale treatment plant.

A pilot treatment plant has been constructed in the Carnon Valley in 1994 and has been designed to treat up to 1.7 l/s of minewater from Jane's Adit through a series of treatment cells promoting the removal of iron, arsenic and manganese by aerobic processes, and cadmium, copper and zinc by anaerobic processes. The pilot plant also incorporates alternative methods of pre-treatment using an anoxic limestone drain and a small lime-dose plant which are intended to enhance the efficiency of metal removal in the aerobic and anaerobic cells.

Figure 10.9 190 l/s Passive Treatment Plant - Indicative Cost Distribution



The pilot plant was commissioned between November 1994 and January 1995. Passive treatment, however, is based upon "natural" biological systems which must be allowed to reach maturity before any detailed performance criteria can be evaluated. The long-term operation of the pilot plant will provide information of value to the treatment of acid minewaters not only in the Carnon Valley but wherever a similar problem occurs.

A preliminary assessment of the requirements for long-term treatment based on predicted flows of minewater to be treated to achieve a series of Water Quality Objectives indicates that there is unlikely to be sufficient suitable land available to accommodate a full scale passive treatment plant.

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11

11. ACTIVE TREATMENT TECHNOLOGY

CONTENTS

11.1 INTRODUCTION

Active treatment can be defined as any process which requires a continuous input of resources to achieve the required improvement in water quality. Unlike passive treatment, in which all the necessary resources are provided during construction, active treatment requires a reduced initial input but the continued introduction of chemical reagents and manpower to maintain ongoing treatment. An active system is typically cheaper to build than a passive plant, but the annual operating costs are higher.

The existing treatment operation at Wheal Jane is a form of active treatment which relies on the availability of the Clemows Valley Tailings Dam for both water/metalliferous sludge separation and sludge disposal. Continued use of the existing system is limited by the remaining capacity in the Clemows Valley Tailings Dam.

Active treatment, however, may be feasible in the long-term, provided that a suitable method of sludge handling and disposal can be developed. Potential active methods of metal precipitation and sludge dewatering have, therefore, been considered based on the following criteria:

- Effluent water quality.
- Sludge physical properties.
- Technical performance.
- Capital and operating costs.

11.2 PROCESS DESCRIPTION

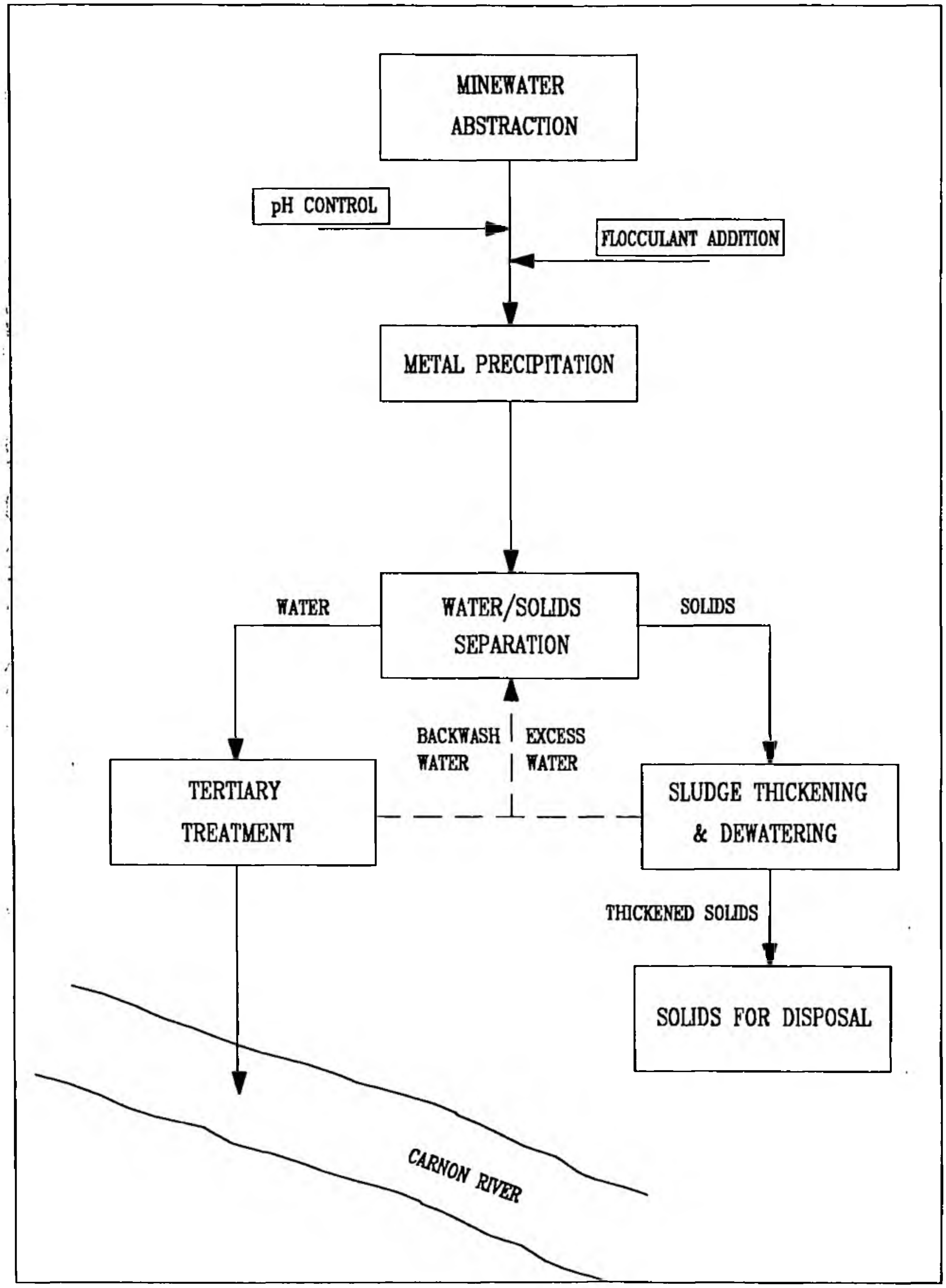
The treatment of minewater can be separated into four basic stages (Figure 11.1), namely:

- Precipitation of the dissolved metal from solution.
- Water/metalliferous sludge separation.
- Sludge thickening and dewatering.
- Tertiary water treatment (polishing).

These four treatment stages are achieved in the existing treatment system by:

- Metal precipitation using lime.
- Primary solids/water separation within the Clemows Valley Tailings Dam.
- Sludge dewatering through consolidation under the weight imposed by subsequent deposition.
- Tertiary treatment of the effluent water in the polishing lagoon.

Figure 11.1 Active Treatment - Block Diagram



11.2.1 Process Selection

The assessment of suitable active treatment technology has been carried out in two principal stages, namely:

- technical appraisal
- financial evaluation.

11.2.2 Technical Appraisal

A database, compiled by the NRA, of approximately 200 companies, each offering expertise in the water treatment field, was examined and the technologies available categorised into the four treatment stages listed in Section 11.2. Representative technologies from each of the four treatment stages were selected for performance appraisal. At this stage, selection was solely on the basis of providing representative technology. However note was taken of:-

- Any patent specific constraints.
- Proven performance of the technique.
- New technology potentially applicable at Wheal Jane.
- The commercial availability of the process equipment.
- The availability of specialist reagents and technical support.

A preliminary technical and economic assessment of each technology was carried out to establish those with sufficient potential to warrant either bench scale or pilot plant testing. The results from these trials have been used to develop the preferred active process route for treating the Wheal Jane minewater.

11.2.3 Financial Evaluation

Budget cost estimates have been prepared for those treatment processes demonstrated to be potentially applicable for treating the Wheal Jane minewater. Capital costs have been established based on the installed treatment capacity whilst operating costs have been prepared using the average flow rate treated.

The cost of each option has been compared and the preferred treatment route derived on the basis of both the technical and financial evaluations.

An accurate estimate of the cost of building and operating the recommended treatment system has been established primarily using quotations and estimates submitted by the manufacturers.

11.2.4 Treatment Plant Size

The active treatment systems have been sized on the basis of achieving both the "No Deterioration" and "North Sea Commitments" Water Quality Objectives with a 5% annual probability of non-compliance. As detailed in Section 7, these objectives can be met by constructing a process plant with maximum capacity of

300 l/s, treating an average flow rate of 190 l/s. The active treatment processes, therefore, have been appraised on this basis. A modular design, comprising a number of parallel streams, has been used in sizing each treatment plant, with the maximum capacity operated only during the winter. Essential maintenance can be carried out during the summer months when the treatment requirement is reduced and one or more of the modules can be taken out of service without compromising water quality.

11.3 METAL PRECIPITATION

Metals can be removed from solution either on mass or selectively depending on the technology employed. Blanket removal of all the metals can be most easily achieved either by pH control, resulting in hydroxide precipitation, or by sulphide precipitation as detailed in Sections 11.3.1.2 and 11.3.1.3 respectively.

Selective metal recovery can be achieved using more complicated treatment routes. The possibility of using these methods for the selective removal of metals from the minewater is reviewed in Section 11.3.2.

11.3.1 Total Precipitation

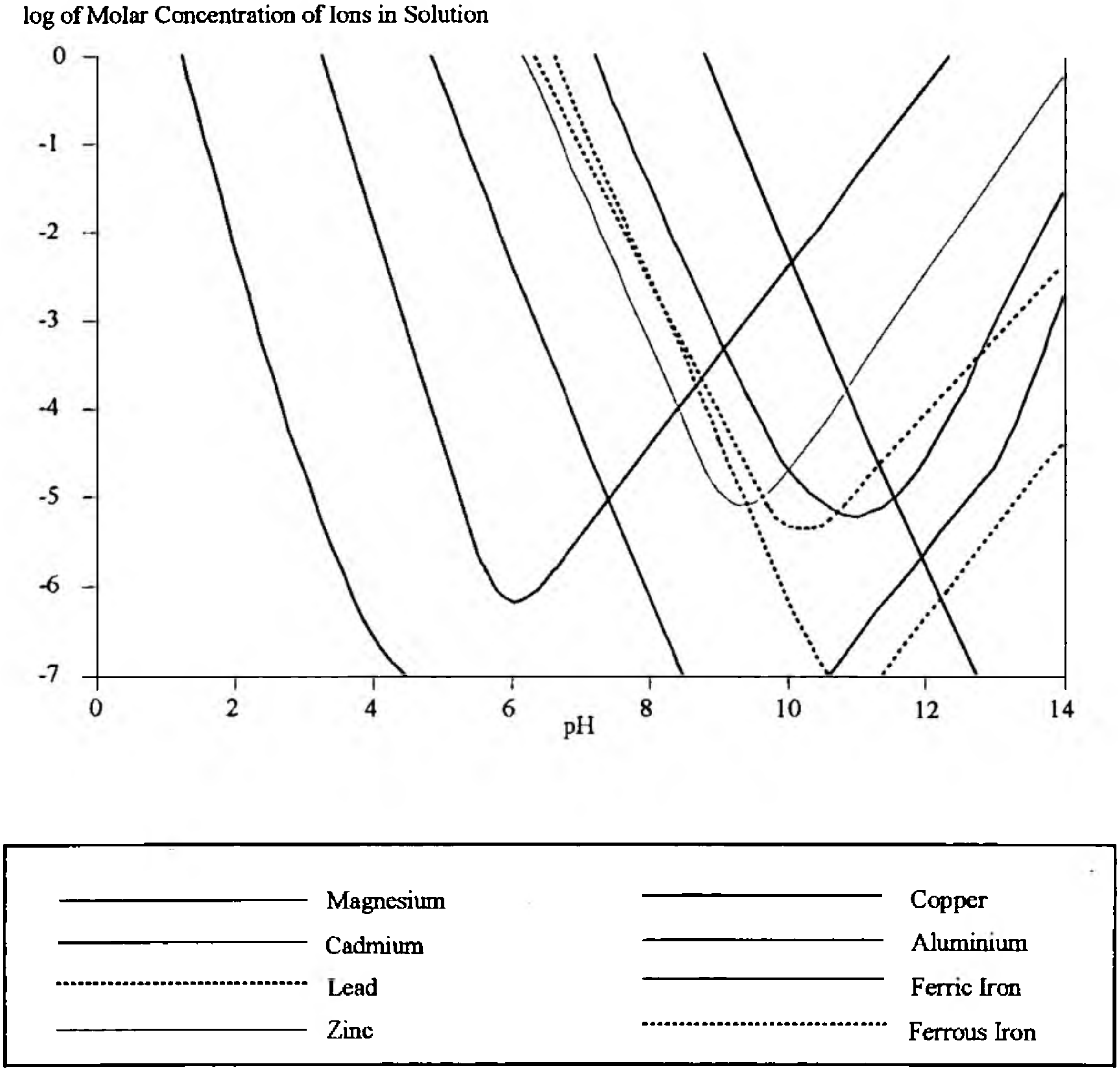
The first stage of an active treatment process will generally involve changing the water chemistry to render the dissolved metals insoluble. The solubility of metals in aqueous solutions is primarily dependent on pH. The concentration of most metals in solution generally increases as the pH is reduced (i.e. becomes more acidic) as shown in Figure 11.2. Changing the pH, by the addition of either acid or alkali, can be used either to increase or reduce the quantity of dissolved metal.

The minewater pumped from Wheal Jane is acidic, with a pH = 3.5, and contains a significant quantity of metals in solution (typically 600 mg/l during 1993 reducing to approximately 500 mg/l during 1994). The addition of an alkaline substance can be used to increase the pH, resulting in the formation of a metal-rich precipitate. The required increase in pH necessary for precipitation varies with the metal species and the concentrations present as shown in Figure 11.2 and Table 11-1.

Table 11-1 : Minimum pH for the Lowest Metal Solubility

Cation	Minimum pH to ensure that metals are substantially insoluble
Fe^{3+}	3.5
Cu^{2+}	6.8
Zn^{2+}	8.5
Fe^{2+}	9.5
Cd^{2+}	9.8
Mn^{2+}	11.2

Figure 11.2 Maximum Ion Concentration, Limited by Hydroxide Precipitation under Aerobic Conditions



In principle, by carefully raising the pH, the metals can be selectively removed from solution.

A residual concentration of metal remains in solution even when the pH is raised above the minimum value listed in Table 11-1.

The typical residual metal concentrations attained by hydroxide precipitation have been determined and are shown in Table 11-2, which demonstrates that, for the metals listed, the EC Directive Water Quality Objectives can be obtained by lime dosing.

Table 11-2 : Measured Minimum Metal Concentration for Minewater Neutralised to pH 10 Using Calcium Hydroxide

Cation	Residual Solubility (mg/l)[1]	EC Directive[2] Water Quality Objectives (mg/l)
Fe^{3+}/Fe^{2+}	0.15	1.0 (D)[3]
Cu^{2+}	<0.02	0.028 (D)
Zn^{2+}	0.18	0.5 (T)
As^{2+}	0.016	0.05 (T)
Cd^{2+}	<0.0005	0.001 (T)
Mn^{2+}	33.6	not given

Notes: [1] Residual total values measured from filtered supernatant following lime dosing through the temporary treatment system.
[2] Ref. 7 - Development of Long-Term Water Quality Objectives
[3] (D) = dissolved (T) = Total

11.3.1.1 Rate of Reaction

The rate at which the chemical reaction proceeds varies with both the form in which the alkaline substance is introduced and the final pH. Powdered alkaline substances have to dissolve in the minewater before the pH raising and precipitation reactions can take place. A finite time is required for the powder to dissolve and the reactions to take place. The length of this period affects the required retention time within the process plant and hence the size of the facility.

The rate of some reactions are also pH controlled and therefore the pH has to be raised sufficiently not only to allow the formation of a precipitate but also to ensure that the reaction takes place relatively rapidly. For example, the rate at which iron oxidizes from Fe^{2+} to Fe^{3+} is dependent on pH. The rate of this reaction can be increased 100-fold by raising the pH by one unit. Processes involving this reaction, therefore, have to be optimised by offsetting any reduction in retention time, and hence plant size, against the cost of increased reagent usage.

The method used to precipitate the dissolved metals from the minewater is dependent not only on the required effluent quality but also on the optimisation of the chemical reactions to achieve the most cost-effective method of treatment.

11.3.1.2 Hydroxide Precipitation

A variety of alkaline substances have been considered to establish their suitability for neutralising the Wheal Jane minewater as detailed in Table 11-3.

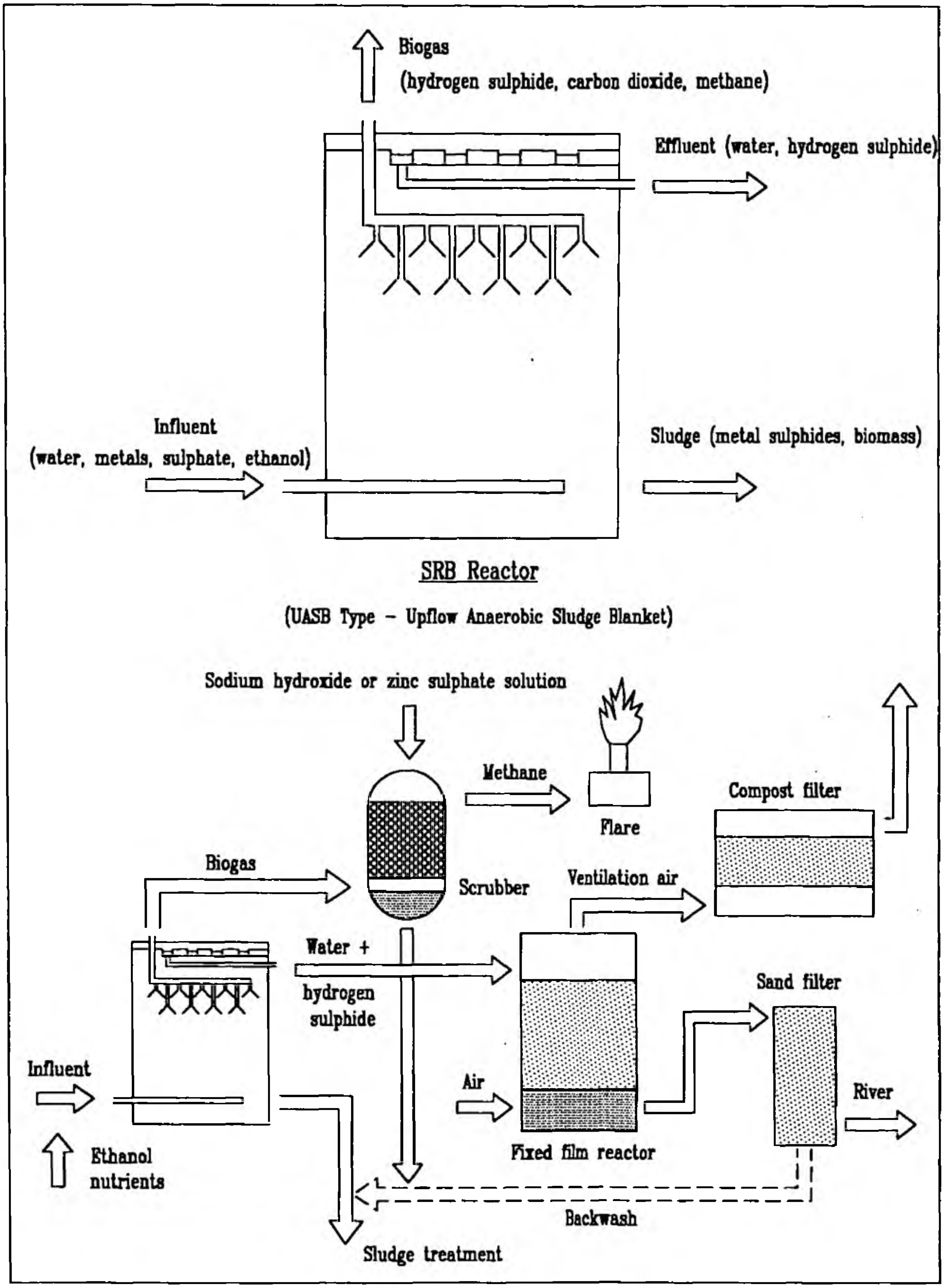
Table 11-3 : Alternative Hydroxide Dosing Materials

Material	Comparative Cost[1]	pH Capability	Comment	Price Comparison and Availability
1. Limestone	0.3	Inadequate	Only able to raise pH to 6-7 over long period of contact	Very cheap and widely available.
2. Calcium Hydroxide (Hydrated Lime)	1	Adequate	Forms loose hydroxide sludges of low density. (Difficult to dewater in a process plant environment)	Cheap.
3. Calcium Oxide (Quick Lime)	0.9	Adequate	Slaking equipment required. Slaking is an exothermic reaction.	Just cheaper than hydrated lime and available.
4. Sodium Hydroxide	2-3	Adequate	Handling difficulties	Expensive.
5. Magnesium Hydroxide	5	Adequate	Forms a larger particle size hence easier to further dewater	Very expensive.
6. P.F.A. (as an addition to Hydrated Lime)	0.3	Adequate	A constructive use of an industrial waste product will produce a predominance of carbonates rather than hydroxides. May import additional impurities to the system.	Very cheap, but complicates the dosing process. Could improve the physical properties of the waste sludge.
7. Cement Kiln Dust (as an addition to Hydrated Lime)	0.3	Adequate	A constructive use of an industrial waste product will produce a predominance of carbonates rather than hydroxides	As for P.F.A.
8. Proprietary Chemicals (several materials have been offered for testwork based on mixtures of 1-5 above)	4/5	Adequate	Most materials have been subjected to either bench scale or pilot testing and none have provided a major improvement in subsequent solid/liquid requirements	Expensive to very expensive.

[1] Expressed relative to hydrated lime.

Representative samples from each of the product groups shown in Table 11-3 have been subjected to laboratory testing. Each material has been compared with reference to cost, product characteristics and availability. This has resulted in the conclusion that the most appropriate method of neutralising the acidic minewater and forming metal hydroxides is by the use of either quick or hydrated (slaked) lime.

Figure 11.3 Basic Process Flow Diagram of SRB Plant



Although the cost per tonne of quick lime is cheaper than slaked lime, additional equipment is required on site to prepare quick lime. Consequently quick lime only tends to be economically attractive in the long-term.

With the possible exception of copper, the use of lime will enable the minewater to be treated to meet the EC Directive Water Quality Objective. The residual concentration of copper in minewater treated with lime varied between 12 and 27 μg/l, which was just less than the EC Directive Water Quality Objective limit of 28 μg/l.

11.3.1.3 Sulphide Precipitation

The dissolved metals also can be removed from the minewater by the formation of sulphides. A sulphate reduction plant has been built in Holland to treat some 60 l/s of groundwater contaminated with up to 250 mg/l of zinc and other metals by precipitation as sulphides. The process involves complex biochemical reactions between the sulphate and the dissolved metals contained within the contaminated water. A colony of sulphate reducing bacteria is established in a reaction vessel (Figure 11.3) within which the bacteria convert sulphate (SO_4) into hydrogen sulphide (H_2S).

The hydrogen sulphide gas is allowed to percolate up through a reaction vessel, designed to ensure that the gas is fully mixed with the inflowing minewater. Chemical reactions between the gas and the dissolved metals form sulphide metal compounds, such as iron pyrite. The reactions take place in a low oxygen environment similar to that achieved in a passive treatment plant anaerobic cell (see Section 10), and essentially reverses the oxidation process which occurred underground.

The precipitated sulphide sludge is separated from the treated minewater using conventional separation and dewatering processes.

The use of sulphate reducing bacteria (SRB) to treat metal contaminated minewater:

- Is technically proven, although not widely employed.

- Potentially advantageous in that sulphides have a lower residual solubility than hydroxide compounds.

- Possibly could be incorporated into a hybrid hydroxide/sulphide process to ensure that the residual copper concentrations are reduced well below the levels required for the EC Directive Water Quality Objective.

Sulphate reducing bacteria systems involve both higher capital and operating costs than hydroxide based precipitation processes. Details of the relative costs are contained in Section 11.7.

11.3.2 Selective Precipitation

In addition to the conventional precipitation/dewatering processes detailed above, the following technologies have been considered:

- Solvent extraction
- Electro-chemical extraction
- Resin ionic exchange
- Biosorption
- Biochemical extraction.

The above process systems have been developed primarily for use in the extraction of specific metals. The techniques are not considered applicable for blanket treatment of the Wheal Jane minewater as, in general, the processes:

- Are metal specific and not designed for blanket metal removal.
- Require subsequent treatment to recover the metals for disposal.
- Tend to require significant additional resources in the form of power, expert manpower and reagents.
- Are more expensive to build than conventional treatment routes. For example a solvent extraction plant has an estimated capital cost of £30 million.

Selective metal extraction is, however, potentially advantageous in the treatment of the Wheal Jane minewater, allowing the commercial recovery of the more valuable metals. Approximately 30% of the metal content within the minewater is zinc which potentially is both of sufficient market value and present in sufficient quantity to warrant selective extraction. In 1994 approximately 1000 t of zinc was deposited in the Clemows Valley Tailings Dam. The market value of this metal was of the order of £750 000, although the actual net revenue available would have been substantially less due to recovery costs.

No other metals are present in sufficient quantity to be of commercial value.

11.3.2.1 Zinc Recovery

A dewatered sludge sample from the existing treatment process was taken to the zinc smelting refinery in Avonmouth to ascertain possible revenue from the zinc. The smelter could not recover useful amounts of valuable metals and imposed a significant penalty because of the contaminants present. The smelter also generated a cost for a "synthetic" product assuming all of the iron had been removed. Even with the iron removed a penalty cost would be imposed because of contamination of the product with the other elements present in the minewater. Zinc recovery would only become viable if the zinc could be separated from the other contaminants.

Preliminary testwork was undertaken, using selective biochemical extraction methods, to examine possible process routes for the selective removal of each metal from the minewater. Theoretically Ferric iron (Fe^{2+}) can be separated from zinc (Zn), as Ferric iron is virtually insoluble above pH 3.0, whilst the pH must be raised to about 6.5 to ensure the precipitation of zinc. The work concentrated on raising the pH to approximately 6 to enable the precipitation of ferric iron without the co-precipitation of zinc. In principle the process involved:

- Raising the pH by the use of crushed limestone
- Oxidation of ferrous iron to ferric iron
- Precipitation and removal of the ferric iron
- Precipitation of the zinc and other metals.

Oxidation of ferrous to ferric iron can be achieved either chemically or biochemically. The rate at which chemical oxidation occurs is pH dependent. At pH 6 chemical oxidation takes place relatively slowly and may be more rapidly achieved biochemically.

Biochemical treatment using the *Thiobacillus ferro-oxidans* bacteria to achieve oxidation has been tested at pilot plant scale. Analysis of the precipitate recovered from the test apparatus contained 99% iron and 1% zinc, confirming that differential precipitation is feasible. The quantity of iron removed was, however, a relatively small proportion of the total iron loading put through the test cell indicating much larger cells would be required for complete iron removal. The technique therefore requires further research and optimisation before it can be considered viable on a large scale.

Significant additional capital costs would be incurred if a zinc recovery plant was adopted due to the need to provide separate solids separation and dewatering plants for the zinc precipitate and the remaining metalliferous sludge.

In addition the smelter indicated that the zinc concentrate would have a negative value unless effectively refined to remove not only the iron but also other contaminants such as arsenic and cadmium, Production of a zinc concentrate would therefore require the use of a relatively sophisticated process plant with operating costs in excess of the value of the zinc produced.

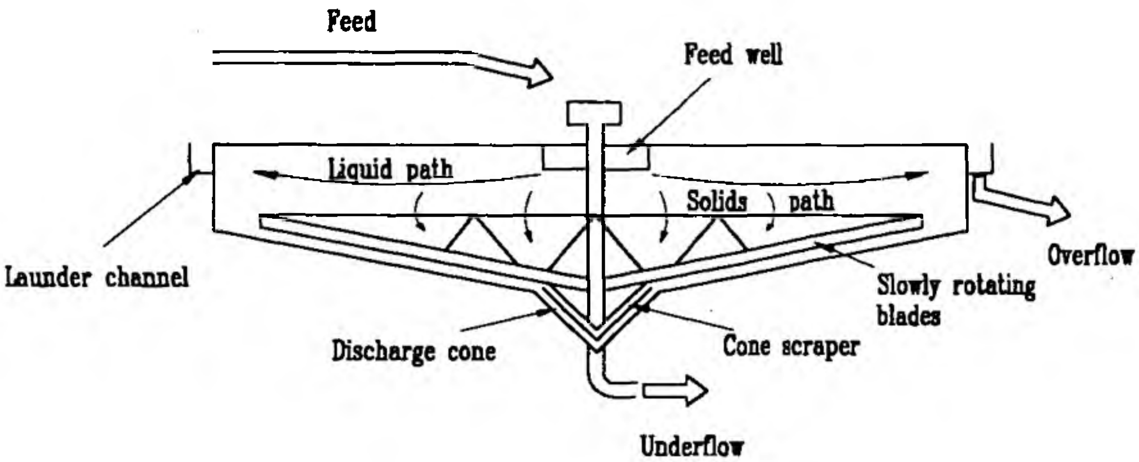
11.4 METAL PRECIPITATE/WATER SEPARATION

The second stage of the treatment process involves the separation of the water from the precipitated solids.

Depending on the physical properties of the precipitate, separation can be achieved by:

- Thickening.
- Modified Thickening (High Density Sludge).
- Hydrocyclones.
- Magnetic Separation.
- Flotation.

Figure 11.4 Typical Thickener/Clarifier Layout



11.4.1 Thickening

Thickening is a well established industrial process which is conventionally undertaken in a circular tank, as shown in Figure 11.4. The treated minewater is introduced into the centre of the tank from where the precipitated metals are allowed to settle to the base of the tank and are removed by a rotating rake to the underflow outlet. The clarified supernatant, which has a very low solids content, is decanted off via a weir into a launder channel located around the periphery of the tank.

The size of the thickener is dictated by the quantity of flow to be treated and the settling velocity of the metal precipitate. The settling velocity can be enhanced by the use of a flocculant to coagulate the particles, thereby enabling a given flow to be treated in a significantly smaller tank.

As part of the existing treatment system, a long chain anionic polyelectrolyte flocculant is added at a rate of 3 mg/l of treated minewater to enhance the settling rate of the metalliferous sludge within the Clemows Valley Tailings Dam (see Section 4). A similar flocculant would be used in any active treatment system involving the use of a thickener. Cationic and non-ionic flocculants have been investigated, by specialist flocculant suppliers, but are not considered to be of any additional benefit.

Field trials carried out using a small 3.4 m diameter thickener have demonstrated that the solid concentration (by weight) can be increased from 0.4% in the treated minewater to 3% in the thickener underflow (an eight-fold reduction in volume). The use of thickeners to treat 300 l/s of minewater would result in approximately 262 l/s of clarified water and 38 l/s of metalliferous sludge.

This technology is applicable to the Wheal Jane minewater project and it is anticipated that a full-scale thickener would produce a slightly more dense underflow containing up to 5% solids by weight.

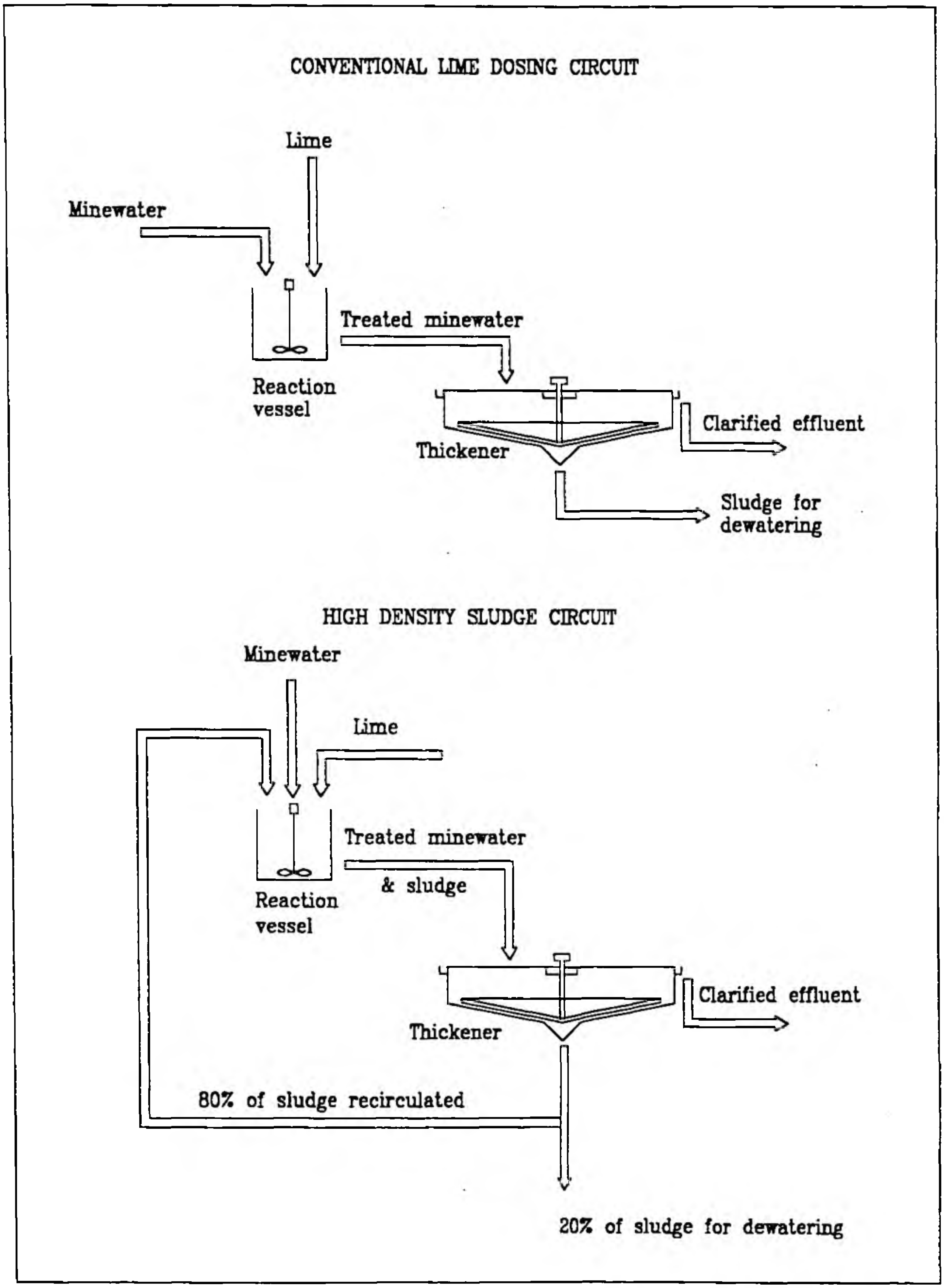
11.4.2 Modified Thickening - High Density Sludge

The concentration of solids in the underflow can be raised from 3% to approximately 20% (by weight) by recirculating about 80% of the underflow sludge back into the reaction vessel as shown schematically in Figure 11.5.

The recirculated sludge forms nuclei on to which further metalliferous sludge precipitates to form a compact dense particle which both settles rapidly and is relatively easy to dewater. Crystal growth occurs in layers and, in section, is similar in appearance to the layers found in an onion.

A number of commercial organisations offer treatment systems based on this technology and have plants in operation worldwide treating both similar qualities and quantities of water. One such plant is operating in the USA treating 60 l/s

Figure 11.5 Lime Dosing Precipitation - Schematic Flowsheet



of minewater with a dissolved metal content of 200 mg/l and a pH of 3.5 (Ref. 1).

Pilot plant trials have demonstrated that the technique can increase the underflow concentration from the 3 to 5% achieved in a conventional thickener to 20%. For a 300 l/s treatment plant, such a process would result in about 294 l/s of clarified water and 6 l/s of sludge (i.e. a 50-fold reduction in the volume). In addition, the system should allow a reduction in the quantity of lime used as recirculation ensures prolonged contact between the lime and metals. The potential reduction in reagent costs however must be offset against the additional pumping required to recirculate the sludge.

This technology is both proven and potentially offers the most effective method of treating Wheal Jane minewater. Full details of the results from the pilot plant testwork are contained in Table 11-4.

11.4.3 Hydrocyclones

Theoretically precipitate/water separation can be achieved by means of a hydrocyclone, as shown in Figure 11.6. A hydrocyclone consists of a cylindrical body with a conical base. The treated minewater is introduced tangentially to form a vortex, within which high acceleration forces occur. The solids are forced by centrifugal action to the outside of the hydrocyclone and are removed via the underflow outlet. The majority of the water is discharged via the overflow and typically contains a small residual amount of solids. Hydrocyclones are used extensively in the mining industry to achieve solids separation by either size or density and are used to separate the coarse and fine tailings that are fed into the Clemows Valley Tailings Dam.

Pilot plant hydrocyclone trials revealed that:

- The flocculated particles were not sufficiently strong to withstand the high shear forces developed within the cyclone.
- Significant quantities of solids appeared in both the overflow and underflow due to the fine particle size.
- the addition of more flocculant did not beneficially improve the performance of the hydrocyclone.

Consequently, it is considered that hydrocyclones are not suitable for minewater solids separation at Wheal Jane.

11.4.4 Magnetic Separation

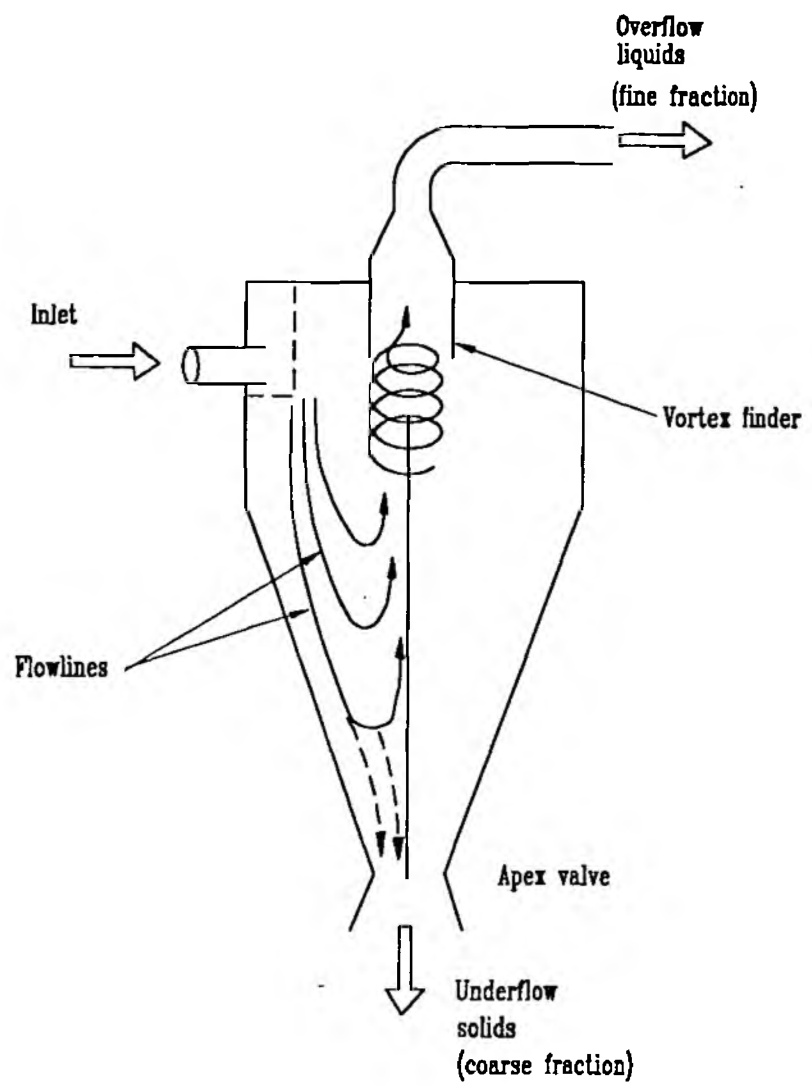
The metalliferous sludge comprises approximately 12% iron and, therefore, it should be feasible theoretically to achieve solid/water separation magnetically.

Table 11-4 : Results from High Density Sludge Pilot Plant Trials

Sample	pH	Iron mg/l	Manganese mg/l	Aluminium mg/l	Cadmium mg/l	Copper mg/l	Lead mg/l	Zinc mg/l	Calcium mg/l	Arsenic mg/l	Suspended Solids mg/l	Total Solids % by weight
Minewater feed 22/12/94	2.8	321	10.6	48.4	0.14	1.64	0.15	252	-	4.5	103	-
Minewater feed 3-7/1/95		278		38.1	0.14	1.82	0.13	74.1				
Effluent 3-7/1/95		17.7		1.8	<0.01	0.04	<0.04	3.21			131	
Effluent filtered 3-7/1/95		<0.6		0.3	<0.01	<0.02	<0.04	0.11				
Minewater feed 12-19/1/95		3.18		38.5	0.14	1.68	0.16	72.4				
Effluent 12-19/1/95		10.3		1.4	<0.01	0.05	<0.04	3.19			44	
Effluent filtered 12-19/2/95		<0.06		0.3	<0.01	<0.02	0.04	0.14				
Minewater feed 24/1/95	3.3	315	7.69	37.1	0.13	1.56	0.16	115		3.51	18	
Effluent am 27/1/95**	8.3	3.82	1.57	0.66	2.05*	49.3* T	<2.5*	1.52		33.4*	45	
Effluent am filtered 27/1/95**	7.9	0.104	1.91	0.241	0.73*	12.6* D	<2.5*	0.121		<1.0*	<5	
Effluent pm 27/1/95***	9.2	3.39	0.284	1.07	1.61*	67.4* T	<2.5*	1.37		22.5*	34	
Effluent pm filtered 27/1/95***	9.2	0.184	0.32	0.748	<0.5*	21.4* D	<2.5*	0.095		1.6*	<5	
HDS Sludge	8.9	189 850	4 630	41 900	75	1 660	57	78 400	56 900	1 810		27.8

* Analytical results reported as ug/l
** Lime dosing pH 9 - 9.2
*** Lime dosing pH 9.5 - 10
T Total
D Dissolved

Figure 11.6 Hydrocyclone



Laboratory trials using a 0.8 Tesla high intensity magnetic separator revealed the technique to be unsuitable due to the low magnetic susceptibility of the combined sludge.

11.4.5 Flotation

Flotation techniques rely on the use of air bubbles and hydrophobic organic compounds to effect separation. The hydrophobic compounds are chemically attached to the surface of the particles to be removed. On the introduction of air into the minewater the hydrophobic compounds become attached to the rising air bubbles dragging the solid particles to the surface.

Final separation is achieved mechanically by a scraper which continuously removes the bubbles and attached solids.

The technique of flotation is extensively used within the mining industry to achieve the separation of finely ground ore minerals from the accompanying waste rock (tailings). However, pilot plant testwork on the Wheal Jane minewater has revealed that the technique is not capable of effectively separating the metal precipitate for the treated minewater.

11.4.6 Preferred Water/Solids Separation Method

Primary water/solids separation can be achieved most effectively using a thickener combined with a high density sludge recirculation system. Further studies are required, however, to confirm the most appropriate type of thickener and to optimise the size.

11.5 SLUDGE DEWATERING

The volume of the waste product arising from the metal precipitation/water separation process can be further reduced by dewatering the resultant metalliferous sludge. The degree of dewatering achieved is dependent primarily on the resources input into the process.

For the purposes of the Wheal Jane study, the following dewatering techniques (listed in order of increasing resource input) have been considered:

- Rotary or horizontal vacuum filters
- Continuous pressure belt presses
- Centrifuges
- Frame and plate presses

These devices are illustrated diagrammatically on Figures 11.7 to 11.10. Details of the relative performance of each technique are summarised in Table 11-5.

Figure 11.7 Rotary Vacuum and Horizontal Vacuum Fliter Presses

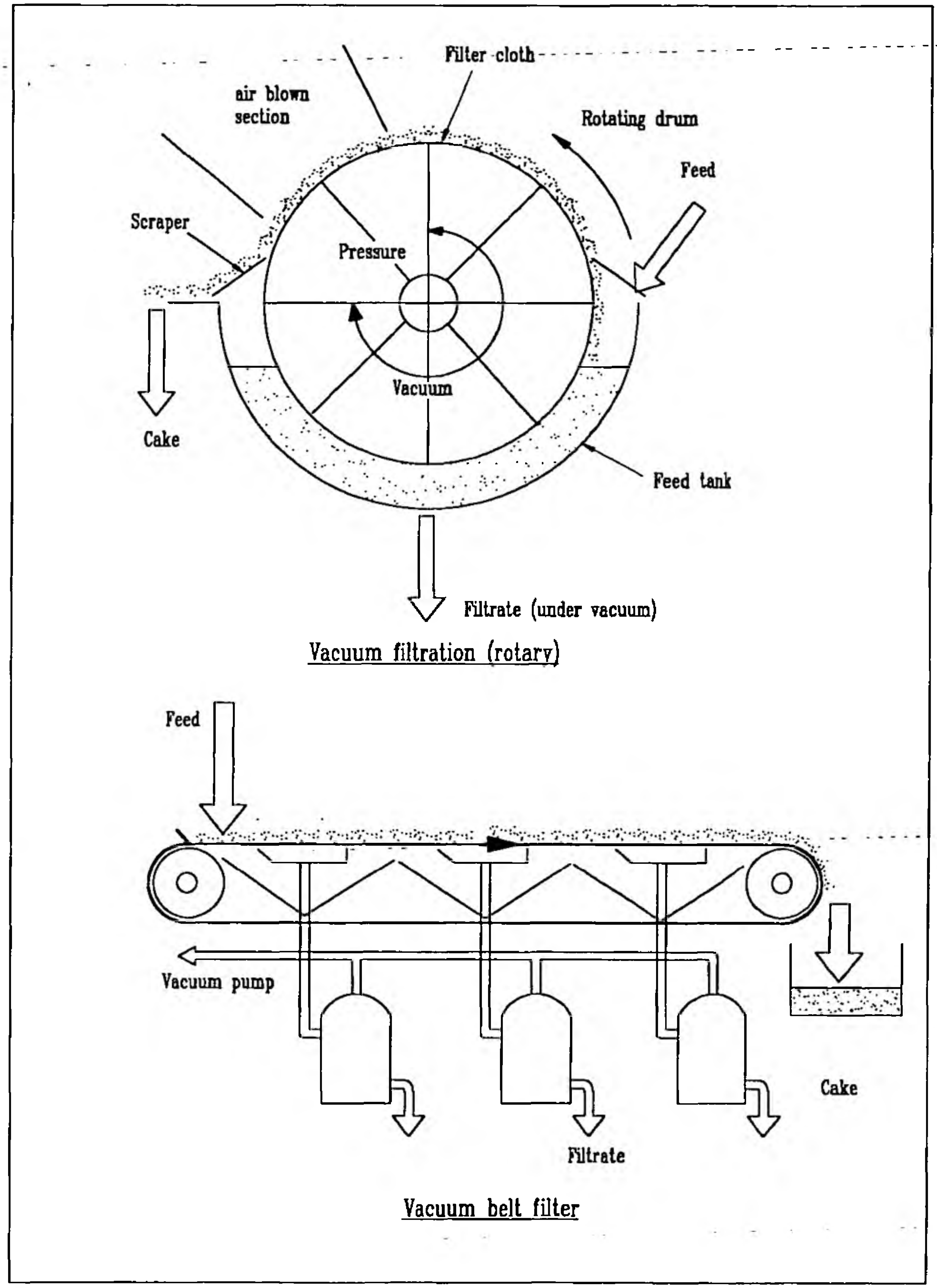


Table 11-5 : Summary of Sludge Dewatering Options

Technique	Operation	Resultant sludge concentration by % weight		Relative Price %	Labour Requirement	Additional Costs (e.g. Power)
		Feed from Conventional Thickeners (at 5%)	High Density Sludge (at 20%)			
Rotary vacuum filter	Continuous	17-20	30-35	100	Low	Medium
Continuous press	Continuous	22-24	35-40	100	Low	High
Centrifuge	Continuous	22	35-40	100	Low	High
Frame and plate	Batch	30	45-50	150-200	High	Low

11.5.1 Rotary and Horizontal Vacuum Filtration

Rotary vacuum dewatering is achieved by means of a slowly rotating cylindrical drum covered with a filter cloth as shown in Figure 11.7. Internal dividers within the drum enable the dewatering and removal of the deposited sludge in two stages:

Stage 1: The lower half of the drum is immersed in a trough containing the thickened sludge. A vacuum is applied pulling the water into the drum leaving the solids on the filter cloth (filter cake).

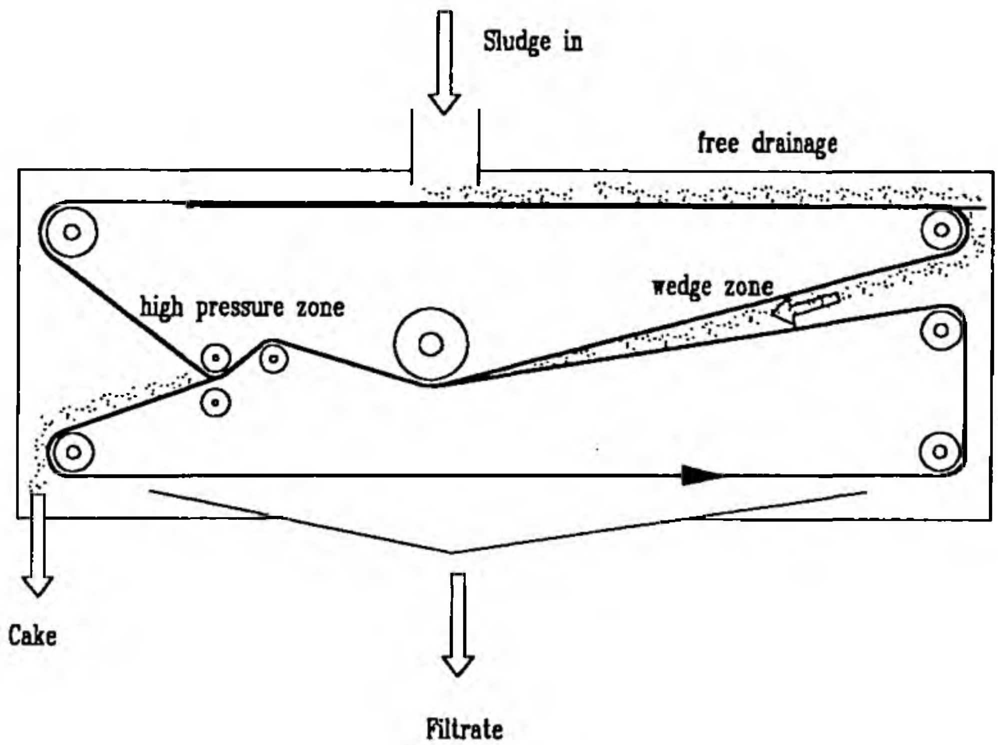
Stage 2: The dewatered cake is removed from the filter cloth by the application of compressed air and the use of a scraper.

The process is undertaken continuously as the drum slowly rotates, first through the trough of thickened sludge and then across the pressurised zone where the cake is removed.

Performance comparisons indicate that sludge concentrations of between 17% and 20% by weight can be achieved by treating the underflow from an ordinary thickener and between 30-33% when treating the product from a high density sludge system.

Horizontal belt filtration comprises similar technology to rotary vacuum filtration and is applied to a continuous slowly moving filter cloth generally carried on a perforated rubber belt. Normally the method is used to dewater relatively coarse material and, therefore, is not considered appropriate for minewater treatment because of the particle sizes involved.

Figure 11.8 Continuous Pressure Dewatering Machine



11.5.2 Continuous Press

Continuous pressure dewatering machines, as shown in Figure 11.8, typically involve three stages:-

- Free drainage.
- Slowly increasing pressure in a belt contained "sandwich" forming a wedge zone.
- A final high pressure dewatering zone.

The filter cake product is more manageable than that from a centrifuge or rotary filter and flocculant consumption is normally lower. However machine reliability and maintenance costs are generally less favourable.

The product is friable and more manageable than that from a rotary vacuum filter or centrifuge.

11.5.3 Centrifuge

The metalliferous sludge can be dewatered successfully using a scroll centrifuge (Figure 11.9). The high centrifugal forces created within the centrifuge, force the solid particles outwards towards the inner face of the rotating centrifuge bowl. The solids and some entrained water are removed by means of a spiral scraper rotating at a marginally slower speed than the bowl, whilst the water removed from the sludge is decanted via a separate discharge pipe. The geometry of the bowl determines the final effluent quality and the final sludge moisture content. Increasing the length of the "beach zone" will tend to reduce the moisture content of the cake and may be beneficial at Wheal Jane in minimising sludge volumes.

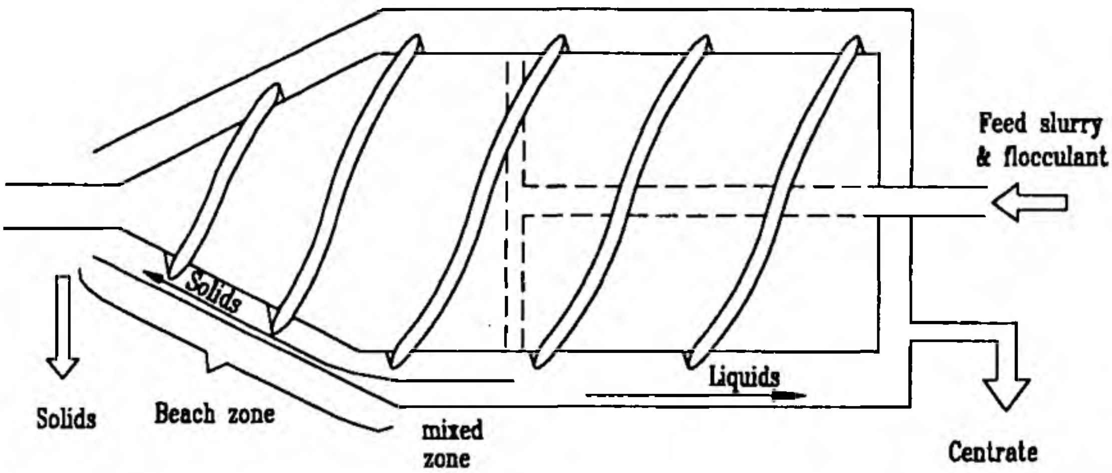
Field trials undertaken at Wheal Jane using a small-scale scroll centrifuge have demonstrated that the solids concentration of the metalliferous sludge can be increased from the 3% achieved by a conventional thickener to 22%.

Although a centrifuge system has not been tested on the more concentrated metalliferous sludge produced from the high density sludge separation process, it is envisaged that sludge concentrations of approximately 40% by weight could be attained. Further field trials are recommended to confirm this value.

11.5.4 Frame and Plate

In this process the solid/liquid mixture is pumped into the machine and contained within porous filter cloths where pressure is applied, either hydraulically or by mechanical screw, to force the water out of the sludge. When the drainage rate reduces to a predetermined limit, the pressure is released, the machine unloaded, and the filter cloths washed. Typically a machine would be loaded for 5-6 hours and take one hour to unload and wash. The very high mechanical pressures used

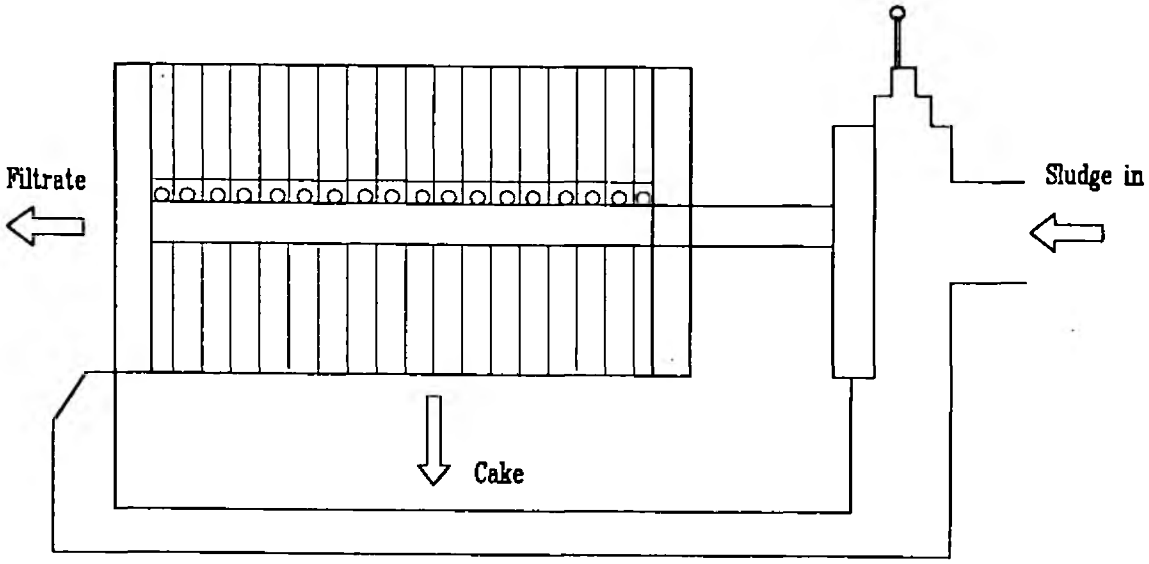
Figure 11.9 Scroll Centrifuge



Typically, case can rotate at 3000 to 5000rpm
inner scroll at just a few revs slower (5 to 20rpm)

(CONTINUOUS SOLID BOWL SCROLL CENTIFUGE)

Figure 11.10 Frame and Plate Filter Press



Hydraulic piston or screw compresses the press, filtrate passes through the filter cloth into plates and is removed. Cake remains in the frame until full, when it is disassembled and washed.

by these machines produce a very dry sludge which would be a major advantage if off-site disposal is necessary.

A sludge product containing between 25-30% dry solids can be achieved by treating the underflow from a normal thickener and between 45-50% from a high density sludge process.

11.5.5 Dewatering Equipment Choice

The choice of dewatering system adopted for the Wheal Jane minewater project is dependent on the final disposal point. Reducing the volume of sludge for deposition by the use of dewatering will increase the life of the depository or allow the waste product to be transported at lower cost. The range of unit disposal volumes associated with each dewatering option is shown in Table 11-6.

Table 11-6 : Dewatered Sludge Volumes

Technology	Sludge Dry Density (t/m^3)	Typical volume per tonne of metalliferous sludge	
Existing treatment	0.23	4.3 m^3/t	Clemows Valley Tailings Dam
Rotary vacuum	0.23	4.3 m^3/t	Conventional Thickener
Centrifuge	22	3.9 m^3/t	Conventional Thickener
Continuous press	22	3.9 m^3/t	Conventional Thickener
Frame and plate	0.30 (max 0.37)	3.3 m^3/t	Conventional Thickener
Frame and plate	0.64 (max 50)	1.6 m^3/t	High Density Sludge Circuit

11.6 TERTIARY TREATMENT

Depending on the Water Quality Objective adopted, a tertiary treatment stage may be required to consistently achieve the required effluent standard. Tertiary treatment/effluent polishing is frequently carried out in the preparation of potable water, by either "sand filtration" or "chemical polishing". The discharge quality following the precipitation and separation stages is better than the predicted water quality of the Carnon River (see Sections 6 and 7) so it becomes increasingly less beneficial to clean this water.

11.6.1 Sand Filtration

The effluent water from the solids separation stage of an active treatment plant should have an acceptably low suspended solids content. However, on occasions some of the precipitated solids may remain suspended in the effluent, necessitating removal by filtration. Adequate filtration can be achieved using a sand filter which would remove the solids, thereby ensuring that a consistent effluent quality is achieved.

Various sand filter systems are potentially applicable at Wheal Jane for the tertiary treatment of the water to be discharged to the river. The filter system would require intermittent backwashing to remove the collected solids and these would be recycled to the plant feed.

Sand filters are standard technology in the water treatment industry and the units are relatively cheap. Installation of a sand filter system would also beneficially provide a holding facility to retain the treated effluent temporarily in the event of a treatment system failure.

11.6.2 Chemical/Solid Polishing

Chemical polishing can be achieved using either activated carbon or alumina to extract residual metals from the treated minewater. The capital cost of a 300 l/s polishing process has; based on the results of field trials, been estimated at approximately £30 million. Such technology is therefore extremely expensive and would be required only to meet the most stringent standards.

11.7 ECONOMIC APPRAISAL

Cost estimates have been prepared to establish both the preferred plant site and the most cost-effective treatment process. In particular estimates have been produced for:-

- Continued operation of the Existing Treatment System.
- Active treatment either using conventional lime-dosing or a High Density Sludge System (HDS system).

Estimates have also been prepared for the three possible active plant locations identified in Section 8:-

- Wheal Jane mine site.
- Carnon Valley Tailings Deposits.
- Point Mills site.

11.7.1 Capital Costs

Detail cost estimates have been prepared for various options, based on a modular plant located both on the existing site and at the two other potential plant location sites. The costs of these options are summarised in Table 11-7 which indicates that some 85% of the plant costs have been obtained from quotations or approved industry practice.

Table 11-7 : Active Treatment - Plant Stream Capital Costs

Component	Qty	Location[1] Module Size (l/s) Price Base	Costs (£'000s) A 140 HDS[2]	A 140	B 140	A 170	A 190
Relocate Lime Dosing Plant	1	Est	0	0	80	0	0
Lime Feed Line	1	Est		6	6	6	6
Raw Water Feed Line	1	Est		6	6	6	6
Agitated Mix Tank	1	Est		110	110	120	140
Flocculant System	1	Est		11	11	11	11
Flocculant Feed Pump	1	Est		5	5	5	6
Thickener	1	Quotation	1385	385	385	410	450
Launder Channels	1	Est		11	11	11	12
Sand Filter	2	Quotation		176	176	200	220
Backwash Pumps	1	Est		12	12	15	15
Centrifuge and Ancillaries	1	Quotation		330	330	360	400
Flocculant System	1	Est		11	11	11	12
Cake Conveyor	1	Est		6	6	6	6
Cement Stabilisation	1	Quotation	200	200	200	200	200
		Sub Total (1)	1 585	1 269	1 349	1 361	1 484
Overheads/Extras	%						
Electrics (inc. generator)	13	CESMM 3	206	165	175	177	193
Inst/Control/Automation (ICA)	6	CESMM 3	95	76	81	82	89
Civils (exc. thickener)	20		317	254	270	272	297
Pipework and Valves	5		79	63	67	68	74
		Sub Total (2)	2 282	1 827	1 943	1 960	2 137
Design/Project Management	15		343	273	287	290	323
STREAM TOTAL			**2 625**	**2 100**	**2 230**	**2 250**	**2 460**
(Equivalent Cost for High Density Sludge Process)						2 820	3 075

[1] A - Mine site : B - Point Mills or Lower Valley
[2] High Density Sludge

The capital costs are cheapest for a plant located at the minesite. This is because a significant proportion of the hardware is already in place (pumps and lime dosing equipment) and the development costs for the rest of the plant are moderate.

11.7.2 Operational Costs

The operating costs derived for the Existing Treatment System have been used to provide indicative operating costs for active treatment. These costs are summarised in Table 11-8.

Table 11-8 : Existing Treatment System Unit Operational Costs

	1994 Average Costs (p/m^3 water treated)[1]
Power	1.8
Maintenance	1.2
Flocculant	0.6
Lime	5.8
Sundries	1.8
Disposal[2]	4.0
Total	15.2

[1] Prices based on average treatment flow rate of 155 l/s. Some items are not directly proportional to flow rate.

[2] Disposal cost based on existing treatment and disposal, with tailings, to CVTD.

The actual disposal cost will depend upon the sludge density achieved and would be adjusted accordingly.

To assess the relative operating costs of each potential active treatment plant site, it has been necessary to estimate the associated pumping costs, as summarised in Table 11-9. These pumping costs are offset against the capital costs mentioned above.

Table 11-9 : Active Treatment Plant Location Estimated Annual Power Costs

		Annual Power Costs (£/year)		
	Average Flow Treated	Mine Site	Carnon Valley	Point Mills
Existing Treatment System	155 l/s	61 700	14 300	9 900
No Deterioration 50% non compliance	170 l/s	66 000	16 000	10 800
No Deterioration and North Sea Commitments 5% non compliance	190 l/s	73 700	17 100	11 900

The cost estimates outlined above have been used to build-up costs for the various treatment options under consideration, as shown in Table 11-10.

Table 11-10 : Active Treatment Cost Comparison
(for achieving 95% non-compliance with No Deterioration and North Sea Commitments Objectives)

			Approximate Costs (£ million)[1]	
Process	Sludge Solids Content	Dry Density (t/m^3)	Capital Cost	Annual Operating Costs with On-site Disposal
Existing treatment system	20%	0.23	0	0.81
Precipitation + centrifuge	25%	0.30	4.4	0.75
Precipitation + frame and plate	30%	0.37	4.4	0.71
Precipitation (high density)	45%	0.64	5.4	0.64
Biochemical Extraction	25%	0.30	25	2
Sulphate Reducing Bacteria	25%	0.30	12	1.2

[1] Installed capacity of 300 l/s and average treatment rate of 190 l/s

Table 11-10 indicates that the Existing Treatment System is the most cost-effective option whilst storage is available within the Clemows Valley Tailings Dam.

Table 11-11 : Active Treatment - Cost Summary

Projected Active Costs		Non-Compliance	Current Operating Flow	No Deterioration 50%	No Deterioration 5%	North Sea Commitments 5%	EC Directive (for comparison only)
Treated Flow	Maximum	l/s		210	300	300	1500
	Average	l/s	155	170	190	190	800
Capital Cost		£m	2.82	3.40	5.44	5.44	20.02
Annual Operating Cost		£m/yr	0.55	0.59	0.64	0.64	1.16
Discounted Capital and Operating Costs (to present day at 6% pa)							
	5 years	£m	5.14	5.89	8.14	8.14	24.91
	10 years	£m	6.87	7.74	10.15	10.15	28.56
	25 years	£m	9.85	10.94	13.62	13.62	34.85
	50 years	£m	11.49	12.70	15.53	15.53	38.30
Existing Treatment Costs							
Annual Operating Cost		£m/yr	0.75	0.78	0.81	0.81	
Discounted Operating Cost over 5 years		£m	3.16	3.29	3.41	3.41	

Notes: Costings are for Active Treatment Plant located on the mine site.

Dewatered sludge deposited to Clemows Valley Tailings Dam (at 45% solids content except the existing treatment system which achieves a 20% solids content)

11.7.3 Discounted Costs

The capital and annual operating costs from Sections 11.7.1 and 11.7.2 have been combined and used to assess the relative merits of the following options as summarised on Figures 11.13 to 11.16:

- Existing vs Active plant treatment over a five year period - this being the assumed life of Clemows Valley Tailings Dam.
- Capital and operating costs for the different plant site locations and the "No Deterioration" and "North Sea Commitments" Objectives over project lives of 10, 25 and 50 years.
- Indicative costs for treating Wheal Jane, County Adit, the Carnon River at Twelveheads and Hick's Mill Stream to achieve EQS iron concentrations (for comparative purposes only).

The discounted costs for each scheme are summarised on Table 11-11.

11.8 PREFERRED TREATMENT SYSTEM

The technical and financial evaluations detailed in the above sections revealed that the preferred active treatment route is:

- Continued operation of the existing treatment system whilst storage is available within the Clemows Valley Tailings Dam for the deposition of aqueous sludge.
- Active treatment using lime to form a hydroxide precipitate using either a conventional treatment system or the high density sludge process.
- Sludge/water separation using thickeners.
- Sludge dewatering using either a centrifuge for on-site sludge storage or a frame and plate filter press for off-site disposal.

Outline flow diagrams for the conventional lime dosed and high density sludge treatment systems are shown in Figures 11.11 and 11.12 respectively.

Figure 11.11 'Conventional' Lime Dosing & Dewatering

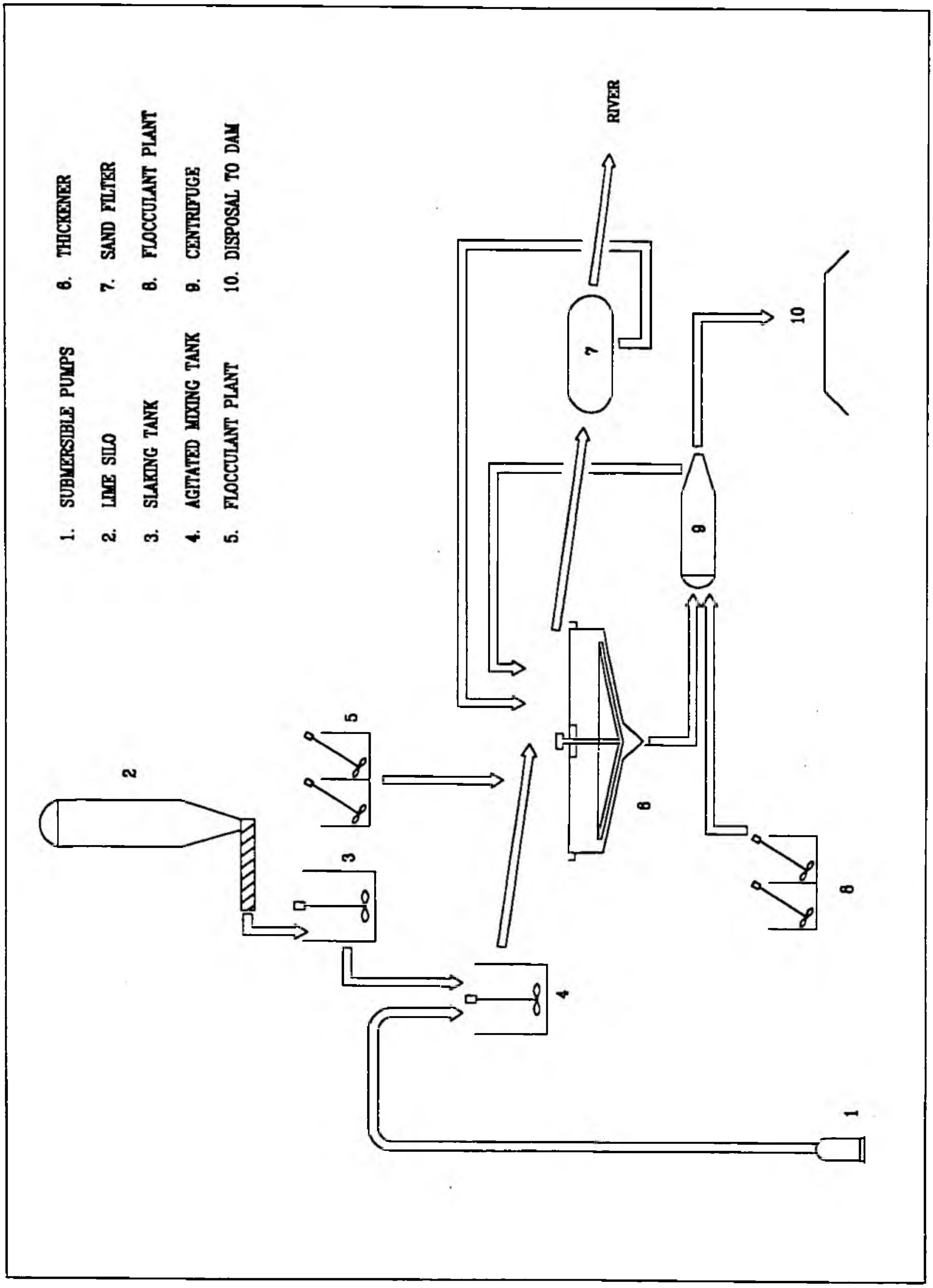


Figure 11.12 High Density Sludge - Typical Flowsheet (Preferred Option)

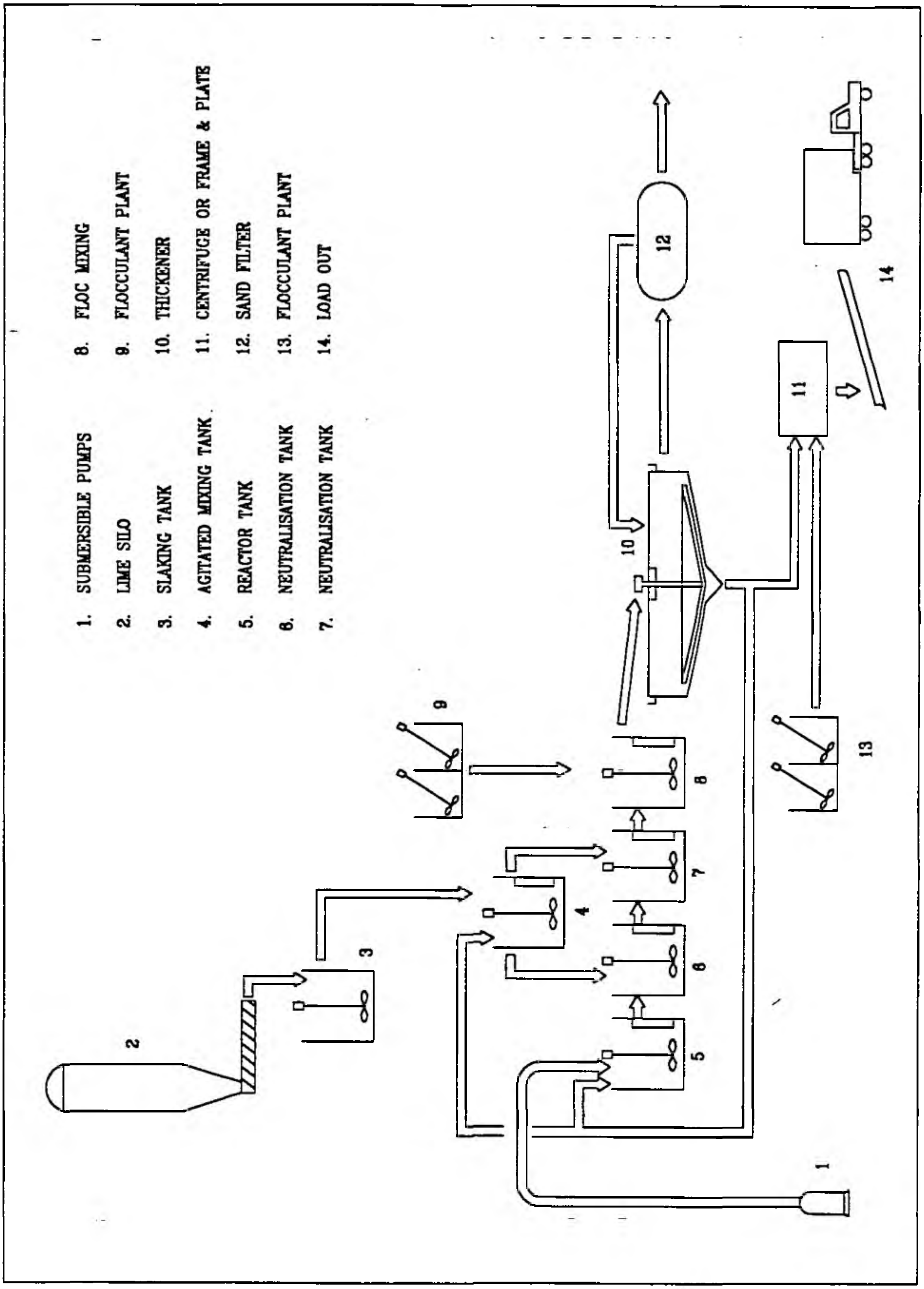
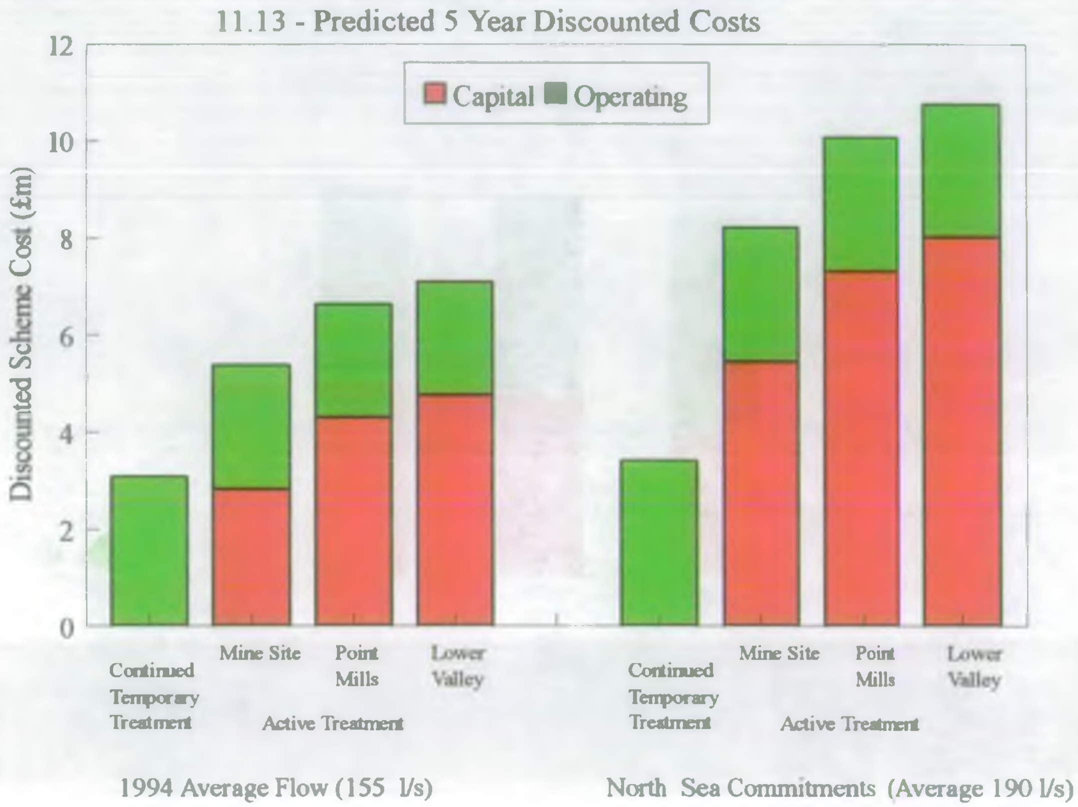


Figure 11.13 & 14 Temporary and Active Treatment Options



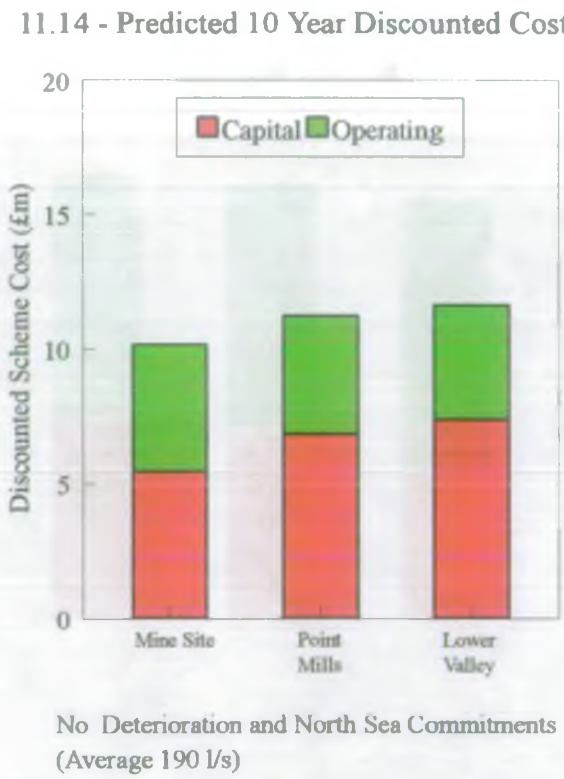
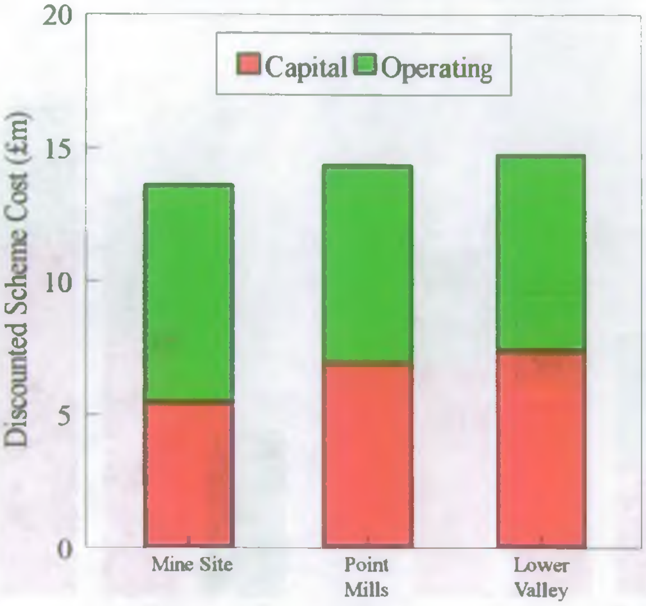


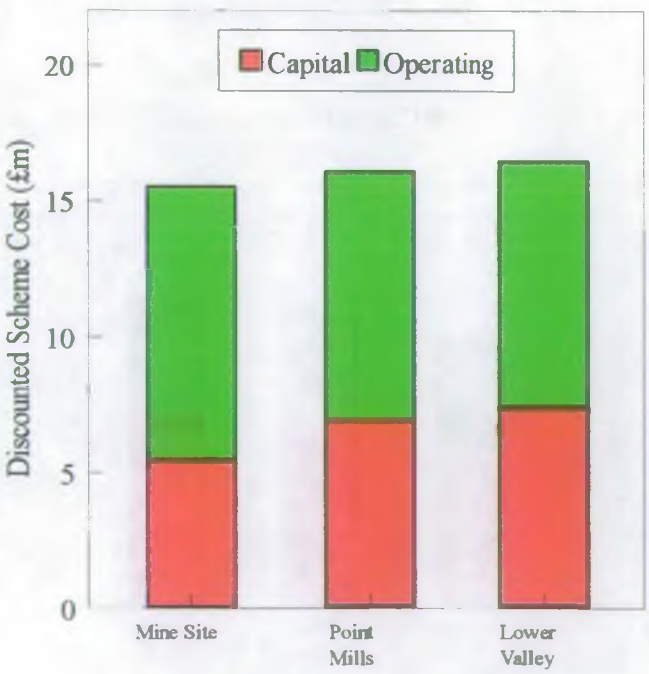
Figure 11.15 & 16 **Active Treatment Options**

11.15 - Predicted 25 Year Discounted Costs



No Deterioration and North Sea Commitments
(Average 190 l/s)

11.16 - Predicted 50 Year Discounted Costs



No Deterioration and North Sea Commitments
(Average 190 l/s)

11.9 CONCLUSIONS

The main conclusions from the assessment of active treatment options are:-

- The Existing Treatment System is the cheapest option whilst the Clemows Valley Tailings Dam is available for the clarification of the treated minewater.

- The choice of active treatment system is dependent on the available sludge disposal site. Sludge volumes can be minimised by use of the high density sludge process combined with frame and plate filtration.

- The minesite is the cheapest location for an active treatment plant, both in terms of capital cost and discounted costs over various project durations.

- A modular active treatment plant is considered to be beneficial as the system can be adapted to cope with changes in:

  - flow
  - metal concentrations
  - legislation.

11.10 ACKNOWLEDGEMENTS

Thanks are expressed in particular to the following companies, and to all the other companies who have provided information for this report.

Tetra Europe	Allied Colloids
Biwater	South Crofty
Biffa	Camborne School of Mines
Brittania Zinc	Pacques
Mozley	Davy International
ECC International	Lakos
Alcan	Dorr Oliver
Blue Circle	Boxmag
National Power	Beaver Engineering
Alfa Laval	Keeco
Edwards & Jones	

11.11 REFERENCES

(1) Engineering and Mining Journal, September 1994, pages 25-30.

12

12. SLUDGE DISPOSAL

CONTENTS

12.1 OBJECTIVES

The existing treatment system results in the formation of metal hydroxide precipitates and relatively clean effluent water for release to the river. The precipitated solids are deposited, as a metalliferous sludge, into the Clemows Valley Tailings Dam (CVTD). Sludge disposal accounted for nearly 50% of the operational cost of the existing treatment system during 1992 but reduced to about 30% in 1994 as a result of the declining minewater metal concentrations. It is, therefore, important to minimize sludge disposal costs:

- In the short term by reducing the volume of sludge produced.
- In the long term by formulating a sludge disposal strategy that complies with accepted good practice for waste disposal.

The following sub-sections describe the main characteristics of the waste material produced by alternative methods of treatment, reviews the legal framework for waste disposal, considers disposal sites both on and off the minesite, and concludes with an economic appraisal of the options considered.

12.2 WASTE CHARACTERISATION

The nature of the waste product is dependent upon the treatment process employed. All waste disposal is regulated under various legislation as discussed in more detail in Sections 12.3 and 12.4. In particular, the legislation is concerned with the containment of waste in a manner which minimises the long-term environmental impact. The degree of containment required is dependent upon both the chemical form and the physical properties of the waste and therefore it is necessary to characteristic the Wheal Jane metalliferous sludge in terms of these properties.

The waste arising from treatment of the minewater has been characterised under the following headings:

Chemical form	- The chemical form and constituents of the product.
Physical characteristics	- The physical properties, volume and production frequency.

12.2.1 Chemical Form and Constituent Elements

The constituents of the metalliferous sludge will be determined by the elements present in the minewater and the process route adopted for water treatment.

Table 12-1 shows the average metal concentrations in the minewater at Wheal Jane for the period October, 1993 to September, 1994. Whilst this table is not exhaustive it demonstrates the wide range of metals present and allows the following broad conclusions to be made:

- the resulting sludge will contain mainly iron and zinc products, zinc being classified as a List II substance under EC Directive 80/68/EEC;
- it will also contain other metals including cadmium, a "Red List" and List I substance and arsenic and copper, both List II substances under the above EC Directive.

Table 12-1 : Typical Minewater Metal Concentrations (Wheal Jane No. 2 Shaft)

Determinand	Wheal Jane
Average Flow	155
Arsenic	8.6
Cadmium	0.085
Copper	1.12
Iron	238
Manganese	8.9
Zinc	109

Note: All values in mg/l (except flowrate in l/s)
Data period - October, 1993 to September, 1994

The form of the metalliferous sludge produced will be dependent on the type of treatment process adopted and this will determine the disposal environment required for long term storage.

The different forms of waste that may arise together with the required disposal environments are listed in Table 12-2 below. If the environmental conditions were changed then the metals may become remobilised by going back into an aqueous solution.

Table 12-2 : Waste Disposal Summary

Chemical Form	Process Type	Preferred Disposal Environment
Hyroxides	Aerobic cells Lime Dosing (Temporary and Active treatment)	Controlled pH (Alkaline)
Sulphides	Anaerobic cells SRB	Oxygen free (Anaerobic)
Carbonates	Bio-Remediation	Controlled pH

SRB - Sulphate Reducing Bacteria

The existing treatment system and the preferred method for active treatment (Section 11) result in the formation of a hydroxide sludge. Consequently the following sections of this report relate principally to hydroxide sludges, produced by either active treatment or passive treatment aerobic cells. Where appropriate comment has been made regarding the anticipated properties of the sulphide waste produced by passive treatment anaerobic cells.

12.2.1.1 Leachate Generation

Even when waste is stored within a contained waste facility some limited leaching will occur due to the infiltration of rainfall or consolidation of the waste sludge after placement. The quantity of leachate generated is governed by the physical characteristics of both the waste and the disposal facility in which the waste is stored (e.g. cell sizes, permeability of the capping material and waste etc). These aspects form the basis of the design of a new disposal facility.

Laboratory testwork has been undertaken on sludge samples generated by the addition of lime to the minewater to determine the likely chemical nature of any leachate generated by the waste. The waste sludge was tested using the German leachate test (DIN-38414) and an American test ("Toxicity Characteristic Leaching Procedure" - TCLP). Both tests involve mixing a known amount of the solid with distilled water (DIN) or a dilute acetic acid solution (TCLP), for preset periods. The DIN test was primarily developed as a cheap easily performed test for the characterisation of a leachate prior to the disposal of wastes. The TCLP test, on the other hand, was developed in order to model the organic acid environment that is common to most co-disposal sites and would tend, therefore, to give a more conservative result (since the dissolution of metals will generally increase with reducing pH).

Table 12-3 : Leachate Metal Concentrations from of Hydroxide Sludge

Concentration of metals following leachate testing					
	DIN 38414 (s4)				TCLP
	[1]	1st leach	2nd leach	3rd leach	
Final pH	9.5	8.14	8.34	8.29	5.23
Aluminium	<0.05	<0.39	<0.39	<0.39	<0.39
Arsenic	–	<0.54	<0.54	<0.54	<0.54
Cadmium	<0.0005	<0.01	<0.01	<0.01	0.753
Copper	<0.02	<0.01	<0.01	<0.01	1.80
Iron	<0.02	<0.06	<0.06	<0.06	0.92
Manganese	<0.02	0.625	0.159	0.149	33.1
Zinc	<0.02	0.035	<0.01	<0.01	–

[1] refers to total concentrations; all others dissolved
<denotes below the limit of detection
All values are as mg/l

The above table demonstrates that the amount of leaching that takes place is primarily a function of the pH and it can be seen from the TCLP results that higher concentrations of cadmium, copper, iron and manganese occurred due to the lower final pH.

12.2.2 Physical Characteristics

12.2.2.1 Existing/Active Treatment

Lime dosing of the minewater results in the production of a metalliferous hydroxide sludge which, at Wheal Jane, has a specific gravity of between 2.85 and 2.99 and a measured permeability of about 1×10^{-9} m/s (at a pulp density of 20%). This permeability is equivalent to a typical "clay" material and is similar to the maximum value often permitted for landfill clay lining and capping layers.

During the pilot trials hydroxide sludges were produced at various pulp densities as summarised in Table 12-4.

Table 12-4 : Sludge Descriptions for Different Pulp Densities

Sludge pulp density	Dry density (t/m^3)	Dewatering method	Description of sludge product
9.4%[1]	0.10	CVTD	Low density slurry (sludge only)
20-23%[2]	0.25	CVTD	Medium - high density slurry (sludge or tailings)
15-20%	0.20	Centrifuge	Highly gelatinous, very low shear strength
20-25%	0.26	Centrifuge	Gelatinous, low shear strength
20-25%	0.26	Centrifuge with cement stabilisation	Sets to form stiff crumbly material. Capable of supporting light machinery
45-50%	0.69	HDS & Frame/Plate	Stiff, crumbly, solid as brittle slabs, smears. Capable of supporting light machinery

[1] - Estimated for aqueous deposition (no tailings deposition)
[2] - Estimated from aqueous deposition with Mill tailings onto CVTD
HDS - High Density Sludge process (Section 11)

For each water quality objective, the quantity and concentration of the minewater to be treated has been determined (see Section 7) and hence the resultant mass of solids is known. The volume of sludge generated is solely a function of the pulp density achieved across the dewatering process. Table 12-5 shows the predicted quantity of sludge expected to arise by treatment, to achieve the "No Deterioration" and "North Sea Commitments" objective, of up to 300 l/s and via the various treatment options under consideration. A full description of the dewatering trials is included in Section 11. It should be noted that the pulp densities achieved are "actual" values obtained from site trials and have not been optimised. Optimisation of the plant performance by changing the many variables (such as flocculant type, quantity and dosing point and plant performance) should reduce the volume of sludge produced.

Table 12-5 : Quantity of Waste Sludge Arising

Method of dewatering adopted	Predicted Pulp Density		Volume
	% by weight	t/m³	cubic metres per year
Existing treatment system with co-deposition of mine tails into CVTD	20	0.23	20 000
Existing treatment system with disposal into CVTD without mine tailings	9.4	0.10	45 000 [1]
Active treatment with centrifuge dewatering	25	0.30	15 000
Active treatment with HDS process and frame&plate dewatering	45	0.64	7 000
Passive treatment - wastes from aerobic and/or anaerobic cells	30 (estimate)	0.37	12 000 [2]

[1] - Assumed deposited dry density is 0.1 t/m^3
[2] - Stoichiometric calculations suggest that the anaerobic cells will last about 25 years.

The volume and physical properties will determine how the depository is operated and what plant is used for waste handling. The material properties can be improved to some extent by stabilising the sludge. Cement addition, at between 1 and 5% weight of solids, will tend to increase the strength of the material and therefore allow machines to work on the surface of the depository, but may increase the permeability. The additional amount of metal leached as a result of any increase in permeability would, however, be restricted by the highly alkaline environment caused by the addition of cement to the waste. The exact amount of cement required to obtain the correct balance between permeability, workability and strength will need to be optimised by further site studies, should this option be adopted.

With an active process the sludge is produced as a continuous stream which is preferred by landfill operators and/or smelters since they are able to blend the waste in with other sources.

12.2.2.2 Passive Treatment

For a passive system the waste products would be stored within the cells. In the aerobic cells, for example, the bed level would rise as the hydroxide sludge is formed and the reeds would continually grow above this bed of sludge. In the case of the pilot passive plant it is anticipated that the sludge bed of the aerobic cells would rise at a rate of around 30 mm per year. For the anaerobic cells, which are initially filled with sawdust (or a similar organic carbon source), the substrate would gradually become replaced by sulphide minerals as the treatment process is effected. Since metal sulphides are more dense than the organic components, the voidage within the cell is expected to be maintained.

The stoichiometry of the reactions taking place within the anaerobic cells indicates that four moles of carbon are required for the formation of each mole of metal sulphide and suggests that the cells will continue to function for about 25 years (Ref. 2). It is therefore anticipated that the disposal of waste (and subsequent re-filling with fresh substrate) would be required at this frequency.

12.3 LEGAL AND PLANNING CONSIDERATIONS

12.3.1 Policies

The September 1994 draft Cornwall County Council Structural Plan and the draft Cornwall Structure Plan (1994) details the County Council's Policy towards waste disposal. The disposal of waste must comply with the Authorities objectives which include:

- Protection and enhancement of the natural environment.
- Respect towards sites of archaeological, scientific or historic interest.
- No degradation of the existing flood plains.
- A principle to encourage opportunities for resource recovery.

In particular the following policy statements are noted:

Policy ENV3 - Proposals for the development likely to have a material impact on the environment and character of Cornwall and/or make material demands on infrastructure, services and natural resources should be accompanied by an Environmental statement. Unless it has been demonstrated that the environmental effects are acceptable within the context of other policies in this Plan such development will not be supported.

Policy ENV25 - Development should not increase pollution (including disturbance of existing pollutants) in the water environment either directly or indirectly.

Policy W1 - The County Council will, where practicable encourage and support appropriate proposals to reduce the levels of waste production, and to increase the recycling, reuse and recovery of resources, including materials and energy from waste, where compatible with the protection of the environment.

Policy W2 - All waste disposal proposals will be assessed against the need for the development, the environmental impact of the proposal and the protection of public health. Proposals will not be permitted where they could adversely effect areas recognised for their landscape, nature conservation, historic, archaeological or agricultural value.

Policy W4 - The high quality restoration of landfill or landraising sites will be required, where practicable, on a progressive basis. Normally planning permission for landfill will only be granted if the proposal demonstrates a positive enhancement both of the site and the landscape character of the area in which it is located.

12.3.2 Legal Framework

The disposal of metalliferous sludge will need to comply with the appropriate parts of the following legislation:

- Mines and Quarries (Tips) Act 1969
- Environmental Protection Act 1990

These acts support the Government White Paper "This Common Inheritance" (1990) which sets out the Government's commitment towards the control of pollution.

Mines and Quarries (Tips) Act 1969

The Mines and Quarries (Tips) Act 1969 relates to the disposal of material discarded from mineral processing operations. In particular, it is relevant to the operation of the Clemows Valley Tailings Dam and the Carnon Valley Tailings deposits.

Clemows Valley Tailings Dam

- This is categorised as an active Classified Tip as the facility is still used for tailings disposal.

- Should South Crofty plc cease tailings disposal but retain ownership and allow the facility to continue to be used for sludge disposal, it would become a classified closed tip.

- If South Crofty plc cease trading or transfer ownership so that the dam is not associated with an active mine, the facility would be reclassified as disused.

Carnon Valley Tailings Deposits

The legal status of these deposits is uncertain, but are considered to be disused.

Environmental Protection Act 1990

The waste sludge is described by the Waste Regulation Authority as "difficult" waste and is therefore a controlled waste under the Environmental Protection Act, 1990, which replaced the Control of Pollution Act 1974.

Controlled waste is managed in accordance with a licensing system under Part II of the Environmental Protection Act 1990, whereby a waste management licence is required in order to treat, keep or dispose of a controlled waste.

In addition, Section 34 of the act imposes a "duty of care" on anyone who has control of, or responsibility for, controlled waste at any stage from its production to its disposal. This duty requires each person to take all reasonable measure:

- To prevent the illegal management of waste.
- To prevent the escape of controlled waste.
- To ensure that, on transfer, waste is only transferred to an authorised person and that a description of the waste is provided which enables subsequent holders to fulfil their duty in regard to that waste.

12.4 DISPOSAL SITES AND MANAGEMENT OPTIONS

In establishing the appropriate method for waste disposal the most cost-effective solution is required that is consistent with sound environmental policies. To comply with these criteria the following factors must be considered:

- The quantity of sludge to be stored (and production frequency).
- The containment environment required.
- Any commercial value that the product may have.

These factors have been considered in the appraisal of future sludge disposal options within the Carnon Valley and off-site.

12.4.1 Disposal within the Carnon Valley

Disposal of the metalliferous sludge in the Carnon Valley can be achieved by:

- Continued disposal to CVTD as a slurry.
- Disposal to CVTD as a dewatered cake.
- Disposal to an alternative local depository.

12.4.1.1 Clemows Valley Tailings Dam

The Clemows Valley Tailings Dam (CVTD) is owned and operated by South Crofty plc for the storage of tailings produced by their mining and processing operations (Figure 12.1). Historically the dam has accepted tailings from the Wheal Jane Mine and is now about 25 years old. In 1994 the dam wall was at a level of 66 m AOD with planning approval up to 70 m. A further rise up to 76 m AOD is technically feasible (Ref. 3) subject to planning permission.

The metalliferous sludge arising from the existing treatment system is deposited into CVTD which acts as a clarifier by depositing the solid precipitates from the water as well as a place of storage. This operation is managed under contract with South Crofty plc, the owners and operators of the dam.

Disposal into the dam is currently the most economic solution for waste disposal since it avoids the need for extensive dewatering equipment. It has also been recognised that this arrangement is temporary as it relies on the continued availability of the dam.

The life of the dam is dependent on the manner of operation as shown in Table 12-6. Contingency plans have, however, also been prepared to cover the possibility of the dam becoming unavailable for either operational or contractual reasons (see Section 4.9).

Metalliferous sludge accounts for about 2.5% of the input to CVTD by weight. Recent analysis indicates that the sludge occupies about 15% of storage volume utilised.

Table 12-6 : Predicted Life of CVTD versus Sludge Density

Solids by weight (%)	Deposited Dry Density (t/m^3)	Years storage on CVTD (to 70 m AOD) from January, 1996[1]	
		Mill contributing tailings [2]	Mill halts deposition January 1996[3]
20	0.23	)	14
25	0.30	) 5	41
45	0.64	)	89

[1] - Assumes current minewater concentrations and average treatment rate of 190 l/s from January, 1996

[2] - Mill contributes 188 500 tonnes of tailings per year, 97000 tonnes as coarse fraction to dam wall.

[3] - Alternative Fill Materials Required for Wall Building.

Figure 12.1 Location of Possible & Existing Disposal Sites in the Wheal Jane Vicinity

It can be concluded that:

- Implementation of Active plant, and improved sludge solids content, has little effect to the life of the depository whilst the mine continue to deposit tails into the dam.

- If sludge only is deposited into the dam then the sludge solids content has a dramatic effect on the life of the depository.

12.4.1.2 New Depository

Alternative Disposal sites have been identified in the near vicinity of the Carnon Valley. These include:

- Lower Minesite
- Lower Carnon Valley)
- Upper Carnon Valley) previously identified sites for tailings disposal
- Poldice Valley)
- Wheal Maid)

The location of the above sites are shown on Figure 12.1.

Prior to permitting the disposal of waste at any of these sites, it is likely that the Waste Regulation Authority and Planning Authority will require full planning and environmental studies, and the construction of a depository, engineered to the appropriate standard. A Waste Management Licence would be required for the deposit of waste at such a site.

None of the sites (other than CVTD) described above are as yet capable of receiving waste sludge and so development and operational costs would be incurred. The cost of this work must be offset by the transport and deposition fees for offsite storage.

Lower Minesite

Lower Minesite lies to the north of CVTD and consists of old worked areas with exposed waste rock. It is bounded by CVTD to the south, Clemows stream to the west and the minesite shaft and crushing area to the east and north. With an active treatment system located on the minesite, transport costs would be small as the waste would not even require lorry haulage. The development of the site would be subject to detailed engineering design, and planning and licensing applications.

The area represents approximately 200 000 m^3 of available storage space following the construction of a small starter wall. This is equivalent to approximately 25 years of storage (7 300 m^3 of dewatered sludge per year at a solids content of 45% by weight).

Lower Carnon Valley

The lower Carnon Valley site has historically received tailings over many decades. This is the proposed site for a passive treatment plant and represents the opportunity to create a substantial disposal capacity. However the site is not considered suitable for a disposal facility for the following reasons:

- It would require major land raising within the valley (see Section 8).

- The development costs are likely to be prohibitive.

Upper Carnon Valley, Poldice Valley, Wheal Maid

All of the three sites listed above have been considered as possible sites for tailings disposal. The studies of these areas suggest that significant space is available for storage but that a large amount of development work would be required. This would include:

- Water course diversion.
- Stabilisation of old workings.
- Waste containment.

12.4.2 **Disposal Off-site**

Disposal of the waste sludge outside of the Carnon Valley can be achieved by:

- Disposal to an existing landfill site.
- Establishment of an end use for the sludge (e.g. metal recovery).

12.4.2.1 Off-Site Disposal to Existing Landfill

Various waste treatment companies, who specialise in the disposal of difficult wastes have been approached, and options have been costed. Also the "Sitefile Digest" database (Ref. 5) has been searched for registered sites within the United Kingdom that are capable of accepting waste of this category. Generally sites are licensed, by the WRA, to accept prescribed amounts of each category of waste per year. Some sites can only accept "inert" waste (such as building debris not including asbestos) whist others can accept limited amounts of "difficult" wastes. Normally the cost of deposition to the site is termed the "gate fee". The more restricted the disposal of a waste category becomes, the higher the gate fee.

The database search revealed that no landfill sites exist in the South-West capable of accepting waste of this sort. This was confirmed by the Cornwall Waste Regulation Authority and by waste disposal companies. The nearest potential sites are believed to be near Swindon and in South Wales.

Transport costs have been obtained from local haulage companies and from the waste disposal specialists. The cost to transport waste to Swindon or South

Wales is estimated at between £7.00 and £9.00 per tonne. For the driest sludge (45% pulp density) this represents about £10.00/m^3.

The estimates for "gate fee" have varied from £20.00 to more than £50.00 per tonne. A reason for these high prices is the amount of listed substances present in the waste. In particular arsenic has a concentration of around 6000 mg/l in the waste solids whereas most licensed disposal facilities are limited to about 500 mg/l or an annual quota which restricts the quantity of sludge that can be accepted. It is possible that a number of separate sites may be required each taking a proportion of the waste in order to disperse the quantities of arsenic. Disposal to an existing landfill is, therefore, likely to be prohibitively expensive.

12.4.2.2 Metal Recovery

The possibility of recovering the metals from the minewater sludge in a commercially attractive form has been recognised and has been discussed in Section 11. Achieving any sort of revenue from the sludge has a dramatic impact on treatment costs and must, therefore, be pursued.

A preliminary appraisal indicates that only zinc has the potential for economic recovery from the minewater. Zinc represents approximately 30% of the dissolved metal in the minewater and has a relatively high market value (approx. £720/tonne pure, January, 1995). Only one zinc smelting plant exists within the United Kingdom and this is located at Avonmouth about 180 miles from Wheal Jane.

A representative sample of the sludge, produced by lime dosing and centrifuge dewatering, was provided to the smelting company together with characteristic physical and chemical data. Analysis of the metalliferous sludge by the company indicated that the zinc recovery was not commercially viable. The smelter was only prepared to accept the sludge for disposal at a significant unit cost. The value of the sludge could be improved by reducing the iron content but is still unlikely to yield a positive cost saving or to be cheaper than landfill disposal.

If iron was recovered in a pure form then it might be acceptable to an iron smelter. However the nearest iron smelting plant is in Port Talbot, South Wales and iron does not hold enough value to warrant transport of that sort of distance. Iron hydroxide resulting from a passive aerobic cell would be contaminated with bio-mass from the reeds which would also be unattractive to the smelter plants. Also the arsenic found in the minewater usually forms compounds with the iron which further reduces any value an iron product may hold.

A possible use of iron hydroxide (ochre) is as a colouring pigment in the paint and brick industries. One company has been approached on this issue but was not interested in the product because of the contaminated nature of the material.

12.5 DISPOSAL COST SUMMARY

The chemical and physical properties of the sludge from each treatment option are summarised in Table 12-7 together with details of the preferred disposal route:

Table 12-7 : Summary of Preferred Disposal Options

Source	Chemical Form	Physical Form	Disposal Options[1]
Existing Treatment System	Hydroxide sludge	Slurry	**Deposition into CVTD**
Active treatment (dewatered)	Hydroxide sludge	Cake	**Surface disposal to CVTD followed by alternative local sites** Surface disposal to Local Depository Surface/Landfill in existing Licensed Tip Smelter for zinc recovery (unlikely)
Passive	Sulphide sludge	Slurry/Cake	**In-situ disposal within treatment cells** Smelter for zinc recovery Landfill to Licensed Tip
Active treatment (dewatered)	Sulphide sludge	Cake	**Smelter for zinc recovery** Landfill to Licensed Tip
Passive aerobic	Hydroxide sludge	Slurry/Cake	**In-situ disposal within treatment cells** Landfill to licensed tip Smelter for Iron recovery (unlikely)

[1] Listed in order of technical preference.

The disposal costs for the options detailed in Table 12-7 are summarised in Table 12-8 which shows the estimated costs for the disposal of wet solids. These costs are only approximate for new sites where development costs are uncertain.

Table 12-8 : Summary of Estimated Disposal Cost against Options Available

Waste Destination	Pulp Density	Mass per year	Handling and Transport Cost	Gate Fee	Total Estimated Annual Cost	
Units	%	(wet solids)	£/tonne (wet solids)		£/yr	
CVTD following Existing treatment	20	23,000	0.20	9.60	225,000	
CVTD following Active treatment	25	18,300	2.00	9.24	206,000	[1]
CVTD following Active treatment (HDS)	45	10,300	1.50	7.80	96,000	[1]
Off-site disposal to landfill	45	10,300	8.00-10.00 [2]	20-30 [3]	288,000 - 412,000	
Disposal to local new depository (Upper Carnon, Wheal Maid, Poldice)	45	10,300	2.00-4.00	35	392,000	[4]
Disposal to lower minesite	45	10,300	1.50	20	221,500	[4]
Disposal for metal recovery	45	10,300	7.00	>100	>1 m	

Notes Sludge volumes based on an average treatment of 190 l/s minewater at Jan 1995 minewater concentrations.
Disposal to CVTD all based on £11.00/m^3.
[1] - Wall building / management costs not included.
[2] - Estimated from local and national waste haulage contractors.
[3] - Estimated from waste disposal specialist companies.
[4] - Estimated to reflect likely development costs.

12.6 CONCLUSIONS

A detailed study of possible future sludge disposal options has been carried out, and the following conclusions made:

- Whilst the existing treatment system continues the only disposal option is CVTD.
- For active treatment the preferred disposal site remains CVTD.
- Disposal to Lower Minesite is probably the next cheapest alternative.
- Various alternative locations exist within the vicinity of the mine for disposal sites but development costs and planning restrictions could be severe.
- Disposal of waste products arising from full scale passive operations should be confined to the treatment cells where possible, and if permitted this aspect would need incorporating into their design.
- Disposal to existing landfill facilities would be expensive.
- Metal recovery is unlikely to be cost-effective.

12.7 REFERENCES

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13

13. ECONOMIC BENEFITS OF IMPROVEMENTS IN WATER QUALITY

CONTENTS

13.1 INTRODUCTION

An economic appraisal has been undertaken in order to assess the potential economic benefits which might be attained from the improvement of water quality achieved by the long-term treatment strategy for Wheal Jane minewater. The appraisal attempts to assess the net economic benefits associated with moving from a "No Treatment" objective to water quality objectives which involve some form of treatment, and thus expenditure. The "No Treatment" objective, therefore, forms the baseline against which benefits are measured.

The assessment of benefits has been based on the use of social cost-benefit analysis. Within such a framework, the aim is to value as many as possible of the costs and benefits of a given action, in monetary terms, to ensure that they are all given equal consideration in the final decision making. This includes the monetary valuation of environmental costs and benefits where possible and/or appropriate.

The approach taken towards the estimation of costs and benefits has involved calculation of changes in producer and consumer surplus associated with a given water quality. Changes in producer surplus have been estimated in terms of changes in economic rent earned by the owner of the resource/operations and are based on a number of assumptions including the appropriate cause and effect relationships, the implications of these for levels of activity, total revenues earned by those in the industry and the proportion of revenue which corresponds to gross profits or rent. In many cases, it has been necessary to rely on information gained through discussions with industry, as published data were not available.

Valuation of losses and gains related to non-marketed effects, such as impacts on conservation, angling and other recreation activities has been more problematic. There are two approaches which can be adopted towards the valuation of these types of effects:

- The first involves the direct application of one of the main valuation techniques, such as contingent valuation, the travel cost method or hedonic pricing. Such applications are both time consuming and costly and have been beyond the scope of this study.

- The second approach is to transfer mean willingness to pay (or consumer surplus) values from previous studies based on a similarity in the problems being examined.

In a few cases, a benefit transfer approach has been applied as a means of providing an indication of the likely magnitude of economic impact. The degree to which benefit transfer could be undertaken has been hindered, however, by a paucity of relevant studies. As a result, it has not been possible to derive monetary values for all predicted impacts.

Undertaking this assessment has involved consultation with a number of different organisations. These have included government departments, County and local councils, local industry representatives, conservation organisations, sports councils and tourism organisations.

13.2 ENVIRONMENTAL AND OTHER EFFECTS OF THE RELEASE OF MINEWATER

Within the Carnon Valley and the Fal Estuary, there is a range of different activities which could be affected by changes in water quality. These include:

- abstractions from and discharges to the estuary area;
- conservation;
- fisheries: including commercial and non-commercial fisheries (including angling);
- extraction of maerl;
- in-stream and out-of-stream recreational activities, including bathing;
- aesthetic and amenity effects and their impacts on property values;
- tourism related effects.

Of the above, initial scoping work found that there were no abstractions in the area which would be affected. The other issues are each considered below.

There may also be educational and technology transfer benefits associated with the treatment technologies adopted for Wheal Jane. Educational benefits may arise principally from the operation of the pilot passive treatment system. The transfer of knowledge and technology gained from Wheal Jane to other sites may be beneficial in the avoidance of environmental damage. Examination of the potential benefits from education and technology transfer has been beyond the scope of this study. The appraisal has been limited, therefore, to consideration of the remaining six categories of use.

13.3 CONSERVATION

13.3.1 Predicted Impacts of Changes in Water Quality

The impacts on estuarine flora and fauna and birds associated with the different water quality objectives are related to both changes in metal concentrations and the potential for smothering from the precipitation of iron.

Under the "No Treatment" objective metal concentrations in the Carnon River would increase, although impacts on the river itself are likely to be negligible (see Sections 2 and 3). Within Restronguet Creek, some changes in structure of the invertebrate communities might be expected, due primarily to higher turbidity and the smothering effects associated with the precipitation of iron hydroxides.

Under the "No Deterioration" objective, no significant changes in the riverine or estuarine ecosystems would be expected, with the current suppression of the natural biological communities in some of these areas, notably the Carnon River and Restronguet Creek, continuing.

Some minor, but largely insignificant, improvements in species abundance and diversity might be expected in Restronguet Creek under the "North Sea Commitments" objective.

Under the "EC Directive" objective, increases in bio-diversity and abundance of both riverine and estuarine flora and fauna would be expected, although improvements would be limited by the accumulated metal-rich sediments in the Carnon River and Restronguet Creek which would continue to exert a significant influence on the ecosystems.

13.3.2 Benefits to Conservation

Within the scope of this study, it has not been possible to derive monetary estimates for the value placed on the conservation importance of the estuary. However, the number of designations applying to the estuary provides an indication of its local, regional and national importance.

In considering the predictions made above on changes in flora and fauna under the different objectives, it is important to recognise the link between these changes and several of the other impact categories. In particular, there will be links between changes in flora and fauna and the quality, abundance and diversity of fisheries in the estuary, in the recreational value of the estuary and thus in tourism to the area.

13.4 FISHERIES

13.4.1 The Oyster Fishery

13.4.1.1 Value of the Oyster Fishery

The most important shellfishery operating in the Fal Estuary is for the native European oyster (*Ostrea edulis*) which is based on natural stocks. There has also been some experimental rearing of small quantities of Pacific oysters (*Crassostrea gigas*), but these are not considered to be commercially viable at this stage. Carrick Roads supports one of the few commercially harvested natural native oyster fisheries in the UK. The fisheries off Turnaware Point and Percuil are designated fisheries under the EC Shellfish Waters Directive (79/923/EEC). Because of high microbial levels (particularly from oysters harvested from other parts of the estuary such as the River Fal), oysters are currently relaid in uncontaminated water for a year before they are marketed. Relaying also takes place to allow shellfish to mature prior to final harvesting and to wait for the "right price" prior to sale. The banks of both the Restronguet and Mylor creeks - below the low tide mark - are used for relaying.

Commercial fishermen hold an annual dredge licence, valid between 1 October and 31 March. The number of dredge licences and per annum catch by fishing season, between 1983-84 and 1993-94, are shown in Table 13-1. Whilst the 1992 incident at Wheal Jane apparently produced a sharp decline in the local demand for native oysters, the total number of oysters harvested continued to increase. There are several likely explanations for this trend. First, and most importantly perhaps, fishermen continued to harvest during 1992 and 1993, but were forced to "relay" oysters due to concerns over metal concentrations. Secondly, the decline in demand took place in what was traditionally a UK-based market. The loss of this market was compensated for by the export of native oysters to foreign markets which had previously been unexploited.

Table 13-1 : Dredge Licences and Per Annum Catch Rates

Fishing Season	Number of Dredge Licences	Total Number of Oysters (millions)
1983-84	24	1.3
1984-85	35	1.3
1985-86	25	0.9
1986-87	32	0.9
1987-88	22	0.7
1988-89	16	0.8
1989-90	19	0.5
1990-91	14	0.5
1991-92	26	0.6
1992-93	33	0.9
1993-94	30	1.8

13.4.1.2 Predicted Impacts of Changes in Water Quality

The prediction of impacts of the treatment objectives on the oyster fishery has taken account of both the direct effects of water quality on the fisheries and their acceptability for human consumption and perceptions of potential customers concerning their acceptability and quality.

There is considerable uncertainty on the biological impacts of changes in metal concentrations on the oyster fishery at Turnaware Point. Although increased metal levels may cause large and persistent population reductions, it is impossible to separate the impacts of this from losses caused by natural mortality or other environmental factors. In general, the oyster fishery is unlikely to be seriously influenced by any of the changes in water quality implied by the four alternative objectives.

Under the "No Treatment" objective, metal levels in oyster flesh may be deemed unacceptable by the Department of Health and MAFF. Although this was not the case immediately following the 1992 incident, concentrations of zinc in oyster flesh were approaching levels at which the Department may have had concerns. Of equal relevance is public perception over the acceptability of oysters for human consumption. As occurred after the 1992 incident, local demand can be expected to decline should water quality deteriorate. This would have significant impacts on the industry as the main market continues to be a local one.

Given the above, and on the basis of discussions with the Falmouth and Truro Port Health Authority and with fishermen, the following assumptions have been made for the base case of this assessment:

- under the "No Treatment" objective, demand for native oysters would be reduced by 75% from current levels, thus reducing harvest rates;
- under the "No Deterioration" objective demand and levels of harvest would continue as at present; and
- under the "North Sea Commitments" and "EC Directive" objectives harvest rates would continue as at present due to the traditional nature of the industry.

The assumptions concerning the "No Treatment" objective are conservative in that they assume that some level of industry would continue (possibly through the continued use of relaying).

The assumptions made above for the "North Sea Commitments" and "EC Directive" objectives also could be considered conservative. In the 1960's, the estuary supported over 100 fishermen using traditional dredging methods. It has been argued by some, therefore, that with improvements in water quality there would also be increases in the extent of and harvest levels from the fisheries, and indeed in natural growth rates of the oyster populations. The more conservative assumption of no increase upon current levels has been made here for the base case, however, as discussions indicate that it is unlikely that there would be new entrants to the industry even with improvements in the quality of the fishery. The overall market also appears to be limited due to the higher price of native oysters as compared to over the more common pacific oysters.

13.4.1.3 Estimated Benefits to the Oyster Fishery

Table 13-2 presents estimates of the value of the oyster fishery under the different water quality objectives. It should be noted that the 1993/94 catch rates have been used as the baseline estimate for these purposes as these figures are considered to be a better indicator of the long-term position of the industry than the lower harvest rates occurring during the mid-80's which were affected by high natural mortality rates.

Table 13-2 : Economic Benefits to Native Oyster Fishery

	No Treatment	No Deterioration	North Sea Declaration	EC Directive
Total oysters harvested (mill.)	0.45	1.8	1.8	1.8
Average price per oyster (£)	0.22	0.22	0.22	0.22
Total per annum revenue (£)	100 000	400 000	400 000	400 000
Total per annum rents (£)	50 000	200 000	200 000	200 000
Incremental benefits (£)	N/A	150 000	150 000	150 000

N/A - not applicable

The per annum increase in value under the three treatment objectives is estimated at £300 000.

No data exist on the level of economic rent as a proportion of revenue accruing to those involved in this industry. Based on anecdotal information provided by oyster fishermen, average profits per boat are equal to roughly 50% of revenues. This information corresponds with the percentages which seem to apply to other commercial fisheries. On this basis, changes in economic rent are estimated at 50% of changes in revenues.

13.4.2 Other Commercial Shellfish

In addition to the oyster fishery, there are also a number of smaller commercial shellfisheries in the Fal system, harvesting stocks of scallops, mussels and crabs. There is also some informal collection of scallops and mussels around the rocky foreshores at low tide. There are also reported to be four commercial crab fishermen harvesting small quantities of mostly green and velvet crab.

Data on the value of these other fisheries are limited. However, anecdotal evidence suggests that the long-term impact on this industry under the "No Treatment" objective could be significant. For example, following the release of minewater in January 1992, significant losses were reported by crab fishermen, including one fisherman who estimated that on the 20th and 21st of January alone he lost over £1,000 in crabs which appeared to be affected by the plume of contaminated water moving through the estuary.

13.4.3 The Sea Bass Fishery

13.4.3.1 Value of the Sea Bass Fishery

Nationally, sea bass are a high value species and prices have risen significantly over the past 15 years, together with the share of the wholesale price received by fishermen. The Cornish sea bass fishery is a 12 month commercial fishery and includes both inshore (e.g. the Carrick Roads) and offshore activity. The nature of the commercial fishery here has changed considerably over the last 20 years. Much of the offshore activity is now directed solely at bass, while in the past bass was viewed as a valuable bycatch. In 1988 the regional fishery (defined by the ICES VIIe designation) included some 319 part-time fishing vessels and 39 full-time vessels.

Within the Fal estuary and harbour area there are both commercial fishermen and charter operators. Four boats are commercially licensed to operate in the Carrick Roads and harbour area, but sources indicated that as many as eight other unlicensed boats may be supplying the local "pub trade". In addition, other boats operate outside of the harbour. Log Book returns made to MAFF indicate that in total 17 boats (including charter fishing boats) operate from Falmouth Harbour.

Given the significance of Carrick Roads as a nursery area, boats operating from other harbours are also likely to rely on juveniles using the area. No data exist to indicate how important the nursery is to the Cornish sea bass fishery overall, but a limit of 50 to 100 miles has been indicated by MAFF scientists and other specialists as the distance which young bass travel within the first two years of leaving a nursery area, with the longer distance being particularly relevant for the south west fisheries.

Commercial Fishery

Estimates of the value of the commercial sea bass fishery associated with the Carrick Roads (see Table 13-3) have been based on the following assumptions:

- mean annual catches for a full-time boat are 961 kg per annum, while those for a part-time boat are 227 kg per annum (Ref. 1); and

- the average annual price per kg of bass is £9.

Table 13-3 : Value of the Commercial Sea Bass Fishery Associated with the Carrick Roads Nurseries

	Full-Time Boats	Part-Time Boats
Mean annual catch per boat (kg)	961	227
Number of boats	8	47
Total annual catch (kg)	7 688	10 669
Price per kg (£)	9	9
Annual catch value (£)	69 192	96 021
Economic rent (£)	34 596	48 010

On this basis, the commercial bass fishery is estimated to be worth about £165 200 per annum, based on total annual catches related to the Carrick Roads of over 18 000 kg. Discussions with CEMARE, University of Portsmouth have indicated that the economic rent associated with the fishery is likely to be about 50% of catch value (taking into account differences between operators in techniques used, effort per unit catch and input costs). Given this assumption, rent is estimated at roughly £82 600 per annum.

Commercial Charter Operations

In addition to the commercial sea bass fishery, the 1987 MAFF census indicated that there were 10 charter boats operating out of Falmouth Harbour and another 29 operating out of the other associated ports. Limited data are available on the value of these activities to the charter operators. However, based on studies elsewhere (Ref. 1) the calculated value of charter activities to these operators is estimated at about £132 400 per annum (see Table 13-4). Assuming that rent for this sector is similar to that estimated for the commercial fishery operations, this is calculated at about £66 200.

Table 13-4 : Value of the Commercial Sea Bass Charter Operations Associated with the Carrick Roads Nurseries

	Full-Time Operators	Part-Time Operators
Number of boats	5	34
Earnings per boat (£)	16 280	1 500
Total annual earnings (£)	81 400	51 000
Economic rent (£)	40 700	25 500

Recreational Bass Fishery

There are 35 angling clubs affiliated to the Cornish Federation of Sea Anglers, five of these are located in the immediate area and have a total of 161 members.

No data are available on the number of non-club anglers in the area, but discussions have indicated that numbers will be significantly greater than those for club membership. This will be particularly true when angling by summer tourists is taken into account (besides those using charter boats considered above).

The research carried out by Dunn et al (Ref. 1) found that there were about 490,000 bass anglers in England and Wales and this figure is considered a reasonable estimate by the MAFF scientists involved in management of the fishery (Ref. 2).

Furthermore, they conclude that there is a concentration of sea bass anglers in the Southwest, and indeed that all sea anglers in this area will also be interested in sea bass.

Given that the Carrick Roads provides 10% of the national nursery areas, it has been assumed for the purposes of this appraisal that 10% of all sea bass anglers will be affected by changes in the quality of these nurseries. On this basis, it has been assumed that some 49,000 anglers would be affected.

The work carried out by Dunn et al (Ref. 1) on bass fisheries also included an examination of the recreational value of bass angling. This work involved surveying over 2,100 individuals involved in bass fishing, with interviews carried out on-site, by post and through bodies and organisations concerned with sea bass fisheries.

Key findings with regard to the recreational fisheries are as follows:

- 38% of sea anglers were fishing with the intention of catching bass, and bass was the most popular species for 45% of shore anglers and 15% of boat anglers;
- bass shore anglers made an average of 7.6 trips per year, while bass boat anglers made an average of 4.6 trips per year (note that these figures have been adjusted to account for potential sampling biases, with unadjusted figures being 24 and 11 trips respectively);
- average expenditures for both shore and boat anglers per trip are about £4.70 and £18.20 respectively (with these figures including travel and other costs);
- the mean willingness to pay per annum by bass anglers to prevent closure or loss of a fishery is about £25.80.

Annual Expenditure by Participants in Recreational Bass Fishery

By combining the estimates given above on a number of affected sea anglers in the region with the figures on average expenditure it is possible to provide an indication of the potential significance of the recreational sea bass fishery to the Cornish economy. Assuming that participation is equally divided between bankside and boat-based fishing, estimated per annum expenditure is indicated in Table 13-5. Although only a portion of this expenditure would be affected by changes in the Carrick Roads nursery areas, the magnitude of annual expenditure indicates that losses to those servicing this activity could be significant.

Table 13-5 : Annual Expenditure by Participants in the Recreational Bass Fishery

	Bankside Angling	Boat Angling	Total
No. of anglers	24 500	24 500	49 000
Trips per angler	7.6	4.6	-
Total trips	186 200	112 700	298 900
Expenditure per trip (£)	4.70	18.20	-
Total expenditure (£)	875 140	2 051 140	2 926 280

Although the above figures indicate the potential importance of the recreational bass fishery to the local and wider Cornish economy in terms of lost revenues, they do not indicate the change in the economic value of the fishery associated with impacts on the nursery area.

As previously indicated, the mean willingness to pay to prevent closure or loss of a fishery has been estimated at about £25.80 per angler per annum. Combining this figure with the estimated 49,000 sea bass anglers, gives an estimated willingness to pay to protect sea bass fisheries in the Southwest against loss of roughly £1.26 million per annum. However, given that the Carrick Roads provides only a portion of the nurseries in this region, it has been assumed here that only one third of the regions anglers would hold this willingness to pay towards the Carrick Roads. This provides an annual estimate of willingness to pay to protect these of about £379,000.

13.4.3.2 Predicted Impacts on the Bass Fishery

Sea bass accumulate heavy metals such as zinc in their tissue and this may influence not only their breeding ability but also whether they are fit for human consumption should concentrations of metals within their tissue rise to high enough levels. Given that many bass are cropped commercially as five year-olds when they leave nursery areas for inshore coastal waters, there may be health implications from the consumption of fish from the estuary under the "No Treatment" objective.

Since 1986 there have been increases in the number of juvenile bass, and reputedly with resultant increases in catches of fast-growing 5 year-olds by commercial fishermen. In 1991, however, very few juveniles were produced in south coast estuaries as a result of strong northerly gales. Within the Fal Estuary, it was this small surviving group of juveniles using the nursery area which were impacted by the Wheal Jane incident in 1992. Due to the small number of fish exposed to the incident and a lack of suitable sampling methods for the estuary, it was not been possible to assess how significant the impact of mine water releases were on the surviving population at this sensitive juvenile stage. No mortality of larger juveniles was observed.

It is impossible, therefore, to state with any certainty what the overall implications of the different water quality objectives would be on the resident and migratory fishery. It is likely that chronic exposure to high levels of metals rather than freak exposure during an episodic event would prove far more detrimental to juvenile development. Improvements in water quality within the Fal estuary could result in improved recruitment rates and fecundity of bass within the nursery, but is it impossible to quantify at what scale at this point in time.

For the purposes of this appraisal, the following have been assumed for the base case:

- chronic exposure to higher contaminant levels under the "No Treatment" objective would lead to a 50% reduction in juvenile populations and thus in catch rates of 5 year-olds;
- no changes would occur under the "No Deterioration" objective; and
- improvements in water quality under the "North Sea Commitments" and "EC Directive" objectives would lead to a 25% increase in populations and catch rates.

13.4.3.3 Estimated Benefits to the Bass Fishery

Estimates of the economic benefits that might be derived from the adoption of water quality objectives involving improvements in water quality have been based of the following assumptions:

- that changes in revenues to commercial fishermen would mirror the changes in catch rates under the different water quality objectives;
- similarly, changes in charter boat activities would mirror the changes in catch rates as demand for charter sea bass fishing would be directly related to the likelihood of catching a fish;

- that the recreational benefits to anglers are equivalent to the damage costs avoided through prevention of, deterioration to, or loss of, the fishery (thus benefits only occur in preventing a decline from the current situation - there are no further gains with improved water quality).

Table 13-6 : Economic Benefits to Sea Bass Fishery

Fishery	Total Per Annum Value (£)			
	No Treatment	No Deterioration	North Sea Commitments	EC Directive
Commercial	41 303	82 606	103 258	103 258
Charter	33 100	66 200	82 750	82 750
Angling	189 500	379 000	379 000	379 000
Total (£)	**263 903**	**527 806**	**565 008**	**565 008**
Incremental benefits (£)	N/A	**263 903**	**301 105**	**301 105**

N/A - not applicable

Based on these assumptions, the incremental benefits associated with treatment of Wheal Jane effluent to meet the "No Deterioration" objective are estimated at about £263 900 per annum, while those for further improvements associated with the "North Sea Commitments" and the "EC Directive" objectives are roughly £301 100 per annum.

13.4.4 Other Recreational Fisheries

In addition to sea bass, recreational angling in the Fal Estuary is mainly for mullet, sea trout, flounder, red bream, bull huss and thornback ray. There is also fishing for pollack, pouting, wrasse, conger eel and green-boned garfish and, in general, a wide variety of species are commonly caught. The Carrick Roads may also be an important feeding area for sea trout which migrate up the Tresillian, Allen and potentially the Kennal Rivers.

Furthermore, a variety of baits are gathered throughout the estuary complex (harbour ragworm, king ragworm, lugworm, "peeler" (or softshelled) crabs, prawns and sand eels, razor fish and mussels). Commercial diggers operate in the area to supply local fishing tackle shops (peeler crab bait is sent to other areas as far afield as Scotland).

Given that migratory fisheries are currently affected by water quality in Restronguet Creek and the Carrick Roads, it is likely that any further reductions in water quality would lead to reduced migration of sea trout up both the Rivers Fal and Kennal. In the extreme, the migratory fisheries may cease to exist.

Under the "North Sea Commitments" and, in particular, the "EC Directive" water quality objectives, numbers of migratory fish in both the Rivers Fal and Kennal would be expected to increase. For the River Kennal, this would result in the creation of a new and sustainable trout fishery which would be highly valued by local anglers. At this time though, data do not exist to allow valuation of the gains in consumer surplus to this group.

13.5 MAERL EXTRACTION INDUSTRY

Theoretically, improvements in water quality should lead to an increase in the productivity and sustainability of the maerl beds off St Mawes and potentially those in the lower estuary. Although this may lead to conservation related benefits, it is unlikely that there would also be increases in use of the beds for production of soil conditioners. It is expected that the proposed total harvest level of 30 000 tonnes per annum is the maximum which would be licensed by the Crown Estate out of concern over the need to ensure that the beds remain both financially viable and biologically sustainable.

With regard to further deterioration in water quality in the estuary, it has not been possible to predict how changes would affect the productivity and sustainability of the beds. Although the current extraction site may be considered to be towards the outer limits of water quality impacts, the Cornish Calcified Seaweed Company (CCSC) have indicated that they would lose existing buyers (due to perceptions concerning contamination of the maerl) should heavy metal concentrations in Carrick Roads rise any higher than current levels. This view is based on the reactions of buyers following the 1992 incident. In addition, the productivity of the beds could be affected by smothering as a result of iron precipitation.

A range of other environmental factors also may be affecting the beds. These include increases in brown algae populations and associated increases in natural sedimentation which are thought to be reducing the viability of the beds over the longer-term. In addition, water sport activities along St Mawes Bank may also considered likely to be causing damage to the highly sensitive maerl beds (Ref. 3). It may be that the combination of these factors together with further degradation in water quality and resultant deposition of precipitated metals could lead to both the loss of these nationally recognised conservation assets and the loss of the associated extraction industry.

It has not been possible to derive a monetary value for the potential damages to or improvements in the maerl beds with regard to their conservation status. However, an estimation of the impacts on the extraction industry has been undertaken, based on discussions with CCSC (see Table 13-7).

Table 13-7 : Benefits to the Extraction Industry

	No Treatment	No Deterioration	North Sea Commitment	EC Directive
Current ('000 tonnes)	0	25	25	25
Additional ('000 tonnes)	0	5	5	5
Total ('000 tonnes)	0	30	30	30
Price per tonne (£)	0	44	44	44
Total per annum revenue (£)	0	1 320 000	1 320 000	1 320 000
Profit per tonne (£)	0	27	27	27
Total per annum profits (£)	0	810 000	810 000	810 000
Incremental benefits (£)	N/A	810 000	810 000	810 000

N/A - not applicable

The estimated changes in economic rent (as measured by profit) when moving from "No Treatment" to one of the three treatment objectives is about £810 000 per annum. Although CCSC have indicated that it may be possible to move elsewhere, the transaction costs would be high. Furthermore, extraction of maerl requires approval and licensing by the Crown Estates and this has proven to be problematic in the past at the existing and other sites.

13.6 RECREATION

A wide range of recreation activities is available in the Fal estuary area. These have been divided into two categories for the purposes of this assessment:

- informal recreation, which includes walking, birdwatching and horse-riding; and
- water sports, which include sailing (the primary activity), windsurfing, canoeing, rowing, waterskiing, bathing and diving.

The current levels of activity under each of these categories, predicted impacts upon activities and estimated benefits are presented in Sections 13.6.1 to 13.6.2.3 below.

13.6.1 Informal Recreation

The two key forms of informal recreation in the area around the estuary are walking and birdwatching. Walking is undertaken along the banks of the Carnon River, Restronguet Creek and Carrick Roads. Within the Carnon River valley, the Kerrier Groundwork Trust (KGT) are responsible for the Mineral Tramways Project which involves restoration of the old tramways and numerous industrial heritage sites in order to create a footpath between the north and south Cornwall Coastal Walk. The Project is funded by the Government's derelict land grant programme, English Nature, the Countryside Commission and British Telecom. It will involve revitalisation of several of the old industrial sites in the valley. No predictions exist, however, on the numbers likely to use this trail when completed.

The Fal Estuary as a whole attracts many walkers, but due to private ownership there is limited public access along the Restronguet Creek foreshore and hinterland and between Turnaware Point and Messack Point. The most heavily used stretches are the Flushing to Mylor Churchtown footpath through the Trefusis Estate on the west bank of the Carrick Roads and the St Just-in-Roseland to St Mawes route on the east bank.

No surveys of user numbers exist, but Table 13-8 presents visitor numbers to car parks on the key routes, thus indicating magnitude of use.

Table 13-8 : Car Park Visitor Numbers

Year	St Anthony Head	Trelissick Gardens
1990	8293	84 400
1991	6888	83 500
1992	5686	85 500
1993	2607	82 600

13.6.1.1 Predicted Impacts on Informal Recreation

The implications of the different water quality objectives for informal recreation relate to two factors:

- the degree and frequency of visible discolouration under a given quality objective; and
- the impact which changes in water quality have on the flora and fauna which support bird populations.

During periods of significant discolouration, it could be expected that the satisfaction or enjoyment gained by the majority of footpath users and bird watchers would diminish (although in the short-term there may be an increase in people wishing to see the "red" Creek and Estuary). Perceptions of the area in ecological terms would be affected and it is likely that levels of use would decrease. Similarly, if diversity and numbers of birds decreased due to a loss of feeding grounds (i.e. the Restronguet Creek), the value of the area as a site for birdwatching would diminish.

For the "No Deterioration", "North Sea Commitments" and "EC Directive" objectives, potential changes in levels of activity and/or satisfaction gained from informal recreation will depend on the nature of any improvements in habitat quality. Adoption of a large scale reed bed based passive treatment system in the Carnon River valley may provide an attraction for users of the Mineral Tramways footpath.

If the water quality improvements associated with the "North Sea Commitments" and "EC Directive" objectives result in significant increases in marine species diversity and abundance, this may result in improved feeding grounds for overwintering wildfowl and other birds. This would obviously increase the value of the estuary for migratory birds and thus birdwatching.

13.6.1.2 Estimated Benefits to Informal Recreation

The economics literature has been reviewed in order to identify whether or not any UK studies exist which address environmental quality changes similar to those predicted here and thus could be used for benefit transfer. None of the studies identified relate to the same kinds of water quality changes (e.g. gross episodic discolouration), but there are studies which have examined informal recreation users' willingness to pay (WTP) for the protection or enhancement of existing water related habitats (see Table 13-9).

Table 13-9 : Relevant UK Contingent Valuation Studies

Study	Environmental Good	Valuation Basis	Estimate
Turner & Brooke (1988)	Coastal Recreation and Amenity	WTP of Local Users	£15 per household/annum
Green et al (1990b)	Recreational Value of Beaches	WTP Visitors	£4.90 per person/annum
Green et al (1991a)	River Water Quality Improvement	WTP Visitors	£15.60 per person/annum
Coker et al (1989)	Recreation Value of Improvements to a river corridor	WTP Residents	£13.90-£16.20 per household/annum
Bateman et al (1991)	Broadland Flood Alleviation	WTP Visitors	£68-£84 per household/annum
Willis et al (1993)	River Darent Alleviation of Low Flow	WTP Residents WTP Visitors	£10.20 per household/annum £7.16 per household/annum
Willis et al (1994)	South Downs and Somerset Levels and Moors	WTP Residents	£17.53-£27.52 per household/annum
Middlesex (1994)	Rivers Misbourne and Wey	WTP Residents	£5.34-£5.92 per household/annum

From an examination of Table 13-9 it can be seen that the mean WTP value varies from just under £5.00 to over £60. In order to err on the side of caution, a value of about £5.50 per household per annum has been selected as a reasonable benefit estimate for willingness to pay to prevent deterioration of the current recreation experience associated with the Fal Estuary. This value corresponds to the lower estimate found for low flow alleviation in work carried out by the University of Middlesex for the NRA.

For the purposes of aggregation, this value has been multiplied by the number of households in Carrick District Council, which currently stands at around 33 000. On this basis, the total per annum willingness to pay to maintain the quality of recreation is estimated at roughly £181 500.

Again, in order to be conservative, it has been assumed that this value covers not only informal recreation, but also local residents WTP to protect water sports activities (see also the discussion given below).

13.6.2 Water Sports

The Fal Estuary is one of the world's largest natural harbours and the protected waters of the Carrick Roads offers an extensive range of water sports, providing one of the largest water sports centres in the southwest. The first World Water Sports Festival and the Tall Ships Race will be hosted on the estuary in 1998. The variety of water sport activities available in the estuary include:

- *Sailing*: the most popular sport on the estuary in terms of both numbers of participants and expenditure; the types of boats used range from one person sailing dinghies to ocean going yachts.

- *Bathing*: although there are no EC bathing waters within the estuary limits (as defined for this study), certain beaches are used by both locals and tourists for bathing.

- *Waterskiing*: there is a limited amount of waterskiing within the estuary, with only about six boats operating on a regular basis.

- *Windsurfing*: a fast growing sport which occurs throughout the Fal estuary.

- *Rowing*: there are two sliding seat rowing clubs located on the Penryn river, with a total combined membership of 45. Teams from the clubs are of a high standard, with members competing nationally. Local interest in the sport is growing.

- *Canoeing*: the Falmouth Canoe club has a membership of 50 and trains exclusively in the Falmouth Harbour area.

- *Pilot Gig Racing*: one of the fastest growing sports in Cornwall, with four clubs operating on the Fal estuary.

- *Diving*: there are 14 diving clubs in Cornwall, all of which dive the Fal estuary.

13.6.2.1 Expenditure on Water Sports

There are a large number of commercial operators involved in selling, repairing, chartering and hiring sports equipment and running training courses. It is estimated that within Carrick District alone, 161 firms are directly involved in the above industries, employing over 2 000 people and thus providing roughly 7% of total employment in the area.

Two of the key local organisations are the Restronguet Creek Society (which has an amenity and recreation brief) with 300 members and the Carrick Maritime Action Group which represents 4 000 local water users. Data are not available on levels of expenditure by local residents, but the scale of activity and the associated industry indicates that it is likely to be significant.

The range of water sports activity available in the estuary is also important to tourism. It is estimated that 6% of tourists to Cornwall (and other regions in the West Country) will undertake water sports when on holiday. Estimates have been made of the annual number of visitors and tourist expenditure for Cornwall as a whole and then for the area within Carrick District Council (see Table 13-10).

Table 13-10 : Annual Tourist Visitor Numbers and Expenditure

	Visitors ('000s)	Expenditure (£000s)
Cornwall		
Total	3 100	620 000
Water Sports	186	-
Carrick District		
Total	565	113 000
Water Sports	33.9	-

There are no data on expenditure specific to water sports. Discussions have indicated that the nine largest operators are likely to have annual tourist bookings of from 500 to 600, with the remaining operators taking much smaller numbers of bookings. On this basis, there are an estimated 4 500 plus bookings per year made by tourists. The average value of each booking is roughly £200, indicating that the value of equipment hire, lessons, etc. to tourists alone is £900 000 plus. Obviously, this value would increase if local expenditure on water sports activities were added. It should be noted that this is a conservative estimate as it represents less than 1% of total tourist expenditure.

13.6.2.2 Predicted Impacts on Water Sports

As for informal recreation, both changes in discolouration and changes in metals concentrations will impact upon water sports. Impacts may vary, however, over the short and longer-term under the different objectives.

Under the "No Treatment" objective, widespread media reporting on the changes in water quality, particularly on any incidents of gross discolouration, is likely to lead to an immediate reduction in the demand for water sports in the area. Following the 1992 event, operators experienced immediate reductions in bookings of 15% within a few days. In the longer term, the impacts on water sports usage are likely to depend upon whether or not the Local Authority advise against undertaking water contact sports, as was the case in 1992. Following discussions with operators and the Authority (given the predicted degradation in water quality under this objective and the likely impacts of media coverage on public perceptions), it was concluded that over the longer-term there would be at least a 50% reduction (for the base case) in the current number of tourist related water sports users. Some argued that the tourist related industry would cease altogether, but this seems unlikely given the level of sailing and other non-contact water sports carried out in the area.

It must also be noted that the three principle EC bathing waters for the Fal area (Gyllyngvase, Swanpool and Maenporth) could also be impacted under the "No Treatment" objective. Following the 1992 incident, discolouration was observable at all of these beaches for a few months. These beaches may be similarly affected on a periodic basis.

The current levels of activity are predicted to continue under the "No Deterioration" objective. Furthermore, operators did not identify current water quality as a barrier to the further development of water sports in general. On this basis, it is concluded that the further improvements in quality under the "North Sea Commitments" and "EC Directive" objectives would not have much influence on the levels of tourist related activity and expenditure.

13.6.2.3 Economic Benefits to Water Sports

The economics literature was examined to determine whether or not there were any willingness to pay studies specific to different water sports activities, but no studies were found. As discussed above, a figure of £5.50 has been taken as an estimate of WTP for all recreation activities for local residents, although it is recognised that this is probably an underestimate given the level of water sports activity in the area.

With regard to visitors, changes in expenditure, and thus rent, has been used instead as a means of calculating economic losses. Due to the absence of WTP information specific to the estuary, it was believed that this would provide a better indication of net national losses than transfer of other benefit estimates. There are difficulties, though in using expenditure data as they do not reflect the willingness to pay of those using the estuary to partake in activities there as opposed to other sites in the Southwest, or England and Wales as a whole. It could be argued that in terms of net national effects, all of the activity currently undertaken on the estuary would merely shift to other locations. Thus, there would be a transfer of expenditure away from Carrick District and the Falmouth area to other counties/regions, but at a national level the economic impact of this would be neutral.

In order to address this issue, the potential for shifting water sports activities to other areas was investigated to identify whether there was any "spare capacity" at a regional and national level, or whether activity would move outside the country (e.g. to Spain). Discussions with the Southwest Region Sports Council have indicated that most of the activity would shift to other locations, with the largest proportion remaining in the region and a smaller proportion shifting to other regions. A review of the key factors affecting tourism to the area, however, indicates that increasingly the Cornish market is being affected by lower priced activity holidays overseas (British Tourist Authority, 1993 - see Section 13.9.2). On this basis, it has been assumed here that about 10% of the total expenditure would most likely be lost both to the region and the nation, with the remaining 90% effectively being a transfer of activity. Based on typical profit levels of this sector, we have assumed that about 25% of total expenditure equals gross profits or rent to the operator (Southwest Region Sports Council, personal communication).

On this basis, the estimated benefits of moving from "No Treatment" to one of the other objectives is estimated at roughly £153 000 (see Table 13-11). These estimates do not account for losses which would be incurred, however, should the Local Authority advise against participation in water sports or use of identified bathing waters under the "No Treatment" objective.

Table 13-11 : Recreation Benefits (£)

	No Treatment	No Deterioration	North Sea Commitment	EC Directive
Total bookings per annum	1 125	4 500	4 500	4 500
Average expenditure per booking (£)	200	200	200	200
Total annual expenditure (£)	225 000	900 000	900 000	900 000
Net national expenditure (10%)	22 500	90 000	90 000	90 000
Economic rent (£)	5 625	22 500	22 500	22 500
Local resident WTP (£)	45 375	181 500	181 500	181 500
Total economic value (£)	**51 000**	**204 000**	**204 000**	**204 000**
Incremental benefits (£)	**N/A**	**153 000**	**153 000**	**153 000**

N/A - not applicable

13.7 COMMERCIAL AND PLEASURE BOAT MOORINGS

There are approximately 1 090 moorings in the Restronguet Creek and Carrick Roads areas which may be affected by changes in water quality.

Following the 1992 incident at Wheal Jane, owners/users of boat moorings in Restronguet Creek in particular complained of increased corrosion of the mooring chains and one or two owners complained of problems with corrosion on engines and other parts of boats. The process taking place was electrolytic corrosion, a process produced by contract with two different metals when an electrolyte (a chemical, or its solution in water, which conducts current through ionization) is present, and current flows. The problem was a result of the electrolytes of zinc and copper, on contact with the metal parts of mooring chains and other metal components, attacking those metals in an attempt to replace them as a solid deposit. Discussions with private owners of moorings have indicated that the 1992 incident led to increased costs in maintaining moorings and navigation buoys (due to reduced life expectancy) in the area. In effect, the incident resulted in moorings having a maximum life of less than two years as compared to between two and four years under current conditions. Similarly, the life expectancy of a navigation buoy fell from between eight to ten years under current (and pre-incident) water quality to under eight years following the 1992 event.

It is predicted that the increase in concentrations of zinc which are expected under the "No Treatment" objective would lead to reductions in the life of mooring chains and navigation buoys in Restronguet Creek and the Carrick Roads. Under this objective, mooring would have a life expectancy of less than two years, while buoys would have an expectancy of less than eight years.

Under the "No Deterioration" objective, life expectancies would remain at current levels of two to four years for moorings and at between eight to then years for buoys.

The further reductions in zinc concentrations which would occur under the "North Sea Commitments" objective and zinc and copper under the "EC Directive" objective are expected to result in greater life expectancies for both moorings and buoys. These would become greater than 4 years and 10 years respectively.

Estimates have been made of the benefits associated with moving from the "No Treatment" objective to higher water quality objectives (see Tables 13-12 and 13-13). The increase in life expectancy and thus reductions in maintenance costs result in per annum benefits in excess of £33 000 in moving from "No Treatment" to "No Deterioration" and of £66 000 in moving from "No Treatment" to the two higher quality objectives.

Table 13-12 : Benefits to Mooring Owners (£)

	No Treatment	No Deterioration	North Sea Commitment	EC Directive
Total number of moorings	1 090	1 090	1 090	1 090
Per annum cost (£) maintaining each mooring	100	70	40	40
Total per annum cost (£) of maintaining all moorings	109 000	76 300	43 600	43 600
Incremental Benefits (£)	**N/A**	**32 700**	**65 400**	**65 400**

N/A - not applicable

Table 13-13 : Benefits to Navigation Buoy Owners (£)

	No Treatment	No Deterioration	North Sea Commitment	EC Directive
Total number of buoys	15	15	15	15
Per annum cost of maintaining each buoy (£)	86	60	35	35
Total per annum cost of maintaining all buoys (£)	1 290	900	525	525
Incremental Benefits (£)	**N/A**	**390**	**765**	**765**

N/A - not applicble

13.8 PROPERTY VALUES

13.8.1 Introduction

There are numerous residential properties located along the banks of Restronguet Creek and the Carrick Roads, with more or less direct water views extending out over various parts of the area. Discussions with estate agents and other relevant authorities concerning these properties have indicated that the value of these residential properties are at least partially related to their water views of the harbour, and that aesthetic changes in water quality due to ochre discolouration would affect the value of these properties. Because there are a relatively small number of commercial properties in the area, these have not been considered further (although other impacts on income, etc. are considered elsewhere in this appraisal).

A total of eight key residential areas have been identified, which include a total of 540 properties, with more or less direct water views of the Creek or Roads (see Figure 13.1). The relative importance of the eight sites is as follows:

- Site 1: 100 properties along the southern banks of Mylor Creek.
- Site 2: 14 properties just south of Weir Point, along the western banks of the Carrick Roads.
- Site 3: 29 properties along the southern banks of Restronguet Creek.
- Site 4: 68 properties along the north eastern banks of Restronguet Creek.
- Site 5: 183 properties along the northern banks of Restronguet Creek.
- Site 6: 44 properties located at Loe Beach and along the banks of Pill Creek.
- Site 7: 2 properties located just east of Messack Point.
- Site 8: 100 properties along the south eastern banks of St Just Pool.

In order to provide an indication of the value of these residential properties, data were collected on the 1991 Council Tax Band classifications. More than half of the 540 residential properties are at Sites 3, 4 and 5 (comprising 52%) which are located either along the banks, or have a view, of Restronguet Creek. Moreover, the majority of all residential properties (64%) are valued in excess of £120 000, suggesting that they tend to occupy the upper-end of the residential property market.

Although properties at the above sites are those which are most likely to be affected by discolouration, it should be noted that there are large numbers of residential and commercial properties along the lower part of the estuary (e.g. St Mawes and Falmouth). These properties taken together will have a value orders of magnitude greater than that estimated above.

13.8.2 Predicted Impacts on Property Values

Changes in the aesthetic or visual appearance of water as a result of ochre-related discolouration in Restronguet Creek and the Carrick Roads are likely to impact upon residential property prices. Widespread discolouration is likely to occur under the "No Treatment" objective (see Section 7). The effect of discolouration on property values has been considered under the "no treatment" objective for the following scenarios:-

- during periods of low rainfall and increased groundwater recharge, the area affected would be mainly within Restronguet Creek, with some impact on the northeastern section of the Carrick Roads;

- during periods of high rainfall and increased groundwater recharge, the area affected would extend throughout the Carrick Roads to Pendennis Point and Zone Point; there would also be some discolouration up the River Fal.

Under the first scenario all of the properties located in Sites 1 to 6 would be affected. Under the second scenario, Sites 1 to 8 would be affected, and it is likely that other properties in Flushing, St Mawes and Falmouth would also be affected on a periodic basis. As indicated earlier, should periodic discolouration in the Falmouth area affect the use of bathing beaches, then property values in Falmouth may also be affected.

The two objectives were presented to two different estate agents to elicit their views on the effects which discolouration would have on property values. From these discussions, a consensus was obtained that some properties would be severely affected, while others would be less so. Surprisingly, the two agents both indicated that most of the properties would experience from between 20 to 40% decreases in value, with the remainder experiencing, say from 5% to 20%. These high values reflect the fact that some buyers purchase a property for location only, then proceed to demolish the existing home and rebuild.

Given the magnitude of these guesstimates, the economics literature was also examined to compare these values to those which have been found through the application of hedonic pricing techniques. Significant positive effects on house prices have been found for proximity to urban parks, greenbelts and forested areas (Ref. 4). Of more relevance are two studies which have estimated the value of proximity to rivers and canals. Garrod and Willis (Ref. 4) applied the hedonic pricing method to the valuation of different countryside characteristics, with proximity to rivers or canals being one of the characteristics examined. The study found that this would raise the average house price by 4.9%. The second study (Ref. 5) focused on waterways and canals and found that premiums ranged from about 2% to 5% depending on geographic location. This second study also elicited estimates from about 60 estate agents on the price premium associated with waterfront locations. From this, an average figure of 18.6% was estimated for location on the waterfront and about 8% for locations adjacent to the waterfront. These findings suggest that estate agents tend to overestimate the premium associated with waterfront locations and associated amenities.

For the purposes of this appraisal, we have adopted conservative premium assumptions and have limited consideration to the eight key sites. It has been assumed that, under the "No Treatment" objective, degradation in water quality and resultant discolouration would result in a 10% reduction in residential property prices for the base case. This premium reduction is significantly less than that suggested by the estate agents, but also takes into account the fact that in general environmental quality losses are more highly valued than environmental quality gains (i.e. compensation requirements are higher than willingness to pay).

Figure 13.1 Location of Key Residential Areas

Under the "No Deterioration" objective, property prices would remain at present levels; while further improvements in water quality under the "North Sea Commitments" and "EC Directive" objectives are not expected to have any significant aesthetic effects and thus would not have a significant affect on residential property prices (although there may be some increase in value of those properties directly located on the foreshore due to the relationship between improved water quality and potential uses of the waters).

13.8.3 Estimated Benefits to Property Values

Table 13-14 presents estimates of the value of all residential properties under the different water quality objectives.

Because prices for individual properties were not available, these estimates have been derived by taking the mid-point for each council tax band as representing the average value of all properties within that band, with the exception of residential properties exceeding £320 000. For those properties valued less than £320 000, it is believed that this approach provides a reasonable estimate as prices are likely to be distributed between the upper and lower limits in each band. However, because there is no upper limit from which to calculate a mid-point, all property prices valued greater than £320 000 are taken as £320 000. While this may tend to bias the total value of residential properties downward, only 10% of residential properties are valued at greater than £320 000.

The 10% change in the capital value of these properties when moving from the "No Treatment" objective to the improved water quality objectives is estimated to be equal to about £8.4 million. Given that this is likely to be an underestimate of the true effects as losses are also likely to occur to owners of properties in the lower part of the estuary, adoption of the "No Treatment" objective could represent significant losses in the capital values of property assets.

Table 13-14 : Economic Benefits to Residential Properties

Site	No Treatment	No Deterioration	North Sea Commitment	EC Directive
1	7 517 700	8 353 000	8 353 000	8 353 000
2	2 368 800	2 632 000	2 632 000	2 632 000
3	4 185 000	4 650 000	4 650 000	4 650 000
4	14 872 500	16 525 000	16 525 000	16 525 000
5	24 607 800	27 342 000	27 342 000	27 342 000
6	7 228 800	8 032 000	8 032 000	8 032 000
7	95 400	106 000	106 000	106 000
8	14 539 500	16 155 000	16 155 000	16 155 000
Total (£)	**75 415 500**	**83 795 000**	**83 795 000**	**83 795 000**
Incremental Benefits (£)	**N/A**	**8,379,500**	**8,379,500**	**8,379,500**

N/A - not applicable

13.9 TOURISM

There are over 3 million visitors per year to Cornwall, with only London and Devon having significantly larger numbers of visitors. Out of this number, there are approximately 575 000 tourists to the Carrick District.

Tourist spending for the county as a whole is estimated at £620 million per annum, with £113 million of this being in Carrick District. Out of the total gross spending of £113 million, it is estimated that about £44 million remains in the District as an important source of net income.

For the county as a whole, tourism related employment is estimated to be at least 30 000 out of a total of 175 000 jobs, or 17% of total jobs. Given that the county currently faces unemployment rates of roughly 12%, the importance of protecting the tourism industry is apparent.

13.9.1 Impacts on Tourism

The impacts on tourism and thus on the regional economy will be related to the effects which the different water quality objectives have on public perceptions of the area, on the loss of key species (e.g. sea bass or waders) and on any restrictions placed on certain activities, such as water sports.

Perceptions of the area as one of high ecological quality and thus natural beauty are likely to be damaged under the "No Treatment" objective with periods of significant discolouration. This is likely to affect not only the numbers coming to the area for recreational purposes, but also the numbers of more general tourists since "natural beauty" is such an important part of choosing Cornwall as a holiday destination. In addition, it is unlikely the estuary would be selected to hold major water sports or sailing events in the future.

Furthermore, should the increases in heavy metal concentrations and in discolouration in water in Carrick Roads and elsewhere in the estuary be great enough, the Local Authority may find it necessary to advise against bathing and water sports. Again, this will lead to a loss of tourism as much of it is tied to bathing and, to a lesser degree, water sports. Impacts on the tourist industry would be particularly hard if the EC identified beaches were affected. Similarly, should decreases in water quality lead to impacts on angling, then there would be further reductions of associated expenditure in the area.

It is less clear what the impact of improvements in water quality above current levels (as represented by "No Deterioration") would mean. It could result in increased tourism as a result of higher quality marine ecosystems and thus species diversity and interest. Increases in water sports may also occur if this led to people viewing the area as a healthier location and engaging in more activities as a result.

13.9.2 Benefits to Tourism

The area is currently viewed as a seaside holiday resort. If the image of the area as having good clean beaches, etc. is eroded as a result of decisions concerning the long-term management of discharges from Wheal Jane, this could have serious implications for the tourist industry. The reality of this is illustrated by the fact that after the 1992 incident there were immediate cancellations of holidays to Truro, Falmouth and the surrounding area.

The tourist industry in Cornwall is already facing a steady decline in visitors. Although it is clear that adoption of the "No Treatment" objective would result in regional losses, it is not clear what proportion of these may also be national economic losses. Some activities will shift to other parts of Cornwall, other parts in the Southwest or other regions in the country. However, it can also be expected that there will be a further shift to discounted overseas holidays, which has already affected the traditional summer seaside holiday market.

13.10 SUMMARY OF RESULTS

13.10.1 National Effects

13.10.1.1 Introduction

The preceding sections presented estimates of the per annum benefits gained in moving from the "No Treatment" objective to the three alternative objectives. Table 13-15 provides a summary of these incremental benefits. In examining this table, it is important to note that it has not been possible to value a number of impacts in monetary terms. These include:

- impacts on the conservation value of the area, including those on marine biota, the maerl beds and on bird populations;
- impacts on the smaller, more informal commercial fisheries (such as crabs); and similarly impacts on some of the recreational fisheries (such as sea trout);
- impacts on informal recreation users of the area, including benefits gained to users of the Mineral Tramways from the creation of a wetland with a passive treatment solution; and
- impacts on the tourist industry.

Of these non-valued effects, potential impacts on the conservation value of the area and on tourism are likely to be extremely significant. With regard to conservation, there is particular concern over the potential general loss in biodiversity and species abundance under the "No Treatment" objective. Similarly, tourism to the area may be seriously affected due both to limits on water sports in the Carrick Roads area, and also due to the potential for unwillingness to bathe at identified EC bathing waters as a result of discolouration.

Table 13-15 : Incremental Benefit Estimates (£)

Activity	No Treatment Baseline Value	Annual Incremental Benefits*		
		No Deterioration	North Sea Commitments	EC Directive
Oysters	50 000	150 000	150 000	150 000
Sea Bass	263 903	263 903	301 105	301 105
Maerl extract.	0	810 000	810 000	810 000
Water Sports	51 000	153 000	153 000	153 000
Moorings	110 290	33 090	66 165	66 165
Property*	75 415 500	8 379 500	8 379 500	8 379 500

* Property related benefits represent a one-off change in capital value, with benefits assumed to occur immediately.

13.10.1.2 Discounted Benefits

From the above, the present value of benefits for each of the higher quality objectives has been estimated. These have been calculated on the following basis:

- three time horizons are considered: 10 years, 25 years and 50 years;
- the discount rate used is 6% (the Treasury rate for the NRA); and
- sensitivity analysis has been carried out to indicate the importance of assumed estimates to the comparison of water quality objectives.

Table 13-16 presents the discounted benefit estimates for each of the use categories and in total. As can be seen from Table 9-1, for the base case the incremental benefits estimated for the "North Sea Commitments" and "EC Directive" objectives are the same. The further improvements in water quality obtained under the "EC Directive" objectives were predicted to provide no additional benefits to the six use categories. Furthermore, the difference in benefits between the "No Deterioration" and "North Sea Commitments" and "EC Directive" objectives are accounted for by impacts on the sea bass fishery and to moorings owners only.

Table 13-16 : Base Case Present Value Estimates (£s)

Objective	Activity	10 Years	25 Years	50 Years
No Deterioration	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 206 000	3 637 000	4 424 000
	Maerl extract.	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	277 000	456 000	555 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 162 000**	**27 805 000**	**32 003 000**
North Sea Commitments	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 517 000	4 150 000	5 047 000
	Maerl extract.	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	553 000	912 000	1 109 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 749 000**	**28 774 000**	**33 181 000**
EC Directive	Oysters	1 258 000	2 074 000	2 523 000
	Sea Bass	2 517 000	4 150 000	5 047 000
	Maerl Extract.	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	553 000	912 000	1 109 000
	Property	8 380 000	8 380 000	8 380 000
	Total	**20 749 000**	**28 774 000**	**33 181 000**

The incremental gains in moving from the "No Deterioration" objective to the "North Sea Commitments" and "EC Directive" objectives are estimated at roughly £1.18 million for the 50 year time horizon. This value represents the further benefits to those involved in the sea bass fisheries and to owners of moorings and navigation buoys only. Of equal, if not greater, importance is the fact that the improved water quality associated with these two objectives is likely to enhance or at least ensure protection of the conservation status of the area, in particular with regard to certain marine biota and bird populations.

13.10.1.3 Sensitivity Analysis

In order to test the sensitivity of the present value calculations to changes in assumptions on the level of impact, a series of alternative assumptions were considered. In particular, two different cases representing a "high estimates" case and a "low estimates" case were developed, with these being defined as follows:

- **High Estimates:** this assumes that the "no treatment" values for the six activities are significantly lower than those assumed under the base case (representing higher levels of environmental damage compared to the current situation), and that the higher water quality objectives lead to significant increases in activity and thus benefits. The areas of use which would benefit under the "North Sea Commitments" and "EC Directive" objectives are the oyster fishery, the extraction industry, water sports and property.

- **Low Estimates:** this assumes that the economic values under the "No Treatment" objective are similar to those for the current situation (representing lower levels of environmental damage), and that there are no further gains over the base case for the two higher quality objectives.

Table 13-17 presents the assumptions made for these two cases concerning the incremental benefits resulting from changes in water quality. Table 13-18 then gives the discounted benefit estimates for the "high estimates" case, while Table 13-19 gives those for the "low estimates" case. Table 13-20 summarises the implications of these two cases with regard to percentage changes in the end present value estimates.

The change in estimated benefits is from roughly 43 to 47% under the "low estimates" case, while the increase in benefits varies from around 36% to 65% under the "high estimates" case. It is important to note those assumptions which account for these changes in value. Under the "low estimates" case assumptions concerning benefits to the maerl extraction industry account for the largest share of the difference (45%), while reductions in the impacts on property values account for over 28% of the decrease in total discounted benefits.

Similarly, impacts on property values account for between 58 to 73% of the difference under the "high estimate" assumptions, with benefits to the sea bass fishery accounting for around 19% and benefits to the oyster fishery accounting for between 7% and 13%. The exception is for the "EC Directive" objective, where increases in maerl extraction leads to incremental gains of a further 16%.

At a more general level, however, the sensitivity analysis indicates that the uncertainty associated with prediction of the potential benefits which might arise from implementation of the "EC Directive" objective, in particular, is important to the comparison of options. These benefits may be far higher than those assumed under the base case.

Table 13-17 : Incremental Benefit Estimates (£s)

Activity	No Treatment Baseline Value	Incremental Benefits		
		No Deterioration	North Sea Commitments	EC Directive
High Estimates Case				
Oysters	0	200 000	250 000	300 000
Sea Bass	131 950	395 850	433 060	433 060
Fertiliser	0	810 000	810 000	1 012 500
Water Sports	51 000	153 000	153 000	204 000
Moorings	110 290	33 090	66 165	66 165
Property*	67 036 000	16 759 000	16 759 000	20 948 750
Low Estimates Case				
Oysters	300 000	100 000	100 000	100 000
Sea Bass	301 100	226 700	263 900	263 900
Fertiliser	405 000	405 000	405 000	405 000
Water Sports	153 000	51 000	51 000	51 000
Moorings	110 290	33 090	66 165	66 165
Property*	79 605 280	4 189 720	4 189 720	4 189 720

* Property related benefits represent a once-off changes in capital value, with benefits assumed to occur immediately.

Table 13-18 : High Estimates Case (Discounted Benefits £s)

Objective	Activity	10 Years	25 Years	50 Years
No Deterioration	Oysters	1 672 000	2 757 000	3 352 000
	Sea Bass	3 309 000	5 456 000	6 635 000
	Fertiliser	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	227 000	456 000	555 000
	Property	16 759 000	16 759 000	16 759 000
	Total	**30 058 000**	**38 686 000**	**43 424 000**
North Sea Commitments	Oysters	2 090 000	3 446 000	4 190 000
	Sea Bass	3 620 000	5 969 000	7 259 000
	Fertiliser	6 772 000	11 165 000	13 577 000
	Water Sports	1 270 000	2 093 000	2 546 000
	Moorings	553 000	912 000	1 109 000
	Property	16 759 000	16 759 000	16 759 000
	Total	**31 064 000**	**40 344 000**	**45 440 000**
EC Directive	Oysters	2 508 000	4 135 000	5 029 000
	Sea Bass	3 620 000	5 969 000	7 259 000
	Fertiliser	8 465 000	13 956 000	16 971 000
	Water Sports	1 693 000	2 791 000	3 394 000
	Moorings	553 000	912 000	1 109 000
	Property	20 949 000	20 949 000	20 949 000
	Total	**37 788 000**	**48 711 000**	**54 710 000**

Table 13-19 : Low Estimates Case (Discounted Benefits £s)

Objective	Activity	10 Years	25 Years	50 Years
No Deterioration	Oysters	836 000	1 378 000	1 676 000
	Sea Bass	1 895 000	3 125 000	3 800 000
	Fertiliser	3 386 000	5 582 000	6 789 000
	Water Sports	423 000	698 000	849 000
	Moorings	277 000	456 000	555 000
	Property	4 190 000	4 190 000	4 190 000
	Total	**11 007 000**	**15 429 000**	**17 858 000**
North Sea Commitments	Oysters	836 000	1 378 000	1 676 000
	Sea Bass	2 206 000	3 637 000	4 423 000
	Fertiliser	3 386 000	5 582 000	6 789 000
	Water Sports	423 000	698 000	849 000
	Moorings	553 000	912 000	1 109 000
	Property	4 190 000	4 190 000	4 190 000
	Total	**11 594 000**	**16 398 000**	**19 036 000**
EC Directive	Oysters	836 000	1 378 000	1 676 000
	Sea Bass	2 206 000	3 637 000	4 423 000
	Fertiliser	3 386 000	5 582 000	6 789 000
	Water Sports	423 000	698 000	849 000
	Moorings	553 000	912 000	1 109 000
	Property	4 190 000	4 190 000	4 190 000
	Total	**11 594 000**	**16 398 000**	**19 036 000**

Table 13-20 : Comparison of Present Value Estimates (£s Change)

Objective	Low Case	Base Case	Best Case
No Deterioration	17 036 000	32 003 000	43 424 000
	-47%	0%	36%
North Sea Commitments	19 036 000	33 181 000	45 440 000
	-43%	0%	37%
EC Directives	19 036 000	33 181 000	54 710 000
	-43%	0%	65%

13.10.2 Regional Impacts

In accordance with Treasury guidelines, this appraisal has focused on the net national economic impacts of the different long-term water quality objectives associated with different long-term management options for Wheal Jane. As can be seen from the above discussion, the net national benefits associated with preventing any further deterioration in water quality are significant, with a discounted value of over £32 million (over 50 years).

In considering this estimate, however, it is also important to recognise the potential regional impacts associated with changes in water quality in the estuary. The appraisal has touched on these in a number of places, with key regional impacts being related to:

- impacts on fisheries;
- impacts on water sports and recreation in the area;
- impacts on the local property market; and
- impacts on tourism.

Expenditure on sea bass angling and water sports was estimated at approximately £3 million and £6 million respectively. Although much of this expenditure would be likely to transfer to other parts of the country should opportunities be lost in the Fal estuary, losses to the local economy would be considerable.

Similarly, tourist related expenditure is currently estimated at around £113 million per annum, with about £44 million of this remaining in Carrick District. If a large proportion of tourists transferred their visits to other parts of the region or country, again the impact on the Cornish economy would be substantial. By way of example, every £17 000 in tourist expenditure is roughly equal to one job. Thus, if 50% of tourists stopped visiting Carrick District, there would be a loss of well over 1 000 jobs. In a region currently facing high levels of unemployment, these losses would have a marked effect on the economy.

13.11 REFERENCES

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(4) Garrod G and Willis K (1991). The Hedonic Price Method and the Valuation of Countryside Characteristics, Working Paper 14, Countryside Change Working Paper Series, Town and Country Planning, University of Newcastle upon Tyne.

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14. TREATMENT OPTIONS

CONTENTS

14.1 INTRODUCTION

The development of an integrated treatment strategy to reduce the impact of metal laden acidic minewater on the Carnon River has required an assessment of the sources of contamination and the detailed appraisal of the potential methods of remediation.

The water quality studies detailed in Sections 6 and 7 have identified that:-

- Wheal Jane and County Adit are the main point sources of contamination.
- Unidentified diffuse sources both upstream and downstream of Bissoe Bridge make a significant contribution to the metal loading in the Carnon River.

Water quality objectives and possible scenarios for achieving these objectives have been identified in the following Sections:

7 Development of Water Quality Objectives
9 Prevention & Control of Discharges
10 Passive Treatment Technology
11 Active Treatment Technology
12 Sludge Disposal

The conclusions from these sections are briefly summarised in the following subsections and comparisons made regarding the technological and economic merits of each of the identified treatment schemes. Conclusions are drawn from these comparisons and a recommendation made regarding the future treatment strategy for the Wheal Jane minewater problem.

14.2 CONTAMINATION SOURCES

The two major sources of contamination entering the Carnon River are the untreated Wheal Jane minewater flow issuing from Nangiles Adit and the flow from County Adit. In 1993/94, despite the operation of the existing treatment system, the flow from Nangiles Adit contributed between 20 and 85% of the average annual metal loading in the Carnon River at Devoran Bridge. During this period the contribution from County Adit was between 8 and 54%. Details for individual metals are summarised on Table 14-1.

Table 14-1 : Relative Importance of Sources of Contamination (with Existing Treatment)

	Al	As	Cd	Cu	Fe	Mn	Zn
Wheal Jane and Nangiles Adit (including treated No. 2 Shaft water)	52%	20%	56%	23%	85%	53%	77%
County Adit	33%	41%	20%	54%	8%	35%	13%

Data Period October 1993 - September 1994.

The predicted contributions from Wheal Jane and County Adit without treatment of the Wheal Jane No. 2 Shaft minewater are summarised in Table 14-2.

Table 14-2 : Predicted Relative Importance of Sources of Contamination (Without Existing Treatment)

	Al	As	Cd	Cu	Fe	Mn	Zn
Wheal Jane and Nangiles Adit	82%	96%	87%	39%	96%	81%	93%
County Adit	12%	2%	8%	43%	2%	14%	4%

Simulation Period October 1993 - September 1994.

The total dissolved metal concentrations in the Wheal Jane No. 2 Shaft minewater have declined from in excess of 3000 mg/l in 1992 to approximately 500 mg/l in 1994. Inspection of the data indicates that the metal concentrations are:

- continuing to decline but at a much reduced rate;
- affected by seasonal changes in flow through the mine.

Continued data collection will allow both seasonal trends to be established and the development of a model to simulate the decline. Until such a model has been developed extrapolation of the data to predict future concentration is considered to be inappropriate. Minewater treatment requirements therefore have been assessed on a conservative basis using the average annual metal concentration measured between October 1993 to September 1994 inclusive.

Additional unidentified sources of contamination contributing to the metal loading in the Carnon River may include:

- runoff from dumps and tailings deposits;
- seepage from old workings and tailings deposits;
- contaminated water from the smelters, chemical and arsenic works which formerly occupied the valley.

14.3 WATER QUALITY AND TREATMENT OBJECTIVES

Three water quality objectives have been developed by the NRA for the Carnon River as summarised in Table 14-3. Numerical modelling of the major sources of contamination entering the Carnon River has enabled the treatment requirements necessary to achieve these objectives to be estimated, as detailed in Table 14-4.

Table 14-3 : Water Quality Objectives for Devoran Bridge

Substance		Predicted "No Treatment" Water Quality	Water Quality Objectives: No Deterioration	North Sea Commitments	EC Directive
Cadmium	95 %ile		11 (T)	-	-
as μg Cd/l	AA	21 (T)	6 (T)	-	1.0 (T)
Copper	95 %ile		0.9 (T)	-	-
as mg Cu/l	AA	0.8 (T)	0.6 (T)	-	0.028 (D)
Zinc	95 %ile		13 (T)	-	-
as mg Zn/l	AA	26 (T)	6 (T)	3 (T)	0.5 (T)
Arsenic	95 %ile		0.3 (T)	-	-
as mg As/l	AA	n/a	0.1 (T)	-	0.050 (T)
Iron	95 %ile		17 (T)	-	-
as mg Fe/l	AA	52 (T)	8 (T)	-	1.0 (D)
Manganese	95 %ile		1.0 (T)	-	-
as mg Mg/l	AA	1.7 (T)	0.7 (T)	-	-
Aluminium	95 %ile		4.0 (T)	-	-
as mg Al/l	AA	6.2 (T)	2.1 (T)	-	-
pH	95 %ile		4.2	-	6.0
as pH units	5 %ile	n/a	7.1	-	9.0

Notes : EC Directive EQS values based on hardness > 250 mg/l $CaCO_3$/l.
AA ... Annual Average
(T) ... Total metal; (D) ... Dissolved metal.
n/a ... not available

Where a particular objective does not contain targets for every parameter, the values ascribed in the preceding objective have been applied.

Table 14-4 : Minewater Treatment Capacity to meet each Water Quality Objective

Annual probability of non-compliance	50%		5%	
	Maximum capacity (l/s)	Average flow (l/s)	Maximum capacity (l/s)	Average flow (l/s)
No Deterioration				
Annual Average	190	160	270	180
95%ile	210	170	300	190
North Sea Commitments				
Annual Average	230	175	300	190
EC Directive	Unable to meet all EC Directive Requirements			

The studies have indicated that:

(a) A maximum treatment capacity of 300 l/s is required to achieve both the "No Deterioration" and "North Sea Commitments" objectives, with a 5% annual probability of non compliance (i.e. on average 1 year in 20 will not comply).

(b) Due to the presence of other, unidentified, dispersed sources of contamination, compliance with the EC Directive objective cannot be achieved by just treating water from Wheal Jane and County Adit.

14.4 PREVENTION

A number of potential options for reducing the quantity of contaminated water released from the mine have been considered. An appraisal of the suitability of each technique for application at Wheal Jane has revealed that the only potentially viable method of amelioration is the control of stream/groundwater interaction.

Piezometric monitoring has demonstrated that it is hydraulically feasible for flow to occur from the river into the groundwater system, but has not quantified the potential quantity of seepage that may be occurring.

Some engineering works were carried out in 1975, where the river crosses the outcrop of the orebody to reduce flow from the river into the old mine workings. It has therefore been assumed that the potential for ground/surface water interaction has been substantially reduced, however, this remains to be confirmed.

14.5 TREATMENT SYSTEM APPRAISAL

Potential future treatment options have been appraised both on a technical and financial basis. Treatment methods which have been demonstrated to be technically viable have been costed for project lives of 5, 10, 25 and 50 years. Where appropriate, allowances have been made for:

- Capital Works
- Power
- Consumables
- Plant Operatives
- Maintenance
- Sludge Disposal
- Planning and Design Engineering Fees
- Upgrading Jane's Adit

Costs have been calculated using a combination of sources, including the existing treatment system, quotations and tendered rates. No allowance has been made for:

- Water quality monitoring
- NRA project management and on site management
- Site Restoration

Since the costs have been discounted to net present values, no allowance has been made for inflation.

The Treasury discount rate of 6% has been used to calculate present values for each treatment option. These values have been used for both comparison and cost benefit analysis purposes.

14.6 EXISTING TREATMENT SYSTEM

The existing treatment system has been progressively developed by the NRA since its inception in 1991. Between 1991 and December 1994, the system has successfully removed some 12 500 t of metal.

The system now has an installed capacity of 300 l/s, but has been operated to treat an average annual flow of approximately 155 l/s. The predicted frequency of compliance with both the "No Deterioration" and "North Sea Commitments" water quality objectives at this flow rate is summarised in Table 14-5.

Table 14-5 : Existing Treatment System Predicted Probability of Compliance with the Water Quality Objectives for a Treatment Rate of 155 l/s

	Probability of Compliance (%)		
	No Deterioration		North Sea Commitments
Metal	Annual Average	95%ile	Annual Average
Cadmium	90	80	-
Copper	70	85	-
Iron	20	5	-
Zinc	55	55	<5
Manganese	90	80	-
Aluminium	80	85	-

Table 14-5 indicates that, with the exception of iron and zinc, the existing treatment system achieves the "No Deterioration" Water Quality Objective with a relatively high annual probability of compliance.

As detailed in Sections 4 and 12, the operating life of the existing treatment facility is limited by the storage capacity remaining within the Clemows Valley Tailings Dam. Sufficient storage is available until the end of 2000 for co-deposition of metalliferous sludge and tailings or until 2010 without tailings addition. This storage capacity can however be increased by dewatering the sludge prior to deposition, using active treatment technology (see Section 14.8).

The estimated costs for the continued operation of the existing treatment facility are summarised in Table 14-4 and have been discounted to present values using a discount rate of 6%.

Table 14-6 : Existing Treatment Facility - Projected Costs

Average annual flow treated (l/s)	155	190
Annual operating costs	748 000	810 000
Discounted Cashflow:		
5 years	3 150 000	3 410 000
10 years*	5 510 000	5 960 000

* Based on sole use of the dam for sludge deposition from January 1996 onwards

Continued operation of the existing treatment system beyond the end of 2000, and hence the discounted cost for a 10 year project life, is dependent on:

- South Crofty plc ceasing to deposit tailings in the Clemows Valley Tailings Dam by the end of 1995.
- Negotiating continued use of the dam and the provision of embankment construction at an equivalent, all inclusive, disposal cost of £48/t of dry sludge.

14.7 PASSIVE TREATMENT

The preliminary passive treatment plant sizing and costings presented in Section 10 have revealed that, based on the current metal loadings:

(a) The land area available within the Lower Carnon Valley may be adequate to allow a passive treatment plant to achieve 50% compliance with the "No Deterioration" objective. Subject to the confirmation of the performance of the pilot treatment plant, passive treatment may therefore offer an alternative to the existing treatment system, provided the risk of non-compliance is acceptable.

(b) There is insufficient space available on the Carnon Valley Tailings Deposits to enable the construction of a passive treatment plant to achieve either the "No Deterioration" or" North Sea Commitments" objectives with a 5% annual probability of non-compliance.

(c) Sufficient land may be available if both the Carnon Valley Tailings Deposits and the surface of the Clemows Valley Tailings Dam are used to construct a passive plant. Construction on the surface of the tailings dam would be both technically difficult and expensive. Additional costs would also be incurred in pumping water from underground and on the water transfer system between the two sites.

The capital cost of a passive treatment system is dependent on both the performance of the pilot plant and the type of substrate used. Indicative construction costs are:

No Deterioration Objective 50% Annual Probability of Non-Compliance	£11 - 18 million
No Deterioration and North Sea Commitments Objectives 5% Annual Probability of Non-Compliance	£15 - 28 million

Passive treatment within the Carnon Valley may offer a technical and financially viable option for treating:

(a) diffuse sources of contamination;

(b) Wheal Jane minewater, should the metal loadings decay significantly.

14.8 ACTIVE TREATMENT TECHNOLOGY

The applicability of various active treatment options has been appraised in Section 11. The assessment of possible sites for the storage of the metalliferous sludge produced by active treatment is detailed in Section 12. The main conclusions from these studies are:

- The existing treatment system offers the most cost effective method of treatment whilst the Clemows Valley Tailings Dam remains available for both effluent clarification and sludge storage.

- Active treatment can be most effectively achieved by means of a high density sludge system, preferably located at the Wheal Jane Mine site.

- Sludge dewatering requirements are dependent on the availability of a suitable waste storage facility. However, the use of frame and plate filters is the preferred option, especially if off-site sludge disposal is necessary.

Various treatment options for attaining the water quality objectives at Devoran Bridge have been considered and costed in Section 11. The costs associated with the preferred active treatment option (high density sludge process followed by dewatering by frame and plate filter press) are summarised in Table 14-7. These include full construction and annual operating costs to achieve both the "No Deterioration" and the "North Sea Commitments" water quality objectives, with a 5% annual probability of non-compliance.

Table 14-7 : Predicted Costs for the Active Treatment System

Installed Capacity Average Flow Rate	300 l/s 190 l/s		
Treatment Plant Location	Mine Site	Mine Site	Carnon Valley
Sludge Disposal[1]	Mine Site	Off Site	Off Site
Capital Cost	£ 5 440 000	£ 5 440 000	£ 7 440 000
Annual Operating Cost	£ 640 000	£ 830 000	£ 774 000
Net Present Value of Costs[2]			
5 yr	£ 7 990 000	£ 8 610 000	£ 10 315 000
10 yr	£ 10 000 000	£ 11 220 000	£ 12 750 000
25 yr	£ 13 475 000	£ 15 725 000	£ 16 950 000
50 yr	£ 15 380 000	£ 18 200 000	£ 19 250 000

[1] High density sludge product dewatered using frame and plate filters.
[2] Assumptions: Continued existing treatment for 1 year whilst plant is built.
Mine site sludge disposal into the Clemows Valley Tailings Dam.
Off site sludge disposal to a licenced landfill site.

Table 14-7 reveals that:

- The most cost effective location for a treatment plant is at the Wheal Jane Mine site.
- On site sludge disposal is approximately £200 000/yr cheaper than removal off site to a licenced landfill site. Over 50 years this amounts to a reduction in the present value of the project costs of nearly £3 million.

14.9 FUTURE TREATMENT STRATEGY

The costs presented in Sections 14.6 to 14.8 have confirmed that the existing treatment system is the most cost-effective method of treating the Wheal Jane minewater. However as previously indicated the system relies on the availability of Clemows Valley Tailings Dam which has a remaining life of between 5 and 14 years. Comparison of both active and passive treatment indicates that:

- Active treatment is the only technically proven method of achieving both the "No Deterioration" and "North Sea Commitments" objectives with an annual probability of non-compliance of not greater than 5%.
- An active treatment system can be constructed either on the mine site or on NRA owned property.

- For a 50 year project life, the discounted cost of active treatment with sludge disposal on site, is £15 million which is less than the indicative upper bound cost of building a passive treatment plant to achieve the "No Deterioration" objective with a 50% annual probability of non compliance.

The recommended future strategy is the continued operation of the existing system, followed by a reappraisal of the treatment requirements, and probably the construction of the preferred active system.

Continued operation of the existing treatment facility will beneficially enable:

- Further monitoring and the more certain prediction of the decline in Wheal Jane metal concentrations. These concentrations determine the size of the required long-term treatment plant and therefore any further reduction will result in a more cost-effective solution.

- The development of an integrated water quality model for the Carnon Valley.

- The identification and assessment of treatment options for the major areas of diffuse contamination.

The effect on project cost of delaying the implementation of the long term treatment system has been established on the assumption that the existing system is operated for either an additional 1, 5 or 12 years and replaced after this period with an active system. The projected cash flow and present value of the costs for these options are summarised in Figure 14.1.

Figure 14.1 indicates that on the assumption that the tailings dam is solely used for the sludge deposition from January 1996, the lowest present value cost is achieved by deferring plant construction for as long as practicable. In particular, for project lives in excess of 25 years, the present value of the proposed treatment strategy can be reduced by up to £900 000.

Delaying the construction of an active treatment system until year 12 is dependent on both successful negotiations with South Crofty Plc, to secure long term use of the tailings dam, and the relocation of South Crofty's milling operations off site. The practicalities and possible timing of the mill relocation remain uncertain and therefore the assumption has been made that tailings deposition into the Clemows Valley Tailings Dam is likely to continue for the next 5 years. On this basis, the Treatment Strategy detailed in Table 14-8 has been developed for the next 5 years.

Table 14-8 : Recommended Future Treatment Strategy

Period	Activity
1996-2000	Continued operation of the existing treatment system.
1996-1999	On-going data collection, planning studies, etc.
1999	Reappraisal of the treatment requirements and detailed design of the long term treatment system.
2000	Construction and commissioning of the long term treatment system at the mine site.
2001-onwards	Active treatment with sludge disposal to the Clemows Valley Tailings Dam.

14.10 COST BENEFIT ANALYSIS

The cost estimates prepared for the Recommended Future Treatment Strategy have been discounted to present values and used in conjunction with the data from the economic benefit assessment, detailed in Section 13, to calculate both net present values and benefit cost ratios.

Net present values (NPV) and benefit/cost ratios (B/C) have been calculated for the recommended future treatment strategy based on:

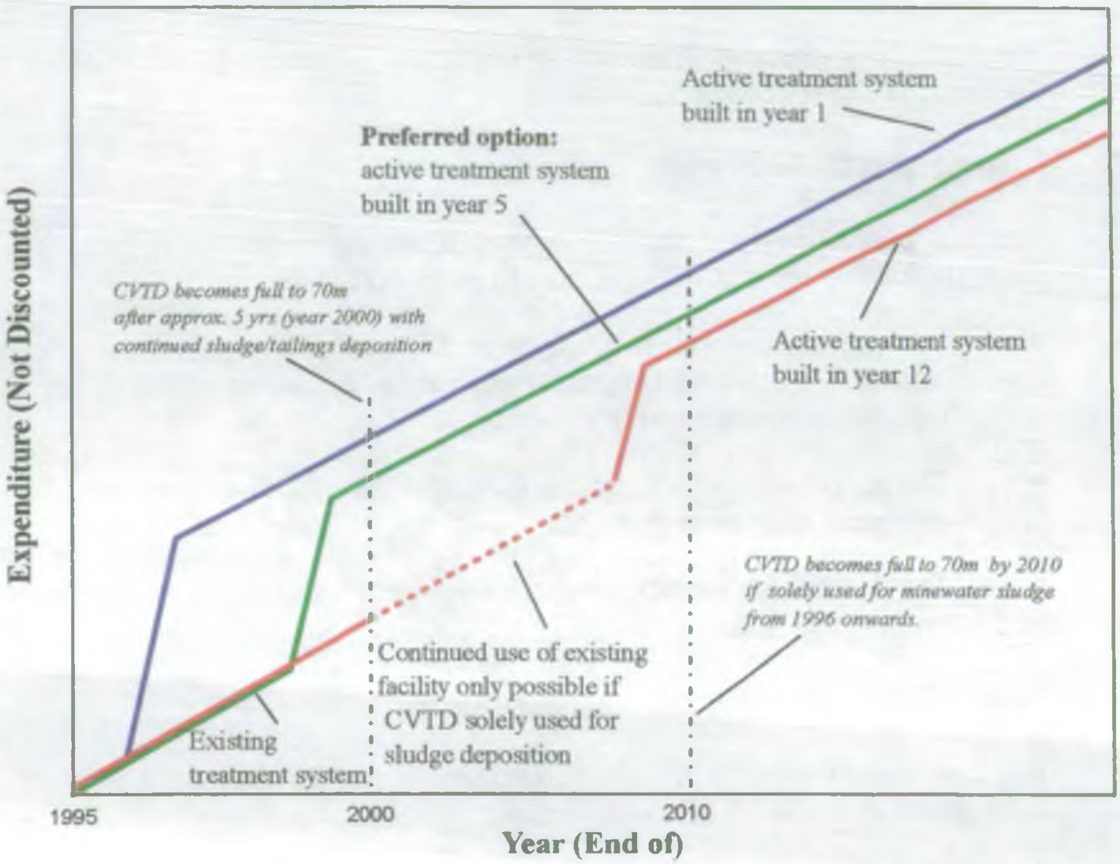
- A treatment plant located at the mine site (i.e. continued use of the existing treatment system until the end of year 2000 followed by active treatment).
- Disposal of the sludge from the active treatment plant both on and off site.
- The 3 benefit scenarios derived in Section 13.
- Compliance with the "North Sea Commitments" water quality objectives with a 5% probability of non-compliance.

As the same average predicted treatment rate (190 l/s) is required to achieve both the "No Deterioration" and "North Sea Commitments" water quality objectives a detailed cost/benefit analysis has only been undertaken for compliance with the "North Sea Commitments" objectives.

14.10.1 Sensitivity Analysis

Sensitivity analyses were carried out to determine the significance of changes in the values derived from the Benefit Analysis. The cost estimates for future treatment were derived from detailed costing data obtained from either known operating costs or quotations. These costs were relatively well defined, and included a contingency allowance, and therefore have not been varied in the sensitivity analysis.

Figure 14.1 Schematic Cost Distribution for Delayed Active Treatment Implementation



Present Value Costs for Different Operating Scenarios (sludge disposal on site)

Year	Continued Existing Treatment (£ millions)	Existing Treatment Plant Replaced by Full Active Plant after: (Total capital and operating costs in £ millions)		
		1 year	5 Years	12 Years
1	0.81	5.89	0.81	0.81
5	3.41	7.99	7.48	3.41
10	5.96	10.00	9.49	5.96
12	6.79	10.66	10.15	9.49
25	N/F	13.47	12.96	12.31
50	N/F	15.38	14.87	14.22

CVTD - Clemows Valley Tailings Dam

N/F - Not Feasible

Costs based on treating an average of 190 l/s to achieve "No Deterioration" and "North Sea Committments" objectives with a 5% annual probability of non compliance

The sensitivity of the analysis to variations in the value of the potential benefits was assessed by means of the lower, base and upper case benefit values derived in Section 13.

The results from these analyses are summarised in Tables 14-9 and 14-10 and are discussed in the following subsections.

14.10.2 Existing Treatment System

The cost benefit analysis for the existing treatment system is summarised in Table 14-9 indicates that for all 3 benefit cases considered:

- The net present values are greater than zero by a significant margin indicating that the cost appraisal is insensitive to minor variations in either the treatment costs or the economic benefits.
- The net present value increases indicating the greater potential benefits of continued long term treatment.
- The cost benefit ratios decrease with project life but remain significantly greater than unity.

14.10.3 Future Treatment Strategy

The cost benefit analysis for the recommended Future Treatment Strategy is summarised in Table 14-10 and indicates:

a) Sludge disposal on site

- The net present values for active treatment, assuming sludge disposal on site, are positive for all the cases considered. Similarly all the benefit/cost ratios are greater than one.
- The net present values increase with project life indicating the greater potential benefits of continued long term treatment.
- The benefit cost ratios increase with project life, with the exception of the higher estimate benefit case.
- The present value of the benefits exceed the costs by a healthy margin, indicating that the financial analysis is relatively insensitive to minor variations in either treatment costs or the value of the benefits gained.

(b) Sludge Disposal off-site

The net present values and benefit/cost ratios for active treatment with sludge disposal to a licenced landfill site indicate that:

- The net present values are positive and increase with time, confirming the potential gains from continued treatment.

Table 14-9 : Cost Benefit Analysis - Existing Treatment System

a) Base Case Assumptions

	No Deterioration and North Sea Commitments (5% Non-compliance)			
	5 years	10 years	25 years	50 years
PV costs	3.41	5.96		
PV benefits	14.99	20.75		
NPV	11.58	14.79	n/a	n/a
B/C Ratio	4.40	3.48		

b) Lower Estimate Assumptions

	No Deterioration and North Sea Commitments (5% Non-compliance)			
	5 years	10 years	25 years	50 years
PV costs	3.41	5.96		
PV benefits	8.14	11.59		
NPV	4.73	5.63	n/a	n/a
B/C Ratio	2.39	1.94		

c) Higher Estimate Assumptions

	No Deterioration and North Sea Commitments (5% Non-compliance)			
	5 years	10 years	25 years	50 years
PV costs	3.41	5.96		
PV benefits	24.40	31.06		
NPV	20.99	25.10	n/a	n/a
B/C Ratio	7.16	5.21		

n/a - not applicable

Assuming an average minewater treatment rate of 190 l/s

Table 14-10 : Cost Benefit Analysis - Proposed Future Treatment Strategy

a) Base Case Assumptions

	Sludge Disposal On Site (preferred option)				Sludge Disposal Off-Site			
	5 years	10 years	25 years	50 years	5 years	10 years	25 years	50 years
PV costs	7.48	9.49	12.96	14.87	7.48	10.09	14.59	17.06
PV benefits	14.99	20.75	28.77	33.18	14.99	20.75	28.77	33.18
NPV	7.51	11.26	15.81	18.31	7.51	10.66	14.18	16.12
B/C Ratio	2.00	2.19	2.22	2.23	2.00	2.06	1.97	1.94

b) Lower Estimate Assumptions

	Sludge Disposal On Site (preferred option)				Sludge Disposal Off-Site			
	5 years	10 years	25 years	50 years	5 years	10 years	25 yers	50 years
PV costs	7.48	9.49	12.96	14.87	7.48	10.09	14.59	17.06
PV benefits	8.14	11.59	16.40	19.04	8.14	11.59	16.40	19.04
NPV	0.66	2.10	3.44	4.17	0.66	1.50	1.81	1.98
B/C Ratio	1.09	1.22	1.27	1.28	1.09	1.15	1.12	1.12

c) Higher Estimate Assumptions

	Sludge Disposal On Site (preferred option)				Sludge Disposal Off-Site			
	5 years	10 years	25 years	50 years	5 years	10 years	25 years	50 years
PV costs	7.48	9.49	12.96	14.87	7.48	10.09	14.59	17.06
PV benefits	24.40	31.06	40.34	45.44	24.40	31.06	40.34	45.44
NPV	16.92	21.57	27.38	30.57	16.92	20.97	25.75	28.38
B/C Ratio	3.26	3.27	3.11	3.06	3.26	3.08	2.76	2.66

Assuming: 5 years operation of the existing treatment plant followed by the commissioning of an Active treatment facility;

an average minewater treatment rate of 190 l/s.

- The benefit/cost ratios are greater than one, but with the exception of the lower estimate assumptions, decrease with project life.
- The magnitude of the NPV confirm that the benefit values exceed the treatment costs by a significant margin.

A comparison of the net present values for on and off site sludge disposal reveals that on site disposal is significantly cheaper than off site storage.

14.11 CONCLUSIONS

Detailed studies have been undertaken to establish possible long term treatment options for the Carnon River and in particular the Wheal Jane minewater problem. The main conclusions from these studies are:

(i) Wheal Jane and County Adit are the two major sources of contaminated water entering the Carnon River.

(ii) Unidentified diffuse sources of contamination, probably from other abandoned mine workings, exist within the Carnon Valley.

(iii) The metal concentrations in the Wheal Jane minewater are reducing with time. The total metal concentrations have decayed exponentially from in excess of 3000 mg/l in 1992 to approximately 500 mg/l in 1994. However, the rate of decline has reduced and a longer data set is required before a reliable trend can be established.

(iv) Water quality modelling using the average minewater metal concentrations measured during the period October 1993 to September 1994, indicates:

(a) Under the "No Treatment" option the metal concentrations in the Carnon River would be an order of magnitude higher than current levels and there would be widespread and prolonged iron discolouration in the Fal Estuary.

(b) The current average treatment rate of 155 l/s will achieve the "No Deterioration" Water Quality Objective with less than a 50% annual probability of non-compliance for all metals other than iron.

(c) An average treatment rate of 190 l/s is required to achieve the "No Deterioration" water quality objective with a 5% annual probability of non-compliance. This treatment rate will also achieve the "North Sea Commitments" water quality objective with a 5% annual probability of non-compliance.

(d) The "EC Directive" water quality objective cannot be achieved by treating only the Wheal Jane and County Adit waters because of contamination from other diffuse sources.

(v) The existing treatment system can be operated to achieve (b) and (c) in (iv) above. The system offers the most cost effective method of treatment. The life of the system is governed by the tailings dam which has available storage until, at least, the end of year 2000.

(vi) The benefit-cost ratios for scenarios (b) and (c) in (iv) above are in excess of 4 over the next five years.

(vii) Treatment beyond 2000 can be most cost effectively provided using active technology.

(viii) The preferred location for an active treatment facility is on the Wheal Jane mine site with disposal of sludge to the Clemows Valley Tailings Dam. The benefit-cost ratio for long-term treatment in this way is approximately 2.

(ix) The life of the Clemows Valley Tailings Dam can be extended beyond the year 2000 by the use of an active treatment system designed to minimise the volume of sludge produced.

(x) The passive treatment trials are, to date, inconclusive and further testing is required to confirm the efficacy of this type of system for long term use at Wheal Jane.

14.12 RECOMMENDATIONS

The main recommendations from the study are:

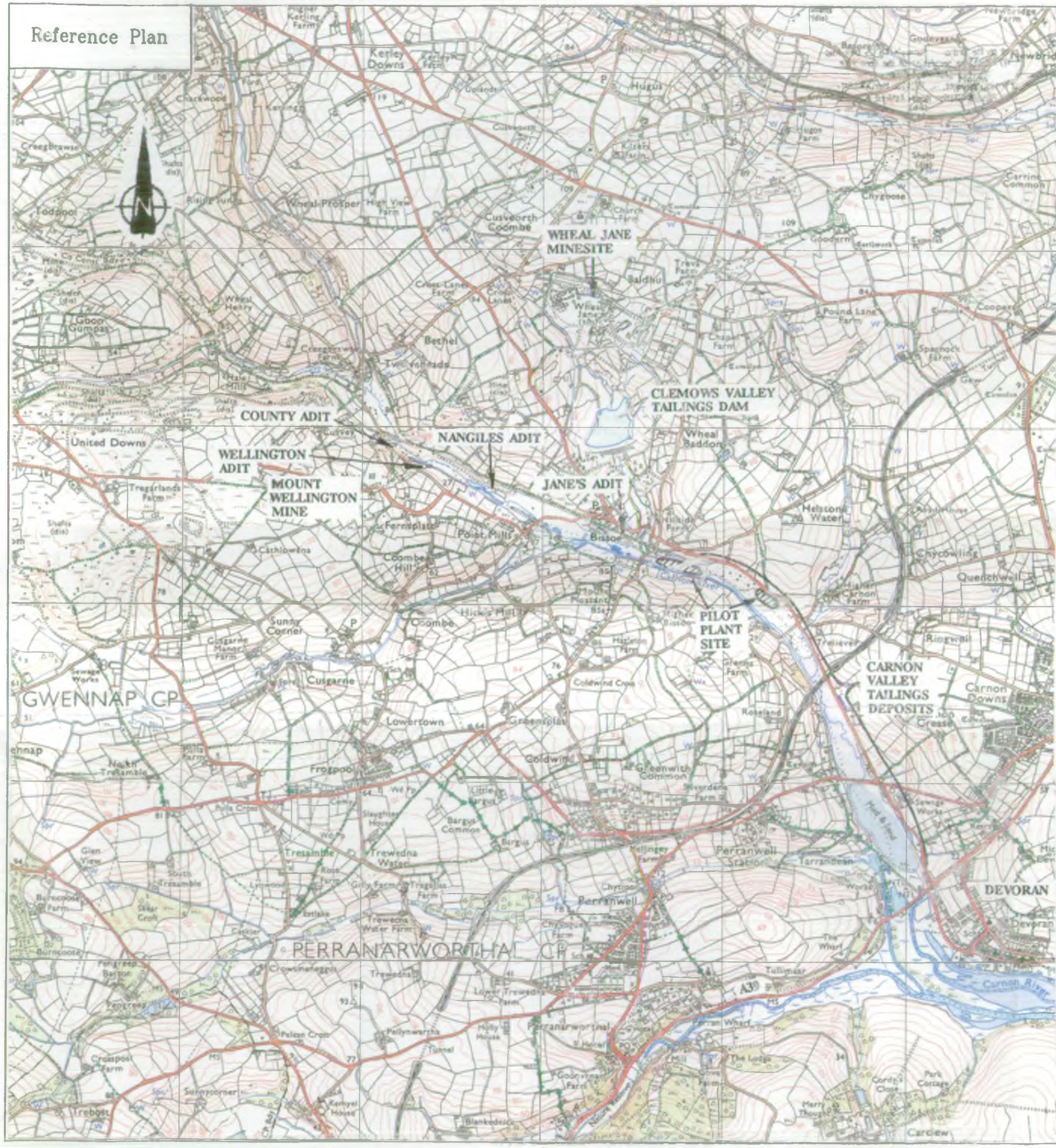
(i) The existing treatment system should continue for at least three years from April 1996 to March 1999.

(ii) The treatment plant should be operated to achieve the "No Deterioration" water quality objective with a 5% annual probability of non-compliance.

(iii) The pilot passive treatment trials should continue for at least three years from April 1996 to March 1999.

(iv) The following studies should be carried out to determine future treatment needs:

- Collection and appraisal of water quality and flow data.
- Develop a model to simulate the decay in the Wheal Jane metal concentrations.
- Identify the diffuse sources of contamination.
- Further develop an integrated water quality model for the Carnon River.
- Assess the long term impact of minewater on the estuary biota.



Reference Plan
N
WHEAL JANE MINESITE
CLEMOWS VALLEY TAILINGS DAM
COUNTY ADIT
NANGILES ADIT
WELLINGTON ADIT
MOUNT WELLINGTON MINE
JANE'S ADIT
PILOT PLANT SITE
CARNON VALLEY TAILINGS DEPOSITS
DEVORAN
GWENNAP CP
PERRANARWORTHAL CP
Carnon River

Reference Plan