ENVIRONMENT AGENCY

Wheal Jane Minewater Project

Consultancy Studies 1996-1999

Appraisal and Selection of Long Term Treatment Option

December 1998

Knight Piésold

in association with

Plymouth Marine Laboratory

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ENVIRONMENT AGENCY (SOUTH WEST)

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Appraisal and Selection of Long Term Treatment Option

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CONTENTS

LIST OF APPENDICES

LIST OF TABLES

LIST OF FIGURES:

PHOTOGRAPHS:

GLOSSARY

List of terms with summary descriptions as used in the report

Water Quality Objectives (WQOs)	Target water quality for the Carnon River at Devoran Bridge and in the Fal Estuary. Report identifies seven WQOs banded as no treatment and lower and higher order objectives (three of each). The higher order objectives are based on EC Directives.
Existing Treatment Plant (ETP)	A lime dosing plant, developed and improved since 1992, that enables the treatment of Wheal Jane minewater by precipitating dissolved metals as solid hydroxides/hydrated oxides, but without any facilities for solid/liquid separation. System uses up to six abstraction pumps to give a maximum treated flow rate of 330l/s.
Clemows Valley Tailings Dam (CVTD)	The existing facility at the Wheal Jane mine site that is used for the clarification and settlement of minewater residues.
Adits	Near horizontal mine tunnels used for mine access and dewatering of upper workings and which reduce pumping requirements from lower workings. The adits in the Carnon Valley discharge into the Carnon River.
Discharge Consent	Formal permission issued to a 'consent holder' for the discharge to 'controlled waters' of treated effluent. Consents, issued by the Environment Agency under the Water Resources Act 1991, define required flow rates and treated water quality and are enforceable by law.
Process Routes	Any combination of physical or chemical unit operations designed to improve the water quality passed through it, usually termed as either Active or Passive Treatment.
Active Treatment	Treatment processes that generally require continued input of power and/or reagents.
Passive Treatment	Treatment processes that are essentially self-sustaining.
Final Treated Effluent Quality	The water quality that is finally discharged from a treatment process.
Treatment Alternatives	Initial and wide ranging possibilities for treatment of waters from Wheal Jane and other sources including primary and secondary methods.

Treatment Routes:	
OCN	Oxidation and Chemical Neutralisation.
BCS	Biochemical Sulphidisation.
IEX	Ion Exchange.
OCN-IEX (I)	Hybrid configured to meet the EC Dangerous Substances Directive Fresh Water Environmental Quality Standards at the discharge point.
OCN IEX (II)	Hybrid configured to meet all higher order WQOs.
Treatment Scenarios	Reduced set of treatment methods that are likely to achieve various WQOs and form the main input to the detailed Water Quality Modelling.
Treatment Options	Treatment methods that will achieve various WQOs as determined by the water quality modelling.
No Treatment	An option whereby minewater is released untreated by gravity drainage.
Six Pumps	A treatment option by OCN of the majority of minewater from Wheal Jane mine using six pumps of the same size as currently installed for the ETP.
All Sources (riverine)	Treatment of all Carnon River flow upstream of Devoran Bridge using OCN-IEX (I).
All Sources (estuarine)	Treatment of all Carnon River flow upstream of Devoran Bridge using OCN-IEX (II).
CAPEX	Capital Expenditure required for the purchase, erection and installation of permanent equipment.
OPEX	Operating Expenditure associated with treating the minewater by a process route at the average flow rate, including the costs of reagents, labour, maintenance and sludge disposal and expressed as an annual cost.
Discount Rate	Indices to reflect change of value with time. The Treasury rate of 6% has been used.
Present Value (PV)	Single value for a series of costs or benefits all discounted to present day (January 1998) by the Discount Rate.
Rate of Return	A number to denote the expected increase in value available from an investment (defined as a discount rate for which the NPV is zero).

Scheme Cost	The combination of CAPEX and OPEX, for a treatment system operated for a particular time period to which contractor's management and profit fees have been added.
Additional Benefit	The benefit value additional to that accrued under the no treatment (baseline) option.
Net Present Value (NPV)	Sum of the *PV Additional Benefit* less the *PV Scheme Cost*, expressed for various timespans.
Benefit / Cost Ratio	Quotient of the *PV Additional Benefit* divided by the *PV Scheme Cost*, which is greater than unity when Benefits exceed Costs.

EXECUTIVE SUMMARY

INTRODUCTION AND APPROACH

The Wheal Jane Minewater Project was initiated following the uncontrolled release of acidic metal laden minewater from the Wheal Jane mine, near Truro, Cornwall. The release, in January 1992, caused widespread discolouration in the Carnon River, Restronguet Creek, Carrick Roads, the Fal Estuary and beyond.

Previous studies (KP et al, 1995, Environmental Appraisal ...) had determined the major influences on the minewater regime to be Wheal Jane mine and County Adit and had made preliminary recommendations regarding a long-term treatment strategy. The study determined that:

- the preferred long-term treatment option involves the construction of an active treatment plant on the Wheal Jane mine site with the resultant sludge dewatered and stored in the Clemows Valley Tailings Dam (CVTD);
- cessation of treatment at Wheal Jane would lead to widespread discolouration of the Fal Estuary and degradation of water quality generally.

The report also recommended that the Existing Treatment Plant (ETP) continue to operate until a long-term treatment option had been determined. The ETP, which has operated since 1992 and enables a water quality of 'No Deterioration' to be maintained in the Carnon River, uses simple lime dosing to neutralise the minewater acidity and precipitate the heavy metals, which are then settled and deposited into the adjacent CVTD. The ETP was shown to be the lowest cost method of minewater treatment whilst the dam is available, this remains the case.

The dependency on CVTD for the continuation of the minewater treatment was recognised in the earlier study and it was predicted that space within the dam, to the maximum permitted elevation of 70 m AOD under current planning permission, would be exhausted within some 5 years. Consequently the Agency wished to be in a position to replace the existing treatment plant with a purpose built long-term facility by 2001. This five year period (from April 1996 to March 2001) gave rise to the current project programme.

The programme of implementation for a long-term treatment plant is still dependent upon the predicted lifespan of the dam. The recent closure of the South Crofty tin mine (March 1998) and cessation of tailings deposition into the dam has altered the deposition regime. The absence of tailings has reduced the mass deposited considerably, but also leaves a light gelatinous metal hydroxide sludge that settles to a lower density and is re-mobilised relatively easily when disturbed. The dam is now estimated to become full by January 2001, although full appraisal of sludge only deposition is still being determined. This issue is developed further within Appendix A, Recent Developments, of this report.

The previous study also recommended that additional water quality modelling, with a view to determining the impact of minewater on estuary biota and decay profiles of minewater sources, should be undertaken to allow a more refined cost-benefit appraisal to be developed.

As a result of the previous studies, the *Wheal Jane Minewater Project* was commissioned in June 1996. This report presents the results of the cost-benefit studies undertaken as part of the overall project. Other aspects of the project, namely management of existing treatment and implementation of long-term options, are continuing.

The cost-benefit appraisal was undertaken in a number of stages as described in the following sub-sections.

WATER QUALITY OBJECTIVES

Seven Water Quality Objectives (WQOs) were established to represent target water qualities at Devoran Bridge (a National Monitoring Network Station where the Carnon River enters Restronguet Creek) and in the Fal Estuary. The WQOs have been categorised into three bands; no treatment, lower order objectives and higher order objectives. Lower order objectives include No Deterioration, No Discolouration and North Sea Declaration Commitments. Higher order objectives are based on Environmental Quality Standards and include Protection of Estuarine Biology and EC Dangerous Substances Directive - Fresh Water Environmental Quality Standards and EC Dangerous Substances Directive - Salt Water Environmental Quality Standards

In addition to WQOs, the Agency has a duty to meet those standards prescribed in EC Directives that have been transcribed into UK Law.

Figure 1, which shows a schematic layout of the catchment including the water sources that make up the Carnon River upstream of Devoran Bridge, demonstrates the distribution of contamination throughout the Carnon Valley as determined by the water quality modelling studies. From the figure it is seen that the majority of metal load enters the Carnon River from Wheal Jane and the second largest contributor is County Adit.

The relative discharge qualities compared to the WQOs are summarised on the lower half of the figure, which demonstrates that no treatment does not allow any of the lower order objectives or higher order objectives to be achieved during the 35 year synthesised modelling period. The lower order objectives require the removal of between 60 - 80% of specific metals, and it is shown from modelling that this can be achieved through the treatment of most of the Wheal Jane minewater. The higher order objectives require between 96 - 99.9% removal of metals and the modelling predicts that these objectives can only be achieved with certainty by the treatment of all river flow down to Devoran Bridge.

TREATMENT OPTIONS

Many treatment alternatives were considered, which were reduced to four main process routes following preliminary cost and technical appraisals, as follows:

- Oxidation and Chemical Neutralisation (OCN);
- Biochemical Sulphidisation (BCS);
- Ion Exchange (IEX), with two hybrid OCN-IEX routes also considered;
- passive treatment systems.

These treatment alternatives have been assessed using pilot trials on site, where feasible, and from discussions with industry. IEX is the least developed technology for minewater treatment and pilot trials on Wheal Jane minewater have not yet been undertaken.

Passive treatment systems, which can be configured in a number of ways, were found to be inappropriate for use in the Carnon Valley mainly due to the lack of sufficient land area, treatment reliability and unfavourable seasonal effects. Passive treatment was, therefore, discounted from further study. Process modifications to target valuable products such as zinc were also considered although no cost effective processes were found.

The effluent quality achievable from each of OCN, BCS and IEX process routes were used in the water quality modelling studies to both predict the long-term quality of the Carnon River at Devoran Bridge and in the Fal Estuary and to assess the extent of treatment required to meet the various WQOs.

Four treatment options emerged from the modelling:

- No Treatment;
- Six Pumps - the treatment of the flow rate currently achieved using the six pumps at the Wheal Jane ETP;
- All Sources - treatment of all the Carnon River flow, at Devoran to OCN-IEX(I);
- All Sources - treatment of all the Carnon River flow, at Devoran to OCN-IEX(II).

The results obtained from the modelling are summarised in Table 1.

Table 1 : Specific Treatment Options

Treatment Option	Primary Treatment Method	Water Quality Objectives Achieved
No Treatment		do nothing - base case option
Six Pumps	OCN	all three lower order objectives and limit values
	BCS	all three lower order objectives and limit values
	IEX	all three lower order objectives and limit values
All Sources	OCN	higher order objectives almost (but not quite) achieved
	BCS	higher order objectives with 'best expected', but not 'guaranteed' outputs
	IEX	EC DS Directive– Fresh Water Environmental Quality Standards and lower order objectives and limit values
	OCN-IEX(I)	EC DS Directive– Fresh Water Environmental Quality Standards and lower order objectives and limit values
	OCN-IEX(II)	EC DS Directive – Fresh Water Environmental Quality Standards, EC DS Directive -Salt Water Environmental Quality Standards, Protection of Estuarine Biology and lower order objectives and limit values.
OCN-IEX is a two stage process using OCN for bulk removal and IEX for polishing. OCN-IEX(I) uses cationic resins and OCN-IEX(II) uses cationic and anionic resins to achieve a higher quality effluent.		

Alternative methods of achieving each of the attainable WQOs were established. To determine the most appropriate long-term treatment option the benefit costs and the treatment costs of each option were then determined. All cost estimates considered project lifetimes of 10, 25 and 50 years and used a common Treasury discount rate of 6%. Sensitivities were also considered and upper bound and lower bound cost estimates were prepared.

BENEFIT VALUES

The benefit values were determined by firstly estimating the biological impact associated with each treatment route. This involved an assessment of the current biological status and the significance of minewater discharges on the floral and faunal communities in the Carnon River and Fal Estuary. The study found that the No Treatment option would lead to slight increases in bioaccumulation in some species and treatment of All Sources would lead to a slight decrease, particularly for iron, zinc and arsenic, and also some increase in selected species populations. It is noted that Restronguet Creek has a long history of mining pollution and the sediments are highly loaded with metals. The biodiversity of the area reflects this with a predominance of metal tolerant species.

Benefits have been measured as additional to that accrued under the No Treatment option using predictions of discolouration events and impacts on water quality. Costs have been established for a number of affected communities including conservation, recreation (informal recreation, bathing and watersports), port operations (pleasure boating, ship repair and moorings), the calcified seaweed industry, fisheries (commercial, shellfish and recreational) and amenity. Benefit values to each community have been assessed using neo-classical welfare economics based principally on the 'willingness to pay' approach. The basic assumptions on environmental change used in the analysis for the various options are as follows.

No Treatment: discolouration would occur almost every year, over the winter and early spring. Iron concentrations would be elevated in the water. Such events would impact upon all recreational activities, and upon biological life.

Six Pumps: the current situation would continue, with occasional discolouration events. Activity levels and industry would continue as at present, with no additional benefit over the current state. There would be some scope for improvement of the environment, although the impact of this would be slight.

All Sources: no discolouration events and further reduction of iron concentrations may have a greater positive impact than under Six Pumps. However, it is not possible to value impacts under All Sources separately to those arising under Six Pumps.

TREATMENT COSTS

The whole life costs associated with each of the treatment options were determined by assessing the capital and operating costs (CAPEX and OPEX, respectively) for each option and for various plant sizes and locations. Two site options were selected, the Wheal Jane mine site, where ETP is undertaken and the Lower Carnon Valley, a site just upstream of Devoran Bridge. The operating costs included items such as reagents, power, maintenance and sludge disposal. The overall sustainability of each option was also assessed mainly from the reagent and sludge disposal quantities involved. The sensitivities of each component cost, as well as the overall range of estimates, were also considered.

Various options for long-term sludge disposal have been assessed. The currently used CVTD remains the preferred site for most types of sludge, but it is recommended that an off-site contingency arrangement should also be available.

Treatment costs have been expressed as base costs for each option and then as present value scheme costs which, for the cost-benefit assessment, are developed for a design, build and operate (DBO) form of contract. Alternative contract types were also reviewed and are considered under the *Implementation* sub-section.

From the cost assessments preferred options are derived as indicated in Table 2.

Table 2 : Summary of Preferred Treatment Options

Treatment Option			Water Quality Objective
	CAPEX (£ M)	OPEX (£ M/yr.)	
No Treatment	1.4(1)	0.02(3)	No Treatment
Six Pumps using OCN at Wheal Jane mine site	4.25	0.76(2)	Lower order objectives and limit values achieved
All Sources using OCN-IEX (I) at the Lower Carnon Valley site	18	2.5	EC DS Directive - Fresh Water Environmental Quality Standards, lower order objectives and limit values achieved
All Sources using OCN-IEX (II) at the Lower Carnon Valley site	29	3.4	EC DS Directive - Salt Water Environmental Quality Standards, Protection of Estuarine Biology and lower order objectives and limit values achieved

(1) A No Treatment option would require Jane's Adit to be refurbished to provide a secure long-term gravity discharge conduit for the Wheal Jane minewater.

(2) Assumes disposal of dewatered sludge to CVTD. Additional cost for off-site disposal is £270 000 per annum or £2.0 M for a 10 year present value cost.

(3) Annual maintenance cost.

COST-BENEFIT ANALYSIS

The benefit values and treatment costs are given in Table 3 including median, upper bound and lower bound estimates for the 10 year timeframe only, together with their respective net present value (NPV) and benefit/cost ratio. The highest NPVs and benefit/cost ratios, which indicate best value options, are shown emboldened.

The final estimated NPVs for the three treatment options are summarised in Table 4 and plotted in Figure 2.

Table 3 : Summary 10 Year Cost and Benefit Results				
Treatment Option	**Present Additional Benefit Value[1][2] (£ M)**	**Present Treatment Cost (£ M)**	**Net Present Value (£ M)**	**Benefit/ Cost Ratio**
Upper Bound Benefit Values and Lower Bound Treatment Costs				
No Treatment	0.0	1.2	-1.2	n/a
Six Pumps (OCN at Wheal Jane)	32.0	9.9	**22.1**	**3.23**
All Sources (OCN-IEX (I) in Lower Carnon Valley)	33.0	30.9	2.1	1.07
All Sources (OCN-IEX (II) in Lower Carnon Valley)	33.0	45.0	-12.0	0.73
Median Estimates				
No Treatment	0.0	2.0	-2.0	n/a
Six Pumps (OCN at Wheal Jane)	17.0	11.2	**5.8**	**1.52**
All Sources (OCN-IEX (I) in Lower Carnon Valley)	18.0	40.4	-22.4	0.45
All Sources (OCN-IEX (II) in Lower Carnon Valley)	18.0	59.1	-41.1	0.30
Lower Bound Benefit Values and Upper Bound Treatment Costs				
No Treatment	0.0	2.8	**-2.8**	n/a
Six Pumps (OCN at Wheal Jane)	10.0	15.4	-5.4	**0.63**
All Sources (OCN-IEX (I) in Lower Carnon Valley)	10.0	59.5	-49.5	0.17
All Sources (OCN-IEX (II) in Lower Carnon Valley)	10.0	86.0	-76.0	0.12

[1] Discounted to present value at 6% Treasury rate.
[2] No Treatment is the baseline for economic benefit values.

Table 4 : Summary NPVs			
Treatment Option / Scheme Duration	**Upper Bound (£ M)**	**Median (£ M)**	**Lower Bound (£ M)**
10 Year Net Present Values			
No Treatment	-1.2	-2.0	**-2.8**
Six Pumps	**22.1**	**5.8**	-5.4
All Sources (riverine)	2.1	-22.4	-49.5
All Sources (estuarine)	-12.0	-41.1	-76.0
25 Year Net Present Values			
No Treatment	-1.3	-2.2	**-3.0**
Six Pumps	**34.5**	**10.8**	-7.4
All Sources (riverine)	5.2	-28.5	-67.3
All Sources (estuarine)	-14.6	-53.0	-102.4
50 Year Net Present Values			
No Treatment	-1.4	-2.3	**-3.2**
Six Pumps	**41.7**	**13.9**	-9.1
All Sources (riverine)	6.5	-32.4	-79.3
All Sources (estuarine)	-16.8	-60.7	-120.0

Highest NPVs shown emboldened.

It is seen from Table 4 that the Six Pumps option at Wheal Jane provides the highest NPV for upper bound and median estimates and that No Treatment provides the more favourable option on lower bound estimates. It is noted also that the investment required for No Treatment is relatively small.

The Six Pumps option represents a situation similar to the existing one. There would be occasional discharges from Nangiles Adit, which could result in discolouration. The likelihood of discolouration is remote, however, as indicated during the winter of 1997/1998 when Nangiles Adit discharged, but there was no recorded discolouration. The probability of discolouration as a result of discharges from the CVTD will also be reduced significantly when the function of water/solids separation is achieved off the dam.

The implication of No Treatment is that discolouration would occur almost every year over extended periods. This has a significant impact on benefits, both conservation and the 'non-use' and 'use' values, such as those related to fisheries, amenity or the calcified seaweed industry. In many cases, the perceived consequences of discolouration are greater than the reality, but this still affects benefits, according to the results of consultations with 30 local groups and organisations. Oysters and shellfish, for example, are unlikely to be adversely affected, but there would be a perception of contamination. There is, however, a possibility of sea bass nurseries and maerl beds being directly affected as a result of increased metal concentrations and sedimentation, respectively.

There are few environmental or cost benefits from adopting either of the All Sources treatment options over and above the Six Pumps treatment option. In addition, the Agency's statutory duty to meet those standards prescribed in EC Directives transcribed into EC law is met by the Six Pumps treatment option, which meets limit values under the EC DS Directive.

These two All Sources treatment options do, however, enable the Environmental Quality Standard (EQS) to be met. Treatment to a higher effluent quality (OCN-IEX(II)) would enable EQS to be met for fresh water and salt water as specified in the two EC DS Directives and with the EC Shellfish Waters Directive.

IMPLEMENTATION

The form of contract used to implement the long-term treatment option will determine the allocation of risks, responsibilities and payment profiles between the three possible contracting parties, (Agency, a contractor/operator and South Crofty plc (SCP), the owner of the Wheal Jane mine site). Three main forms of contract that have been assessed are as follows:

- Traditional - design and build phases followed by a separate operating contract;
- Design, Build and Operate (DBO) - a single contractor designs, installs and runs the plant; Agency pays for the CAPEX and OPEX directly;
- Design, Build, Finance and Operate (DBFO) - similar to DBO except that interim finance is put up by the contractor, possibly within a PFI framework, and the Agency pays for the service.

The Agency, for example, could retain the responsibility for achieving water quality at the discharge of the treatment plant or it could be passed to the operator in the form of a

Discharge Consent. Different risks can be allocated in this way, each with a cost to the Agency. Various appropriate forms of contract have been assessed and, where possible, the associated risks have been evaluated to determine the best 'value for money' form of contract. As more risk is passed on, then contract cost, complexity of selecting the preferred bidder and tender/selection periods will all tend to increase.

Overall the DBO option is considered to offer the best contract option and should be implemented for about a twelve year period (two years design and build, ten years operation) in the first instance. Thereafter, a purchase upgrade operate (PUO) style contract could be used for continuation of services. A DBFO (or PFI) contract could be used and is attractive because payment by the Agency is deferred, however, as stated above, tendering requirements are more onerous than the DBO option.

The programming dates for implementation are dependent on various factors, in particular, the remaining life of CVTD and the time required for the tendering procedure. Whilst actual dates may vary depending on which long-term option is selected it is recommended that tender documents are in place during the early part of 1999 to allow a plant to be implemented the following year.

SUMMARY OF CONCLUSIONS

The conclusions drawn at each stage of the study are summarised below.

Treatment Alternatives

- Existing treatment still provides the cheapest form of treatment for Wheal Jane minewater, but has a limited lifespan.
- Oxidation and Chemical Neutralisation (OCN) treatment is the cheapest process route identified. The final water quality is inferior to other types, but results in compliance with EC DS Directive limit values.
- Ion Exchange (IEX or OCN-IEX) can produce a water quality that satisfies higher order objectives.

Treatment Requirements

- Minewater contaminant concentrations have decreased since 1992 and are not expected to reduce significantly further over time. The catchment modelling results are based on long-term minewater quality predictions and any treatment towards achieving WQOs can be expected to be required for many years to come.
- The No Treatment option would require Jane's Adit to be refurbished to provide a secure long-term egress point for the Wheal Jane minewater.
- The Six Pumps treatment option (up to 330 l/s from Wheal Jane) using the three identified treatment routes will achieve the lower order WQOs at Devoran Bridge and in the Fal Estuary and EC DS Directive limit values.
- The All Sources treatment option using an IEX or OCN-IEX treatment route is required to meet the EC DS Directive - Fresh Water Environmental Quality Standards.

- The EC DS Directive - Salt Water Environmental Quality Standards and the Protection of Estuarine Biology WQO could be achieved by an IEX or OCN-IEX treatment route if a higher effluent quality for copper and zinc were achieved (but at a cost penalty).

Plant Site and Sludge Disposal Locations

- The Wheal Jane mine site is the preferred location for the Six Pumps treatment option for cost and planning reasons. Treating Six Pumps with OCN is then essentially an add-on to the existing treatment operations.
- The Lower Carnon Valley site (just upstream of Devoran) should be used for the All Sources treatment option.
- Sludge should continue to be deposited into the CVTD, but will need to be dewatered to extend the life of the facility.
- An off-site contingency arrangement for sludge disposal should be developed.

Cost-Benefit Appraisal

- The most attractive option, identified as the largest positive NPV and with the highest benefit/cost ratio, in almost all cases is Six Pumps using OCN located at the Wheal Jane mine site. The Six Pumps options also achieves compliance with EC DS Directive limit values.
- The No Treatment option is slightly more favourable than the Six Pumps treatment option using lower bound estimates.
- The No Treatment option results in regular and extended periods of discolouration, which have an impact on benefits, both because of perceived contamination and, in some cases, the possibility of actual contamination by metals and increased sedimentation.
- Treatment of All Sources is necessary for the higher order WQOs to be met, however, the cost-benefit appraisal indicates that this treatment option is not favourable.
- Treatment of Wheal Jane minewater discharge to an effluent quality of EC DS Directive - Fresh Water Environmental Quality Standards was not included as a study objective. This can be achieved, however, by an OCN-IEX or BCS treatment route at a cost between the Six Pumps and All Sources treatment options.

Contract Strategy

- The three principal forms of contract listed in increasing overall cost to the Agency and decreasing responsibility are: Traditional, DBO, DBFO.
- The DBO contract option appears to provide best overall balance between cost and risk to the Agency although this conclusion will be subject to issues, such as the availability and funding.

- Tender documentation should be prepared to allow tenders to be invited by January 1999. This will allow time to implement initial treatment before the winter of 1999/2000.
- The worst case situation, where the CVTD becomes full by October 1999, would require a fast-track implementation.
- An initial DBO contract term of about twelve years (two years design and construction and a ten years operating period) is considered appropriate in the first instance.
- The key responsibility for attaining the required treatment water quality should be managed via a Discharge Consent. The contractor/operator should hold this consent.
- SCP own the Wheal Jane mine site and control the tailings dam, which are key features to both the Six Pumps (OCN) and All Sources (OCN-IEX) treatment options. It is, therefore, expected that SCP would feature in some way through either of these treatment option contracts in the long-term.

RECOMMENDATIONS

- The Six Pump treatment option is pursued using the OCN treatment route at the Wheal Jane mine site and implemented using a DBO form of contract. This will achieve compliance with the EC DS Directive limit values for cadmium.
- The initial treatment contract extends for a term of about twelve years.
- Tender documentation should be prepared to allow tenders to be invited by January 1999. This will allow time to implement initial treatment before the winter of 1999/2000.
- Sludge, as a dewatered cake, should be deposited on the CVTD. An alternative sludge disposal site should also be identified as a contingency arrangement should the CVTD become unavailable for any reason.

1. INTRODUCTION

The abandonment of the Wheal Jane mine in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and, therefore, limit the impact of the release on the environment. A location plan is given in Figure 1.1.

Emergency pumping and treatment measures have been progressively developed to form the existing treatment system, which will remain in operation until a long-term solution is implemented. The existing treatment process relies on the Clemows Valley Tailings Dam for the settlement and storage of treated minewater sludge. The dam was expected to become full by 2001, assuming continued use for minewater sludge and mine tailings deposition, and this storage depletion date determined the programme for the present study.

An initial study, completed in May 1995 (KP et al, 1995, Environmental Appraisal ...) considered a range of active and passive minewater treatment options. That study also proposed possible Water Quality Objectives (WQOs) for the Carnon River and Fal Estuary and produced an outline cost-benefit appraisal for achieving each objective. The study concluded that Wheal Jane minewater was the dominant source of pollution within the Carnon catchment and that continued treatment of Wheal Jane would achieve certain WQOs. Significant additional treatment would be required, however, to meet more stringent water quality criteria. The study also concluded that the existing treatment system was the most cost effective method of treatment whilst the tailings dam storage was available. Further studies were recommended to evaluate the key chemical and biological features of the Carnon River and Fal Estuary, to model water quality and provide a more rigorous cost-benefit appraisal of alternative WQOs.

Knight Piésold was commissioned by the Agency in June 1996 to undertake this study as lead consultant to a six party consortium covering eight separate briefs as follows:

Existing Treatment Plant	- Knight Piésold
Pilot Passive Treatment Plant	- Knight Piésold
Catchment Modelling	- W S Atkins
Biological Assessment	- Plymouth Marine Laboratory
Social Economic Analysis	- Risk & Policy Analysts
Active Treatment Plant Outline Design	- Rio Tinto/Knight Piésold
Outline Planning Consent	- Henry Butcher Smith Vincent
Contract Strategy	- Knight Piésold

A report has been produced for each of the study briefs, with the exception of Outline Planning Consent, for which a Planning Application document has been prepared. The Technical Summaries contained in those reports (with the exception of Existing Treatment Plant) are included as an appendix to this appraisal report. The overall report structure is given in Figure 1.2.

A schematic diagram of water quality terminology used in this report is given in Figure 1.3.

Specific reports have been reviewed externally by Professor A J Monhemius (Imperial College) and Dr P Younger (Newcastle University) as well as by Agency personnel and the contributions made by the reviewers is gratefully acknowledged.

1.1 PROJECT DESCRIPTION

1.1.1 Previous Studies

The previous study report (KP et al, 1995, Environmental Appraisal ...) drew the following conclusions:

- insufficient land is available in the Carnon Valley to allow treatment solely by passive technology;
- active treatment is both a proven and cost effective method of minewater treatment;
- the preferred long-term treatment option involves the construction of an active treatment plant on the Wheal Jane mine site with the resultant sludge dewatered and stored in the Clemows Valley Tailings Dam (CVTD);
- cessation of treatment at Wheal Jane would lead to widespread discolouration of the Fal Estuary and degradation of water quality generally.

The report also made the following recommendations:

- temporary treatment should continue for at least three years (by which time a long-term option could be determined);
- passive treatment trials should continue for at least three years;
- studies of water quality modelling, impact of minewater on estuary biota and determination of decay profiles of minewater sources should be undertaken to allow a more refined cost-benefit appraisal to be developed.

1.1.2 The Current Project

Project Preparation

The current project was initiated through a Project Initiation Document (PID) (NRA, 1995, Project Initiation ...). That document considered the processes necessary to provide for the long-term treatment of the minewater and the programme required to achieve these. During the progress of the studies the scope of the services has been amended to accommodate changed circumstances, particularly the closure of the mine at South Crofty and the knock on effect of the cessation of milling at Wheal Jane.

Project Programme

The dependency of CVTD for the continuation of the minewater treatment was recognised in the earlier study and it was predicted that space within the dam, to the maximum permitted elevation of 70 m AOD under planning permissions, would be exhausted within some 5 years. Consequently the Agency proposed to be in a position to replace the existing treatment plant with a purpose built long-term facility by 2001 if required. This five year period (from April 1996 to March 2001) gave rise to the current project programme.

To enable commissioning of the long-term treatment plant by 2001 the following processes were first deemed necessary:

- prediction of the long-term minewater quality;
- confirmation of the most appropriate method of treatment;
- development of a contract strategy for the long-term treatment operations;
- preparation of an outline design for the long-term treatment process;
- obtaining outline planning consent;
- preparation of contract documents.

In order to confirm the most appropriate method of treatment it was recognised that both the cost and benefit of achieving treated effluent qualities and how these treatments relate to water quality objectives required analysis. The programme required completion of these cost-benefit studies by June 1998 to be followed by a decision by the Agency on a long-term treatment strategy. This date is the main study milestone. Originally tender documentation was also required at the same date to allow contractors to tender and be in place by April 1999 but was completed following acceptance of the cost-benefit studies, with the same contract award date. A two year period would then be available for the design, construction and commissioning of a plant prior to the dam becoming full in March 2001. The dam is now expected to become full in January 2001 following closure of South Crofty's mining operations. This is a preliminary estimate as more detailed appraisals are ongoing (see Appendix A). Consequent cessation of the deposition of tailings and availability of the dam, therefore, continues to drive the implementation programme. Concern also exists over the ability to settle the sludge adequately and this issue is also the subject of an ongoing review.

The existing treatment of Wheal Jane minewater would continue until the long-term treatment facility became operational.

Project Tender

Tender documents for the project were prepared and put out to competitive tender in March 1996. Knight Piésold was commissioned by the Agency in June 1996 as lead consultant to undertake the project in association with the five sub consultants referred to in Section 1.

Project Purpose

The aim of this project is to undertake the processes described above and in particular to provide an appraisal of various long-term options for the treatment of minewater from the Wheal Jane mine and other sources within the Carnon Valley catchment. A cost-benefit appraisal of various treatment options was selected as the basis of study by the Agency to allow the selection of an appropriate and sustainable long-term strategy, which would fulfil statutory duties and address legal requirements.

Project Objectives

During the earlier studies it was recognised by the National Rivers Authority (NRA, now the Agency) that it served two conflicting roles; those of minewater treatment plant operator and water quality regulator. A major requirement of any future contract for the long-term operation of the minewater treatment plant is to permit the Agency to revert to its role of water quality regulator.

A further objective desired by the Agency was to delay substantial commitments to capital investment for as long as possible. Since the ETP remains the cheapest form of treatment, at least whilst the CVTD is available for continued minewater sludge deposition, then it is appropriate to continue with the ETP until a long-term decision has been made and implemented.

The key objective of this study phase is to determine the most appropriate long-term treatment option by undertaking a cost-benefit appraisal of alternatives. The final option should offer a value for money, sustainable solution to the minewater legacy.

Project Structure and Scope of Work

The Project Brief requires the key aspects shown in Table 1.1 to be undertaken.

Table 1.1 : Summary Description of Study Briefs

Brief Title	Description
Project Management (B1)	Overall project co-ordination and management
Existing Treatment Plant Management (C)	Continued management and optimisation of the Existing Treatment Plant
Pilot Passive Treatment Plant Management (D)	Continued operation and assessment of the Pilot Passive Treatment Plant
Catchment Modelling (E)	Development of hydrological and hydrogeological models to determine water quality across the Carnon catchment and Fal Estuary and variation with time. Determination through modelling of what treatment effort is required to reach each of seven WQOs
Biological Assessment (F)	Determination of the impact to the flora and fauna under various possible long-term treatment scenarios
Environmental and Social Benefit Analysis (I)	Determination of the benefit value associated with the various possible long-term treatment options
Active Treatment Plant Outline Design (G)	Appraisal of alternative treatment options and determination of whole life costs associated with achieving each WQO through various treatment options
Outline Planning Consent (H)	Attainment of outline planning permissions for the preferred options
Contract Strategy (B2)	The consideration of alternative contract vehicles with which to implement the possible options, in particular the difference in the allocation of risk between contract types
Brief Reference in brackets.	

An organisational chart showing the project structure is included as Figure 1.4.

The conclusions and recommendations of the appropriate study briefs have been drawn on to develop the proposals for the long-term treatment option. Costs from the active treatment outline design have been combined with the benefits determined from the environmental and social benefit analysis to calculate the cost-benefits of the various treatment options. The overall approach and final report structure is described in the following sections.

1.2 APPROACH

A cost-benefit appraisal is essentially concerned with value for money, which, in the context of the Wheal Jane Minewater Project, means the cost efficiency with which the undesirable metals and acidity can be removed from the water system.

To determine the cost-benefit a number of WQOs have been established for the river at Devoran Bridge and the cost of treatment required with the corresponding benefit to the downstream communities determined for each WQO in terms of present value costs.

Seven WQOs have been established and these are listed in Table 1.2 together with their broader categorisations.

Table 1.2 : Water Quality Objectives

Objective	Broad Categorisation	Water Quality Objective [1]
1	Do nothing	No Treatment (baseline)
2	Lower order objectives	No Deterioration
3		No Discolouration
4		North Sea Declaration Commitments
5	Higher order objectives	Protection of Estuarine Biology [2]
6		EC Dangerous Substances Directive – Fresh Water Environmental Quality Standards
7		EC Dangerous Substances Directive – Salt Water Environmental Quality Standards

(1) WQO is defined in Section 4.3
(2) In addition, achievement of lower order objectives also ensures that EC DS Directive limit values are met.

The evaluation of the many possible treatment alternatives to satisfy the seven WQOs considered not only effluent quality, but also process reliability, track record and the whole life cost for each alternative. These factors determined the cost of removal of metals and have been assessed in a progressive way, whereby more promising alternatives were considered in increasing detail. Less advantageous or desirable alternatives were ruled out and discarded early in the evaluation process. For the selected options whole life costs were developed, derived from the capital cost (CAPEX) associated with constructing and installing the plant and combined with the ongoing operational costs (OPEX). Net present value scheme costs were considered for the 10, 25 and 50 year lifespans required by the brief to allow the comparison of alternative treatment options and their associated benefits. Benefits are valued as additional to that accrued under the No Treatment option.

The sensitivities of the treatment costs and benefit values have also been considered.

Other factors associated with the various treatment strategies are also considered. These include:

- the sustainability of the option;
- proximity to existing facilities, particularly for sludge disposal;
- compatibility with Agency, national, European Union and international requirements.

Another aspect of the study has been to determine an appropriate contract mechanism with which to implement any long-term treatment requirement. This required an appraisal of the following:

- the risks to the Agency associated with any long-term treatment option and methods for their minimisation;
- different contractual arrangements with regard to the transfer of risk to a third party and the associated costs of doing so;
- the possible sources of funding for the construction and operation of any new treatment plant.

1.2.1 Report Structure

This appraisal report seeks to provide the Agency with a stand-alone document to support the application to the DETR for continuation of the Wheal Jane minewater treatment. As such it relates the Wheal Jane story and makes a recommendation on the preferred long-term treatment option. Technical Summaries prepared for the companion reports as described in Table 1.1 are contained in Appendices B - G. They summarise the content and findings of the various components of the project.

The following sections of the final report, summarised below, detail the development and appraisal of appropriate treatment methods, their cost and associated benefit values and subsequent cost-benefit appraisal.

Section 2 - Background
A general description of the Carnon Valley catchment and the minewater regime including the discharge incident in 1992 and subsequent phases of treatment.

Section 3 - Existing Treatment
The development of temporary treatment of minewater from Wheal Jane and the current operating principles, costs and potential long-term use.

Section 4 - Water Quantity and Quality
The existing and predicted water qualities in comparison with the WQOs and the actual metal removals required for each WQO.

Section 5 – Process Route Alternatives
A technical review of minewater treatment options comprising three 'active' methods and a 'passive' option and the expected water qualities resulting from each option including sludge disposal. An alternative to treatment, such as diversion or sealing of workings, is also investigated. It is demonstrated that a passive treatment alone will not achieve the required water qualities and this option is discounted from further study.

Section 6 – Derivation of Treatment Options
A discussion of the iterative process of modelling including postulated initial treatment scenarios leading to the required treatment options for each WQO.

Section 7 – Biological Impacts
Assessment of the effect of treatment options on the biology of the Carnon River and Fal Estuary.

Section 8 - Treatment Costs
The development of treatment costs, comprising capital and operational costs over project lifetimes of 10, 25 and 50 years, have been determined as present value costs based on Agency standard financial indices.

Section 9 – Environmental and Social Benefits
Consideration of the socio-economic benefits associated with achieving each WQO on the river and estuary environments.

Section 10 - Cost-Benefit Appraisal
Comparison of the treatment costs and benefit values to produce a Net Present Value (NPV) and a benefit-cost ratio for each WQO.

Section 11 – Implementation
The method by which a long-term solution should be implemented, in particular the risks and responsibilities associated with the options and alternative contract mechanisms.

Section 12 - Conclusions and Recommendations
The preferred long-term treatment option, as determined by the above cost-benefit approach, is identified and a recommended method of implementation is established.

Section 13 - References

1.3 ACKNOWLEDGEMENTS

The Project is multi-disciplined, requiring the interaction of many specialist and diverse inputs. The close co-operation of all the consultants involved as well as the two external reviewers, the Agency personnel, South Crofty plc staff and many other interested parties has been essential in realising the project objectives. The project team also gained benefit from the foundation provided by previous studies and the extensive data collection undertaken by the Agency since the Incident in January 1992.

2. BACKGROUND

2.1 REGIONAL CONTEXT

2.1.1 Site Description and Catchment Characteristics

The Carnon Valley catchment is located in south-west Cornwall in between Redruth, Truro and Falmouth. The catchment extends to the village of Carnhot to the north, Unity Wood to the north-west and Tolcarne and Tresavean to the west.

The catchment, which drains an area of 45.5 km^2, comprises five tributaries: Poldice Stream; Wheal Maid Stream; Hick's Mill Stream; Clemows Stream and Helston Water (see Figure 2.1). These all flow into the Carnon River. The river is 9 km long and discharges via the sub-tidal Restronguet Creek and then into Carrick Roads and the Fal Estuary, one of the largest estuaries in the UK.

The Fal Estuary is a ria (drowned river valley) characterised by extensive areas of sheltered marine habitats including steep rocky shores, broad mudflats and a considerable sub-tidal sediment area. Ecologically it is one of the richest estuaries in Britain, with a high habitat diversity and community type. The area is of high conservation value and, as a result, has been subject to a range of county and national designations. Some specific areas and their designations include:

- Fal Estuary as a candidate Special Area of Conservation (cSAC) and Area of Outstanding Natural Beauty (AONB);
- Roseland Peninsula as a Heritage Coast area;
- Upper Fal Estuary and Woods as a Site of Special Scientific Interest (SSSI).

Other specific areas within the catchment and estuary are noted for distinctive habitats. In particular, defined areas are recognised for dragonflies, maerl, eelgrass (Zoostera) and various birds. These designations are described in more detail in Section 3 of the social economic assessment report (KP et al, 1998, Environmental and Social ...)

2.1.2 Economic Perspective

Many traditional Cornish industries, such as agriculture, fishing, china clay extraction, tin mining and defence, are in decline and causing economic pressures in the region.

Between 1988 and 1995, there was a 9% reduction in the total agricultural labour force in Cornwall. Full-time, regular employment fell even further, by 24%. Tin mining has suffered recently with the closure of the South Crofty tin mine and English China Clay, Cornwall's largest private company, has recently announced job losses.

The region currently has EU Objective 5b status, which entitles it to EU funds intended to 'facilitate the development and structural development of rural areas', and primarily addresses employment issues. Cornwall County Council is now bidding for Objective 1 status designated to the poorest regions of the EU, which will provide access to funds for wider purposes, including health and education.

2.1.3 Geology and Mining History

The western part of Cornwall is composed primarily of intensely faulted and folded non-calcareous sedimentary rocks of the Devonian age. These strata were subsequently uplifted by a major igneous intrusion followed by a period of hydrothermal activity when fissures in the country rock were injected with mineral bearing fluids.

The resultant mineralisation formed lode deposits primarily of tin and copper that trend east-west. A later phase of mineralisation principally of lead, zinc and some silver deposits, known as 'caunter' lodes, runs at right angles to the main set. The economic mineral formations of the region, therefore, are primarily tin and copper, but with subsidiary lead, zinc, silver and other associated minerals.

It is believed that during the Permian age, mineralised zones were exposed and then eroded. This produced alluvial deposits in the lower reaches of 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.

Mining activity in the region possibly goes back to 2000 BC, however, extensive mining dates back to the seventeenth century. By 1678 the Poldice mine in the Upper Carnon Valley was producing tin and by the early nineteenth century the local mining area, known as Gwennap, was producing about one third of the world's copper output. Associated industry to the mining included copper smelting, tin streaming, sulphuric acid production (from pyrite), tin smelting, arsenic recovery and ochre works (producing pigment). (KP et al, 1995, Environmental Appraisal ...).

The first recorded working of the alluvial deposits was in 1778 and they were extensively worked in the early 1800s. At the same time mining residues were deposited into the creeks to such an extent that the tidal limits receded and areas previously used as ports became unnavigable.

By the 1900s the large scale mining and the associated industries had virtually all ceased production with only small scale reworking of old deposits taking place. This continued sporadically until the 1970s.

Wheal Jane Mine

By the eighteenth century Wheal Jane was a major producer of tin with lesser quantities of arsenic and copper. It later became a producer of pyrite. Works ceased in about 1875 and the mine was amalgamated with Nangiles and Wheal Widden into the Falmouth Consolidated Group in 1915. This amalgamation is of considerable importance as it lead to many interconnections of the workings. These interconnections are not all recorded and the precise extent is not always known. Nevertheless, it is acknowledged that, for example, Nangiles and Wheal Jane interconnect either through adits or shallow workings and the same may be true for Wheal Widden, Wheal Hope and Wheal Baddern (see Figure 2.2).

In 1970, after redevelopment, the mine reopened and became one of the largest metal mines to operate in the UK. It was one of four mines in Cornwall, two of which, Wheal Jane and Mount Wellington, were in the Carnon Valley. To re-open the mine it is reported that the adits which were almost completely filled with ochre were flushed out and some hundreds of tonnes was discharged into the river system, to regain access. The mine subsequently processed up to 900 tonnes per day of tin and copper/zinc ores. The concentrates (about 5% by mass) were shipped via Truro for smelting whilst the waste product from the refining process, comprising 95% of throughput, was discharged into the CVTD. To operate the mine it was necessary to pump water at a significant rate. The water was pumped from underground, lime dosed and discharged via the tailings dam into the Clemows Stream.

The mine has changed ownership a number of times. The most recent owner was Carnon Holdings, which registered as a public limited company in June 1994 and changed its name to South Crofty plc (SCP). Crew Natural Resources, a Canadian Company, is the major shareholder in South Crofty.

2.2 THE MINEWATER LEGACY

2.2.1 Mechanisms and Historic Levels

Acidic minewater occurs when sulphide minerals (principally pyrite) are exposed to air and water, conditions which promote the oxidation of sulphides and the generation of acidity. The chemical reaction involving pyrite, which is accelerated by the activity of the bacteria *Thiobacillus ferrooxidans*, is presented below:

$$2FeS_2 + 7\frac{1}{2}O_2 + H_2O \Rightarrow 2Fe^{3+} + 2H^+ + 4SO_4^{2-}.$$

The resulting minewater is thus acidic and contains dissolved iron in the oxidised ferric form.

This acidic minewater can then accelerate the oxidation and dissolution of additional pyrite and other metal sulphide minerals, as indicated by the two reactions shown below:

$$14Fe^{3+} + FeS_2 + 8H_2O \Rightarrow 15Fe^{2+} + 16H^+ + 2SO_4^{2-};$$

$$8Fe^{3+} + ZnS + 4H_2O \Rightarrow 8Fe^{2+} + Zn^{2+} + 8H^+ + SO_4^{2-}.$$

These mechanisms have resulted in the generation of the metal laden acidic minewater at Wheal Jane and the other historic mine workings in the Carnon Valley wherever the principal requirements of sulphidic minerals being exposed to air and water prevail. The historic water qualities, for 1980-1990 as being demonstrative of pre-incident levels, recorded in the Carnon River, which have resulted from acidic minewater generation are presented in Table 2.1. Also shown is one of the Environmental Quality Standards (EQS) for comparison, which demonstrate that EQS were being exceeded even before the Wheal Jane Incident in 1992. Compliance with limit values was, however, being achieved.

Table 2.1 : Annual Average Metal Concentrations in the Carnon River at Devoran Bridge

Year	Annual Mean Concentrations (μg/l total metal)								Hardness (mg/l $CaCO_3$)
	Cadmium	Lead	Chromium	Zinc	Copper	Nickel	Arsenic	Iron	
1980	29.9	32.7	9.4	11 520	652	96.1		14 427	-
1981	8.0	26.1	11.0	5 367	517	74.9		8 555	-
1982	18.8	76.6	11.8	12 572	1 059	112.0		29 178	202
1983	22.6	154.0	9.7	15 415	676	155.0		31 031	421
1984	15.9	60.0	7.2	11 811	790	108.0		19 600	464
1985	11.6	19.3	10.5	15 591	638	94.5		8 920	464
1986	9.5	14.2	6.8	6 595	534	87.0		9 337	391
1987	8.7	12.7	1.4	6 474	516	81.1	131	8 695	453
1988	12.7	11.6	2.7	8 981	519	89.5	133	9 478	428
1989	10.3	6.0	1.0	8 310	405	87.7	44	6 937	541
1990	13.1	13.1	1.1	8 615	451	84.5	39	5 124	635
Limit Value(1)	200								
EQS(2)	1^T	250^D	250^D	500^T	28^D	200^D	50^D	$1\,000^D$	-

(1) Limit value for cadmium as set in 83/513/EEC Limit values and Quality Objectives for Cadmium Discharges.

(2) Environmental Quality Standards for List I and List II Substances. EC Dangerous Substances Directive- Fresh Water Environmental Quality Standards for protection of aquatic life, e.g. cyprinid fish for hardness >250 mg/l $CaCO_3$. Annual averages.

Hardness >250 mg/l $CaCO_3$ due to lime dosing during mine operation. Hardness 50-100 mg/l $CaCO_3$ without lime dosing.

^{T} denotes total concentration.

^{D} denotes dissolved concentration.

Cd EQS set at Devoran Bridge as part of the National Monitoring Network.

2.2.2 Effect of Closure of Wheal Jane

Wheal Jane Closure

The working of the Wheal Jane mine was formally terminated by Wheal Jane Limited, a subsidiary of Carnon Holdings Ltd, on 9 September 1991 under Section 139 of the Mines and Quarries Act, 1954.

Dewatering of the mine had already been stopped (on the 6 March 1991) and, as a consequence, the water levels within the mine workings began to rise. Enhanced monitoring was established to allow the location, time, quantity and quality of the eventual release of minewater from the workings to be predicted. Monitoring of the wider water, sediment and biota regimes downstream of the mine was also initiated.

Four major adit systems could potentially drain the workings in the Carnon Valley (see Table 2.2) and drainage from the lowest adit was expected which, for the Wheal Jane workings was Jane's Adit. Hydraulic connectivity between the lower mineworkings was indicated by the common rise in various shaft water levels.

Table 2.2 : Adit Decant and Portal Levels		
Adit	**Decant Level (m AOD)**	**Portal Floor Level (m AOD)**
Jane's	14.75	≈ 10
Nangiles	15.86	≈ 13
Mount Wellington	19.6	≈ 17
County	Unknown	17.11
Number of significant decimal places indicates degree of accuracy.		

As the level of the minewater approached the decant level of Jane's Adit, pumping from the adit's No. 9 shaft commenced on 16 November 1991 in an attempt to prevent an untreated release through the adit. A relatively crude lime dosing system treated the pumped water and the precipitates were settled directly in the CVTD. However, the minewater overwhelmed the treatment system and on 17 November 1991 untreated water issued from Jane's Adit rising to about 5 000 m^3/day. A plug was used to close off flow from Jane's Adit on 20 November 1991 and treatment continued in an attempt to limit the rise in groundwater levels.

High winds in December 1991 hindered the settlement of the hydroxide particulates and water effluent quality deteriorated. Water levels within the dam were raised until, on 4 January 1992, it was decided to suspend treatment and rely on underground water storage until the weather improved sufficiently for treatment to recommence without compromising the safety of the dam. Underground water levels continued to rise.

The Incident

On 13 January 1992, a sudden uncontrolled release of minewater occurred. This was originally thought to have been caused by the failure of an adit plug, designed to keep flood river levels out of the mine. However, more recent inspections of the adit (SCP, 1998, Nangiles Adit ...) suggest that a collapse of some sort occurred some way into the adit system releasing the water and leaving a partially blocked passage. This exit point now acts as a throttle to the minewater discharge as opposed to a free discharge that might normally be expected.

The adit collapse released an estimated 25 000 m^3 to 50 000 m^3 of minewater into the river within the first 24 hours, carrying with it about 100 tonnes of suspended and dissolved metals. The flow declined over the succeeding days, but remained at about 6 000 m^3/day for several weeks.

Immediately following this incident, minewater treatment was re-established and then successively upgraded until it formed the ETP.

Legal Consideration

The historic difficulty in achieving the water qualities specified under EC directives in the Carnon River and parts of the estuary has long been recognised by the Agency and its predecessor, the NRA. The closure of Wheal Jane and subsequent release of minewater in January 1992 served to highlight this long standing problem.

The NRA decided to exercise statutory powers under Section 161 of the Water Resources Act 1991 to minimise the short-term impacts of the release of minewater and to alleviate public concern. This entailed resuming, and progressively improving, the temporary treatment system as well as evaluating options for long-term treatment.

Legal advice was sought and it was determined that a prosecution could not be sustained against the mining company. It was concluded that the mine was part of a large interconnected series of mainly historic workings and that most of the water pumped from the mine had drained to Wheal Jane from other abandoned workings. It was, therefore, considered that Wheal Jane Ltd could not be said to have 'caused' the pollution. The NRA decided to approach the problem of release of untreated minewater in co-operation with the mine owners.

Under Section 161 of the Water Resources Act 1991, the Agency has discretion on whether or not to carry out anti-pollution works and the extent of these works (Meeks, 1996, Legal Preference ...). The Agency, therefore, is at liberty to cease operations as it deems appropriate without incurring liability. One exception to this is the obligation to maintain Statutory Water Quality Objectives. None have been set for the Carnon River or related waters and so no obligation exists. Had they been set then Section 84 of the Act would have obliged the Agency to continue to exercise its powers under Section 161 to prevent pollution.

There are also legal obligations to comply with those standards under EC directives which have been transposed into UK law. At Wheal Jane, compliance may be achieved through the use of the limit value approach for cadmium, where discharge quality must meet 200μg/l.

Impact on Water Quality

The water quality in the Carnon River, which is generally measured at Devoran Bridge, has been adversely affected by mining activity for many years. Even prior to release of untreated minewater from Jane's Adit and Nangiles Adit, in January 1992, the river failed to meet EQS for a number of metals (see Table 2.1). Nevertheless, the discharge incident in January 1992 had a significant deleterious impact on water quality in the river.

Peak metal concentrations following the discharge incident were several orders above EQS requirements. Table 2.3 and Figure 2.3 show recorded peak concentrations compared to a current WQO. The metal concentrations declined with time as the flow rate from the adits settled and as water treatment took effect. By October 1992 water quality had returned to pre-Incident levels.

Table 2.3 : Peak Metal Concentrations at Devoran Bridge Following the January 1992 Incident

Parameter	Pre-incident Levels (Mean 1991)	Peak Metal Concentration (14 January, 1992)	EC DS Directive - Fresh Water Environmental Quality Standards
pH	5.1	3	6 – 9$^{(1)}$
Arsenic	-	6 000	50^{D}
Cadmium	29	600	1
Copper	444^{D}	7 000	28^{D}
Iron	308^{D}	600 000	1 000^{D}
Nickel	132^{D}	1 200	200^{D}
Zinc	18 025	440 000	500

All data, except pH, expressed as μg/l total metal.

EC DS Directive – Fresh Water Environmental Quality Standards expressed as annual average concentrations for hardness >250 mg/l $CaCO_3$.

Total concentration unless denoted otherwise.

^{D} denotes dissolved concentrations.

$^{(1)}$ Range within which 95% of samples should lie.

Impact on the Fal Estuary

A detailed description of the historical impact of minewater on the estuary is included as Appendix E to the Catchment Modelling report (KP et al, 1998, Final Catchment ..., Volume 2).

The most obvious impact resulting from the incident was widespread discolouration of the Fal Estuary (see Photograph 2.1). A vivid orange-brown plume of iron hydroxide (ochre) spread across Restronguet Creek, Carrick Roads and into Falmouth Bay and became the focus of intense public and media attention. By 16 January 1992 the sea had discoloured beyond Pendennis Point and at one stage nearly as far as the Helford Estuary to the south-west (see Figure 2.4). The discolouration slowly dispersed, however, and was absent from Carrick Roads by mid-February and was intermittent only in Restronguet Creek by mid-March.

2.2.3 Recent Changes to the Minewater Regimes

Since the Wheal Jane discharge incident, described above, the only significant change to the minewater regime within the Carnon catchment was the closure of the ore milling operations at the Wheal Jane mine site. The main effect of the closure has been a change to the material types being deposited in the CVTD and this is discussed further in Section 3.2.2.

The various minewater sources that contribute to the Carnon River are now considered to be close to steady state conditions. The Wheal Jane minewater source, the most recent, has reached a relatively constant concentration and is considered unlikely to change significantly for tens to hundreds of years (KP et al, 1998, Final Catchment ..., Volume 1).

3. EXISTING TREATMENT

3.1 INTRODUCTION

The ETP was implemented by the NRA in co-operation with the mine owners, SCP, as an emergency response to the release of acidic metal laden minewater from the Wheal Jane mine into the Carnon River. The primary objective was to minimise the environmental impact on the river and estuary by treating as much water as possible.

A full description of the ETP is included in a separate report (KP et al, 1998, Existing Treatment ...) and is summarised below.

3.2 DESCRIPTION AND PERFORMANCE

Following a number of stages of development the ETP now consists of a pumping and lime dosing facility situated around the No.2 Shaft, which is a main access point to the old Wheal Jane mine. Water is pumped and then dosed with lime to raise the pH and form a metal hydroxide precipitate sludge, which is settled and deposited into the adjacent CVTD. Use of the dam is made through a contract between the Agency and SCP first established in December 1993 (Environment Agency, 1997, Contract ...). The tailings dam thus serves to clarify the treated minewater as well as being the point of deposition for the sludge.

The treatment system is managed and operated under an operations manual, (KP, 1997, Operations Manual ...). In essence the manual incorporates the following requirements:

- the maintenance of a shaft water level of between 15.0 and 15.5 m above ordnance datum (AOD) by pumping from the No.2 Shaft;
- compliance with target pH values set for key locations throughout the system, as shown in Table 3.1:

Table 3.1 : Existing Treatment System Target pH's

Location	Probe No.	Target pH		Notes
		Objective	Acceptable Range	
Inlet to dam	A2	10 – 11	9 – 11	
Dam decant	A5	8 – 8.5	8 - 9.5	
Polishing lagoon	A6	7.5 – 8.0	6 – 9	Consented discharge into Clemows Stream

Minewater is pumped from the No.2 Shaft under an abstraction license held by SCP using up to six submersible stainless steel pumpsets that each deliver a maximum of 55 l/s. Treatment is undertaken by adding a lime slurry solution to the minewater at a header tank and is then carried to the tailings dam via one of two pipelines. A schematic of the treatment system is shown in Figure 3.1.

Over the past two years the ETP has treated an average of 180 l/s removing some 96% of the metals (KP et al, 1998, Existing Treatment ...). A graph to show the quantity of minewater treated and the corresponding shaft level and untreated discharge is shown as Figure 3.2. The figure demonstrates that maintaining a shaft water level of around 15 m AOD prevents the uncontrolled flow of untreated water from Nangiles Adit.

During the winter of 1997/1998, when all Six Pumps were operating with a treatment flow rate at the maximum currently possible of 330 l/s, the shaft water level was not maintained and untreated discharge occurred. Untreated flow had not occurred during the previous two winters and it is predicted that a flow of 330 l/s from the Wheal Jane mine would be exceeded on 26 occasions during the simulated period of 35 years. The majority of these events would be for a duration of less than 7 days, resulting in short-term discolouration in Restronguet Creek. Only one or two events would be of sufficient magnitude to cause discolouration at the top end of Carrick Roads.

3.2.1 Contingency Design

The reliance on the tailings dam and contractual arrangements with SCP was recognised and a contingency plan developed (KP et al, 1997, Contingency Design ...). A draft tender document was prepared, (KP et al, 1997, Draft Treatment Plant ...) following the announcement by SCP in August 1997 of the cessation of operations. It was based upon the plan and the latest active treatment design for a plant capable of treating the Wheal Jane minewater flow using the lime dosing method currently used by the ETP. The contingency plan required clarification, filtration and dewatering equipment to be designed and installed under a contract based on the Institution of Chemical Engineers standard 'Green Book' form of reimbursable contract. In the event the contingency plan was not invoked following assurance by SCP that the company would remain in business despite the cessation of mining operations.

3.2.2 Cessation of Mining by SCP

The subsequent closure of South Crofty mine, in March 1998, meant that tailings were no longer available for co-deposition with minewater sludge into the CVTD. The tailings were observed to interact with the relatively light metal hydroxide sludge particles improving their settling properties. Thus the effluent clarity achieved with the co-deposition of tailings was better than that achieved from the deposition of minewater sludge on its own.

The absence of tailings, for co-deposition has, therefore, required a review of the deposition strategy. Minewater sludge is of low density and is particularly vulnerable to wind disturbance when deposited on its own. Effluent clarity is now less reliable. It is likely that attainment of previous discharge standards will be difficult during inclement weather and particularly winter periods when wind and pumped minewater flow rates both tend to be high. A review of deposition options (KP et al, 1998, Sludge Disposal Strategy ...) indicates that the current methods being employed are the most appropriate given the facilities available, but effluent clarity cannot be guaranteed during adverse weather. The study of alternative deposition options is continuing and reported on in Appendix A, Recent Developments.

3.3 MANAGEMENT AND OPERATION

Overall direction and responsibility for the treatment operations remains with the Agency, but routine management is devolved to Knight Piésold. Operation and maintenance services are provided by South Crofty plc (SCP) under a contract agreement (Environment Agency, 1997, Contract ...) that also provides for sludge deposition in the dam. Supply of services and consumables is effected under a series of contracts, most of which were competitively tendered. In addition to sludge disposal and operation and maintenance services mentioned above, other services procured via contracts include pump maintenance, pipe cleaning, hydrated lime supply, flocculant supply, purchase of electrical power and supply of town water.

The performance of the existing treatment system is monitored by the Agency on a continuous basis and by means of regular water quality sampling. The system is partially automated with monitoring of key parameters at various points throughout the treatment system. Significant monitoring points are linked to alarms that automatically raise various actions when activated. Details of the alarm system and required responses are set down in the operations manual. Staff cover is provided during normal working hours and pager cover is provided so that breakdowns are responded to at other times usually within two hours of an alarm being raised.

3.3.1 Discharge Consent

South Crofty plc hold the existing Discharge Consent for discharges to the Clemows Stream from Wheal Jane Mill and Shaft No.2 (15/48/19E/P/17). Occasional discolouration of the discharged water does occur during inclement weather, as detailed in Section 3.2. A revised draft Discharge Consent (NRA-SW-7810 Schedule No. TN/02) was also established to reflect the minewater treatment and use of the tailings dam (KP et al, 1998, Existing Treatment ...).

3.3.2 Treatment Costs

The costs associated with the existing treatment system are summarised in the following sections. It is noted that these actual costs are less than the estimated costs for long-term treatment (see Section 8). This is because major capital expenditure is avoided and existing facilities, with short-term lives only, are fully utilised.

Capital Purchases

Major capital purchases made since February 1992 are indicated in Table 3.2.

The long-term treatment options that involve the Wheal Jane mine site, which are developed in Section 6 of this report, show that the existing capital equipment is retained and thus it has not been included in subsequent cost estimates.

Table 3.2 : Major Capital Purchases	
Item	**Cost (£)**
Submersible pumps	70 000
Pump lifting frame	15 000
Lime dosing equipment	120 000
Dam discharge pipe	35 000
Emergency overland discharge pipe	12 000
Toe drain return scheme	35 000
Total	**287 000**

Operating Costs

Table 3.3 indicates the operating costs associated with minewater treatment for 1996 and 1997 during which time the current operating regime of maintaining shaft water level with up to six pumps has been in place.

Table 3.3 : Summary Volume Treated Costs for ETP				
Item	**1996**	**1997**	**Average**	**Percentage**
Total Volume Treated **Average Flows**	**5 661 000 m^3** **180/ls**	**5 696 000 m^3** **181 l/s**	**5 678 500 m^3** **180 l/s**	
Costs	**(£)**	**(£)**	**(£)**	**%**
Lime	272 738	248 445	260 592	38.1
Town water	3 671	4 239	3 955	0.6
Flocculant polymer	30 569	30 756	30 663	4.5
Power	75 268	72 916	74 092	10.9
Maintenance	97 722	135 085	116 404	17.0
Sludge disposal	179 249	199 800	189 525	27.7
Other regular maintenance(1)	8 750	8 750	8 750	1.2
Total (£)	667 967	699 991	683 979	**100**
Unit treatment cost (pence/m^3)	11.8	12.3	12.1	
(1) Pipe cleaning and pump maintenance contracts.				

Table 3.3 shows an average treatment cost of 12.1 pence/m^3. It will be seen later in the report that this is slightly cheaper than estimated long-term treatment costs.

The ten-year present value cost for continued treatment using the ETP is estimated at £5.54 M. Whilst this is about half the equivalent median ten-year cost (£11.2 M) for the preferred long-term solution (see Table 8.6) it should be realised that the ETP has a restricted life because of the limited capacity within the tailings dam.

4. WATER QUANTITY AND QUALITY

4.1 WATER QUANTITY AND QUALITY

The catchment modelling studies (KP et al, 1998, Final Catchment Modelling ...) provided long-term predictions of the quantity and quality of water discharging from various sources within the Carnon catchment. These predictions were based on evaluation and interpretation of flow and water quality data collected by the Agency and short-term investigative surveys. A technical summary of the catchment modelling studies is presented in Appendix C.

Hydrological and hydrochemical models were developed for the Carnon catchment and validated for the period between 1992 and 1997 for which the most complete data set was available. The relationship between flow, quality and rainfall and evapo-transpiration was used to extrapolate the flow record and to predict long-term fluctuations in water quality using the daily rainfall and evapo-transpiration data for a 35 year period between 1962 and 1996.

The Carnon catchment has an area of around 45 km^2 down to the gauging station at Devoran (see Figure 2.1). Flows at Devoran are derived from the catchment upstream of Twelveheads (which contributes some 18% of the total flow at Devoran), Hick's Mill Stream (20%), and other smaller catchments which contribute around 21% of the flow. The remainder is made up from discharge from County Adit (27%) and Wheal Jane (14%). Excess, untreated discharge from Wheal Jane occurs occasionally via Nangiles Adit when the capacity of the pumps is exceeded (see Section 3.2).

The total flow at Devoran is greater than the runoff that would be expected, probably as a result of inflows to mineworkings beyond the surface catchment boundary.

The relative contribution of contaminants from each source in the Carnon catchment is illustrated in the upper part of Figure 4.1 which shows, in bar chart format, the percentage input from each source to total loadings at Devoran, assuming that Wheal Jane is not treated. The major source of contaminants is untreated Wheal Jane minewater, but County Adit also contributes significant proportions of copper, cadmium, manganese and zinc.

Seasonal and long-term variations in concentrations occur with metal concentrations increasing following periods of high rainfall. This suggests that metals are being removed from the unsaturated zone by flushing. In County Adit, resuspension of ochre from the adit walls also occurs during initial high winter flows.

Since the recovery of Wheal Jane minewater levels in 1992 there has been a marked decline in contaminant concentrations (see Figure 4.2). This decline is probably as a result of dilution and replacement of the minewater generated during re-filling of the mine. Statistical evaluation of the data indicates that by 1999 all metal concentrations are likely to be within 1% of their long-term values. Seasonal variations will continue as metal concentrations in the unsaturated zone are gradually depleted over a period of tens to hundreds of years.

The model predictions incorporate seasonal variations, but assume that the initial decline in metal concentrations has levelled off. There will, therefore, be no natural improvement in water quality and additional treatment will be required if concentrations are to be reduced further.

4.2 INFLUENT WATER QUANTITY AND QUALITY

The hydrological and hydrochemical models were used to predict the quantity and quality of water which may have to be treated. The 35 year period was used to represent a wide range of meteorological conditions and to support a statistical approach.

Predicted flows include annual average values and the 95 percentile annual flows, defined as the flow which would only be exceeded for 5 percent of the days throughout any year. The average of the annual average flows was used as the design average flow for the treatment options. In a similar way the maximum of the 95 percentile annual flow for this 35 year period was used to establish the design maximum flow.

The quality of the minewater requiring treatment was predicted by the hydrochemical models for Wheal Jane No.2 Shaft and County Adit in the first instance. A 35 year database of daily predictions for total and dissolved concentrations and loadings was determined for iron (Fe), zinc (Zn), copper (Cu), arsenic (As), manganese (Mn) and cadmium (Cd). From this the estimated long-term water quantities and qualities throughout the system were determined as shown in Table 4.1.

Table 4.1 : Influent Water Quantity and Quality for Treatment Options

Treatment Options	Wheal Jane Six Pumps	All Wheal Jane	Wheal Jane plus County Adit	All Sources
Design maximum flow, l/s	330	430	1590	3720
Design average flow, l/s	180	190	510	1150
Total Loading, g/s	74.6	78.7	81.2	79.1
Total concentration, mg/l:	395.5	395.5	169.7	78.9
Fe, mg/l	296.1	296.1	125.6	57.9
Zn, mg/l	76.7	76.7	33.7	17.0
Cu, mg/l	0.78	0.78	0.71	0.46
As, mg/l	5.8	5.8	2.6	1.3
Mn, mg/l	8.9	8.9	4.2	2.2
Cd, µg/l	51.3	51.3	22.8	11.7
pH	3.5	3.5	-	4.6
SO_4^{2-}, mg/l	1 037	1 037	-	234

The total loading for All Sources is less than Wheal Jane plus County Adit as a result of iron removal in the Carnon River.
Values are averages of annual averages for 35 year period.

4.3 WATER QUALITY OBJECTIVES

Seven WQOs were defined for the Carnon River at Devoran Bridge and for the Fal Estuary (see Table 4.2). One of the objectives is based on No Treatment so is not included in Table 4.2.

The remaining six WQOs form two distinct groupings: No Deterioration, No Discolouration and North Sea Declaration Commitments were termed 'lower order objectives' whilst the WQOs based on EC Directive Environmental Quality Standards were termed 'higher order objectives'.

All the lower order objectives relate to water quality in the Carnon River at Devoran Bridge, part of the National Monitoring Network. An evaluation of water quality data at Devoran Bridge for recent years indicates that the existing treatment, combined with the reduction in metal concentrations in the minewater, results in compliance with the No Deterioration and North Sea Declaration Commitments WQOs. Some discolouration may occur with the existing treatment when the six pump capacity is exceeded or if the treatment plant fails. These events are expected to be short (less that 7 days) and will seldom extend into Carrick Roads. In most years it is predicted that there will be no discolouration.

The higher order WQOs based on the EC Dangerous Substances (DS) Directive – Fresh Water Environmental Quality Standards also apply at Devoran Bridge. There are two sets of values, depending upon water hardness. If lime is used in the treatment process the hardness at Devoran Bridge exceeds 250 mg/l. For other forms of treatment and untreated water a range of hardness of 50 – 100 mg/l $CaCO_3$ applies. These two sets of values are designated I and II, respectively (see Table 4.2). The higher order objective for the Carnon River (EC DS Directive – Fresh Water Environmental Quality Standards) is not achieved with existing treatment. This EC directive was also being breached before 1992 and the Wheal Jane discharge incident.

The two remaining higher order WQOs apply to salt water in the Fal Estuary. Monitoring data from the Fal Estuary indicates that the EC DS Directive - Salt Water Environmental Quality Standards and the Protection of Estuarine Biology (as defined in the EC Shellfish Waters Directive) WQOs are not being met with existing treatment for copper and zinc in Restronguet Creek and possibly in the north-west areas of Carrick Roads. Figure 4.3 illustrates compliance and failure for conditions similar to those occurring in recent years under existing treatment. The figure is based on model results for treatment of All Wheal Jane discharge.

4.4 STATUTORY REQUIREMENTS

The Agency has a commitment to meet those standards prescribed in EC Directives that have been transcribed into UK Law. Limit values for cadmium (200 μg/l) are a legal requirement in the UK, and it should be noted that these limit values are being achieved at the present time.

The higher order objective for the Carnon River (EC Dangerous Substances Directive – Fresh Water Environmental Quality Standards) is not achieved with existing treatment at Devoran Bridge. The Environmental Quality Standards (EQS) were also being exceeded before 1992 and the Wheal Jane discharge incident (see Table 2.1). For example, EQS for cadmium, a List I substance, is being exceeded. However, EQS for cadmium at Devoran Bridge is set at 1 µg/l (annual mean total) because it is part of the National Monitoring Network whereas, the quality objective for inland surface waters, other than National Monitoring Network sites, is 5 µg/l (annual mean total). Moreover, compliance with EC DS Directive limit values for cadmium (200 µg/l) is being achieved.

Monitoring data from the Fal Estuary indicates that the EC Dangerous Substances Directive – Salt Water Environmental Quality Standards and the Protection of Estuarine Biology (as defined in the EC Shellfish Waters Directive) WQOs are not being met with existing treatment for copper and zinc in Restronguet Creek and possibly in the north-west areas of Carrick Roads. Figure 4.3 illustrates compliance and failure for conditions similar to those occurring in recent years under existing treatment. The figure is based on model results for treatment of All Wheal Jane discharge.

Biodiversity and the Habitats Directive

There is a duty on the Agency to consult with statutory conservation agencies before carrying out, or authorising others to carry out, work which may damage the special conservation interest of designated sites. The Fal Estuary is a candidate Special Area of Conservation (cSAC) so formal notification of the selected treatment option requires presentation to English Nature, as a statutory consultee, for their comment. English Nature has the power to object to proposals which it is felt would have significant effect on designated European sites.

English Nature has been fully consulted on the treatment options presented in this report.

4.5 REQUIRED METAL REMOVAL

The average influent load of metals for all sources entering the Carnon River is presented in Table 4.3 together with the loadings for the lower order WQOs and higher order WQOs.

This table shows the relative contributions of the different minewater sources to the average loading of each of the six metals. These average metals loadings indicate where metals removal is required in order to achieve a particular WQO.

Table 4.2 : Water Quality Objectives

Parameter	No Deterioration		No Discolouration(3)	North Sea Declaration Commitments	Protection of Estuarine Biology(8)
	Annual average	95 %ile		Annual average	Annual maximum
Fe	8,000 T	17,000 T	10 – 20 mg/l(3) T	-	-
Zn	6,000 T	13,000 T	-	3,000T	40 SD
Cu	600 T	900 T	-	-	5 SD
As	100 T	300 T	-	-	25 SD
Mn	700 T	1,000 T	-	-	-
Cd	6 T	11 T	-	-	5 SD
pH(7)	-	4.2 – 7.1	-	-	7 – 9 S

Parameter	EC DS Directive – Fresh Water Environmental Quality Standards (I) (4)		EC DS Directive – Fresh Water Environmental Quality Standards (II) (5)		EC DS Directive – Salt Water Environmental Quality Standards (6)	
	Annual average	95 %ile	Annual average	95 %ile	Annual average	95 %ile
Fe	1,000 D	-	1,000 D	-	1,000 SD	-
Zn	500 T(1)	2,000(1)	175 T(1)	700(1)	40 SD	-
Cu	28 D	112	6 D	22	5 SD	-
As	50 D	-	50 D	-	25 SD	-
Mn	-	-	-	-	-	-
Cd	1 (200) T(2)	-	1 (200)T(2)	-	2.5 SD	-
pH(7)	-	6 – 9	-	6 – 9	-	6 – 8.5S

All concentrations in µg/l at Devoran Bridge (unless in estuary as stated in (6) and (8)).

S : denotes salt water concentration in estuary.

D : Dissolved concentration.

T : Total concentration.

(1) Protection of non-sensitive aquatic life (e.g. cyprinid fish).

(2) EQS at Devoran Bridge (part of the National Monitoring Network) (Limit Value for cadmium in discharge given in brackets).

(3) Estimate of threshold at Devoran Bridge above which discolouration is assumed to occur, based upon observations from past discolouration events in Restronguet Creek. Iron loading threshold at Devoran Bridge 2 000-4 000 kg/d.

(4) European Community Dangerous Substances Directive – Fresh Water Environmental Quality Standards (I) assumes Oxidation and Chemical Neutralisation (OCN) continues (Hardness > 250 mg/l $CaCO_3$). Taken from DoE Circular 7/89, for the protection of aquatic life.

(5) European Community Dangerous Substances Directive – Fresh Water Environmental Quality Standards (II) assumes Oxidation and Chemical Neutralisation (OCN) ceases (Hardness between 50 and 100 mg/l $CaCO_3$). Taken from DoE Circular 7/8, for the protection of aquatic life.

(6) European Community Dangerous Substances Directive – Salt Water Environmental Quality Standards. Taken from DoE Circular 7/89 for the protection of salt water life. Water quality in estuary.

(7) 95% of samples must lie within range shown. 75% for EC Shellfish Waters Directive (Protection of Estuarine Biology).

(8) Water quality in estuary. Taken from Implementation of the EC Shellfish Waters Directive. NRA Water Quality Series No. 16, March 1994.

Table 4.3 : Average Influent Load of Metals from Different Sources compared with the Loadings for the Water Quality Objectives at Devoran Bridge and Fal Estuary

	All Wheal Jane	Wheal Jane plus County Adit	All Sources	Lower Order Objectives			Higher Order Objectives		
				No Deterioration	No Discolouration Limit	North Sea Declaration Commitments	Protection of Estuarine Biology	EC/DS Directive Fresh Water Environmental Quality Standards (I)	EC/DS Directive Fresh Water Environmental Quality Standards (II)
	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day	kg/day
Fe	5134	5231	5031[(1)]	795	2000		-	99^D	99^D
Zn	1328	1402	1478	596		298	4^D	50	17
Cu	15	34	47	60			0.5^D	2.8^D	0.6^D
As	87	88	93	10			2.5^D	5.0^D	5.0^D
Mn	154	174	187	70				-	-
Cd	0.97	1.06	1.175	0.60			0.5^D	0.1	0.1

(I) EC Dangerous Substances Directive - Fresh Water Environmental Quality Standards (hardness >250 mg/l $CaCO_3$)
(II) EC Dangerous Substances Directive - Fresh Water Environmental Quality Standards (hardness 50-100 mg/l $CaCO_3$)
^{D} Dissolved
(1) The total iron loading for All Sources is less than for Wheal Jane plus County Adit as a result of iron removal in the Carnon River.

5. PROCESS ROUTE ALTERNATIVES

5.1 INTRODUCTION

Reducing the metal loads and acidity of discharges into the Carnon River could be achieved using a combination of a large number of methods. The principal options, however, remain those of *prevention* or *removal*.

Prevention of discharges, either by eliminating the ongoing production of minewater or by reducing the flow rates by isolating the minewater body are considered in Section 5.2.

The removal options have been categorised into two main forms of treatment; active and passive. Active methods rely on continued input to maintain performance whilst passive methods aim to be self sustaining. These two methods are discussed in Section 5.3 and Section 5.4, respectively. Some overlap between these categories obviously occurs.

Removal of metal ions inevitably results in the production of by-product materials and these are considered in Section 5.5, Sludge Management. Since some of the metals, such as zinc, have commercial value, the selective removal and recycling of specific metals is considered. This could allow cost savings to be made as well as reducing the proportion of sludge product requiring long-term disposal. Minimisation of sludge is also considered.

5.2 PREVENTION AND CONTROL OF DISCHARGES

Minewater contamination could possibly be reduced by prevention or control measures where either the process of minewater production is inhibited or the discharges are managed so as to reduce the contamination load that enters the water system. Such measures could involve the sealing of workings to prevent ongoing acidic minewater production or the re-routing of surface flows to reduce the flushing of existing minewater bodies.

The two major minewater sources, Wheal Jane and County Adit, both drain significant areas of land and the physical sealing to reduce water inflow and oxygen availability is not considered feasible. County Adit, for example, is thought to extend for over 40 km in length (see Figure 2.2) draining an area of about 6 km^2. Surface spoil heaps, such as old surface workings and mine spoil heaps, also contribute as diffuse sources. Whilst there are a wide range of techniques which, theoretically, could be used to control the generation of acidic or metalliferous minewaters in underground mines, these techniques are only considered to have potential benefits at small mine sites.

Several techniques have been tested in field trials on surface spoil heaps and have been shown to be effective, for example, capping with low permeability covers or the application of long-life bactericides. None of the techniques have a proven track record, however, particularly for mine sites with large volume discharges and for those draining such extensive areas. Similar trials for deep mine workings appear not to have been carried out. Also, contamination from diffuse sources is considered unlikely to cause a breach of lower order WQOs. With ongoing treatment at Wheal Jane, the major cause of failure of the higher order WQOs is contamination from County Adit. The loadings evaluation suggests that, excluding discharges from Nangiles Adit, arsenic loadings at Bissoe GS and at Devoran Bridge originate from diffuse sources. However, diffuse source arsenic contamination appears to be very close to being within the higher order limits at

Devoran Bridge. Based on this, measures to control diffuse source contamination are of lower priority, in terms of achieving additional WQOs, than preventative measures or treatment of County Adit.

An example of a preventative measure is the canalisation of the Carnon River. Following the collapse in 1975 of near surface workings major inflows into the Wheal Jane and Mount Wellington mines occurred. The Carnon River was subsequently canalised for a length of 80 m where the river crossed the ore bodies. More recent hydrogeological investigations suggest that some limited inflow may still occur, but that the flows have been substantially reduced.

If preventative measures for diffuse sources are nonetheless considered desirable, the first step would be, following the regional evaluation carried out here, to characterise key potential sources through localised investigative surveys. The priority areas for such investigations would be the Carnon River between Points Mill and Bissoe, as a potential source of arsenic, the Wheal Maid Tailings Dam, as a potential source of contaminant loadings to the Wheal Maid Stream, and County Adit.

Treatment of point sources (Wheal Jane mine and County Adit) remains the most economic option for achieving the WQOs at Devoran Bridge. The hypothetical benefit of treating diffuse sources would be limited and the measures required to achieve this are likely to prove very expensive and impractical to employ.

5.3 ACTIVE TREATMENT

Three routes for the treatment of Wheal Jane minewater were selected for detailed consideration from a wide range of alternatives:

- Oxidation and Chemical Neutralisation (OCN), using well-established recycled sludge technology based on lime dosing;
- Biochemical Sulphidisation (BCS), using relatively new technology based on sulphate reducing bacteria;
- Ion Exchange (IEX), using synthetic resins to extract the metals followed by a conventional, but small lime dosing system.

A technical summary of a study performed on active treatment processes (KP et al, 1998, Active Treatment ...) is presented in Appendix E.

5.3.1 Oxidation and Chemical Neutralisation (OCN)

The most widely used method for the active treatment of metal bearing acidic water is chemical neutralisation. This is normally achieved using a suspension of hydrated lime as neutralising agent. An oxidation step following an initial dosing of lime enhances the removal of iron and arsenic as ferric hydroxide and amorphous ferric arsenate. The remaining metal content of the water is then removed with further lime dosing, precipitating the respective metal hydroxide in the form of a sludge.

Testwork was conducted by Anamet Services to confirm the applicability of chemical neutralisation processes to Wheal Jane minewater independently of technology suppliers.

The different options available for neutralisation have been evaluated, and the use of quick lime together with a slaking unit is considered to be the preferred option for this project. Slaked lime, limestone, magnesium hydroxide and caustic soda are the possible alternatives, with limestone providing the possibility for initial neutralisation up to pH 5.

Following neutralisation and precipitation, a solid/liquid separation stage is required to remove the thickened metal hydroxide sludge from the liquid effluent. Conventional clarifiers or thickeners have been identified as the most appropriate equipment for achieving this separation, in combination with the patented Tetra recycle sludge technology. Dewatering of this sludge is then required to lower the total volume of sludge for disposal. When judged against other alternatives - using product cake water content, cycle times and manpower requirements as the main performance criteria - a horizontal plate and frame filter press emerges as the best option. The liquid effluent from this sludge dewatering is treated in a final polishing stage to provide a further improvement in effluent quality. Sand filtration has been identified for this final polishing, improving the removal of the remaining suspended solids in the effluent prior to discharge.

5.3.2 Biochemical Sulphidisation (BCS)

Biochemical Sulphidisation is a relatively new technology which is being applied commercially for the removal of sulphate and metals from effluent streams. Anaerobic micro-organisms and organic reagents are used to reduce (extract the oxygen from) the sulphate in the minewater to produce sulphide. This sulphide can then combine with the metals in solution to produce a metal sulphide precipitate and generate solutions with low dissolved metals concentrations. For optimum performance these organisms require the temperature of the minewater to be raised to between 25 to 30°C through the use of a heat exchanger. Also, an adjustment of the pH to 7 by the addition of caustic soda is required. Paques BV has commercialised this technology as the THIOPAQ process, installing a plant in the Netherlands in 1992 to remove zinc and iron from contaminated ground water at a flow rate of 80 l/s.

In the THIOPAQ process, this reduction takes place in an Upflow Anaerobic Sludge Blanket (UASB) Reactor in which the sulphate content of the incoming water is reduced by micro-organisms from a concentration of 1 000 mg/l to about 200 mg/l. This reduction of the sulphate produces approximately 250 mg/l of sulphide, which can combine with the dissolved metals to induce the metal sulphide precipitation. Polymeric flocculant and nutrients are added to the UASB reactor influent with Aquaguard, a mixture of organic acids, being envisaged as the necessary reducing agent. The effluent from the UASB reactor contains residual dissolved sulphide not consumed by metals precipitation. This is oxidised to elemental sulphur by air in a submerged fixed film biological reactor. Solids are removed from both the anaerobic and aerobic stages followed by thickening and the generation of a sludge cake for disposal. As in the case of the OCN route, sand filtration is also included for final liquid effluent polishing.

A pilot plant has been operated on site by Paques to demonstrate the applicability of the THIOPAQ process to the treatment of Wheal Jane minewater. Preliminary results are in line with the expected effluent qualities presented in Table 5.1.

5.3.3 Ion Exchange (IEX)

Ion exchange is a relatively mature technology used in the metals processing industry for the separation and purification of metal bearing solutions, with many examples of industrial applications in gold and uranium extraction. It is also applied for softening process water streams in the chemical and power generation industries, as a polishing stage in wastewater processing, for potable water production and for nitrate removal. IEX is still relatively new for the treatment of minewaters, where the requirement is to remove metals from relatively high flow rates, where hardness can also be present. Ion exchange technology has been piloted at 0.3 l/s for the treatment of a low acidity minewater, with testwork having been performed in South Africa by JCI on their GYP-CIX process. No commercial scale plant has yet been developed, however, and extensive testwork and a significant amount of engineering design would be required to develop a plant for processing Wheal Jane minewater.

For minewater treatment, the raw minewater is passed to a strong acid cation exchange bed in which all the metal ions are adsorbed on to the resin in exchange for hydrogen ions producing an acidic solution. The solution can then be passed to an anion exchange unit where the sulphate ions and arsenate ions are adsorbed in exchange for hydroxyl ions to produce a purified effluent solution. The cation exchange resin is regenerated by the action of sulphuric acid, which is subsequently neutralised with lime to give a precipitate of gypsum and metal hydroxides. The anion exchange is regenerated by the action of lime to produce gypsum. The gypsum and hydroxides sludge is of a similar nature to the sludge produced by the OCN treatment and would be disposed of in a similar way.

Three alternatives have been considered for the applicability of ion exchange for this project:

- the use of cationic and anionic exchange resins for the Six Pumps treatment option (minewater from Wheal Jane) or All Sources treatment option to achieve effluents which comply with the EC DS Directive - Fresh Water Environmental Quality Standards (IEX);
- the use of a cationic exchange resin for polishing the effluent from an OCN plant and the remaining sources entering the Carnon River to the EC DS Directive - Fresh Water Environmental Quality Standards (OCN-IEX (I));
- the use of cationic and anionic exchange resins for polishing the effluent from an OCN plant and the remaining sources entering the Carnon River to achieve all the higher order WQOs (OCN-IEX (II)).

The cost of ion exchange is largely determined by the total resin requirement, which is dependent on the amount of cations and anions to be removed. IEX in combination with OCN treatment for bulk metal removal is, therefore, a potential alternative to meet the higher order WQOs at Devoran Bridge in a cost effective way.

5.3.4 Treated Effluent Quality (TEQ)

The quality of the treated effluent, which could be guaranteed by the technology suppliers for each of the treatment processes, is given in Table 5.1. The compositions correspond to 95 percentile concentrations, which would be achieved and could, therefore, be used as the basis for a Discharge Consent. In the case of OCN and BCS processing, these guarantees are based on pilot testing on Wheal Jane minewater as well as industrial experience from commercially operating plants.

Expected TEQs are also included in Table 5.1. These values correspond to the concentrations, which are expected to be achieved by the treatment processes on an annual average basis, and were used as input concentrations in the catchment modelling studies.

Table 5.1 : Guaranteed and Expected Concentrations of Various Parameters in Treated Water Using OCN, BCS and IEX Processes

Parameter	OCN		BCS		IEX/OCN-IEX (I)	OCN-IEX (II)
	Guaranteed (1)	Expected(2)	Guaranteed (1)	Expected(2)	Expected(3)	Expected(4)
Arsenic	-	0.01	0.1	0.05	0.05	0.025(5)
Aluminium	1.0	-	2.1	-	-	-
Cadmium	0.15	0.001	0.01	0.001	0.001	0.001
Copper	0.08	0.04	0.1	0.02	0.028	0.005(5)
Iron	5.0	2.8	1.0	0.5	1.0	1.0
Manganese	1.0	0.14	-	0.5	-	-
Nickel	0.1	-	0.2	-	-	-
Lead	-	-	0.25	-	-	-
Zinc	2.5	1.75	0.1	0.05	0.5	0.04(5)
Sulphate	-	-	100	<200	-	-
Total suspended solids	14	14	30 - 50	<30	-	-

All concentrations in mg/l.
(1) Guarantee values which could be used for Discharge Consents.
(2) Expected values from test work and industrial operations.
(3) The expected concentrations for IEX designed to meet the EC DS Directive - Fresh Water Environmental Quality Standards, although not confirmed through testwork.
(4) The expected concentrations for IEX designed to meet all higher order WQOs although not confirmed through testwork.
(5) Annual maxima values.

BCS offers a better TEQ compared with OCN with respect to the concentration of copper, zinc and iron in the final effluent and is also able to lower the concentration of sulphate. In contrast OCN produces lower concentrations of arsenic in the final effluent. IEX can be designed to meet higher TEQs compared with OCN and BCS.

5.3.5 Alternative and Emerging Technologies

Other possible forms of treatment were also examined, including the use of specific reagents for metals removal, the use of membranes to achieve a more concentrated solution and the selective removal of metals for subsequent recovery. None of these options were considered to have sufficient economic advantage to merit incorporation into any of the treatment routes.

This is because:

- proprietary reagents were not considered to have a clear cost advantage and a long-term commitment to a specific proprietary product would be required;
- membrane technology could concentrate the metals into a stream of about one quarter of the total treatment flow, but would require some form of additional treatment for metals removal resulting in a high total cost;
- the additional capital and operating costs associated with the selective removal of metals for subsequent recovery, compared with the limited revenues produced by the low quantities of recoverable metal values, prevent these options being economically attractive.

5.4 PASSIVE TREATMENT

5.4.1 Introduction

Passive treatment is a generic term used to describe water treatment systems that, once established, require a minimum of continued inputs (raw materials, energy and labour) to maintain performance. Many passive systems are modelled on natural systems, such as reed beds or marshes, where self sustaining treatment processes have developed naturally. A detailed understanding of the complex physical, chemical and biological processes that operate in these systems is still developing and, consequently, the design of such systems is still based largely on empirical parameters.

Due to the wide variation in minewater quality encountered at different sites, it was considered prudent to undertake pilot trials in order to confirm the validity of the design parameters and operating procedures. Accordingly, a pilot passive treatment plant was designed and constructed in the Carnon Valley and subsequently operated and monitored. A summary of the Pilot Passive Treatment Plant is included in Appendix G and the supporting report (KP et al, 1998, Final Pilot Passive ...) and only the applicability of passive treatment for treatment in the Carnon Valley is considered here.

5.4.2 Descriptions

The Pilot Passive Treatment Plant consists of three separate systems each comprising three basic treatment components, that is aerobic cells, anaerobic cells and aerobic rock filters. The systems differ in the type of pre-treatment utilised to increase the pH of the influent minewater and the maximum flow at which they were operated:

- the Lime Dosed System employs a small lime dosing plant and precipitate trap (sludge channel) and was operated up to 0.6 l/s;
- the Anoxic Limestone Drain System employs a small anoxic (without oxygen) cell (Pre-ALD) and an Anoxic Limestone Drain (ALD) and was operated up to 0.6 l/s;
- the Lime Free System has no pre-treatment and acts as a control to the other two systems, operating up to 2 l/s.

Initially, the minewater flowed sequentially through the aerobic cells, anaerobic cells and rock filters, with the aerobic cells operated in series, as shown in Figure 5.1.

At the end of 1996, this flow arrangement was modified to investigate the performance of the aerobic cells operated in parallel and the anaerobic cells receiving raw or pre-treated minewater directly rather than after treatment in aerobic cells.

5.4.3 Performance and Results

The performance of the three systems is summarised in Table 5.2, showing the range of metal removal achieved by each of the three treatment components as percentage removal and effluent concentration.

Table 5.2 : Summary of Pilot Passive Treatment Plant Performance

Component	Metal	Influent Concentration(1) (mg/l)	Percentage Removal (unless stated) and pH(1) (%)	Effluent Concentration(1) (mg/l)
Aerobic Cells	Iron	142	62 to 97	3 to 56
	Arsenic	2.6	84 to 100	<0.001 to 0.130
Anaerobic Cells	Zinc	76	29 to 100	0.1 to 36
	Copper	0.4	100	<0.03
	Cadmium	0.15	75 to 100	<0.001
	Iron(2)	142	11 to 81	35 to 137
	pH	3.9	Increase to 5.9 across cell	-
Rock Filter	Manganese	23	0 to 97	0.7 to 47
	Biochemical Oxygen Demand	<4 to 29	71 to 100	<4 to 19

(1) Data presented as median values or the range of median values under variable flow rates and operating conditions. Aerobic and rock filter removal values are due to treatment alone (i.e. with an allowance for dilution/evaporation). 100% removal indicates removal to below detection limits.

(2) Performance data for anaerobic cells receiving raw or pre-treated minewater directly, rather than after treatment in aerobic cells.

The removal rates were generally good demonstrating that low effluent concentrations can be achieved for the levels of flow treated by the pilot plant.

5.4.4 Applicability of Passive Treatment

The possibility of a full scale passive treatment plant for treatment towards the specific WQOs has been determined by considering various alternative configurations of plant. For example, a plant designed for the No Discolouration lower order WQO would be configured solely for maximum iron removal, whereas a plant for a higher order objective would be required to remove all significant metals.

The applicability of passive treatment has been assessed by determining the maximum flow which could be treated within the limits of the 21 ha. of land available. This assessment is presented in Table 5.3 for the principal plant configurations, together with cost estimates and comments on expected performance.

Table 5.3 : Summary Table of Passive Treatment Options for Wheal Jane

Treatment Type	Plant Configuration	Area (ha)	Treatment Flow (l/s)	CAPEX /OPEX(1) (£ M)	Predicted Approximate Effluent Concentration (mg/l)
Primary	Aerobic only	21	240	5.7/0.04	Iron 80(2)
(Wheal Jane minewater)	Anaerobic only	21	50	15.7/0.22	Iron 200, Zinc 15
Secondary (after OCN)	Aerobic only	5(3)	430	3	Iron <1
(Wheal Jane minewater)	Anaerobic only	21	160	15.7/0.22	Zinc <0.1 Copper <0.03 Cadmium <0.001 Iron <0.5
Primary (County Adit)	Anaerobic only	21	160	15.7/0.22	Zinc <0.1(4)
Diffuse Sources (Carnon River)	Insufficient land area				

(1) CAPEX - estimated capital cost; OPEX - estimated annual operating cost.
(2) System operated in-parallel enabling 1 500 kg/day iron removal.
(3) Based upon results from a secondary reed bed operated by IMC Engineering Consultants at Woolley Colliery, West Yorkshire.
(4) Based upon treating only 160 l/s out of the total County Adit flow.

The primary treatment of Wheal Jane minewater by parallel aerobic cells only was examined with a view to maximising the removal of iron within the available land area. A maximum of 1 500 kg/day of iron could be removed by this configuration, which is insufficient to meet the No Discolouration WQO.

The primary treatment of Wheal Jane minewater by anaerobic cells only was examined, based on the specific removal rates and effluent concentrations achieved by this configuration in the pilot plant. The combination of high effluent concentrations and a low treatable flow resulted in none of the WQOs being met.

An aerobic system used as a secondary polishing stage after an active treatment process could manage higher flow rates as the land area required would be manageable (5 ha. for the Wheal Jane flow from previous estimate). It will be seen later that such a reed bed would be more expensive than a sand filter, which is an alternative. It is realised that the main task of the sand filters would be to reduce entrained solids rather than reduce dissolved concentrations in the effluent stream, but the effluent quality would be expected to be more consistent.

Specific removal rates were used to assess the volumes of flow which could be treated by anaerobic cells for the secondary treatment of Wheal Jane minewater or the primary treatment of County Adit. Low effluent concentrations could be achieved with flows up to 160 l/s.

It is shown later in the report that up to 330 l/s of Wheal Jane minewater must be treated to achieve any WQO that needs treatment and it is, therefore, concluded that none of the WQOs could be reliably achieved using passive treatment alone. The main constraint is land area, which is limited to 21 ha. of available land in the Lower Carnon Valley. If unlimited suitable land area were available then it would in theory be possible to treat the minewater to attain the relevant WQOs using passive treatment systems. The construction costs would, however, be extremely high and the effluent quality not consistent. This is because bacterial metal removal processes may be affected by variations in the influent water quality (both physical and chemical). In addition, evaporation and dilution (by rainfall) may affect final effluent quality by effectively increasing metal concentrations and exceeding treatment capacity, respectively.

5.4.5 Summary

The potential use of passive treatment technology for the treatment of Wheal Jane and Carnon Valley minewater sources has been thoroughly assessed via the operation of three pilot treatment systems since 1994. As a result of this and earlier studies, the following conclusions have been drawn:

- there is insufficient suitable land area available within the Lower Carnon Valley site to contain a treatment plant capable of achieving any of the required WQOs;
- if sufficient land were available then substantial removal of metals from the Carnon River system would be possible, but at significant cost due to the large minewater flow to be treated;
- the TEQ of a passive plant can be variable, thus a third party (Contractor) would be unlikely to take on the liability of a strict discharge consent and the Agency could not, therefore, pass this responsibility on and revert to a role of regulator;
- an aerobic reedbed system could be used as a polishing stage after active treatment, although final effluent qualities might be inconsistent.

5.5 SLUDGE MANAGEMENT

The hydroxide residues resulting from OCN and IEX treatment are considered stable under atmospheric conditions, which means that open air deposition is acceptable and deposition in the CVTD is possible. The addition of cement to the hydroxide sludges could increase the strength of the dewatered cake sufficiently to allow vehicle access on to the surface. This would allow easier cake handling and would increase dam restoration alternatives.

The sulphide residues resulting from BCS treatment will readily oxidise on exposure to air, repeating, in fact, the original reaction that formed the acidic minewater. These residues must, therefore, be disposed of into a contained landfill facility operating a day/night cover system or other approved containment method. Such sludges cannot, therefore, readily be deposited in the CVTD without extensive modification to the disposal system.

The review of alternative sludge disposal locations (KP et al, 1998, Active Treatment ...) indicates the following preferred primary sludge disposal locations:

- CVTD for hydroxide sludges (OCN and IEX);
- off-site disposal (to the Welford landfill site, Northants; Linghall Quarry, West Midlands or similar) for sulphide sludges (BCS).

A purpose built sludge disposal facility 'the Lower Mine Site' was considered at the Wheal Jane site. However, it has not been pursued further since it was established, by joint consent in November 1997, that the current hydroxide sludges could continue to be placed into the CVTD (KP et al, 1998, Active Treatment ...). The Lower Mine Site would involve substantial construction costs (estimated at £2.0 million) and be of limited life (17 years maximum for the Six Pumps OCN treatment option), but could be used for the disposal of BCS sludge.

As previously suggested, a contingency site will always be required to cover unforeseen circumstances and so an off-site disposal option should be developed for any long-term treatment option involving residue disposal.

Summary of Sludge Disposal Options

- If the CVTD is available then it represents the optimum site for long-term sludge disposal from OCN or IEX process routes.
- Sludge from a BCS plant would always require a dedicated cover or containment system, which is not available from the existing Wheal Jane site facilities. This sludge would, therefore, require off-site disposal to an appropriate landfill. The Welford landfill is the most appropriate site identified.
- An alternative, or contingency, site will always be required to cover unforeseen circumstances. Off-site disposal to a licensed landfill facility should be available.
- Passive treatment plants require the construction of large cells containing either aerobic or anaerobic systems. The resulting metalliferous sludges would probably be left in situ, although this would result in a finite cell life. The cost of removing the sludges to landfill and then reconstructing the cells, however, is prohibitive.

The costs associated with sludge disposal appropriate to each of the process routes are identified in Section 8 of this report.

5.6 COMPARISON OF ALTERNATIVES

The various possible forms of minewater treatment have been reviewed briefly and the associated performances and dependencies highlighted. Table 5.4 provides a summary comparison between these basic options. It is important to realise, at this stage, that each process route can be configured in a large number of ways to suit particular requirements.

5.6.1 Sustainability

The sustainability of minewater treatment is assessed by considering the consumption of non-renewable resources and land use for the different treatment options, looking specifically at the long-term requirements for sludge disposal, reagent consumption and fuel and energy demand. These items are compared relatively in the summary of the treatment options in Table 5.4 and are discussed below.

Passive treatment would appear to be the most sustainable option, if sufficient land could be made available and the precipitated metals could be left in situ.

OCN treatment produces a hydroxide sludge enabling disposal on site in the existing CVTD facility. This option is relatively low in both reagent consumption and energy demand. Neutralisation can be achieved by lime with the potential for substitution by limestone for the initial pH adjustment.

BCS treatment produces a sulphidic sludge requiring transportation and off-site disposal at an appropriate landfill facility. This option requires both neutralising reagents and an organic reductant and has a high total energy demand in view of the need to elevate the temperature of the minewater before anaerobic treatment. This treatment option does, however, have the capability of producing a separate zinc sulphide sludge for metal recovery, resulting in a reduction in sludge disposal volumes. However, the revenues associated with the low metal volumes do not compensate for the higher costs associated with this treatment option.

IEX treatment of minewater has been developed to pilot scale, producing a hydroxide/gypsum sludge. The demand for reagents and total energy is expected to be greater than OCN treatment, although the potential exists for producing metal salts and reducing disposal volumes.

In summary land requirements preclude passive treatment as an alternative, and the higher reagent consumption and energy demand associated with BCS or IEX treatment with limited scope for metals recovery, favour OCN as the most sustainable treatment option for Wheal Jane.

Table 5.4 : Summary of Treatment Options

Treatment Route	OCN	BCS	IEX	Passive
Overall performance(1)	Good	Medium	Good	Poor
Land take	Low	Low	Low	High
Relative cost	Low	High	High	Medium(2)
Dependency on sludge storage	High	High(3)	High(3)	High (usually as part of the system)
Maturity of technology	Mature	Developing	Mature (4)	Developing(5)
Commercial acceptances for minewater treatment	Well established	Relatively new	Pilot scale only	Relatively new
Relative reagent consumption	Low	High	Medium	Very low
Relative energy demand	Low	High	Medium	Very low

(1) Rating based on technical appropriateness for treatment of Wheal Jane minewater and ability for Agency to transfer treatment responsibility.

(2) Using maximum land area available. WQO not achieved.

(3) Alternative configurations for selective removal reducing sludge requirements and producing saleable products has been considered, but no viable options were identified.

(4) Ion Exchange is widely used in many metal extraction processes, but has not yet been adopted for large scale minewater treatment.

(5) Technology is developing fast especially for low concentration minewater and where land is cheap.

6. DERIVATION OF TREATMENT OPTIONS

6.1 INTRODUCTION

This section of the report describes the water quality modelling and the process by which the required level of treatment to achieve each WQO was derived.

Firstly, a wide range of possible *treatment alternatives* were considered using combinations of treatment processes and minewater sources. These were reduced using deduction and demonstration down to a set of *treatment scenarios*. Secondly, these scenarios were modelled to determine which, if any, WQOs were achieved. Thirdly, as a result of the modelling results, some additional treatment scenarios were modelled and specific *treatment options* were developed that would enable all possible WQOs to be satisfied.

This decision process, and how it fits into the overall approach to appraisal and selection of the long-term treatment option, is illustrated in Figure 6.1.

6.2 IDENTIFICATION OF TARGET TREATMENT ALTERNATIVES

At the start of the study a large number of alternative solutions were considered (see Table 6.1). A process of reduction then followed involving methods of deduction and demonstration to derive a smaller set of options for more detailed evaluation.

6.3 TREATMENT SCENARIOS

From the initial review of possible treatment alternatives many options were dismissed because it could be seen, from a mass balance, that even total removal of the metals in question would not achieve the WQOs. The three preferred treatment routes identified in the previous section, OCN, BCS and IEX treatment, were used in combination with a number of different minewater sources, described in Section 4, to form a set of treatment scenarios for detailed appraisal and quantitative modelling. These aspects were under consideration early on in the project and some treatment alternatives, notably IEX, had not been fully determined and were introduced later. The scenarios also included sensitivity cases, as summarised below.

Treated effluent quality was based on 'expected' values (see Table 5.1) and, therefore, gave a realistic prediction of the effect of treatment.

No Treatment

Worst case	-	Wheal Jane minewater quality based on No.2 Shaft water quality.
Best estimate	-	Wheal Jane minewater quality based on Nangiles Adit water quality, which is slightly better quality than No.2 Shaft for most contaminants.
Sensitivity case	-	Wheal Jane minewater quality based on 10% of No.2 Shaft concentrations to illustrate the consequences of order of magnitude changes.

Table 6.1 : Initial Treatment Alternatives and Process of Reduction				
Ref.	**Minewater Source**	**Primary Treatment Method**	**Secondary Treatment Method**	**Significant Aspects**
1	No Treatment	N/A		Base case option
2	Diffuse Sources Only	OCN		By deduction from the metal load contributions total removal of the Diffuse Sources loads would not achieve any WQO
3		OCN	Passive	
4		BCS / IEX		
5		Passive[1]		
6	County Adit	OCN		By deduction from the metal load contributions total removal of the County Adit loads would not achieve any WQOs
7		OCN	Passive	
8		BCS / IEX		
9		Passive[1]		
10	Wheal Jane (Six Pumps)	OCN		Widely used process
11		OCN	Passive	Large land take
12		BCS / IEX		Better effluent quality achievable than Ref. 10 OCN alone
13		Passive[1]		Insufficient land space
14	All Wheal Jane	OCN		Widely used process
15		OCN	Passive	Large land take
16		BCS / IEX		Better effluent quality than Ref. 14 OCN alone
17		Passive[1]		Insufficient land space
18	Wheal Jane plus County Adit	OCN		May not attain sufficient water quality to achieve the higher order objectives
19		OCN	Passive	Insufficient land space
20		BCS / IEX		Better water quality than Ref. 18 OCN alone
21		Passive[1]		Insufficient land space
22	All Sources (to Bissoe)	OCN		May not attain sufficient water quality to achieve the higher order objectives
23		OCN	Passive	Insufficient land space and may not achieve WQO
24		BCS / IEX		Better water quality than Ref. 22 OCN alone, expected to achieve WQO
25		Passive[1]		Insufficient land space
26	All Sources (to Devoran)	OCN		May not attain sufficient water quality to achieve the higher order objectives
27		OCN	Passive	Insufficient land space and may not achieve WQO
28		BCS / IEX		Better water quality than Ref. 26 OCN alone, expected to achieve WQO
29		Passive[1]		Insufficient land space
[1] Passive could be configured a number of ways depending on the target WQO.				

Treatment of Wheal Jane with Six Pumps to OCN Effluent Quality

Up to 330 l/s (capacity of Six Pumps) of Wheal Jane discharge treated. The remainder discharges untreated from Nangiles Adit.

Full Treatment of All Wheal Jane

All discharge from Wheal Jane treated to OCN effluent quality.

Treatment of All Wheal Jane plus County Adit

All discharge from Wheal Jane plus County Adit treated to BCS effluent quality.

Treatment of All Sources down to Bissoe

All Sources, including County Adit, Wheal Jane, Twelveheads, Hick's Mill Stream, and diffuse sources upstream of Bissoe treated to BCS quality.

6.4 DESCRIPTION OF MODELLING

The model runs were performed for each metal species under each treatment scenario to predict water quality at Devoran Bridge and in the Fal Estuary.

The model comprised a suite of linked models including:

- seven rainfall - runoff models based on a 35 year record with daily time steps;
- six hydrochemical models, made up from separate models for six metals (iron, copper, cadmium, zinc, manganese and arsenic) and pH, based on a 35 year record with daily time steps;
- a hydrodynamic model of the Carnon River and Restronguet Creek using MIKE11, to estimate flow at Devoran Bridge daily for a five year period;
- a hydrodynamic advection-dispersion 2D tidally varying model of Restronguet Creek and the Fal Estuary using MIKE21 to predict 95% removal rates for five metals at 12 hours, 48 hours, 7 days and 30 days (the removal rate represents the net effects of dilution, deposition and resuspension).

All models were calibrated and validated against monitoring data and the results of detailed investigative surveys. The reliability of the models and the effect on the results and conclusions was determined by sensitivity analyses and the results of the validation process.

6.5 MODELLING RESULTS

The models were used to predict the quantity and quality of water from sources in the Carnon catchment as described in Section 4.

The models were also used to predict the effect of treatment scenarios and to assess compliance with WQOs. This involved prediction of water qualities at Devoran Bridge and in the Fal Estuary, which could be compared with those set in the WQOs.

Iron loadings at Devoran Bridge were also used to assess discolouration by deriving an empirical relationship between total iron loading at Devoran Bridge and observations of discolouration in Restronguet Creek. Discolouration has been observed in Restronguet Creek for iron loading at Devoran Bridge in the order of 2 000 – 4 000 kg/day. This enabled predictions of the frequency and duration of discolouration events to be made. Predictions of the extent of discolouration in Restronguet Creek and Carrick Roads were more subjective and based on the modelled concentrations in the estuary and the assumption that iron discolouration becomes visible in the estuary at concentrations between 0.2 mg/l and 2 mg/l (KP et al, 1998, Catchment Modelling ..., Appendix F).

Comparison of model predictions with WQOs was made for the 35 year period of rainfall and evapo-transpiration events. WQOs are expressed as a combination of annual averages, 95 percentiles and annual maxima so the same data were selected for comparison from the 35 year record. The results indicated which of the treatment scenarios would result in compliance with the various WQOs (see Table 6.2 and Table 6.3).

The above treatment scenarios did not enable Environmental Quality Standards to be met although limit values are achieved. Cadmium (a List I substance), copper and zinc failed to meet the EC Dangerous Substances Directive – Fresh Water Environmental Quality Standards. Copper and zinc failed to meet the EC Dangerous Substances Directive – Salt Water Environmental Quality Standards and the EC Shellfish Waters Directive (Protection of Estuarine Biology).

The reasons for failure were attributed to:

- the guaranteed final treated effluent concentrations for OCN and BCS technologies exceeding EQS for certain metals (Table 5.1);
- further contributions from diffuse sources between Bissoe and Devoran Bridge.

Consequently, options to treat all water down to Devoran Bridge to a guaranteed higher quality were included in this study (OCN-IEX (I) and OCN-IEX (II).

Table 6.2 : Simulated Implication of Minewater Treatment Options on Water Quality Objectives at Devoran Bridge

	No Deterioration	North Sea Declaration Commitments	EC DS Directive - Fresh Water Environmental Quality Standards (hardness >250 mg/l)	EC DS Directive - Fresh Water Environmental Quality Standards (hardness 50-100 mg/l)
No Treatment (worst case)	Fail	Fail	Fail	Fail
No Treatment (best estimate)	Fail	Fail	Fail	Fail
No Treatment (sensitivity)	Fail for As	Fail	Fail	Fail
Treatment of Wheal Jane Six Pumps by OCN	Comply	Comply	Fail	Fail
Treatment of All Wheal Jane by OCN	Comply	Comply	Fail	Fail
Treatment of All Wheal Jane plus County Adit by BCS	Comply	Comply	Fail for Zn, Cu, Cd	Fail for Zn, Cu, Cd
Treatment of All Sources down to Bissoe by BCS	Comply	Comply	Fail for Cd (a.a), Cu (95%)	Fail for Cd, Zn (a.a), Cu, Zn (95%)
Treatment of All Sources down to Devoran by OCN-IEX (I)	Comply	Comply	Comply	Comply

(a.a) = annual average concentrations.
(95%) = 95 percentile annual concentrations.

Table 6.3 : Simulated Implication of Minewater Treatment Options on Water Quality Objectives in Restronguet Creek and Carrick Roads

	No Discolouration	EC DS Directive - Salt Water Environmental Quality Standards	Protection of Estuarine Biology
No Treatment (worst case)	Fail	Fail	Fail
No Treatment (best estimate)	Fail	Fail	Fail
No Treatment (sensitivity)	Fail occasionally	Fail	Fail
Treatment of Wheal Jane Six Pumps by OCN	Possibly fail occasionally	Fail Zn, Cu	Fail Zn, Cu
Treatment of All Wheal Jane by OCN	Possibly fail occasionally	Fail Zn, Cu	Fail Zn, Cu
Treatment of All Wheal Jane plus County Adit by BCS	Comply	Fail Zn, Cu	Fail Zn, Cu
Treatment of All Sources down to Bissoe by BCS	Comply	Fail Zn, Cu	Fail Zn, Cu
Treatment of All Sources down to Devoran by OCN-IEX (I)	Comply	Fail Zn, Cu	Fail Zn, Cu
Treatment of All Sources down to Devoran by OCN-IEX (II)	Comply	Comply	Comply

Compliance/failure for EC DS Directive - Salt Water Environmental Quality Standards is based on annual average and 95 percentile concentrations.
Compliance/failure for EC Shellfish Waters Directive – Protection of Estuarine Biology is based on annual maxima concentrations.

The following conclusions can be drawn.

- The treatment of the quantity of Wheal Jane minewater produced by Six Pumps using an OCN process route is expected to result in a quality of water in the Carnon River at Devoran Bridge, which will meet the No Deterioration, No Discolouration and North Sea Declaration Commitments WQOs. Some discolouration may occur with the existing treatment when the Six Pumps capacity is exceeded. The results are illustrated in Figure 6.2, which shows compliance/failure graphs at Devoran Bridge for six contaminants over a 35 year period. The bar charts show that the main contribution to loadings at Devoran Bridge, if the Six Pumps treatment option is used at Wheal Jane, is then County Adit.
- The treatment of Wheal Jane minewater from Six Pumps by the BCS or IEX treatment route will also achieve a quality of water at Devoran Bridge which meets the lower order WQOs.
- Six Pumps treatment will not achieve any of the higher order WQOs (see Figure 6.2 for failure at Devoran Bridge and Figure 4.3 for failure in the estuary). However, cadmium limit values will be achieved.
- The higher order WQOs are not achieved by treating all, or part, of Wheal Jane, or All Wheal Jane plus County Adit minewater using any of the treatment routes.
- The higher order WQOs at Devoran Bridge could be achieved by treatment of All Sources using BCS or IEX treatment at Devoran to an effluent quality equal to

the EC DS Directive – Fresh Water Environmental Quality Standards. It should be noted that technical compliance would be met at the National Monitoring Network Station at Devoran, but not upstream in the Carnon River.

- Treatment to Fresh Water Standards at Devoran will not achieve compliance with EC DS Directive - Salt Water Environmental Quality Standards or Protection of Estuarine Biology (EC Shellfish Waters Directive) standards for copper and zinc (see Figure 6.3). The standards are higher for these metals in the estuary than at Devoran (see Table 4.2). The currently designated shellfish sites are indicated on Figure 9.1. These are expected to expand so the EC Shellfish Waters Directive was applied throughout the system.
- Compliance with the higher order WQO's for both the estuary and at Devoran could be achieved by using an IEX treatment designated to meet EC DS Directive Fresh Water Environmental Quality Standards for iron and cadmium and the EC Shellfish Waters Directive for arsenic, zinc and copper.

6.6 TREATMENT OPTIONS

As a result of the water quality modelling, four *Treatment Options* were identified to achieve the various WQOs. The results are summarised in Table 6.4.

Table 6.4 : Water Quality Objectives and Treatment Options

Broad Categorisation	Water Quality Objective	Treatment Option
Do Nothing	No Treatment	No Treatment
Lower Order Objectives	No Deterioration	Six Pumps at Wheal Jane, with treatment by Oxidation and Chemical Neutralisation
	No Discolouration	
	North Sea Declaration Commitments	
Higher Order Objectives	EC Dangerous Substances Directive - Fresh Water Environmental Quality Standards	All Sources in the Carnon River down to Devoran, treated by OCN-IEX (I)
	Protection of Estuarine Biology	All Sources in the Carnon River down to Devoran treated by OCN-IEX (II)
	EC Dangerous Substances Directive - Salt Water Environmental Quality Standards	

OCN-IEX (I) is a hybrid plant configured to meet EC DS Directive - Fresh Water Environmental Quality Standards.
OCN-IEX (II) is a hybrid plant configured to meet all the higher order water quality objectives.

The water quality achieved in the Carnon River and the Fal Estuary for the four treatment options and their effect upon biology is considered in the following section.

7. BIOLOGICAL IMPACTS

7.1 INTRODUCTION

The study provides an assessment of the present biological status and the significance of the minewater discharges on the floral and faunal communities in the Carnon River and Fal Estuary. The existing relationships between the biota and metal levels in the water and sediments in the Fal system have been established as well as wider comparisons with other estuaries in south-west Britain. Predictions concerning the effects of various minewater treatment solutions have then been made by extrapolation.

7.2 SUMMARY OF FINDINGS

The floral and faunal communities of the Carnon River are greatly impoverished and of little conservation value. The Fal Estuary, on the other hand, is of high conservation, recreational and economic value. The emphasis of the biological work was, therefore, placed on the estuary.

The Carnon River is almost devoid of macroscopic plants below Chacewater, which is well upstream of Wheal Jane and County Adit. The river is devoid of fish, although tributaries to the Carnon River, such as the Kennall support brown trout fisheries. The biological surveys principally indicate that the Carnon River is low in organic pollution and that toxic contaminants are responsible for the absence of biota.

Metal concentrations in sediments around the Fal Estuary differ widely. Sediments in creeks that are otherwise similar, except for the historic mining activities in the upper catchments, have heavy metal concentrations (including copper, zinc, arsenic, cadmium and iron) which differ by orders of magnitude. The metals levels within the Fal have been elevated for so long that events in the estuary cannot be viewed simply as short-term pollution/recovery incidents. Direct correlation between observed effects and metal species is made difficult by the large number of metals involved, chemical and biological interaction and the induction of metal tolerance. Nevertheless, heavy metal concentrations in the sediments correlate most strongly with the composition of the invertebrate communities and are, therefore, the most likely causal agent.

The major influence of the Carnon River discharges lies within Restronguet Creek. Effects of heavy metal discharge beyond the mouth of the creek extend to Mytton, but elsewhere are comparatively small. Elsewhere in the Fal system other sources of contamination, notably china clay wastes and Tri-Butyl Tin (TBT), may also be responsible for impoverishment, though impacts from these sources are less well characterised.

The biological assessment report (KP et al, 1998, Final Biological ...) detailed the specific biological communities (see Table 7.1), bioaccumulation characteristics (see Table 7.2) and estuarine chemistry within the catchment. A technical summary of the biological assessment studies is presented in Appendix D. Predicted changes in water chemistry as a result of treatment options were used to assess the effect of treatment on sediment concentrations and the biological communities and populations. The findings are summarised briefly in the following sections, and used to develop the benefit assessment in Section 9.

Table 7.1 : Summary of Biological Communities

Ref.	Community Type	Description of Biology
1	Macrobenthos	Metal pollution clearly accounts for unusual community composition of some macrofaunal species in Restronguet Creek as compared to adjacent creeks
2	Meiobenthos	Nematode community structure is consistent with increasing metal concentrations. Copepods do not show a correlation
3	Phytoplankton	'Red Tides' caused by toxic strain *Alexandrium tamarense* and first seen in 1995 have been linked to elevated metal concentrations, but this is still under scientific debate
4	Seaweeds	Some rare and important algae are known to occur in the maerl beds in the St Mawes area
5	Maerl	Lower than expected abundance of many species is probably due to mud and silt in the bed with no evidence to suggest this is metal related Maerl bed in the Fal is the only extensive living bed in southern Britain
6	Fish	Reduction of metal concentrations is unlikely to significantly affect the 90 recorded species of fish in the Fal Estuary. Carnon River is devoid of fish
7	Bass	The Fal is a bass nursery ground and while there is no direct evidence that moderate levels of metal contamination are detrimental to young bass the Fal may have reduced recruitment compared with other estuaries
8	Migratory species (such as salmon)	No salmon now, but sea trout are present in several tributary rivers to the Fal though not the Carnon River
9	Birds	The Fal supports no internationally important populations of birds, but does support a nationally important population of the Black-tailed Godwit. The 1992 incident had no appreciable effect on the numbers of wildfowl and waders
10	Swans	Increasing swan mortality between Autumn 1992 and 1995 is largely attributed to heavy metal toxicity, but evidence remains equivocal. Other possible causal agents are PSP and TBT
11	Rare species	Examples 'Couch's goby' and certain seaweeds; by their nature these are difficult to survey. The fact that they are present at all means that they can tolerate the present metal levels in the system and it is possible that reductions in these levels, through extended minewater treatment, could favour other more metal-sensitive competitors

7.2.1 Estuarine Chemistry

A study of the behaviour and fate of metals in Restronguet Creek and how they partition between sediments and water is still in progress and interim results only are available.

In the meantime an empirical approach was adopted which uses two sets of regression relations:

- total concentration of metals in the water column;
- proportion of metal which is particulate.

It was also assumed that metal concentrations in the superficial sediment was the same as that in particulate material in the water column. Surface sediment concentrations were estimated from water concentrations at Devoran.

Iron was found to be a key component as it affects the particle-water partitioning of other metals.

Table 7.2 : Summary of Bioaccumulation in Species

Species	Description of Findings
Oysters *(Ostrea edulis)*	Carrick Roads supports one of the few commercial native oyster fisheries in the UK. Presence of copper and zinc are consistently high and did not appear to change following the 1992 incident. Detoxification is suspected.
Cockles *(Cerastoderema edule)*	Widely distributed in the estuary except only rarely in Restronguet Creek. Copper is thought to be the most damaging, measured at 20 times background at Mylor and Restronguet Creek and zinc up to threefold.
Other Shellfish	General elevated burdens of copper and zinc and corresponding sparse populations especially in Restronguet Creek (Mussels and Periwinkles).
Algae/Seaweed *(Fucus vesiculosus)*	Almost all metals (except cadmium), particularly iron, zinc and copper, increase in concentration towards Devoran Bridge. No long-term changes noted over a twenty year period, but iron and zinc in algae were elevated following the Incident and these only returned to pre-incident levels by 1997/98
Macrofauna	Some polychaete species have enhanced metal tolerance in Restronguet Creek whereas bivalve and gastropod molluscs are absent from the most metal contaminated sites. Copper and zinc believed to inhibit the settlement of juvenile bivalves

7.2.2 Predicted Effect of Minewater Treatment

The effect of the treatment options on sediment and biology was assessed.

Sediment concentrations increased for the No Treatment option with the most significant changes occurring for iron and arsenic, which increased by an order of magnitude. Zinc concentrations increased by a smaller factor and changes to copper, cadmium and manganese were less pronounced (see Table 7.3).

Table 7.3 : Predicted and Observed Range of Sediment Concentrations for Treatment Options

	Fe mg/g	Cu mµg/g	Zn mg/g	Cd x 10^{-3} mg/g	Mn mg/g	As mg/g
Observed (Autumn 1997)	34 – 55	1.8 – 4.0	2.4 – 4.1	1.5 – 2.1	0.63 – 0.7	0.7 – 1.8
No Treatment	470 - 600	4.0 – 7.5	11 - 16	1.2 – 1.7	0.52 – 0.97	7.5 – 13
Six Pumps	35 – 64	3.4 – 8.2	3.0 – 6.5	1.4 – 2.7	0.34 – 0.77	0.33 – 1.0
All Sources	21 - 35	0.9 - 2.0	0.9 - 1.5	0.7 - 0.9	-	0.58 – 1.6
Range relates to wet and dry conditions for range of salinity.						

The Six Pumps treatment option resulted in little change from observed sediment concentrations. This is as expected since Six Pumps is comparable to the existing treatment scenario and represents the status quo.

The All Sources treatment option resulted in a predicted decrease in sediment concentrations by around 50% when compared with observed concentrations. Changes in sediment concentration were predicted to occur relatively quickly (within a year of change in treatment).

The effect of these changes in water quality and sediment concentration on the biology was made by comparing relationships between biota and metal concentrations in the Fal and other estuaries. The prediction of the consequence of the three treatment options in terms of biological community, population of key species and bioaccumulation are summarised in Table 7.4.

Table 7.4 : Summary of Predicted Effects

Treatment Option	Predicted Outcome
No Treatment	Major increase in iron could affect communities of invertebrates and algae in Restronguet Creek through toxic effects and Carrick Roads, for example through smothering effects on the maerl beds. Major or significant changes in communities unlikely. Bioaccumulation unlikely to prove detrimental or to affect oyster consumption. Possibility of localised increased toxicity to oyster embryos and larvae, but impact on populations unknown. Small increase in intake of metals (Zn and As) via diet in swans and other algal-feeding birds.
Six Pumps	Status quo maintained.
All Sources	Possible increase in small worm population in Restronguet Creek and introduction of viable population of cockles in parts of Restronguet Creek. Meiofaunal communities may change, but effects likely to be minor. Possible, but unproven enhancement of bass populations. Bioaccumulation of Cu, Cd, Zn and Fe in oysters will reduce slightly, but consumption unaffected. Small reduction in bioaccumulation of Cu and Zn in algae and consequent reduction in dietary intake in swans and other algal feeding birds, but unlikely to be significant for bird populations.
Timescale for changes in biology likely to be related to duration of life-cycle.	

7.2.3 Conclusions

The biological assessment studies concluded that with the exception of the Six Pumps treatment option, the treatment options required to meet the WQOs will result in changes to water quality and sediment concentrations. Significant changes to biological communities and populations are not, however, expected. The No Treatment option may result in toxic effects to communities of invertebrates and algae, and increased sedimentation may be detrimental to the maerl beds. There is a possibility of localised increased toxicity to oyster embryos and larvae and also bass nurseries may be affected, but the impacts are not known with certainty. The main effect of the No Treatment option on benefits is the occurrence of discolouration, which results in a perception of pollution (see Section 9).

8. TREATMENT COSTS

This section describes the development of the possible treatment options and then determines the cost estimates for undertaking treatment at various plant locations using each of the alternative treatment routes.

8.1 DEVELOPMENT OF TREATMENT OPTIONS

Remediation of minewater in the long-term will involve the construction of a treatment plant somewhere near Wheal Jane or in the Carnon Valley. Plant location, land ownership, planning implications (visual impact, noise and traffic generation) and the supply costs (the cost associated with delivering minewater to the treatment plant) are all important considerations, the main influence being plant location.

8.1.1 Plant Location

Two possible treatment plant locations have been identified, the Wheal Jane mine site and the Lower Carnon Valley (see Figure 8.1 through Figure 8.3 and Photograph 8.1 and Photograph 8.2). Other sites were assessed, but were considered either to be too remote from the minewater sources or are now under development by others.

Previous studies (KP et al, 1995, Environmental Appraisal ...) concluded that: -

- the Wheal Jane mine site is the preferred location for an active treatment plant;
- the most secure method of recovering Wheal Jane minewater for treatment is by pumping from the Wheal Jane No.2 Shaft;
- the Lower Carnon Valley Tailings Deposit is the most suitable site for a passive treatment plant.

Indeed, topographic constraints mean that the Lower Carnon Valley is the only suitable site for a passive treatment plant of any significant size.

8.1.2 Site Descriptions

Wheal Jane Mine Site

The Wheal Jane mine site comprises about 16 hectares of brownfield land, excluding the CVTD, which is a major feature of the site. The site lies either side of the Clemows Valley and is bounded by farms and the hamlet of Baldhu in a predominantly rural part of the Carrick District of Cornwall.

The Wheal Jane mine site has been heavily developed as a hard-rock underground mine. A large part of the site is set out as a flat working area established by a cut/fill operation. A major part of this is now paved and surrounded by old workshops and mine buildings, all in various states of repair, and mineshafts. Within this part of the site is an area that is understood to be available for use as a treatment plant location, subject to negotiations with the mine owner. This area includes the existing treatment plant.

The site overlies mine workings and various shafts extend to surface including the No.2 Shaft from where the minewater is currently abstracted for the existing treatment operations. Detailed and accurate plans of the workings show that they are at a reasonable depth below the large flat area (at 69 m AOD). Nevertheless, presence of the old workings will warrant consideration when locating major plant items.

Lower Carnon Valley

The Lower Carnon Valley has been owned by the Agency since 1992 and comprises some 44 ha. of land on either side of the Carnon River. The property extends some 2.5 km from the A39 road bridge at Devoran, at the south-western end, up to and just beyond Bissoe Bridge. The approximate grid reference at the centre of the site is at about SW 787 403 (KP et al, 1998, Carnon Valley ...).

A small area of land located towards the northern end of the site remains the property of Cornwall County Council and is understood to have been used previously as a landfill site.

The site has been subjected to intensive mining activity in the past and the valley floor now predominantly comprises an area of generally flat land raised 1 - 2 m above the current river level, formed by infilling with tailings. Tailings were last deposited or reworked some 20 years ago. The valley itself is relatively steep sided, rising some 50 - 60 m above river level and is generally rural in character. Within the Agency's ownership there are four roads which border or cross the land. The most southerly of these being the main A39. Semi mature and mature shrub and tree cover along most adjacent road routes and the general topography of the area restrict views into the body of the site.

There are a number of residential properties scattered along the valley sides, however, the most dominant development directly adjacent to the site consist of a small industrial estate just north of Devoran and the precast concrete fabrication works at Bissoe.

8.1.3 Land Ownership

Ownership of the two potential sites is as follows:

- Wheal Jane Mine Site - South Crofty plc;
- Lower Carnon Valley - Environment Agency.

An expression of interest has been made to SCP for a portion of land within the Wheal Jane mine site and negotiations are continuing.

Various possible uses for the Lower Carnon Valley are described elsewhere (KP et al, 1998, Carnon Valley ...). It is recognised within the report that the valley was originally purchased by the Agency as a possible long-term treatment plant site particularly for passive treatment. It is, therefore, suggested that no other permanent uses should be considered until a long-term treatment decision has been taken.

8.1.4 Proximity

A major cost consideration will comprise the proximity of the minewater sources, the treatment plant site and the sludge disposal site to each other and to the various utilities and services required.

8.1.5 Minewater Supply

The water quality modelling has allowed the specific minewater sources that require treatment to be determined for each WQO. These sources must be tapped and water delivered to the treatment plant which would involve a sump and pipe system. Pumps may also be required if the relative levels dictate. Water could be transported by gravity to the Lower Carnon Valley site option although a low head pump may be required at the front end of the treatment plant. The long-term supply of minewater under each option is described briefly below.

No Treatment

Ceasing the ETP operations would cause minewater levels to rise until the Nangiles Adit overflowed unless water was drained from Jane's Adit. Recent surveys of the Nangiles Adit have concluded that the adit is in a poor state of repair and would cause the minewater levels to fluctuate widely possibly affecting local groundwater regimes. For a long-term solution, therefore, a more secure and acceptable egress point must be established. Earlier studies (KP et al, 1995, Environmental Appraisal ...) identified five alternative possible methods of long-term minewater abstraction (Nangiles Adit and Jane's Adit, Wheal Jane No.2 Shaft, a new adit or directional drilling). The study compared the alternatives and determined approximate costs for improving adits as necessary. Recent appraisal identifies the refurbishment of Jane's Adit to be the cheapest secure long-term option at an approximate price of £1.4 M.

Six Pumps

The earlier studies also concluded that the Wheal Jane No.2 Shaft was the most secure long-term access point to the Wheal Jane minewater and this is still preferred for any Wheal Jane site location. The alternative would be to run water out of Jane's Adit and then carry it through a pipe to the Lower Carnon Valley treatment site.

All Sources

The *All Sources* option involves treating all of the water sources upstream of Devoran. In this case clearly the river system itself could channel the water to the Lower Carnon Valley site. Treatment of All Sources at the Wheal Jane mine site, however, would require a substantial water transfer system.

Degradation in the Carnon River upstream of Devoran, for unconfined flows, is expected as contaminants are picked up from the existing sediments in the river channels (KP et al, 1998, Final Catchment ...). It is predicted that the higher order WQOs could not be achieved unless either:

- the minewater were isolated from the sediments to avoid degradation; or
- the treatment plant was located close to the monitoring point at Devoran to avoid treated water passing over any substantial reach of river bed.

So, to achieve the higher WQOs an All Sources treatment plant must be located either:

- at Wheal Jane and all treated flows then culverted to Devoran; or,

- close to Devoran.

Summary

Table 8.1 summarises the availability of the various services and utilities to each plant location.

Table 8.1 : Proximity to Utilities

Item	Wheal Jane Mine Site (69 m AOD)	Lower Carnon Valley (8 m AOD)
Minewater sources	Located above Wheal Jane mine Pumping system now established Remote from Carnon River	Good elevation that allows the natural river system to collect the minewater Segregation of specific minewater sources would require substantial piping
Power	Existing established (but ageing) supply system	About 500 m from mains supply
Sludge disposal	Adjacent to CVTD (within mine site)	2 km approximately to CVTD
Access roads	Mine lorries transporting ore have operated into the Wheal Jane site for many years	Close to A39, but narrow public access only or new access road into the area from the A39
Site establishment	Existing levelled paved area and supporting infrastructure (water and other general services)	Level site, but unconsolidated tailings and high water table will make substantial foundations necessary

8.1.6 Planning Implications

The planning requirement for a minewater treatment plant at either of the plant site options has been addressed in the active treatment report. Regular liaison has taken place with the local authority planners and with the Agency's planning staff.

The development plan for the Wheal Jane mine and surrounding area consists of the adopted Cornwall County Structure Plan and the Cornwall Countryside Local Plan and the Carrick District Wide Local Plan. Under these provisions, any planning application submitted on the Wheal Jane mine site will be considered in terms of conformity with development plan policies. Section 54A of the Town and Country Planning Act, 1990, requires that, where an adopted development plan contains relevant policies, an application for planning permission shall be determined in accordance with the plan, unless material considerations indicate otherwise. Among these material considerations would be the policies and proposals in any emerging local plans which would, when adopted, form part of the development plan.

The pollution of the water environment by abandoned mines is specifically recognised. The Structure Plan sets out the County Council's commitment to work with other statutory agencies to tackle the historical pollution load within Cornwall. Policy ENV14 provides that development should not (either directly or indirectly) increase the pollution (including disturbance of existing pollutants) of the water environment.

It is recognised that the need to provide for waste management in Cornwall will present considerable challenges over the lifetime of the plan. In Cornwall, current waste disposal practice is almost exclusively reliant on landfill. The Plan seeks self-sufficiency in terms of the management and disposal of waste in Cornwall, other than special or hazardous waste for which specialist processes are required. Regular liaison with the planners has helped to ensure that the CVTD is fully recognised within the County Waste Plan as a strategic facility for the long-term storage of appropriate minewater residues.

Informal discussions were held with the local planning authority on the location of a long-term minewater treatment plant. The Wheal Jane mine site was indicated as a preferred location in planning and technical terms. The alternative of locating a treatment plant in the Lower Carnon Valley was considered less desirable from a planning standpoint. It would introduce further built development into what is predominantly a rural area, which is subject to the district and county councils polices for enhancement. The District Wide Local Plan seeks to improve public access to, and enjoyment of, the countryside. One specific proposal is to reinstate the former mineral tramway from Devoran to Portreath, which includes a trail along the Carnon Valley. Policy 10H provides that planning permissions will not be granted for developments which conflict with the implementation of this Mineral Tramways Project.

Planning Applications

The Agency require that long-term treatment plant proposals are acceptable, in principle, in planning and environmental terms. Also, any risk and uncertainty in terms of the acceptability of the long-term treatment plant from a planning standpoint is to be minimised, as far as possible, prior to the tender stage.

With these objectives in mind, the Agency has agreed to make a planning application for two process options at the Wheal Jane mine site based upon the Six Pumps treatment option. Draft application documents were submitted in April 1998 and a formal application is ready to be made. The outline planning application document (KP et al, 1998, Outline Planning ...) contains a summary environmental impact assessment of traffic, noise and visual impacts resulting from a treatment plant.

A planning application was not submitted for a plant site at the Lower Carnon Valley as it was considered premature in light of the discussions with the planning authorities.

8.1.7 Summary of Treatment Options

From the appraisal of the alternative site options it was concluded:

- No.2 Shaft should continue to be used for the Six Pumps treatment option (abstraction of Wheal Jane minewater only) as:
  - it is located at the Wheal Jane mine site;
  - it is a brownfield site and preferred by the planning authorities;
  - existing equipment can be sensibly re-used in the longer term.
- the Lower Carnon Valley is the only reasonable site for the All Sources treatment option:
  - WQOs could not be achieved using other plant location because of degradation between the plant site and Devoran;

– the Carnon River serves as a natural collection system for the minewater sources, moreover minewater supply costs would be prohibitive for the Wheal Jane site.

Before the plant locations are finally determined both plant sites have been assessed under each process route as indicated in Table 8.2.

Table 8.2 : Summary of Site Options

Treatment Option	Process Route	Plant Site Location (1)	
		Wheal Jane Mine Site	Lower Carnon Valley
No Treatment	None	n/a	n/a
Six Pumps	OCN	✓	✓
	BCS	✓	✓
	IEX	✓	✓
All Sources	OCN	✓	✓
	BCS	✓	✓
	IEX	✓	✓
	OCN-IEX(I)	✓	✓
	OCN-IEX(II)	✓	✓

(1) The planning authorities have expressed a preference for the Wheal Jane mine site.

8.2 TREATMENT COST ESTIMATES

8.2.1 Scope of Evaluation

An economic evaluation has been carried out on all the cases that comprise the possible combinations of treatment option, process route and plant site location (see Table 8.2). Although it is recognised that treatment of All Sources at Wheal Jane is unlikely, the following cost estimates do include this option for comparison only. Base cost estimates have been prepared, which include capital expenditure (CAPEX) and annual operating costs (OPEX).

The CAPEX base cost estimates include:

- infrastructure for the minewater supply to the treatment plant;
- design and contractors management of installation;
- installation, erection and commissioning of the treatment plant (including all civils);
- a 25% injection of capital each 25 years for plant upgrades.

It should be noted that no contingency costs have been included in these estimates.

The OPEX base cost estimates include:

- reagents (lime, flocculants, organic reducing agent fuel oil, etc.);
- electrical power costs;
- staffing and maintenance (as manpower and spares provision);
- sludge disposal.

The base case cost estimates are then presented as present value (PV) scheme costs for 10, 25 and 50 years and based on the Treasury discount rate of 6%.

The scheme costs have been developed to represent a design, build and operate (DBO) style of implementation, where a third party contractor is commissioned to undertake the design, construction and operation of the treatment plant under a single contract. The DBO style of contract was chosen for illustrative purposes because it most closely satisfies the various requirements of the project of the contract options available. The costs associated with other forms of contract are assessed in Section 11.

To determine the scheme costs the base cost estimates must be inflated by multipliers that reflect the anticipated rate of return associated with each form of implementation. The rates of return applicable to a DBO style contract were established in the contract strategy study (KP et al, 1998, Final Contract ...) and are discussed in Section 11 of this report. A technical summary of the contract strategy is presented in Appendix B. Alternative rates of return apply to other forms of implementation, but these are relative only and do not, therefore, affect the outcome of the cost-benefit assessment. The following rates of return have been used for the DBO option:

- 4% on Capital Expenditure (CAPEX);
- 10% on Operational Expenditure (OPEX).

These multipliers represent the costs associated with undertaking the project and cover the contractor's profits, insurances, financing (not required for the DBO option) and other risks.

8.2.2 Capital Costs

No Treatment

Were the No Treatment option to be decided upon then some decommissioning work would be required at the ETP and a secure long-term discharge route for minewater from the Wheal Jane mine would need to be established.

The existing equipment at the ETP is relatively new with a total original value of about £287 000. Much of the equipment (silos, mixing tanks and shaft pumps) are still in good condition and would have value as second hand items. For the purposes of this study it is assumed the residual value of the equipment would cover the costs associated with plant decommissioning. The net cost of closing ETP would then be insignificant.

The cost of refurbishing Jane's Adit as a long-term egress route for the Wheal Jane minewater has been estimated at £1.4 M. These costs have little significance in the overall cost-benefit assessment.

Treatment Options

Cost enquiries were issued to a number of suppliers to form the basis for estimating the capital cost requirements for the OCN and BCS process plants. Indicative (±50%) cost estimates are also included for IEX and OCN-IEX treatment based on development work being carried out by JCI in South Africa.

The capital cost of constructing each type of process plant and at each plant location is summarised in Table 8.3.

Table 8.3 : Summary of Capital Costs

			Costs (£ M)			
Treatment Option	**Plant Location**	**Treatment Route**	**Minewater Supply**	**Site Establishment**	**Equipment**	**Total**
Six Pumps	Wheal Jane mine site	OCN	0	0	4.25	4.25
		BCS	0	0	6.26	6.26
		IEX	0	0	12[1]	12
	Lower Carnon Valley	OCN	1.88	0.70	4.25	6.83
		BCS	1.88	0.40	6.26	8.54
		IEX	1.88	0.70	12[1]	15
All Sources	Wheal Jane mine site	OCN	4.62	3.47	17.24	25
		BCS	4.62	1.98	41.53	48
		IEX	4.62	3.47	50[1]	58
		OCN-IEX (I)	4.62	1.12	13.50[1]	19
		OCN-IEX (II)	4.62	1.81	23[1]	29
	Lower Carnon Valley	OCN	2.41	5.28	17.24	25
		BCS	2.41	3.08	41.53	47
		IEX	2.41	5.28	50[1]	58
		OCN-IEX (I)	2.41	2.41	13.50[1]	18
		OCN-IEX (II)	2.41	3.46	23[1]	29

[1] Only indicative, total plant quoted.
Total capital costs rounded to reflect accuracy of total estimate.

8.2.3 Operating Costs

The annual operating cost associated with running each type of plant and at each plant location is summarised in Table 8.4.

Table 8.4 : Summary of Annual Operating Costs

Treatment Option	Plat Location	Treatment Route	Costs (£ Mpa) Power	Reagents	Man-power	Maintenance	Sludge Disposal	Total
Six Pumps	Wheal Jane mine site	OCN	0.140	0.243	0.115	0.064	0.200	0.76
		BCS	0.160	1.081	0.109	0.094	0.408	1.85
		IEX	1.4					1.4
	Lower Carnon Valley	OCN	0.080	0.243	0.115	0.102	0.210	0.75
		BCS	0.100	1.081	0.109	0.128	0.408	1.83
		IEX	1.4					1.4
All Sources	Wheal Jane mine site	OCN	0.907	0.391	0.249	0.380	0.220	2.2
		BCS	0.757	2.517	0.201	0.722	0.432	4.6
		IEX	4.0					4.0
		OCN-IEX (I)	3.0					3.0
		OCN-IEX (II)	4.0					4.0
	Lower Carnon Valley	OCN	0.318	0.391	0.249	0.374	0.230	1.6
		BCS	0.168	2.517	0.201	0.705	0.432	4.0
		IEX	3.5					3.5
		OCN-IEX (I)	2.5					2.5
		OCN-IEX (II)	3.4					3.4

Reagents include reducing agent, fuel oil and other minor costs.
IEX and OCN-IEX costs are indicative only (±50%).
Total annual operating costs rounded to reflect accuracy of total estimate.

Sludge Disposal

Costs for sludge disposal have been established based on the continued use of the CVTD for hydroxide sludge and off-site storage for sulphide sludge.

Ongoing use of the CVTD is only possible if the sludges are dewatered to form a higher density solid material and this is a central feature of the proposed OCN and OCN-IEX options. The additional cost of transporting hydroxide sludge to an off-site facility has been determined at £270 000 per year, which equates to £2.0 M as a 10 year present value cost, as shown in Table 8.5.

Table 8.5 : Sludge Disposal Costs

Disposal Site	Estimated Annual Cost for Disposal (£)	Estimated 10 year Present Value Cost (£ M)
CVTD	200 000	1.47
Off-site	470 000	3.46
Estimated Additional Cost of Disposal Off-site	270 000	2.00

Based on OCN Six Pumps option.
Off-site disposal to Linghall Quarry, Rugby.

8.2.4 Cost Comparison and Sensitivity Analysis

The final scheme costs for all considered treatment alternatives and using the rates of return already discussed are presented in Table 8.6. Minimum value scheme costs are highlighted for each option.

The Active Treatment Review also identified the sensitivity of the main components of each cost and derived upper and lower bound values for use in the final cost-benefit appraisal. The resulting upper and lower bound cost estimates are shown in Table 10.1 through to Table 10.3, as part of the cost-benefit appraisal.

Discussion of Results

Table 8.6 identifies the estimated median costs for various treatment options and the two alternative plant locations. The following conclusions can be deduced from the table:

- No Treatment is the least cost possible option;
- the mine site is a lower cost site alternative to the Lower Carnon Valley for the Six Pumps treatment option;
- the OCN process, situated at Wheal Jane mine site represents the least cost method of treating to Six Pumps over all of the time periods considered;
- OCN is the cheapest method of treating All Sources (but not all WQOs are achieved).

Table 8.6 : Median Project Cost Estimates

Cost Estimate for No Treatment Option (£ M)[6]	
Base Cost	
CAPEX	1.54[1]
OPEX	0.023
Present Value Scheme Costs (for DBO Option)[2] [3]	
10 Years	2.0
25 Years	2.2
50 Years [4]	2.3

Cost Estimate for Six Pumps Treatment Option (£ M)

Location	**Wheal Jane Mine Site**			**Lower Carnon Valley**		
Treatment Route	**OCN**	**BCS**	**IEX**	**OCN**	**BCS**	**IEX**
Base Costs						
CAPEX	4.25	6.26	12	6.83	8.54	15
OPEX	0.76	1.85	1.4	0.75	1.83	1.4
Present Value Scheme Costs (for DBO Option) [2] [3]						
10 Years	11.2	22.8	25.1	13.3	24.4	27.4
25 Years	16.2	34.6	34.3	18.3	36.3	36.8
50 Years [4]	19.1	41.5	40.1	21.4	43.2	42.8

Cost Estimate for All Sources Treatment Option (£ M)

Location	**Wheal Jane Mine Site**					**Lower Carnon Valley**				
Treatment Route	**OCN[5]**	**BCS[5]**	**IEX**	**OCN-IEX (I)**	**OCN-IEX (II)**	**OCN[5]**	**BCS[5]**	**IEX**	**OCN-IEX (I)**	**OCN-IEX (II)**
Base Costs										
CAPEX	25	48	58	19	29	25	47	58	18	29
OPEX	2.2	4.6	4.0	3.0	4.0	1.6	4.0	3.5	2.5	3.4
Present Value Scheme Costs (for DBO Option) [2] [3]										
10 Years	45.1	90.3	95.5	46.7	65.4	39.1	83.4	89.5	40.4	59.1
25 Years	59.0	120.0	121.4	66.3	91.1	49.3	109.3	111.7	56.5	81.0
50 years [4]	67.9	138.9	138.8	78.2	106.8	56.3	126.1	127.2	66.4	94.7

(1) Refers to Adits upgrades.
(2) Scheme costs include a 4% rate of return on CAPEX and 10% rate of return on OPEX (Final Contract Strategy Assessment Report refers).
(3) Discounted to Present Value using a Treasury rate of 6%.
(4) Capital injection of 25% after 25 years operation.
(5) Section 6 identifies that these two options do not achieve all the higher order WQOs but are shown to indicate possible better value for money options.
(6) All costs are in 1998 £ M.

8.2.5 Preferred Options

The above conclusions must now be considered along with those already drawn from Section 6 (Derivation of Treatment Options) where it has been shown that:

- treatment of Six Pumps using OCN will achieve the lower order WQOs and limit values;
- treatment of All Sources using IEX or OCN-IEX (I), at Devoran is required to attain the EC DS Directive - Fresh Water Environmental Quality Standards at Devoran;
- the other higher order WQOs for the Fal Estuary could be met by upgrading the OCN-IEX (I) treatment to OCN-IEX (II) to meet the Salt Water Environmental Quality Standards for arsenic, copper and zinc (but at additional cost).

and also that:

- the Wheal Jane mine site is the preferred site option for the Six Pumps treatment option;
- the Lower Carnon Valley site is the only site suitable for use in association with the higher order WQOs.

These factors are summarised in Table 8.7.

Table 8.7 : Summary of Preferred Treatment Options

Treatment Option	Water Quality Objectives Achieved
No Treatment	No Treatment
Six Pumps using OCN at Wheal Jane	No Deterioration No Discolouration North Sea Declaration Commitments
All Sources using OCN-IEX (I) at Lower Carnon Valley	EC DS Directive - Fresh Water Environmental Quality Standards
All Sources using OCN-IEX (II) at Lower Carnon Valley	EC DS Directive - Salt Water Environmental Quality Standards Protection of Estuarine Biology

The costs to be taken forward to the cost-benefit appraisal for the four treatment options are:

- No Treatment - Refurbishment of Jane's Adit only;
- Six Pumps using the OCN treatment route located at the Wheal Jane mine site and using No.2 Shaft for minewater abstraction;
- All Sources using an OCN-IEX (I) treatment route, to an effluent quality equal to the EQS specified in the EC DS Directive - Fresh Water Environmental Quality Standards, located close to Devoran within the Lower Carnon Valley;
- All Sources using an OCN-IEX (II) treatment route, to an effluent quality equal to Fresh Water Environmental Quality Standards for iron and cadmium and to EC Shellfish Waters Directive for arsenic, zinc and copper also located close to Devoran.

9. ENVIRONMENTAL AND SOCIAL BENEFITS

9.1 INTRODUCTION

The impact associated with each WQO on the flora and fauna in the river and estuary was summarised in Section 7. The wider impact associated with each WQO has been appraised by a socio-economic analysis of environmental and other benefits associated with each option. These studies are reported in the Environmental and Social Benefit Assessment (KP et al, 1998, Environmental and Social ...). A technical summary of the assessment is presented in Appendix F and summarised below.

Benefits have been measured as additional to that accrued under the No Treatment WQO. Economic values have been placed on the environment and other areas through contingent valuation surveys using a benefit transfer approach, in which individuals are asked to value a particular environment, often in a polluted or degraded state, and in an improved state and reflect the individual's 'willingness to pay'. These are based on the general water quality, discolouration and environmental effects predicted through the modelling and biological impact studies.

Values have been established for a number of categories that have been broadly categorised as *use values* and *non-use values*. *Use values* are those associated with the benefits gained from actual use of the environment and include, recreation (informal recreation, bathing and watersports), port operations (pleasure boating, ship repair and moorings), tourism, the calcified seaweed industry (which produces a soil conditioner), fisheries (commercial, shellfish and recreational) and amenity. Three of these categories, informal recreation, bathing and recreational fishing all used contingent valuation and benefit transfer. All of the other *use values* relate to marketed commodities where the estimation of the change in value is then relatively straightforward by using cause and effect relationships.

Non-use values relate to an individual's desire for a future use to be secure either for their own use (option value), for the use of future generations (bequest value) or from an altruistic desire to preserve an environmental asset (existence value).

To improve the estimates the estuary has been divided into five reaches over which the benefits are then calculated independently. This ensures that any change in water quality that does not extend over the whole extent of the estuary can be assessed.

The division of the Fal Estuary into reaches is shown on Figure 9.1. It also shows the various conservation designations around the estuary, which help to indicate the wider environmental perspective.

The basic assumptions on environmental change used in the analysis for the various WQOs are as follows.

No Treatment: discolouration would occur almost every year, especially over the winter and early spring. Iron concentrations would be elevated in the water, especially in Reach 1 and Reach 2. Such events would impact upon all recreational activities, and upon biological life, although the levels of the latter are not certain.

Six Pumps: the current situation would continue, with occasional discolouration events. Activity levels and industry would continue as at present, with no additional benefit over the current state. There would be some scope for improvement of the environment, although the impact of this would be slight.

All Sources: no discolouration events and further reduction of iron concentrations may have a greater positive impact than under the Six Pumps treatment option. However, it is not possible to value impacts under All Sources separately to those arising under Six Pumps.

9.2 SUMMARY OF RESULTS

The resulting estimates are presented in the following tables. The present value estimates are given as category totals only for the median estimates. All values are given to a maximum of two significant figures. Full tables of discounted benefits, by both category and reach, and including both the upper and lower bound estimates are given in the Environmental and Social Benefit Assessment report.

Table 9.1 : Median Present Value Estimates Under the No Treatment Option

Benefit Category	10 years	25 years	50 years
Non-use values	-	-	-
Informal recreation	£1 300 000	£2 200 000	£2 700 000
Bathing	£43 000	£75 000	£93 000
Water sports	£5 800 000	£10 000 000	£12 000 000
Pleasure boating	£6 900 000	£12 000 000	£15 000 000
Port operations	£290 000	£510 000	£630 000
Tourism	£22 000 000	£38 000 000	£47 000 000
Calcified seaweed	-	-	-
Commercial fisheries	-	-	-
Shellfisheries	£1 710 000	£3 000 000	£3 700 000
Recreational fisheries	£1 510 000	£2 600 000	£3 200 000
Amenity	£0	£750 000	£920 000
Total	**£39 553 000**	**£69 135 000**	**£85 243 000**

The present value estimates presented in the No Treatment summary in Table 9.1 show the baseline benefits against which the six treatment WQOs were assessed. The estimates are significant, varying between £40 M and £85 M over the different time periods used.

Table 9.2 : Median Present Value Estimates of Additional Benefit Accrued Under the Six Pumps Treatment Option			
Benefit Category	**10 years**	**25 years**	**50 years**
Non-use values	£2 600 000	£4 400 000	£5 500 000
Informal recreation	£81 000	£140 000	£170 000
Bathing	£140	£240	£300
Water sports	£410 000	£710 000	£880 000
Pleasure boating	£80 000	£140 000	£170 000
Port operations	£35 000	£61 000	£75 000
Tourism	£1 100 000	£1 900 000	£2 300 000
Calcified seaweed	£7 700 000	£13 000 000	£17 000 000
Commercial fisheries	£36 000	£87 000	£115 000
Shellfisheries	£1 000 000	£1 800 000	£2 200 000
Recreational fisheries	£125 000	£220 000	£270 000
Amenity	£4 300 000	£4 300 000	£4 300 000
Total	**£17 467 140**	**£26 758 240**	**£32 980 300**
These benefits are additional to those presented in Table 9.1, hence the overall total is the combined total.			

Table 9.3 : Present Value Estimates of Additional Benefit Accrued Under the All Sources Treatment Option			
Benefit Category	**10 years**	**25 years**	**50 years**
Non-use values	£2 600 000	£4 500 000	£5 600 000
Informal recreation	£99 000	£170 000	£210 000
Bathing	£140	£240	£300
Water sports	£470 000	£820 000	£1 000 000
Pleasure boating	£90 000	£160 000	£190 000
Port operations	£37 000	£64 000	£79 000
Tourism	£1 300 000	£2 300 000	£2 800 000
Calcified seaweed	£7 700 000	£13 000 000	£17 000 000
Commercial fisheries	£47 000	£110 000	£150 000
Shellfisheries	£1 100 000	£1 900 000	£2 300 000
Recreational fisheries	£140 000	£250 000	£300 000
Amenity	£4 400 000	£4 400 000	£4 400 000
Total	**£17 983 140**	**£27 674 240**	**£34 029 300**
These benefits are additional to those presented in Table 9.1, hence the overall total is the combined total.			

The All Sources treatment option leads to the best water quality and, therefore, also has the highest benefits. Additional benefit ranges from £18 M to £34 M for the different time period as shown in Table 9.3.

The discounted additional benefits are seen to be dominated by use values (those associated with recreation, pleasure boating and port operations, tourism, calcified seaweed, fisheries and amenity), with these making up about 85% of the Six Pumps treatment option, and 87% for the All Sources treatment option.

9.3 SENSITIVITY ANALYSIS

In order to test the sensitivity of the calculations to changes in the amount of impact, alternative calculations were made relating to the 'worst case scenario' and 'least case scenario'. These scenarios were used alongside varying assumptions for categories and these assumptions are catalogued within the Environmental and Social Benefit Assessment report (KP et al, 1998, Environmental and Social ...). Such assumptions include numbers of visitors or users, and differences in the amount of activity for commercial purposes. This gave the upper bound and lower bound calculations presented in the results tables for each category.

The worst case scenario assumed that discolouration would occur more frequently, and would last for longer periods, which resulted in the upper bound estimations.

Conversely, the least likely case scenario assumed much lower levels of impact and gave the lower bound estimations.

These alternative scenarios are not entirely theoretical, but assume that extreme events happen more (or less) regularly. They also relate to the extremes of the predictions from the biological assessment and catchment modelling studies.

The range of estimated benefit value has been determined under upper bound, median and lower bound conditions and for 10, 25 and 50 year time horizons as present value costs. These values form the input of benefit costs used as part of the cost-benefit appraisal, which forms the next section of the report.

10. COST-BENEFIT APPRAISAL

10.1 INTRODUCTION

The costs of the treatment options identified and developed in Sections 6 through to Section 8 and the benefit values determined in Section 9 are appraised in this section of the report.

Both the estimated scheme cost of treatment for each option and the corresponding benefit value have been reduced to present value (PV) costs for the three time periods of 10, 25 and 50 years. Note that the No Treatment option is used as a base line, and the additional benefit associated with the other treatment options has been used for this cost-benefit appraisal. Sensitivity analyses have also determined upper bound, median and lower bound values for both sets, which are all based on the same discounting rate (6%). The cost and benefit values are, therefore, considered equivalent.

10.2 DEFINITION OF TERMS

Either the costs and benefits can be subtracted from one another to form the Net Present Value (NPV) or they can be divided to form the Benefit/Cost (or Cost-Benefit), ratio. Both are expressions of the performance of each option.

In this study the following calculations are used:

- NPV = PV additional benefit - PV treatment cost;
- Benefit/Cost (B/C) Ratio = PV additional benefit/PV treatment cost.

When NPV is calculated in this way, a positive NPV indicates that benefit exceeds cost and the option is favourable. The NPV itself represents the absolute gain (or loss) associated with each option. The maximum NPV of all alternative options will, therefore, identify the most favourable option. If all possible options are considered, as they are here, then the maximum NPV will indicate the most attractive option, from a cost-benefit point of view. The upper bound and lower bound NPVs then help to identify the range of possible outcomes, which indicate the associated degree of risk.

A benefit/cost B/C ratio greater than (>) 1 also indicates a viable option, since benefit exceeds cost, but shows the scale of each cost rather than the absolute difference.

With both numbers (NPV and B/C ratio), therefore, the absolute gain (or loss) associated with an option as well as the scale of the investment required can be ascertained.

10.3 ECONOMIC COMPARISON AND SENSITIVITY ANALYSIS

The upper bound, median and lower bound additional benefit and treatment cost PVs for 10, 25 and 50 year periods for each of the four identified options (No Treatment, Six Pumps (at Wheal Jane with OCN) and All Sources (at Lower Carnon Valley with both OCN-IEX options) are tabled in the following sections. Summary results and graphs (see Figure 10.1) are then shown.

Table 10.1 : Summary 10 Year Cost and Benefit Results

Treatment Option	Present Value of Additional Benefit (£ M)	Present Value of Treatment Cost (£ M)	Net Present Value (NPV) (£ M)	Benefit/ Cost Ratio
Upper Bound Benefit Values and Lower Bound Treatment Costs				
No Treatment	0.0	1.2	-1.2	n/a
Six Pumps (OCN at Wheal Jane)	32.0	9.9	**22.1**	**3.23**
All Sources (OCN-IEX (I) in Lower Carnon Valley)	33.0	30.9	2.1	1.07
All Sources (OCN-IEX (II) in Lower Carnon Valley)	33.0	45.0	-12.0	0.73
Median Estimates				
No Treatment	0.0	2.0	-2.0	n/a
Six Pumps (OCN at Wheal Jane)	17.0	11.2	**5.8**	**1.52**
All Sources (OCN-IEX (I) in Lower Carnon Valley)	18.0	40.4	-27.4	0.45
All Sources (OCN-IEX (II) in Lower Carnon Valley)	18.0	59.1	-41.1	0.30
Lower Bound Benefit Values and Upper Bound Treatment Costs				
No Treatment	0.0	2.8	**-2.8**	n/a
Six Pumps (OCN at Wheal Jane)	10.0	15.4	-5.4	0.63
All Sources (OCN-IEX (I) in Lower Carnon Valley)	10.0	59.5	-49.5	0.17
All Sources (OCN-IEX (II) in Lower Carnon Valley)	10.0	86.0	-76.0	0.12

Table 10.2 : Summary 25 Year Cost and Benefit Results

Treatment Option	Present Value of Additional Benefit (£ M)	Present Value of Treatment Cost (£ M)	Net Present Value (NPV) (£ M)	Benefit/ Cost Ratio
Upper Bound Benefit Estimates and Lower Bound Treatment Costs				
No Treatment	0.0	1.3	-1.3	n/a
Six Pumps (OCN at Wheal Jane)	49.0	14.5	**34.5**	**3.38**
All Sources (OCN-IEX (I) at Lower Carnon Valley)	51.0	45.8	5.2	1.11
All Sources (OCN-IEX (II) at Lower Carnon Valley)	51.0	65.6	-14.6	0.78
Median Estimates				
No Treatment	0.0	2.2	-2.2	n/a
Six Pumps (OCN at Wheal Jane)	27.0	16.2	**10.8**	**1.67**
All Sources (OCN-IEX (I) at Lower Carnon Valley)	28.0	58.5	-28.5	0.50
All Sources (OCN-IEX (II) at Lower Carnon Valley)	28.0	81.0	-53.0	0.35
Lower Bound Benefit Estimates and Upper Bound Treatment Costs				
No Treatment	0.0	3.0	**-3.0**	n/a
Six Pumps (OCN at Wheal Jane)	16.0	23.4	-7.4	0.68
All Sources (OCN-IEX (I) at Lower Carnon Valley)	17.0	84.3	-67.3	0.20
All Sources (OCN-IEX (II) at Lower Carnon Valley)	17.0	119.4	-102.4	0.14

Table 10.3 : Summary 50 Year Cost and Benefit Results

Treatment Option	Present Value of Additional Benefit (£ M)	Present Value of Treatment Cost (£ M)	Net Present Value (NPV) (£ M)	Benefit/ Cost Ratio
Upper Bound Benefit Estimates and Lower Bound Treatment Costs				
No Treatment	0.0	1.4	-1.4	n/a
Six Pumps (OCN at Wheal Jane)	59.0	17.3	**41.7**	**3.41**
All Sources (OCN-IEX (I) at Lower Carnon Valley)	61.0	54.5	6.5	1.12
All Sources (OCN-IEX (II) at Lower Carnon Valley)	61.0	77.8	-16.8	0.78
Median Estimates				
No Treatment	0.0	2.3	-2.3	n/a
Six Pumps (OCN at Wheal Jane)	33.0	19.1	**13.9**	**1.73**
All Sources (OCN-IEX (I) at Lower Carnon Valley)	34.0	66.4	-32.4	0.51
All Sources (OCN-IEX (II) at Lower Carnon Valley)	34.0	94.7	-60.7	0.36
Lower Bound Benefit Estimates and Upper Bound Treatment Costs				
No Treatment	0.0	3.2	**-3.2**	n/a
Six Pumps (OCN at Wheal Jane)	19.0	28.1	-9.1	0.68
All Sources (OCN-IEX (I) at Lower Carnon Valley)	20.0	99.3	-79.3	0.20
All Sources (OCN-IEX (II) at Lower Carnon Valley)	20.0	140.0	-120.0	0.14

10.4 SUMMARY OF COST-BENEFIT APPRAISAL

The final estimated NPV for the four treatment options are plotted on Figure 10.1 and summarised in Table 10.4. Note that the OCN-IEX(I) treatment option relates to riverine water quality requirements, whereas the OCN-IEX(II) treatment option relates to estuarine requirements.

Table 10.4 : Summary Net Present Values

Treatment Option / Scheme Duration	Upper Bound (£ M)	Median (£ M)	Lower Bound (£ M)
10 Year Net Present Values			
No Treatment	-1.2	-2.0	**-2.8**
Six Pumps	**22.1**	**5.8**	-5.4
All Sources (riverine)	2.1	-22.4	-49.5
All Sources (estuarine)	-12.0	-41.1	-76.0
25 Year Net Present Values			
No Treatment	-1.3	-2.2	**-3.0**
Six Pumps	**34.5**	**10.8**	-7.4
All Sources (riverine)	5.2	-28.5	-67.3
All Sources (estuarine)	-14.6	-53.0	-102.4
50 Year Net Present Values			
No Treatment	-1.4	-2.3	**-3.2**
Six Pumps	**41.7**	**13.9**	-9.1
All Sources (riverine)	6.5	-32.4	-79.3
All Sources (estuarine)	-16.8	-60.7	-120.0
Highest NPVs shown emboldened.			

10.5 DISCUSSION OF RESULTS

From the cost-benefit appraisal of the treatment options the following conclusions are drawn:

- The most attractive treatment option in almost all cases is Six Pumps using OCN located at the Wheal Jane mine site.

  The Six Pumps treatment option represents a situation similar to the existing one. There would be occasional discharges from Nangiles Adit which could result in discolouration. The likelihood of discolouration is remote, however, as indicated during the winter of 1997/1998 when Nangiles Adit discharged, but there was no recorded discolouration. The probability of discolouration as a result of discharges from the CVTD will also be reduced significantly when the function of water/solids separation is achieved off the dam.

- The lower bound scenario suggests that No Treatment is (just) preferable over the Six Pumps treatment option, although the NPV is negative.

- No Treatment represents the smallest expenditure of the options.

  The implication of No Treatment is that discolouration would occur almost every year over extended periods. This has a significant impact on benefits, such as those related to fisheries, amenity or the calcified seaweed industry. In many cases, the perceived consequences of discolouration are greater than the reality, but this still affects benefits, according to the results of consultations with 30 local groups and organisations. Oysters and shellfish, for example, are unlikely to be adversely affected, but there would be a perception of contamination. There is, however, a possibility of sea bass nurseries and maerl beds being directly affected as a result of increased metal concentrations and sedimentation respectively.

- Treatment of All Sources shows a negative NPV (except for upper bound 25 year and 50 year values).

  There are few environmental or cost-benefits from adopting the All Sources treatment options over and above the Six Pumps treatment option. The Six Pumps option meets EC DS Directive limit values.

  These All Sources options do, however, enable EQS to be met and, in particular, the EQS set for cadmium, a List I substance, could be met at Devoran Bridge. Treatment to a higher effluent quality (OCN-IEX (II)) would enable EQS for fresh water and salt water as specified in the EC Dangerous Substances Directive – Fresh Water Environmental Quality Standards, EC DS Directive – Salt Water Environmental Quality Standards and with the EC Shellfish Waters Directive to be met.

11. IMPLEMENTATION

11.1 INTRODUCTION

If a long-term treatment option is selected then a mechanism for implementation is required that allows the Agency to manage the associated risks in a determined way. The Contract Strategy element of the project is, therefore, concerned with identifying:

- the risks associated with any long-term treatment option and methods for the minimisation and management of these risks;
- different contractual arrangements with regard to the transfer of risk to a third party and the associated costs of doing so;
- the possible sources of funding for the construction and operation of any new treatment plant;
- the programme implications of each contract option.

These aspects are discussed in the contract strategy report (KP et al, 1998 Final Contract ...) and summarised within this section. A technical summary of the strategy is presented in Appendix B. The programme implications are discussed further in Appendix A (Recent Developments).

A current dilemma is that the Agency has the role of treatment operator as well as water quality regulator. This is the case currently for the ETP operations and whilst some responsibilities have been passed on to others via contract agreements the main conflict of operator and regulator remains. Separating these two roles, by passing on the responsibility of operations to a third party and thus allowing the Agency to revert to it's role of regulator, is thus a key aspect of this part of the study.

The allocation of responsibility and risk for any of the long-term options will depend on the form of contract used. Three main forms of contract are available as follows:

- *Traditional*: this option requires the Agency to employ contractors to design and construct the treatment plant with subsequent operation of the treatment plant let through a separate operating contract;
- *Design, Build and Operate (DBO)*; under this form of contract, the contractor is responsible for designing, building and operating the treatment plant, with the Agency providing the funding;
- *Design, Build Finance and Operate (DBFO)*; this is similar to a DBO contract, except in that the contractor is responsible for funding the construction and the Agency only pays for treatment services provided.

These three contract options will each apportion the various risks associated with long-term treatment differently and demand different cash amounts and cash profiles from the Agency. These aspects have been examined (KP et al, 1998, Final Contract ...) and are outlined in the following section.

11.2 IDENTIFICATION OF RISKS

In this context risk means any aspect of work that can be identified discretely and the responsibility apportioned. The aim is to allocate each risk to the body most capable of managing it, so, for example, the operating risk would be the responsibility of achieving the desired TEQ from the treatment plant. This particular risk, which is fundamental to a water treatment operation, would be managed under a Discharge Consent. It is then important that the party that holds the Discharge Consent has the right interests in maintaining the desired discharge quality. In this case the operator should hold the Discharge Consent and have contractual as well as legally enforceable and meaningful penalties against him should it be breached.

The contract type will determine who holds each risk, and for the above example either a DBO or DBFO type of contract would be appropriate (and in so doing allows the Agency to revert to role of the regulator).

Three possible contracting parties have been identified; the Agency, South Crofty plc. (SCP) and a third party contractor. SCP own the Wheal Jane mine site and the CVTD and so they inevitably have an interest in long-term operations involving either of these two facilities. The CVTD has been identified as the preferred location for long-term sludge disposal and the Agency does not intend to take on the facility. Therefore, it seems inevitable that SCP will have a long-term role of some sort, either as a treatment operator in its own right or as a sub-contractor for matters such as sludge disposal.

Various risk categories have been identified within the contract strategy study and are listed in Table 11.1 against their allocation under each of the main contract types. Also, the shaded boxes identify the party that, on the face of it, is best able to manage each risk category.

The form of contract that would pass the most risk from the Agency is a DBFO type contract, closely followed by a DBO arrangement, with a traditional arrangement passing over the least risk. Therefore, in order to best satisfy the aim of transferring responsibility for treatment to a third party, a DBFO or DBO contract should be used. By comparing the allocation with the shaded boxes it is seen that the DBO option provides the best overall allocation.

Table 11.1 : Allocation of Risk Under Different Contracts for the Six Pumps Treatment Option

	Form of Contract								
	Traditional			**DBO**			**DBFO**		
Recipient / Risk Category	**Agency**	**SCP**	**Third Party**	**Agency**	**SCP**	**Third Party**	**Agency**	**SCP**	**Third Party**
Design risk			✓			✓			✓
Construction risk			✓			✓			✓
Operating risk (1)			✓			✓			✓
Residual value risk	✓			✓					✓
Technology risk(2)	✓			✓		✓	✓		✓
Regulatory risk	✓		✓			✓			✓
Financing risk	✓			✓					✓
Sludge disposal risk(3)	✓	✓	✓		✓	✓		✓	✓
Planning risk(2)	✓		✓	✓		✓	✓		✓

Shaded boxes identify the recipient considered most capable of managing each risk.
(1) Design and build phases and the operating phase would go to separate contractors.
(2) Some risk can be allocated to more than one recipient.
(3) Sludge disposal risk with SCP only where CVTD used.

11.3 OWNERSHIP

The ownership of various assets will be determined by contract type. The key aspect is the eventual owner of the treatment plant who would then naturally hold the Discharge Consent. All contract types would allow this ownership to be passed to the operator although the traditional route would place ownership first with the Agency from where it could be transferred. This is more complex and means that it would be less easy for the Agency to pass on the Discharge Consent and thereby revert to a role of regulator under the Traditional route. The ownership aspects are considered in detail within the contract strategy report.

11.4 CASH PROFILES

The cash profile, or payment schedule, associated with each contract type is shown in Figure 11.1. This figure demonstrates the typical cumulative overall relative cost for each option, it does not show the relative NPV of the different options, which are shown in the next section. The base cost, which is shown on the figure, is the basic costs of the equipment that must be paid (for example, to an equipment supplier) whatever the form of contract is used. This is the base cost identified within Section 8 of this report.

The final scheme cost of a treatment option is expected to increase from base cost to the traditional cost, DBO and finally the DBFO option. In each case more risks are being passed over to the contractor and these increased responsibilities are reflected in the higher total price. To determine the optimum contract approach for the Agency it is, therefore, necessary to examine the value for money associated with each route, that is, what risks are transferred and at what cost? This comparison is shown in the next section.

11.5 COMPARISON OF OPTIONS

Table 11.2 shows a comparison of the estimated total 10 year scheme cost for the three forms of contract including upper bound and lower bound estimates.

Table 11.2 : Comparison of 10 Year Scheme Costs

Contract Route\Treatment Option	Estimate	Traditional	DBO	DBFO
No Treatment	Upper	2.6	2.8	4.6
	Median	1.8	2.0	2.4
	Lower	0.9	1.2	1.2
Six Pumps	Upper	14.1	16	17.4
	Median	10.2	11.2	12.1
	Lower	9.3	10.1	10.7
All Sources	Upper	58.1	63.8	82.6
	Median	40.6	44.1	48.7
	Lower	30.5	33.3	34.8

The table shows that for each of the treatment options, the cost to the Agency differs depending on the type of contract used. This reflects the increase in risk transferred from the Agency by these contract forms and the corresponding increase in compensation sought by those accepting this risk.

The cheapest contract form is the traditional contract, which requires the Agency to accept a considerable degree of risk. In addition, it would require the Agency to accept responsibility for achieving the water quality standards stipulated in the Discharge Consent, at least in the short-term, which is required to allow treated effluent to be discharged into controlled waters. Therefore, the contract form would not allow the Agency to achieve one of its stated project aims of passing on responsibility for treatment to a third party.

The DBO and DBFO contracts both result in more cost to the Agency for the treatment options. However, they do pass on more risk and, crucially, they allow the Agency to easily assign the Discharge Consent for the treated effluent to a third party, thereby achieving the objective of passing on treatment responsibility.

From the appraisal of contract options issues the following conclusions can be made:

- the traditional form of contract provides the lowest cost solution, but allocation of risk does not fit the desired profile;
- a DBFO contract route involves additional apparent costs over the DBO option, but does defer payments, which may have an intrinsic value of its own;
- The DBO option provides a good overall solution when final scheme cost and risk allocation are considered.

11.6 THE PROCUREMENT PROCESS

The decision making process, for each contract type, is identified on Figure 11.2. Depending upon which long-term option is chosen, the following considerations would apply.

No Treatment

A relatively small amount of work is required to Jane's Adit to ensure a secure long-term egress point for the minewater. This work involves adit refurbishment and clearance and is specialist in nature. SCP are considered well placed to undertake this type of work, under a normal civil engineering style contract.

Six Pumps

The Agency should negotiate with SCP to secure future access to both the CVTD and the mine site and also to determine if they would be capable of undertaking the work themselves, whether under a traditional, DBO or DBFO type arrangement. It would then normally be necessary to proceed on a competitive procurement route, in accordance with EU procurement rules. Since SCP have ownership of the Wheal Jane mine site and the CVTD it is suggested that they would naturally form part of a long-term solution involving those assets either as a main or sub contractor.

All Sources

The same issues for Six Pumps remain if the OCN-IEX option is pursued. The alternative treatment options, such as IEX at Lower Carnon Valley, would be independent of the mine site, but at a considerable cost premium.

Also, the following considerations may affect the choice of contract.

The competitive tender process will depend on the type of contract to be used. If a DBFO type of contract is chosen then extensive negotiations will be required with potential contractors, regarding issues such as risk allocation and payment mechanisms. In addition, a bespoke contract will need to be written, as standard contracts for DBFO contracts do not exist. This means that the tender period for a DBFO type of contract is likely to be the longer than for a DBO or traditional contract. If a DBFO route is chosen then an updated outline business case should then be undertaken to complete the studies of the previous business case to determine private or public funding for the route. If this route is not chosen then the business case should not be required. The first outline business case was prepared before any treatment option was established and so a large number of variables were unresolved. Once a single WQO or treatment option has been specified then a more detailed and more accurate business case can be prepared.

For a DBO and traditional type of arrangement, the preparation of documentation is far more straightforward than for a DBFO contract, and negotiations with contractors, whether they be to discuss construction or operational issues, will be simpler. The programme implications between each of the options are discussed in the next section.

11.7 SUMMARY OF OPTIONS

The appraisal of alternative contract types and the resulting allocation of risks determined by the contract strategy (KP et al, 1998, Final Contract ...) together with the programme implications, detailed in Appendix A, leads to the following conclusions.

- The traditional route does not allow the Agency to revert to a role of regulator as easily as the other options, although it is likely to be the cheapest option.
- The DBO option is easily defined and the allocation of risks generally seems to be the most appropriate. It is unlikely to be the cheapest option, but does allow the Agency to pass on a discharge consent easily.
- Tender documentation should be prepared to allow tenders to be invited by January 1999. This will allow time to implement initial treatment before the winter of 1999/2000.
- The worst case situation, where the CVTD becomes full by October 1999, would require an accelerated implementation using a traditional contract route.
- An initial DBO contract term of about twelve years (two years design and construction, ten years operating) is considered appropriate in the first instance.
- The DBFO alternative will demand additional funds to cover the financing costs incurred by a contractor. It is possible that the contractor may require higher rates of return from the loan amount than the Agency would expect, although payments would be deferred, which has an intrinsic value of its own.
- SCP seem to be the only party likely to be interested in the long-term management and operation of the CVTD. This is a vital facility for short-term and long-term operations and means that SCP are likely to have a continuing role in the project if treatment continues.
- A DBFO route will involve a more complex and more time consuming tender process than the other two options because the additional burden of financing the project will require more overall appraisal by contractors.

The ultimate choice of contract type is clearly a subjective matter as the perceived value of some aspects will differ widely between interest groups. However, for a long-term minewater treatment plant within the Carnon Valley catchment it is considered that a DBO contract type delivers the best overall solution.

12. CONCLUSIONS AND RECOMMENDATIONS

12.1 SUMMARY OF CONCLUSIONS

The conclusions drawn at each stage of the study are now summarised below.

Treatment Alternatives

- Existing treatment still provides the cheapest form of treatment (of Wheal Jane minewater), but has a limited lifespan.
- Oxidation and Chemical Neutralisation (OCN) treatment is the cheapest process route identified, though the final water quality is inferior to other types.
- Ion Exchange (IEX) treatment can be designed to produce a water quality that satisfies the EC DS Directive Fresh Water Standards, and all the higher order WQOs.

Treatment Requirements

- A No Treatment option would require Jane's Adit to be refurbished to provide a secure long-term egress point for the Wheal Jane minewater.
- Treatment of Six Pumps (up to 330 l/s from Wheal Jane) using any of the three identified treatment routes will achieve the lower order WQOs at Devoran and limit values.
- Treatment of All Sources using the OCN-IEX (I) combination is required to meet the EC DS Directive Fresh Water Environmental Quality Environmental Quality Standards.
- Treatment of Wheal Jane plus and County Adit, the two major identified point sources within the catchment, using any identified treatment route will not achieve the higher order WQOs.
- The higher order WQOs (EC DS Directive – Fresh Water Environmental Quality Standards, EC DS Directive - Salt Water Environmental Quality Standards and Protection of Estuarine Biology) can be met by treatment of All Sources by OCN-IEX (II).
- Minewater concentrations are not expected to reduce significantly over time. The modelling results are based on long-term minewater quality predictions and treatment can be expected to be still required for many years to come.

Plant Site and Sludge Disposal Locations

- Wheal Jane mine site is the preferred location for the Six Pumps treatment option for cost and planning reasons. Treating Six Pumps with OCN is then essentially an add-on to the existing treatment operations.
- Wheal Jane includes the CVTD site which is the preferred site for long-term sludge disposal.
- An off-site contingency arrangement for sludge disposal should also be developed.

- The Lower Carnon Valley site (just upstream of Devoran) should be used for the All Sources treatment option.

Cost-Benefit Appraisal

- OCN is cheaper than other forms of treatment.
- The most attractive option, identified with the largest positive NPV and highest benefit/cost ratio, in almost all cases is Six Pumps using OCN located at the Wheal Jane mine site.
- The No Treatment option is marginally more favourable than the Six Pumps treatment option using lower bound estimates.
- The No Treatment option results in regular and extended periods of discolouration which have an impact on benefits, both because of perceived contamination and, in some cases, the possibility of actual contamination by metals and increased sedimentation.
- The cost-benefit appraisal indicates that treatment to meet all WQOs is not favourable. This treatment of All Sources is necessary, however, if EQS are to be met.

Contract Strategy

- The three principal contract alternatives listed in increasing overall cost to the Agency and decreasing responsibility are Traditional, DBO and DBFO.
- The DBO contract option appears to provide best overall balance between cost and risk to the Agency although this conclusion is subjective.
- Tender documentation should be prepared to allow tenders to be invited by January 1999. This will allow time to implement initial treatment before the winter of 1999/2000.
- The worst case situation, where the CVTD becomes full by October 1999, would require an accelerated implementation.
- An initial DBO contract term of about twelve years (2 years design and construction and ten years operating period) is considered appropriate in the first instance.
- The key responsibility for attaining the required treatment water quality should be managed via a Discharge Consent. The operating Contractor should hold this consent.
- For the Six Pumps treatment option SCP own the Wheal Jane mine site and control the tailings dam, which is a key feature of Six Pumps as a sustainable long-term option. SCP will therefore have a long-term role in this option.

12.2 FINAL RECOMMENDATIONS

As a result of the cost-benefit appraisal undertaken within the Wheal Jane Minewater Project and as described within this report the following recommendations are made.

- The Six Pumps treatment option is pursued using the OCN process route, located at the Wheal Jane mine site and implemented using a DBO style of contract.
- The initial treatment contract extends for a term of about twelve years.
- Tender documentation should be prepared to allow tenders to be invited by January 1999. This will allow time to implement initial treatment before the winter of 1999/2000. If the rate of rise of the dam is quicker than currently anticipated then the accelerated traditional route (see Appendix A) should be pursued whereby the same treatment option is implemented under a fast-track approach to be in place by October 1999.
- Sludge, as a dewatered cake, should be deposited in the CVTD. An alternative sludge disposal site should also be identified as a contingency arrangement should the CVTD become unavailable for any reason.

It should be noted that the above recommendations are based on a cost-benefit appraisal and will meet EC DS Directive limit values. EQS for cadmium would, however, be exceeded in the Carnon River, and copper and zinc would be exceeded in the Fal Estuary. Treatment of All Sources to Devoran by OCN-IEX (I) would enable EQS to be met at the National Monitoring Network Station at Devoran Bridge, but would be of little environmental benefit.

Treatment of All Sources to Devoran by OCN-IEX (II) would enable EQS to be met in the estuary and at Devoran Bridge, but also with little environmental benefit beyond that attained by the Six Pumps treatment option.

13. REFERENCES

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APPENDICES

APPENDIX A

Recent Developments

This Appendix contains information which has been gathered since Version 4 of this report (May 1998) was published. That version of the report was considered in the deliberations to determine the long-term treatment strategy.

RECENT DEVELOPMENTS

The cessation of operations by South Crofty plc (SCP) has caused a change to the deposition into the Clemows Valley Tailings Dam (CVTD). This has raised two concerns; the affect on programme since a key milestone is the date that the CVTD becomes full, and the effluent clarity achieved from the Existing Treatment Plant (ETP) in the mean time. Both issues are addressed below followed by a recent update on Private Finance Initiative (PFI), treatment of Wheal Jane minewater to meet Environment Quality Standards and Water Quality Predictions.

PROGRAMME IMPLICATIONS

Figure A.1 indicates the programme for various contract implementation routes as well as the estimated dates that the CVTD will reach 70 m AOD on the outer wall. The dam dates are based on the recent in situ monitoring data following the cessation of mining operations and subsequent sludge only deposition.

It should be noted that the dam can technically be raised beyond 70 m AOD, subject to planning permission. For example the outer wall could be raised further, if additional space for wet deposition was required, and then lowered back to 70 m once the wet deposition had ceased and a dewatered dry deposition strategy was in place. The programme dates shown in Figure A.1, therefore, are not absolute constraints. For any case there would be ample space for long-term storage of dewatered sludge, partly because the wet deposited sludge will dry out and settle once wet deposition ceases. Also the 1.25 m freeboard, which is required when running a wet process, but not required once the pond is drained, would provide additional storage volume.

Figure A.1 compares contract options with dam life to demonstrate that all contract options are available under the best estimate fill date, but that it is possible that the dam will fill more quickly, in which case the accelerated route would be required. The accelerated route involves following the draft Contingency Plan already in existence, which defines the scope of work, but could be based on a traditional tendered form of contract. Operation would either continue with SCP or some other third party. The accelerated route is, therefore, merely a fast-track approach to the traditional form of contract.

The recommendations made within the main report support the Six Pumps option. Moreover, the recommended treatment option for All Sources would be for OCN at Wheal Jane with an IEX plant in the valley as a secondary 'polishing' stage. The installation of the thickeners and dewatering equipment that comprise the OCN Six Pumps option, therefore, applies to any long-term treatment decision other than No Treatment. The Contingency route would specify the process (OCN) to be used whereas the other routes leave this final selection with the contractor.

Should the Agency decide to adopt the No Treatment option as its long-term treatment strategy then there would still be time to cancel procurement works even if the decision to proceed on a fast-track approach were made prior to June 1998.

DAM EFFLUENT CLARITY

When the South Crofty mine closed (7th March 1998) mine tailings ceased to be deposited into the dam with the following implications:

- settlement of the residues was no longer assisted by the higher density particles (tailings) in the deposited blend;

- the total mass being deposited reduced markedly (to about 15% of previous) though settled densities would reduce.

Prior to the mine closure a study was initiated to determine how deposition would be affected. This was reported in the Sludge Disposal Strategy Report (KP et al, 1998, Sludge Disposal ...) which determined:

- that effluent clarity will be increasingly influenced by the prevailing weather conditions, in particular wind, which remobilizes the settled residues causing high suspended solids (and discolouration) at the dam outlet;
- that the existing operating procedure was the most appropriate, given the facilities available, to maintain good deposited density, effluent clarity and to maintain the overall dam integrity;
- some minor modifications to the dam, such as leat extension or an additional groin, could further improve effluent clarity.

Ongoing monitoring of the in situ material confirms the above conclusions. However, the deposited material is not achieving the densities predicted in the above report, mainly due to the need to maintain a large pool to encourage settlement and because the beach lengths and slopes available do not permit sub-aerial deposition and drying out of the sludge. Figure A.1 is based on recent data acquired through in situ monitoring of the sludge material.

The main concern is that effluent clarity will deteriorate during the next winter period, despite the proposed minor modification works, to such an extent that unacceptably high and prolonged periods of discolouration will occur.

Quantitative prediction of the future extent of discolouration (turbidity) is difficult, monitoring of wind speeds and turbidity at the dam outlet is in progress, but no firm correlation yet exists. However, it is expected that the suspended solids discharged from the dam would breach the existing (and draft) Discharge Consent, possibly for extended periods of time.

Implementation of the sludge thickening equipment to be independent of the dam for the purpose of water/solids separation (although deposition of dewatered material would continue) is the only guaranteed way of controlling the effluent quality.

PFI ROUTE

An outline business case was developed in October 1997 to test the feasibility of using private finance, via the PFI to fund a scheme at Wheal Jane. The report (KP et al, 1997, Outline Business ...) concluded that there was little difference in cost between public and privately financed routes and that the decision would need to be based on the degree of risk to be transferred to the contractor. It has subsequently been decided, by the Agency's Private Finance Programme Board, that adequate risk transfer can be achieved by a more conventional Design Build Finance Operate (DBFO) route and hence that further consideration of the PFI for Wheal Jane would not be necessary.

TREATMENT OF WHEAL JANE MINEWATER TO EQS

Although not included as a study objective it would also be feasible for the effluent from a treatment plant for Wheal Jane minewater to meet Environmental Quality Standards (EQS).

Biochemical Sulphidisation (BCS) technology would be expected to meet EQS on an average annual basis and OCN-IEX technology is capable of producing guaranteed effluent to EQS.

The cost of treating Wheal Jane to EQS would be higher than using Six Pumps to OCN effluent quality, but lower than the All Sources treatment option.

Present Value scheme costs for OCN-IEX are expected to be slightly lower than BCS, however, further testwork would be required on site to firm up costs and design requirements for the IEX polishing treatment (resin, reagent and power requirements).

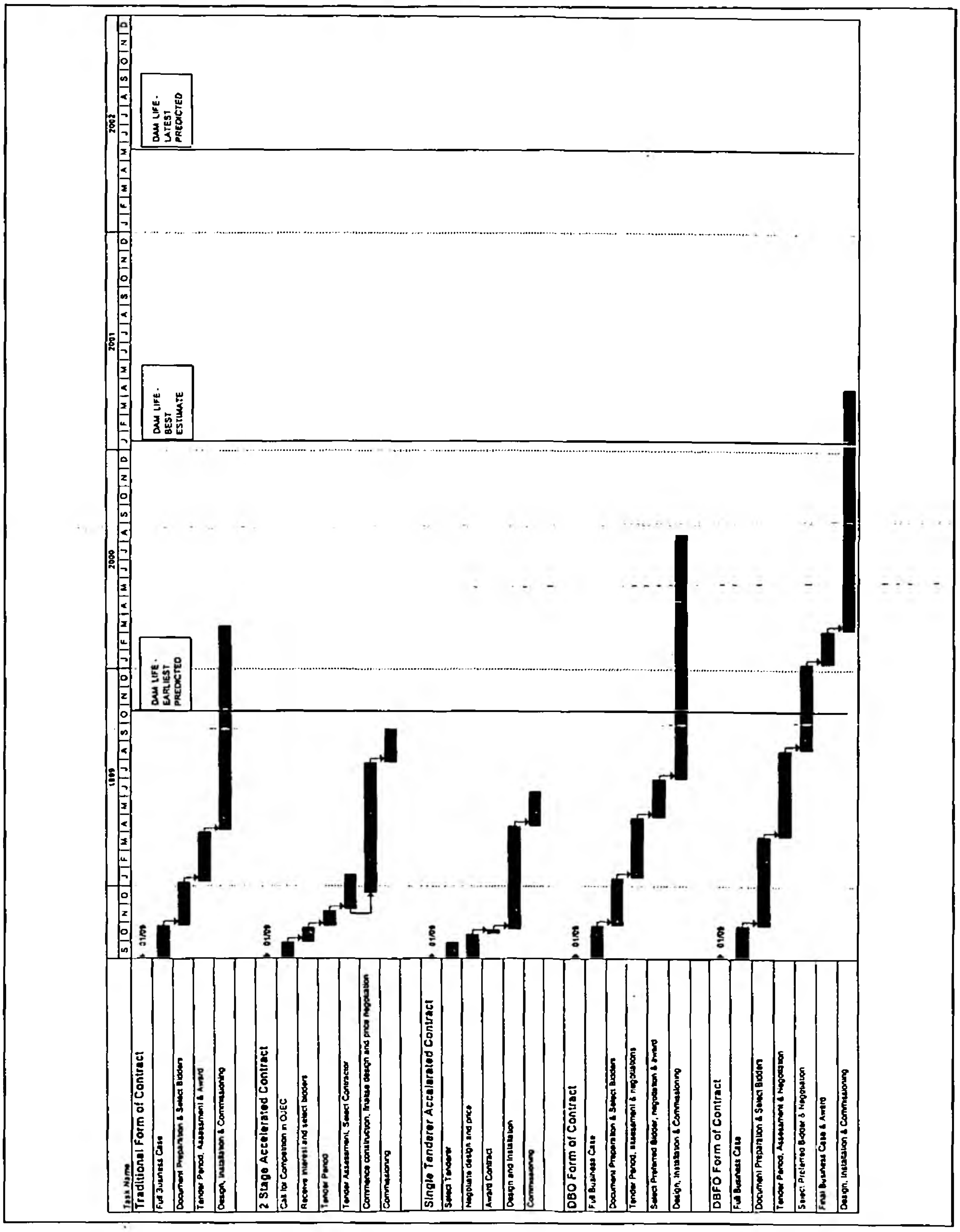
WATER QUALITY PREDICTIONS

The long-term predictions of No.2 Shaft minewater quality presented in this study are the result of modelling performed on rainfall and minewater data up to April 1997. Statistical evaluation of these data indicated that all metal concentrations are likely to be within 1% of their long-term values. For iron, an average concentration of 297 mg/l was expected for the recommended ten year operating period with the total precipitated solids predicted to be 990 mg/l.

As a result of the observed decline in No.2 Shaft metal concentrations since April 1997, additional modelling of minewater quality has been performed.

The variable costs for minewater treatment for example, lime consumption, are dependant on minewater concentration and flow. In view of the continuing decline in metals concentrations, it is recommended that the annual operating costs for the OCN treatment plant be reviewed by the Agency and the contractor throughout the anticipated ten year operating period.

Figure A.1 : Summary Programmes for Various Contract Types



APPENDIX B

Technical Summary of Final Contract Strategy Assessment Report

TECHNICAL SUMMARY

INTRODUCTION

The abandonment of the Wheal Jane mine in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and therefore limit the impact of the release on the environment.

Knight Piésold were commissioned by the Agency in June 1996 as lead consultant to undertake a number of study briefs which together comprise the Wheal Jane Minewater Project Consultancy Studies 1996 - 1999.

The Agency's project brief for the Wheal Jane Minewater Project Consultancy Studies 1996-1999 includes a requirement to study the contractual issues related to the implementation of long-term treatment operations for the minewater should they be found to be necessary.

The stated aims of the Agency with regard to the study are:

- that the risks to the Agency associated with any long-term treatment option are identified, analysed, and methods for their minimisation be assessed;
- that different contractual arrangements be investigated to implement the construction of any long-term treatment system;
- that the possible sources of funding for the construction and operation of any new treatment plant be explored.

The Agency have stated also that any future contractual arrangement should:

- if possible, seek to transfer its current responsibility for minewater treatment to a third party, thus allowing it to revert to a role of statutory regulator only;
- provide the best value for money solution for the Agency.

THIS REPORT

This report is the second and final concerning contract strategy and considers the aforementioned issues with regard to the following strategic treatment options available to the Agency:

- cease treatment;
- upgrade the existing facilities (the 'Six Pumps' option): this lower order strategic option would refine but not increase the magnitude of the current treatment process and has been identified within the Active Treatment Outline Design report as being the most appropriate means of achieving the lower order Water Quality Objectives (WQOs) of the study;
- construct new facilities (the 'All Sources' option): this higher order strategic option would require a complete new facility to treat all flow at Devoran Bridge and has been identified within the Active Treatment Outline Design report as being the most appropriate means of achieving the higher order WQOs of the study;

- a combination of the Six Pumps and All Sources options: this option (Upgrade Strategic Option) would allow the Agency initially to treat the minewater to a lower order water quality, thereby delaying expenditure and then, if circumstances dictate, treat to the higher standard at some time in the future.

The Six Pumps option (Accelerated Strategic option) could be built to an accelerated programme to have the facilities operational as soon as possible.

The allocation of responsibility and risk for these strategic options will depend on the form of contract used. This report assesses the implications to the Agency of using the following forms of contract for the strategic options:

- Traditional - this requires the Agency to operate any necessary treatment facility and employ contractors to design and construct it;
- Design, Build and Operate (DBO) - under this form of contract, the contractor is responsible for designing, building and operating the treatment plant, with the Agency providing the funding;
- Design, Build Finance and Operate (DBFO) - this is similar to a DBO contract, except in that the contractor is responsible for funding the construction also, and the Agency only pays for treatment services provided.

This report also considers the funding sources and procurement process for the different forms of contract and the documentation that will be necessary to invite tenders.

REPORT FINDINGS

The report considers a number of technical, contractual and funding issues, which influence the contract strategy. The key observations are outlined below.

Strategic Treatment Options

All of the strategic options considered in this report, and as listed above, are feasible. The costs of the Six Pumps and All Sources treatment options over a 25 year period, using a traditional means of procurement, are shown in Table B.1. It can be seen that to achieve the higher order WQOs, the cost to the Agency over a 25 year period is almost four times that to achieve the lower order objectives.

Table B.1 : Cost to the Agency of Water Treatment

Strategic Treatment Option	Present Value Cost to the Agency using a Traditional Contract
Cease Treatment	£1.9 M
Six Pumps (achieves lower water quality objectives)	£14.4 M
All Sources (achieves higher water quality objectives)	£ 54.3 M

Forms of Contract

The form of contract that would pass the most risk from the Agency is a DBFO type contract, closely followed by a DBO arrangement, with a traditional arrangement passing over the least risk. This is demonstrated in Table B.2. Therefore, in order to best satisfy the Agency's stated aim of transferring responsibility for treatment to a third party, a DBFO or DBO contract should be used.

Table B.2 : Allocation of Risk by Different Contracts

	Form of Contract								
	Traditional			**DBO**			**DBFO**		
Recipient of Risk	Agency	SCP	External	Agency	SCP	External	Agency	SCP	External
Design Risk			✓			✓			✓
Construction Risk			✓			✓			✓
Operating Risk	✓					✓			✓
Residual Value Risk	✓			✓					✓
Technology Risk	✓			✓		✓	✓		✓
Regulatory Risk	✓					✓			✓
Financing Risk	✓			✓					✓
Waste Disposal Risk	✓	✓				✓			✓
Planning Risk	✓		✓	✓			✓		

However, if the Agency wishes to adopt a value for money option, regardless of who has responsibility for treating the minewater, a traditional form of contract might prove to be more appropriate. Value for money assessments need to determine whether it is worth paying the higher costs of the DBO and DBFO options to transfer the risk that a traditional form of contract would retain.

Cost of Risk Transfer

Table B.3 shows the cost to the Agency of using the different forms of contract for each strategic option.

Table B.3 : Strategic Option Costs

Strategic Option	Traditional Contract (£ M)	DBO Contract (£ M)	DBFO Contract (£ M)
Cease Treatment	£1.9	£2.0 (£0.1)	£3.0 (£1.1)
Six Pumps	£14.4	£16.2 (£1.8)	£17.5 (£3.1)
All Sources	£54.3	£60.3 (£6)	£69 (£14.7)

Costs are present values (1/1/98) based on providing treatment for 25 years.
No value has been placed on the allocation of risk which can only be determined by negotiation with contractors.
Values in brackets represent the cost of transferring the risk carried by the Agency under a Traditional Contract.

The benefit to the Agency of adopting a DBO or DBFO option is dependent on the potential cost of the risks that would otherwise be retained, and the likelihood of their occurrence. In addition, for the DBFO option, there is also the benefit of avoiding paying large capital costs upon completion of construction, thereby allowing these sums to be used elsewhere.

The cost of risk transfer for the DBO form of contract represents the minimum cost to the Agency of reverting to the role of regulator as this is the cost of transferring responsibility for minewater treatment, and all its attendant risks, to a third party.

Project Funding

The report considers the following sources of funding for the project:

- grant funding via English Partnerships and the European Union;
- loans from the European Investment Bank;
- private funding via the Public Private Partnership/Private Finance Initiative;
- Agency funding via the Department of Environment, Transport and the Regions (DETR).

The report concluded that only the options of private finance and Agency funding via the DETR are feasible for this project.

An Outline Business Case has been prepared for the Agency assessing the feasibility of using private finance for this project. This concluded that it may be feasible to use private finance, but no definite conclusions could be made until after the publication of the main report. The Agency have indicated that they would prefer to wait until an assessment of the feasibility of using private finance is complete before committing DETR funds to the project.

South Crofty plc

The studies for this report demonstrated very clearly that for all the possible upgrade treatment options, South Crofty plc (SCP) would almost certainly be involved. The main reason for this is because they own and have responsibility for the current sludge depository, the Clemows Valley Tailings Dam (CVTD). Studies have shown that this is the most logical and cost effective place to deposit sludge, whichever of the treatment options is chosen. Therefore, to be cost effective, the chosen treatment option would need to use the CVTD. However, no party, other than SCP, are willing to take responsibility for the CVTD. Therefore, to continue to use the CVTD, SCP would need to be involved, at least as a disposal sub-contractor.

In addition to owning the CVTD, SCP also own the land on which the current treatment plant is sited. This site is the most appropriate location for the Six Pumps treatment option, and has been identified by Cornwall County Council planners as their favoured site for any treatment option. The Agency has no interest in owning this land, and it is unlikely that any third party would wish to do so either. Therefore, a leasing agreement with SCP, that allows for access to the land for the duration of any contract, would be the approach favoured by the Agency or third parties. However, this may not be favoured by SCP and ultimately, the Agency may have to purchase the land outright.

Procurement Process

If the Agency decides to continue treatment, the next stage of the procurement process would be to obtain approval to proceed from the DETR. A full business case can subsequently be prepared, based on the previous outline business case (KP et al, 1998, Outline Business ...). The full business case should determine whether it is feasible to proceed along a procurement route which may lead to the use of private finance for the funding of the project.

If a Six Pumps treatment option is decided upon, it is recommended that the Agency enters into negotiations with SCP to secure future access to both the CVTD and the land on which the current treatment facility is located. The discussions should also determine if SCP would be capable of undertaking the work themselves, whether under a traditional, DBO or DBFO type arrangement. It would then normally be necessary to proceed on a competitive procurement route, in accordance with EU procurement rules. However, this may not be required if it can be demonstrated clearly that a competitive process is not necessary to procure the most cost effective solution. As SCP have been identified already as being central to any cost effective solution, it may be possible to negotiate an agreement with them that could not be matched by any other party. In this situation, it would not be necessary or indeed ethical to adopt a competitive process.

If an All Sources treatment option is decided upon, then it is unlikely that SCP would be in a position to take full responsibility for the project. In this case, the Agency would be required to proceed on a competitive procurement route in line with EU procurement rules.

The competitive tender process will depend on the type of contract to be used. If a DBFO type of contract is chosen, extensive negotiations will be required with potential contractors, regarding issues such as risk allocation and payment mechanisms. In addition, a bespoke contract will need to be written, as standard contracts for DBFO contracts do not exist. This means that the tender period for a DBFO type of contract is likely to be the longer than for a DBO or traditional contract.

For a DBO and traditional-type of arrangement, the preparation of documentation is far more straightforward than for a DBFO contract, and negotiations with contractors, whether they be to discuss construction or operational issues, will be simpler.

CONCLUSIONS

The conclusions of the report are:

- that all of the strategic treatment options considered are feasible;
- that the use of both the DBO and DBFO forms of contract would achieve the Agency's objective of reverting to the role of regulator;
- the benefits of using a DBO or DBFO contract is dependent on the potential costs to the Agency of retaining the risks of a traditional contract;
- that an option which relieves the Agency of its responsibilities for treating the minewater may not also provide the best value solution;
- that the Agency has a series of decisions to make after the publication of the main report, which are:
  - the water quality standard to adopt for any future treatment;
  - whether to actively pursue the use of private or public finance to construct any new facility, following a full business case;
  - whether to pursue a best value option, even if this results in retaining responsibility;
- that any future treatment option must involve the co-operation of the current mine owners (SCP), or any successors, to a significant degree to provide value for money to the Agency.

APPENDIX C

Technical Summary of Final Catchment Modelling Report

INTRODUCTION

The abandonment of the Wheal Jane mine, in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and, therefore, limit the impact of the release on the environment.

Emergency pumping and treatment measures have been progressively developed to form the existing treatment system and will remain in operation until a long-term solution is implemented. This treatment process relies on the Clemows Valley Tailings Dam for disposal of treated minewater sludge.

An initial study, completed in May 1995 (KP, 1995, Wheal Jane Minewater ...) considered a range of active and passive minewater treatment options. The present study built on that work and has the objective of formulating the long-term treatment solution.

This report considers the catchment modelling aspects and forms part of the suite of reports for the study. The Carnon River catchment and the Fal Estuary, both of which are covered under the catchment modelling brief, are shown in Figure C1.

The key deliverables arising from the modelling work are predictions of the following:

- the consequences of ceasing all minewater treatment in terms of water quality and the potential for discolouration in the Carnon River, Restronguet Creek and Carrick Roads;
- the extent of minewater treatment required to achieve compliance with the Water Quality Objectives (WQOs) set by the Agency for the Carnon River and the Fal Estuary;
- the impact of a range of treatment options on water quality and the potential extent of discolouration in the Carnon River, Restronguet Creek and Carrick Roads.

In order to facilitate the above, the modelling work has had to take account of the following:

- the effects of ongoing decay in minewater metal concentrations;
- surface/groundwater interaction and the response of both to meteorological conditions;
- the potential effects of other sources of contamination (for example, sediment);
- changes in water quality due to attenuation and other chemical processes;
- a range of treatment pumping rates of Wheal Jane minewater;
- treatment of other point sources, for example County Adit; and
- elimination or treatment of other diffuse sources of contamination.

APPROACH

The development of a suite of linked models capable of taking account of all these factors is an extremely complex technical and logistical task. The 'model' described in this report comprises

- the integration of seven rainfall-run-off models;

- six hydrochemical models, each made up of separate models for the behaviour of six metals (iron, copper, cadmium, zinc, manganese, arsenic) and pH;
- a MIKE11 hydrodynamic model of the Carnon River and Restronguet Creek;
- a MIKE21 hydrodynamic/advection-dispersion model of Restronguet Creek and the Fal Estuary.

The development of linked models of the Carnon catchment and the Fal Estuary has essentially involved an iterative progression through five stages. These are discussed in turn below and the process is illustrated in Figure C2. The scope of work involved at each stage has varied with the type of model being constructed, something which will generally be apparent in the more detailed sections on model development (see Section 3 through to Section 7).

All models have been calibrated and validated against monitoring data from the catchment. For the rainfall-runoff and hydrochemical models, calibration was generally carried out against 1995 and earlier data and validation against 1996 and early 1997 data. The MIKE 11 and MIKE 21 models of the river and estuary, respectively, were calibrated and validated using various sources of data, including flow measurements, dye and drogue tests, current meter readings and tidal elevations. The Integrated Model of the Carnon catchment has also been validated against monitoring data for the Agency statutory monitoring site at Devoran Bridge for 1993 to 1996.

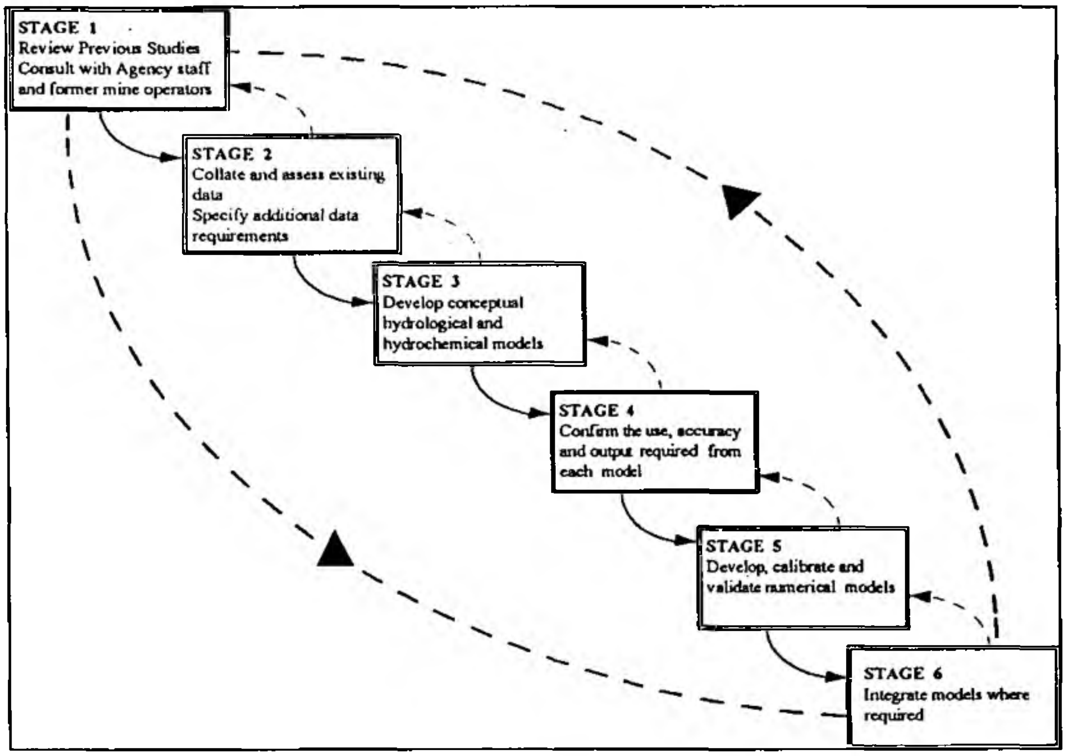


Figure C2 : Stages Involved in the Development of an Integrated Water Quality Model of the Carnon River Catchment

APPLICATION OF THE MODELS

Using the Integrated Model of the Carnon catchment and the Estuary Model, the impact of minewater treatment scenarios on the compliance or failure of a range of WQOs for the Carnon River and Fal Estuary has been assessed.

As set out in the Appraisal and Selection of Long Term Treatment Option report (KP, 1998), logical deduction and demonstration were used to select a priority set of treatment scenarios from a more comprehensive range of treatment alternatives. The treatment scenarios and sensitivity cases, which were identified through this process, and have been assessed using the Integrated Model, are:

1. **No Treatment**

   1a - No Treatment 'worst case' - in which the Wheal Jane mine discharge was based on the validated hydrochemical model for No.2 Shaft water quality (which is more concentrated for most contaminants than a gravity-fed discharge from Nangiles Adit);

   1b - No Treatment 'best estimate' - in which the Wheal Jane mine discharge was based on the validated hydrochemical model for Nangiles Adit (slightly better quality than No.2 Shaft for most contaminants);

   1c - No Treatment 'sensitivity case' - in which the Wheal Jane mine discharge was based on 10% of No.2 Shaft concentrations to indicate, as an extreme end-member case, the consequences of an order of magnitude improvement in discharge quality;

2 **Treatment of Wheal Jane with six pumps** - in which predicted discharges from Wheal Jane up to the capacity of six pumps (taken as 0.33 m^3/s) were treated to oxidation and chemical neutralisation (OCN) expected effluent quality; and the remainder discharged from Nangiles Adit at a water quality based on the Nangiles Adit hydrochemical model;

3 **Full Treatment of Wheal Jane** - in which the entire volume of predicted discharges from Wheal Jane were treated and discharged via Clemows Stream at a water quality based on OCN expected effluent quality;

4 **Full Treatment of Wheal Jane and County Adit** - in which loadings from these two main point discharges was treated and discharged via Clemows Stream at a water quality based on biochemical sulphidisation (BCS) expected effluent quality;

5 **Treatment of All Sources down to Bissoe** - in which the Carnon River, including discharges from County Adit, Wheal Jane, Twelveheads, Hicks Mill Stream and diffuse sources upstream of Bissoe, was treated and discharged via Clemows Stream at a water quality based on BCS expected effluent quality.

The results of the model simulations for these treatment options have been assessed against a number of different WQOs for the Carnon River (at Devoran Bridge) and in the Fal Estuary. The seven WQOs detailed parameter thresholds are provided in Section 6 of this report, Section 4 of the Appraisal and Selection of Long Term Treatment Option Report (KP, 1998) and summarised below (Table C.1). One of the objectives was based on 'No Treatment' so is not included in the tables.

Table C.1 : Summary of WQOs for the Carnon River at Devoran Bridge and the Fal Estuary

Water Quality Objective	Comments
No Deterioration	Based on Devoran Bridge water quality for 1993–94
No Discolouration	Discolouration in the Fal Estuary related to iron loading thresholds at Devoran Bridge
North Sea Declaration Commitments	
EC Dangerous Substances Directive - Fresh Water Standards	Taken from DoE Circular 7/89
EC Dangerous Substances Directive - Salt Water Standards	Taken from DoE Circular 7/89
Protection of Estuarine Biology	Taken from Implementation of the EC Shellfish Waters Directive

RESULTS AND CONCLUSIONS

In the course of model development considerable insight has been gained into the hydrological and hydrochemical processes operating in the Carnon catchment. The key conclusions arising from the various contributing studies are summarised below. Following this, the implications of different minewater treatment options on WQOs for the Carnon River and Fal Estuary are summarised. Finally, key conclusions arising from an assessment of the potential for acid mine drainage (AMD) prevention in the catchment are summarised.

Hydrology and Hydrogeology

- Taking Clemows Stream discharge, which includes the abstraction from No.2 Shaft, together with the discharge at Bissoe Gauging Station (GS), it is clear that the effective catchment upstream of Bissoe Bridge is significantly larger than the topographic catchment, possibly by as much as 40%. The most likely source of this additional water is through sub-surface inflows to the mineworkings along the WSW-ENE trending faults, which traverse the catchment.
- Net inflows to County Adit from outside the surface catchment area upstream of Twelveheads GS are negligible. It can, therefore, be assumed that the catchment area for County Adit GS and Twelveheads GS is approximately the same, with flows in the adit being derived primarily from baseflow and intercepted infiltration in the Wheal Maid Stream and Poldice Stream catchments. Based on a comparison of measured discharges with effective rainfall, approximately 35-40% of the effective rainfall on this sub-catchment discharges via Twelveheads GS, with the remaining 60-65% discharging via County Adit.
- Rainfall-runoff models provide a good representation of the behaviour of the Carnon catchment. Models of the sub-catchments generally predict stream flows to within a few percent. In addition, by using combinations of the models it is possible to achieve good predictions of minewater discharges both from County Adit and the Wheal Jane mine system.

Hydrochemisty and Water Quality

- Short term controls on discharges from the Wheal Jane mine and County Adit correlate with rainfall summed over the previous 28 days. This suggests that near-surface processes, probably relating to flushing of contamination from the unsaturated zone, are the primary controls on contaminant loadings. In addition to the direct relationship with time-lagged rainfall, contaminant concentrations in Wheal Jane are controlled by fluctuations of minewater level, and tend to increase when minewater levels rise. County Adit discharges are also subject to additional controls, the most important of which is the resuspension of ochre from the adit walls during initial high winter flows, and consequent high iron and arsenic loadings.
- During minewater recovery, both the Wheal Jane mine and County Adit were subject to marked deteriorations in water quality. Water quality deterioration in both systems was followed by an initial decline in contaminant concentrations which was quite rapid, but which was beginning to stabilise 3-4 years after recovery (that is, by 1995/96). This initial decline is thought to be controlled by the replacement, dilution and reaction of the heavily contaminated minewaters generated during minewater recovery. This rapid decline has now given way to a much slower decline (tens to hundreds of years), which is thought to relate to depletion of metals in overburden and near-surface workings. Statistical evaluation of data to April 1997 for the Wheal Jane mine and County Adit indicates that by 1999 all metal concentrations are likely to be within 1% of their long-term (tens to hundreds of years) values.
- Hydrochemical models of adit discharges, stream discharges and diffuse sources provide a good representation of the behaviour of the Carnon catchment. The models, which are based on a combined mechanistic and empirical approach, predict total and dissolved concentrations for six contaminants and pH on a daily basis for all significant discharges. Models of the primary minewater discharges generally predict annual average concentrations to within 10%.

Impact of Minewater Treatment on Water Quality in the Carnon River

The Integrated Model of the Carnon catchment has been validated against monitoring data from Devoran Bridge for 1993-96 and shown to provide a good representation of the response of the catchment to meteorological effects and variable pumping from the Wheal Jane mine. The simulated response of the catchment to a long-term (35 year) meteorological record and a range of treatment options have then been predicted with this model, which predicts daily flows and metal loadings to the Carnon River and the resulting water quality at Devoran Bridge. Statistical analysis of the results has been carried out to permit comparison of the simulations with WQOs. The results of the long-term (35 year) simulations of the catchment are described below.

No Treatment Option

The No Treatment option was investigated using three sensitivity cases based on a range of possible discharge qualities from the Wheal Jane mine. The implications of each of the cases for WQOs at Devoran Bridge is effectively the same: the No Deterioration, North Sea Declaration Commitments and EC DS Directive - Fresh Water Standards would all be failed for most or all years of the 35 year simulations.

Treatment of the Wheal Jane Mine

Two Wheal Jane treatment options were investigated: the first based on treatment to a maximum capacity of six pumps (0.33 m^3/s) and the second based on full treatment in which no adit discharges were permitted. The implications of the two cases for WQOs at Devoran Bridge is the same: compliance is achieved for the No Deterioration and North Sea Directive WQOs, but the river would fail the EC DS Directive - Fresh Water Standards.

Treatment of the Wheal Jane Mine and County Adit

This option is based on full treatment of these two discharges. The results indicate that no benefits with regard to WQOs are achieved by including County Adit in the treatment. Although there is some improvement in water quality, the EC DS Directive - Fresh Water Standards is still failed for a number of metals (zinc, copper and cadmium).

Treatment of All Sources Down to Bissoe

This option assumes that all discharges to the Carnon River upstream of Bissoe Bridge are treated and that metal loadings at Devoran Bridge comprise only the treated water quality and diffuse sources between Bissoe and Devoran Bridges. The results demonstrate a further improvement in water quality, but indicate that it is likely that the EC DS Directive - Fresh Water Standards would still be failed for cadmium, copper and, if hardness in the river falls below 250 mg/l, also for zinc.

In summary, all No Treatment scenarios are predicted to lead to failure of all WQOs for the Carnon River. Conversely, expanding the scope of treatment from the existing treatment of the Wheal Jane minewater is unlikely to achieve further objectives (see Table C.2).

Table C.2 : Simulated Implication of Minewater Treatment Options on WQOs at Devoran Bridge

Treatment Option	WQO			
	No Deterioration	North Sea Declaration Commitments	EC DS Directive – Fresh Water Standards (hardness >250 mg/l)	EC DS Directive - Fresh Water Standards (hardness 50-100 mg/l)
No Treatment (worst case)	Fail	Fail	Fail	Fail
No Treatment (best estimate)	Fail	Fail	Fail	Fail
No Treatment (sensitivity)	Fail for As	Fail	Fail	Fail
Treatment of Wheal Jane (with six pumps)	Comply	Comply	Fail	Fail
Full Treatment of Wheal Jane	Comply	Comply	Fail	Fail
Full Treatment of Wheal Jane and County Adit	Comply	Comply	Fail for Zn, Cu, Cd	Fail for Zn, Cu, Cd
Treatment of All Sources down to Bissoe	Comply	Comply	Fail for Cd (a.a) Cu (95%)	Fail for Cd Zn (a.a), Cu, Zn(95%)

(a.a) = annual average concentrations.
(95%) = 95 percentile annual concentrations.

It was concluded that the EC DS Directive – Fresh Water Standards WQO could only be met by treating all the water at Devoran to an effluent quality equal to the WQO concentrations. This would achieve technical compliance at the monitoring station, but would not improve the Carnon River upstream.

Prediction of Discolouration and Water Quality in the Fal Estuary

Discolouration in the Fal Estuary

- An evaluation of the relationship between the total iron loading discharged at Devoran Bridge and observations of discolouration in Restronguet Creek has been carried out. Discolouration has generally occurred when the iron loading at Devoran Bridge has been in the order of 2 000-4 000 kg/day. Using this as a basis, the occurrence of discolouration in the Creek can be predicted with some degree of confidence for different treatment options, based on the results of the 35 year Carnon River simulations described above.
- It is more difficult to assign thresholds for discolouration in Carrick Roads because the only reported discolouration is related to the initial incident when iron loadings at Devoran were in the order of 20 000-30 000 kg/day. There are no intermediate cases.
- The results of the long-term simulations indicate that for the No Treatment scenarios (worst case and best estimate) discolouration would be semi-continuous in Restronguet Creek for 3 to 8 months each year and would probably affect north-western areas of Carrick Roads.
- For the No Treatment scenario (sensitivity case), based on a discharge at 10% of predicted No.2 Shaft concentrations, and the Treatment of Wheal Jane mine with the six pumps options, discolouration thresholds are exceeded for short periods (in the order of a week or two). Recent experience (the winter of 1997/98) suggests that such short-lived events have not led to discolouration complaints.
- For all remaining treatment scenarios, that is, full treatment of Wheal Jane mine, Treatment of Wheal Jane mine plus County Adit and Treatment of the Carnon River at Bissoe Bridge, no discolouration is predicted.

Prediction of Water Quality in the Estuary

A two-dimensional (2D) model of Restronguet Creek and the Fal Estuary, which simulates hydrodynamics and advection-dispersion, has been developed. The output used from the model is a series of contour maps showing mean, maximum and minimum conversion factors for a range of solute 'loss' constants (L_{90}). These represent the time taken for 90% of a given discharge concentration from the Carnon River to be lost from the water column, through precipitation and deposition. At any given point in the estuary, the conversion factor shown on the contour maps represents the combined effects of dilution and this loss from the water column on the concentration of a metal species discharged into Restronguet Creek from the Carnon River.

Based on an evaluation of estuary water quality data from 1994 to 1996, it is evident that mean annual average concentrations in the estuary can be simulated well in the proximal areas of the estuary using this approach. However, in more distal parts of the estuary, and across much of Carrick Roads, there is evidence of a residual background concentration. This residual concentration may relate to a combination of background loadings from influent rivers other than the Carnon River, to sediment interactions and to non-uniform mixing caused by stratification in the estuary, which is not accounted for in the 2D model. These residual concentrations are, in any case, lower than the standards set for salt water under the EC Dangerous Substances Directive – Salt Water Standards for all metals and lower than the standards set under the EC Shellfish Waters Directive for all metals except zinc. This means that model predictions can be used to provide a reasonable spatial representation of likely failure or compliance with the WQOs set for the estuary under various treatment scenarios, but may only be within an order of magnitude at best when predicting actual concentrations.

With regard to WQOs, monitoring data over recent years indicate that the EC DS Directive – Salt water Standards and the Shellfish Waters Directive are being breached within and close to the mouth of Restronguet Creek for a number of contaminants, particularly zinc and copper. Simulation results for the Wheal Jane Treatment with six pumps are in broad agreement with this situation and the results for the Full Treatment of Wheal Jane indicate that little or no improvement would be achieved (see Table C.3). For the higher specification treatment options, based on Treatment of Wheal Jane plus County Adit and Treatment of All Sources down to Bissoe, the water quality in the estuary improves, but failures for both the EC DS Directive - Salt Water Standards and the EC Shellfish Waters Directive are predicted to occur both inside and close to the mouth of Restronguet Creek.

Table C.3 : Simulated Implication of Minewater Treatment Options on WQOs in Restronguet Creek and Carrick Roads

Treatment Option	WQO		
	No Discolouration	EC DS Directive - Salt Water Standards	EC Shellfish Directive
No Treatment (worst case)	Fail	Fail	Fail
No Treatment (best estimate)	Fail	Fail	Fail
No Treatment (sensitivity)	Fail Occasionally	Fail	Fail
Treatment of Wheal Jane (with six pumps)	Possibly fail Occasionally?	Fail Zn, Cu	Fail Zn, Cu
Full Treatment of Wheal Jane	Possibly fail Occasionally?	Fail Zn, Cu	Fail Zn, Cu
Full Treatment of Wheal Jane and County Adit	Comply	Fail Zn, Cu	Fail Zn, Cu
Treatment of all Sources down to Bissoe	Comply	Fail Zn, Cu	Fail Zn, Cu

Compliance/failure for EC DS Directive - Salt Water Standards is based on annual average and 95 percentile concentrations.

Compliance/failure for EC Shellfish Waters Directive is based on annual maxima concentrations.

The more stringent WQO for the estuary could be met by treating all water at Devoran to an effluent quality equal to the WQO concentrations.

Summary of the Implications of Treatment Options on WQOs

Combining the results for the river and estuary modelling, the overall implications of the various treatment options are summarised below.

No Treatment

If treatment is ceased all three of the cases modelled imply that all WQOs for the Carnon River will be breached. In estuarine waters, the EC DS Directive - Salt Water Standards and the EC Shellfish Waters Directive will be breached and discolouration will occur probably for several months each year and is likely to extend into the northern area of Carrick Roads.

Treatment of Wheal Jane (Full Treatment and Treatment with six pumps)

These treatment strategies achieve the No Deterioration and North Sea Declaration Commitments for the Carnon River, but give rise to failure of the EC DS Directive - Fresh Water Standards. In estuarine waters, the EC DS Directive - Salt Water Standards and the EC Shellfish Waters Directive will be breached. Discolouration may occur for limited periods (a few days or possibly a few weeks) in some years, but is likely to be restricted to Restronguet Creek.

Treatment of Wheal Jane and County Adit

Modelling studies predict that although including County Adit Treatment causes an improvement in water quality in the Carnon River, no additional WQOs are achieved compared with Treatment of Wheal Jane alone.

Treatment of All Sources down to Bissoe

Inputs to the Carnon River for this treatment option comprise diffuse sources downstream of Bissoe and treated water quality based on expected effluent water quality for BCS. Based on these inputs, the Carnon River is still predicted to fail the EC DS Directive - Fresh Water Standards for copper zinc and cadmium. In estuarine waters, failure of the EC DS Directive - Salt Water Standards and the EC Shellfish Waters Directive is predicted for zinc and copper. No discolouration is predicted to occur.

In order to meet the Higher Order WQO, the Carnon River would have to be treated at Devoran to an effluent quality equal to the WQO concentrations.

Assessment of the Potential for Acid Mine Drainage Prevention

Based on the improved understanding of the catchment provided by the modelling studies, the potential for AMD prevention and control measures at source have been assessed.

In the Carnon River catchment, the Wheal Jane mine is the main potential cause of contamination. The mine is extensively interconnected to other mine systems via horizontal drives and high permeability shear zones. It receives much of its recharge from beyond the surface catchment of the Carnon River. Minewater quality is strongly influenced by near-surface processes, primarily the leaching of contamination from the unsaturated zone. Passive control measures would require regional sealing of recharge routes to the both inside and outside the catchment, and are considered to be impractical. It is conceivable that localised sealing may reduce the volume of water to be treated from Wheal Jane, however this is unlikely to cause any reduction in metal concentrations.

Contaminant concentrations at No.2 Shaft during recovery were up to an order of magnitude higher than for other locations in the interconnected mineworkings. In addition, there are differences in contaminant concentrations between No.2 Shaft and discharges from Nangiles and Jane's Adits.

There is, therefore, a remote possibility that by pumping from an alternative location, improvements in pumped minewater quality could be achieved.

Whilst the discharge from Wheal Jane is being treated, the County Adit discharge is the major cause of failure to comply with the EC DS Directive - Fresh Water Standards at Devoran Bridge, particularly for copper, which fails by an order of magnitude. However, for model simulations based on full treatment of County Adit (see Section 6), these objectives are still failed for a number of metals (copper, cadmium and zinc). Therefore, the likelihood is that the partial improvement in minewater discharges from County Adit, which might be achieved by passive control measures, would not have any benefits for WQOs.

Contamination from diffuse sources is considered unlikely to cause a breach of the No Discolouration, No Deterioration or North Sea Directive WQOs. The loadings evaluation suggests that, excluding discharges from Nangiles Adit, the major source of arsenic loadings at Bissoe GS and at Devoran Bridge is diffuse sources. However, diffuse source arsenic contamination appears to be very close to being within EC DS Directive - Fresh Water Standards limits at Devoran Bridge. Based on this, measures to prevent diffuse source contamination are a low priority, in terms of achieving additional WQOs.

OVERALL SUMMARY

The central findings of the catchment modelling study are as follows:

1. There appears to be little scope remaining for further significant improvement in water quality discharged from the Wheal Jane mine system in the absence of treatment. The implication of this is that, based on minewater quality alone, the treatment strategy implemented on completion of this project will require continued implementation for at least 50 to 100 years and possibly considerably longer.

2. A strategy of No Treatment would result in serious failures of all five numerically based WQOs for the Carnon River and Fal Estuary and would lead to significant discolouration in the river, Restronguet Creek and parts of Carrick Roads for several months each year.

3. The current treatment strategy is capable of achieving compliance with three of the WQOs for the Carnon River (No Deterioration, No Discolouration and the North Sea Declaration Commitments relating to zinc). However, it is highly unlikely that any more extensive treatment, which falls short of treating the entire river at Devoran Bridge could ensure compliance with the remaining Higher Order WQOs.

APPENDIX D

Technical Summary of Final Biological Assessment Report

TECHNICAL SUMMARY

Introduction

The abandonment of the Wheal Jane mine, in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and therefore limit the impact of the release on the environment.

Emergency pumping and treatment measures have been progressively developed to form the existing treatment system and will remain in operation until a long-term solution is implemented. This treatment process relies on the Clemows Valley Tailings Dam for disposal of treated minewater sludge.

An initial study, completed in May 1995 (Knight Piésold Wheal Jane Minewater Study Environment Appraisal and treatment Strategy, May 1995), considered a range of active and passive minewater treatment options. The present study builds on that work and has the objective of formulating the long-term treatment solution.

This report considers the biological aspects and forms part of the suite of reports for the study.

1. The report provides an assessment of the present biological status of the Carnon Catchment and the Fal Estuary and the significance of the minewater discharges on the floral and faunal communities in the Carnon River and Fal Estuary.

2. The flora and fauna of the Carnon River itself are greatly impoverished and of little conservation value. On the other hand, the Fal estuary system is of high conservation, recreational and economic value and the major emphasis of the biological work was therefore placed on the estuary.

3. The existing relationships between the biota and metal concentrations in the water and sediments in the Fal system were established, and also some wider comparisons with other estuaries in South West Britain were made, in order that predictions concerning the effects of various treatment options can be made by extrapolation.

4. Literature data and some more recent data collected by the Plymouth Marine Laboratory (PML) were used to provide a qualitative assessment of treatment options.

Historical significance of minewater discharges on biological communities

The Carnon River

1. The Carnon river is almost devoid of macroscopic plants in the stream channels, except at Chacewater which is well upstream of the Wheal Jane mine complex. The BMWP (Biological Monitoring Working Party) scores, based on the relative sensitivities of the recorded invertebrate taxa to organic pollution, are exceptionally low. However, the average BMWP score per taxon (ASPT) is relatively high, suggesting that it is not organic pollution but toxic contaminants which are responsible for the absence of biota.

2. The Carnon River is devoid of fish, although other rivers entering Restronguet Creek such as the Kennall support brown trout fisheries.

The Fal estuary and its tributaries

1. Over the centuries a marked gradient of sediment metal concentrations has built up in the Fal estuary system and sediments in otherwise similar creeks in different parts of the system have concentrations of heavy metals (including copper, zinc, arsenic, cadmium, iron) which differ by orders of magnitude.

2. Metal concentrations have been elevated in the Fal for such a long period that events in the estuary cannot be viewed as simple pollution/recovery incidents. A number of metals are involved, and concentrations of different metals are correlated, making it difficult to ascertain which metals are responsible for observed effects. Chemical and biological interactions, and the induction of metal tolerance, modify the potential toxicity of these metals. Nevertheless, heavy metal concentrations in the sediments correlate most strongly with the composition of the invertebrate communities and are therefore the most likely causal agents.

Carrick Roads

The effects of heavy metal discharge from the mouth of Restronguet Creek are comparatively small, although communities are generally impoverished over most of the area, and metal contamination, the presence of china clay wastes, and TBT contamination may be at least in part responsible for this impoverishment.

Biology of the Carnon River and Fal estuary

Biological communities

1. *Macrobenthos.* Analysis of PML's survey data shows that Restronguet Creek has a distinct community composition compared with Mylor, Pill, St Just and Percuil creeks, which are not ordered in a pattern that is consistent with decreasing metal concentrations. This suggests that other factors are influencing the community structure of macrofauna in these creeks. Neither the sediment metal concentrations or the macrofaunal community in Restronguet Creek altered significantly between November 1991 and March 1992 following the overspill of untreated minewater from the Wheal Jane mine in January 1992. Compared with other less contaminated estuarine systems in SW Britain, the Fal has a very low abundance of the crustacean *Corophium volutator* and an absence of *Cyathura carinata*, whilst certain small annelid worms are more abundant in the Fal than other estuaries. Metal pollution is clearly implicated as the cause of these differences.

2. *Meiobenthos.* Analyses of PML's survey data show a gradation in nematode community structure consistent with increasing metal concentrations, but copepods do not present a pattern that is so readily related to the metal gradient. Changes after the 1992 overspill could not be linked unequivocally to the discharge from the Wheal Jane mine.

3. *Phytoplankton.* "Red tides", caused by the toxic strain of *Alexandrium tamarense,* occurred for the first time in the Fal in 1995. The high heavy metal concentrations in the Fal have been implicated as causal agents of these blooms, but this is currently under scientific debate.

4. *Seaweeds.* Some rare and important algae are known to occur in the maerl beds in the St Mawes area.

5. *Maerl.* The maerl bed in the Fal is the only extensive living bed in southern Britain. Many of the species typically associated with these beds are lower in abundance than might be expected, probably due to the presence of larger quantities of mud and silt in the bed. There is no evidence that metal contamination is responsible for the low abundances of certain species.

6. *Fish.* 90 species of fish have been recorded from the Fal estuary. Many of these are rare and found mainly in the outer and deeper parts of the estuary and in Falmouth Bay. It is unlikely that any reduction in metal concentrations will have any significant effect on overall fish species diversity.

7. *Bass.* Parts of the Fal are designated as a bass nursery ground. There is no direct evidence that moderate levels of metal contamination are detrimental to young bass, although the Fal may have reduced levels of O-group recruitment compared with other south west estuaries. O-group bass feed on benthic invertebrates and amelioration of metal concentrations may see an increase in potential prey and a consequent extension of the nursery areas.

8. *Impacts on migratory species such as salmon.* The Fal does not now support a salmon fishery, but sea trout are present in several tributary rivers and can apparently tolerate the polluted conditions. There is no run of sea trout through to the Carnon River. Reduction in metal concentrations is likely to improve the status of both these species in the Fal.

9. *Birds.* The Fal estuary, considered as a whole, supports no internationally important populations of birds, but does support a nationally important population of Black-tailed Godwit (a Biodiversity long-list species). The 1992 overspill had no appreciable effect on numbers of wildfowl and waders.

10. *Swans.* The increasing mortalities and occurrences of sick swans in the Fal between the Autumn of 1992 and 1995 have been attributed largely to heavy metal toxicity but the evidence remains equivocal. Other possible causal agents are paralytic shellfish poisoning (PSP) and tri-butyl tin (TBT).

11. *Impacts on important (rare) species.* By their very nature, rare species such as Couch's goby and certain seaweeds associated with the maerl beds are difficult to survey. The fact that they are present at all means that they can tolerate the present metal concentrations in the system, but it might be that reductions in these concentrations could favour more metal-sensitive competitors.

Bioaccumulation

1. Oysters *Ostrea edulis.* The Fal Estuary supports a number of commercial shellfish beds, primarily for native oysters, and Carrick Roads represents one of the few commercially exploitable fisheries for this species in the UK. Mechanisms of tolerance to heavy metal toxicity in the Fal were reviewed. The presence of more or less consistently high copper concentrations in Fal oysters since records began contrasts with the more distinctive patterns of copper-mining activity. The impact of the Wheal Jane discharge in 1992 had little effect on copper concentrations in populations present in the Carrick Roads off the mouth of Restronguet Creek. Likewise, zinc in

tissues has not changed systematically or significantly over the period for which data are available.

The 1992 discharge gave no additional cause for concern with regard to the consumption of oysters. The gradients and trends in contamination reflected by oysters are not as marked as expected given the environmental (water and sediment) loadings. Detoxification systems are presumably the explanation, and it seems unlikely that the treatment strategy options at Wheal Jane will have any impact on oyster populations and only small effects on their associated metal burdens.

2. Cockles *Cerastoderma edule* are fairly widely distributed throughout the Fal Estuary, but are rarely found in Restronguet Creek. Although the species has previously been collected at several sites in Mylor Creek with copper concentrations between 10 and 20 times background, in most other creeks copper concentrations in *C.edule* are not usually significantly elevated. Zinc concentrations in Mylor and Restronguet cockles exceed background by up to three-fold suggesting regulation of body burdens has broken down, although it is the accumulation of copper which is thought to be most damaging to Restronguet cockles. Moribund cockles were found on the surface of the sand flats at Restronguet Passage immediately after the Wheal Jane overspill, caused by the massive increase in dissolved metals, which may have taken it's toll before steady-state could be achieved in the animals.

3. *Other shellfish species.* Metal concentrations in Fal mussels are often in the upper part of the range for other areas in the UK, but are not exceptional. This may reflect their absence from the most contaminated parts of the system. Nevertheless most metals are enhanced by a factor of 5-10 relative to baseline values. Winkles (*Littorina littorea*) appear to be more tolerant and have a wider distribution, but are not found in Restronguet Creek. Zinc and copper in winkles are at the upper end of the range found in the UK. Flat periwinkles *Littorina obtusata* (*+mariae*) are somewhat more tolerant and are found inside Restronguet Creek as far as Pandora: this distribution and tolerance are reflected in extremely high body burdens of copper and zinc.

4. Seaweed *Fucus vesiculosus.* Algae are potentially good indicators of water column metal concentrations, but there are problems of interpretation due to the presence of metal mixtures. In the case of Restronguet Creek, cadmium bioaccumulation is less of a problem than expected because of the presence of other metals, particularly zinc. *F. vesiculosus* has a strong affinity for copper and lead, and accumulation is proportional to the external medium, with little suppression by manganese or zinc. More detailed and recent estimates of concentration factors were obtained in view of the observed variability, and helped in assessing the consequences of different water treatment strategies for bioaccumulation in algae. Copper, iron and, to a lesser extent, zinc, arsenic, manganese and lead concentrations in macroalgae increase in progression from Carrick Roads (and other creeks in the Fal system) towards the mouth of Restronguet Creek, and subsequently upstream in the Creek towards its upstream limit of distribution of the plants. Surprisingly, this does not apply to cadmium, despite the fact that the major input of cadmium is the Carnon River.

   Data for metals in *Fucus vesiculosus* collected in Restronguet Creek over more than twenty years show no evidence of long-term change during the period prior to abandonment of Wheal Jane. The major influx of mine water in 1992 had a significant impact on zinc and iron concentrations in *Fucus*, much less so for copper, cadmium and manganese (perhaps due to competition).

Concentrations in algae from the August 1997 survey appear have returned to pre-flooding values though this return to 'steady state' has taken several years to achieve.

5. *Distribution of macrofauna.* The conspicuous absence of bivalve and gastropod molluscs from highly metal-contaminated sites (Restronguet Creek) is a consequence of the long history of metal mining in that area. Copper and zinc are believed to act by inhibiting the settlement of juvenile bivalves, including *Scrobicularia plana, Cerastoderma edule* and *Mytilus edulis*. Certain polychaete species, however, have enhanced metal tolerance.

Estuarine Chemistry

This section synthesises the current interpretation of some of the ongoing work undertaken under the Additional Services Field Studies. The main objective is to improve the overall assessment of biological impact by investigating the behaviour and fate of metals in Restronguet Creek, and how they partition between sediments and water.
This work includes:

1. Determination of the concentrations of metals in the water column of Restronguet Creek (baseline review) and their behaviour throughout the estuarine system, at different salinities and tidal states.

2. Provision of recent data on the metal composition of estuarine sediments in Restronguet Creek and other sub-components of the Fal system, together with allied contemporary biological data (community impact and bioaccumulation)

3. Determination of the relative retention of metals in sediments of Restronguet Creek and potential for release, from water column studies. Field-based derivation of Kd - partition coefficients - essentially the ratio of; metal in sediment:overlying water.

4. Simple modelling of partitioning behaviour of metals between sediment and water, using data from water column studies, to show how this affects distributions and fate within the estuary (and hence the biota). Extrapolation to predict sediment and water quality under different treatment options. This report outlines how these predictions were made, and uses the results to predict the outcomes of the different treatment options on the biota.

Effect of minewater treatment

Various Treatment Scenarios were evaluated as part of the Wheal Jane Minewater project. From these, three Treatment Options were selected to meet the Water Quality Objectives. The three Treatment Options form the framework upon which the assessment of the biological effects of minewater treatment are based. They are:

- no treatment;
- six pumps at Wheal Jane with treatment by oxidation and chemical neutralisation (OCN);
- All Sources in the Carnon River down to Devoran with treatment by ion exchange (IEX)

For each of these scenarios, predictions of the consequences in terms of changes in biological communities, populations of key species, and bioaccumulation were made as far as is possible on the basis of the available evidence. These may be summarised as follows:

1. *No treatment.* Increases in iron could have effects on biological communities in Restronguet Creek due to changes in the nature of the sediment, and Carrick Roads by increasing

sedimentation; increase in zinc in sediments without comparable increase in copper is unlikely to lead to significant changes. At worst concentrations of arsenic, copper, zinc and iron in oysters might double at sites nearest Restronguet Creek, but there is unlikely to be any significant change in cadmium. In *Fucus* small increases in zinc and arsenic (less than a factor of two) are predicted, with no significant change in other metals. Values for all metals in *Fucus* remain within current range for Restronguet. This option is not likely to have a major additional impact on macroalgae or on intake of metals via the diet in algal-feeding birds e.g. swans.

2. *Six Pumps.* Biological communities remain as they are. In oysters, tissue concentrations of copper, and to a lesser extent, zinc are of most concern because of their relatively high values (up to 40 and 6 times those found in relatively uncontaminated sites, respectively), though zinc is inherently high, even in control oysters. Arsenic, cadmium and lead also tend to be enhanced in Fal oysters (six, four and eight times baseline values, respectively) but are not considered to be toxicologically critical. The status quo to be maintained in terms of metal concentrations and distributions in macroalgae.

3. *All Sources.* There is a predicted increase in numbers of small worms in Restronguet Creek, where community composition comes to resemble that presently in Mylor Creek, but no other major changes are expected. Copper concentrations in oysters might be reduced by two-fold if the standard at Devoran Bridge of 28 μg Cu l^{-1} is achieved, but decreases in cadmium, iron and zinc would be relatively small, if they occurred at all, and there would be no change in arsenic. A slight drop (~25%) in copper and zinc concentrations in *Fucus* is likely to occur, but copper would remain within the current range for Restronguet, zinc just below, with no change for iron, arsenic or cadmium.

Conclusions and Recommendations

The study indicates no changes in the biological communities since 1991, prior to the uncontrolled release of metal laden minewater in 1992, and the status quo of flora and fauna has been maintained since the inception of the existing minewater treatment system.

The Biological Assessment predicted the effect of the Treatment Options on sediment concentrations and biological communities and populations. There will be changes in water quality and sediment concentration as a result of treatment but these are not expected to cause significant biological changes as indicated below:

- No Treatment would lead to a slight deterioration in terms of changes in biological communities and bioaccumulation of some metals though these are unlikely to prove much more detrimental than the status quo.
- Six Pumps treatment is expected to maintain the status quo.
- All Sources treatment might achieve some reduction in bioaccumulation of copper and zinc particularly within Restronguet Creek.

APPENDIX E

Technical Summary of Active Treatment Outline Design Report

TECHNICAL SUMMARY

INTRODUCTION

The abandonment of the Wheal Jane mine in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and therefore limit the impact of the release on the environment.

Knight Piésold were commissioned by the Agency in June 1996 as lead consultant to undertake a number of study briefs which together comprise the Wheal Jane Minewater Project Consultancy Studies 1996 - 1999.

Active Treatment Outline Design, one of these study briefs, is an appraisal of the alternative technologies suitable for the treatment of Wheal Jane minewater and other minewater sources in order to achieve certain Water Quality Objectives in the Carnon River at Devoran Bridge.

Earlier studies on Active Treatment examined the available treatment routes for processing minewater, focussing in particular on effluent quality, process reliability and maturity, residue handling and the whole life cost. The objectives of the Active Treatment Outline Design are to progress the study by using the results of the Catchment Modelling to evaluate which combinations of minewater sources and treatment technologies will result in the required water quality standards being achieved. Estimates of the capital and operating costs for selected treatment scenarios are developed to an accuracy which will enable a recommendation of the preferred treatment route to be made for each of the water quality standards.

Three routes for the treatment of Wheal Jane minewater were selected for detailed consideration from a wide range of initial alternatives:

- Oxidation and Chemical Neutralisation (OCN), using well-established recycled sludge technology based on lime dosing;
- BioChemical Sulphidisation (BCS), using relatively new technology based on sulphate reducing bacteria;
- Ion Exchange (IEX), using synthetic resins to extract the metals followed by a conventional but small lime dosing system.

A number of alternative treatment stages have been examined as part of this study on Active Treatment, and some emerging technologies have been identified as having future potential for minewater treatment. None of these options are considered to have either sufficient economic advantage or to be sufficiently mature to merit incorporation into either of the flowsheets at the present time.

OXIDATION AND CHEMICAL NEUTRALISATION (OCN)

The most widely used method for the active treatment of metal bearing acidic water is chemical neutralisation. This is normally achieved using a suspension of hydrated lime as neutralising agent. An oxidation step following an initial dosing of lime enhances the removal of iron and arsenic as ferric hydroxide and amorphous ferric arsenate. The remaining metal content of the water is then removed with further lime dosing, precipitating the respective metal hydroxide in the form of a sludge.

Testwork was conducted by Anamet Services to confirm the applicability of chemical neutralisation processes to Wheal Jane minewater independently of technology suppliers (see Active Treatment Review Report).

The different options available for neutralisation have been evaluated, and the use of quick lime together with a slaking unit is considered to be the preferred option for this project. Slaked lime, limestone, magnesium oxide and caustic soda are the possible alternatives, with limestone providing the possibility for initial neutralisation up to pH 5.

Following neutralisation and precipitation, a solid/liquid separation stage is required to remove the thickened metal hydroxide sludge from the liquid effluent. Conventional clarifiers or thickeners have been identified as the most appropriate equipment for achieving this separation, in combination with the patented Tetra recycle sludge technology. Dewatering of this sludge is then required to lower the total volume of waste for disposal. When judged against other alternatives using product cake water content, cycle times and manpower requirements as the main performance criteria, a horizontal plate and frame filter press emerges as the best option. The liquid effluent from this sludge dewatering is treated in a final polishing stage to provide a further improvement in effluent quality. Sand filtration has been included for this final polishing, improving the removal of the remaining suspended solids in the effluent prior to discharge.

BIOCHEMICAL SULPHIDISATION (BCS)

Biochemical Sulphidisation is a relatively new technology which is being applied commercially for the removal of sulphate and metals from effluent streams. Anaerobic micro-organisms and organic reagents are used to reduce (extract the oxygen from) the sulphate in the minewater to produce sulphide. This sulphide can then combine with the metals in solution to produce a metal sulphide precipitate and generate solutions with low dissolved metals concentrations. For optimum performance these organisms require the temperature of the minewater to be raised to between 25 to 30°C through the use of a heat exchanger. Also, an adjustment of the pH to 7 by the addition of caustic soda is required. Paques BV have commercialised this technology as the THIOPAQ process, installing a plant in the Netherlands in 1992 to remove zinc and iron from contaminated ground water at 80 l/s.

In the THIOPAQ process, this reduction takes place in an Upflow Anaerobic Sludge Blanket (UASB) Reactor in which the sulphate content of the incoming water is reduced by micro-organisms from a concentration of 1 000 mg/l to about 200 mg/l. This reduction of the sulphate produces approximately 250 mg/l of sulphide which can combine with the dissolved metals to induce the metal sulphide precipitation. Polymeric flocculant and nutrients are added to the UASB reactor influent with Aquaguard, a mixture of organic acids, being envisaged as the necessary reducing agent. The effluent from the UASB reactor contains residual dissolved sulphide not consumed by metals precipitation. This is oxidised to elemental sulphur by air in a submerged fixed film biological reactor. Solids are removed from both the anaerobic and aerobic stages followed by thickening and the generation of a waste cake for disposal. As in the case of the OCN route, sand filtration is also included for final liquid effluent polishing.

A pilot plant has been operated on site by Paques to demonstrate the applicability of the THIOPAQ process to the treatment of Wheal Jane minewater. Preliminary results are in line with the expected effluent qualities.

ION EXCHANGE (IEX)

Ion exchange is a relatively mature technology used in the metals processing industry for the separation and purification of metal bearing solutions, with many examples of industrial applications in gold and uranium extraction. It is also applied for softening process water streams in the chemical and power generation industries, as a polishing stage in waste water processing, for potable water production and for nitrate removal. The process has not been widely used for minewater treatment, and no testwork has currently been performed on Wheal Jane minewater.

For minewater treatment, the raw minewater is passed to a strong acid cation exchange bed in which all the metal ions are adsorbed onto the resin in exchange for hydrogen ions producing an acidic solution. The solution is then passed to an anion exchange unit where the sulphate and arsenate ions are adsorbed in exchange for hydroxyl ions to produce a purified effluent solution. The cation exchange resin is regenerated by the action of sulphuric acid which is subsequently neutralised with lime to give a precipitate of gypsum and metal hydroxides. The anion exchange is regenerated by the action of lime to produce gypsum. The hydroxides and gypsum sludge is of a similar nature to the sludge produced by the OCN treatment and would be disposed of in a similar way.

Three alternatives have been considered for the applicability of ion exchange for this project:

- the use of cationic and anionic exchange to treat minewater from Wheal Jane or All Sources, termed IEX;
- the use of cationic exchange for polishing the effluent from an OCN plant; together with the remaining sources entering the Carnon River. This has been termed OCN-IEX(I);
- the use of cationic and anionic exchange resins for polishing the effluent from an OCN plant together with the remaining sources entering the Carnon River. This will result in achieving a further improvement in water quality and has been termed OCN-IEX(II).

Ion exchange technology has been piloted at 0.3 l/s for the treatment of a low acidity minewater, with testwork having been performed in South Africa by JCI on their GYP-CIX process. No commercial scale plant has yet been developed, however and extensive testwork would be required to confirm the requirements for processing Wheal Jane minewater.

TREATMENT SCENARIOS

This Active Treatment Outline Design has used the results of Catchment Modelling studies to evaluate which combinations of minewater sources and treatment technologies will result in the required water quality standards being achieved in the Carnon River at Devoran Bridge.

A number of Treatment Scenarios have been considered, comprising combinations of the OCN, BCS and IEX treatment routes with four influent minewater options:

- Wheal Jane operated with the existing six pumps only;
- All Wheal Jane minewater;

- All Wheal Jane minewater plus County Adit minewater;
- All Sources entering the Carnon River and treated at Devoran Bridge.

The following conclusions were drawn from a technical evaluation of these Treatment Scenarios:

- the treatment of the quantity of Wheal Jane minewater produced by the existing six pumps using an OCN process route is expected to result in a water quality which will meet the No Deterioration, No Discolouration and North Sea Declaration Commitments Water Quality Objectives;
- the treatment of Wheal Jane minewater from the six pumps by the BCS and IEX treatment routes will also achieve a water quality which meets these Lower Order Objectives;
- neither of the treatment routes will result in a water quality at Devoran Bridge which meets the Higher Order Objectives where minewater from Wheal Jane only, or Wheal Jane and County Adit is treated;
- the Higher Order Objectives at Devoran Bridge can only be achieved by including the treatment of All Sources and by using a process route incorporating IEX treatment at Devoran Bridge.

ECONOMIC EVALUATION OF TREATMENT OPTIONS

The results of an economic evaluation for the treatment of Wheal Jane minewater produced by the existing six pumps by a plant at the mine site, and the treatment of minewater from All Sources by a plant installed in the Lower Carnon Valley are presented in Table E.1. Also included in Table E.1 are the combined costs for OCN treatment of minewater produced by Six Pumps and IEX treatment of the effluent from OCN and the remaining sources entering the Carnon River.

Table E.1 : Cost Summary

Parameter	Six Pumps			All Sources				
Maximum flow (l/s)	330			3 720				
Average flow (l/s)	180			1 150				
Concentration (mg/l)	396			61				
Loading (g/s)	74.6			79.1				
	OCN	**BCS**	**IEX**	**OCN**	**BCS**	**IEX**	**OCN-IEX(I)**	**OCN-IEX(II)**
Sludge production (dry tpa)	5 625	4 251	5 625(2)	6 183	4 673	6 183(2)	6 183(2)	6 183(2)
TOTAL CAPEX (£ M)	4.25	6.26	12	25	47	58	18	29
TOTAL OPEX (£ M per year)	0.76	1.85(3)	1.4	1.6	4.0	3.5	2.5	3.4
WHOLE LIFE PRESENT VALUE(1) (£ M)								
10 years	11.2	22.8	25.1	39.1	83.4	89.5	40.4	59.1
25 years	16.2	34.6	34.3	49.3	109.3	111.7	56.5	81.0
50 years	19.1	41.5	40.1	56.3	126.1	127.2	66.4	94.7

(1) Present value costs discounted at 6% and including 4% rate of return on CAPEX and a 10% rate of return on OPEX.
(2) Assumed from hydroxide/gypsum from OCN treatment; additional gypsum production from IEX requires confirmation by testwork.
(3) A maximum benefit of £0.33 million per year could be achieved through the production of zinc sulphide sludge.

The main points to be concluded from this economic evaluation are:

- OCN treatment was found to be far cheaper than BCS or IEX treatment in both Capital Cost and Annual Operating Cost for treating minewater produced by the existing six pumps at Wheal Jane. A difference of at least £2 million in CAPEX and £17 million in Whole Life Present Value over a 25 year period is apparent comparing these three treatment routes.
- If the sole requirement is to meet the Lower Water Quality Objectives, there would appear to be no economic incentive to install BCS or IEX treatment for the Six Pumps option with no net advantage resulting from the production of a saleable zinc sulphide sludge.
- In order to achieve the Higher Water Quality Objectives, the installation of an IEX plant for treating All Sources at the Lower Carnon Valley site would be required with the OCN Six Pumps/IEX treatment combination providing a more economic alternative.

It is recommended that the above whole life costs for Active Treatment be used in the cost-benefit appraisal of Wheal Jane minewater treatment.

APPENDIX F

Technical Summary of Final Environmental and Social Benefit Assessment Report

TECHNICAL SUMMARY

INTRODUCTION

The abandonment of the Wheal Jane mine, in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. The Environment Agency (Agency) implemented a series of emergency measures to control and treat the minewater discharge and, therefore, limit the impact of the release on the environment.

Emergency pumping and treatment measures have been progressively developed to form the existing treatment system and will remain in operation until a long-term solution is implemented. This treatment process relies on the Clemows Valley Tailings Dam for disposal of treated minewater sludge.

An initial study, completed in May 1995 *(KP, et al, 1995, Wheal Jane Minewater ...)*, considered a range of active and passive minewater treatment options. The present study built on that work and has the objective of formulating the long-term solution.

This report considers the environmental and social benefit aspects and forms part of the suite of reports for the study. Only the benefits associated with meeting different treatment options are discussed here, with costs presented in the Appraisal and Selection of the Long Term Treatment Option Report (KP, 1998).

Net economic benefits associated with moving from the No Treatment WQO to higher water quality objectives WQOs), resulting from treatment of part or all sources in the Carnon Valley, are assessed. Benefits are measured in comparison to the No Treatment WQO, which acts as the do-nothing baseline for the analysis. Such an approach requires the monetary valuation of all the categories considered, including environmental costs and benefits.

To avoid over-estimation of the impacts, the area has been divided into five reaches:

- Reach 1: Carnon River;
- Reach 2: Restronguet Creek;
- Reach 3: area to the north-west of the Carrick Roads, from Trelissick to Mylor Creek;
- Reach 4: area to the south-west of the Carrick Roads, from Mylor Creek to Pendennis Point;
- Reach 5: the eastern side of the Carrick Roads, east of the deep water channel.

ENVIRONMENTAL AND OTHER EFFECTS

There are seven WQOs:

Objective 1: No Treatment;
Objective 2: No Deterioration;
Objective 3: No Discolouration;
Objective 4: North Sea Declaration Commitments;
Objective 4: Protection of Estuarine Biology;
Objective 5: EC Dangerous Substances Directive- Fresh Water Standards;
Objective 7: EC Dangerous Substances Directive - Salt Water Standards.

Predictions of impacts on water quality and discolouration events were made by under the catchment modelling study and the biological assessment study and have been used to estimate the economic impacts. The basic assumptions on environmental change used in the analysis for the various WQOs are as follows.

- Objective 1: Discolouration would occur almost every year, over the winter and early spring. Iron concentrations would be elevated in the water, especially in Reach 1 and Reach 2. Such events would impact upon all recreational activities, and upon biological life, although the levels of the latter are not certain.

- Objective 2: The current situation would continue, with occasional discolouration events. Activity levels and industry would continue as at present, with no additional benefit over the current state.

- Objective 3 and Objective 4: No discolouration events, and reduced iron concentrations would have less impact than under Objective 2. There would be some scope for improvement of the environment, although the impact of this would be slight.

- Objective 5 through to Objective 7: No discolouration events, and further reduction of iron concentrations may have a greater positive impact than under Objective 3 and Objective 7. However, it is not possible to value impacts under these WQOs objectives separately to those arising under Objective 3 and Objective 4.

CONSERVATION AND NON-USE VALUE

Economic values are placed on the environment through contingent valuation surveys, in which individuals are asked to value a particular environment, often in a polluted or degraded state, and in an improved state. The difference between the two values gives the value of improving that particular environment. However, there are no studies which relate to reducing minewater discharges typical of Wheal Jane. Therefore, valuations from studies considering other environmental improvements have been used.

Ideally, economic valuations that distinguish between the small improvements seen between the WQOs proposed here would have been used. However, this has not been possible due to a paucity of economic valuations. As a result, a single value has generally been used across all the WQOs. To reflect the uncertainty involved in using values developed for other purposes, a value of £5.86 per household per annum (related to beach cleanliness) was taken as the upper bound, £0.73 per household per annum (from valuations of water quality discharges) as the mid bound, and a lower value of £0.61 per household per annum (relating to a maintenance of a wetland nature reserve). These values are used for the estuarine environment.

Different values are used to value changes in river water quality. A value of £0.00201 per household per kilometre of river per annum to move from a poor state to a medium state affected has been assumed in this case. 'Poor' relates to a 'dead' river, holding little or no life, and being discoloured; 'medium' is a river with some life, and little or no discolouration. However, even under the higher order WQOs the river would not improve to the full amount. The lower bound and mid bound assume, therefore, an improvement to half the non-use value, while the upper bound (as a sensitivity indicator) takes the full value.

A key issue surrounding the estimation of non-use values concerns the population over which benefits are aggregated. Although studies have found that individuals living long distances from a resource hold non-use values and a positive willingness to pay for the protection and conservation of assets, it is also acknowledged that there is likely to be some distance-decay relationship. Three alternative assumptions have been used to develop lower bound, mid bound and upper bound estimates:

- lower bound: non-use households in Carrick, Cornwall and the South West Water service area all hold a value of £0.77;
- mid bound: non-use households in Carrick hold a value of £6.18, while households in Cornwall and the South West Water service area hold a value of £0.77;
- upper bound: non-use households in Carrick and Cornwall hold a value of £6.18, while households in the South West Water service area hold a value of £0.77.

Total annual benefits across the estuary are £800 000 under the upper bound, £350 000 for the mid bound, and £200 000 for the lower bound. The mid bound is probably the most reliable estimate. These figures are the same across Objective 2 through to Objective 7.

The value of conservation impacts for the river are zero under the No Deterioration WQO. There is some benefit in moving to the other WQOs (Objective 3 through to Objective 7) of £11 000 for the upper bound, and £6 000 for both the mid bound and the lower bound. These values are lower than those for the estuary because the river is currently very degraded. Even under these WQOs, there is no guarantee that significant improvements will be made as there are numerous other diffuse minewater sources in the Carnon valley. Furthermore if water is treated at Devoran, or other sites towards the lower end of the catchment, there will be no improvement to water quality in the Carnon River.

RECREATION

Recreation includes activities such as walking, picnicking, birdwatching, bathing, sailing, canoeing, pilot gig racing, etc. These are grouped as informal recreation, bathing, and watersports for the purposes of this assessment.

Informal Recreation

Visitor counts made during site visits, car park figures, surveys of footpath users, and discussions with rambling organisations have given estimates of the number of people who may be engaged in informal recreational activities around the Carrick Roads. These indicate about 53 000 walkers, picnickers, birdwatchers and cyclists every year, with the highest concentration of informal recreation in Reach 4.

The main impact upon these people is in the form of discolouration which can reduce the number of visitors to the area through people deciding not to partake in recreational activity, or moving to alternative sites, and through loss of enjoyment when an area is perceived to lose some of its natural beauty.

Such losses have been estimated using a factor of 30% to account for all of the above when a reach becomes discoloured. Indirect losses are also estimated, where visitors are assumed to be impacted when neighbouring reaches are discoloured, but the reach that they are visiting is not. However, the loss is considered to be less, at 15%.

WQOs, Objective 2 through to Objective 7, yield benefits for the mid bound estimates of:

- Objective 2: £11 000;
- Objectives 3 and 4: £13 500;
- Objectives 5,6 and 7: £13 500.

Bathing

Numbers of bathers have been estimated from counts made during site visits, and using figures from the Cornwall Tourist Board. The site visits also allowed an assessment of the quality of the beaches around the Carrick Roads to be made, with many beaches deemed to be unsuitable for bathing. The total number of bathers per annum is estimated to be 4 600.

The small number of potential bathers have been assumed to be affected during a bathing season, running from May to September, when the reach in which they would bathe is discoloured. Due to the water contact nature of this activity, it has been assumed that losses would be 50% of the total value of a beach activity user day.

Annual benefits to bathing are very small, at just £20 per year for Objective 2 through to Objective 7, under the mid bound.

Watersports

This includes a wide range of activities, both water contact and non-water contact, with seasons varying in length. Sailing is the most important activity in terms of total activity per year, both casual and club based, and through competitions, regattas and taught courses. Motor boating, windsurfing and canoeing are similarly conducted on a casual, club, taught course and hire basis. Other sports include pilot gig racing, rowing, and diving. Water-skiing takes place in Reach 5 only, due to imposed restrictions.

Levels of activity per sport have been estimated through discussions with club secretaries and hire outlet owners and operators, and site counts. A range of estimates have been used, with the best estimate taken as the mid bound. This indicates around (all person-trips rather than boat trips):

- sailing: 57 000 trips;
- pilot gig racing: 7 500 trips;
- motorboating: 5 700 trips;
- windsurfing: 4 900 trips;
- rowing: 1 600 trips;
- diving: 800 trips;
- canoeing: 700 trips;
- water-skiing: 600 trips.

Impacts vary according to the particular sport, with the non-water contact activities (sailing, rowing, motor boating and pilot gig racing) assumed to lose 30% of activity upon direct discolouration (discolouration in the reach where the activity is taking place) and 15% through indirect discolouration. For the water contact activities (diving, windsurfing, water-skiing and canoeing), losses of 50% and 25% are taken, respectively. This ensures that the methods are consistent with informal recreation and bathing.

Annual benefits to watersports accrued under each of the WQOs for the mid bound are:

- Objective 2: £56 000;
- Objective 3 and Objective 4: £64 000;
- Objective 5 through to Objective 7: £64 000.

Total Benefits

The total recreation benefits accrued under the WQOs, Objective 2 through to Objective 7, for the mid bound are:

- Objective 2: £67 000;
- Objective 3 and Objective 4: £77 000;
- Objective 5 through to Objective 7: £77 000.

Economic valuations are not sensitive enough to the changes between Objective 3 and Objective 4, and Objective 5 through to Objective 7, to allow the slight differences between them in terms of water quality to be reflected in the annual benefit calculations.

PLEASURE BOATING AND PORT OPERATIONS

Pleasure boating covers the local cruises and ferry trips around the Carrick Roads and Fal Estuary, with port operations covering the repairs to ships, boats and yachts, and maintenance of mooring chains and buoys.

Pleasure Boating

There are four ferries and four cruises available for visitors to the Fal Estuary. Each visits or crosses between different parts of the Fal Estuary so that most of the creeks are visible from at least some of the trips. The estimated number of pleasure boat trips made per year is 17 500, with this concentrated in a season running from May to September. The value of pleasure boating has been estimated using a value of £2.83, where this is calculated from the average price of a ferry or cruise trip on the Fal Estuary.

Impacts have been valued in a manner similar to that for informal recreation, with discolouration taken as the main cause. The number of visitor trips affected under a discolouration event is, therefore, taken at 30% for direct impacts and 15% for indirect impacts.

Annual benefits gained with reductions in the number and duration of discolouration events after treatment for the mid bound are:

- Objective 2: £11 000;
- Objective 3 and Objective 4: £12 000;

- Objective 5 through to Objective 7: £12 000.

Ship Repair and Maintenance

There are fourteen boat and yacht yards around the Fal Estuary offering repairs and maintenance. It is anticipated that 2 000 to 4 000 boats will require these facilities each year. Average maintenance costs are estimated at £50 for sailing dinghies and £650 for larger yachts. Repair prices for motorboats are taken as £510 to £1 015 depending again on the type and size of boat. The lower values are taken to estimate the benefits of treatment since the majority of boats using the Carrick Roads and the Fal Estuary are dinghies or small motorboats.

Discolouration is taken as the cause of impact on ship repair yards, with this resulting from the perception of pollution and the effect this may have on yachts and boats (such as staining, corrosion, etc.). Losses are taken at 30% for boatyards located in directly affected reaches, and at 15% for the times when neighbouring reaches are affected.

Annual benefits, across all the reaches are estimated for the mid bound at:

- Objective 2: £4 300;
- Objective 3 and Objective 4: £4 600;
- Objective 5 through to Objective 7: £4 600.

Estimates of benefits to ship repair and maintenance only take account of losses in economic rent (assumed for the mid bound to be 12%), as this reflects the national benefit from improvements in water quality for this category.

Moorings

Impacts are determined by the change in maintenance and replacement costs of mooring chains and buoys with moving from the No Treatment WQO to treatment. Such changes are estimated by considering the relative corrosiveness of the water.

As the predicted water qualities did not allow actual corrosiveness to be calculated, an estimate of the relative change in life expectancy between the WQOs is taken. Hence, for the No Treatment WQO, life expectancies are reduced to less than two years for mooring chains, and to less than eight years for navigation buoys. WQOs, Objective 2 through to Objective 7 are then assigned life expectancies of two to four years, and eight to ten years, respectively. Each life expectancy band is associated with an annual repair and maintenance cost. Benefits from treating Wheal Jane, therefore, come from reductions in these costs relative to the No Treatment WQO.

Only mooring chains and buoys located in Reach 2 are impacted, therefore, the benefits associated with moorings are small. Annual benefits for WQOs, Objective 2 through to Objective 7, under the mid bound estimates are:

- Objective 2: £490;
- Objective 3 and Objective 4: £490;
- Objective 5 through to Objective 7: £490.

Total Benefits

The total annual benefits accrued over the categories of pleasure boating, ship repair and maintenance and port operations for WQOs, Objective 2 through to Objective 7 are:

- Objective 2: £16 000;
- Objective 3 and Objective 4: £17 000;
- Objective 5 through to Objective 7: £17 000.

TOURISM

The average number of tourists visiting the District of Carrick in 1996 was 664 000, each spending an average of about £200 on accommodation, food and leisure activities during their stay. Visitors to the area would be affected by both the degree and duration of discolouration events.

The main tourist season is in July and August, and has not been impacted to any large degree by discolouration. However, some visitors are affected. Care had to be taken since many visitors will already have been counted as walkers, or taking part in watersports or local cruise trips, etc. Therefore, the full 30% attributed to direct impact under other non-water contact categories is not taken. Instead, 15% is used.

Benefits per annum under each of the Objectives are:

- Objective 2: £150 000;
- Objective 3 and Objective 4: £180 000;
- Objective 5 through to Objective 7: £180 000.

CALCIFIED SEAWEED INDUSTRY

Dead maerl deposits are harvested, cleaned, and occasionally milled to produce a soil conditioner used, for example, by dairy farmers to improve grassland quality. Production currently runs at around 35 000 tonnes per annum.

Under the No Treatment WQO it is assumed that there would be no demand for the soil conditioner as it would be perceived to contain high heavy metal concentrations. Therefore, the benefits under the WQOs, Objective 2 through to Objective 7, take the total value of the industry to reflect that this is a unique process which could not be continued at alternative locations.

With the total value of the Calcified Seaweed industry lost under the No Treatment WQO, the annual benefits under the WQOs, Objective 2 to Objective 7, are very significant:

- Objective 2 £1 050 000;
- Objective 3 and Objective 4: £1 050 000;
- Objective 5 through to Objective 7: £1 050 000.

FISHERIES

Commercial Fisheries

Fishing is a major industry in Cornwall, and this is true also of the Fal Estuary with Falmouth being one of the country's major fishing ports. Commercial species considered here are inshore species such as pollack, mackerel, conger eels, and dogfish. Sea bass are also a highly prized commercially fished species as it is a non-quota fishery of high value.

The Fal Estuary contains two sea bass nursery areas including all of Reach 1 and Reach 2, and part of Reach 3 through to Reach 5. The nursery areas are closed for fishing between March and December, but it is the stock that they support which can move out of the more sheltered parts of the creeks and supply commercial fishermen with good quality fish that are important here.

However, inshore commercial species can move relatively easily away from any plumes of polluted water, with this only impacting upon fishermen if their costs increase as they follow the fish. Sea bass could be affected if metal concentrations were persistently elevated, but the effects of higher concentrations are unknown. Impacts are predicted, therefore, on juvenile bass living and growing in the nursery areas, and have been agreed through discussions with the Agency as follows.

- Objective 1: 100% loss of the nursery area in Reach 1 and Reach 2, and 75% loss in Reach 3 (this is larger than the relative size of the area likely to be impacted due to the importance of the deep water areas during periods of cold weather).
- Objective 2: no change in the productivity of the bass nursery areas.
- Objective 3 through to Objective 7: an increase by 25% in the productivity of the bass nursery resulting from an increase in the biomass supported by an improvement in water quality.

The benefits are estimated through increases or decreases in catches at local ports (those within 50 miles as this is considered to be a good estimate of the distance sea bass migrate upon leaving a nursery area).

Annual benefits under WQOs, Objective 2 through to Objective 7, for the mid bound are, therefore:

- Objective 2: £9 400;
- Objective 3 and Objective 4: £12 000;
- Objective 5 through to Objective 7: £12 000.

Commercial benefits take the national benefit (or rent) associated with sea bass fishing. For the mid bound this is taken as 12%.

Shellfisheries

Oysters growing in the Fal Estuary are collected by sailing boats and haul tow punts, with these traditional methods used to preserve the stocks for the continuation of the industry. The industry is still volatile, however, with diseases caused by the parasite *Bonamia* responsible for a large decrease in harvests during the mid to late 1980s.

There are about eleven shellfish sites in the Fal Estuary, with two designated under the EC Shellfish Waters Directive. The standard of the beds varies, although most oysters need some pre-treatment or long periods of relaying before they can be consumed.

Impacts upon the oysters themselves are believed to be minimal, even under the No Treatment WQO, although such predictions are highly uncertain. It is the public (or buyers) perceptions, however, that the oysters may be harmful if consumed that would impact most upon the oyster industry. Therefore, it is assumed that a discolouration event that occurs during any oyster season (seasons run from October to March) would result in a decrease in demand by 50%. Oysters beds and lays in Reach 5, however, are unlikely to be affected, and these have been assumed to face no such decreases.

Each oyster is assumed to be worth £0.22 on average, 1.8 million oysters were gathered in the 1996 to 1997 season, giving a total value for the fishery of £396 000. Annual benefits under the WQOs, Objective 2 through to Objective 7, for the mid bound are, therefore:

- Objective 2: £140 000;
- Objective 3 and Objective 4: £150 000;
- Objective 5 through to Objective 7: £150 000.

These benefit estimates are based on the full value of the lost fishing as for the calcified seaweed industry.

Recreational Fisheries

Six angling clubs regularly fish from sites around the Carrick Roads, with the annual number of trips estimated at 6 200. There are also non-members and visitors to the area who also fish, with these estimated at 20 500. Total shore angling trips are, therefore, estimated at 28 000.

Charter boats operate out of the area and, although many such trips take place in wrecks outside of the estuary, there is some extra activity. Similarly, private boat fishing trips are also made.

Impacts are assumed to relate to the number and duration of discolouration events with such events perceived to affect fish, or to force them to migrate to other areas. Many fishing trips could move to alternative sites, but some are likely to be lost. Anglers could also lose some of their enjoyment if they cannot move to alternative areas. Impacts on all angling trips (whether shore, charter boat or private boat) are assumed to result in a 50% decrease in the recreational value of the fishery in reaches that are directly affected.

Figures taken to estimate the total value of recreational fishing included a willingness to pay value of £2.59 per trip, travel costs of £3.19 for shore trip, £6.90 for a charter boat trip and £1.91 for a private boat trip (where distance and time travelled to a site are given values of £0.075 per mile and £0.035 per minute), and a willingness to accept loss of fishing for one season of about £810 per angler.

Annual additional benefits for the mid bound are estimated to be:

- Objective 2: £17 000;
- Objective 3 and Objective 4: £19 000;
- Objective 5 through to Objective 7: £19 000.

Total Benefits

Annual benefits, as given above, can be combined to give the total benefits accrued under each of the WQOs as:

- Objective 2: £170 000;
- Objective 3 and Objective 4: £180 000;
- Objective 5 through to Objective 7: £180 000.

AMENITY

There are more than 700 properties that have a view over the Fal Estuary and which may be impacted by periods of discolouration. This is because there is a price premium associated with living in houses with pleasant views over water. Discoloured water, however, is not considered to be as attractive aesthetically and some (if not all) of the price premium can be lost.

Opinions vary as to what these premiums may be. Some estate agents quote figures as high as 20%. Here, the premiums are taken as 2%, 5% and 10%, with these percentages equivalent to the lower bound, mid bound and upper bounds, respectively.

Discolouration is assumed to impact upon price premiums when events lasted for a minimum of one month. Under the No Treatment WQO, this results in the total loss of premium in Reach 2, Reach 3 and Reach 4. Such losses are only experienced in Reach 5 under the upper bound scenario. Some losses in this reach, although smaller, are also felt under the No Deterioration WQO (Objective 2).

The annual benefits for amenity are estimated as (for the mid bound values):

- Objective 2: £250 000;
- Objective 3 and Objective 4: £340 000;
- Objective 5 through to Objective 7: £340 000.

These values are give as annual equivalent values over the 25-year discounting period. Such values are calculated by dividing the one-off price premium increase by the discount factor (in this case 12.7834). The total value to amenity is, therefore, £4.3 million for Objective 2, and £5.5 million for Objective 3 through to Objective 7.

SUMMARY OF RESULTS

The values of impacts from discolouration and elevated iron concentrations have been given as per annum values above (with the exception of amenity, which is expressed in annual equivalent terms). Such values can also be given over a specific time period to give the overall value of treatment into the future. Three time horizons have been taken here:

- 10-years;
- 25-years;
- 50-years.

The additional discounted values for the WQOs, Objective 2 through to Objective 7, are calculated for each activity. The overall benefits from each WQO can then be expressed as (mid bound figures).

For Objective 2:

- 10-years: £17 million;
- 25-years: £27 million;
- 50-years: £33 million.

For Objective 3 and Objective 4:

- 10-years: £18 million;
- 25-years: £28 million;
- 50-years: £34 million.

For Objective 5 through to Objective 7:

- 10-years: £18 million;
- 25-years: £28 million;
- 50-years: £34 million.

It can be seen from above, that there are considerable benefits in moving to one of the higher order WQOs. There are only small differences, however, between benefits under Objective 2 and Objective 3 through to Objective 7 of £1 million, or 6% over 10 years, and 4% over 25 and 50 years. The economic methods used do not allow all categories to be distinguished, and the differences between WQOs may be under-estimated. This is more evident when considering Objective 3 and Objective 4, and Objective 5 through to Objective 7, where impacts could not be valued separately..

The discounted benefits are dominated by use values (those associated with recreation, pleasure boating and port operations, tourism, calcified seaweed, fisheries and amenity), with these making up 84% of Objective 2 benefits, and 86% of Objective 3 through to Objective 7 benefits. Benefits to the calcified seaweed industry dominate the total benefits, making up about 49% of the total benefits (this ranges from 44% to 51% over the upper, mid and lower bounds for Objective 3 through to Objective 7).

APPENDIX G

Technical Summary of Final Pilot Passive Treatment Plant Appraisal Report

TECHNICAL SUMMARY

INTRODUCTION

The abandonment of the Wheal Jane mine in 1991, followed by recovery of water levels, caused an uncontrolled release of acidic metal laden water into the Carnon River and the Fal Estuary. As part of an overall strategy to determine the most cost effective long-term solution to the minewater discharge, a Pilot Passive Treatment Plant was constructed in 1994 in order to evaluate the use of passive treatment as a viable long-term treatment option. Due to the complex nature and low pH of the minewater, a variety of different passive treatment scenarios were investigated.

DESCRIPTION OF THE PILOT PASSIVE TREATMENT PLANT

The Pilot Passive Treatment Plant consists of three separate systems, each comprising the following principal treatment components:

- aerobic reed beds designed to remove iron as ferric hydroxide/oxyhydroxide, with arsenic removal by co-precipitation and adsorption onto the iron precipitate;
- an anaerobic cell designed to enhance the bacterial reduction of sulphate and hence to remove zinc, copper, cadmium and residual iron in the form of metallic sulphides;
- an aerobic rock filter designed to promote the growth of aquatic algae which have been shown to promote the removal of manganese as an oxide, along with a reduction in the BOD of the anaerobic cell effluent.

The systems differed in the type of pre-treatment they utilise to increase the pH of the influent minewater, as follows:

- the Lime Dosed System employed a small lime dosing plant and precipitate trap (sludge channel);
- the Anoxic Limestone Drain System employed a small anoxic (without oxygen) cell (Pre-ALD) and an Anoxic Limestone Drain (ALD);
- the Lime Free System had no pre-treatment and acted as a control to the other two systems.

Modification works were undertaken during the period October 1996 to February 1997, in order to enhance the performance of certain components, and to increase the number of potential flow pathway options.

OBJECTIVES OF OPERATION

The Pilot Passive Treatment Plant was operated principally with the following objectives:

- to confirm and / or revise the design principles;
- to provide information relating to the operation of a passive treatment plant;
- to evaluate the potential use of passive treatment as part of an overall long-term treatment strategy for treating minewater from the Wheal Jane Mine complex, and other minewater discharges within the Carnon Valley;

- to provide design and operational information, which may be applicable to other proposed passive treatment sites in the UK.

This report provides:

- an operational and performance record covering the period November 1994 to January 1998;
- a summary of research into use of alternative anaerobic cell substrates;
- a summary of the use of passive treatment technologies elsewhere in the UK and overseas;
- conclusions, where possible, concerning the principles of the design of the Pilot Passive Treatment Plant;
- confirmation of earlier preliminary conclusions concerning the applicability of passive technologies for the treatment of Wheal Jane minewater;
- options for the long-term use of the Pilot Plant and the land owned by the Environment Agency in the Carnon Valley.

The performance, and hence operation of the individual components in the three systems was constrained to a certain extent, particularly prior to the modification works, by the performance of the preceding treatment components. After the modification works, it was possible to operate the individual components more independently, except for the rock filters, which received minewater directly from the anaerobic cells. Overall, the aim was to obtain performance datasets for a particular operating scenario over a reasonable period of time and within that period to maintain constant flow rates to allow a comparison of the performance between each system.

PRE-TREATMENT

Lime Dosing

Lime dosing of the influent minewater was performed between a target range of pH 4.6 to 6.5. After the modification works, the influent minewater from the ALD System was also dosed with lime prior to the ALD in order to remove a significant proportion of the aluminium.

Pre-ALD and ALD

The Pre-ALD successfully reduced the dissolved oxygen concentration (DO) of the influent minewater to below 1 mg/l, thus reducing the impact of ferric iron armouring of the limestone in the ALD.

The ALD consistently raised the pH of the minewater to approximately pH 6, and generated 80 to 100 mg/l of alkalinity. The precipitation of aluminium hydroxide within the cell caused blockages to flow, which did not reoccur after lime dosing was introduced.

Summary and Conclusions

Summary and conclusions relating to pre-treatment were:

- at an influent pH less than 5, a form of pH elevating pre-treatment may be beneficial;

- passing pre-treated minewater directly into an anaerobic cell proved beneficial to anaerobic cell performance;
- the addition of bicarbonate alkalinity and increase in pH as the minewater passed through the ALD was presumed to be responsible for the more abundant and luxurious reed growth observed in the ALD system;
- pH elevating pre-treatment did not result in enhanced iron removal in the aerobic cells, compared to the system without pre-treatment, at comparable influent iron loads;
- lime dosing pre-treatment has the disadvantage of on-going management and maintenance requirements;
- the use of an Anoxic Limestone Drain (ALD) is advantageous if the aluminium concentration in the influent minewater is approximately 5 mg/l or less, otherwise precipitation of aluminium hydroxide may reduce the flow rate through the cell.

AEROBIC CELLS

The aerobic cells have been operated with the primary aim of observing the iron removal efficiency over a range of influent flow rates.

Summary and Conclusions

A summary of performance and conclusions relating to aerobic treatment were:

- in all three systems, iron removal (allowing for dilution/evaporation) ranged from 51 to 98% or 0.2 to 5.5 g Fe/m^2/day, with arsenic removal close to below detection limits (see revised design parameters in Table G.1).
- for the Lime Free System over a limited period, iron removal per unit area in the first of the five aerobic cells was found to be significantly higher than in subsequent cells with a median of 10g Fe/m^2/day.
- a system of aerobic cells configured in parallel would be capable of treating a proportionately higher flow rate, and would remove a greater amount of iron per unit area, although at the risk of higher iron concentrations in the treated effluent.
- at comparable influent iron loads in all three systems, the use of pre-treatment did not result in higher iron removal rates.
- sizing an aerobic system for iron removal should be based upon the relationship between influent iron load and iron removal per unit area.
- the actual contribution of the reeds themselves in enhancing metal removal, in the short term is inconclusive. In the longer term, it is anticipated that the presence of reeds would be beneficial as a source of organic matter that may encourage bacterial processes associated with metal removal.
- reed growth would likely benefit from an organic rich substrate.
- the main limit to iron removal within the aerobic cells is the reduction in pH resulting from ferric iron hydrolysis.

- within cost constraints, an aerobic cell with an organic rich substrate incorporating limestone is preferred due to the enhanced metal removal expected from limestone dissolution and bacterial sulphate reduction processes.

ANAEROBIC CELLS

The Lime Dosed System anaerobic cell was modified between October 1996 and February 1997 to give the option of feeding lime dosed minewater directly into the cell, rather than via the aerobic cells. During these modification works, cattle manure and hay were added to the existing sawdust/hay substrate, in order to improve cell performance. These changes resulted in an improvement in the level and consistency of sulphate removal. There was little observed variation in metal removal over the lime dosing pH range of pH 6.5 down to 4.0, although this may have been influenced by the addition of fresh organic matter to the substrate. Similar modifications were made to the Lime Free System anaerobic cell, with cattle manure hay and limestone being added to the existing substrate. This lead to an increase in sulphate and zinc removal compared to that observed immediately prior to the modifications. An investigation into alternative anaerobic cell substrates revealed the potential of a variety of different substrate materials that included sewage sludge, newspaper and cardboard.

Summary and Conclusions

A summary of performance and conclusions relating to anaerobic treatment were:

- sulphate removal ranged from zero to 0.57 moles/m^3/day, although generally removal was much lower than this maximum value, at around 0.08 moles/m^3/day (see revised design parameters in Table G1);
- target metal removal (Zn, Cd, Cu, Fe) was lower, at approximately 0.04 moles/m^3/day, with minewater pH increasing from approximately pH 3, to pH 4 to 6 across the cells;
- zinc removal ranged from zero to 100% (below detection limits), with removal generally above 60%. Cadmium and copper were, for the majority of the time, removed to below detection limits;
- receiving raw minewater directly, the Lime Free system anaerobic cell successfully removed a median of 80% zinc, 33% iron, with arsenic, cadmium and copper all being removed to below detection limits;
- overall, the low pH of the aerobic cell effluent was detrimental to anaerobic cell performance, thus emphasising the benefit to be derived from passing pre-treated minewater directly into an anaerobic cell;
- to achieve the maximum removal of as wide a range of metals as possible in a given land area, minewater passed directly into an anaerobic system is the preferred configuration (with pre-treatment to pH 5 to 6, if necessary);
- it is anticipated that the inclusion of limestone in the anaerobic cell substrate would be beneficial, leading to higher and more sustained levels of metal removal.

ROCK FILTERS

Manganese removal has been variable due to a lack of sustained algal growth. This is believed to be partly due to the variable effluent pH from the anaerobic cells and a further decrease in pH caused by the hydrolysis of residual iron. Between June and August 1996, a median of 97% manganese removal was observed in the ALD System rock filter, coinciding with abundant algal growth. After the modification works, the Lime Dosed System rock filter has proved to be successful in removing a median of approximately 60% influent manganese, coinciding with a higher pH of the anaerobic cell effluent.

Summary and Conclusions

A summary of performance and conclusions relating to rock filter treatment were:

- at times, high levels of manganese removal have been observed in the rock filters, with enhanced removal coinciding with a higher influent pH. Sustained manganese removal, however, has not been consistently demonstrated.
- the rock filters have proved to be efficient at reducing the Biochemical Oxygen Demand (BOD.) of the anaerobic cell to acceptable levels.

ALTERNATIVE PASSIVE TREATMENT TECHNOLOGY

Since the conception of the Pilot Passive Treatment Plant in early 1994, other alternative treatment scenarios have gained credence worldwide, for example, the vertical flow pond, or 'Successive Alkalinity Producing System' (SAPS).

SAPS typically offer:

- an efficient use of available land area (due to the vertical flow), with the potential for combining both aerobic and anaerobic treatment in one system;
- good pH buffering capacity due to the organic rich substrate containing limestone.

The main potential drawback to vertical flow ponds is the difficulty of maintaining substrate permeability over time. At Wheal Jane, the shallow groundwater and unconsolidated tailings material at the site would present particular construction difficulties, if this type of system were built.

APPLICABILITY OF PASSIVE TREATMENT AT WHEAL JANE

Revision of Design Parameters

A summary of the original and revised Pilot Passive Treatment Plant design parameters are given in Table G.1.

Table G.1 : Revision of Original Pilot Passive Treatment Plant Design Parameters

System	Design Parameter
Original design parameters (1994)	
Aerobic	At pH < 5.5 iron removal at between 2 - 4 g iron/m^2/day
	At pH > 5.5 iron removal at between 5 - 11 g iron/m^2/day
Anaerobic	Sulphate removal (and hence target metal$^{(1)}$ removal) at 0.3 moles/m^3/day
	Area Loading factor of 20 m^2/l/min
Revised design parameters (1998)	
Aerobic	At pH < 6.0 iron removal at between 2 - 5 g iron/m^2/day$^{(2)}$
Anaerobic	Sulphate removal at 0.08 moles/m^3/day
	Target metal$^{(1)}$ removal at 0.04 moles/m^3/day
	Insufficient data to enable revision of area loading factor

$^{(1)}$ Target metals are zinc, copper, cadmium and iron.
$^{(2)}$ Removal rate proportional to influent iron load.

The range of potential treatment scenarios for both active and passive minewater treatment are summarised in Table G.2. This list of treatment scenarios is not exhaustive, but serves to highlight the disparity that exists between the main treatment options, and the level of treatment which would theoretically be required to achieve all the designated Water Quality Objectives (WQO) at Devoran Bridge. The inclusion of the relative capital expenditure for each treatment scenario is intended to act as a rough guide to rank the treatment options, as increasing cost is associated with increased complexity of plant and associated engineering requirements. The main potential passive treatment options are examined below.

Primary Passive Treatment of Wheal Jane Minewater

Assuming that the main criterion for treating the minewater would be to remove the greatest amount of as wide a range of metals as possible, the results of the Pilot Passive Treatment Plant study indicates that the preferred passive treatment option to fit into the available 22 ha of land within the Carnon Valley would be an anaerobic system, most likely with lime dosing pre-treatment. It is acknowledged that such a system would only be able to treat a proportion of the total minewater flow, and would not alone result in the required water quality objectives being met.

Secondary Passive Treatment of Wheal Jane Minewater

Aerobic treatment of the effluent from an active primary Oxidation and Chemical Neutralisation (OCN) plant would result in an improvement in the final iron concentration, although this might also be achieved more economically by upgrading the active plant by including a secondary filtration stage. Anaerobic treatment, at best, would remove zinc to below detection limits, but could only treat a proportion of the total flow.

Passive Treatment of Other Minewater Sources Within The Carnon Valley

County Adit represents the largest single source of copper entering the Carnon River. An anaerobic system, at best, would be capable of reducing the copper concentration to below detection limits, but could only treat a proportion of the total flow. In order to meet the most stringent WQO, the results of other studies indicate that all minewater sources in the valley would require treating, This effectively means treating minewater from Wheal Jane and County Adit, as well as the Carnon River in its entirety. This is not a practical proposition due to the flow rates concerned.

CONCLUSIONS

The preliminary conclusions of the potential for passive treatment of Wheal Jane minewater recorded in the 1995 report (KP, NRA, RPA, 1995, Environmental Appraisal ...) remain unchanged. On the basis of the flows to be treated and the defined treatment objectives, there is an insufficient area of suitable land within the Carnon Valley to accommodate a full sized passive treatment plant to treat the whole minewater flow. There is, however, the potential to use passive treatment as a 'polishing' stage to treat the effluent from an active treatment plant. While this would result in a marked improvement in the quality of the treated minewater, it would only be possible to treat a proportion of the total flows and hence the improvement in overall water quality would be limited.

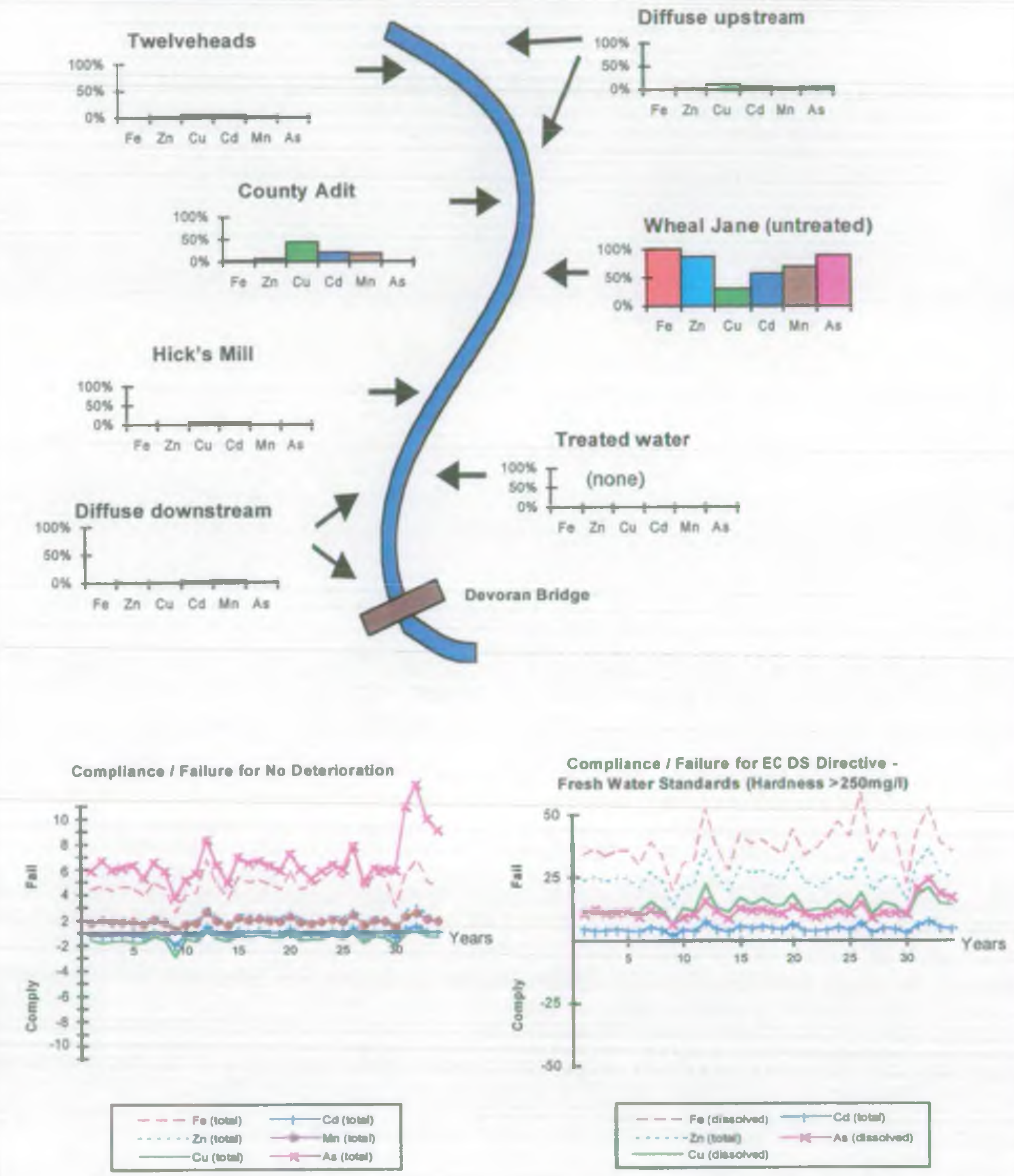
Table G.2 : Passive Treatment in the Carnon Valley in Context

Treatment Scenario	Treatment Method	WQO Achieved	Approximate Relative Cost[5]
No treatment (no pumping)	none	• No treatment	1/3[6]
Wheal Jane (Six Pumps)	Oxidation & Chemical Neutralisation (OCN)[1]	• No Deterioration • No Discolouration • North Sea Declaration Commitments	1
Wheal Jane (Six Pumps)	**Primary Passive Aerobic Treatment**	none[4]	1
	Primary Passive Anaerobic Treatment	none[4]	4 times
Wheal Jane (Six Pumps)	Oxidation & Chemical Neutralisation (OCN)[1] **+ Passive Secondary Aerobic Treatment[4]**	• No Deterioration • No Discolouration • North Sea Declaration Commitments	2 times
Wheal Jane (Six pumps)	Oxidation & Chemical Neutralisation (OCN)[1] **+ Passive Secondary Anaerobic Treatment[4]**	• No Deterioration • No Discolouration • North Sea Declaration Commitments	5 times
Wheal Jane (Six Pumps)	Oxidation & Chemical Neutralisation (OCN)[1] **+ Passive Anaerobic Treatment of County Adit Minewater[4]**	• No Deterioration • No Discolouration • North Sea Declaration Commitments	5 times
Wheal Jane + County Adit + Carnon River	Biochemical Sulphidisation (BCS)[2]	• No Deterioration • No Discolouration • North Sea Declaration Commitments	11 times
Wheal Jane + County Adit + Carnon River	Ion Exchange (IEX)	Achieves all the above WQO, plus : • EC DS Directive – Fresh Water Standards[7]	14 times
Wheal Jane + County Adit + Carnon River	Oxidation & Chemical Neutralisation (OCN)/Ion Exchange (IEX)	Achieves all the above WQO, plus : • EC DS Directive – Fresh Water Standards[7]	5 times

[1] OCN = lime dosing.
[2] BCS = sulphate reducing bacterial process active plant.
[3] Shellfish WQO applies to existing designated sites, the area of which may be reviewed at a future date, possibly extending these sites.
[4] Passive treatment would result in a marked improvement in the quality of the treated minewater, with respect to certain metals. Overall, the improvement in water quality would be minor, due to there being an insufficient area of suitable land within the Carnon Valley to treat the entire flow rates from the respective minewater sources.
[5] Relative costs refer to capital expenditure only, and are : active OCN plant £4.3 million; 21 ha aerobic cell £5.7 million; 5 ha aerobic cell £2.9 million; 19 ha anaerobic cell £15.7 million; active BCS plant £47 million; active IEX plant £58 million; active OCN/IEX plant £22 million.
[6] Cost estimate of £1.4 million for essential upgrade to Jane's Adit.
[7] European Community Dangerous Substances Directive – Fresh Water Standards.

FIGURES

Figure 1 : Relative Contribution of Contaminant Loadings and Implications for WQOs - No Treatment



Note 1: Percentage contributions for all contaminants are based on total concentrations.

Note 2: Compliance / failure plots show the factor by which simulated annual average concentrations at Devoran Bridge achieve or fail the specified WQOs.

Figure 2 : Cost-Benefit Analysis - Summary

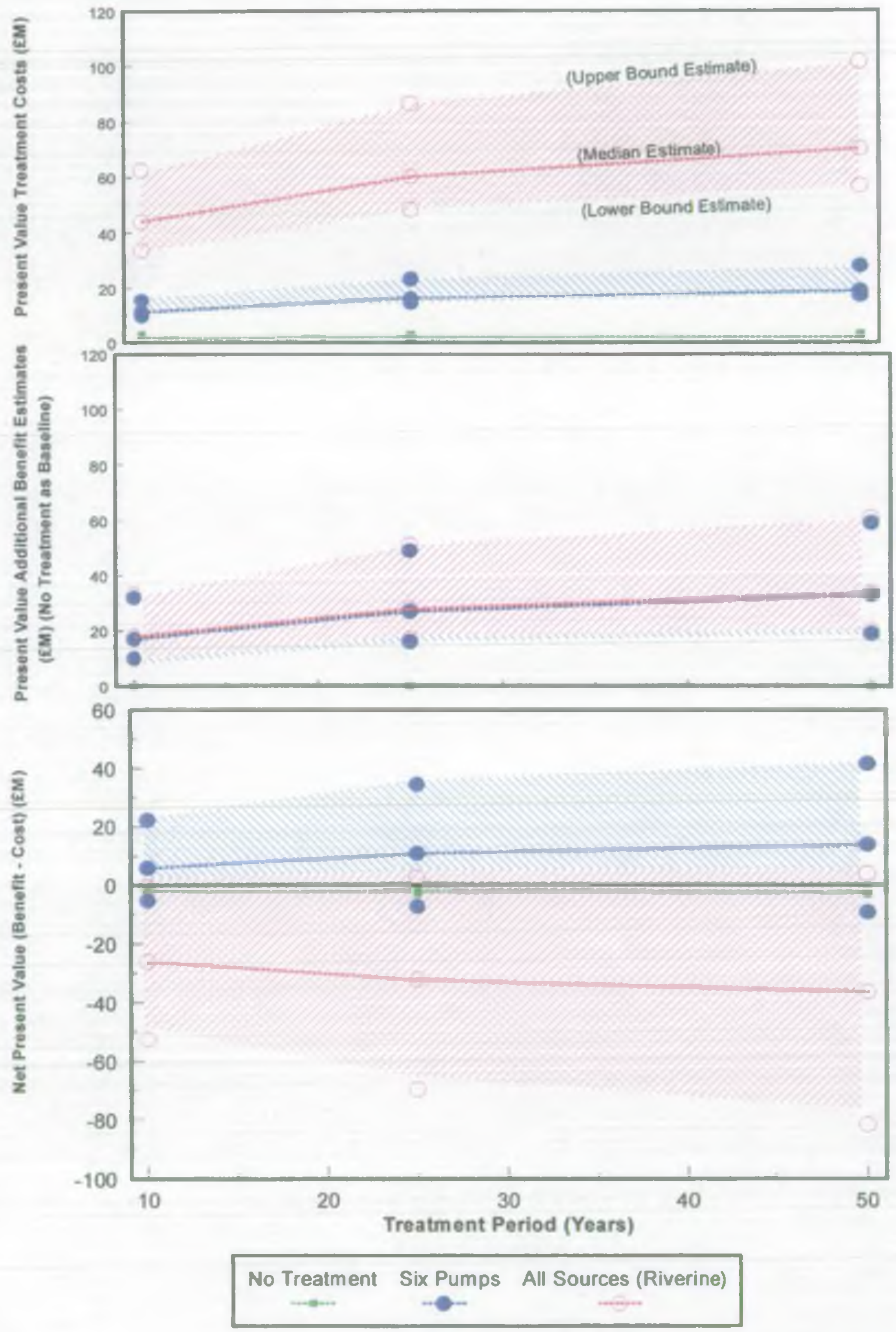


Figure 1.1 : Location Plan

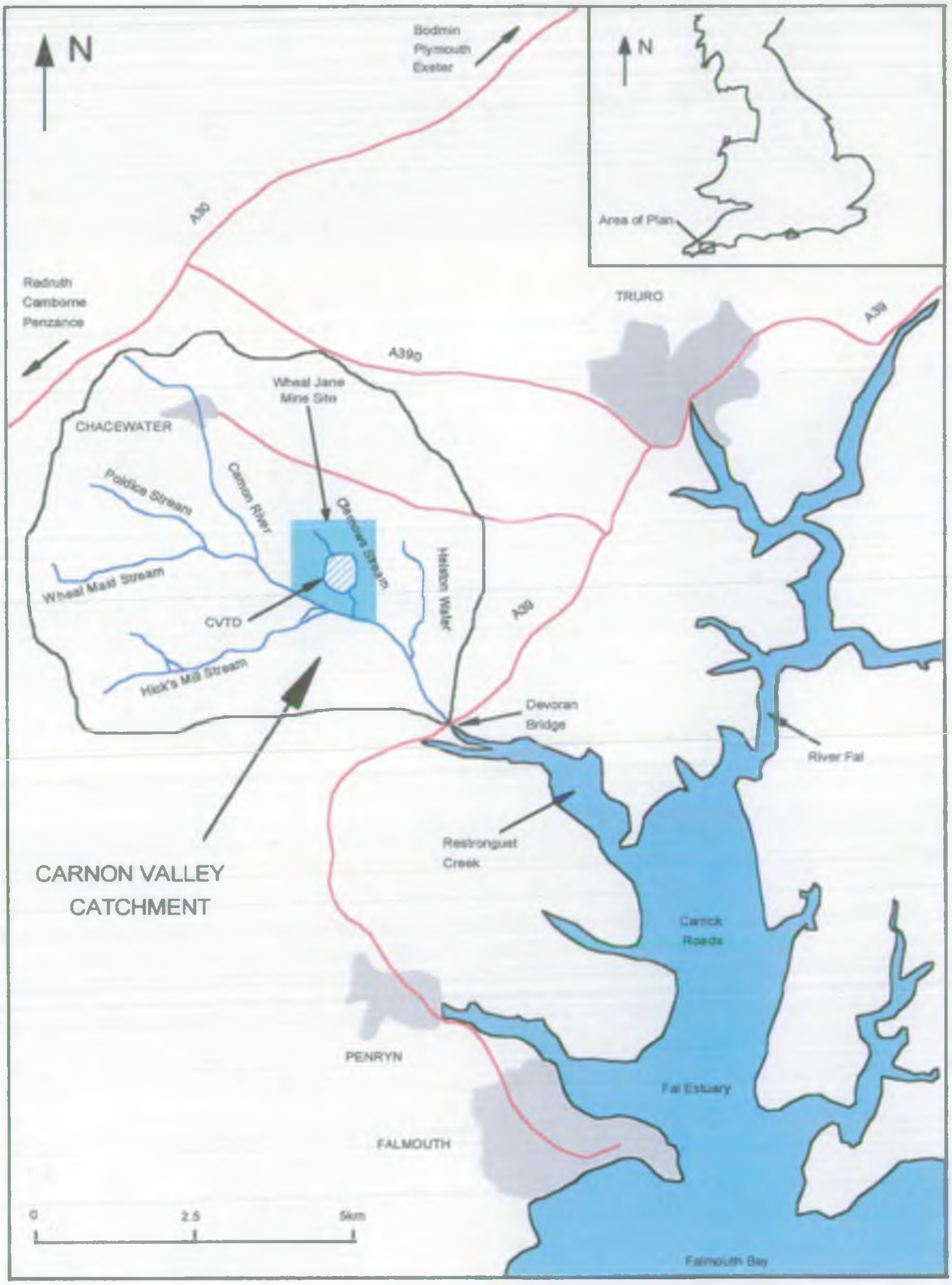


Figure 1.2 : Reporting Structure

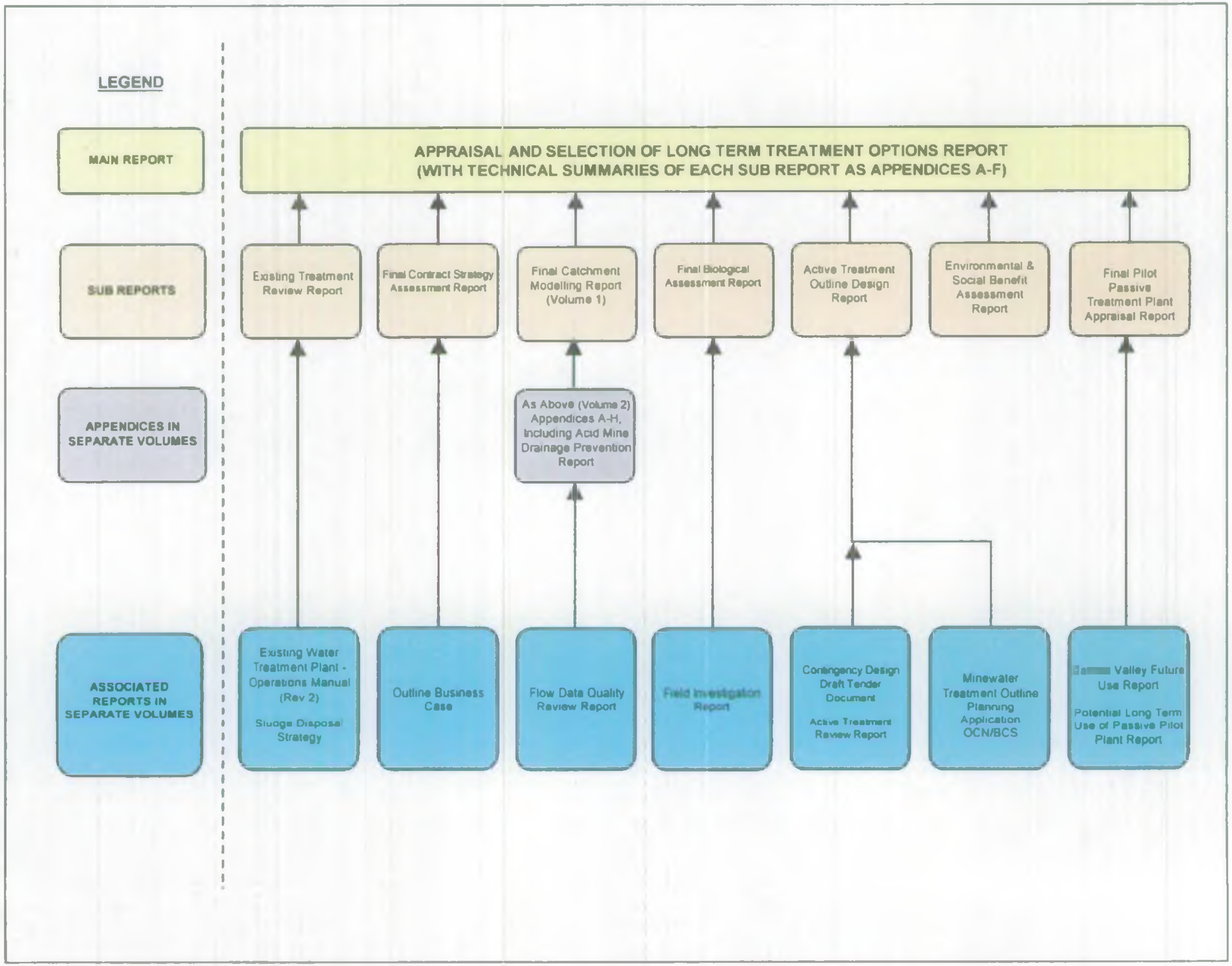


Figure 1.3 : Schematic Diagram of Water Quality Terminology

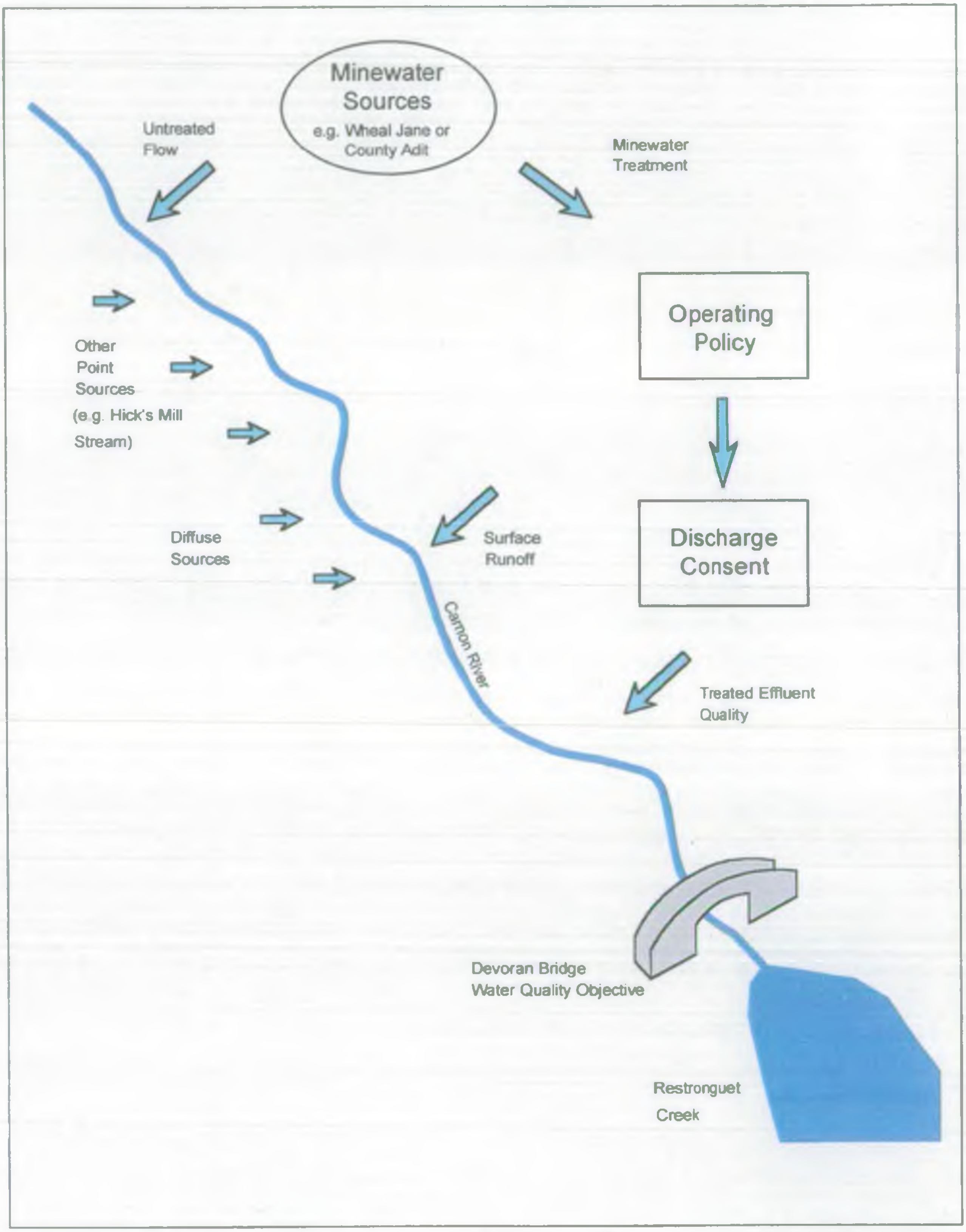


Figure 1.4 : Project Organisation

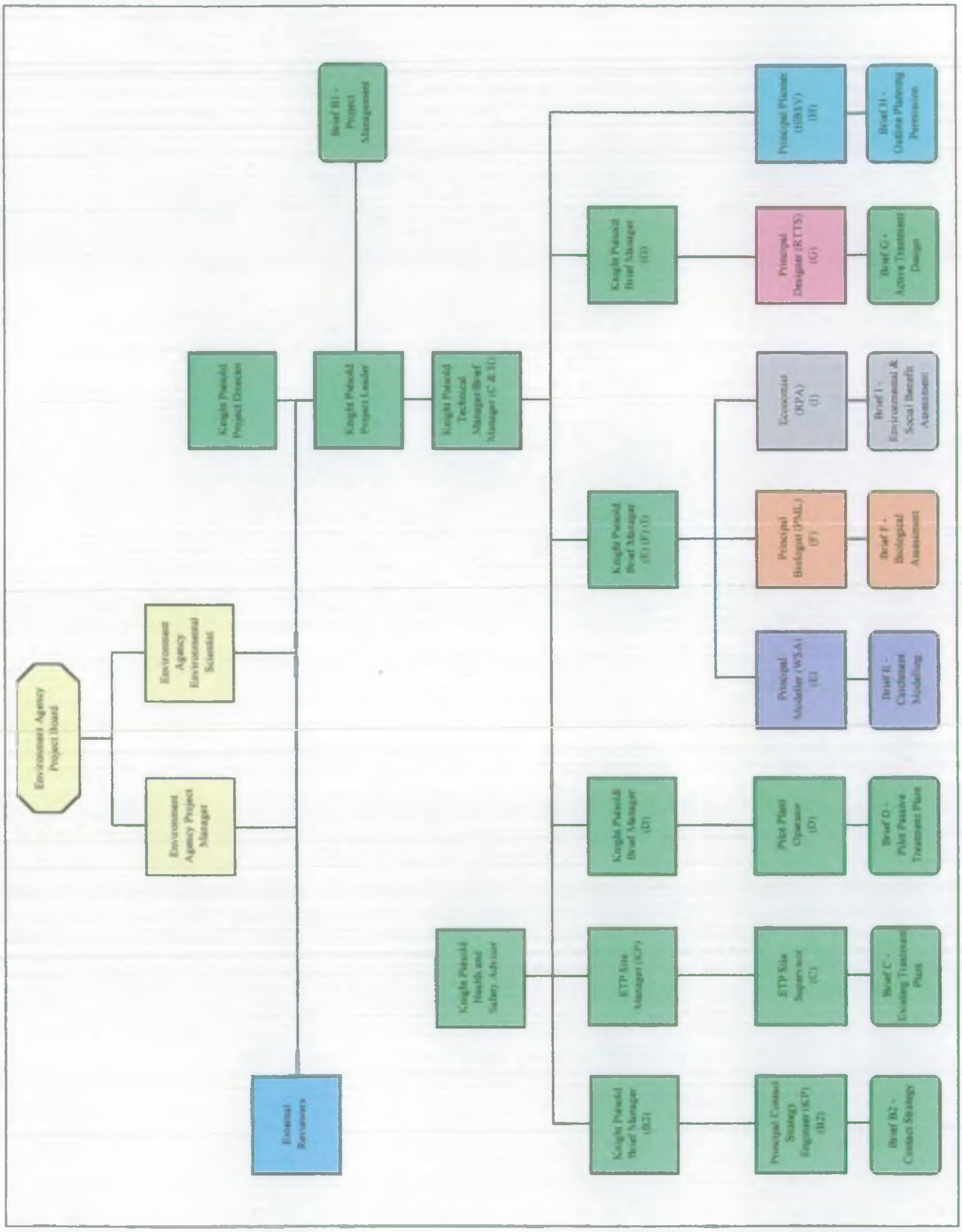


Figure 2.1 : Carnon River Catchment

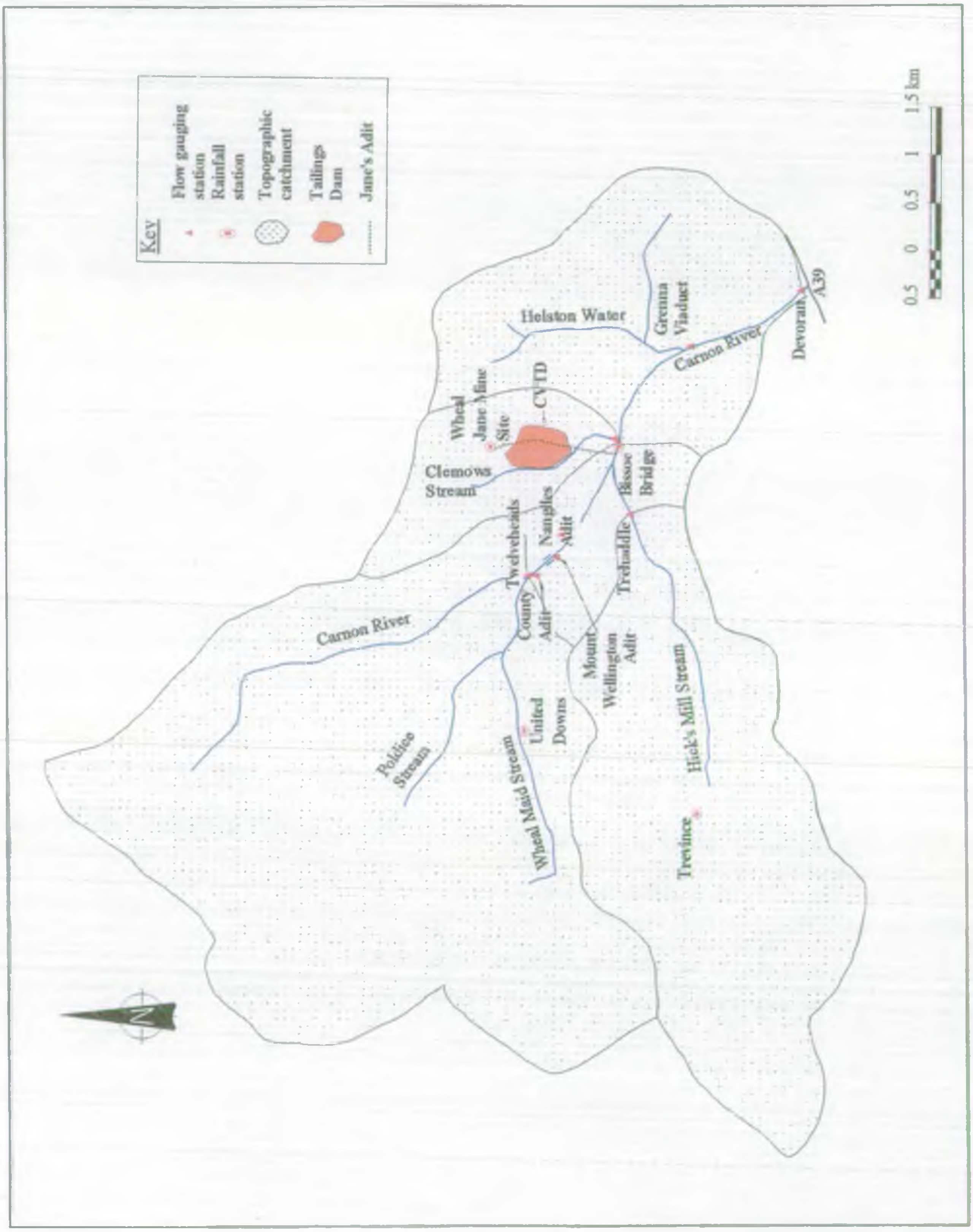


Figure 2.2 : Adits and Mineworkings

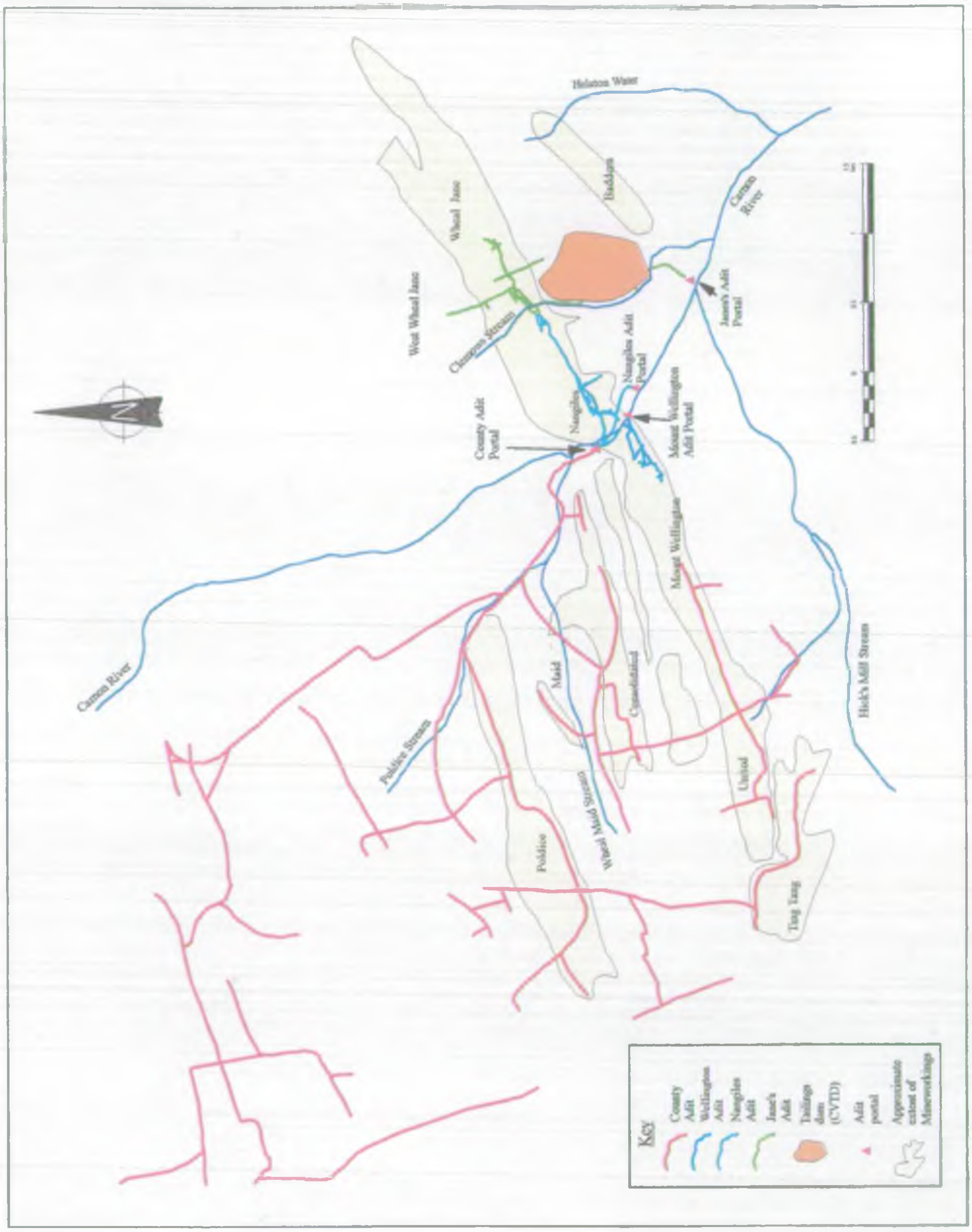


Figure 2.3 : Water Quality at Devoran Bridge

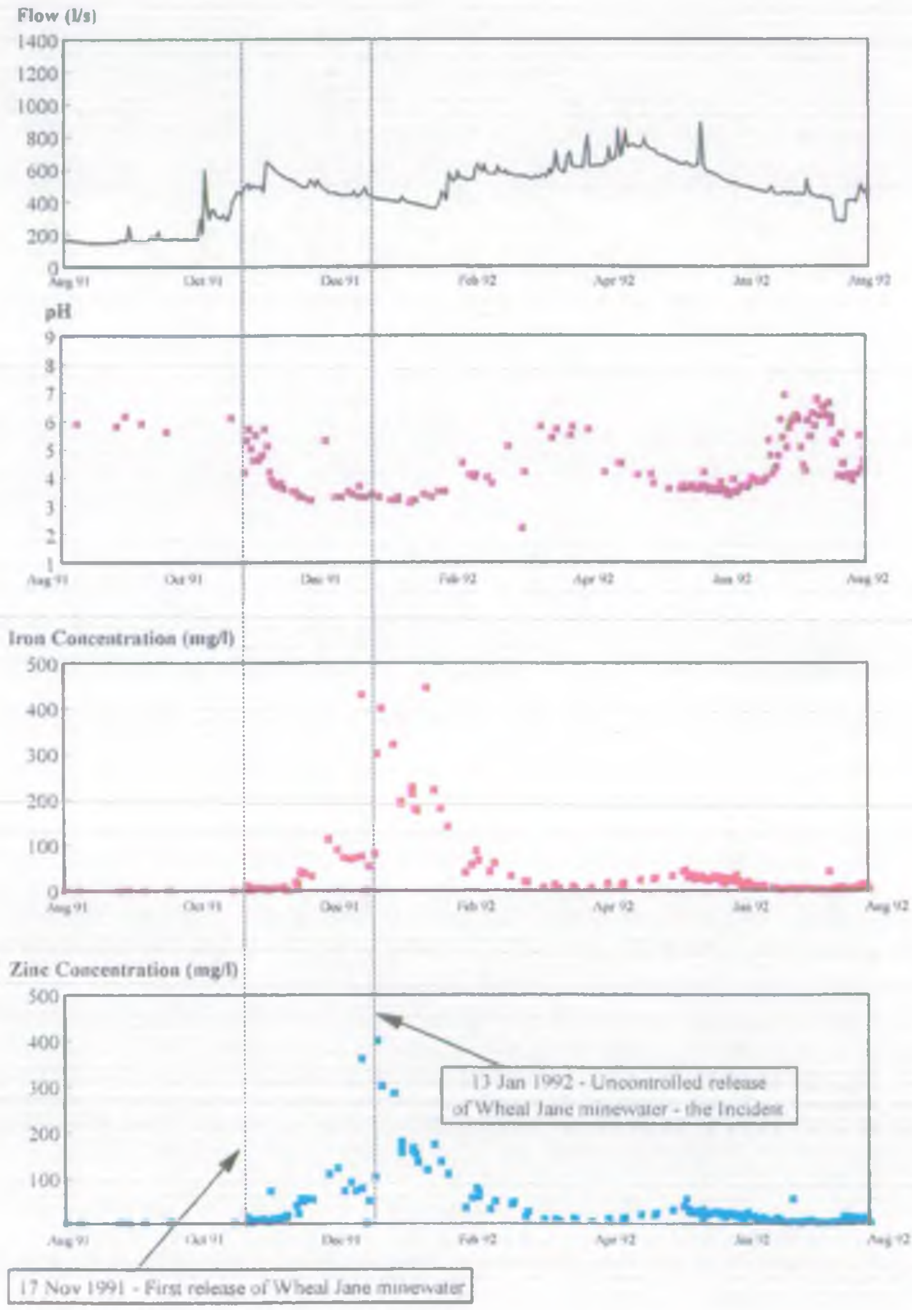
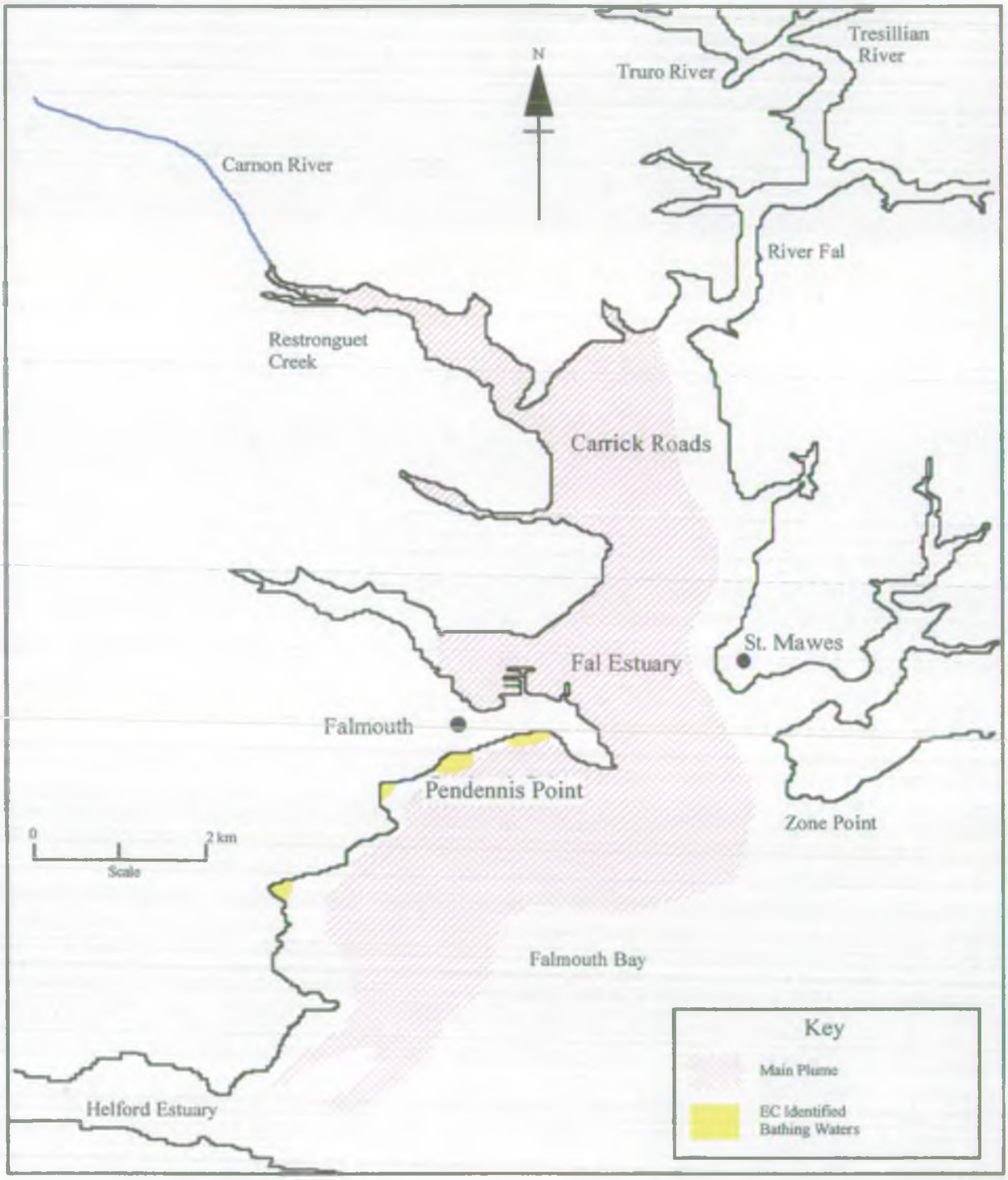


Figure 2.4 : Maximum Extent of Discolouration (16/1/92)



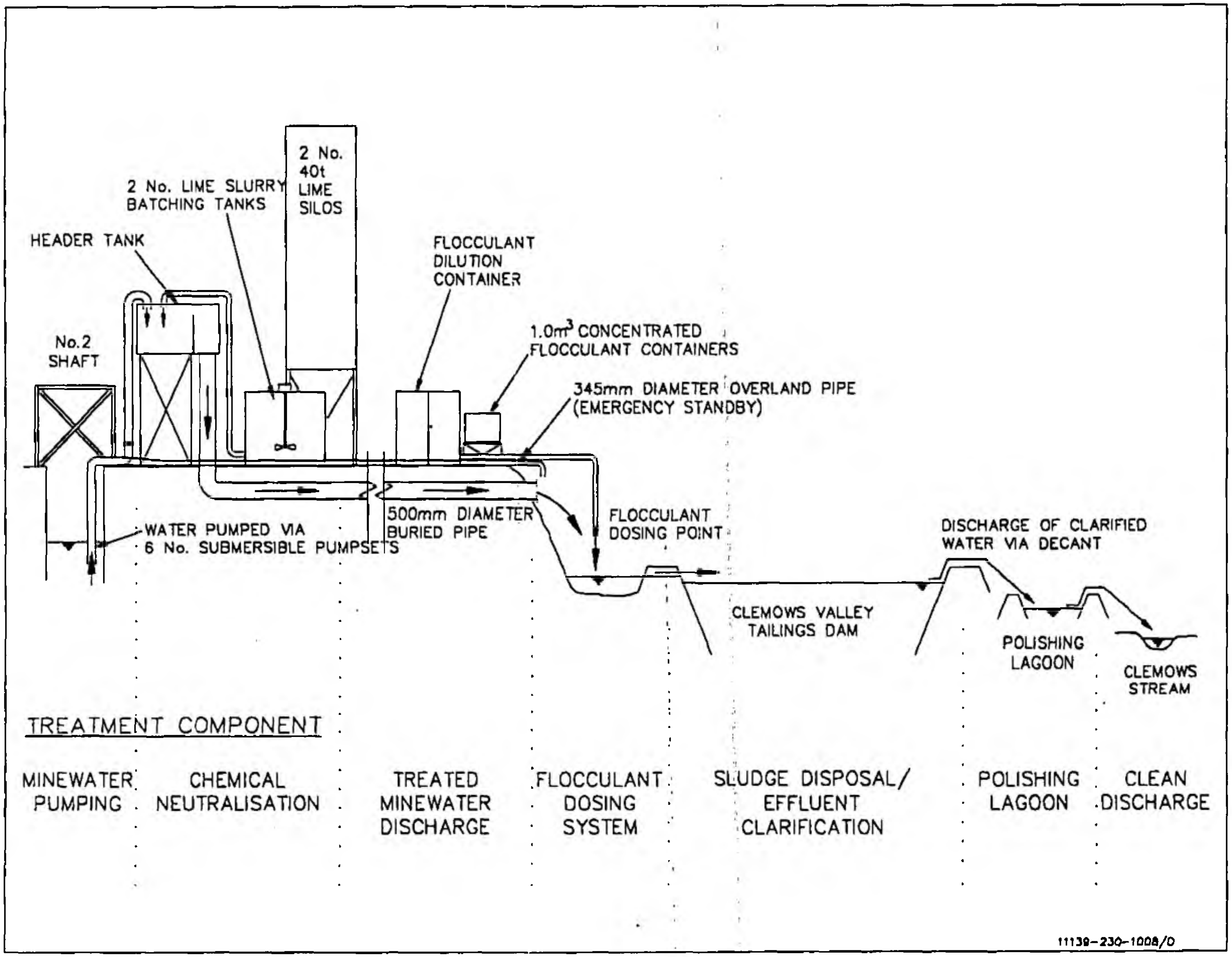


Figure 3.1 : Schematic of Treatment System

Figure 3.2 : Summary of ETP Performance

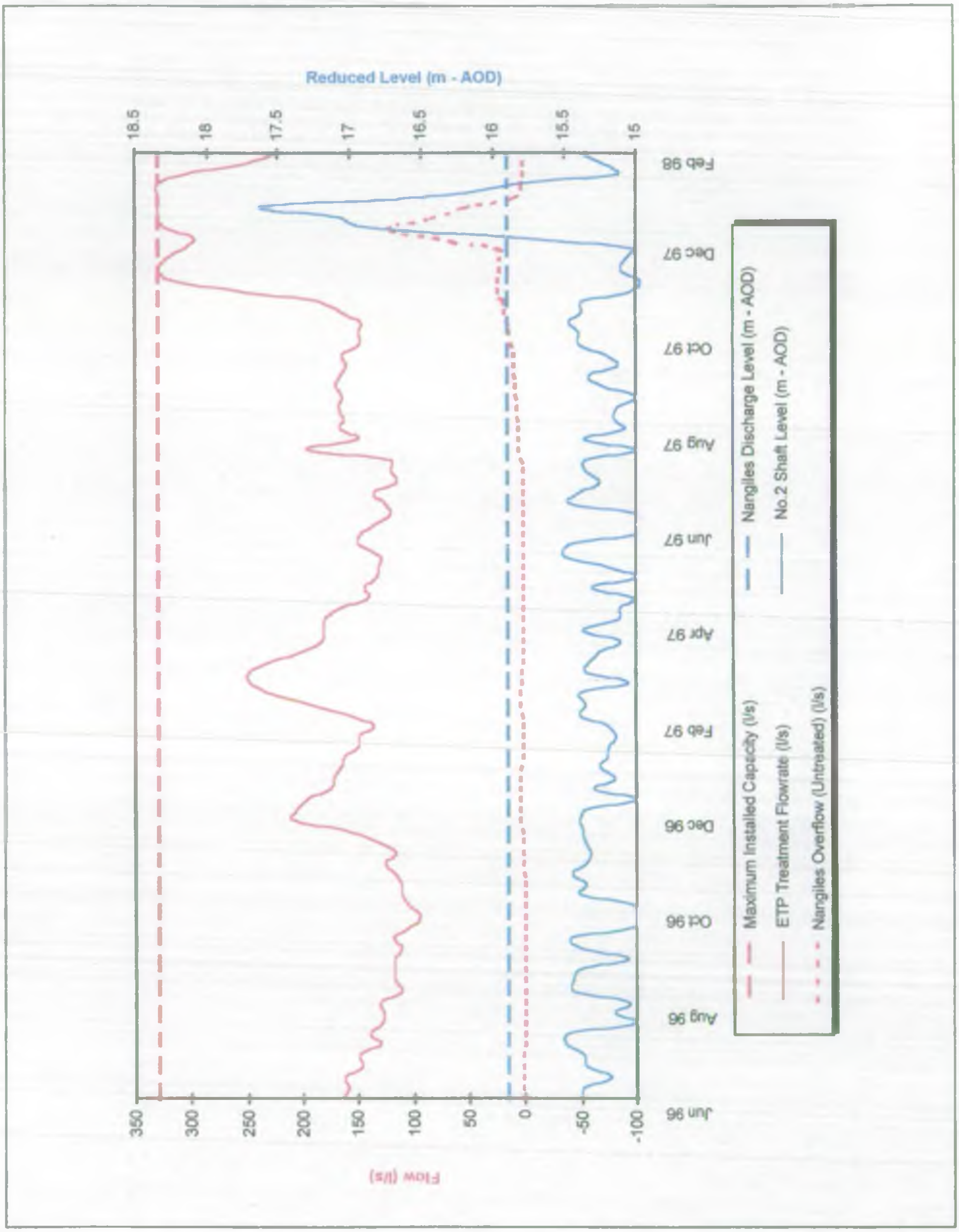
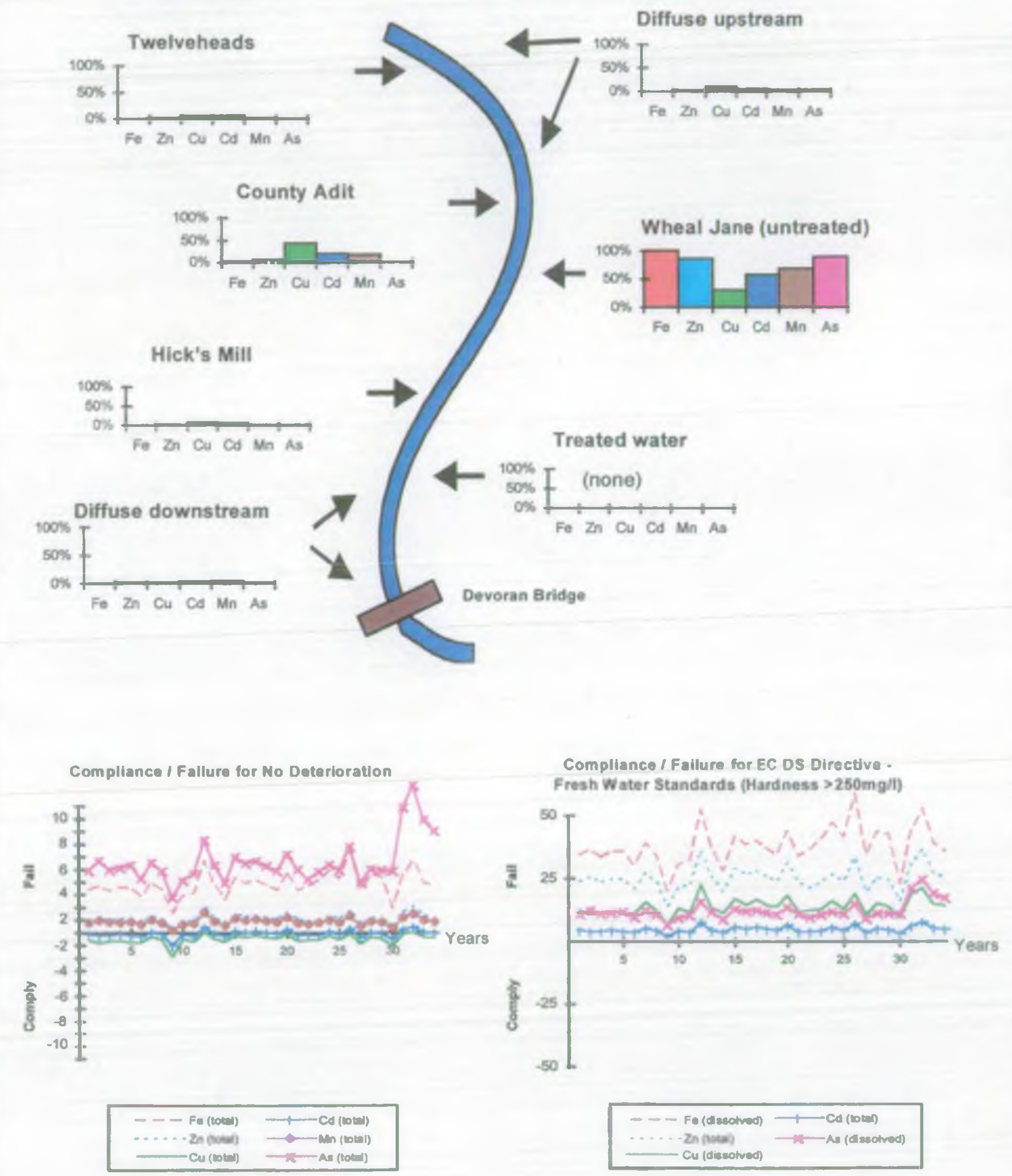


Figure 4.1 : Relative Contribution of Contaminant Loadings and Implications for WQOs - No Treatment



Note 1: Percentage contributions for all contaminants are based on total concentrations.

Note 2: Compliance / failure plots show the factor by which simulated annual average concentrations at Devoran Bridge achieve or fail the specified WQOs.

Figure 4.2 : Long Term Trends in Metal Concentrations (Wheal Jane Mine No. 2 Shaft)

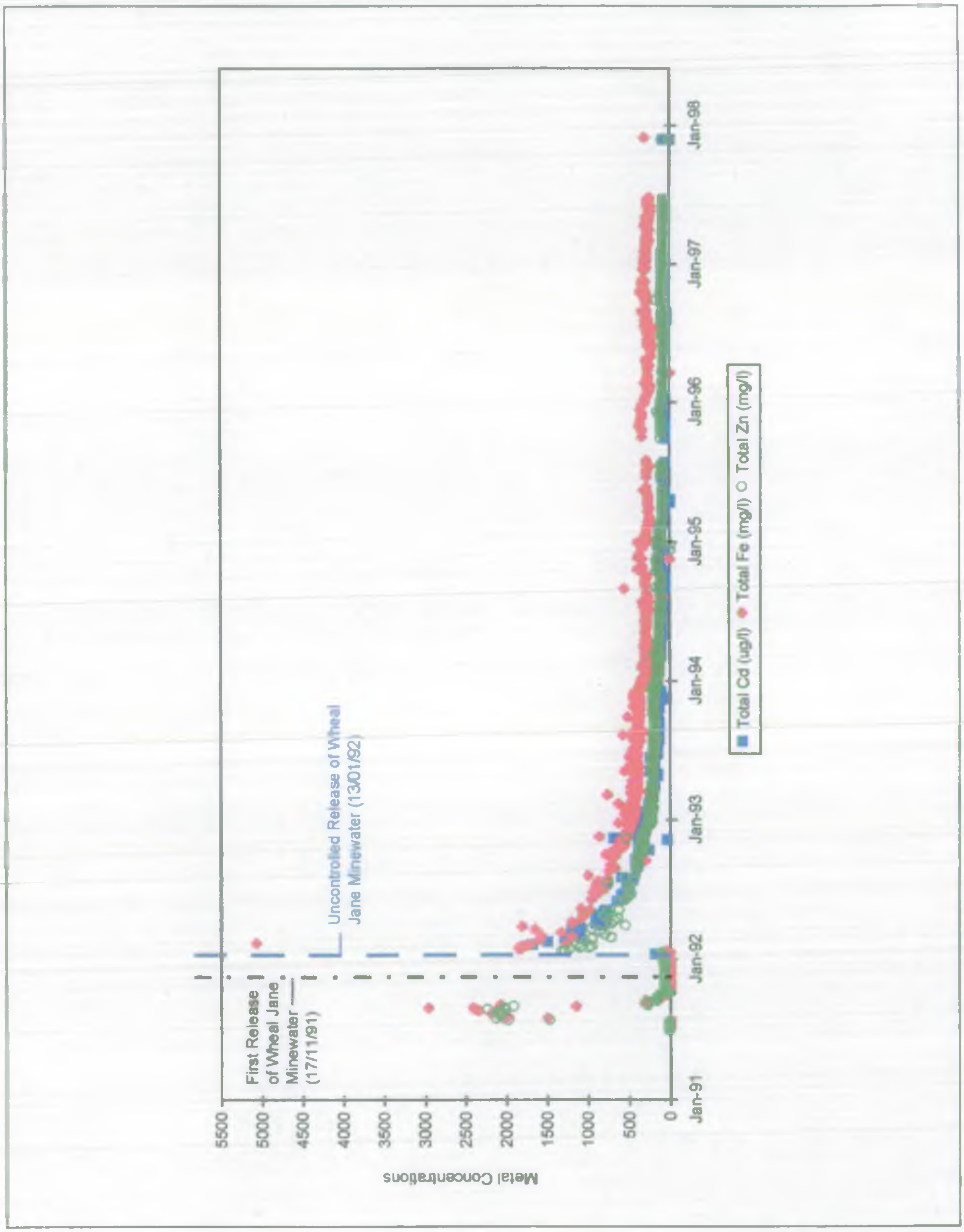
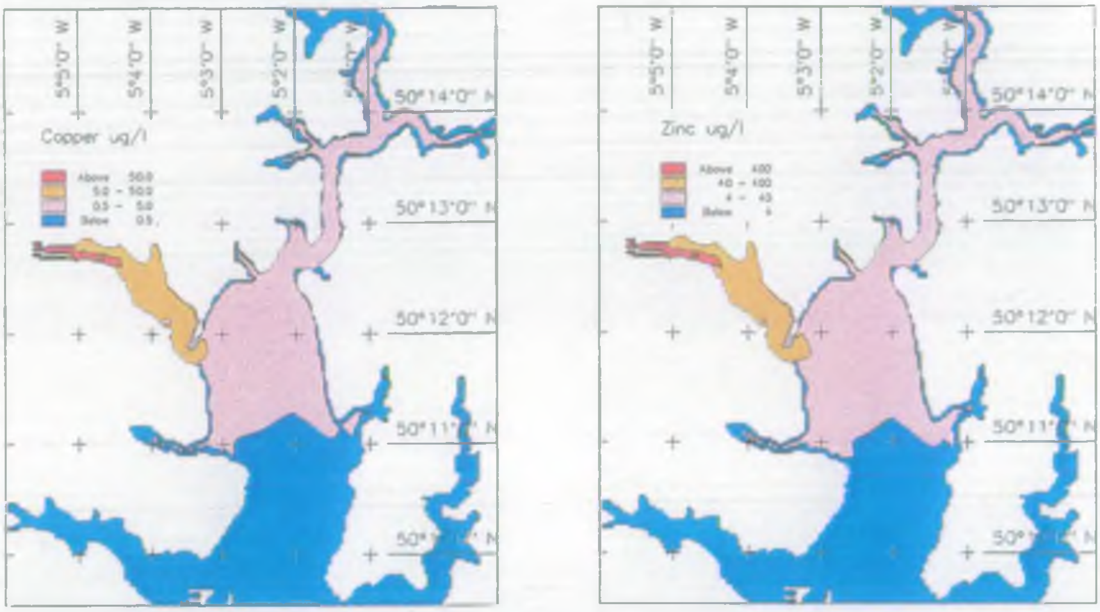
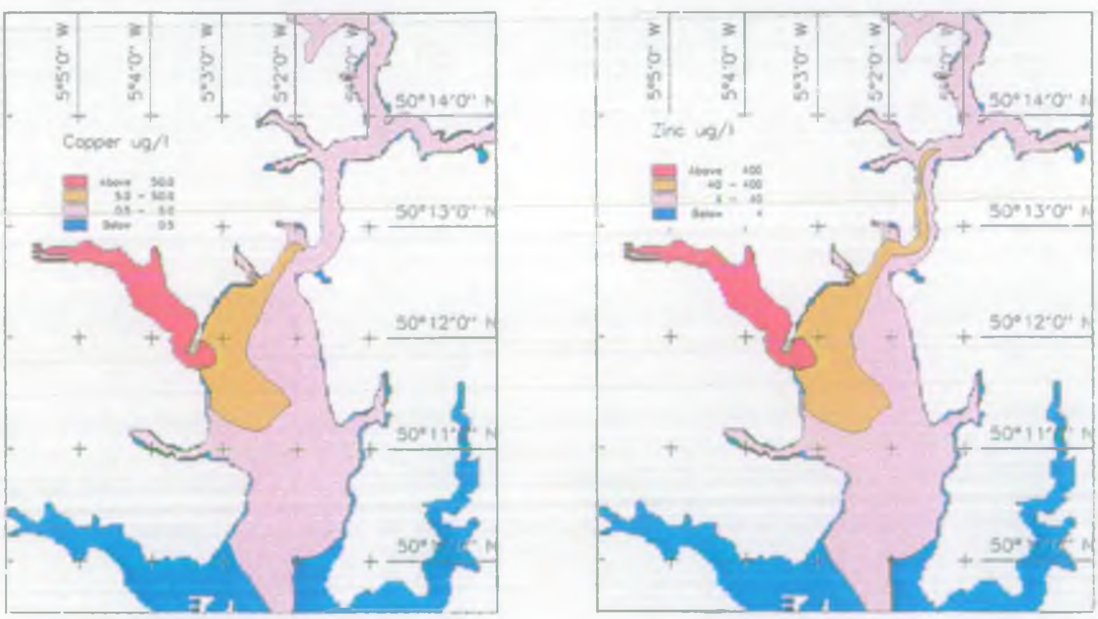


Figure 4.3 : Modelled Concentrations of Copper and Zinc in the Fal Estuary – All Wheal Jane to OCN Treated Effluent Quality



(a) Predicted annual average concentrations based on the average of annual averages for the 35 year period of predicted discharges from the Carnon River. Areas which fail the salt water standards under the EC Dangerous Substances Directive are mapped in orange. Uncertainty in the predictions is represented by the red and pink areas.



(b) Predicted absolute maximum concentrations based on the maximum predicted discharge over 35 years from the Carnon River and the minimum dilution likely to occur within a spring neap cycle. Areas predicted to fail the standards set under the EC Shellfish Waters Directive are mapped in orange. Uncertainty in the predictions is represented by the red and pink areas.

Figure 5.1 : Schematic Layout of Pilot Passive Treatment Plant

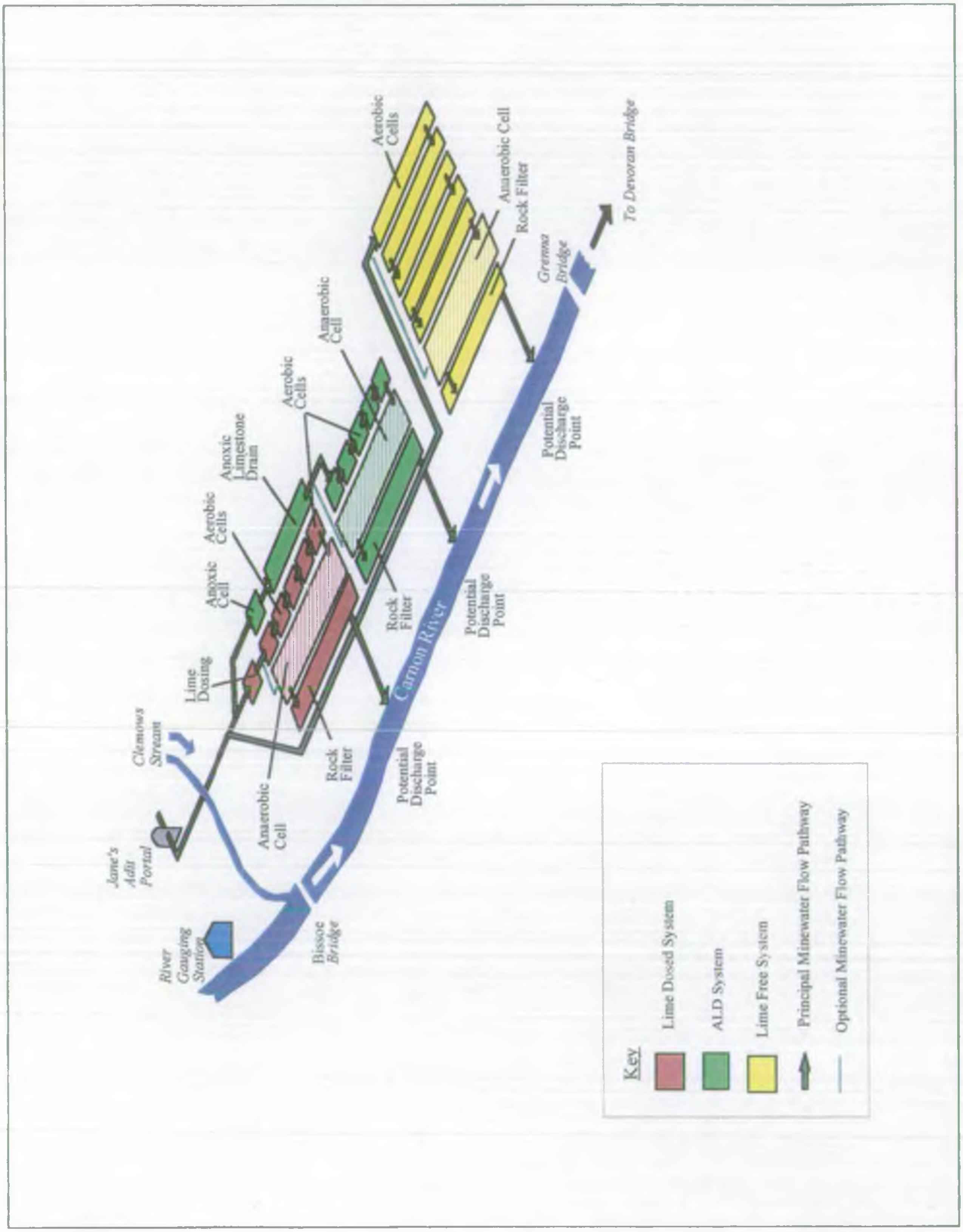


Figure 6.1 : Schematic to Illustrate Approach to Appraisal and Selection of Long Term Treatment Option

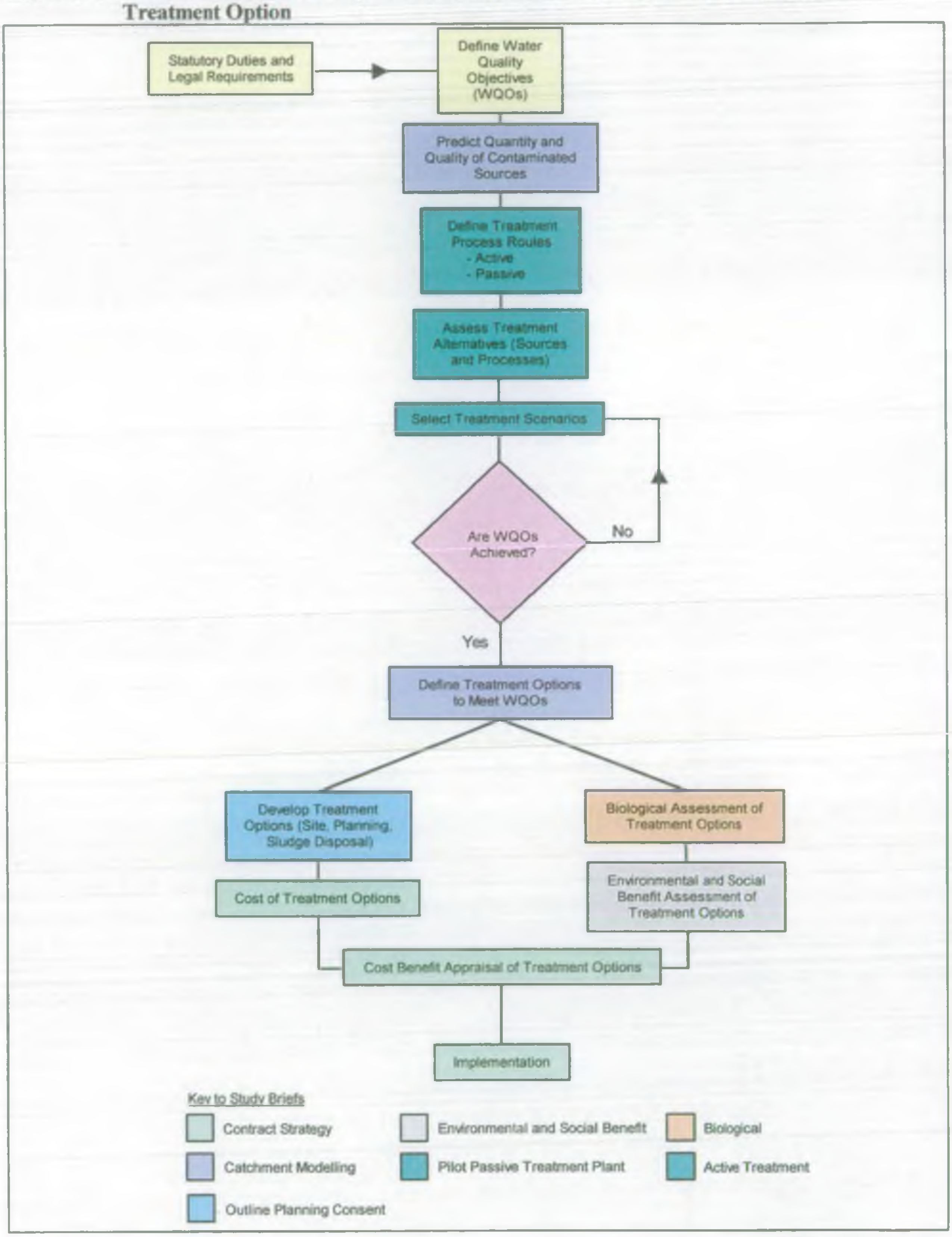
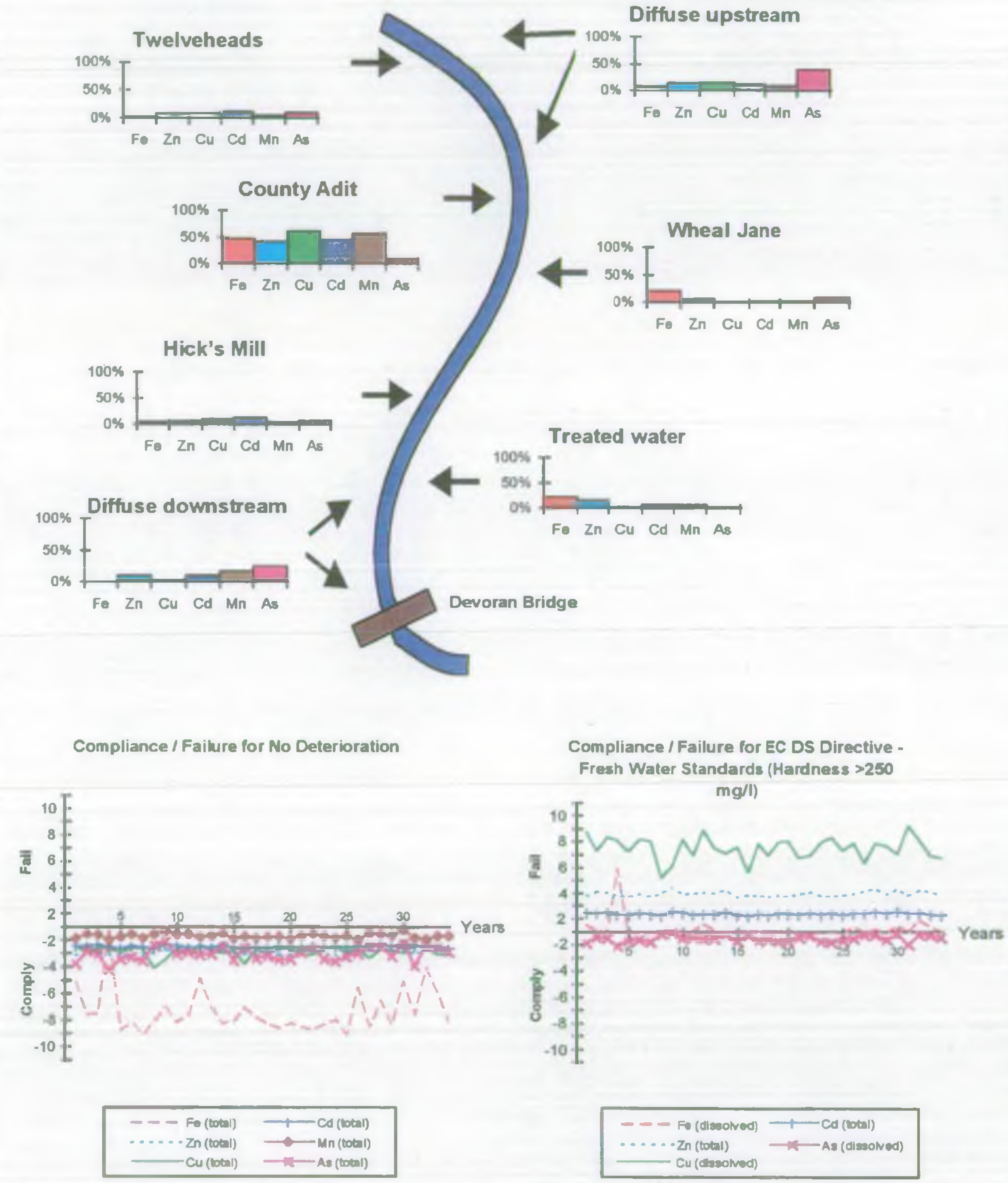


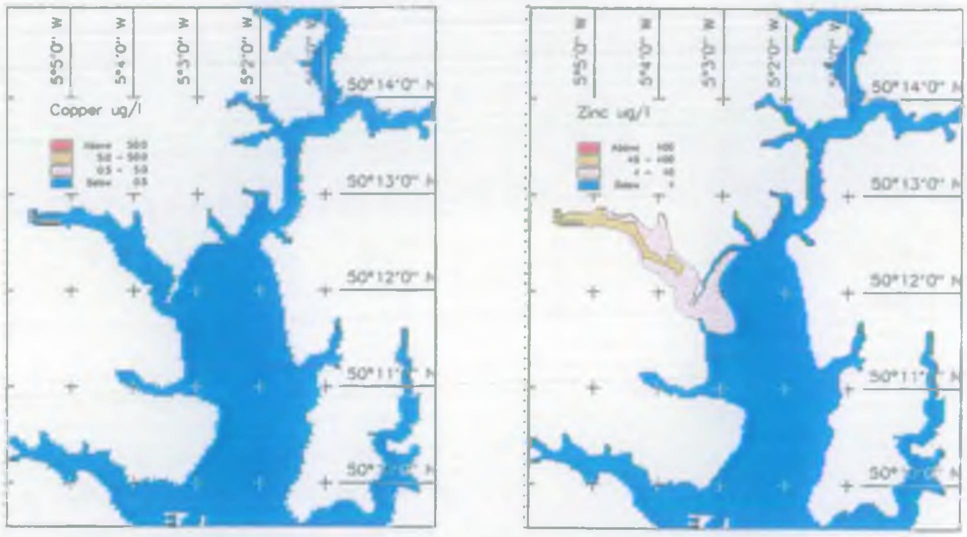
Figure 6.2 : Relative Contribution of Contaminant Loadings and Implications for WQOs - Six Pumps, OCN



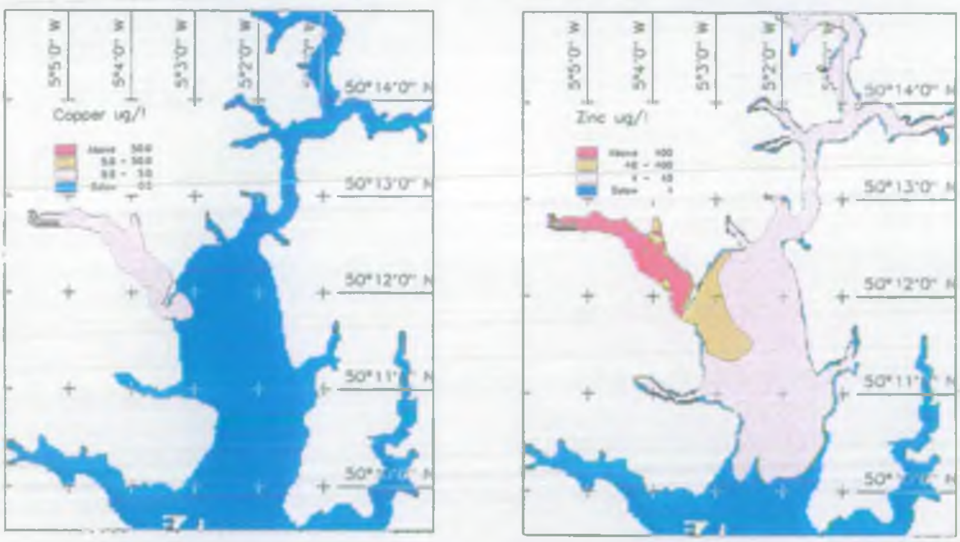
Note 1: Percentage contributions for all contaminants are based on total concentrations.

Note 2: Compliance / failure plots show the factor by which simulated annual average concentrations at Devoran Bridge achieve or fail the specified WQOs.

Figure 6.3 : Modelled Concentrations of Copper and Zinc in the Fal Estuary – Treatment of All Sources to Dervoran to OCN-IEX (I) Effluent Quality



(a) Predicted annual average concentrations based on the average of annual averages for the 35 year period of predicted discharges from the Carnon River. Areas which fail the salt water standards under the EC Dangerous Substances Directive are mapped in orange. Uncertainty in the predictions is represented by the red and pink areas.



(b) Predicted absolute maximum concentrations based on the maximum predicted discharge over 35 years from the Carnon River and the minimum dilution likely to occur within a spring neap cycle. Areas predicted to fail the standards set under the EC Shellfish Waters Directive are mapped in orange. Uncertainty in the predictions is represented by the red and pink areas.

Figure 8.1 : Site Location Plan

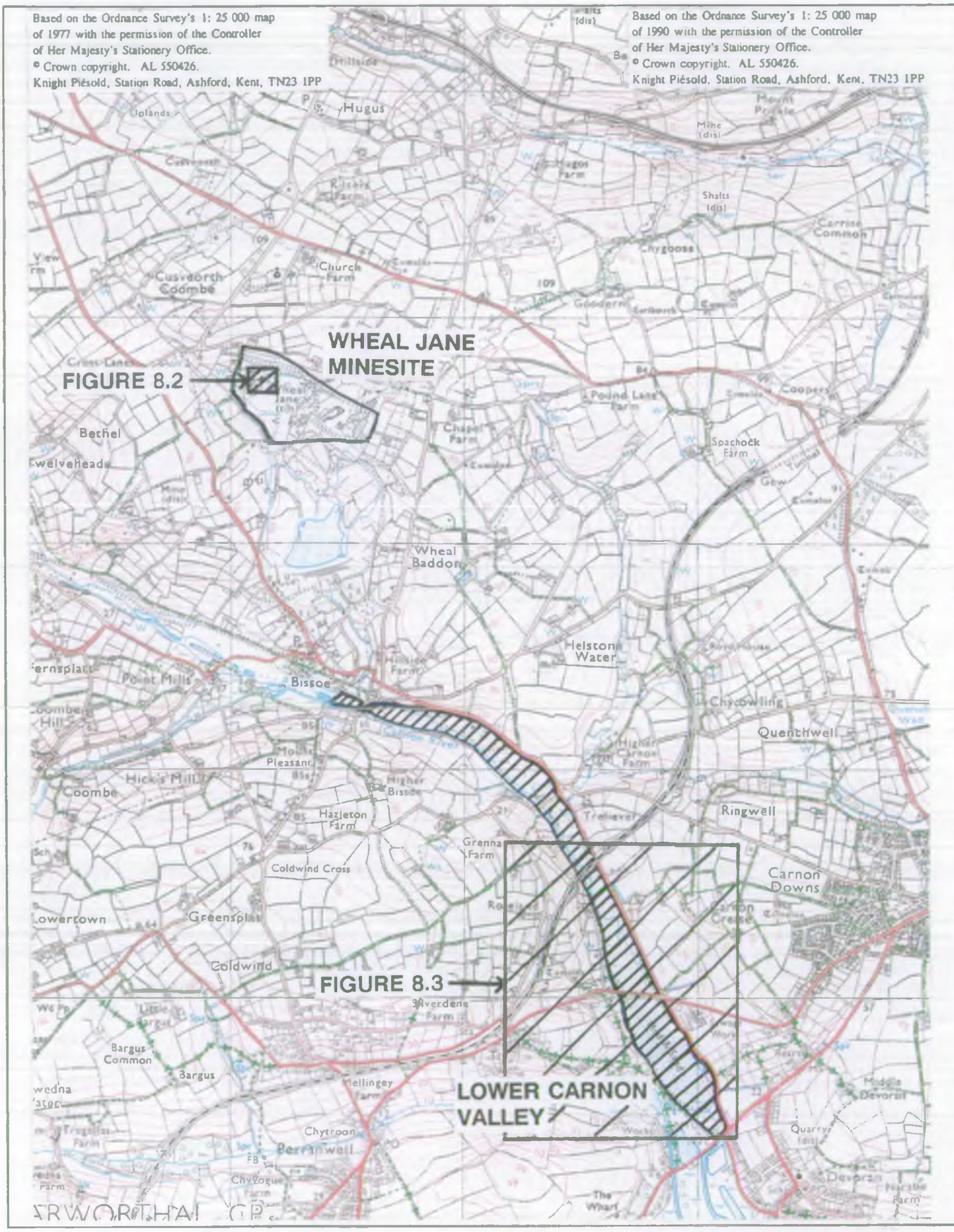


Figure 8.2 : Possible Plant Layout Diagram (OCN, Six Pumps at Wheal Jane)

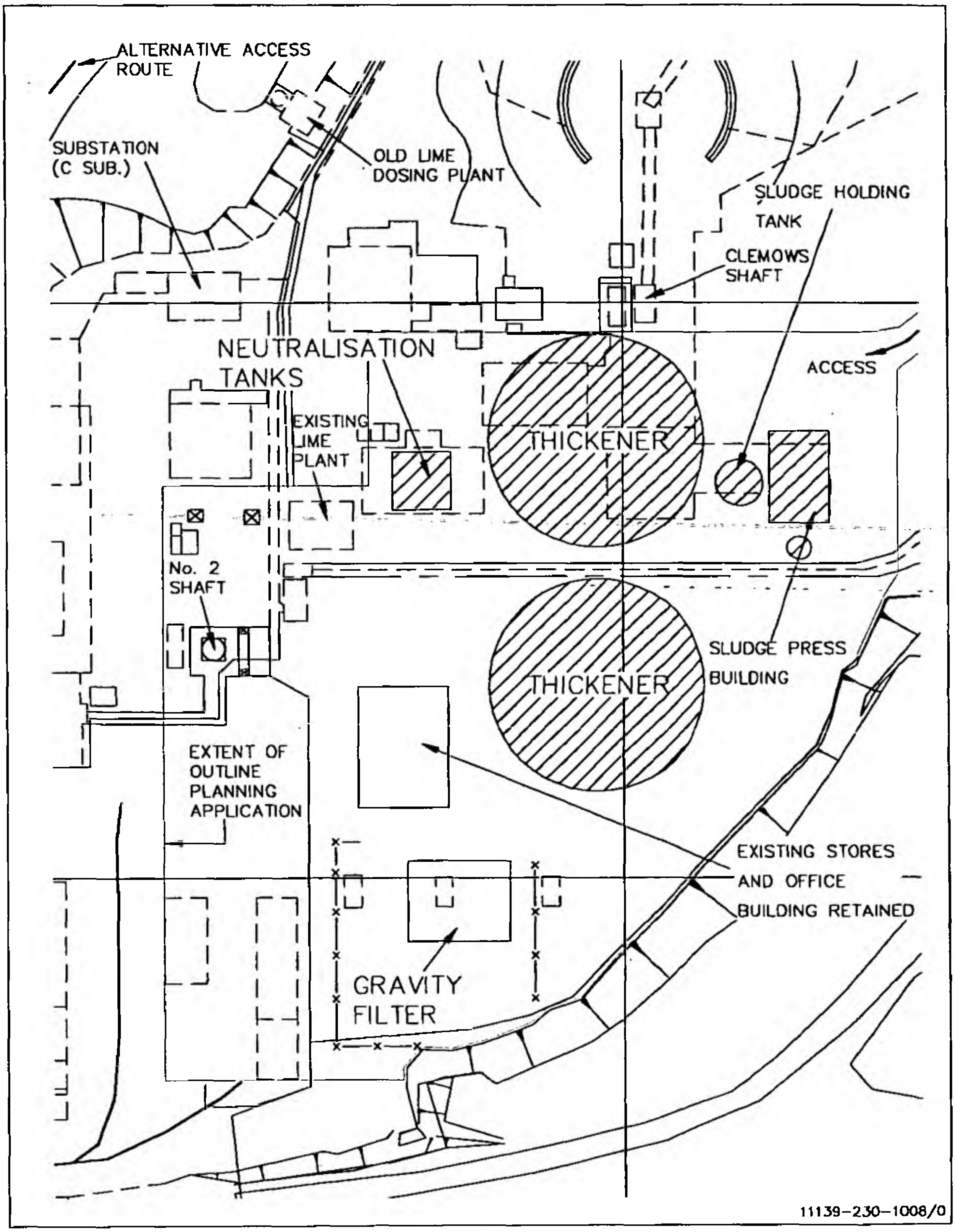


Figure 8.3 : Possible Plant Location Diagram, All Sources at Lower Carnon Valley.

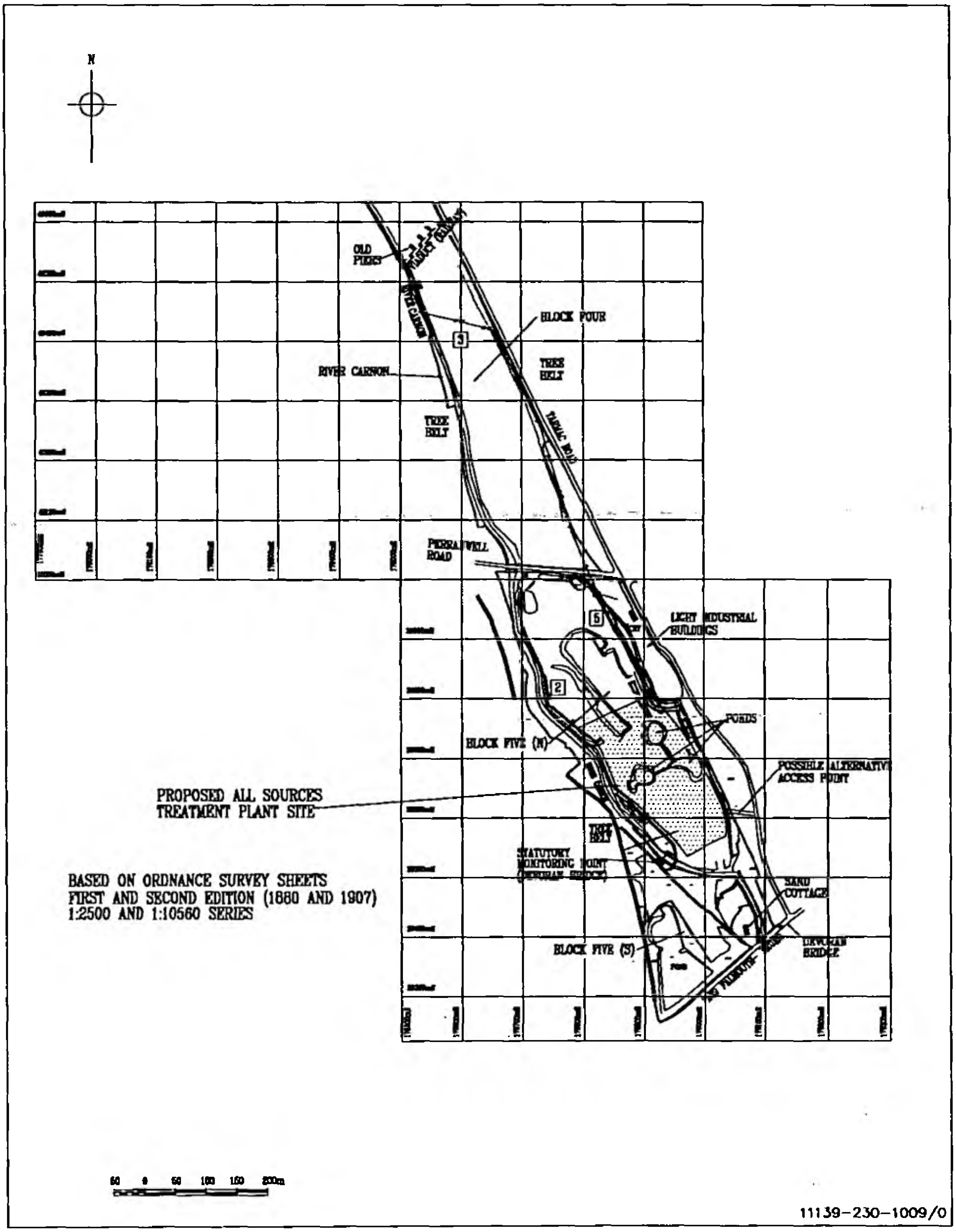


Figure 9.1 : Diversion of Catchment and Estuary into Reaches and Conservation Designations

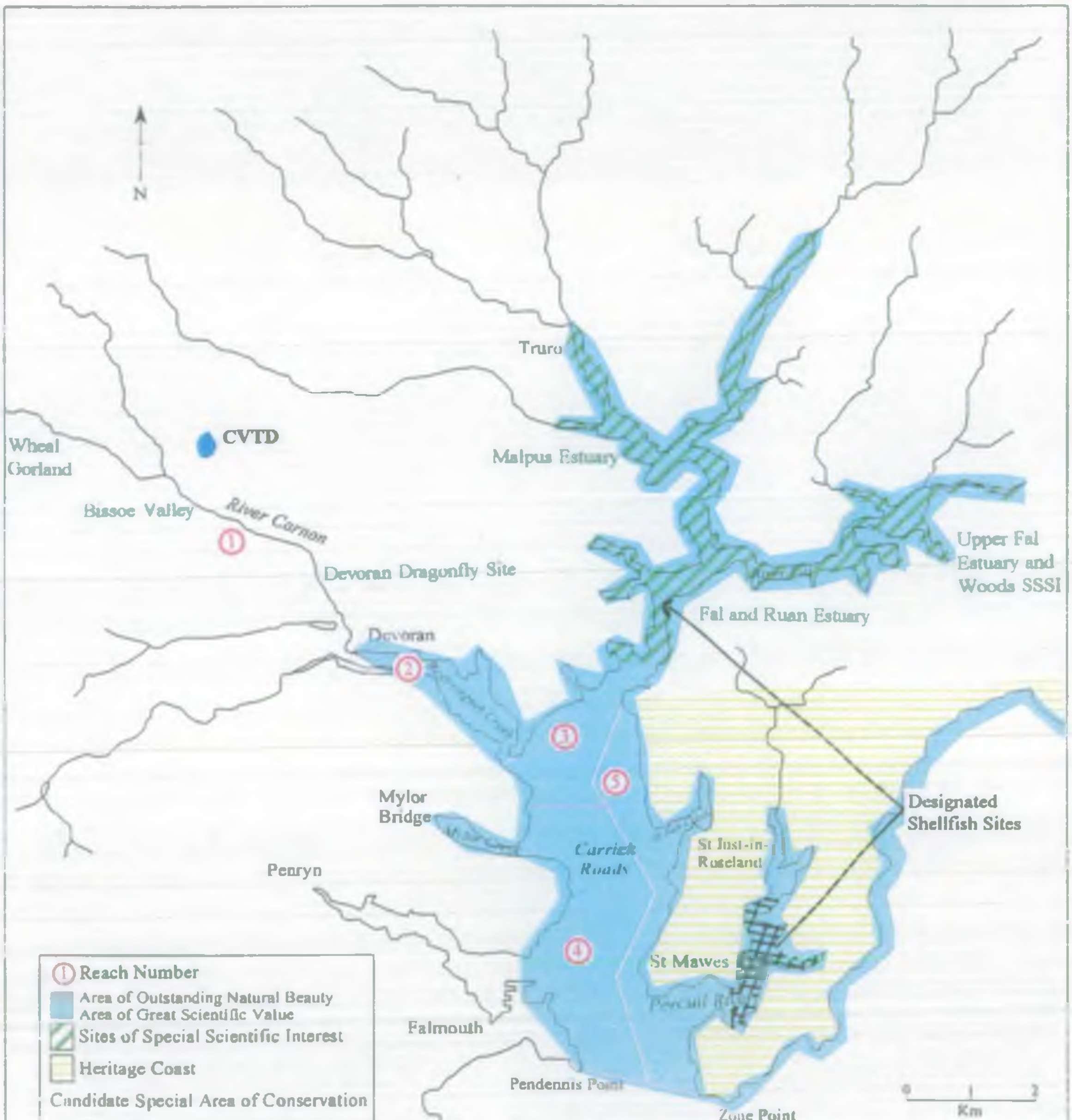


Figure 10.1 : Cost-Benefit Analysis - Summary

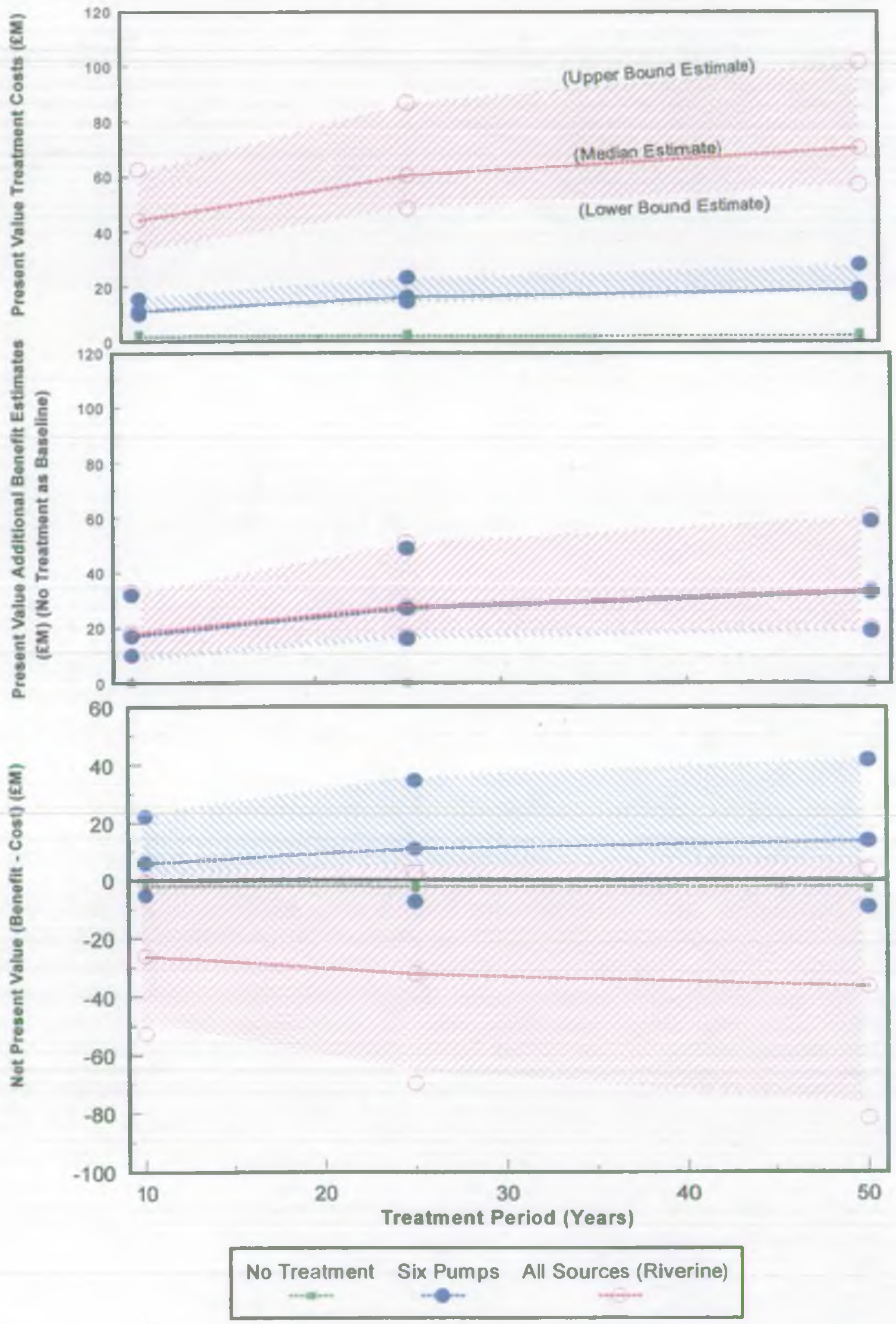


Figure 11.1 : Schematic of Payment Schedules Under Alternative Forms of Contract

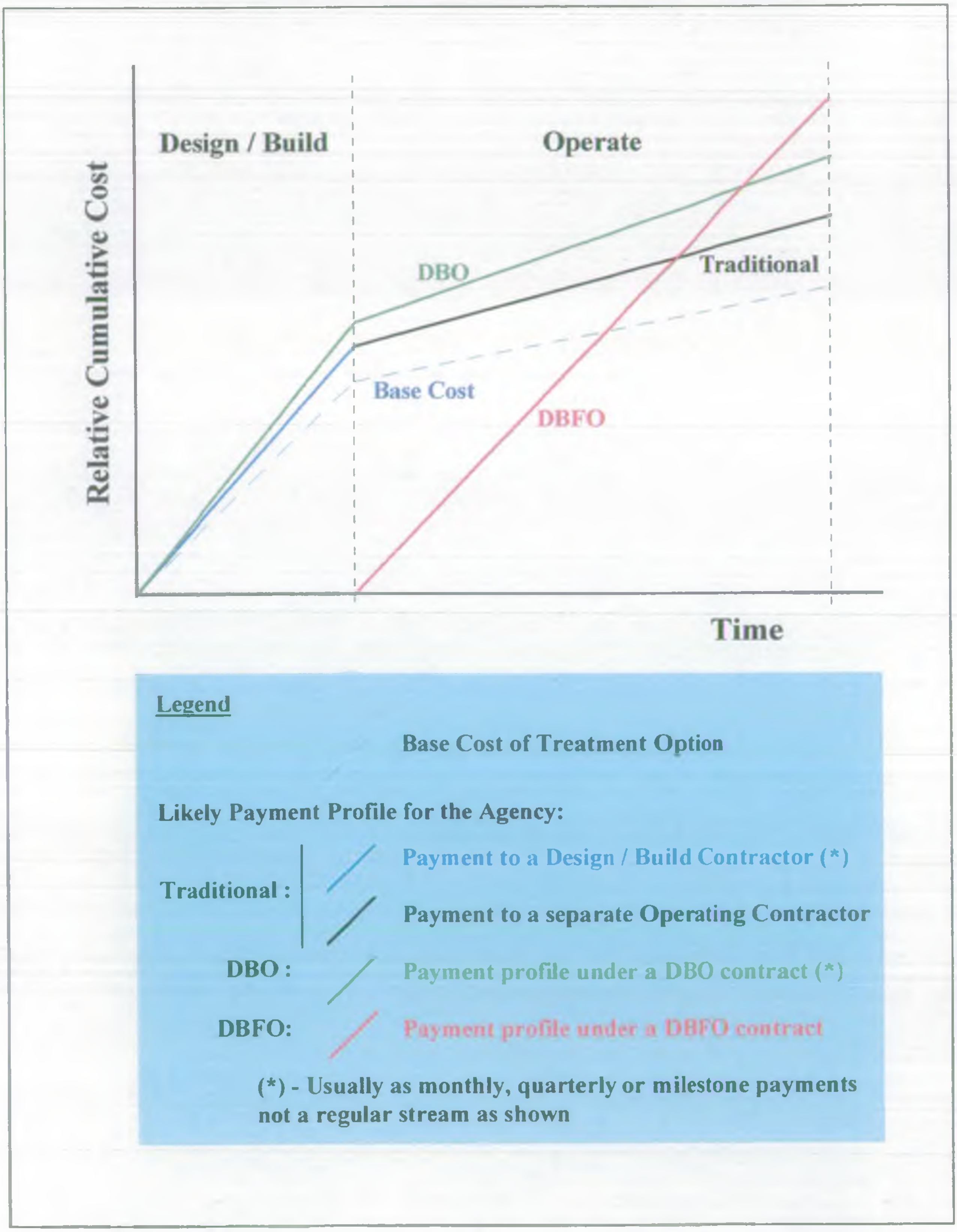
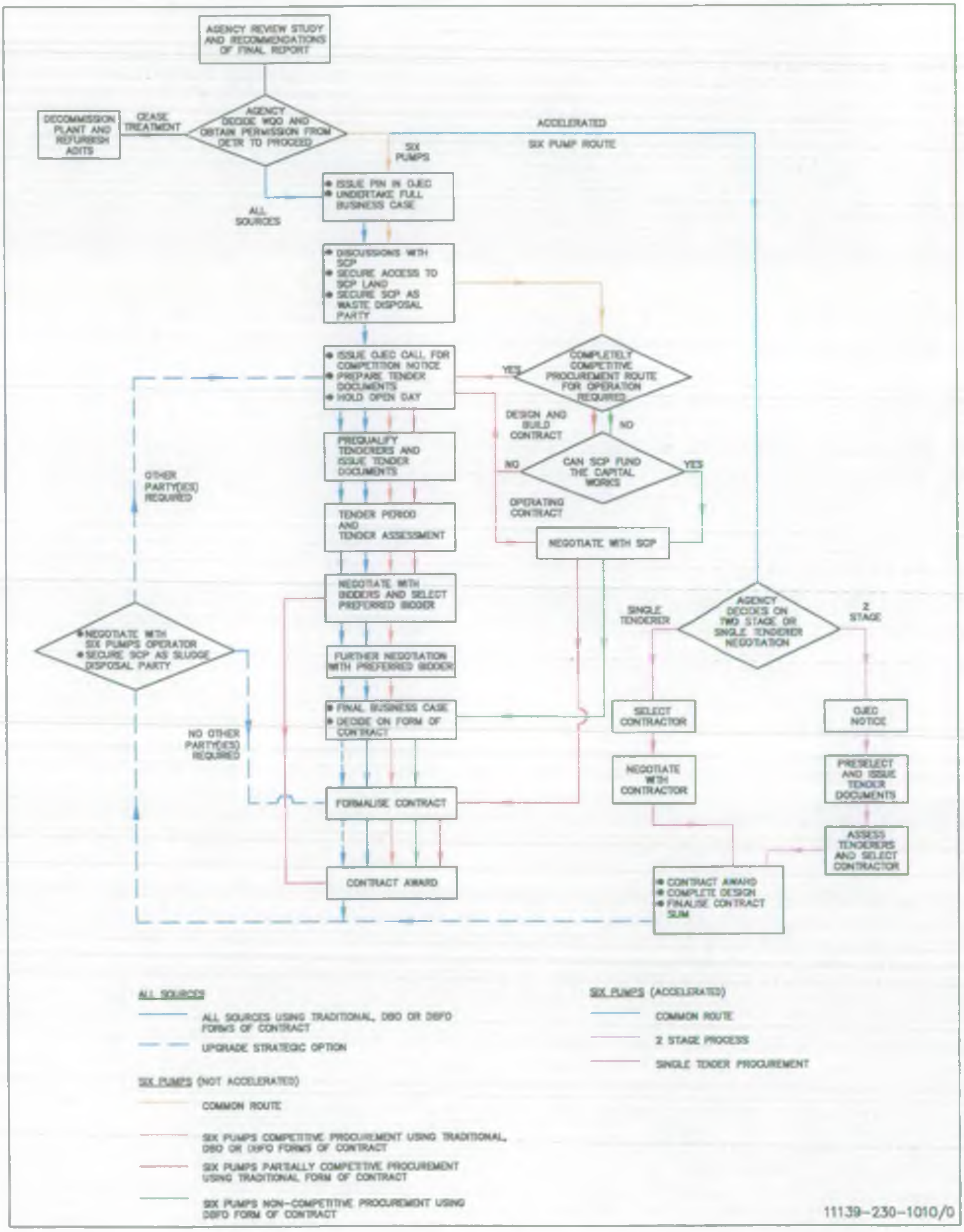


Figure 11.2 : Decision Paths for Alternative Treatment Options



PHOTOGRAPHS

Photograph 2.1 : Pollution Plume in Carrick Roads

Photograph 8.1 : Wheal Jane Mine Site and Clemows Valley Tailings Dam

Photograph 8.2 : Lower Carnon Valley