Management of the Eutrophication of the Peel Harvey Estuarine System

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MANAGEMENT OF THE EUTROPHICATION OF THE PEEL HARVEY ESTUARINE SYSTEM,

REPORT 3: FINAL REPORT

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Preface

Preparation of this final report of the feasibility study of management options for the Peel-Harvey Estuary was financially supported by the Department of Conservation and Environment and the Public Works Department of Western Australia.

This report summarises work done jointly by Bob Humphries and Chris Croft in the Centre for Water Research, The University of Western Australia, from March to November 1983.

Many of the management options discussed in this report were identified in a separate study undertaken by Bob Humphries in 1982. A number of other possible options arose during the course of this study.

The multidisciplinary nature of most of the options required a high level of interaction among several disciplines: primarily biology and engineering, but also agriculture, chemistry, forestry and others.

Chris Croft took principal responsibility for evaluating the engineering and catchment management options, including modified agriculture, conversion to forestry, use of wetland filters and bauxite residue amendment. He formulated the management strategy combining several options. Bob Humphries evaluated in-estuary chemical treatment, algae and weed harvesting options and the chemical treatment of surface drainage, predicting the probable effects of some options with a mass-balance model of salinity and nutrient dynamics.

Many people have contributed to this assessment of various management options, providing data, or advice, or both. We wish like to acknowledge:

- Dr Ernest Hodgkin, Dr Peter Birch, Dr Ross Field and Greg Forbes, Department of Conservation and Environment for advice and assistance on a wide range of topics covered by this study.

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- Warren Tacey and Don Glenister of Alcoa of Australia Ltd for information on soil amendment with bauxite residue and on chemical treatment of water draining to the Estuary.

- Keith Quayle of Atlas Copco for information on the Riplox method of sediment treatment.

- Jane Chambers, Department of Botany, The University of Western Australia for an evaluation of wetland filters.

- Phil Dufty and Rod Lukatelich of the Centre for Water Research, The University of Western Australia for the provision of data and advice on a wide range of topics. Phil Dufty and Keith Bowden also provided computer modelling support.

Many people assisted in the preparation of the reports for this study. We are grateful for the assistance of the typing and drafting staff at the Centre for Water Research, and for figure drafting by Brian Stewart and Tony Berman at the Department of Conservation and Environment. Sally Robinson (Department of Conservation and Environment), Bruce Simpson (Kinhill Stearns) and Lani Freeman (Centre for Water Research) critically reviewed the manuscripts.

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CHAPTER 1 INTRODUCTION

1.1 General

The Peel-Harvey Estuarine system, is a large (13300 ha), shallow (average depth 1 m) estuary approximately 70 km south of Perth, Western Australia (Fig. 1.1).

This study was initiated to investigate the feasibility of a wide range of management options proposed to solve the eutrophication problems in the estuary by evaluating for each option;

- the likelihood of success,
- the time required for the desired effect to occur,
- the practicability and cost,
- the potential level of nutrient reduction,
- the effects of implementation on the environment of the catchment and the estuary.

1.2 Statement of the Management Problem

Large algal populations in Peel Inlet and Harvey Estuary have reduced the amenity of the estuary for nearby urban areas, recreation, and professional fishing, and threaten the stability of the estuarine ecosystem.

Peel Inlet supports large populations of green algae which have created a public nuisance by fouling beaches since the early 1970's. These algae, primarily of the genera *Cladophora*, *Chaetomorpha*, *Enteromorpha* and *Ulva* grow in the deeper basins of eastern and western Peel Inlet, and on the marginal shallows of the system, including those in the northern Harvey Estuary.

The sources of nutrients supporting this growth were investigated in a comprehensive study of the estuary from 1976-1980. This study identified phosphorus as the primary nutrient controlling algal growth. The major source of phosphorus is the leaching and runoff of superphosphate from coastal plain agricultural soils into the surface drainage of the estuary's catchment.

The bulk of the phosphorus enters the estuary in winter during the seasonally high river inflows. The primary mechanism of phosphorus entrapment is diatom blooms, which trap phosphorus and allow subsequent recycling within the water, and between the water and the sediments. Recycling extends the residence period of phosphorus in the estuary, and results in enrichment of the estuarine sediments.

In the summers of 1978-1979 and every summer from 1980-1983, the nitrogen-fixing cyanobacterium *Nodularia spumigena* has bloomed, first in Harvey Estuary and then in Peel Inlet, leading to displacements of fish populations and localised fish kills. Collapse and decomposition of the *Nodularia* blooms releases nitrogen and phosphorus, which supports further growth of diatoms and green algae.

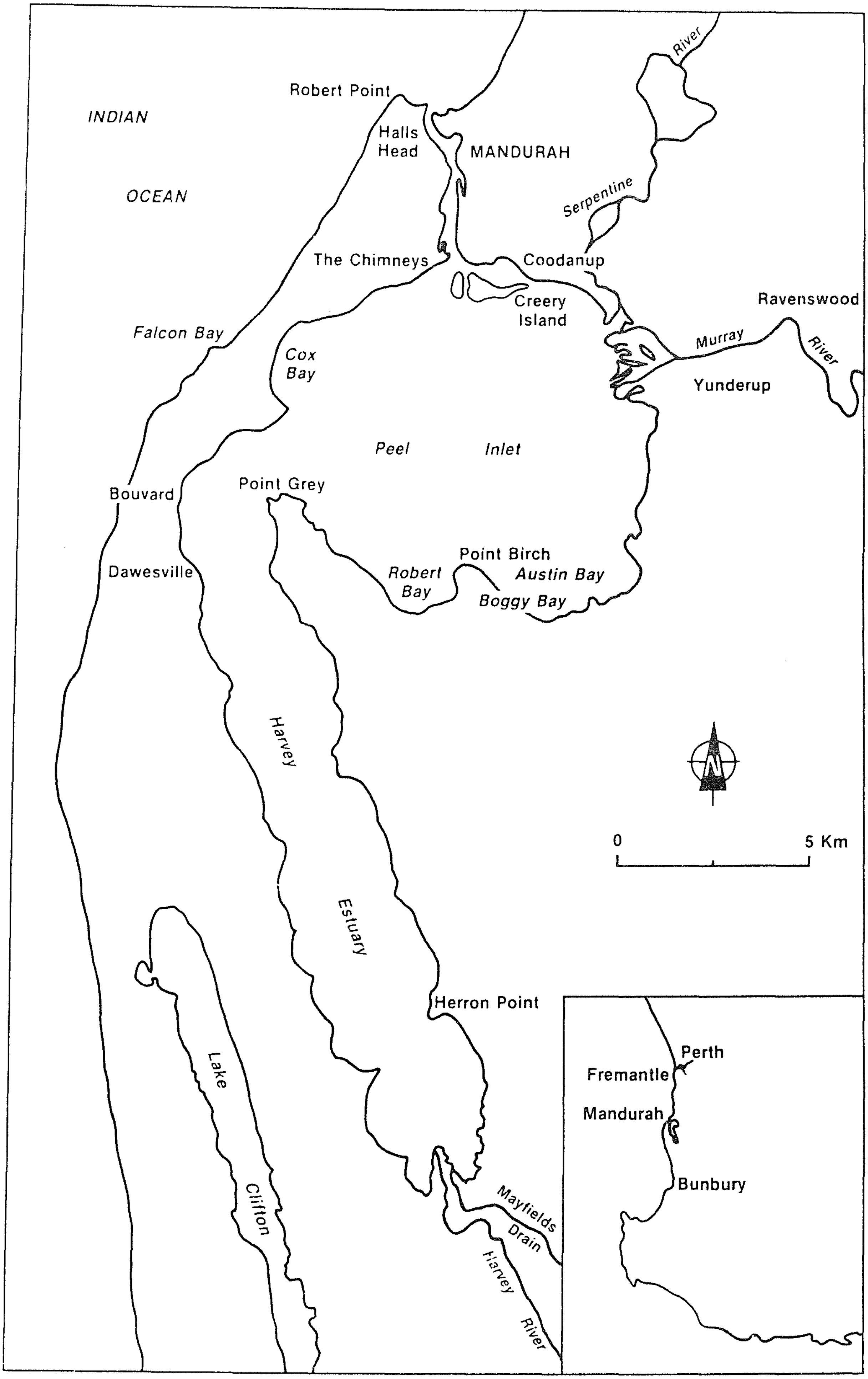

Figure 1.1 Locality plan

Systematic examination of the available data has shown that:

- about 80% of the external phosphorus load to the estuary originates from coastal plain agriculture,
- the annual phosphorus load is a function of coastal plain river inflow to the estuary (Figure 1.2),
- the severity of the Harvey Estuary *Nodularia* bloom (as measured by the observed peak of chlorophyll$_a$ concentration) is related to total phosphorus load into Harvey Estuary (Figure 1.2),
- winter diatom blooms probably represent the most important mechanism by which phosphorus is trapped in the estuary, because the inflowing phosphorus is mostly in soluble form. Sedimentation and recycling of this biologically 'fixed' phosphorus provides nutrition for subsequent macroalgal growth in Peel Inlet and for *Nodularia* growth,
- estuarine sediments seem to provide a transient nutrient storage, supporting further algal growth within the same growth season. In the absence of significant river inflow and phosphorus loading to the estuary (for example, as in 1979), major diatom and *Nodularia* blooms do not occur.

The causes of the progressive eutrophication of the estuary appear to be:

- the clearing of leaching soils for agriculture,
- increasing rates of superphosphate application from the mid-1940's until about 1970,
- increased runoff to the estuary due to clearing,
- introduction of seasonal, shallow-rooted crops,
- the construction of an elaborate artificial drainage network to reduce flooding of agricultural land.

At present, the yield of phosphorus from the catchment is primarily determined by the amount of rainfall and the resulting runoff to the estuary.

1.3 Potential Management Measures

Partial correction of the problem may be achieved in several ways, including:

- reduction of phosphorus fertiliser application rates,
- enhancement of agricultural soils' phosphorus retention
- diversion of phosphorus-enriched inflow from the estuary,
- chemical removal of phosphorus from waters flowing into the estuary,

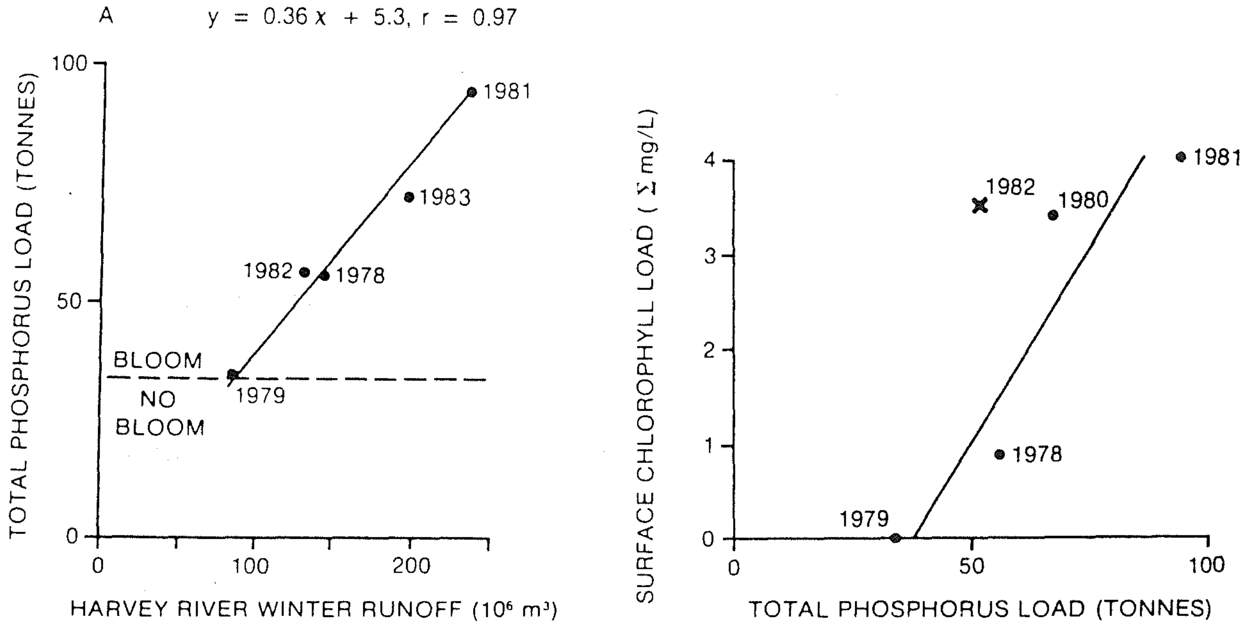

Figure 1.2 Interrelationships among Harvey Main Drain runoff, total phosphorus load and surface chlorophyll load for Harvey Estuary

- enhancement of marine flushing losses of phosphorus from the estuary,

- removal of nutrients stored within the estuary as sediment or biomass.

Figure 1.3 summarises the phosphorus flow paths to and within the estuary, and possible management responses. This study examines the relative merits of specific options derived from the general measures outlined above, with the aim of defining a cost-effective, ecologically and socially beneficial solution to the eutrophication of the estuary.

Two distinct management problems exist in the estuarine system: that of *Nodularia* blooms, predominantly in Harvey Estuary, and that of excessive macroalgal growth in Peel Inlet.

Control of *Nodularia* will only be achieved through sufficient reduction of the effective phosphorus loading to Harvey Estuary from the coastal plain catchment. Macroalgal growth in northern Harvey Estuary and in the Cox Bay (Falcon) area of western Peel Inlet (Fig. 1.1) also depends on nutrients from Harvey Estuary; these populations will decline if adequate control of phosphorus inputs is achieved.

Macroalgal populations in eastern Peel Inlet, however, are supported primarily by nutrient loads from the coastal plain catchments of Serpentine and Murray River systems; control of these algal populations will require either reduction of effective phosphorus loading from these sources, or direct attacks on the algae. These two geographically separate algal problems and their possible solutions are discussed more fully in subsequent chapters.

1.4 Philosophy of the Study

Managing the eutrophication of the estuary entails the clear conceptualisation of the goals of that management: that is, an image of the estuary as it might be in the future, with nutrient loading and algal growth kept within acceptable limits. As criteria for the design of a management strategy, these acceptable limits must be defined. For example, if it is suggested to reduce the phytoplankton population of Harvey Estuary to a particular level by increasing marine flushing, it is necessary to first define an acceptable level of phytoplankton, and then design a tunnel or channel of appropriate size to bring seawater into the estuary.

Table 1.1 lists proposed objectives for a management strategy for the estuary.

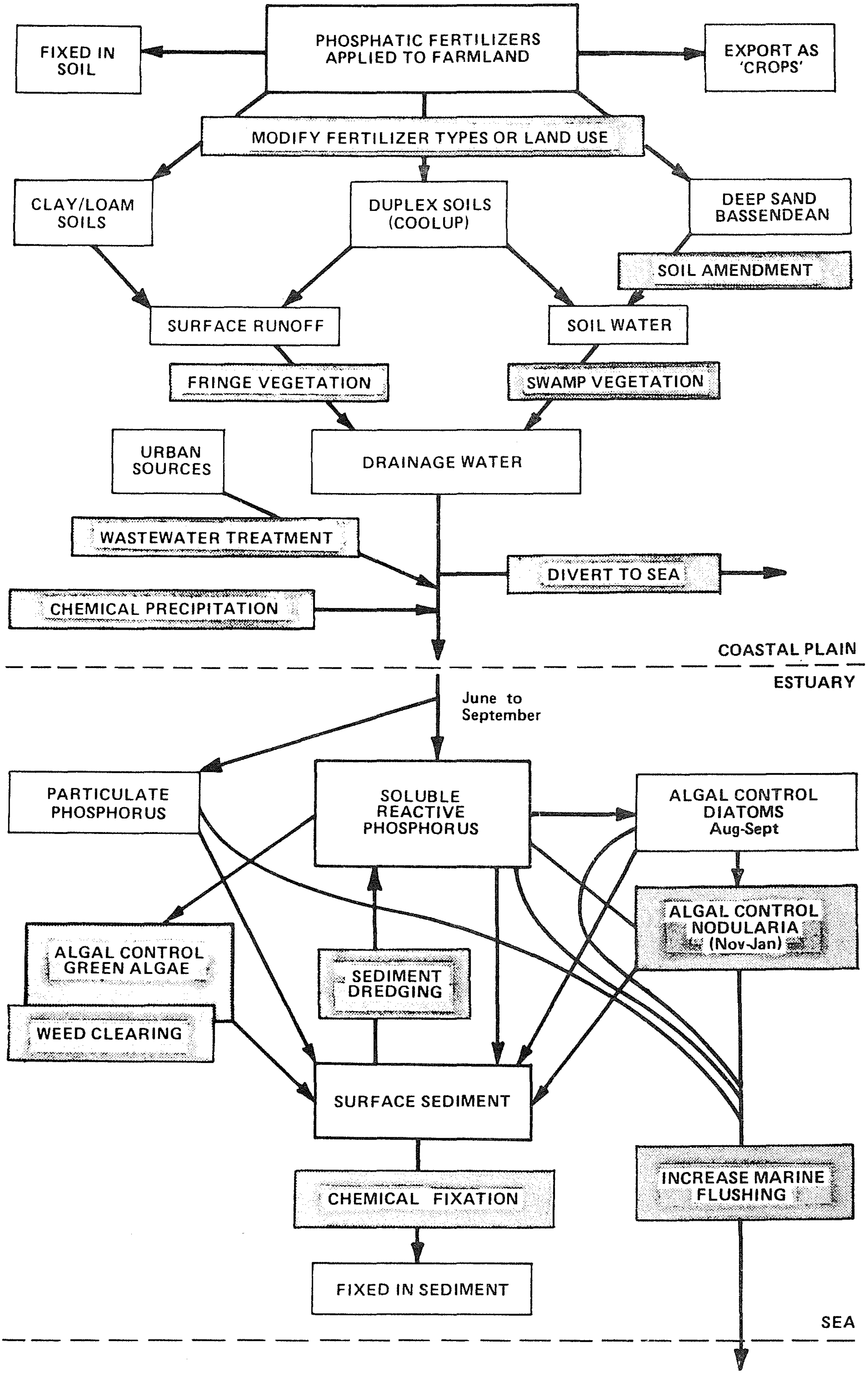

Figure 1.3 Phosphorus flow paths and potential management measures in the coastal plain and estuary

Table 1.1 A statement of proposed management objectives

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1. Cyanobacterial blooms are not to occur more often than one year in five. A bloom is defined as a peak cyanobacterial chlorophyll$_a$ concentration of 20 $\mu g l^{-1}$ or greater.
2. Macroalgal populations should not foul populated estuarine beaches.
3. Public access to the estuary by water or land should not be reduced.
4. Productivity of the estuarine fishery should be maintained.
5. Productivity of coastal plain agriculture should be maintained.
6. Changes to surrounding ecosystems should be minimised.
7. Introduction of exotic plants and animals should be avoided.
8. Major physical changes to the estuary, for example new channels, islands of dredge spoil, increased depth, changed bottom morphology, salinity and temperature regimes, should occur only in pursuit of the objectives stated above.

The size and complexity of the Harvey Estuary and its catchments make the choice of management strategies difficult, and predictions of the success of implementation uncertain. Major peculiarities of the estuarine system include:

- Extremely infertile, sandy, highly leaching soils throughout the coastal plain. Fairly high levels of phosphate fertiliser application are required to develop and sustain agriculture, and result in leached phosphorus entering the drainage in soluble form, rather than bound to particles.

- Most rainfall concentrated in the winter months of each year; this normal pattern results in an intense period of river-borne nutrient loading to the estuary, followed by a long period of high solar radiation, creating ideal conditions for aquatic plant growth.

- Highly variable rainfall and hence inflow to the estuary, and complex interrelationships among annual fertilizer application rates, soil types, and agricultural practices which aggravate nutrient loss to the estuary; estimates of the effectiveness of remedial measures will be necessarily uncertain.

- The large size of the estuary (13 300 ha) and its coastal plain catchment (280 000 ha), and the relative unimportance of point-source nutrient pollution; most corrective measures must be applied over large areas and distances, resulting in high costs.

Measures to reduce the loss of catchment nutrients to the estuary should take priority; the existing nitrogen and phosphorus leaching losses not only cause excessive algal growth within the estuary, but also reduce agricultural production and profit. Therefore, practical improvements to catchment management will improve both agriculture and the estuary.

Nonetheless, reduction of catchment nutrient losses alone may be insufficient to correct the eutrophic state of the estuary. Additional options were therefore considered and evaluated.

The performance of both the catchment and in-estuary management programmes will be subject to uncertainty. The 'data' will always be insufficient to dictate unambiguous conclusions, therefore management should remain flexible and ready to adapt to uncertainties.

As a corollary of this, fundamentally irreversible, or 'hard' options should be avoided where possible, and reversible or 'soft' options should be preferred.

A major advantage of 'soft' options is that they are usually applicable in other, similar situations. For example, use of slowly leaching (slow-release) fertilisers would probably benefit all sandy agricultural soils. Further, the performance of management manipulations can be monitored so that specific techniques can be improved, or abandoned as appropriate. 'Hard' options, in contrast, are usually site-specific, and involve the construction of permanent or semi-permanent structures in particular locations.

Changing various properties of the estuary in an attempt to reduce eutrophication may be viewed as an experiment. Many properties of the behaviour of the system will be revealed as a consequence of changing it, and uncertainty will be reduced if the processes of continual observation, analysis and interpretation are maintained.

1.5 The Assessment Procedure

The systematic procedure adopted for the evaluation of the individual management options is summarised in Fig. 1.4. Each option was subjected to a preliminary evaluation sequence, the procedure and criteria for which are summarised in Report 1 of this study. If the option appeared viable after preliminary evaluation, it was considered in more detail (see Report 2).

The more detailed evaluations were performed using computer modelling in the Centre for Water Research, preliminary design and evaluation studies by various branches of the Public Works Department, and joint studies with Officers of the Departments of Conservation and Environment and Agriculture, the Government Chemical Laboratories, and other members of the 'core' study group.

All estimated costs for the preliminary and detailed evaluation are expressed in 1983 dollars.

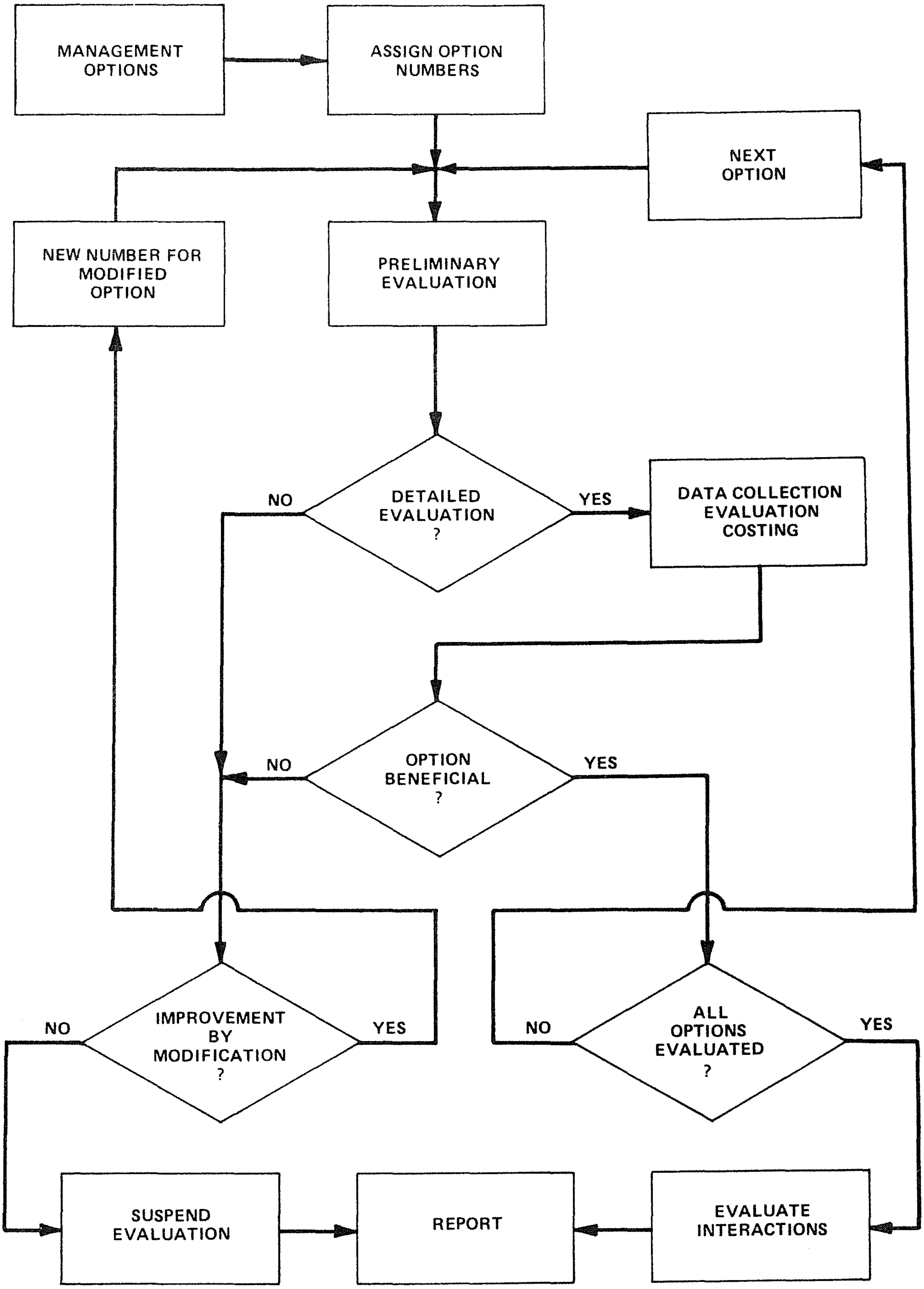

Figure 1.4 Management option evaluation logic

CHAPTER 2 THE RANGE OF OPTIONS

2.1 Introduction

The terms of reference for the feasibility study (included as Appendix I of this report) required canvassing a number of sources to define possible management options. Approximately 120 options were identified, some of which represented minor variations on each other.

The options considered can be broadly classified into five major groups:

- Direct attack on nuisance organisms, including harvesting, use of algicides, viral/bacterial control and dredging.
- Reduction of phosphorus application to the catchment and subsequent phosphorus leaching from the crop root zone to drainage. This includes the use of soil testing to determine phosphorus requirements, new slow-release fertilisers, altered times of fertiliser application, changes in current land use, and soil amendment with bauxite residues.
- Reduction of phosphorus export to the estuarine system through the drainage network. This includes the use of biological filters, diversion and chemical treatment of drainage water.
- Reduction of estuarine sediment phosphorus re-cycling within the water column by dredging or chemical treatment of sediments.
- Increasing phosphorus loss through enhanced marine flushing. This includes modification of existing Mandurah Channel, tidal pumping, redirection of Harvey River Diversion Drain flows to the Harvey Main Drain, and the creation of new ocean channels.

2.2 Results of Preliminary Evaluations

The results of the preliminary examination of all options, detailed in Report 1, are summarized in Tables 2.1 to 2.5.

The options were first examined for their potential to control the algal problems, and their estimated cost; other important effects were tentatively identified. After this initial study, options considered unsuitable were discarded. The remaining options are discussed in Chapter 3 of this report.

Table 2.1 Options to reduce populations of nuisance algae

Option Description	Results of Preliminary Investigation	Recommendation
Biological control by - Pathogens to attack *Nodularia* - Grazing by fish, zooplankton or protozoa - Environmental changes	1) No suitable pathogens have been found to control *Nodularia* blooms. 2) *Nodularia* generally unpalatable to grazers. 3) Macroalgal blooms are the result of insufficient grazing potential within the system. 4) Literature survey suggest no suitable exotic fish species could tolerate the current salinity ranges in the estuary. 5) No current information available to evaluate either iron chelation to prevent algal growth, or dyes to prevent light penetration to the water sediment interface.	Detailed evaluation not recommended.
Explosive treatment of positively buoyant algae	1) Peak pressures of 450 kPa required to collapse gas vacuoles. 2) Possible mortality of 40% of fish population 3) Algae recover in 72 hours.	Detailed evaluation not recommended.
Dredging to: - deepen marginal shallows to approximately 1 m - prevent macroalgal growth in selected areas	1) Dredging of marginal shallows should be to at least 1.5 m to have a benefit under current light conditions. 2) Disruption of habitat for juvenile commercial fish. 3) Dredged shallows would act as a pool for decomposing algae washed in from deeper regions. 4) Dredging to prevent macroalgal growth could increase phytoplankton and alter the food chain.	Detailed evaluation not recommended.

Table 2.1 Continued

Option Description	Results of Preliminary Investigation	Recommendation
Beach and offshore harvesting in Peel Inlet to remove macro-algal accumulations from populated areas.	1) Two operations used: - removal from beaches using front-end loaders and truck transport. - offshore harvesting, with truck transport. 2) Beaches cleared of algae require periodic nourishment to replace lost sand. 3) Offshore harvesting preferable, to minimise impact on estuary beaches. 4) Occasional algal beachings will result from winter storms. 5) These options will reduce the adverse effects of macroalgae, but will not significantly deplete nutrients from the estuary. 6) The harvested algae are used for soil stabilization, but may also be used for stockfeed.	Detailed evaluation required for incorporation into a management strategy.
Algicides to control nuisance algae.	1) Two types of compounds considered, toxins and growth inhibitors. 2) Information from suppliers on cost, application timing and techniques, chemical and physical properties, toxicity and availability. 3) Two chemical groups identified - **copper compounds**: not recommended due to toxicity to non-target organisms, accumulations in food chains and inactivation in alkaline waters, - **organic compounds** recommended for further evaluation. 4) Best time of application for Nodularia prior to bloom. 5) Best time of application for macroalgae in early summer to enhance nutrient loss. 6) Problems associated with sediment application through adsorption, coverage by settling sediment and dilution through mixing into the water column.	1) Further evaluation of copper compounds not recommended. 2) Detailed evaluation of organic compounds required

Table 2.2 Options to reduce phosphorus fertiliser application and leaching rates

Option Description	Results of Preliminary Investigation	Recommendation
Test of soil phosphorus status to predict application rate and fertilizer type.	1) Previously used calibration curve resulted in excessive use of fertilisers. 2) Cost of testing \$30 for 6 samples. 3) Cost savings to farmers from reduced fertiliser application \$3-\$6 ha^{-1} yr^{-1}. 4) Reduction in application of 60% short-term, 40-50% long-term for deep grey sands.	1) Use of soil test recommended. 2) Detailed evaluation required.
New slow-release fertilisers that provide a plant-available phosphorus source that is not readily leachable and can provide sulphur to maintain production.	1) Fertilisers are being developed to reduce leaching and provide adequate phosphorus for plant growth. 2) Sulphur requirements could be provided by either gypsum or bound elemental sulphur. 3) Cost of new slow-release phosphate fertilisers higher than superphosphate, but cost per ha similar.	1) Use of new fertilisers recommended. 2) Detailed evaluation required.
Application of fertilisers in spring rather than in autumn.	1) Increased plant uptake of phosphorus variable and marginal. 2) Timing of fertiliser application for maximum uptake may not result in maximum yield. 3) Adverse farmer reaction to early spring application due to wet soil leading to bogging and also possible disruption to mechanised hay carting because of ruts in paddocks.	1) Delaying fertiliser application not recommended. 2) Detailed evaluation not required.
Changes in current land use by conversion of agricultural land to parkland or forest.	1) Cost of resumption of Bassendean sands in the Harvey catchment about \$10M. 2) Forestry would reduce the quantity of fertilizer applied, intercept phosphorus in ground water, reduce runoff to estuary, use present soil store of phosphorus and partially offset cost of resumption.	1) Detailed evaluation required.
Amend leaching soils with bauxite residue.	1) Reduction in phosphorus leaching rates probable. 2) Application rates 200 to 1000 t ha^{-1}. 3) Some increase in productivity probable. 4) Cost to load, cart and spread approximately \$4 t^{-1} (i.e. \$800-\$2000 ha^{-1}).	1) Detailed evaluation required.

Table 2.3 Options to reduce the export of phosphorus to the estuary through the drainage network

Option Description	Results of Investigation	Recommendation
Use of biological filters to strip phosphorus from surface drainage.	1) Even for minor drains, inflow rates were too high to permit adequate phosphorus removal by plant uptake.	Detailed evaluation not recommended.
Biological filters or chemical methods to treat rural point source effluents.	1) In successful use elsewhere. 2) Point sources of nutrients not currently considered an important component of phosphorus load to estuary.	Detailed evaluation required.
Nutrient removal by swamps and swamp margins.	1) Fringing vegetation could remove nutrients and impede flow from the swamps. 2) No acceptable open water plant types were found that would remove significant quantities of phosphorus from the swamps.	Detailed evaluation not recommended.
Diversion of drainage to sea through coastal lakes with a barrage at Herron Ford (i.e. through lakes Clifton and Preston).	1) Diversion would cause coastal lakes to become eutrophic. 2) Changes in salinity regimes in coastal lakes would favour freshwater cyanobacteria.	Detailed evaluation not recommended.
Diversion of drainage to sea with a barrage at Point Grey and outflow tunnels to the ocean.	1) Harvey Estuary would become a freshwater lake. 2) No expected reduction in algal blooms for Harvey Estuary, however, a change in species would occur. 3) Significant inundation of land behind barrage.	Detailed evaluation not recommended.
Diversion of drainage to sea with a barrage at Herron Ford.	1) Outlet by gravity through tunnel and pipes, low level pumping through tunnels and pipes or high level pipelines, high level pumping and open channels. 2) Barrage pipes and tunnels designed for 1982 winter inflows with barrages 1.5 m and 3 m above existing water level and with flow rates of 5.8 and 10.4 $m^3 s^{-1}$. 3) Capital and operating costs evaluated for each scheme ranged from \$17.4M capital \$1.4M yr^{-1} operating to \$49.1M capital \$1.2M yr^{-1} operating cost. 4) Inundation areas behind barrages calculated to be 500 ha for +1.5 m water level and 1400 ha for +3.0 m water level.	Detailed evaluation required.

Table 2.3 Continued

Option Description	Results of Preliminary Investigation	Recommendation
River flow deflectors in Peel Inlet.	1) Full and partial deflectors considered. 2) Deflectors would tend to trap algae near Coodanup beaches. 3) For the partial deflectors, even a narrow gap would not direct sufficient flow away from the estuary. 4) Full levee would restrict access to Coodanup area from the water, and would increase Yunderup and Coodanup flood risk.	Detailed evaluation not recommended.
Chemical removal of phosphorus from surface drainage using limestone adsorbants.	1) Adsorbant capacity of limestone low compared with clays or bauxite residue. 2) Length of bed 1.3 km in the drain for anticipated 50,000 m^3 day^{-1} throughput. 3) Adsorbant capacity at anticipated throughput exhausted in 2 days.	Further evaluation not recommended.
Chemical treatment plants to remove phosphorus from Harvey Main Drain flows.	1) A number of different schemes were reviewed. Significant problems due to: - inability to provide impoundment, therefore high rate of treatment required, - floc filtration or stilling away from the from the estuary not feasible, - high capital and operating costs of high efficiency systems to cater for low concentration of phosphorus in water input. 2) Small scale treatment at effluent point sources or minor drains may be possible.	1) Further evaluation of large scale treatment not recommended. 2) Further evaluation of small scale treatment required.

Table 2.4 Options to reduce estuarine sediment phosphorus recycling with the water column

Option Description	Results of Preminary Investigation	Recommendations
Chemical treatment of estuarine sediments to inactivate phosphorus.	1) Two chemicals investigated, alum and nitrate salts. 2) Application to the water column not favoured due to advective losses and chemical disturbance. 3) Application to sediments by compressed air and a harrow may be beneficial, however sediment resuspension and biogenic disturbance of sediments may reduce its effectiveness. 4) A significant reduction in external phosphorus loading must be achieved for these techniques to work.	Further evaluation required.
Dredging to remove sedimentary phosphorus store in the top 100 mm.	1) A significant reduction of external phosphorus loading must be achieved for this technique to provide long term benefits. 2) Expensive when compared with chemical treatment of estuarine sediments.	Further evaluation not recommended.

Table 2.5 Options to increase the loss of nutrients by enhanced marine or river flushing

Option Description	Results of Preliminary Investigation	Recommendations
Mandurah Channel dredging to increase nutrient loss to the sea by marine flushing.	1) Dredging in four areas was examined and increases in nutrient loss of 33-40% in summer and 20-30% in winter were calculated. 2) The cost of improvements to the existing channel plus a new 200-m wide channel across the southern shelf was about $3M and would take approximately 1-2.5 years to complete. 3) Increased flow rates of about 20% may cause scour problems near the existing Mandurah Bridge. 4) Temporary disruption to benthic habitats and the passage of migratory organisms would occur; however, these effects could be minimised by staged dredging. 5) Some spoil could be used to create an island in Peel Inlet.	Detailed evaluation is required.
Creation of a new Channel parallel to the existing Mandurah Channel.	1) Existing development at Halls Head would restrict the channel width to 120 m. 2) Maximum increase in water exchange only 20% 3) Excavation of approximately 1.5 million m^3 of material required. 4) Cost of construction about $10M. 5) Proposal suggested construction cost would be borne by Parrys Esplanade Limited. 6) This scheme is not compatible with existing development.	Further evaluation not recommended.
Tidal pumping through a tunnel or pipes from the ocean to southern Harvey Estuary.	1) Diurnal tidal differences between Estuary and ocean approximately 0.4 M. 2) Long term barometric tidal level differences would not provide significant additional pumping potential. 3) A 3 m diameter tunnel would introduce about 70% of the Harvey Estuary volume in sea water per year.	Further evaluation not recommended.

Table 2.5 Continued

Option Description	Results of Preliminary Investigation	Recommendations
Redirection of Harvey Diversion Drain flow to Harvey Main Drain.	1) Rerouting flow would increase inflow to the estuarine system from 5.5 to 5.8 estuary volumes in an average year. 2) Flooding of 3000-4000 ha yr^{-1} would result if widening of the Harvey Main Drain were not undertaken. 3) Cost of widening Harvey Main Drain about $10M. 4) No significant decrease in nutrient concentration or increase in flushing would be achieved.	Detailed evaluation not recommended.
Siting of a power station on the southern shores of Harvey Estuary.	1) Proposal was to use seawater cooling for the power station to increase flushing. 2) Proposed power station was coal fired and a 15 km railway spur would be required at a cost of about $15M. 3) Cooling water outflow 50 m^3s^{-1} at a temperature of 8-12° above inflow temperature. 4) Increased temperature and salinity of cooling water may cause undesirable changes in the biology of the estuary.	Detailed evaluation not recommended.
Creation of new ocean channel near Dawesville.	1) 200 m wide, 3 or 4.5 m deep, 1.6 km long channel proposed in two configurations, with or without a plug between the Peel and Harvey. 2) Substantial increases in flushing of Harvey Estuary possible, and hence loss of nutrients would be enhanced. 3) Maximum summer salinities of Peel Inlet and Harvey Estuary would reduce. 4) Increased spring salinities would restrict the period suitable for Nodularia growth. 5) Excavation of 4-5M m^3 of material and construction of a new traffic bridge on the Old Coast Road required. 6) Shoaling and erosion at ocean entrance would be minimised by sand bypassing. 7) Approximate cost of option $15M-$20M without sand bypassing.	Detailed evaluation required.

CHAPTER 3 OPTIONS RECOMMENDED FOR DETAILED EVALUATION

3.1 Introduction

After the preliminary evaluation of all the suggested options, eight long-term options and three interim options were recommended for further consideration. These options are summarised in Table 3.1.

Table 3.1 Management options recommended for detailed evaluation

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Long-term Management Options

- Modification of agricultural fertiliser application practices
- Land use changes of highly leaching agricultural soils, for example deep grey sands
- Use of bauxite residue to amend leaching sands
- Wetland filters or chemicals to treat suitable rural point sources of nutrients
- Small-scale chemical treatment of surface drainage water
- Diversion of Harvey Main Drain flows to sea using a barrage at Herron Ford
- Hydraulic improvement of the Mandurah Channel
- Construction of a new marine channel near Dawesville

Interim Management Options

- Use of chemicals to oxidise sediments and/or to precipitate or inactivate sedimentary phosphorus
- Use of algicides to control cyanobacteria, diatoms or macroalgae
- In-estuary harvesting and beach clearing of macroalgae

3.2 Modification of Agricultural Fertiliser Application Practices

The suggested modification of fertiliser application involves both soil testing and the use of slow-release fertilisers.

The soil test calibration curves used before 1978 were not applicable to the deep grey sands within the Harvey Estuary (see Fig. 3.1). A new calibration curve revealed that lower fertiliser application rates could

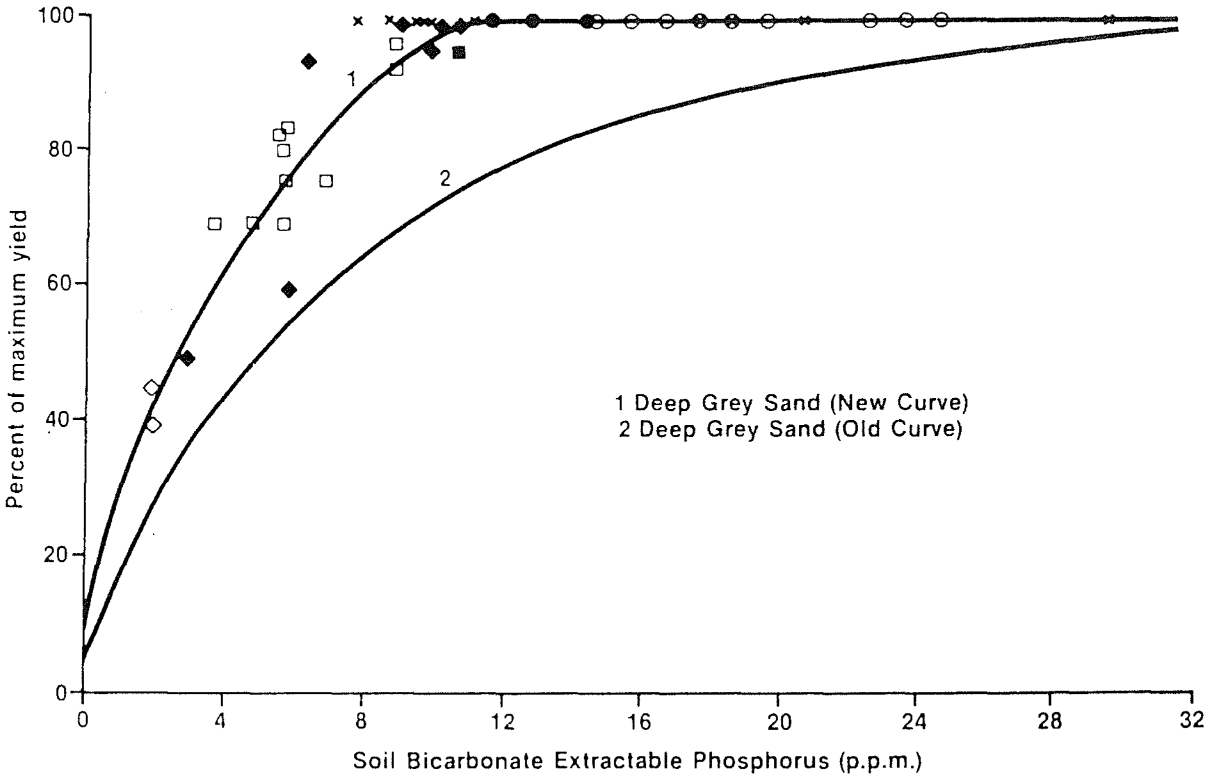


Figure 3.1 Percentage yield as a function of plant-available phosphorus (soil bicarbonate extractable phosphorus)

achieve nominated production levels.

Significant residual phosphorus (up to 50% of the total phosphorus applied) remains in the deep grey sands after the growing season. Application of less phosphorus is possible where sufficient residual soil phosphorus remains for pasture growth.

Soil tests at a suitable scale (to paddock level), costing $30 for six samples, (about $60-$100 for an average farm) could be used to match annual fertiliser application rates and type to actual requirements of phosphorus, potassium and sulphur. A scheme for soil testing is shown in Fig. 3.2.

It was estimated that if all farmers in the Harvey Estuary catchment followed soil test recommendations for deep grey sands, the following would apply:

- short-term reduction in applied fertiliser of about 60%,
- longer term (maintenance application rates), reduction of about 40 to 50%,
- cost savings for farmers of \$3-6 ha^{-1} yr^{-1}.

- For sand-over-clay soils the following would result:
  - A short-term reduction in applied fertiliser of 90%,
  - Longer term (maintenance application rates), reduction of about 50%.

Similar reductions in applied fertiliser may be possible for other soils in the Harvey Estuary catchment.

In conjunction with soil tests, different types of fertiliser should be used to ensure both immediate and long-term reduction of eutrophication. A number of different mixes have been proposed, and their potential should be determined by soil tests. The mixes currently being considered, with their estimated costs, are shown in Table 3.2, and the following points should be noted:

- In some years sulphur alone may be necessary as a fertiliser.
- A phosphate source of low water solubility is needed to achieve a long-term reduction in phosphorus export rates from the sandy soil groups within the catchment.
- Slow-release fertilisers have been developed to:
  - provide plants with a freely-available phosphorus source which leaches slowly from the root zone (0-100 mm)
  - supply adequate sulphur to soils for plant maintenance.

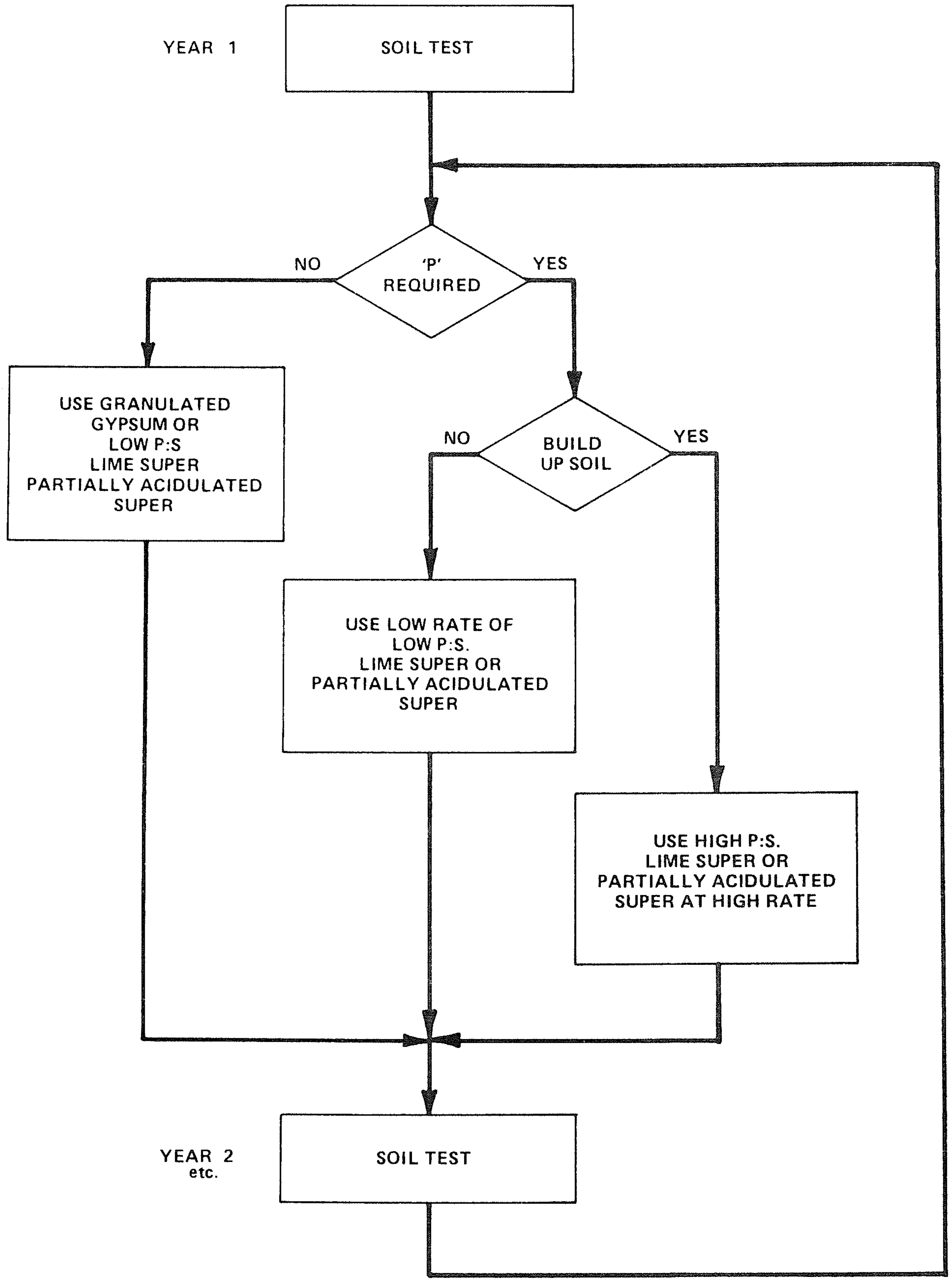


Figure 3.2 Application of soil tests to determine fertiliser requirements

Table 3.2 Fertiliser options

Products		Analysis		Status	Estimated costs
	% Phosphorus	% Potassium	% Sulphur		$/tonne
Superphosphate	9.1	-	10.5	Commercially available	90
Reverted Super (Coastal Superphosphate)	7.5	-	9	Commercially available	95
Partially acidulated super with sulphur (AS3)	10*		34*	Under development- may be cheaper than reverted super on a ha^{-1} basis	160*
Elemental sulphur	-	-	100	Commercially available but not feasible - explosive	194
Gypsum	-	-	18	Requires spring application- not preferred by farmers	7
Granulated Gypsum	-	-	?	Under development - applied in autumn	Not available
Reverted Super + Sulphur 3-2	6.5?	-	20?	Under development	Not available
Super Potash 5-1	7.4	7.4	9	Commercially available	106
Super Potash 3-2	5.3	18.2	6	" "	122
Reverted Super Potash 3-2	4.4	18	5	" "	135
Muriate of Potash	-	50	-	" "	158
Sulphate of Potash	-	41	18	" "	394

* Estimated.

Detailed evaluation of the strategies shown in Fig. 3.2 was required to refine estimates of reduced phosphorus application to soils, and time scales for the rundown of phosphorus stored in catchment soils. 'Rundown' is the time taken for a reduction in phosphate fertiliser application to be reflected as a reduction in phosphorus entering the estuary. As the phosphorus load entering the estuary depends on rainfall, we would know that the required reduction has occurred when the flow-weighted concentration of phosphorus in the inflowing water reaches the new, lower equilibrium level at which Nodularia blooms are prevented in four out of every five years.

It was estimated that the use of partially acidulated rock phosphate fertiliser (AS3) at the minimum phosphorus application rate required to maintain maximum yield would result in a reduction of long-term phosphorus leaching losses of 49% for deep grey sands and 57% for sand-over-clay soils.

This analysis was undertaken with only one year's data, and clearly depends on assumptions made about long- and short-term leaching loss rates. Nevertheless, the reductions appear substantial, and ongoing monitoring should enable a more rigorous evaluation of these rates to be made.

Phosphorus cycling and leaching mechanisms are shown in Fig. 3.3. Leaching of previously applied fertiliser from the readily available organic and inorganic soil residue occurs throughout the year, resulting in changes to the equilibrium existing among the various pools of phosphorus in the soil.

The time taken for phosphorus leached from the root zone to reach the drainage is controlled by a complex interaction of the adsorption, desorption and flushing mechanisms. The initial flushing of weakly bound organic phosphorus after the first rains may release up to 50% of this phosphorus pool, and results in the downward leaching of phosphorus. The leaching of phosphorus and the uptake of inorganic phosphorus by plants (leading to a breakdown of residual soil phosphorus) occurs throughout the winter. Some of the remobilised phosphorus from this source would be lost to surface drainage.

The adsorption and desorption of phosphorus within the soil profile, and at interfaces between sand and coffee rock, or sand and clay, stores or releases phosphorus. Preliminary data suggest that the water permeating the coffee rock is stripped of phosphorus by the highly adsorbant nature of this material, but that it can be desorbed and later become available for leaching.

Because of these mechanisms, large amounts of phosphorus may be present in subsurface pools, either highly concentrated in the groundwater, or adsorbed on to coffee rock, clay or yellow sands.

Phosphorus-rich water can enter the drainage network through surface runoff, subsurface (near-surface) lateral flow and deep lateral flow. Swamps and depressions are important in intercepting both subsurface and surface flows. If they overflow, trapped nutrient-rich waters can flow to drainage canals.

Surface runoff occurs only when the whole soil profile is saturated after an initial 'wetting-up' period. Surface runoff from the catchment

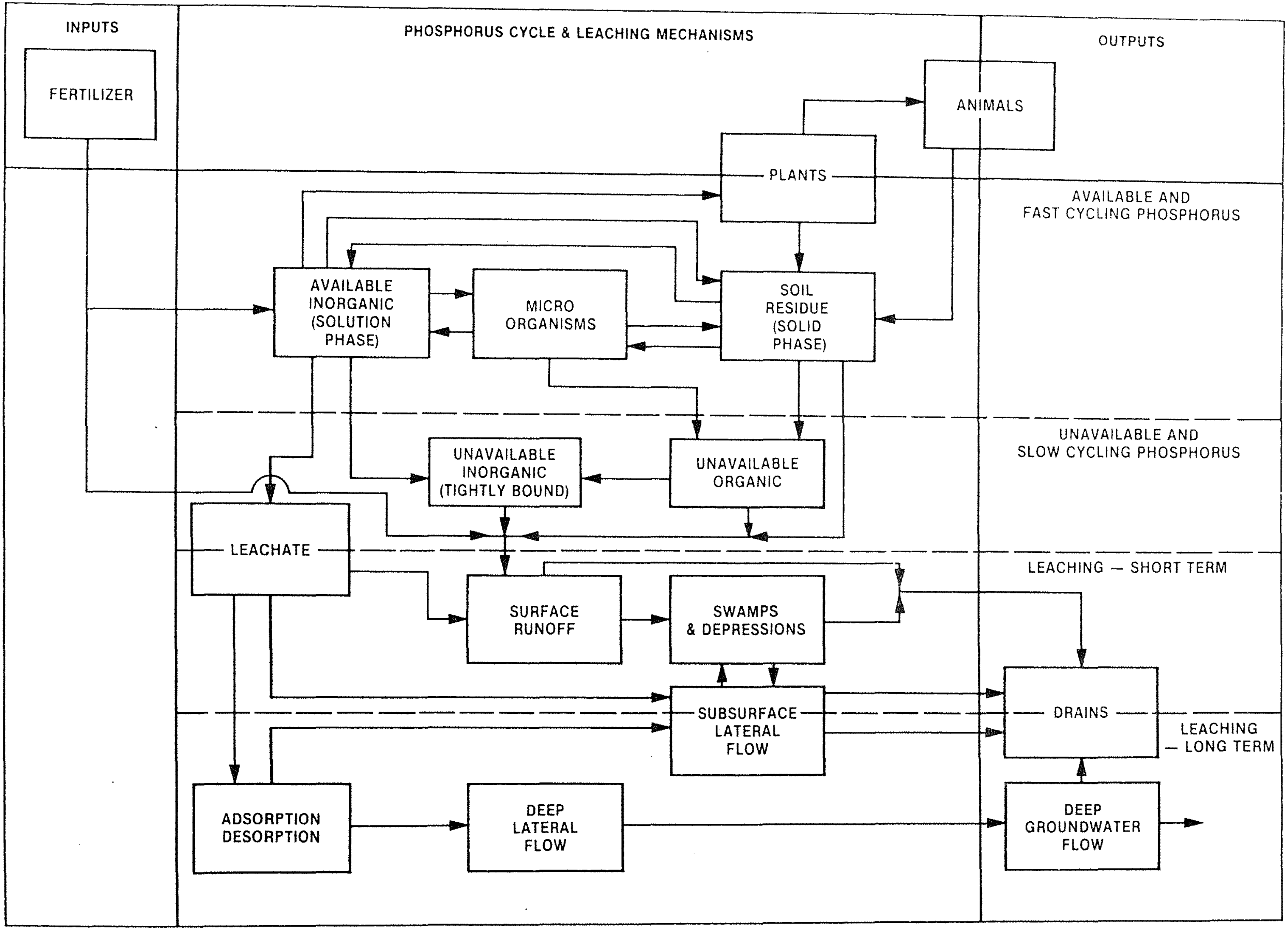


Figure 3.3 Phosphorus input, output, cycling and leaching mechanisms

is rapid, although some delay is caused by swamps and depressions.

Subsurface flow in a large undrained area can be less than 0.1 m day^{-1}. However, calculations indicate that a flow rate of about 1.6 m day^{-1} may apply to a smaller drained catchment.

One of the Commonwealth Scientific and Industrial Research Organization (CSIRO) current projects will enable predictions to be made of the rates and directions of movement of deep groundwater flow. Preliminary results indicate that the rate of movement is much slower than that of near-surface flow.

If all farmers in the estuary catchment followed the soil-test-based phosphorus application recommendations, a reduction of 20-30% of leached phosphorus entering the estuary would be achieved in the short term, that is, within 1 year.

The long-term time scale for rundown of stored phosphorus in the catchment soils is difficult to determine, and no specific prediction of this rundown time can be made; however, it may be several years.

3.3. Changes in Current Land Use

Rates of phosphorus loss to drainage were found to correlate with soil type (see Fig 3.4). Conversion of the highly leaching soils from agriculture to other land uses requiring lower rates of phosphate application would ultimately result in lower phosphorus leaching losses.

Table 3.3 shows estimated areas of catchment land which could be converted, according to soil type. Soil groups other than those shown have low phosphorus leaching rates and conversion would not be cost effective.

Table 3.3 Potential areas of agricultural land for resumption

	Estimated Area	
Catchment	Deep Grey Sands ha	Sand Over Clay ha
Serpentine	30100	18700
Murray	3000	16300
Drains	4000	22600
Harvey	13500	15200
TOTAL	50600	72800

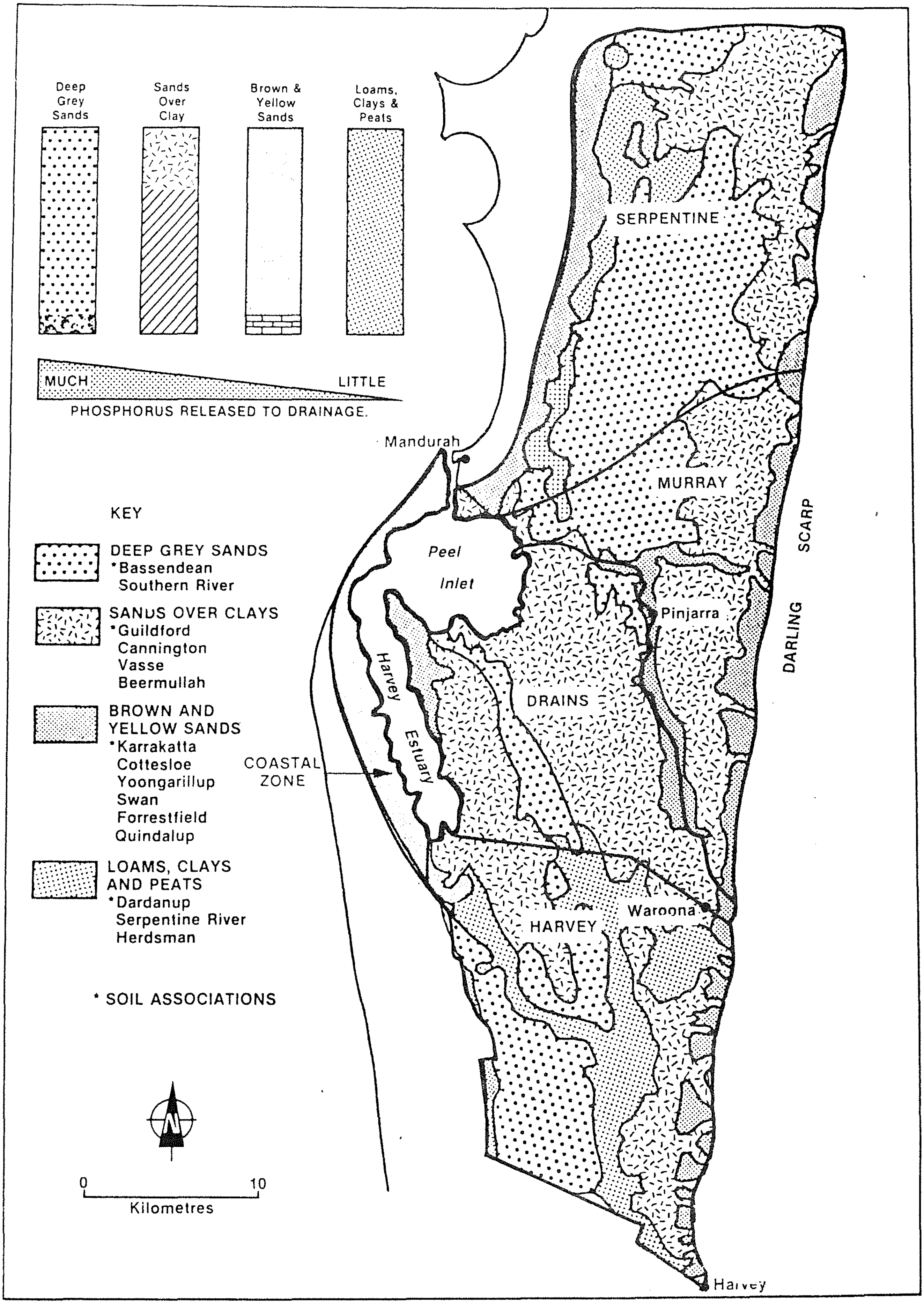


Figure 3.4 Leaching potential of soil categories in the coastal plain catchment of the Peel-Harvey Estuarine System

Two possible options are the purchase of land and conversion from agriculture to forestry, or from agriculture to parkland.

The high phosphorus-leaching soil groups considered for possible conversion of land use are:

- Southern River sands (about 3 500 ha),
- Bassendean sands (about 10 000 ha).

Assuming \$1000 ha^{-1}, the cost of purchasing the Bassendean and Southern River soil groups (13 500 ha) in the Harvey Catchment would be about \$13.5M.

The first option, conversion to forestry could:

- reduce the input of phosphorus-rich groundwater into the drainage system by increasing evapo-transpiration,
- use the present soil reserves of phosphorus,
- provide financial returns from timber production.

Evaluation of conversion of agricultural land to forestry required determination of:

- the time scales and costs of establishing forests,
- fertiliser requirements and likely reduction in rates of soil phosphorus export,
- economic returns from forestry,
- the feasibility of changing land use on other soil groups in the Murray and Serpentine coastal plain catchment areas.

The cost of establishing two distinct types of forest in the catchment soils were \$1500 ha^{-1} for Pinus pinaster on the non-water-logged Gavin ridges of the Bassendean sands, and \$425 ha^{-1} for eucalypts in wetter areas.

On a statewide basis, the Forests Department currently achieves planting rates of 2500 ha yr^{-1} for pines and 1500 ha yr^{-1} for eucalypts and other hardwoods.

Reducing the amount of fertiliser applied to the catchment and intercepting groundwater would both reduce phosphorus export. Application rates of phosphorus to forested areas could be about 55% of current agricultural application rates.

At a stocking rate of 1500 trees ha^{-1}, pines and eucalypts may prevent groundwater recharge 6 to 8 years after planting. These species can further reduce phosphorus input by intercepting and transpiring shallow groundwater.

Nevertheless, assuming a 60-yr growth period with some intermediate yields for pine sawlogs and an initial 15-yr growth period for eucalypts for wood chips, economic analyses show that returns from forestry may be uneconomic when compared with conversion to parkland.

3.4 Amendment of Leaching Soils with Bauxite Residue

The application of bauxite residue from Alcoa of Australia Limited's alumina refineries would improve phosphorus retention in highly leaching soils (e.g. the deep grey sands). Application rates of 1000 to 2000 t ha^{-1} of bauxite residue have been suggested previously; however, current studies indicate rates as low as 200 t ha^{-1} may effectively reduce phosphorus leaching.

One beneficial effect is that bauxite residue improves soil water retention and crop yield. Preliminary estimates suggest that substantial increases in pasture productivity are possible on Gavin soils of the Bassendean sands.

For the deep grey sands, assuming an application rate of 200 t ha^{-1} on 10 000 hectares of cleared land in the Harvey coastal plain catchment, two million tonnes of residue would be required.

Assuming a 40-km cartage distance, a cost of approximately \$4 $tonne^{-1}$ to load, cart and spread material was estimated. The cost of application per hectare would therefore be \$800 or more. Some form of cost-sharing arrangement among Alcoa, the farmers and possibly the State Government would be needed to make this technique viable. Because of changes in Alcoa's bauxite residue treatment, this option would not be feasible to implement until approximately 1987.

Additional study was required to assess:

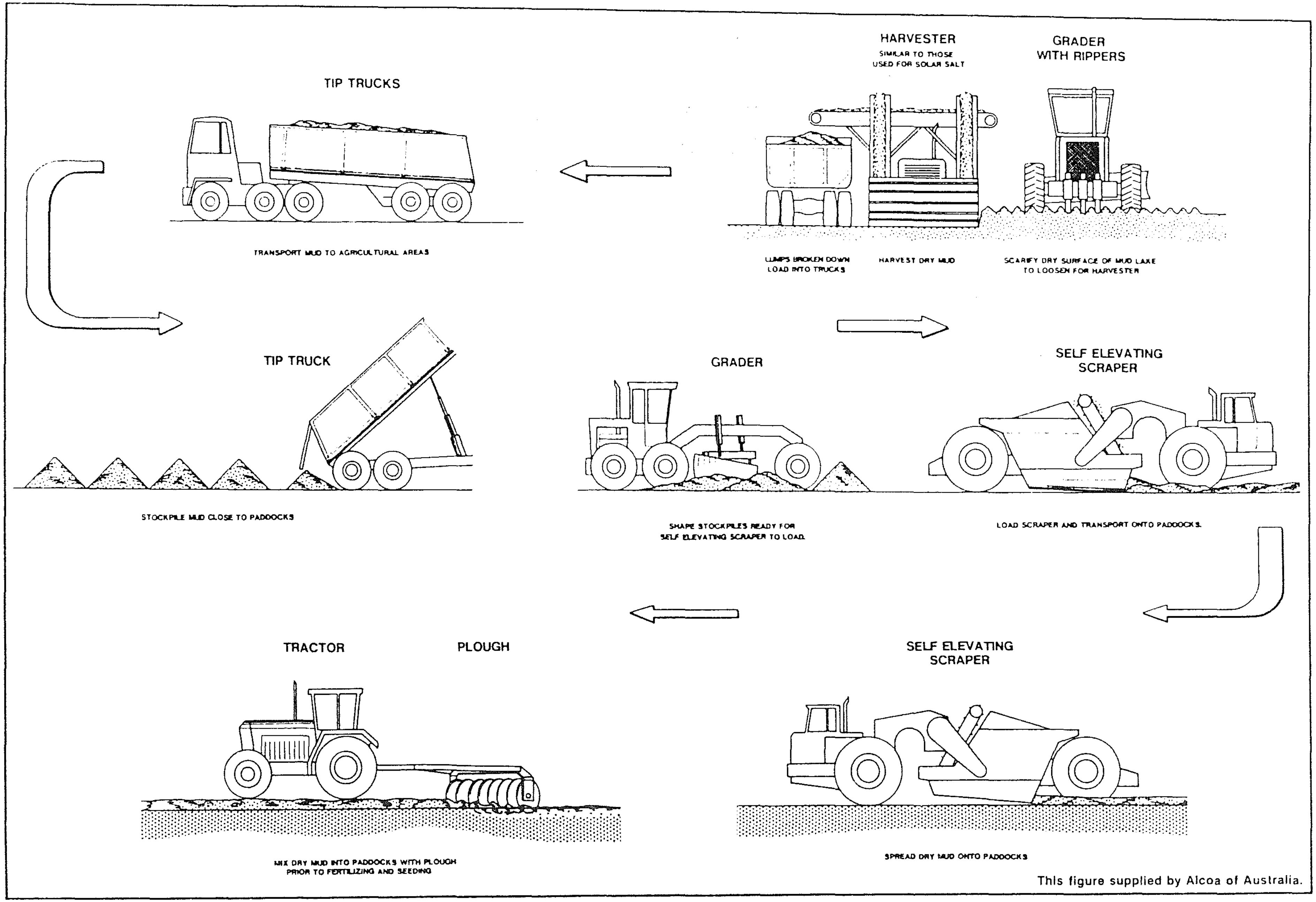
- methods for reducing transport costs,
- possible loss of bauxite residue or leachates (e.g. cadmium) to the estuary through erosion,
- the effectiveness of bauxite residue in binding phosphorus and increasing soil water retention.

If Wagerup were used as the source of bauxite residue, new roads to reach the deep grey sands in the Harvey catchment would add \$0.66 per tonne to the cost of residue (based on 1000 t ha^{-1} application rate).

Transport costs account for approximately 50% of the total cost of the residue application; these costs could be reduced by pumping a slurry (approximately 45% solids) to holding areas for later redistribution.

The incorporation of bauxite residue into the soil profile by thorough grading and other mixing techniques (see Fig. 3.5) would improve retention of residue in treated paddocks. In addition, most of the catchment is level and would trap any eroded material from the steeper Gavin ridges before it entered the drainage system.

Studies were undertaken in the winter of 1983 to determine the loss rates of heavy metals in leachate; the results are not yet available.



This figure supplied by Alcoa of Australia.

Figure 3.5 Schematic diagram of soil amendment with bauxite residue

Preliminary results from field trials undertaken in 1983 by Alcoa of Australia Limited suggest that increases in soil water retention by bauxite residue incorporation may have brought about improved pasture growth in the Gavin soils, but not in the Joel soils of the Bassendean soil group.

Harvey catchment phosphorus export may be reduced by about 30% if the deep grey Bassendean sands (Southern Rivers, Gavin and Joel) are treated, or 50% if both the deep grey sands and the sand-over-clay soils are treated. The time scale for this reduction is unknown, as phosphorus losses from the deeper groundwater pools will not be reduced by this option.

3.5 Chemical Precipitation of Phosphorus from Surface Drainage

The further evaluation of large-scale chemical removal of phosphorus from surface drainage was not recommended. However, Alcoa explored a proposal to remove phosphorus from surface water in the Harvey Estuary catchment; the residue could then be reused for soil amendment.

This proposed option is shown in Fig. 3.6. The process involves:

- washing and thickening bauxite residue to remove caustic soda,
- adding La Porte ferrous sulphate waste to increase phosphorus adsorption capacity and neutralise the causticity,
- mixing drainage water to strip phosphorus,
- solar drying residue for application to farms,
- discharging treated drainage water to the Harvey Main Drain.

Preliminary results of testing suggest that phosphorus concentration in water from the Meredith Drain and the upper Harvey Main Drain can be reduced by 98%, giving a total phosphorus load reduction of about 33% for the Harvey Main Drain at the Harvey Estuary, assuming 1982 flows.

The estimated capital cost of this scheme would be \$16M, with operating costs of \$2.5M yr^{-1}.

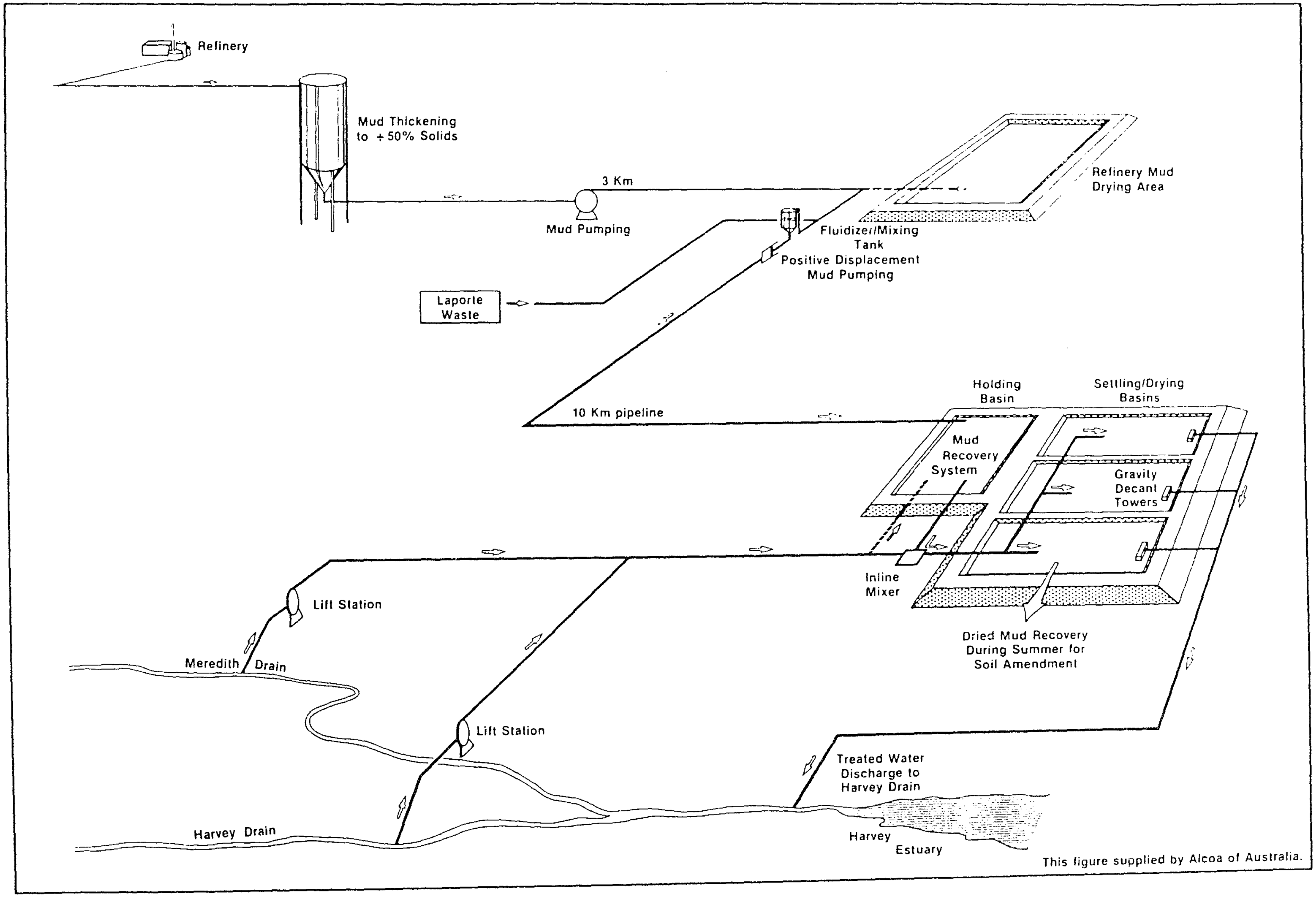
3.6 Wetland Filters at Point Sources

The treatment of effluent water involves the 'stripping' of phosphorus by plant uptake and perhaps by sediment adsorption. This technique could be used for high concentration-low flow phosphorus sources such as piggery effluents.

The configuration of this type of treatment facility would depend on the flow rate of the effluent; an areal loading rate of about 2.4 l m^{-2} day^{-1} would be required. Waters stripped of phosphorus could then be channelled to the drainage network.

3.7 Herron Ford Barrage Options

A barrage and pipeline or tunnel would divert flows from Harvey Main Drain, South Coolup Drain and Mayfields Drain directly to the ocean. A barrage at Herron Ford across Harvey Estuary with an outfall to the ocean would prevent most of the Harvey catchment phosphorus entering the Harvey



This figure supplied by Alcoa of Australia.

Figure 3.6 Schematic diagram of chemical precipitation of phosphorus from surface drainage

Estuary, and would result in a rapid reduction in the frequency and intensity of Nodularia blooms.

A range of options designed to divert the 1982 flows is shown in Fig. 3.7, together with estimated capital, operating and present-worth costs for each option.

The extent of inundation for each of the three water-storage depths considered is shown in Fig. 3.8. With a 3-m water-storage depth, 1400 ha of land would be inundated, and 500 ha would be inundated with a 1.5-m storage depth. A mixture of Crown reserves and freehold land would be flooded, and some land resumption would be necessary. Estimated costs for these options (in 1983 dollars) range from \$25.4M to \$61.1M.

Detailed studies were required to:

- predict the frequency of overtopping of the barrages under a range of river flows,
- examine hydrodynamic changes in the estuary likely to result from a barrage at Herron Ford,
- examine the likely effects of altered salinity regimes in Harvey Estuary due to the diversion of the fresh water input,
- examine the consequences of almost total nutrient diversion from Harvey Estuary on beneficial primary and secondary production within the system.

A computer model was used to simulate daily flows for several years for all drain inputs behind the barrage. The simulated flows were used by another model to compute the quantity of water overtopping the barrage with different pumping rates to sea.

In three out of ten years, a 1.5-m water-storage depth with a diversion rate of $1 \times 10^6 m^3 day^{-1}$ would spill a volume equal to or greater than the 1982 total inflow into the estuary. This inflow would cause a Nodularia bloom in Harvey Estuary of similar magnitude to the 1982/83 bloom.

In order to meet the 'no bloom' criterion of four in five years, different water-storage depths and pumping rates were examined, and the cost of these variations estimated.

The estimated capital and operating costs (including maintenance) of options with 3, 4 and 5-m water-storage depths ranged from \$40M capital and \$1.4M operating to \$83M capital, \$3.6M operating cost.

Model studies indicate that wind and tide are the dominant mixing and flushing mechanisms of the estuary, and that a barrage across Herron Ford would have little effect on the mixing of water between the Harvey Estuary and Peel Inlet. A reduction in river inflow would not significantly alter the retention rate of phosphorus within the system.

It was found that reduction of freshwater inflow by the barrage would not increase summer salinity to levels which would seriously affect the plant and animal communities in the estuary; nonetheless, it might increase spring salinity to levels which would inhibit the growth of Nodularia.

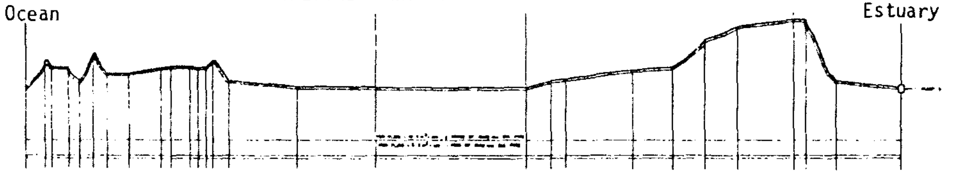
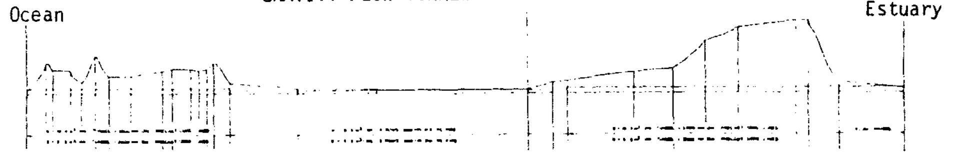
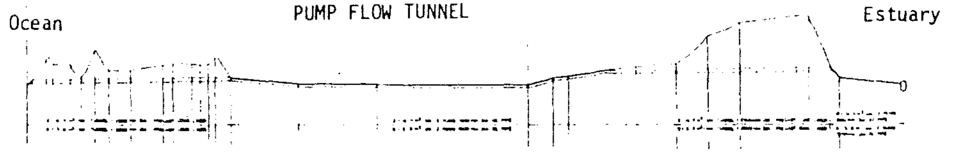
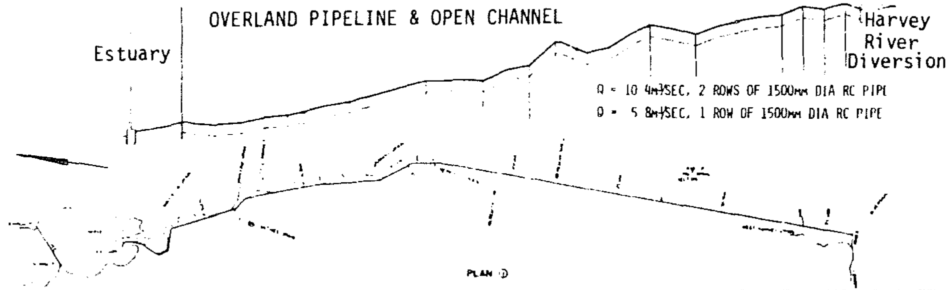
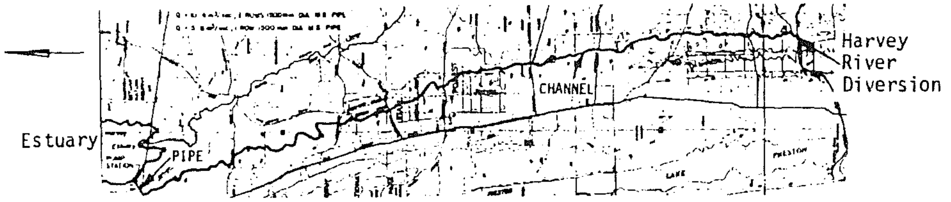
OUTLET	OPTION DESCRIPTION	PWD NO.	VARIATION	CAPITAL COST IN $M	OPERATING COST IN $M	TOTAL COST = CAPITAL COST + 10 X OPERATING COST IN $M
OCEAN OUTLET OPTIONS	PIPELINE OVERLAND  	1.1	3m Barrage Flow Rate = $10.4m^3/sec.$	20.0	1.2	32.0
		2.1	4.5m Barrage Flow Rate = $5.8m^3/sec.$	17.4	1.4	31.4
	GRAVITY FLOW TUNNEL  	1.2	3.0m Barrage Flow Rate = $10.4m^3/sec.$	45.0	-	45.0
		2.2	4.5m Barrage Flow Rate = $5.8m^3/sec.$	30.1	-	30.1
	PUMP FLOW TUNNEL  	1.3	3.0m Barrage Flow Rate = $10.4m^3/sec.$	22.9	.3	25.9
		2.3	4.5m Barrage Flow Rate = $5.8m^3/sec.$	22.4	.3	25.4
HARVEY DIVERSION DRAIN OUTLET OPTIONS	OVERLAND PIPELINE & OPEN CHANNEL  	3.1.1.	3m Barrage Flow Rate = $10.4m^3/sec.$	49.1	1.2	61.1
		3.2.1.	4.5m Barrage Flow Rate = $5.8m^3/sec.$	33.6	1.4	47.6
	 	3.1.2.	3m Barrage Flow Rate = $10.4m^3/sec.$	19.2	1.2	31.2
		3.2.2.	4.5m Barrage Flow Rate = $5.8m^3/sec.$	20.0	1.4	34.0

Figure 3.7 Summary of Herron Ford barrage and diversion options for 1982 flows

Modelling studies indicate that the maximum summer salinity could reach 55°/oo (the maximum now observed is 52°/oo). An increase in summer salinity of about 3°/oo would not detrimentally affect the primary or secondary production within the system. An increase in spring salinity could prevent a *Nodularia* bloom.

Complete diversion of freshwater inflow and nutrients from rivers would probably result in a rapid reduction in nuisance blooms of cyanobacteria. In the longer term the phytoplankton would be dominated by diatoms. Initially this would enhance the estuarine habitat for fish, although a substantial diversion of nutrients could lead to a gradual reduction in productivity of the fishery.

As Fig. 3.8 shows, most of the land subject to inundation consists of low lying flats, of limited economic value, to the south of the nature reserve. The increase in area of inundation within the Harvey Estuary Nature Reserve between 3 and 5-m water storage depths is approximately 170 ha. To minimise the inundation of this reserve, the diversion option using a 3-m depth would cost $14.7M more than a 5-m depth because of higher pumping costs and a larger diameter tunnel.

3.8 Improvement of the Existing Mandurah Channel

This option was suggested to increase the rates of nutrient loss to the sea by marine flushing. Four possible areas of dredging are shown in Fig. 3.9. By combining these areas of dredging, two dredging options were identified. These are:

1) Dredging channels A, B and D

2) Dredging channels A, C and D.

Two spoil areas would be created, one in the estuary, the other adjacent to the new or existing channel, shown in Fig. 3.9.

Simulation of dredged channel flow rates for options 1 and 2 indicated an increase in current speed of about 20%. This increase could result in differential scour and sediment mobilisation in the Mandurah Channel and may affect the structural integrity of the existing Mandurah bridge.

The variations in flushing time (time taken to replace 63% of the estuary water) for the two channel options, and for existing conditions are shown in Table 3.4. These estimates were derived from 14-day simulations of the estuary, without any advective flushing due to river inflow or rainfall.

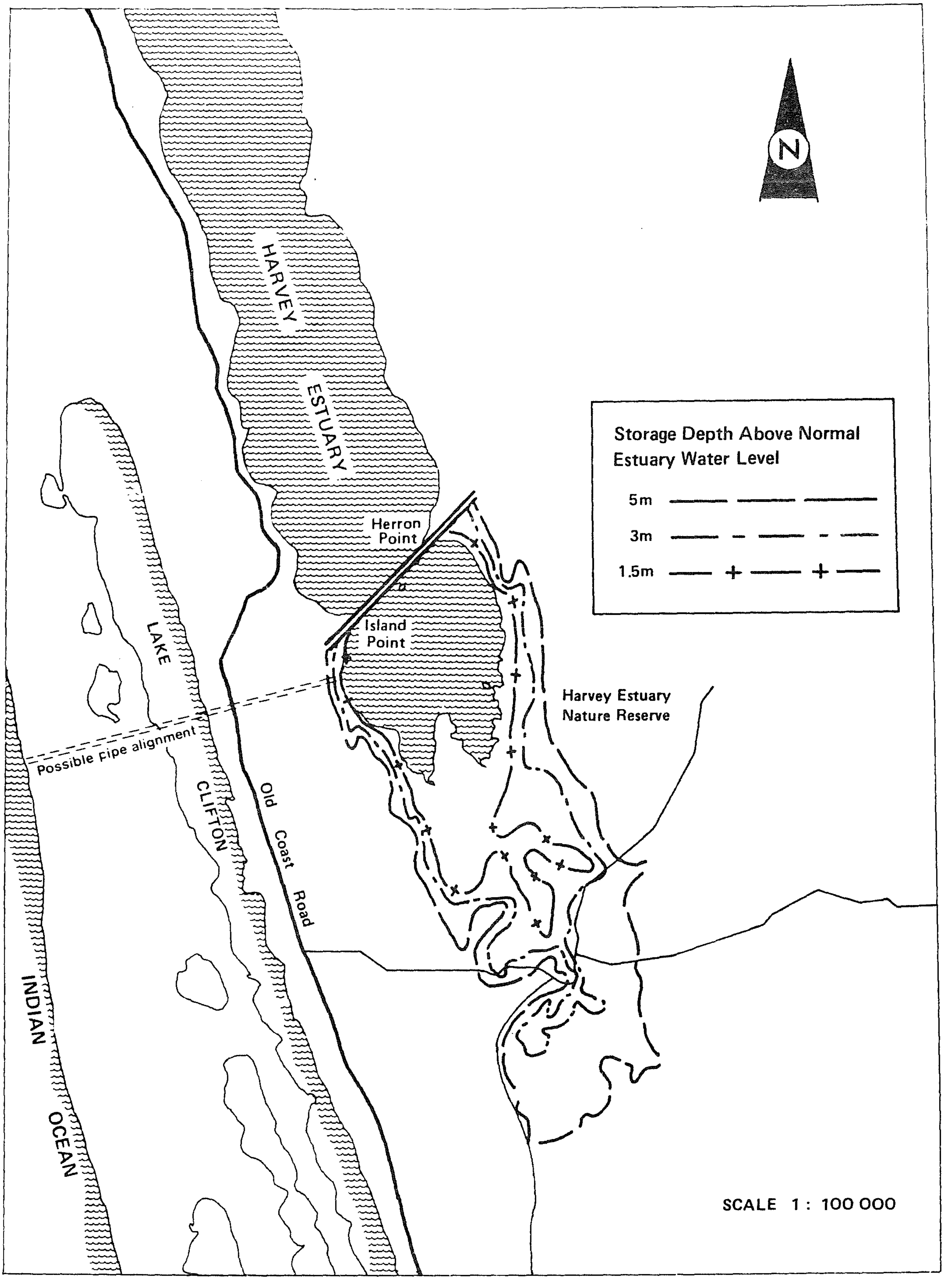


Figure 3.8 Extent of inundation for different water storage depths behind the Herron Ford barrage

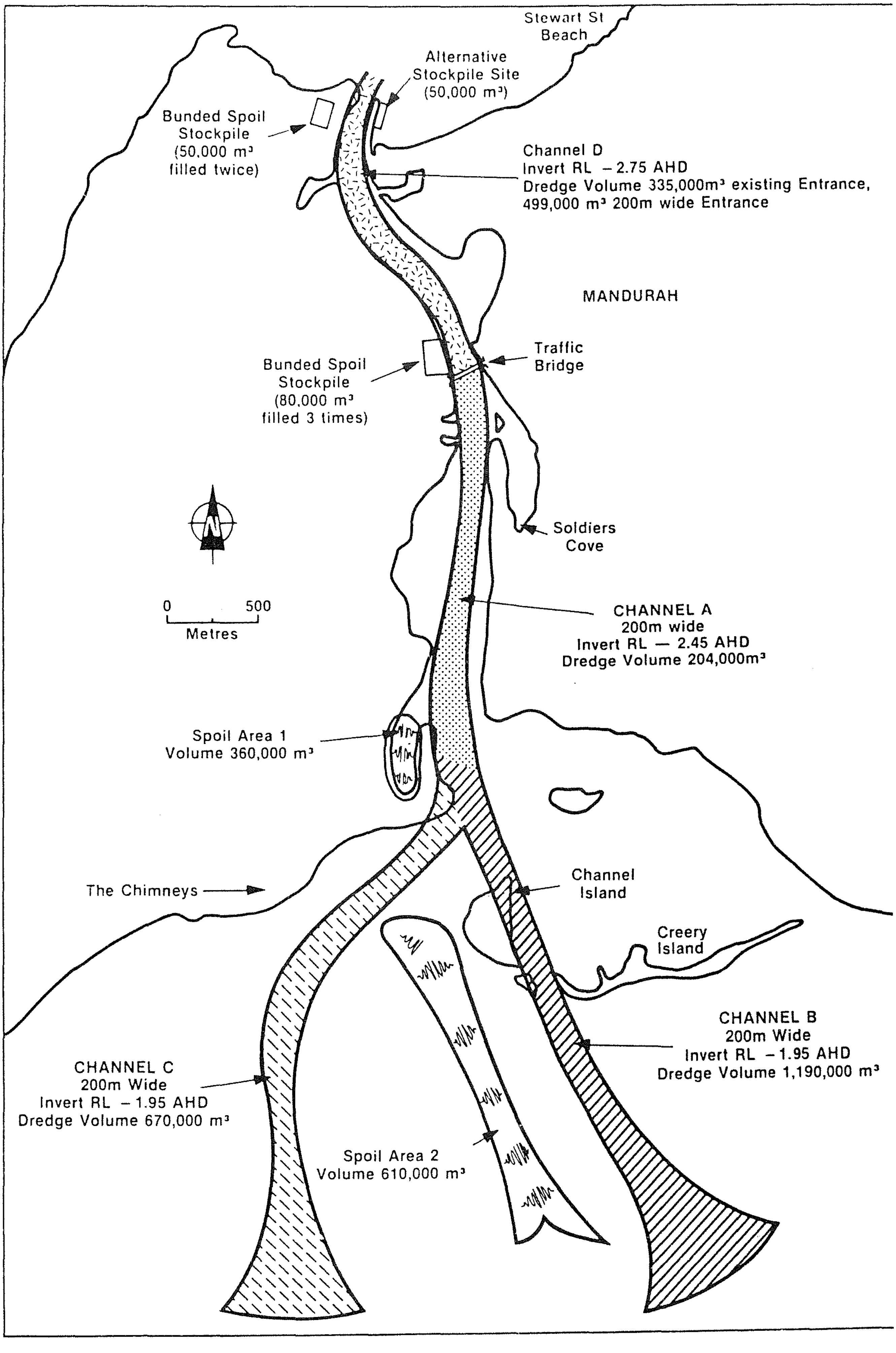


Figure 3.9 Possible areas of dredging for improvement of the existing Mandurah Channel

Table 3.4 Changes to the estuary flushing times due to different channel options

Wind and Tidal Condition	Option	Flushing Time (Days) Harvey*	Flushing Time (Days) Peel and Harvey**
Summer	Existing	128	103
	1	85	70
	2	84	62
Winter	Existing	84	47
	1	59	38
	2	58	35

* Flushing times of Harvey Estuary to Peel Inlet and the ocean combined
** Flushing times of the whole estuary to the ocean

Some disruption of benthic and migrating organisms during construction may occur; however, the system should recover in 2 to 8 months. The enhanced penetration of marine water into Peel Inlet would extend the distribution of the present 'channel' biota, which is more diverse than that of the estuary basins themselves.

Rates of nutrient loss from the estuary would increase, and would probably be about 33-40% in summer and 20-33% in winter (see Table 2.5).

The estimated costs, volumes of material dredged, and project duration using only one dredge for each dredged channel are summarised in Table 3.5.

Table 3.5 Volumes of spoil, project duration and estimated costs for dredging channel areas A, B, C and D

Channel Dredging area	Spoil volume	Project duration (one dredge only)	Estimated cost $M
A	205 000 m^3	20 weeks	$0.6
B	1190 000 m^3	54 weeks	$1.7
C	670 000 m^3	35 weeks	$1.1
D	335 000 m^3	23 weeks	$1.1

For the cheapest option (1), the total cost would be about $3.1M.

Options 1 and 2 were modelled to determine the effects of widening the training walls, deepening the ocean outlet and building new training walls on flushing times, current speed, water levels and sediment movement. Modelling studies indicate that flushing of south-eastern Peel may increase slightly; however, flushing near Coodanup may be reduced slightly with option 2.

Currently *Ulva* is the major nuisance alga in Peel Inlet, and maximum flushing of the flats near Coodanup with option 1 is favoured. Should algae return to the deep basin of the estuary, option 2 would provide the greater benefit. Flushing of the Cox Bay area was similar for both options. These differences are considered marginal; other considerations, including public amenity and cost, could determine the most favourable option.

Computer modelling showed that neither option would have a significant effect on the flushing in Harvey Estuary.

Modelling studies also show that increasing the width and depth of the ocean entrance will have little effect on water levels within the estuary. The additional dredging cost for widening the entrance to 200 m and dredging from -2.75 AHD to -3.75 AHD would require an additional capital expenditure of about $1.8M with only a small increase in water exchange and an even smaller increase in nutrient loss.

3.9 Creation of a New Channel near Dawesville

This option involves the creation of a direct ocean entrance to Harvey Estuary, greatly increasing losses of phosphorus from the system via marine flushing. The channel alignment and a cross section with two alternative depths are shown in Fig. 3.10.

The channel would require the excavation and disposal of approximately 4 - 5 million m^3 of material. Approximately 4 million m^3 of fill could be as a 'plug' between the two estuaries. However, if the isolation of the Peel and Harvey Estuaries is not desirable, alternative spoil disposal sites are available.

This option also involves the construction of:

- training walls at the ocean entrance to prevent excessive shoaling at the mouth. This entrance would ensure adequate water exchange, but would not be safe for navigation.

- a two-lane bridge across the channel at the Old Coast Road.

Besides increasing nutrient losses from flushing, the channel would also tend to restrict the summer salinity to near 35°/oo and to increase spring salinity. This reduced annual range of salinity would make the estuary a more favourable environment for marine species.

Based on limited geological data, cost estimates for the channel with two alternative depths are shown in Table 3.6.

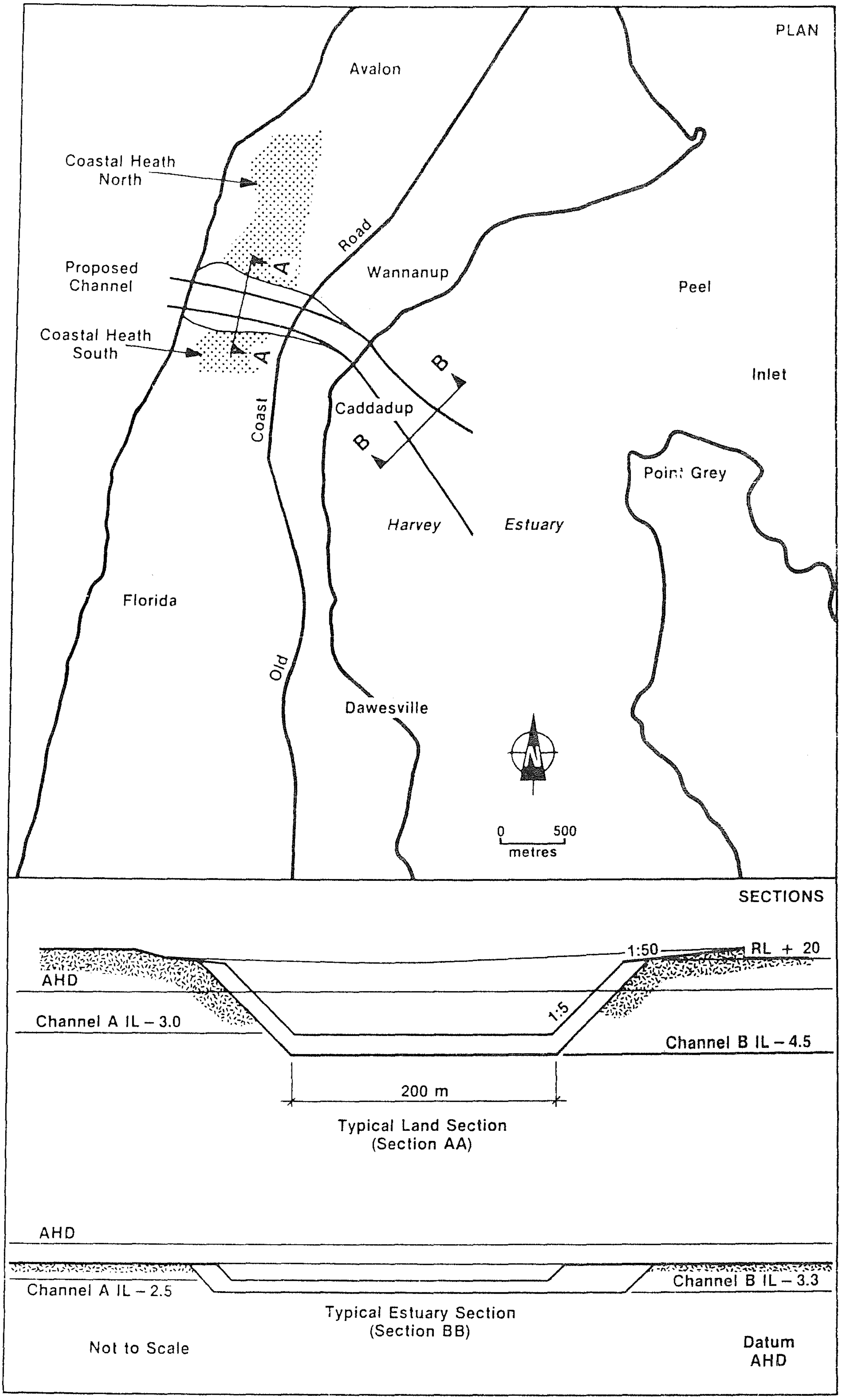


Figure 3.10 Plan and sections of the new channel near Dawesville

Table 3.6 Summary of estimated costs for a new ocean channel near Dawesville

	Estimated Costs $M					
Channel Depth	Dredging Ocean and Estuary	Other Excavation	Roadworks and Bridgeworks	Training Walls at Ocean Entrance	Contin-gencies	Total
-3.0 m AHD	1.4	6.5	5.0	0.6	1.4	14.9
-4.5 m AHD	2.6	8.4	5.0	0.8	1.7	18.5

Note: Estimated costs for sand bypassing not included

For evaluation, it was necessary to:

- estimate the cost of land resumption,
- ascertain the effect of the new channel on the flushing rate, and water levels of the estuary,
- assess the environmental impact of the channel on the estuary with regard to phosphorus retention, salinity, biological structure and productivity.
- assess changes in the coastal sediment transport regime,
- estimate the costs of maintaining a navigable channel.

The cost of resumption for an area of approximately 50 ha would be about $1-1.5M for the channel and batters.

To estimate water level changes, further modelling studies were undertaken. Two channel configurations were considered:

- with a 'plug' of dredge spoil between Peel Inlet and Harvey Estuary,
- with a free connection between Peel Inlet and Harvey Estuary.

During a one-hundred-year flood, a 'plug' would cause an additional level rise of about 100 mm. The diurnal tidal range would increase from about 100 mm to 200 mm. The effect of the channel with the 'plug' on

Harvey Estuary would be to increase the diurnal tidal range from about 100 mm to a maximum 600 mm, and floods would have little effect. Both flood levels and diurnal tidal levels in Harvey Estuary would be smaller without the 'plug', and a lower long-term average level, nearer to sea level, would result.

The present major level changes in the estuary occur on a time scale of 8-15 days (the 'barometric' tide). With a new channel, the major water level changes would take place on a daily time scale (the 'astronomic' tide).

Two changes in the coastline may ensure. First, erosion may take place downstream of the channel entrance, because of an interruption of longshore sediment drift. Second, shoaling may take place near the channel entrance. Aerial photographs show beach rock, at or near the low water mark, which may reduce downstream erosion. Shoaling, however, would make maintaining a navigable channel difficult. Some form of sand bypassing operation or dredging would be required to ensure navigability. The order-of-magnitude cost for a proposed bypassing operation at Mandurah is $2M capital cost and $300 000 yr^{-1} operating cost.

The direction of seasonal longshore sediment drift may be either northward or southward; however, the nett littoral drift would be northward, and any sand-bypassing measure should allow for this.

The channel without the 'plug' would improve the flushing of nutrients from Peel Inlet and particularly from the Cox Bay area. The major environmental changes likely to occur in Harvey Estuary and Peel Inlet because of an open channel are as follows:

- greater changes in daily water level would favour more intertidal plant and animal species, which would colonise greater areas of the marginal flats, increasing habitat diversity,

- increased flushing rates in Harvey Estuary (by a factor of four) and in Peel Inlet (by about 1.5) would cause proportional increases in marine losses of nitrogen and phosphorus, reducing the level of eutrophication and nuisance phytoplankton growth,

- the salinity regime would become more marine: minimum winter salinities would be similar to current winter levels, although the duration of low salinity periods would shorten, and maximum salinities would reach only 40°/oo, thus reducing the period suitable for the growth of Nodularia,

- improvement of water clarity and more diurnal tidal variations would allow macroalgae and seagrasses to extend their distribution south into Harvey Estuary, thus extending the nursery areas suitable for juvenile fish.

Other beneficial effects include:

- longer periods of estuary residence by species intolerant of low salinity,

- increased access to the estuary for migratory species,

- a greater range of species, since more marine fish species would utilise the estuary.

3.10 Chemical Treatment of Surface Sediments

Sediment phosphorus inactivation, by either alum precipitation or nitrate oxidation of sediments, was evaluated. These options would only be feasible if external phosphorus loading to the estuary was first markedly reduced and only necessary if significant water column loading of phosphorus from sediments persisted after nutrient import reduction.

Tests used Harvey Estuary water and sediment, allowing completely anaerobic conditions and high concentrations of filterable reactive phosphorus (FRP) to develop in the water before dosing. Results indicate that alum at 80 g aluminium m^{-3} or 3 g aluminium m^{-2}, and nitrate at 90 g nitrate-nitrogen m^{-3} or 3.5 g nitrate-nitrogen m^{-2} considerably reduced phosphorus release from sediments.

The estimated costs of ammonium nitrate or alum for treating Harvey Estuary range between $4-$9M for treatment of the estuary volume and $0.14-$0.27M for treatment of the surface sediment area. The length of time for effective suppression of sediment phosphorus release is unknown. A capital cost of about $1M would be required for surface injection equipment.

3.11 Algicides

Simazine and terbutryn remain the most likely candidates for laboratory and field testing.

Terbutryn is more attractive since effective doses (about 0.02 mg l^{-1}) are much lower than those of simazine (0.5-2.0 mg l^{-1}). Both compounds are available in liquid formulations of 500 g l^{-1} active ingredient, and the active ingredient is also available for custom formulation into granules or a heavier-than-water bivert emulsion.

Granular formulations could be applied from the air, so response to the threat of a bloom could be rapid. A liquid formulation would probably have to be applied from a barge, to avoid lateral drift of material onshore.

A preliminary estimate of costs for treating the whole area of sediment of Harvey Estuary and for the macroalgal growth areas of Peel Inlet is given in Table 3.7. The potential areas for treatment are shown in Fig. 3.11. Treatment of macroalgal beds rather than sediments has the higher probability of success, since the algae would minimise burial or dispersive loss of the active compound.

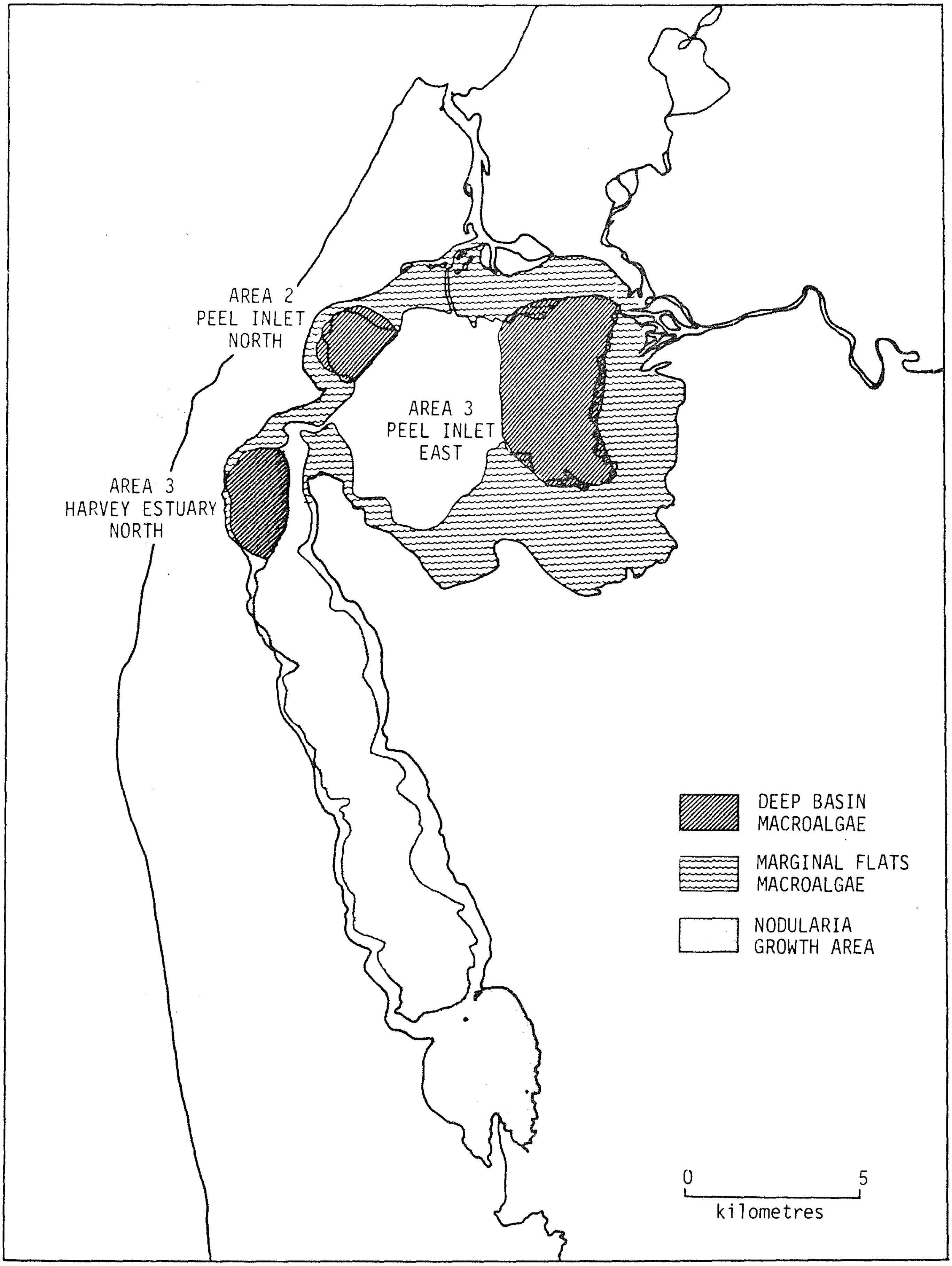


Figure 3.11 Areas for treatment with algicides

Table 3.7 Cost of algicide treatment

i) Cost of chemicals and dose rate, assuming dissolution of algicide in a 0.25 m depth of water

		Terbutryn	Simazine	
		0.02 mg l^{-1}	0.5 mg l^{-1}	2.0 mg l^{-1}
Peel Inlet - flats	2500 ha	$3 750	$31 250	$125 000
Peel Inlet - basin	2000 ha	$3 000	$25 000	$100 000
Harvey Estuary	5600 ha	$8 400	$70 000	$280 000

ii) Formulation into granules, assuming 10% w/v product

		Terbutryn	Simazine	
		0.02 mg l^{-1}	0.5 mg l^{-1}	2.0 mg l^{-1}
Peel Inlet - flats	$440	$11 000	$ 44 000	
Peel Inlet - basin	$350	$ 8 750	$ 35 000	
Harvey Estuary	$980	$25 000	$100 000	

iii) Aerial application, assuming $5.50 ha^{-1} fixed cost

Peel Inlet - flats	2500 ha	$13 750
Peel Inlet - basin	2000 ha	$11 000
Harvey Estuary	5600 ha	$38 000

The low cost of algicide treatment may make it suitable as a long-term management option; however, further work is necessary to evaluate its potential.

3.12 Weed Harvesting

The offshore harvesting capability will be upgraded during 1983 from one to two units, and the harvested algae partly dewatered by rollers, extending the harvesting time possible each day. The main areas of harvesting are shown in Fig. 3.12.

Estimates are that the upgraded offshore harvesting capacity of 3000 wet tonnes yr^{-1} will be sufficient to achieve acceptable control of beach fouling by algae about 85% of the time.

Uncontrolled algal beachings by storms, and material not picked up by the harvester will be removed from Coodanup and Novara beaches with tractors.

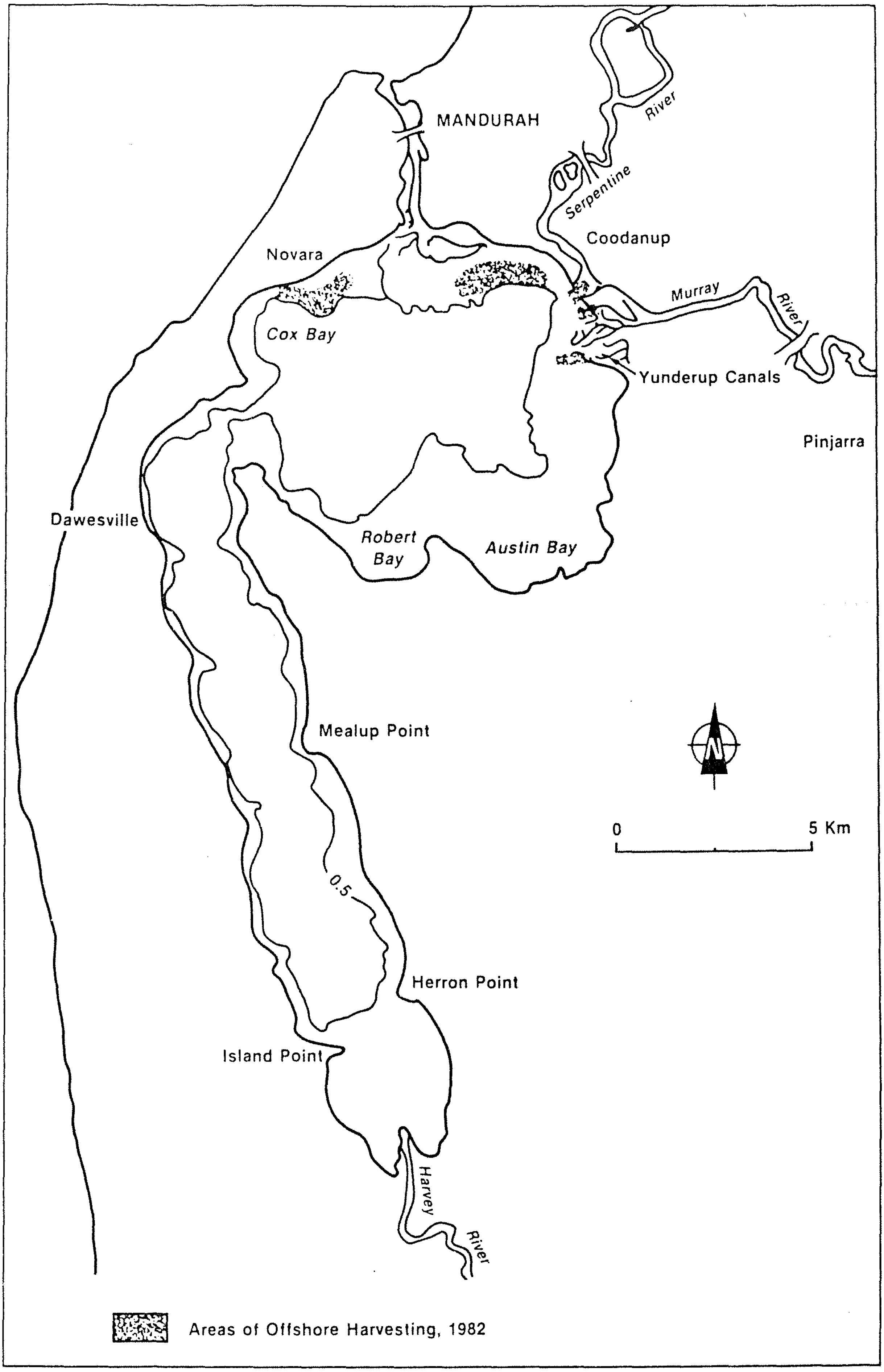


Figure 3.12 Areas of offshore harvesting

CHAPTER 4 RECOMMENDATIONS

4.1 The Recommended Management Strategy

It is recommended that soil tests be implemented to determine the phosphorus requirements of all agricultural soils in the estuary catchment, and that phosphorus fertilisers be applied only according to the results of the soil tests. Suitable slow-release fertilisers should be used on sandy agricultural soils to minimise leaching losses of phosphorus to the estuary drainage.

In combination with changes in fertiliser use, it is recommended that a new channel to the ocean near Dawesville (without the 'plug') be constructed.

Implementation of these recommendations will keep eutrophication of the estuary within acceptable limits.

An alternative is to implement the fertiliser management options, while continuing to harvest algae as necessary. Further (short- or long-term) control of algae may be achieved by use of Terbutryn if tests demonstrate that it may be used safely and is otherwise suitable for use in the estuary. This combination of options may, if optimum effectiveness is achieved, obviate the need for a new channel at Dawesville. However, this alternative strategy requires a continuous maintenance and monitoring programme.

4.2 Formulation of the Management Strategy

Study of interactions among options was an integral part of this investigation and enabled the formulation of a cost-effective, adaptable management strategy. Other possible effects of the combined options were also examined.

Data produced during the study were used to determine the phosphorus load reduction required to control the algal problems in Harvey Estuary. A reduction of 70% would be required for the 1 year in 5 year estimated phosphorus load to exceed the level in 1979, when *Nodularia* did not bloom in Harvey Estuary.

The required phosphorus load reduction for Peel Inlet is more difficult to assess because:

- the estimates of phosphorus loads available for the rivers entering Peel Inlet are relatively poor,
- there has been no observation of a phosphorus-limited 'no bloom' year for the macroalgae in Peel Inlet,
- the most important limiting factor for macroalgal growth in the deep water is light, rather than phosphorus.

For options which directly control the phosphorus load flowing from the catchment to the estuary, the load reduction potential can be readily determined. It is more difficult to predict the (phosphorus reduction) potential of other options.

For the options listed in Table 4.1, conservative estimates of phosphorus load reduction for both Peel Inlet and Harvey Estuary are shown. From this table, combinations of options were selected to provide a phosphorus load reduction equal to or greater than that required to prevent *Nodularia* blooms in Harvey Estuary for the nominated frequency of four years out of five.

Table 4.1 Potential for phosphorus load reduction of various options

Option	Potential Phosphorus Load Reduction	
	Harvey Estuary	Peel Inlet
Modification of agricultural practices	40%-50%	50%
Changes in current land use	35-85%$^{-1}$	45-90%[1]
Amendment of leaching soils with bauxite residue	15-50%$^{-1}$	35-65%$^{-1}$
Wetland filters[3]	?	10%
Chemical precipitation of phosphorus from surface drainage	30%	?
Diversion of drainage by using a barrage at Herron Ford	70%	?
Improvement of the existing Mandurah Channel	5%	20-40%[2]
Creation of a new channel near Dawesville	50%	25%

Notes:
1. Range of reduction dependent on areas of catchment treated.
2. Range of reduction in nutrient retention over summer and winter.
3. Wetland filters used in Serpentine Catchment only.

The reductions shown on the table are not additive, especially if options are applied concurrently at the same locations; for example, the combination of soil amendment with bauxite residue with the modification of agricultural practices will not reduce the phosphorus load to Harvey Estuary by 100%.

A number of single options and combined options could achieve the required phosphorus load reduction; however, the modification of agricultural practices combined with a new channel near Dawesville provides the most reliable solution. The combined effect of a 40% reduction in phosphorus input with increased marine flushing is shown in Fig 4.1.

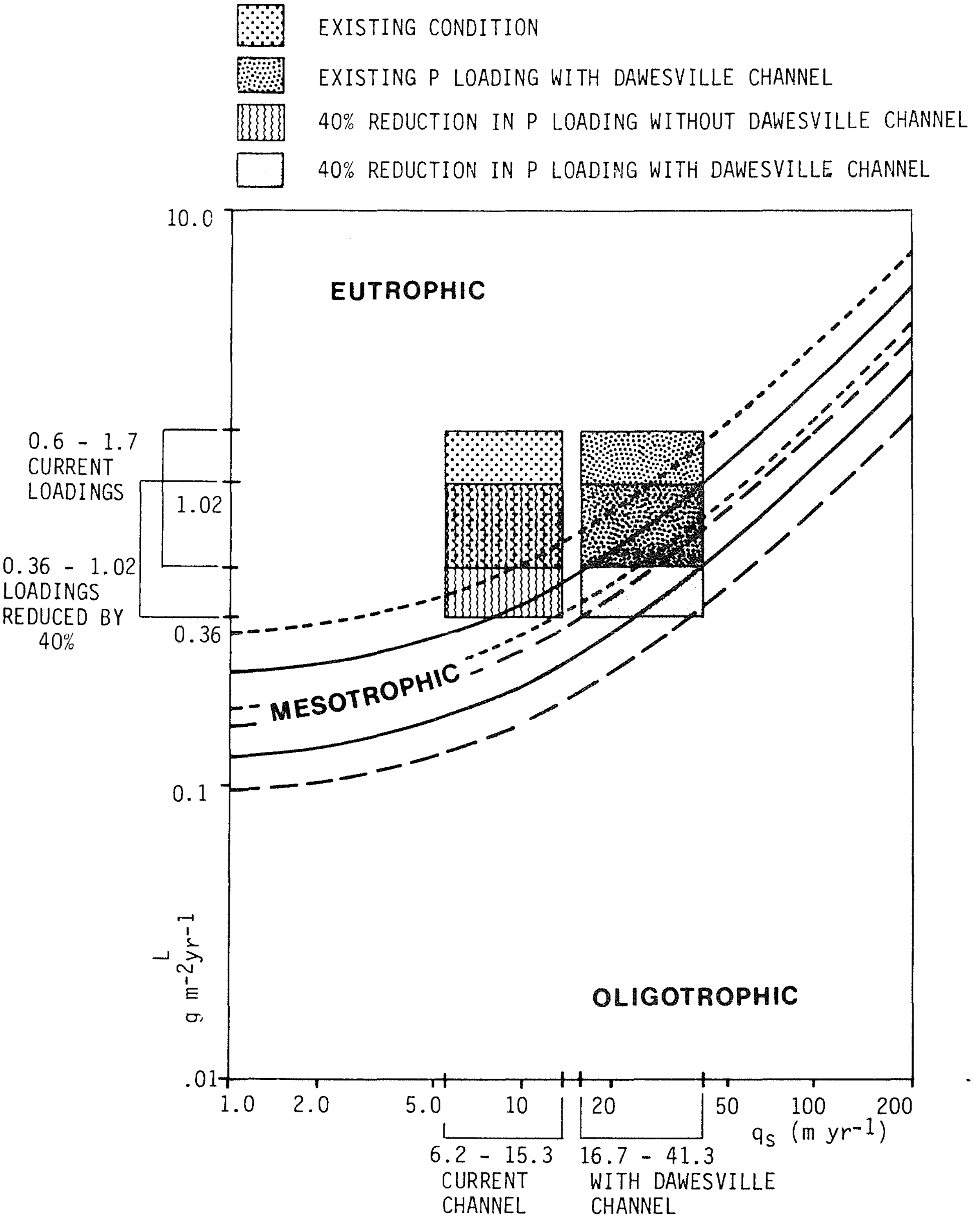


Figure 4.1 Effect of the recommended management strategy on the reduction of eutrophication of Harvey Estuary

The Harvey Estuary would evolve from its current eutrophic state into a mesotrophic/oligotrophic state.

The formulation of a management strategy has necessarily relied, in some cases, on interim conclusions based on one year's data from small-scale trials. Before the selected management strategy is implemented in its entirety, further analysis will be required, using catchment data from 1983 and 1984. The proposed management strategy includes the performance of the necessary work remaining, and is shown in Fig. 4.2.

4.3 Supplementary Procedures

Options which would be beneficial but not essential also comprise part of the management strategy shown in Fig 4.3; termed supplementary procedures, they would be implemented concurrently with the recommended strategy.

These supplementary procedures can be viewed as fulfilling three useful roles in the management of the nuisance algal problem: the direct control of nuisance algae, some reduction of phosphorus loading to the estuary, and some increase in phosphorus loss from the estuary, particularly from Peel Inlet.

Harvesting of macroalgae and the use of algicides, if proved to be acceptable, will reduce or remove the effects of the nuisance algae, though they will not effectively change the eutrophic state of the estuary. The use of these options would be seasonal, and they could be implemented when required.

Another group of supplementary procedures would include small-scale changes in land use, Mandurah channel dredging, biological filters and soil amendment with bauxite residue. These may either reduce the export of phosphorus from the catchment or decrease the retention of nutrients in the estuarine system.

4.4 Effect of the Management Strategy

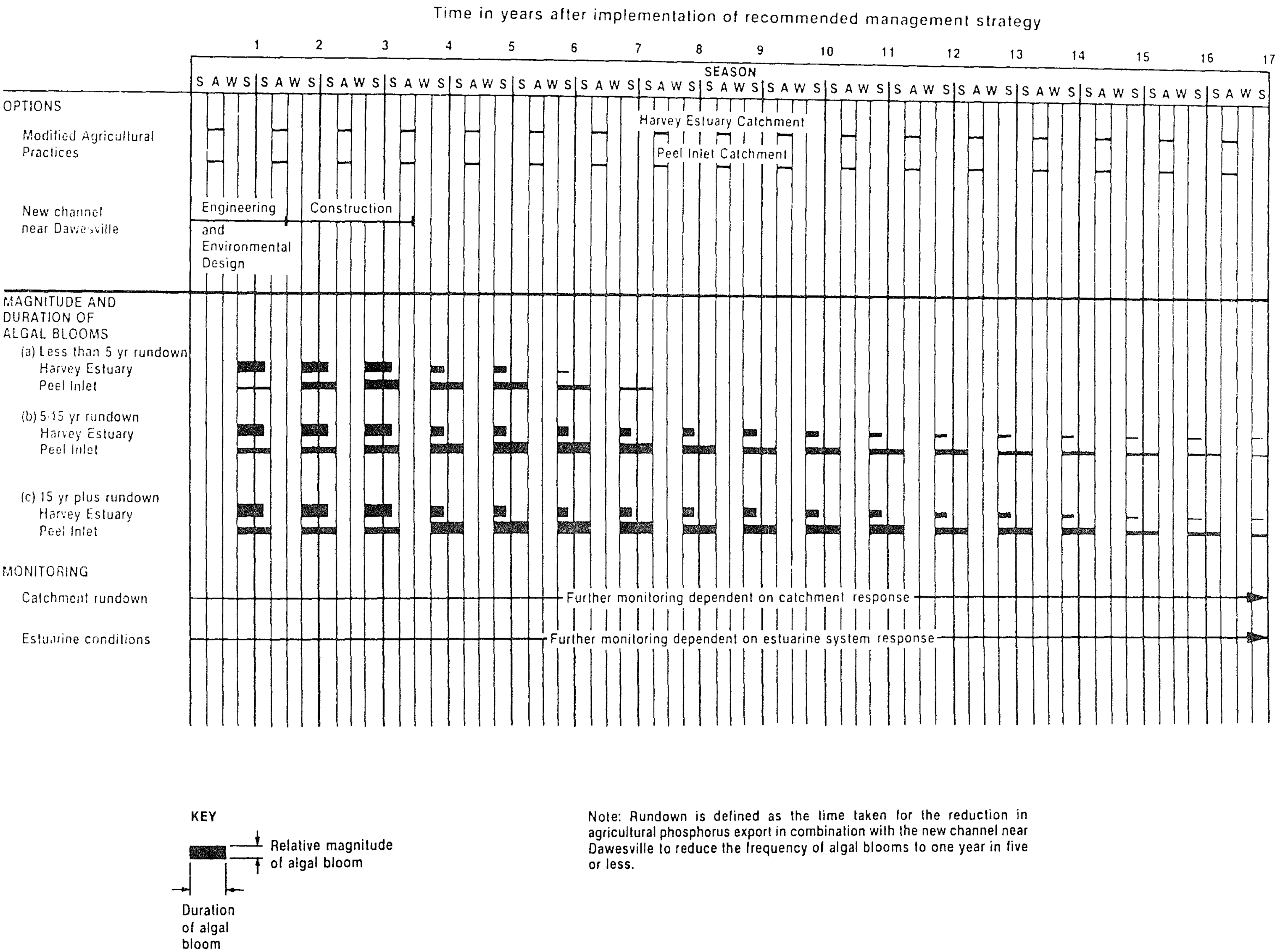
The modification of agricultural practices in the catchment would reduce the amount of phosphorus entering the estuarine system.

The effect of constructing a new marine channel near Dawesville would be to at least double the loss of phosphorus in dissolved or particulate forms to the ocean. The channel without the 'plug' would also reduce the blooms of macroalgae in the western Peel Inlet by:

- improving flushing of this area,
- reducing phosphorus currently supplied to this area from Harvey Estuary.

The timescales for implementation and effects of this strategy are shown in Fig. 4.2. The combined effect of these options would be to reduce the size and duration of the Harvey Estuary *Nodularia* bloom.

With the likely increase in water clarity in both Peel Inlet and Harvey Estuary, the seagrass population in the shallows may expand. A return of benthic algae is also possible in the deeper basins of both estuaries. Over time, reduction in the phosphorus input from the



Note: Rundown is defined as the time taken for the reduction in agricultural phosphorus export in combination with the new channel near Dawesville to reduce the frequency of algal blooms to one year in five or less.

Figure 4.2 Proposed management strategy, magnitude and duration of algal blooms and monitoring

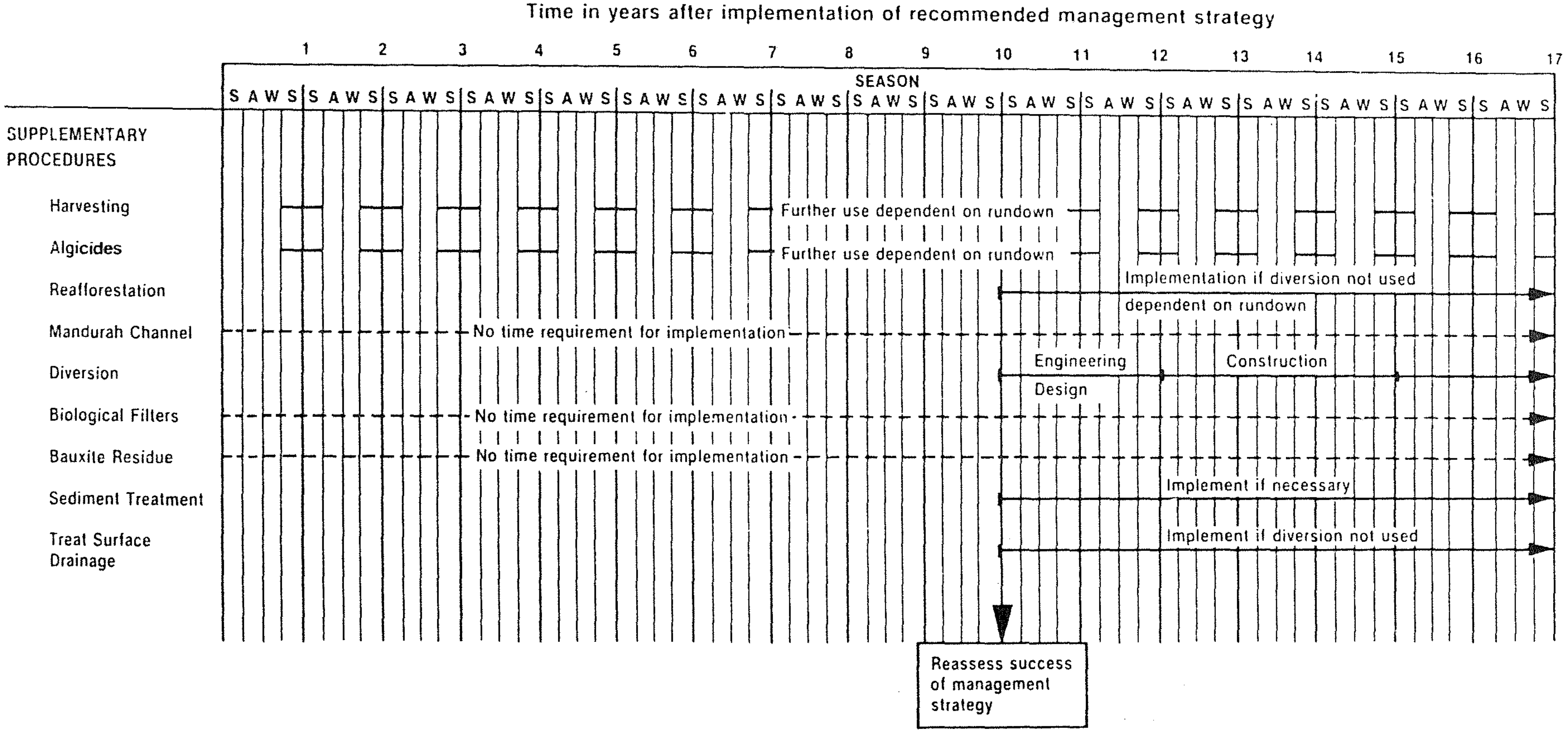


Figure 4.3 Supplementary management procedures

Serpentine and Murray River system should alleviate any macroalgal problem which may develop in Peel Inlet.

Should benthic macroalgae bloom in the Peel Inlet, current harvesting and beach clearing capacity should be adequate to solve the beaching problem. The short-term use of algicides may also be warranted, to treat the nuisance algae in both Peel Inlet and Harvey Estuary until sufficient reduction of phosphorus load from the catchment is achieved.

Three possible time scales are considered for the rundown of soil phosphorus export from the catchment. These are: less than 5 years, 5 to 15 years and longer than 15 years. The time scale for phosphorus load reduction will depend on the soil phosphorus rundown time for the catchments. The recommended management strategy is therefore able to meet all of the management objectives stated in Table 1.1, although the use of 'hard' options could not be avoided. The alternative recommendation does not involve any structural change to the estuary, and may be considered a 'soft' option.

4.5 Estimated Cost of Implementing the Management Strategy

The estimated cost of the recommended strategy is shown in Table 4.2. The final cost for the channel and associated bridge will depend on the design dimensions, to be determined after a thorough geotechnical investigation.

Table 4.2 Estimated capital, operating and present-worth costs for the recommended management strategy and supplementary procedures

	Estimated Capital Cost \$M	Estimated Annual Operating cost \$M yr^{-1}	Estimated(3) Present Worth of Operating and Capital cost
Management Strategy			
Modification to agricultural practices (including soil testing)	-	0.07(1)	0.7
Creation of a new channel near Dawesville(2)	17-22	0.3	20.0-25.0
Sub Total	17-22	0.37	
Supplementary Procedures			
Harvesting	0.26	0.12	1.5
Algicides(4)	-	-	-
Harvey	-	0.04-0.41	0.4-4.1
Peel		0.03-0.33	0.3-3.3

Notes:
(1) Cost of enforcement or inducements not included
(2) Estimated sand-bypassing costs included
(3) Estimated operating costs multiplied by 10 for present-worth value (i.e. interest rate of 10%)
(4) Estimated cost for one application only

4.6 Time for Reduction of Nuisance Algal Blooms

The time required to reduce nuisance algae in the estuaries to acceptable levels is directly related to the rate of catchment phosphorus rundown. Three possible time scales are shown in Fig. 4.2 for this rundown. It is assumed that reduction of the algal nuisance is proportional to actual phosphorus input into the estuary, and that losses of phosphorus from marine flushing are negligible. These assumptions result in extremely conservative estimates, since enhanced phosphorus loss from the estuary by flushing will also reduce the amount of phosphorus available for algal growth.

Modelling studies indicate that a new channel near Dawesville could increase the flushing rate for Harvey Estuary by a factor of four; for Peel Inlet by 1.5. It is possible that this channel could control nuisance algae adequately even if the fully estimated reduction of phosphorus input through modified agricultural practices cannot be achieved. The estimated magnitude and duration of the algal problem in both the Peel Inlet and Harvey Estuary shown in Fig 4.2 therefore represents a conservative view.

The successful control of nuisance algae does not depend on the implementation of the supplementary procedures, but they would provide benefits to the system and hasten the control of nuisance algal blooms. Their introduction could be gradual.

The other procedures, including large-scale changes in land use, diversion of drainage using a barrage at Herron Ford, treatment of sediments and treatment of surface drainage provide the basis for a contingency plan, if successful management cannot be achieved.

The implementation of the procedures in this third group would have to be based upon a thorough investigation of current conditions within the estuary and catchment. From our knowledge of present conditions, these options should not be required.

4.7 Administration of Management

It is recommended that a full-time task force be established to plan, implement and monitor the management strategy adopted. It should consist of a scientific director/manager, an ecologist and an engineer plus appropriate supporting staff, and should be responsible for the following:

- further evaluation of the chosen strategy, and its planning,
- supervision of the implementation,
- monitoring its effects on the estuarine system,
- design and funding of specific management-oriented research, the interpretation of those findings, their synthesis with the existing knowledge of the system, and their application to the management of the estuarine system.

4.8 Further Studies and Ongoing Monitoring

The recommendations discussed in this report have been made using the data available. A number of studies are due for completion in 1984; before implementation, it is therefore recommended that the major conclusions of this study be reviewed once data from the ongoing studies has been analysed.

The proposed new channel's effectiveness in reducing estuarine phosphorus levels is of particular concern. A simple, predictive model was constructed to simulate this process. The use of this model should be continued and extended to provide better prediction of the degree of nutrient reduction expected in the estuary.

Monitoring of phosphorus rundown from the catchment soils and drainage should be continued, frequently at first, then at lengthening intervals once trends become clear.

The rate at which a reduction in applied phosphorus can benefit the estuary is not known. Further studies should investigate soil phosphorus cycling and leaching mechanisms, and the rate of groundwater movement from the catchment to the estuary. Once these mechanisms are better understood, loss rates from the catchment can be more accurately estimated, and decisions regarding the continuation of harvesting and algicide use can be made.

Monitoring is particularly important in the operation of these supplementary procedures, if the proposed strategy is to meet the management objectives.

APPENDIX 1

TERMS OF REFERENCE

The terms of reference for this study are summarised in the proposal for this study submitted to the Public Works Department and the Department of Conservation and Environment in October 1982.

CENTRE FOR WATER RESEARCH
THE UNIVERSITY OF WESTERN AUSTRALIA
NEDLANDS WA 6009

PROPOSAL FOR THE SECOND STAGE OF A FEASIBILITY STUDY OF THE MANAGEMENT OPTIONS FOR THE PEEL - HARVEY SYSTEM

October, 1982

Aim

To examine the feasibility, cost, likelihood of success and time for implementation and effect for the management options listed in DCE Report No. 9, Notes of the Public Works Department Technical Steering Committee Meeting held on July 23, 1982 and any others which may emerge during the study. This would include consideration of the compatibility of mixed short-term and long-term solutions to the eutrophication of the estuary.

Preamble

The first stage of a feasibility study of the management options proposed for the algal nuisance in the Peel/Harvey estuary has been in progress since mid-July, and will be complete by late November, 1982.

This work has the following specific objectives :

1. To prepare a working paper describing the physical, chemical and biological data bases available for the system during the period late 1976 to early 1982. The working paper would include maps of measurement locations, and descriptions of each variable incorporating such attributes as duration of record, sampling frequency, computer file format and known deficiencies (if any). An archive of these data would be installed on the UWA CYBER, to facilitate free access by appropriate users, to cover a one-year timespan with the best available coverage of data.

2. Define possible management options, which will include the following:

   2.1 Modification of agricultural practice on the coastal plain, particularly with regard to phosphatic fertilizer use and type, and soil modification.

   2.2 Diversion or interception of nutrient-enriched drainage water by natural or artificial wetlands.

   2.3 Treatment of coastal plain drainage by salts of calcium, aluminium or iron to precipitate phosphorus.

   2.4 Diversion of nutrient-enriched drainage (particularly the Harvey River and tributaries) to the sea, with or without barrages in the estuary.

   2.5 Inactivation or removal of sedimentary nutrient sources by precipitation and/or dredging.

   2.6 Application of algicides, algistatics or inorganic nitrogen to change the species composition of the algal flora away from dominance by Nodularia.

   2.7 Weed cleaning to remove macroalgae.

   2.8 Enhancement of estuarine flushing by construction of embankments and realignment of channels, diversion of freshwater inflows or deliberate water release from Darling Scarp pondages.

3. Review appropriate literature to obtain for each management option a preliminary estimate of :

   (i) the likelihood of success;

   (ii) time required for the desired effect to occur;

   (iii) practicability and cost of each option;

   (iv) the potential level of nutrient reduction (not necessarily appropriate for all options);

   (v) the preliminary definition of possible changes to the hydrology of the catchment, and hydrodynamics and ecology of the estuaries.

Exercise (v) would provide more tightly-defined questions for quantitative examination in collaboration with the engineer after November.

4. Search for and review the usefulness and requirements of suitable synthetic models for application to various parts of the system. Investigate the data requirements of these models, and discuss obvious deficiencies with appropriate team members. A limited amount of time will be spent on this aspect of the work, as determined in consultation with the Technical Steering Committee.

5. Communicate with other team members to discuss and evaluate information deficiencies revealed in steps 2, 3 and 4 above. Investigate ways to remedy critical deficiencies.

6. Write concise notes on each topic reviewed.

   Recognizing the lag inherent in obtaining appropriate literature and other information from diverse sources, the work done in the first stage will lead naturally to an intensive refining of the tasks outlined in point 3 above.

Personnel

The Management Study will have the following well-defined tasks:

(i) Canvas all appropriate government departments and other parties regarding possible management options, and address them in the report.

(ii) Refine the individual management options, and consider their applicability in terms of :

  - Their likelihood of controlling the algal problems.
  - The time required for effect(s) to occur.
  - Their practicability and compatibility, either as short-term or long-term solutions to the problem.
  - Their biological consequences within the estuary, and any other major effects on the environment.

(iii) Carry out order-of-magnitude calculations to identify the dominant biological, chemical and physical parameters, that is, compare the relative importance of each of the processes in determining the observed and likely future behaviour of the system.

(iv) Carry out a preliminary costing of each option, although a rigorous economic study of benefits and costs will not be done.

(v) From the above, recommend further research to fully evaluate each option, or compatible group of options.

(vi) Prepare a framework within which relevant information obtained subsequent to this study may be incorporated and assessed. This would include recommendations on the use of suitable management-oriented simulation models.

Reporting

Reporting would comprise the following:

(i) Frequent contact with the appointed project officers from DCE and PWD, to provide a vehicle for routine communication from the Centre for Water Research to appropriate sections of government.

(ii) Informal reports by Professor Imberger and/or Professor McComb and/or Study Team members at monthly meetings of the Technical Steering Committee - particularly during early stages of the Study.

(iii) Brief interim written reports each quarter.

(iv) An opportunity would be provided for the Technical Steering Committee to comment on a draft of the Final Report.

(v) A final report one year after the full initiation of stage two of this work.

APPENDIX II

Framework

This study has assembled an information base, data processing and computer simulation capability which can now be extended for further detailed evaluation of the chosen management strategies, and for the longer term monitoring of the Estuary and the performance of the management strategy(s) after implementation.

The framework consists of the following elements:

i) Computer data files, plots and listings of time series information such as river flows, nutrient concentrations and loads. Copies will be held by Public Works Department Water Resources Section, Department of Conservation and Environment and the Centre for Water Research.

ii) A working mass balance model for phosphorus and salt, copies of which are held by DCE and CWR.

iii) A guide to the database and study bibliography by Humphries, Lukatelich and Simpson (1982).

iv) Collated calculation sheets from this study.

v) The three technical reports of the feasibility study, and the other published material from Phases 1 and 2.

vi) The 2-dimensional RAND water quality model and the DWOPER flood routing model, held and maintained by the CWR.