POTENTIAL FOR MANAGEMENT OF THE PEEL-HARVEY ESTUARY

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POTENTIAL FOR MANAGEMENT
OF THE
PEEL-HARVEY ESTUARY

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Western Australia, 28-29 November 1983

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Compiled by E P Hodgkin

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LIST OF THOSE WHO ATTENDED THE PEEL-HARVEY SYMPOSIUM 28&29 NOV.1983

SPEAKERS

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Mr C M Croft	UWA Water Research Centre
Mr N J Halse	Task Force on Land Resource Management in S W Aust.
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Mr B Hewson	
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Dr R A Field	
Mr G G Forbes	
Dr B H Hamilton	
Mr K W McAlpine	
Ms K Majer	
Ms S J Robinson	
Ms J Saggers	
Mr C H Welker	
Dr C Whitaker	
Mr R Atkins	Waterways
Mr R Brindley	
Mr C Liddle	
Mr P Bayley	CSIRO

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		Mr M Height	
		Dr K Skinner	

Mr D Glenister	ALCOA
Mr J Summers	
Mr S Wara	

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Mr A Deeney	Geological Survey
Sir D Eckersley	LIMA
Mr G Elliot	WAIT
Mr R Hiller	TPD
Mr D Hurle	D Hurle and Associates
Dr RCJ Lenanton	Fisheries and Wildlife
Dr F H McKinnell	Forests Department
Mr N J Mulcahy	Taskforce on Land Resource Management in S W Aust.
Mr P Southern	CSBP
Mr O Tuckey	PIMA

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Ernest P Hodgkin
Department of Conservation and Environment

The Peel-Harvey Estuarine System Study began in 1976 with two objectives:

1. Specific: To determine the causes of the excessive growth and accumulation of green algae in Peel Inlet and if possible to propose methods for its control.

2. General: To gain an understanding of the working of this estuarine ecosystem so that environmental problems can be foreseen and decisions made about its management on the basis of sound knowledge.

That turned out to be only Phase 1 of the study because after the findings were reported in 1980 (DCE Report No.9, DCE Bulletin No.88) the study moved into Phase 2, from early 1982. This second phase aimed to determine just how the estuary can be managed so as to prevent the algal problems. During the study the algal problems have increased and diversified, but the cause has remained the same - the excess of plant nutrients available to algae in the estuary. It is natural therefore that the Phase 2 studies have concentrated mainly on how best to reduce this eutrophic condition, prevention, although some attention has rightly been given to control of the symptoms, treatment.

The symposium held in December 1982 concentrated largely on efforts to find out how best "to reduce the quantity of phosphorus discharged to the estuary from agricultural land", as recommended by the Estuarine and Marine Advisory Committee (DCE Bulletin No.88, 1981).

This year's Symposium has a much wider scope. The aim is to review all research which has any relevance to management of the present eutrophic condition of the estuary and then to decide what recommendations can now be made with respect to management (Phase 3), and what further Phase 2 type studies are necessary. Clearly a two-year study into how to manage such a complex ecosystem as that represented in Figure 1, which has been mis-managed or not managed at all for half a century, cannot be expected to have all the answers. There are still far too many areas of uncertainty for the comfort of most scientists involved, particularly with respect to the agricultural aspects.

Predictions as to what can be achieved by alterations to a complex biological system will, at best, be only as good as the data on which they are based. In the past we have failed to predict major changes to the estuarine ecosystem and it would be unwarranted and conceited to assume that we can do so now with certainty, despite our much greater knowledge. Nevertheless we have to make recommendations for management - recommendations as to what can be achieved and what measures are required in order to achieve them -

recommendations which if implemented could cost the State millions of dollars, affect the lives of many thousands of people, and change the face of an agricultural industry worth $30 million a year to farmers.

Fortunately perhaps, it is not our job to decide what should be done in Phase 3 of this study, the management stage; rather we have to assess what can be achieved by the various measures which have been investigated and to identify the constraints which apply to them. This is not to suggest an ivory tower approach, we must obviously be aware of social, financial and other constraints and make due allowance for them, but in making judgements we need to be conscious of the assumptions we have made. As an extreme example, the commitment to having both a viable agricultural industry on the coastal plain and a healthy, largely weed-free estuary is an assumption. Other people, farmers, Mandurah residents, politicians, may justifiably question our assumptions and place a different set of values on them. They are value judgements which will influence decisions as to what should be done.

Objectives for management

It is well to be clear at the outset what our objectives for management are, and to be agreed on them. They are listed in detail in the Croft - Humphries report. However, the principal aim is to reduce the algal nuisance to acceptable levels without further damage to the estuarine environment, and if possible without loss of production of the estuarine fishery and of agricultural production in the catchment.

'Acceptable levels' of algal abundance are defined as:

- Blue-green algal blooms should not occur more often than once in five years, that is only in years of well above average rainfall.
- Large green algae should not cause fouling of beaches near populated areas.

Management measures

Once the cause of the algal problem was identified the logical solution was obvious: reduce the input of fertilizer-derived phosphorus to the point at which it will no longer result in blooms of nuisance algae. To do this requires an agricultural revolution, something that is possibly long overdue but cannot be achieved overnight. It also requires a detailed understanding of the behaviour of the phosphate ion in the highly complex media of plants and soils in the paddocks, something that is not available from text books.

The management studies indicate that the input of phosphorus to the estuary cannot be reduced sufficiently to prevent algal blooms by agronomic measures alone, within an acceptable time. Of course this does not mean that such measures should not be pursued actively, it does however mean that other measures to reduce the phosphorus available to algae will have to be employed in order to achieve the management objectives. Acceptance of this fact means that other measures have to be evaluated for their capacity to contribute to a reduction in nutrient levels in estuary water sufficiently without undue disruption to the ecosystem, and again within an acceptable time.

It is unlikely that any measure we can recommend will achieve a significant reduction in the eutrophic condition of the estuary within the next three to five years. We must therefore also consider what measures can be taken to ameliorate the worst effects of the algal blooms in the interim, again with the minimum damage to the ecosystem.

The papers presented here, whether or not they say so explicitly, relate to these management considerations and should be read for their contribution to determining what recommendations can be made for management at this time.

The comments which follow are intended merely as thought starters. The facts will be found in succeeding papers and the figures used here are mostly only approximations, near enough I hope for the validity of the arguments presented.

The catchment source

There have been Nodularia blooms in the estuary in every year from 1978 - except in 1979. The estimated input of phosphorus in that year (1979) was 46t to Harvey Estuary. In 1981, still a year of only marginally above average river flow, the figure was 124 tonnes of phosphorus, nearly three times the 1979 figure. In the absence of any better criterion, the requirement of a 70% reduction on present loads is therefore regarded as the maximum acceptable phosphorus input if Nodularia and other cyanobacterial blooms are not to occur more frequently than about one year in five.

Given that the minimum quantity of phosphate fertilizer is used to maintain production on the coastal plain and that only slow release fertilizers are used, the release of phosphorus to drainage could immediately be reduced by about 30%. This low response is mainly because about 70% of the phosphorus lost from paddocks comes from the soil store, the farmers' 'super bank' which has built up over many years. Only 30% is accounted for by fertiliser applied in the current year.

In 1982, experimental work in the catchment concentrated mainly on the deep grey (Bassendean) sands (Figure 2) because of the high leaching losses from them (Table 1). The 1983 studies have been extended to the sands over clays (Coolup) soils from which leaching is less. But because of the greater area of these soils they contribute a larger proportion of the phosphorus load. Although the leaching rate from the other soil types on the coastal plain is low they do make a significant contribution to phosphorus input to drainage and cannot be neglected in any measures to reduce the phosphorus load to the estuary.

Table 1. Estimated Phosphorus export from the Harvey River and Mayfields Drain catchments to Harvey Estuary[1]. 1982

	Catchment area		Fert. appl.	Phosphorus to drainage				
				Rate		Quantity		
	km^2	%	kg/ha	kg/ha	%	tonnes	%	
Deep grey sand	143	22.4	4.6	1.4	30	20	33)	) 79
Sand over clay & B & Y sand	213	33.4	11.5	1.3	11	28	46)	
Clays & loams	143	22.4	15.4	0.7	5	10	16	
Foothills	139	21.8	-	0.2	-	3	5	
	638	100				61	100	

1. The Harvey River and Mayfields Drain catchments represent about 80% of the total Harvey Estuary catchment, but deliver about 90% of the total load to it.

The 1978 studies estimated that the plateau catchment of the Murray River only contributed 10% (17 tonnes) to the input of phosphorus to the estuary. Rainfall and river flow were well below average. Birch estimates this contribution to have been 14 tonnes and 20 tonnes in 1981 and 1982 respectively, both years of below average flow. Management of this source may have to go into the "too hard basket" for the present, but it is clearly an important contributor to Peel Inlet's problems and input from this source cannot be disregarded.

The estuary's response

We are dealing with an ecosystem that is out of balance. Not only is there an excess of plant nutrients, but the estuary has not had time to learn how to use them. Primary production has greatly outstripped secondary production and given time or, as Atkinson suggests, by giving a boost to secondary production this might well catch up. Alternatively, as Kidby early suggested, it is possible that a harvestable crop could be propagated which would mop up the excess nutrients. Or there may be some exotic species of fish which would harvest the present crop for us, were Australia prepared to risk importing an aquatic 'rabbit'. Such biological solutions to the algal problems have an obvious appeal; unfortunately they take time to research adequately, and to implement, more time than social pressure and the deteriorating condition of the estuary will allow us.

In 1976, when we were asked to investigate the 'algal problem' in Peel Inlet the nuisance alga was *Cladophora*. Subsequently *Chaetomorpha* and then in 1982-83 *Ulva* have been the dominant algae. The change cannot be assumed to have been fortuitous and probably represents a further deterioration in the condition of the Inlet. These algae only penetrate the northern 15% of Harvey Estuary. The first *Nodularia* bloom we observed came in 1978. It was confined to Harvey Estuary until tidal currents carried it out into Peel Inlet. Since then blooms have affected the whole estuary, except in 1979, and bloom intensities have been roughly proportional to the input of phosphorus which, in turn, has been roughly proportional to rainfall and river flow. The two years 1973 and 1974 had well above average rainfall. There were *Nodularia* blooms in both years in Peel and Harvey. They are faithfully recorded in the Government Chemical Laboratories reports of the time, though there is no measure of their intensity. I am not aware that there was any public outcry.

In 1983 the phosphorus load to Harvey Estuary was similar to that of 1980 and 1982, but less than that of 1981. The biomass of the *Nodularia* bloom was as big as ever before, though the mean chlorophyll a concentration was less than in the last three years and the bloom was of slightly shorter duration.

A disturbing fact of 1983 has been the intensity of the diatom blooms of July to September and the large proportion of phosphorus trapped by them and transferred to the sediments.

The increase in diatom (and dinoflagellate) populations appears to be attributable to increased recycling of phosphorus through the surface sediment, a mechanism which is adequate to fuel the *Nodularia* blooms, as Gabrielson's work has shown.

It is difficult to predict the response of the estuarine biota to this increased load and the potential of greater inputs with any return to above average rainfall. It is important to remember that 1981 was the only year in which river flows, and phosphorus input, was above average. We can still do little more than guess what will happen when and if rainfall recovers. McComb's prediction that Nodularia will be light-limited at concentrations above the 1981 level is not particularly comforting. Figure 3.

The potential of the sediment store of phosphorus to fuel future blooms must be taken into consideration in assessing the future of the estuary.

It is probably true that if phosphorus input is reduced below the 1979 level the sediment store will run down rapidly. However, that situation is likely to be some years away and in the meantime there is little prospect of the present unhealthy condition of the estuary improving greatly. It is in that context that we need to examine any measures which can be used to ameliorate the present problems, even if they do nothing to reduce the eutrophic condition of the estuary.

If this is too depressing a note on which to conclude this introduction it will be clear from the papers which follow that the work of the last two years does offer a good basis for management within a time period much shorter than that in which the estuary has been brought to its present unsavoury condition. There will be some hard decisions to be made but the community can be assured that there are ways to reverse the present deterioration in the condition of the estuary, even if they may be expensive and take several years to implement.

Appreciation

W.A. is rightly famous for the way in which scientists and engineers co-operate in attacking a problem such as the one with which we have been confronted in the Peel-Harvey estuary. The participants in this Symposium, and they are by no means all of those who have been involved in the Study, come from a wide range of disciplines in a common purpose to discover how to solve a serious biological problem that has become a social issue.

It has been a privilege as Research Co-ordinator to lead such an enthusiastic and supportative team. Sometimes I think I have been like the Duke of Plaza-Toro who 'led his regiment from behind' though not because I 'found it less exciting' and have been carried along in the wake. If at other times I have been a nagging nuisance pressing for information and reports from busy people with other responsibilities, my apologies. But to all, my grateful thanks for the support they have given me personally and the willing co-operation there has been to make the team work.

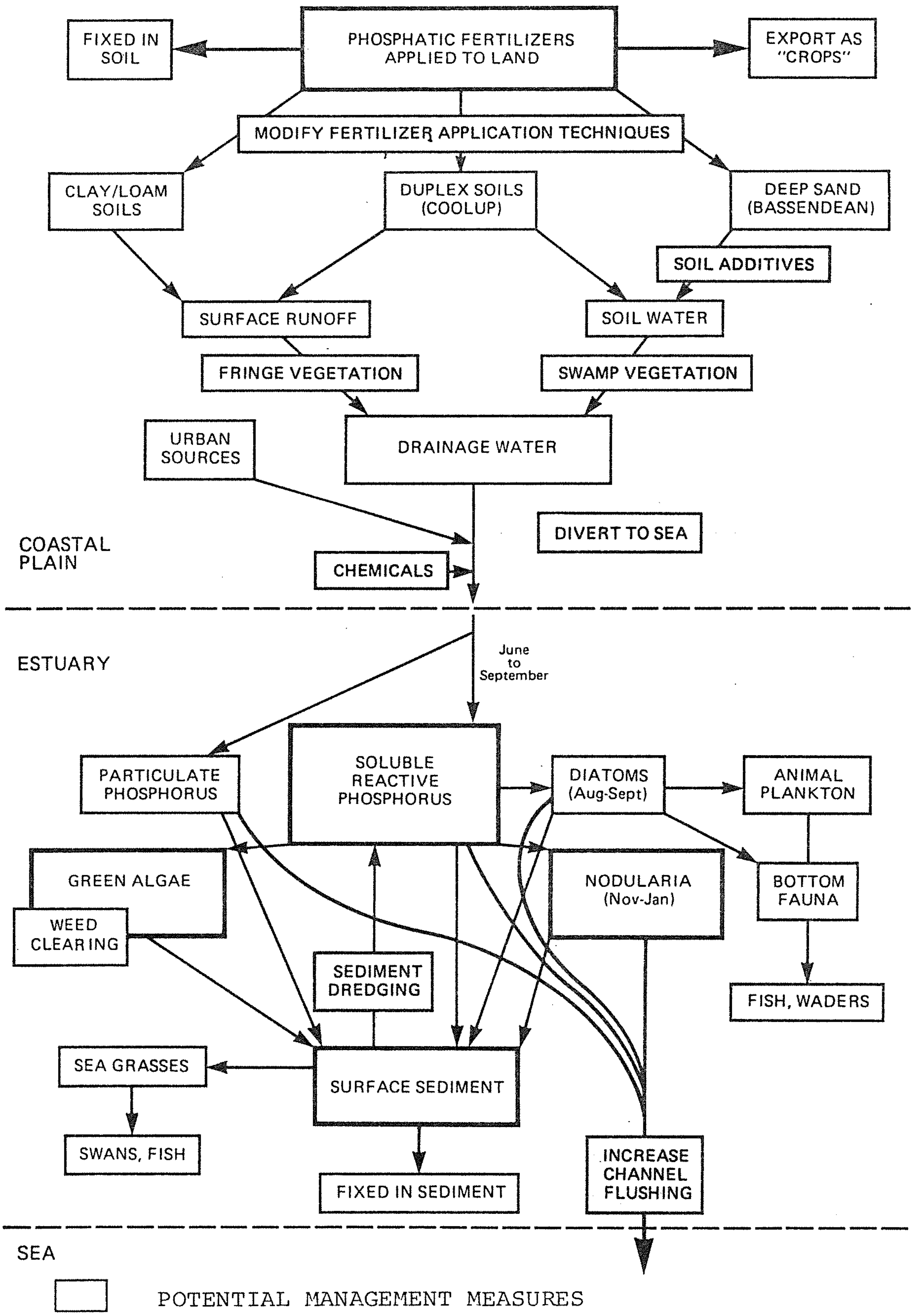
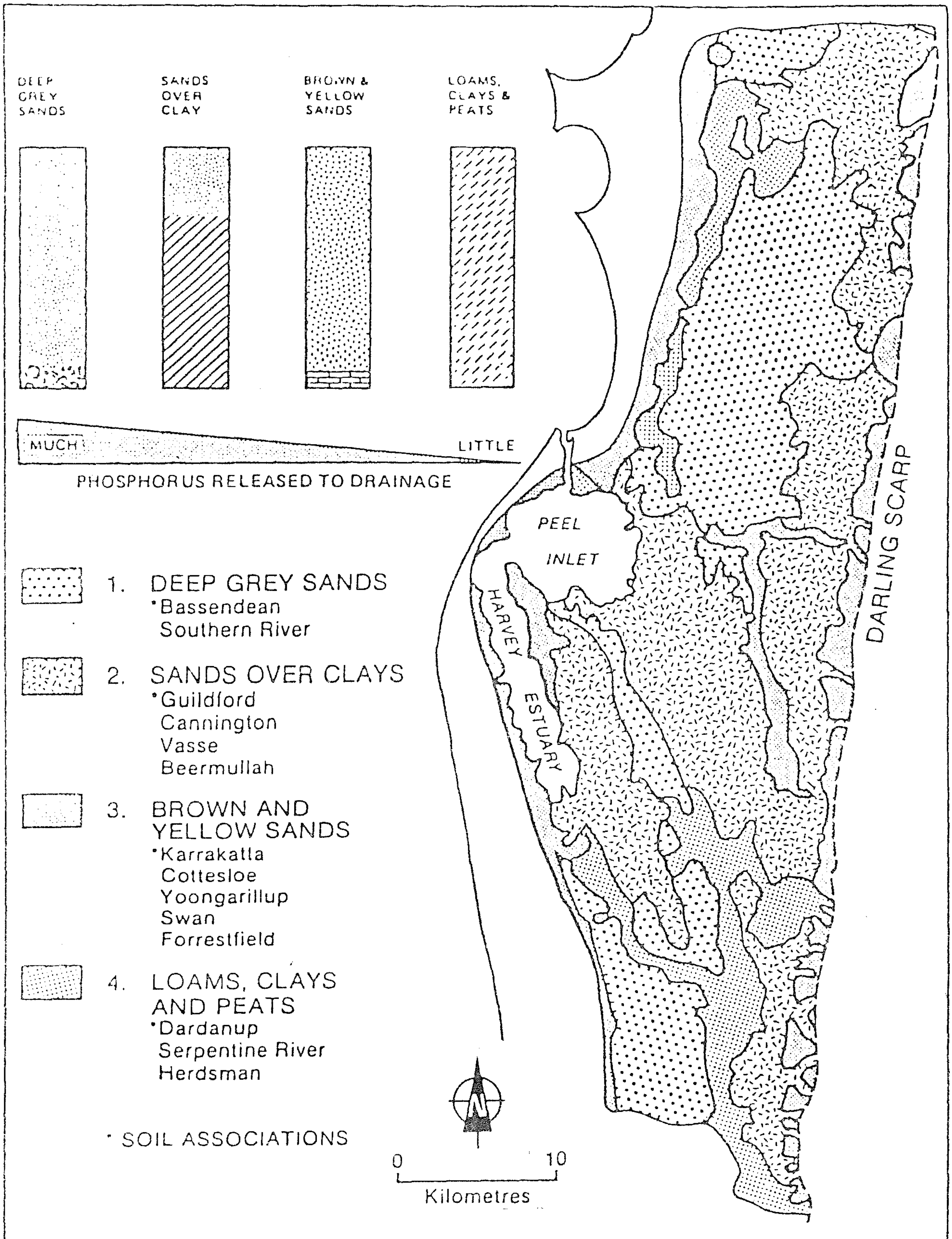


Figure 1. Phosphorus flow paths in the coastal plain/estuary ecosystem.



The BASSENDEAN Soil Association includes JOEL sands on the flats with 1 to 2 m of sand over coffee rock and GAVIN dunes with up to 5 m of sand over the coffee rock.

Figure 2. Soil categories on the coastal plain catchment of the Peel-Harvey estuary.

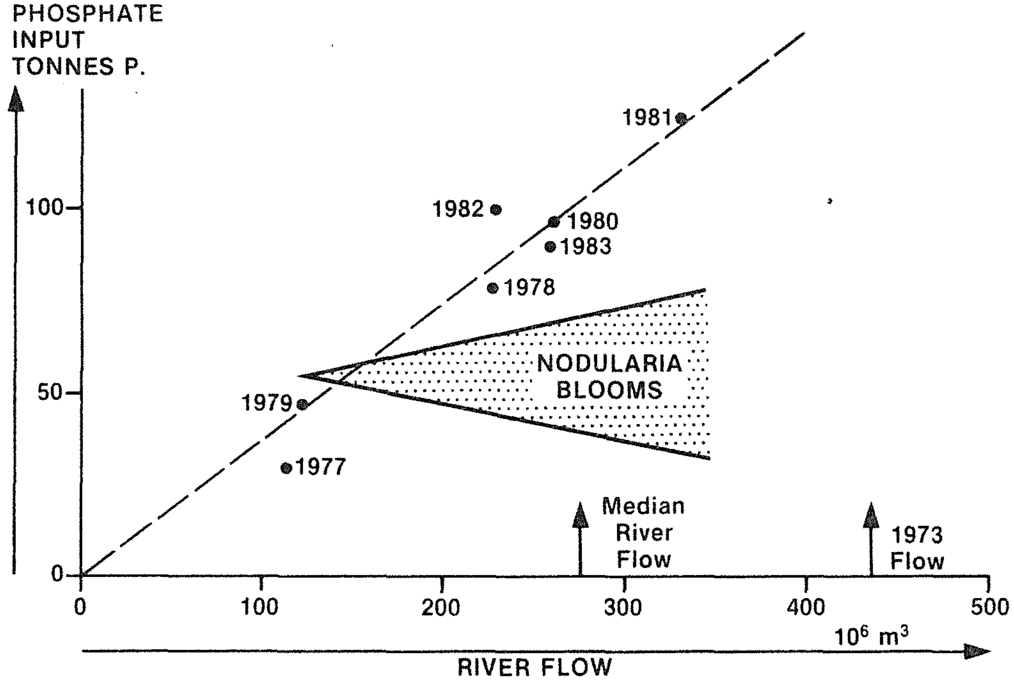


Figure 3. Phosphorus input to Harvey Estuary, flow in Harvey River and Mayfield Drain and size of nodularia blooms.

Review of Humphries, R.B. and Croft, C.M., Management of the eutrophication of the Peel-Harvey Estuarine System, Department of Conservation and Environment Bulletin No.165, 1983.

by

S J Robinson
Department of Conservation & Environment

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SEMINAR ON MANAGEMENT OPTIONS FOR THE PEEL-HARVEY SYSTEM

1. INTRODUCTION

A feasibility study of management options for the Peel-Harvey system has been carried out by R B Humphries and C M Croft at the Centre for Water Research, University of Western Australia.

The study team produced three reports

1. Report 1 (dated August, 1983) - a working document which considered all the management options, rejected those considered to be impractical and made recommendations on areas of additional work required to test further the feasibility of the remaining options
2. Report 2 (dated November, 1983) - considered the more promising options in greater detail
3. Report 3 (dated November, 1983) - contains a summary of the earlier reports and makes recommendations on management packages

The purpose of this summary document is to present in brief all the options, indicate the reasons for rejection at an early stage and to provide a concise account of the modus operandi, advantages and disadvantages of each of the most promising options. The document forms a discussion paper for the seminar to be held on November 28 and 29, 1983.

2. PURPOSE OF THE SEMINAR

It is intended to limit discussion at the seminar strictly to the options believed to be feasible and to give no further consideration to those strategies that were rejected early (a list of these is appended). There is a lot to cover in two days and the time schedule will be rigidly adhered to. If any seminar delegate wishes to make any comment about the rejected options they should consult the full reports which can be seen at the Department of Conservation and Environment (Dr P Birch), Public Works Department and the Centre for Water Research. Any enquiries should be directed to Dr P Birch at DCE or Dr Bob Humphries or Mr Chris Croft at the Centre for Water Research before Friday 25 November 1983.

3. STATEMENT OF THE PROBLEM AND PROPOSED MANAGEMENT OBJECTIVES

Elevated phosphorus levels in the Peel-Harvey system have been identified as the prime cause of the nuisance algal blooms that frequently occur. Management objectives are aimed particularly at methods of reducing input of nutrients to the estuary from the surrounding catchment. Other problems such as retention of phosphorus in the sediments have also been considered.

Four management mechanisms have been identified:

- reduce phosphorus input to the Peel-Harvey system
- increase phosphorus export from the system
- reduce sediment phosphorus supply within the system
- manage the macroalgal nuisance

A statement of proposed management objectives is given in Table 1.

Table 1 - Statement of Proposed Management Objectives

Objectives

1. Cyanobacterial blooms are not to occur with a frequency greater 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 cause fouling of the populated estuarine beaches.

Constraints

3. The environmental impact from any strategy adopted should be far less than the existing impact caused by the present nutrient enrichment.
4. Public access to the estuary by water or land should not be reduced.
5. Productivity of the estuarine fishery should not be reduced.
6. Productivity of coastal plain agriculture should be maintained where practicable.
7. Changes to surrounding natural ecosystems should be minimised.
8. Introduction of exotic plants and animals should be avoided.
9. Major physical changes to the estuary, for example new channels, islands of dredge spoil, increased depth, changed bottom morphology, salinity and temperature regimes, should only occur for attainment of the objectives stated above or to satisfy normal flood relief and navigation needs.

4. SUMMARY OF MANAGEMENT OPTIONS

All the management options considered could be broadly classified into eight groups, these are

(i) modifications to agricultural practices

(ii) wetlands as nutrient traps

(iii) chemical removal or inactivation of phosphorus

(iv) diversion of drainage water to the sea

(v) direct attack on algae

(vi) dredging of the estuary

(vii) increased marine flushing

(viii) miscellaneous options

Of these groups (vi) and (viii) were rejected early (see Appendix). Specific proposals within the other categories were evaluated further and are summarised in the following pages.

4.1 MODIFICATIONS TO AGRICULTURAL PRACTICES

4.1.1 Soil Tests, Types of Fertilisers and Application (Sections 3.1.1 and 3.1.2 of Report 1)

Rationale

Soil tests can be used to establish fertiliser requirements and particularly to determine optimum fertiliser application rates and type of fertiliser. New fertilisers are required that will slowly leach from the upper soil horizon yet provide freely available phosphorus to plants and supply adequate annual essential sulphur to the soils. Initial studies indicate that very significant reductions in phosphorus leaching can be achieved.

Results

According to preliminary estimates, for the partially acidulated rock phosphate fertiliser (AS 3) a reduction in phosphorus application of 69% for deep grey sands and 78% for duplex soils can be achieved while maintaining productivity.

The estimated reduction in loss by leaching was 49% for deep grey sands and 57% for duplex soils.

ACTION

Continue investigations

4.1.2 Changes in Current Land Use (3.1.3 in Report 1)

Rationale

Conversion of highly leaching soils from agriculture to land uses requiring low phosphorus fertiliser application rates may be beneficial.

Two possible conversion alternatives have been considered:

(a) total removal of land from production and conversion to parkland which would give no financial return

(b) conversion from agriculture to forestry. This could reduce phosphorus export by reducing the phosphorus requirement in the catchment and by interception of groundwater by the trees. Financial return would be possible from either pine or eucalypt plantings.

Results

The total reduction in phosphorus application to forested areas would be some 45%.

At 1 500 trees ha^{-1} pines will be preventing groundwater recharge after 6-8 years from planting. Assuming that phosphorus input will cease with a reduction in groundwater recharge, a reduction in phosphorus export may be produced in 6 to 8 years.

Costs

Cost of establishing Pinus pinaster on the non-waterlogged Gavin ridges is \$1 500 ha^{-1}.

Cost of establishing eucalypts in the wetter areas is \$425 ha^{-1}.

Pines could give a total rate of return of \$5 600 ha^{-1} (1983 dollars) over a 60 year period, ie \$93 yr^{-1}.

Assuming an initial 15 year (and subsequent 10 year) growth for eucalypts for woodchips, the returns would be \$45 ha^{-1} yr^{-1}.

4.1.3 Amendment of Leaching Soils with Bauxite Residue (3.1.4 in Report 1)

Rationale

Bauxite residue has been suggested as a possible soil additive capable of reducing phosphorus leaching losses; it also improves water retention capacity and yield. Application rates of 1 000 to 2 000 t ha^{-1} of red mud have been previously suggested; later work shows that rates as low as 200 t ha^{-1} may reduce phosphorus leaching. Up to a 10-fold increase in pasture productivity may occur on some deep sands.

Results

A reduction in phosphorus in Harvey catchment and drains of about 23% would be possible if the deep grey sands were treated and 57% if the Bassendean sands and Coolup (duplex soils) were both treated.

Costs

For a 40 km cartage distance a cost of \$4 tonne^{-1} to load, cart and spread was obtained.

At a rate of 200 t ha^{-1} this cost is upwards of \$800 t^{-1}.

Transport costs are about 50% of the total cost of the residue and reduction could be achieved by pumping a slurry of approximately 45% solids to holding areas for later redistribution.

4.2 WETLANDS AS NUTRIENT TRAPS

4.2.1 Wetland Filters at Point Sources (3.2.1 in Report 1)

Rationale

The treatment of effluent water at point sources eg piggeries, involves the stripping of phosphorus by plant uptake and perhaps by sediment absorption.

This technique could be used for high concentration, low flow sources.

Results

If used at piggeries wetland filters may achieve a reduction of applied phosphorus of 14% in the Serpentine catchment. The amount of this phosphorus that is available for leaching to the estuary is not known. Wetland filters at piggeries could be implemented in about 1 year.

4.3 CHEMICAL REMOVAL OR INACTIVATION OF PHOSPHORUS

4.3.1 Chemical Removal of Phosphorus from Surface Drainage (3.3.2 in Report 1)

Rationale

Locally it has been suggested that red mud could be added directly to agricultural drainage water to absorb phosphorus, settle out and thereby reduce the nutrient flux into the Harvey Estuary. Addition of red mud slurry to open drains is not seen as acceptable environmentally. A process has been designed which can treat the Meredith catchment drainage water in a contained system prior to its release back into the Harvey Main Drain. The process uses ferrous sulphate (copperas) waste from the Laporte plant at Australind to neutralise the causticity of the red mud and to increase phosphorus adsorption capacity.

Results

Preliminary results of testing suggest that treatment could remove approximately 40 tonnes of phosphorus or 33% of the total estimated Harvey River inflow.

Costs

Capital cost of this scheme would be \$16 million with annual operating costs of \$2-5 million.

ACTION

Further work is required to confirm chemical aspects and preliminary engineering design and cost estimates should be carried out.

4.3.2 Chemical Treatment of Sediments

(3.3.3 in Report 1)

Rationale

Internal phosphorus loading in the sediments may still be an important source of phosphorus even after successful reductions in external phosphorus loadings are achieved Direct treatment of sediments with suitable chemicals (eg alum and nitrate salts) to precipitate and bind the phosphorus could substitute for dredging and would be cheaper and could be applied more rapidly.

Results

Tests using Harvey Estuary water and sediment allowing completely anaerobic conditions and high filterable reactive phosphorus (FRP) concentrations to occur before dosing indicate that alum at 80 g Al m^{-3} or 3 g Al m-2 and nitrate at 90 g NO_3-N m^{-3} or 3.5 g NO_3-N m^{-2} considerably reduced phosphorus release from the sediments.

Costs

Costs of chemicals for treating Harvey Estuary are:

(i) $4-9 million for whole Harvey Estuary volume

(ii) $136 000 - $271 000 for surface treatment

A capital cost of about $1 million would be required for surface injection equipment.

4.4 DIVERSION OF DRAINAGE TO THE OCEAN

4.4.1 Herron Ford Barrages (3.4.3 in Report 1)

Rationale

The proposed strategy is to divert to the ocean sufficient inflowing Harvey Main Drain, South Coolup and Mayfields Drain flows to prevent *Nodularia* blooms occurring in 4 out of 5 years. This would prevent all Harvey catchment phosphorus from being bound in either sediments or biomass. Construction of the barrage would alter salinity in the estuary by complete diversion of freshwater inflow.

Results

Modelling studies indicate that maximum summer salinity could reach 55% which would not detrimentally affect the primary or secondary production in the system.

Increased winter salinity could restrict a *Nodularia* bloom

Complete diversion of fresh river inflow and nutrients would probably result in a rapid reduction in nuisance blooms of cyanobacteria which would enhance the estuarine habitat for fish, however diversion of nutrients could lead to a gradual reduction in productivity of the fishery with time.

Construction of the barrage would result in inundation of the Nature Reserve, the extent depending on the height of the barrage. The conservation value of this reserve would need to be assessed.

Costs

For options with a 3 m maximum water level, a land resumption of 1 400 ha would be necessary and for options with a 1.5 m maximum water level land resumption would be 500 ha.

Costs for these schemes in 1983 dollars range from $50 million for the 3 m barrage to $100 + million for the 5 m barrage (including resumption costs)

4.5 DIRECT ATTACK ON ALGAE

4.5.1 Weed Harvesting from Beaches
(3.5.1 in Report 1)

Rationale

Specially modified Volvo loaders with rakes are used to collect beached algae and stockpile it to allow trapped water to drain away. The combination of rotting beached algae and working heavy machinery reduces the amenity of the populated beaches. Beach clearing only achieves the short-term goal of removal of nuisance algae from public beaches.

Cost

Annual cost is about $70 000.

ACTION

Weed harvesting on beaches should be continued. The need for it should become less as other more successful methods are used to intercept algae before they beach.

4.5.2 Offshore Weed Harvesting
(3.5.2 in Report 1)

Rationale

Algae, particularly *Chaetomorpha*, *Cladophora*, *Ulva* and *Enteromorpha* can be intercepted before they beach or can be harvested from growing algal beds. This reduces the requirement for removal of algae from beaches.

The offshore harvesting capacity will be upgraded during 1983 from one unit to two.

Results

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

ACTION

Weed harvesting should be continued.

4.5.3 Algistats (3.5.3 in Report 1)

Rationale

Algistats (growth inhibitors) could be one of the few control options available for single season reduction of both macroalgal and phytoplankton growth and can be applied rapidly.

Results

The most promising substances for further testing are simazine and terbutryn.

Costs

Highly variable depending on whether macroalgae or *Nodularia* are being treated and depending on the area/ volume of treatment required.

Maximum cost would be about $1.46 million for treatment of the whole of the Harvey Estuary volume with simazine or $47 000 for treatment with terbutryn (single treatments).

4.6 INCREASED MARINE FLUSHING

4.6.1 Improvements to the Existing Mandurah Channel (3.7.1 in Report 1)

Rationale

The objective is to increase the rates of nutrient loss to the sea by increasing marine flushing. Many schemes have been proposed which are variants on four basic components, Channels 1A, 1B, 1C and 1D. (see Report 1)

Two spoil areas would be created, one in the estuary and the other adjacent to a new or existing channel. The dredged southern channel could be located to the east or west of

Channel Island.

Results

Dredging the Mandurah Channel could increase the flushing rate of Peel Inlet by 22-34% depending on which option was adopted. Some long-term harvesting would still be required.

Modelling studies indicate that the extra cost of increasing the width and deepening the ocean entrance ($1.5 million) is not warranted as the increases in water exchange and nutrient loss are small.

The most favourable new channel location could be determined by considerations including public amenity and cost as the differences in flushing are only slight.

Costs

For the most effective option the cost would be about $3.1 million. Dredging to deepen the ocean entrance and increasing the width would be an additional $1.5 million.

4.6.2 Creation of a New Channel from Harvey Estuary to the Ocean (3.7.3 in Report 1)

Rationale

Current research has indicated that Nodularia populations stop growing and collapse at salinities of about 31‰ or above. The creation of a new channel from Harvey Estuary to the ocean would cause the salinity in the estuary to reach 31‰ earlier in the growth season. The channel would also increase flushing of Harvey Estuary and increase loss of nutrients to the ocean.

Results

The channel could produce a 4 fold increase in flushing rate in Harvey Estuary and a 1.5 fold increase in flushing rate in Peel Inlet. These would produce proportional increases in marine losses of nitrogen and phosphorus thereby reducing the level of eutrophication and nuisance phytoplankton growth.

Salinity changes would reduce the period suitable for the growth of Nodularia.

Improved water clarity and increased diurnal tide variations would allow macroalgae and seagrasses to extend their distribution south into Harvey Estuary, thus increasing the areas suitable for fish nursery areas.

Costs

For an approximate resumed area of 50 ha for the channel and batters the resumption costs would be about $1-1.5 million.

For a channel depth of about -3.3 m AHD cost would be in the region of $15 million.

For a channel depth of -4.5 m AHD cost would be about $18.5 million.

These costs include dredging ocean and estuary, other excavation, roadworks, training walls at ocean entrance and contingencies.

5. INTERACTIONS AMONG OPTIONS

5.1 REQUIRED PHOSPHORUS REDUCTIONS

Data produced during the study were used to determine the amount of "effective" phosphorus reduction required to reduce the algal problem in the Harvey Estuary. To achieve a frequency of Nodularia blooms of less than 1 yr in 5 the "effective phosphorus load to the estuary would have to be reduced by about 70%.

The required phosphorus reduction for the Peel Inlet is more difficult to assess.

5.2 PHOSPHORUS REDUCTION POTENTIAL OF THE OPTIONS

Table 2 shows the conservative effective phosphorus reduction for both Peel Inlet and Harvey Estuary.

Table 2 Effective Phosphorus Reduction Potential of the Options

Option	Effective Reduction Harvey Estuary	 Peel Inlet
Modify agricultural practices	40% (from paired catchment studies)	50%
Bauxite residue amendment	15 - 50% (1)	35 - 65% (1)
Wetland filters	-	10%
Changes in land use	35 - 85% (1)	45 - 90% (1)
Mandurah Channel dredging	5%	20 - 55% (2)
New channel near Dawesville	50%	25%
Diversion of drainage	70%	?

Notes: (1) Range of reduction dependent on areas of catchment treated.

(2) Range of reduction in nutrient loss over summer and winter based on flushing.

Combining similar strategies will not necessarily have an additive effect eg combining bauxite residue treatments with modifications to agricultural practices. Combining options involving reduction in phosphorus input and increased phosphorus loss by flushing will have an additive component.

6. SUMMARY OF INTERIM AND LONG-TERM MANAGEMENT OPTIONS

Table 3 summarises the nature of the options in terms of time.

Table 3 - Summary of Interim and Long Term Management Options

Interim Management Options

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

Long-term Management Options

- Modification of agricultural practices, particularly fertiliser types and application rates/frequencies.
- Bauxite residue for amendment of leaching sands.
- Wetland filters to treat suitable point sources of nutrients.
- Land use changes of highly leaching agricultural soils, for example Bassendean sands to uses such as forests.
- Hydraulic improvements of the Mandurah Channel.
- Construction of a new marine channel near Dawesville.
- Barrage at Herron Ford for diversion of Harvey River flows to sea.

7. REFERENCES

HUMPHRIES, R.B. and CROFT, C.M., 1983, Management of the eutrophication of the Peel-Harvey Estuarine System:

Report 1 : Preliminary Evaluation. Centre for Water Research, University of W.A. Report WP83-018. Department of Conservation & Environment Bulletin No.163.

Report 2 : Detailed Evaluation. Centre for Water Research, University of W.A. Report WP83-019. Department of Conservation & Environment Bulletin No.164.

Report 3 : Final Report. Centre for Water Research, University of W.A. Report ED83-066. Department of Conservation & Environment Bulletin No.165.

APPENDIX 1

LIST OF MANAGEMENT STRATEGIES THAT WERE REJECTED EARLY

1. WETLANDS AS NUTRIENT TRAPS

1.1 Use of Wetlands in Drainage Canals (3.2.2 in Report 1)

Rationale

Wetland plants may be useful in drainage canals as a means of stripping phosphorus. Preliminary analyses show use of this option even for catchments of 10 ha is not practical because length of filter is excessive and the phosphorus concentration in the inflow is low.

Rejected

Because length of filter required is excessive and the inflow rates are too high to enable phosphorus removal by plant uptake.

1.2 Nutrient Removal by Swamps and Swamp Margins (3.2.3 in Report 1)

Rationale

Reduction of nutrient concentrations in wetlands may be achieved by use of floating or semi-submergent plants in open water. This is not a short-term solution.

Rejected

Because no acceptable open-water plant types were found that would remove significant quantities of phosphorus from the swamps.

1.3 Artificial Wetlands (3.2.4 in Report 1)

Rationale

Creation of artificial wetlands at outlets of swamps and drains may be used as in 1.2.

Rejected

Because the high winter flows in the Harvey catchment area would greatly exceed the capacity of any artificially constructed swamp and drain outlets to remove phosphorus.

2. CHEMICAL REMOVAL OR INACTIVATION OF PHOSPHORUS

2.1 In-Channel Limestone Adsorbents (3.3.1 in Report 1)

Rationale

Phosphorus can be removed from drainage water by passing the water through a channel lined with limestone.

Rejected

Because the adsorbent capacity of limestone is low compared to clays or bauxite residue. The adsorbent capacity was exhausted in about 2 days.
The length of the wall required for sufficient contact time was excessive.

2.2 Large-scale Chemical Removal of Phosphorus from Surface Drainage Using Flyash and other Industrial Waste Products
(3.3.2 of Report 1)

Rationale
A wide range of possibilities exists for the precipitation of phosphorus from surface water. Chemical removal may be achieved using compounds of iron, calcium and aluminium. Other materials including Laporte strong effluent and copperas, Alcoa bauxite residue and flyash from the Bunbury Power Station might also be used.

Rejected
Large scale treatments were rejected as too expensive. A small scale plant using Alcoa and Laporte wastes requires further evaluation.

3. DIVERSION OF DRAINAGE TO SEA

3.1 Diversion of Water Through Coastal Lakes
(3.4.1 in Report 1)

Rationale
To divert nutrient-rich water from the Peel-Harvey Estuarine System to the ocean via Lakes Clifton, Martin Tanks and Preston. It requires construction of a barrage at Herron Ford, and ocean outlets at either Myalup (via the Harvey River Diversion Drain) or via Leschenault Inlet to the Cut.

Initial investigations indicated that the proposed changes would produce eutrophic conditions in the Lakes or in Leschenault Inlet, the changed salinity conditions in the lakes would cause changes to the flora, and freshwater cyanobacterial blooms would occur which could be toxic to animals. A barrage at Herron Ford may affect Harvey Estuary detrimentally.

Rejected
Because the scheme would produce eutrophic conditions in the coastal lakes or Leschenault Inlet.

The changed salinity conditions would produce freshwater cyanobacterial blooms which could be toxic to animals.

3.2 Barrage at Point Grey (3.4.2 in Report 1)

Rationale
To prevent nutrient-rich water from entering Peel Inlet from Harvey Estuary. Harvey Estuary remains eutrophic. The proposal requires construction of a barrage from Point Grey to Ward Point and

a tunnel with an ocean outfall. The biological consequences of this proposal are severe and include conversion of Harvey Estuary into a freshwater lake with corresponding loss of fishery, continuation of algal blooms.

Rejected

Because of the severity of the biological consequences of the proposal : conversion of Harvey Estuary into a freshwater lake, loss of fishery, continuation of algal blooms.

3.3 River Flow Deflectors in Peel Inlet

(3.4.4 in Report 1)

Rationale

The objective of this proposal was to divert the flows from the Serpentine and Murray Rivers away from Peel Inlet and into the ocean. Both full and partial deflectors were considered.

Rejected

Because a full deflector would restrict water access to the Coodanup area, a partial deflector may not be sufficiently effective. Both would tend to trap algae near Coodanup Beaches.

4. DIRECT ATTACK ON ALGAE

4.1 Copper Algicides (3.5.3 in Report 1)

Rationale

These are toxins which kill algae or higher plants by directly poisoning critical biochemical pathways. The most common algicide is copper either as copper sulphate or as various organic copper compounds. Copper has undesirable properties for this type of use in that it is highly toxic to non-target organisms, particularly fish; it accumulates in aquatic food chains and sediments; it is less active and is precipitated in alkaline, hard waters such as those of the Peel-Harvey system.

Rejected

Because they contain copper compounds and are more toxic to fish and invertebrates than to algae.

4.2 Modification of Estuarine Water Quality

(3.5.4 in Report 1)

Rationale

To reduce the suitability of aquatic habitats for algal growth by modifying the growth environment. Three main methods were considered:

- reduction of light penetration into the water column with a dye that abosorbs light strongly in the photosynthetically active regions of the spectrum
- use of iron chelators to limit cyanobacterial growth

- delay or prevention of seasonal transition from diatoms to Nodularia by providing high concentrations of available inorganic nitrogen (eg from calcium nitrate, ammonium nitrate, ammonium sulphate or urea).

Rejected

Because no current information is available to evaluate either iron chelation or use of dyes.

4.3 Use of Explosives to Collapse Cyanobacterial Blooms (3.5.5. in Report 1)

Rationale

Cyanobacterial algae contain gas vacuoles which confer positive buoyancy on the algae. Temporary control of cyanobacterial blooms has been achieved by bursting their gas vacuoles, using explosives. The algae then sink to the bottom of the water body.

Rejected

Because the technique would result in massive fish kills in Harvey Estuary, would be costly and cyanobacteria would rebuild their gas vacuoles within 72 hours.

4.4 Biological Control (3.5.6 in Report 1)

Rationale

That algae can be controlled by biological methods including

- use of pathogens, eg fungi, viruses and bacteria
- grazing by fish, zooplankton or protozoans
- manipulations of the inter-relationships among plants, animals and their physical and chemical environment to cause changes in the distribution and abundance of species

Rejected

Because no suitable pathogens have been able to control current blooms; Nodularia is generally unpalatable to grazers.

5. DREDGING OF ESTUARY

5.1 Dredging of Estuary Basin and Flats (3.6.1 in Report 1)

Rationale

Dredging can be used as a means of removing nutrients trapped in sediments, however, dredging above will be ineffective in controlling eutrophication of water bodies as it only attacks the internal loading of the system. Three dredging strategies were considered:

- removal of top 100 mm of sediment (skimming)
- dredging to remove marginal shallows
- dredging of selected areas to prevent growth of macroalgae

Rejected

- Surface skimming was rejected because it is too expensive and smaller-scale, more selective dredging would be more sensible
- all dredging options would produce severe local impacts, particularly disruption of habitat for juvenile fish. Dredged shallows would act as pools for decaying algae. Dredging to reduce macroalgal growth could increase phytoplanktonic species and disrupt the food chain.

6. INCREASED MARINE FLUSHING

6.1 Creation of a New Mandurah Channel (3.7.2 in Report 1)

Rationale

A member of the public suggested that Parry's Esplanade Development cut a channel, parallel to the existing Mandurah Channel. The proposal suggested construction of a grid aquaduct to protrude 100 m out to sea at the ocean entrance of the new channel. Locks would be provided to 'capture' high tidal levels to flush the estuary and remove the sand bar at the ocean entrance.

Rejected

Because the maximum possible increase in flushing rate of 20% would not greatly increase the loss of nutrients (flow rate was taken as equating to flushing rate). The scheme would be unlikely to be acceptable to Parry's Esplanade Ltd.

Rationale

6.2 Tidal Pumping (3.7.4 in Report 1)

This option was suggested by a member of the public. The proposed strategy supposes that tidal level differences between the ocean and the estuary may be used to pump seawater into the estuary, thereby diluting estuarine water, decreasing estuarine flushing times and increasing the nutrient loss to the ocean.

Rejected

Because only small flows can occur in a feasible tunnel, because of the low amplitude of the signal available from diurnal tides.

7. MISCELLANEOUS OPTIONS

7.1 Re-route Harvey Diversion Drain Flows

(3.8.1 in Report 1)

Rationale

The diversion of flow from the Harvey Diversion Drain to the Harvey Main Drain was proposed as a means of increasing flushing and dilution of nutrients currently entering the estuarine system during the winter inflow period.

Rejected

Because the proposed flow re-routing would not significantly alter the concentration in or flushing of nutrients from the estuarine system.

7.2 Introduction of New Plants to the Estuary

(3.8.2 in Report 1)

Rationale

It had been proposed that the nutrient-rich estuary might be used for aquaculture of commercially useful plants, for example the agar-producing alga Gracilaria sp. Introduction of such algae could

- direct nutrients into useful biomass rather than into nuisance algal species
- generate income
- probably shade the floor of the estuary if the cultured species were grown on rafts, leading to light limitation of nuisance benthic algae.

Suspended

Because the introduction of an exotic algae would be a protracted affair, even if a suitable species was located.

7.3 Siting of a Power Station on Harvey Estuary

(3.8.3 in Report 1)

Rationale

The strategy involves the relocation of the new Bunbury Power Station from Leschenault Inlet to the southern end of Harvey Estuary. The cooling water from the power station could be used to reduce the flushing time of the estuary, therefore increasing losses of nutrients to the sea.

Rejected

Because of high infastructure costs (eg an extra $15 mission to construct the railway spur to deliver coal). The use of power station outflow is not recommended, as it could result in increased retention of phosphorus by the sediments or by diatoms.

CATCHMENT MANAGEMENT TO REDUCE PHOSPHORUS DISCHARGE INTO THE ESTUARY - SETTING THE SCENE

by Peter Birch

The problems in the Peel-Harvey estuary are caused by an excessive input and subsequent availability of phosphorus for growth of nuisance algae and cyanobacteria. About 90% of this phosphorus is derived from coastal plain catchments where rates of phosphorus loss are greatest.

There are several interacting factors which cause this relatively high loss of phosphorus from the coastal plain. These include:

- soil type
- land use
- fertilizer application (past and present)
- drainage density
- rainfall
- topography

Of these the major ones contributing to high phosphorus loss from the coastal plain compared to the plateau are -

i) sandy soils (highly leaching sands are common on the coastal plain;

ii) higher drainage density on coastal plain ($0.64\ km/km^2$ compared $0.13\ km/km^2$); and

iii) higher rainfall on coastal plain (850 - 1000 mm/yr compared to 450 - 800 mm/yr).

These factors combined with somewhat higher fertilizer use on the coastal plain result in a phosphorus export rate about 30 times higher than that of the plateau. Thus 90% of the phosphorus is derived from 20% of the total catchment for the estuary (see Table 1).

Within the coastal plain there is a two fold difference between the two major catchments, the Serpentine and the Harvey and drains (Harvey Estuary) catchments. Since the distribution of soils generally similar between the two it is believed that higher runoff (because of higher drainage density and rainfall) and possibly higher fertilizer applications on the Harvey Estuary catchment are the major reasons for higher P export from this catchment compared to the Serpentine River catchment.

On average about 66% of the total phosphorus load is derived from the Harvey Estuary catchment even though it only represents about 10% of the total catchment for the Peel-Harvey system.

Within the Harvey Estuary catchment the importance of soil type and rate of runoff as influenced by drainage density is emphasized (Table 2). The highest proportion of applied fertilizer was lost from representative sub-catchments with sandy soils (19-33%) compared to 7% from those with clays and loams. Very little phosphorus was exported from the mostly forested, hills catchment of Clarke Brook.

Using the data of Table 2 and those of previous years it is estimated that approximately three quarters of the phosphorus entering the Harvey Estuary is derived from sandy soils. Even though there is less runoff from deep sands this is more than compensated by greater leaching losses.

The rate of fertilizer use on the different soils is not simply correlated with P export from the various soils because of differences in sorption capacity, as has been shown in Table 2. However, for each soil a certain portion of the total phosphorus runoff each year is derived from currently applied fertilizer and the balance from the phosphorus bank which has built up in soil from previous applications. An important question being answered this year is what are these proportions when a maintenance rate of phosphorus application is made on the various soil types. Knowing the answer to this and knowing the best type and amount of fertilizer required for a maintenance dressing tells us the amount by which phosphorus loading to the estuary could be reduced by improved fertilizer management without loss of agricultural production.

Yearly Variations in Rainfall and Runoff

The above comments largely relate to what happens in a particular year. Rainfall and runoff and hence P export varies considerably from year to year. Over the duration of the Peel-Harvey study there has been a threefold variation in runoff to the Harvey Estuary although unfortunately this range has been from well below average to about average. At the same time phosphorus load has also varied by almost the same amount, meaning that the flow-weighted concentration of phosphorus in Harvey River water has varied little, averaging about 0.4mg/L (Figure 1). This implies that there is a relatively large pool of phosphorus in the catchment which is readily leachable.

Where Does All the Phosphorus Go?

Figures 2 and 3 summarize present knowledge with regard to phosphorus fluxes in deep sands and sand over clay soils. The values are estimates only for a hypothetical average situation for non-irrigated pastures for cattle or sheep. For irrigated dairy farms and for hay cut paddocks the agricultural export and fertilizer application would both be greater.

Even though the data in Figures 3 and 4 are only approximate they do serve to indicate that of the fertilizer applied 20-30% is lost in runoff and 20-30% is exported in agricultural produce. Of the remaining 50-70% there is an accumulation of about 20% in the top soil (0-10cm). About 40% is presumably accumulating in the sub-soil and deep groundwater.

It must be stressed that in any particular situation these soil fluxes will be different depending on the fertilizer history, even with the same annual application rate. An old paddock, in which a larger bank has built up, will lose more phosphorus in runoff.

The ultimate goal is a maintenance situation where fertilizer applications virtually equal agricultural export with minimal runoff losses and no further accumulation in the soil. Evaluation of fluxes under maintenance is difficult because little is known at present about the fluxes between the various phosphorus pools in the soil (Figures 2 and 3). Also the fluxes and pools may change if the chemical nature of the fertilizer is varied, ie if slow-release fertilixers are used..

Methods of Reducing Phosphorus Input From Catchments

(i) Fertilizer Management

Figure 4 is a simplified version of Figures 2 and 3 on which is indicated the various points at which phosphorus flux can be intercepted or modified.

Firstly the type and amount of fertilizer can be varied as already mentioned and further details of this option will be dealt with by subsequent speakers. Knowing what can be achieved technically is one thing but farmers must adopt these new management strategies, either voluntarily or within a legislative framework, for anything to be achieved in practice.

(ii) Alternative Land Uses

Other forms of land use such as forestry require much lower phosphorus inputs than the present land use. As a result runoff of phosphorus should be reduced over time. The rate at which the rundown occurs will depend on the uptake rate by the trees and the rate of leaching and runoff from the existing pools of phosphorus. This could take from 5 to 10 years on Bassendean sands.

(iii) Biological Filters

Biological filters in the form of wetland vegetation can be effective phosphorus sinks which significantly reduce the phosphorus concentration of water as it passes through the system. They appear most useful in treating rural point sources such as piggeries where the effluent discharge is relatively constant. They are less practical in treating large volumes of water with relatively low concentrations in a short time, as would be required for coastal plain runoff during winter.

(iv) Bauxite Residues

As discussed earlier excessive leaching of phosphorus from sandy soils is a major cause of phosphorus eutrophication in the Peel-Harvey estuary. Incorporation of bauxite residue into topsoil will increase phosphorus adsorption of sandy soils. The residue will also improve water holding capacity of deep sands. Thus yields can be increased and phosphorus runoff reduced, provided treated soils are not excessively fertilized.

(v) Chemical Treatment

Phosphorus concentrations in runoff water can be reduced by treatment with iron, aluminium or calcium ions or with industrial wastes such as bauxite residue. A treatment plant in which phosphorus is precipitated with iron has been successfully employed on the Wahnbach River in Western Germany. Such a scheme could be adopted here but would be very expensive. (ca $50 million plus running costs).

(vi) Diversion of Drainage

Complete diversion of the Harvey River, Mayfields Drain and South Coolup Drain would solve the eutrophication problem, but the price would be high, and there could be undesirable side-effects on the estuarine ecosystem.

Acknowledgements

Data Sources (i) Flows : R.E.Black and J.E. Rosher
Public Works Dept. (R.Harvey, R.Sheridan)

(ii) Phosphorus analysis : Govt. Chemical Labs.
Botany Dept. U.W.A.

(iii) Phosphorus flow diagrams : Information supplied by many members of the Catchment Studies Group.

Table 1(a) Approximate annual flows from the major river systems to the Peel-Harvey Estuary. Means (and standard deviations) for the 5 year period 1978-82

River Systems	Undammed Catchment Area (km^2)	(% of total)	Drainage Density (km/km^2)	Runoff (mm)	($10^6 m^3$)	(% of total)
(i) <u>Coastal Plain</u>*						
Harvey + Drains	990	10.4	0.84	240(76)	210(130)	37.5
Serpentine	910	9.6	0.42	120(47)	110(43)	19.6
Total	1900	20	0.64		320	57.1
(ii) <u>Plateau</u>*						
Murray	7600	80	0.13	28(17)	240(75)	42.9
Total to Estuary	9500	100		59(24)	560(230)	100

Table 1(b) Approximate annual export of phosphorus from the major river systems to the Peel-Harvey Estuary. Means (and standard deviations) for the 5 year period 1978-82.

River Systems	P. Conc (mg/L)	P Exported (Tonnes)	(% of total)	(kg/ha)	P Applied (kg/ha)	P Exp./P Appl. (%)
(i) <u>Coastal Plain</u>*						
Harvey + Drains	0.38	89(29)	61	0.90	8	11
Serpentine	0.36	39(18)	27	0.43	4.1	10
Total	0.37	128(47)	88	0.67	6.1	11
(ii) <u>Plateau</u>*						
Murray	0.09	18(12)	12	0.024	3.7	0.7
Total to Estuary	0.26	146(54)	100	0.15	4.3	3.5

* About 6800 km^2 of the Murray catchment is east of the Darling Scarp. Most of the drainage from the Harvey and Serpentine is from the Coastal plain.

Table 2 PHOSPHORUS EXPORT FROM VARIOUS CATCHMENTS OF THE HARVEY ESTUARY RUNOFF DATA ARE PRELIMINARY ESTIMATES FOR 1983 WINTER (JUNE - SEPT)

Catchment	Area (km^2)	Runoff (m^3/ha)	Drainage Density (km/km^2)	P Conc (mg/L)	P exported[1] (kg/ha)	P applied[1] (kg/ha)	$\frac{\text{P exp}}{\text{P appl}}$	Fertilizer History (years)	Dominant Soil Type	Land[2] Use
Meredith Dr.	52	1100	0.55	1.2	1.3(4.0)	4(12)	33%	10-15	Deep Sands	1
Mayfield G Dr.	10	3800	1.51	0.61	2.3(2.3)	12(12)	19%	30-50	Sand over Clay	1
Samson Br.N.Dr.	18	3300	1.58	0.3	1.0(1.0)	16(16)	6%	30-50	Clays and Loams	1+2
Clark Br. (Hills)		4000		0.05	0.20(-)	little		-	Lateritic	3

1. Values in brackets are estimates for cleared area of the catchments.

2. Land Use Categories
   1 Non-irrigated pastures for beef and sheep
   2 Irrigated pastures for beef and dairying
   3 Mostly forest

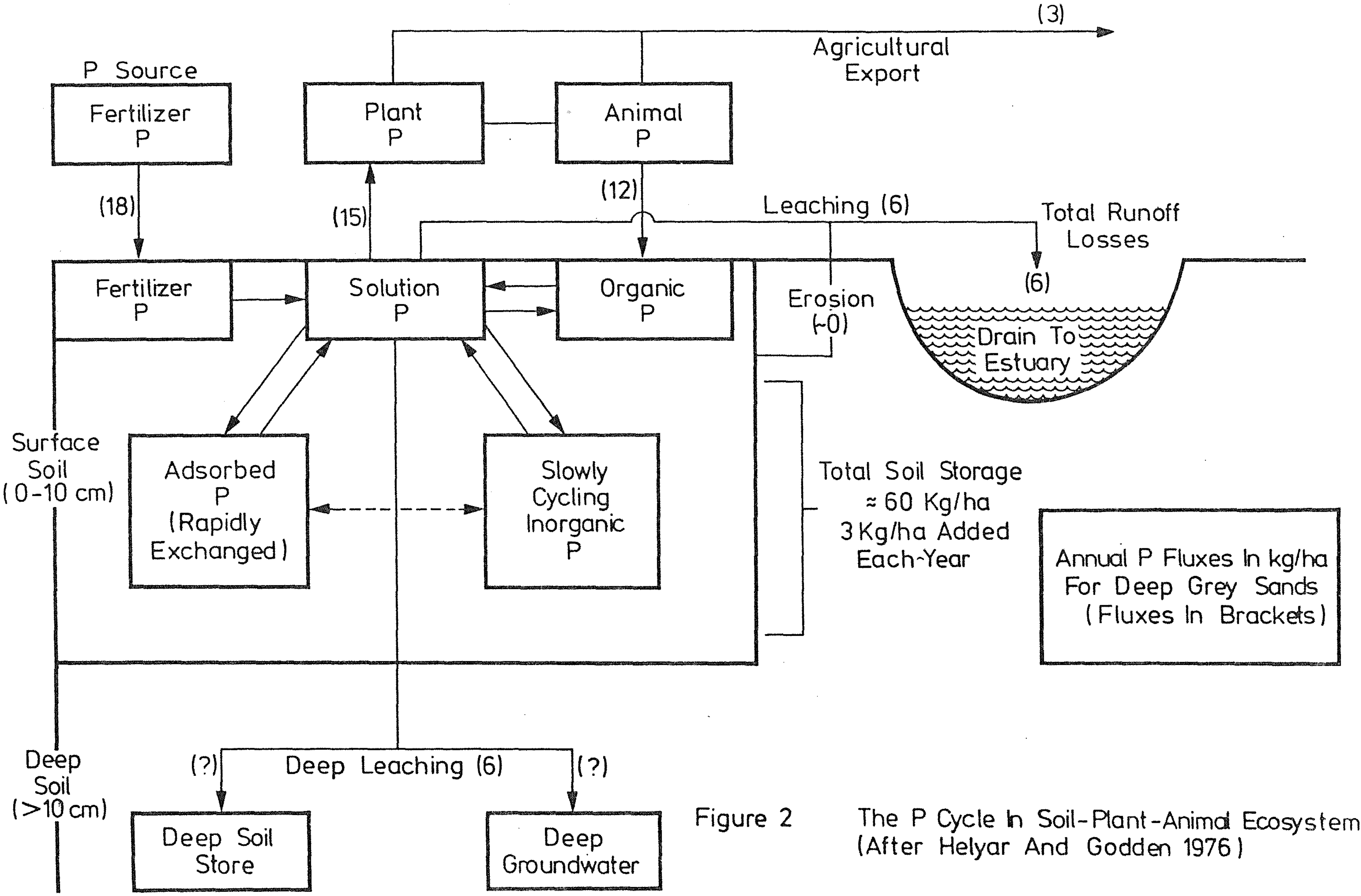

Figure 2 The P Cycle In Soil-Plant-Animal Ecosystems (After Helyar And Godden 1976)

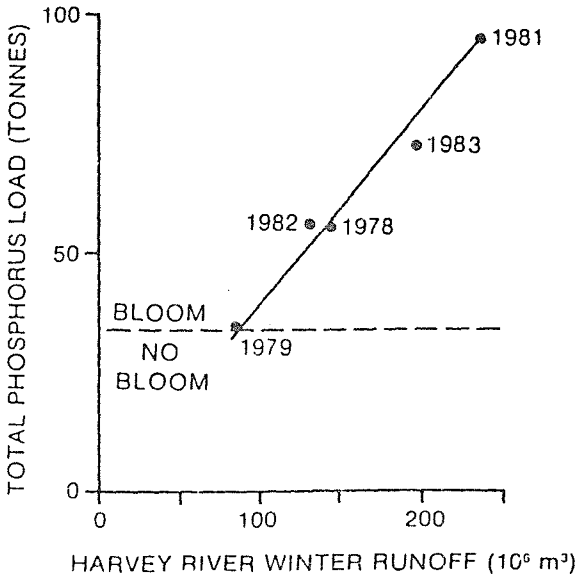
TOTAL PHOSPHORUS LOAD (TONNES)
100
50
0
HARVEY RIVER WINTER RUNOFF (10^6 m³)
0
100
200
1981
1983
1982
1978
1979
BLOOM
NO BLOOM

Figure 1

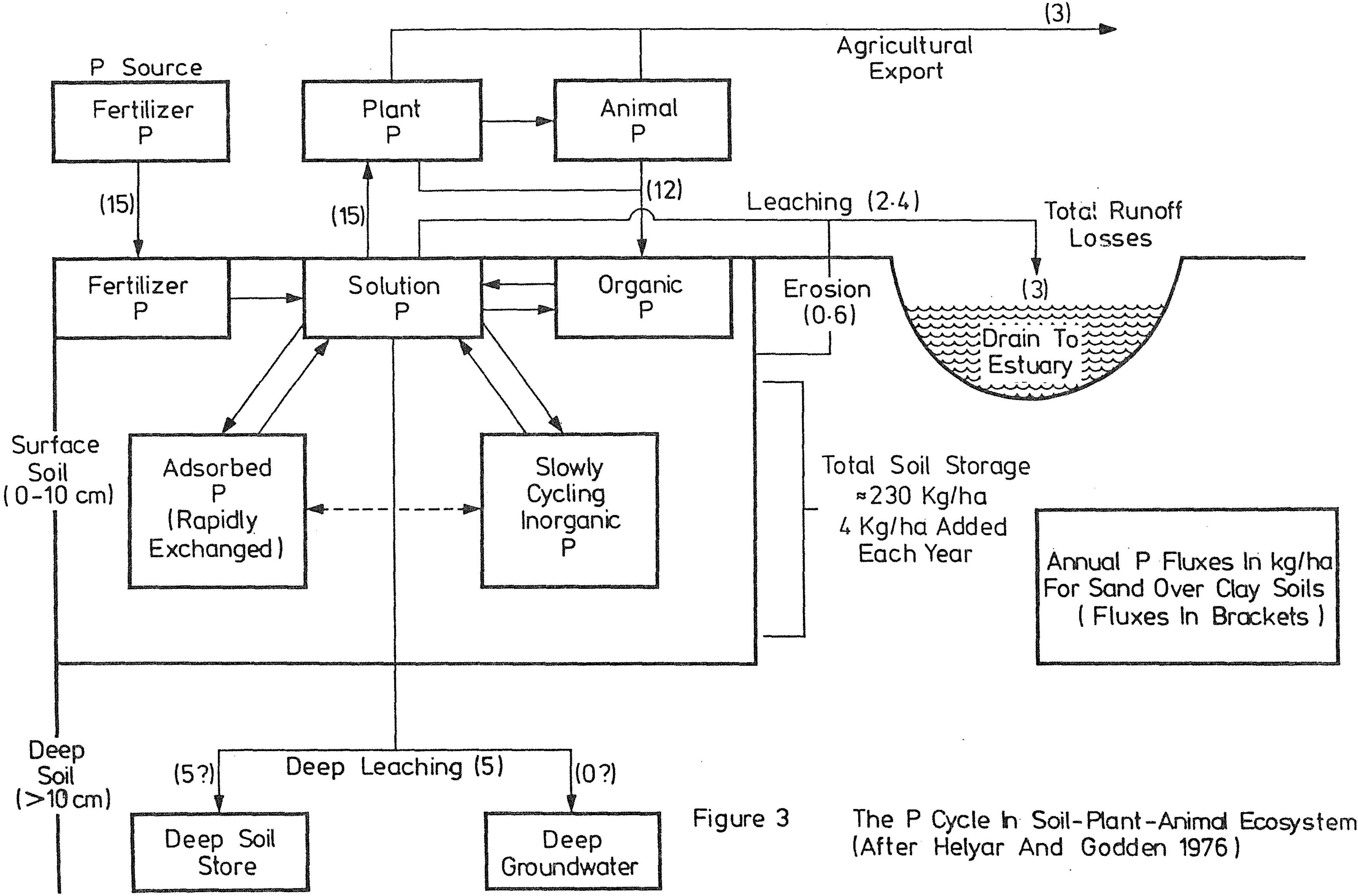

Figure 3 The P Cycle In Soil-Plant-Animal Ecosystems (After Helyar And Godden 1976)

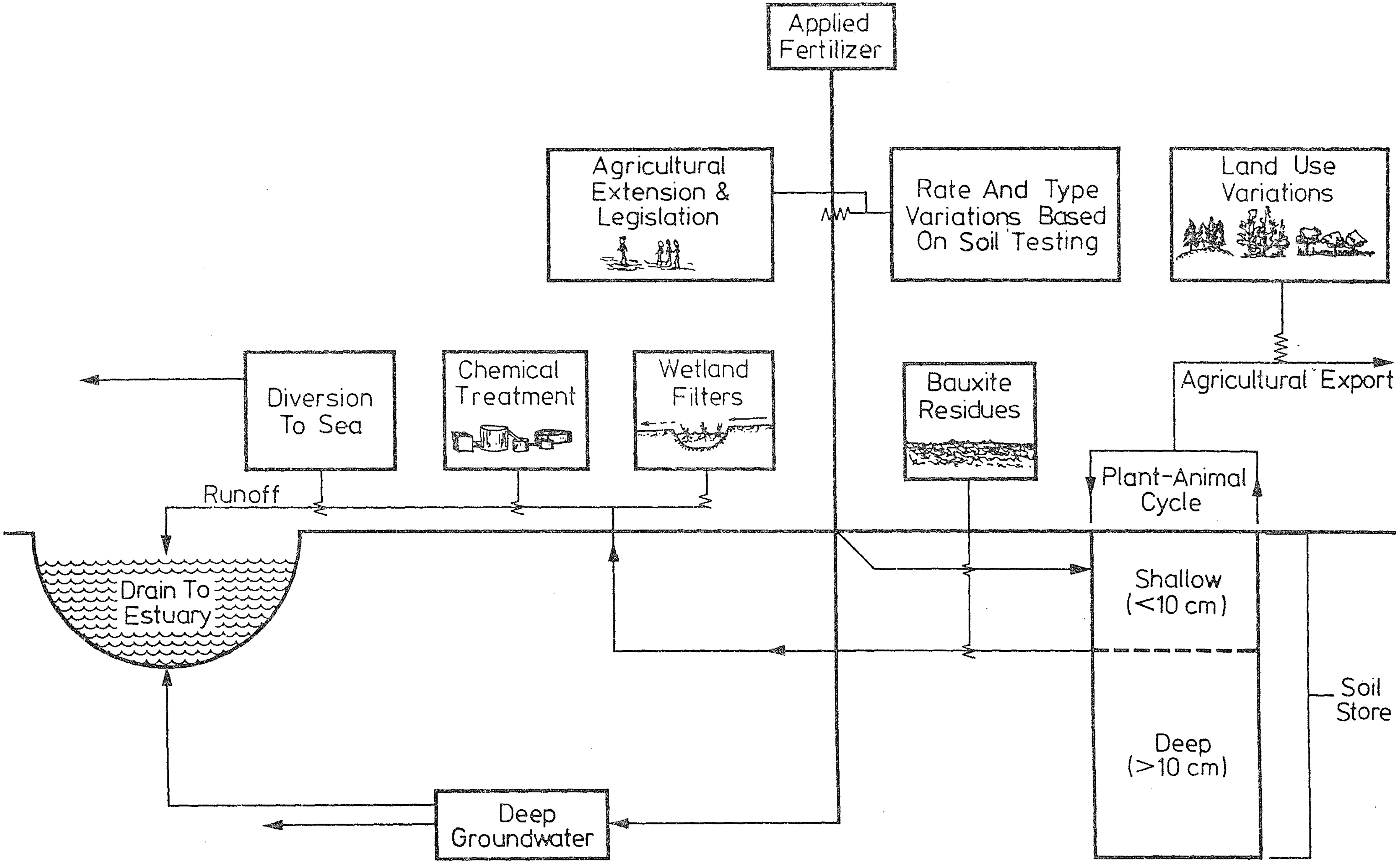
Applied Fertilizer
Agricultural Extension & Legislation
Rate And Type Variations Based On Soil Testing
Land Use Variations
Diversion To Sea
Chemical Treatment
Wetland Filters
Bauxite Residues
Agricultural Export
Plant-Animal Cycle
Runoff
Drain To Estuary
Shallow (<10 cm)
Deep (>10 cm)
Soil Store
Deep Groundwater

Figure 4

FERTILIZER MANAGEMENT - AGRONOMIC ASPECTS

J.S. Yeates*, D.M. Deeley*, and D. Allen+

INTRODUCTION

Two major modifications to current fertilizer practice with potential to reduce leaching losses of phosphorus applied to pastures of the sandy soils of the Peel-Harvey Estuarine system catchment have been identified. Both are within the initially specified constraints of maintaining the current type and profitability of agricultural production on the soils. Two related areas, the use of 'red mud' to increase P retention of the sands, and alternative agricultural or semi-agricultural land uses are covered in other papers.

MODIFICATIONS TO CURRENT FERTILIZER PRACTICE

1. Accurate definition of phosphorus requirements of the sandy soils

General considerations

To accurately define P requirements the parameters of response curves for currently applied P (Figure 1) and the residual value of past P applications need to be established. From these, a prediction of P rate required to achieve a nominated level of production in year 1, and the rate necessary to return to that level in year 2, 3, 4 etc. can be made. Residual value of past fertilizer applications can be estimated either from a previously defined residual value function (RVF) (Figure 2), or by use of soil tests calibrated to growth potential in the subsequent season (Figure 3).

The ultimate aim of accurate prediction of P requirement is to determine the maintenance application rate for any desired level of production (i.e. the optimum economic rate, determined by the cost/price ratio applicable). The maintenance rate is the minimum required to maintain growth which does not increase soil P storage, and this rate will determine the magnitude of long term leaching losses as, at true equilibrium (assuming asymptotic soil P 'pools'), P applied = P lost in product + P lost as leachate.

In practice both the shape of the response curve for currently applied P, and the residual value function of P applied to the sandy soils are variable because of seasonal influences on plant growth, fertilizer dissolution and leaching characteristics, and differences in soil type and fertilizer history. Estimates of the various parameters required for prediction of long term P requirements are therefore difficult. That residual value of super (as measured by bic P) is affected by field conditions (site and year) is evidenced by the data in Table 1 for two sites at Albany on deep grey sands which received applications of P as superphosphate on experimental plots, and by Table 2 data showing changes in bic P over time at a number of sites following a single application of super.

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+ Government Chemical Laboratories, Plain Street, East Perth

FIG 1. PHOSPHORUS RESPONSE CURVE (MITSCHERLICH FUNCTION)

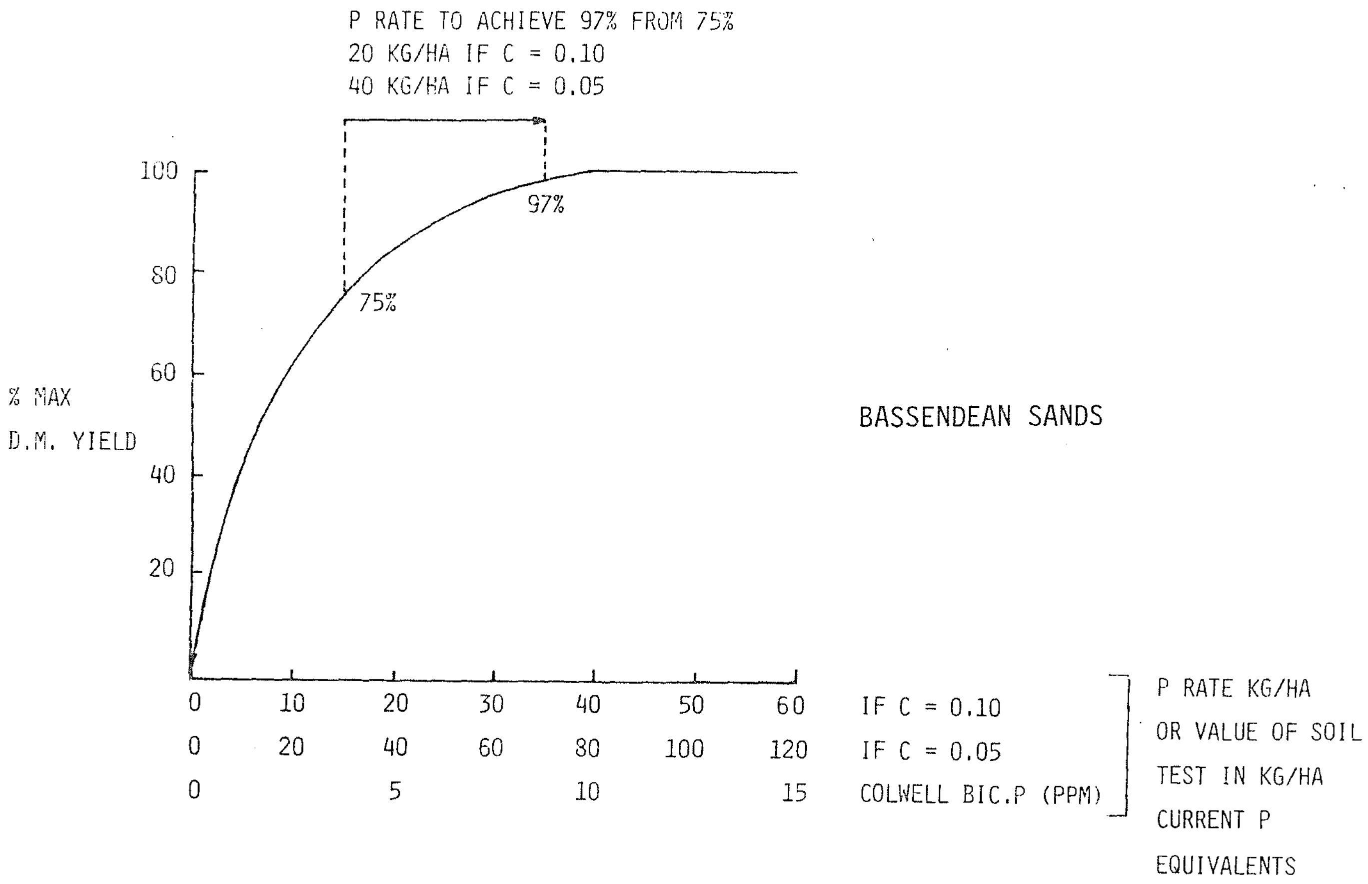


FIG 2. THE RELATIVE VALUE OF APPLIED PHOSPHORUS IN YEARS FOLLOWING THE YEAR APPLICATION (RESIDUAL VALUE FUNCTION, R.V.F.)

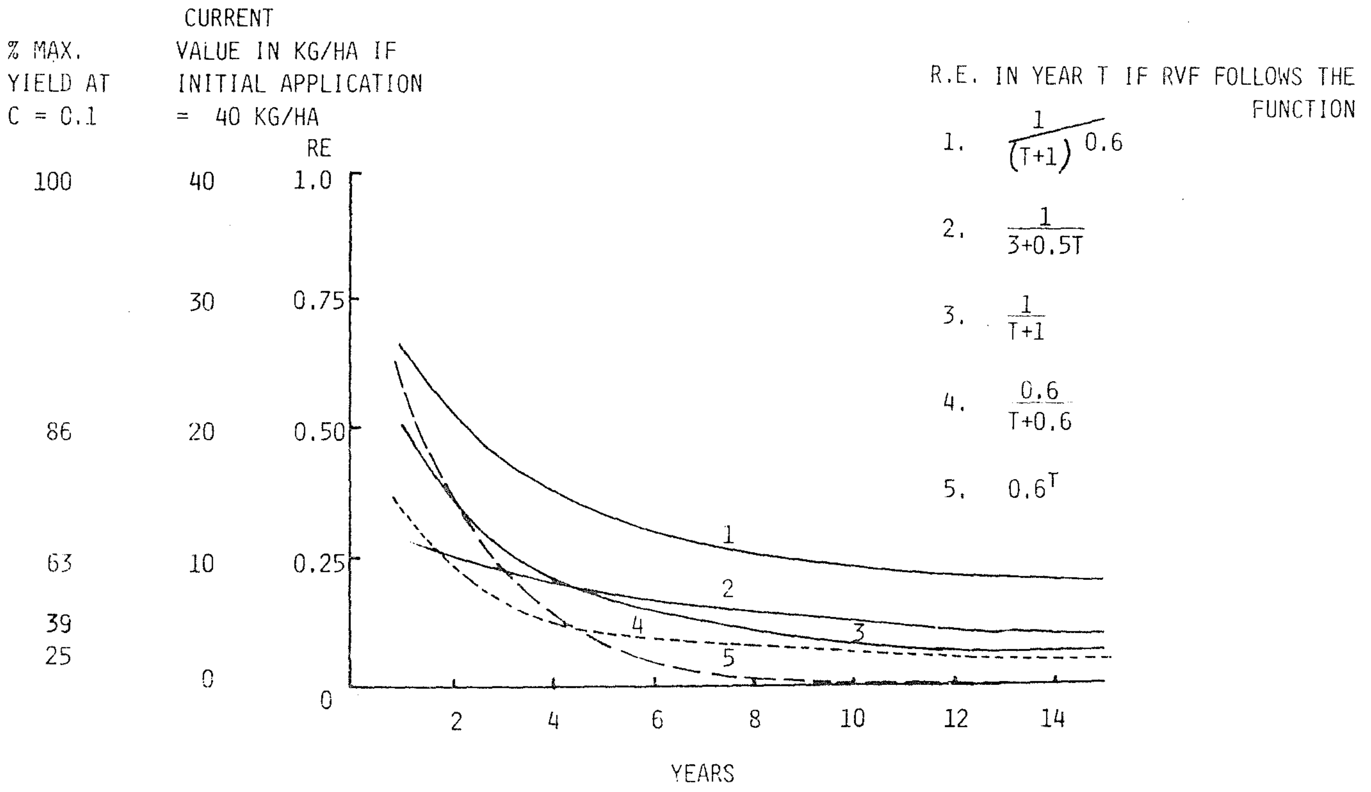


TABLE 1

Site and seasonal effects on bicarbonate extractable residual P one year after application of superphosphate (0-10 cm)

P rate (kg.ha)	Site 1			Site 2		
	Applied 1980 Sampled 1980/81	Applied 1981 Sampled 1981/82	Applied 1982 Sampled 1982/83	Applied 1980 Sampled 1980/81	Applied 1981 Sampled 1981/82	Applied 1982 Sampled 1982/83
0	10	8	8	6	6	5
10	10	13	11	9	5	10
30	10	11	14	6	6	8
90	25	30	28	9	7	18
180	36	26	26	9	11	25

TABLE 2

Change in bicarbonate-extractable P (ppm) over time on deep sands (permanent undisturbed pasture, 0-10cm)

Site	Nil Plots Year				Superphosphate Application 90 kg/ha year 1 Year				Superphosphate Application 180 kg/ha year 1 Year			
	0	1	2	3	0	1	2	3	0	1	2	3
1	3	6	6	5	-	9	6	6	-	9	6	6
2	10	8	8		-	25	19	15	-	36	30	35
3	15	11	2		-	17	5		-	20	7	
4	2	2	2		-	15	9		-	21	17	
5	4	2	2		-	7	2		-	30	15	
6	12	15	12		-	21	77		-	25	31	

Year 0 = Prior to application. Bic P measured over summer

Prediction of current P requirements - soil test

Current work has established a soil test calibration curve for the Bassendean sands (Figure 3) which, with an estimated Mitscherlich 'C' coefficient for the response curve for currently applied P, results in recommendations for reduced P applications compared to previous recommendations and rates in common usage.

FIG **3** SOIL TEST CALIBRATION DATA. YIELDS REFER TO THE GROWING SEASON FOLLOWING SUMMER SOIL SAMPLING.

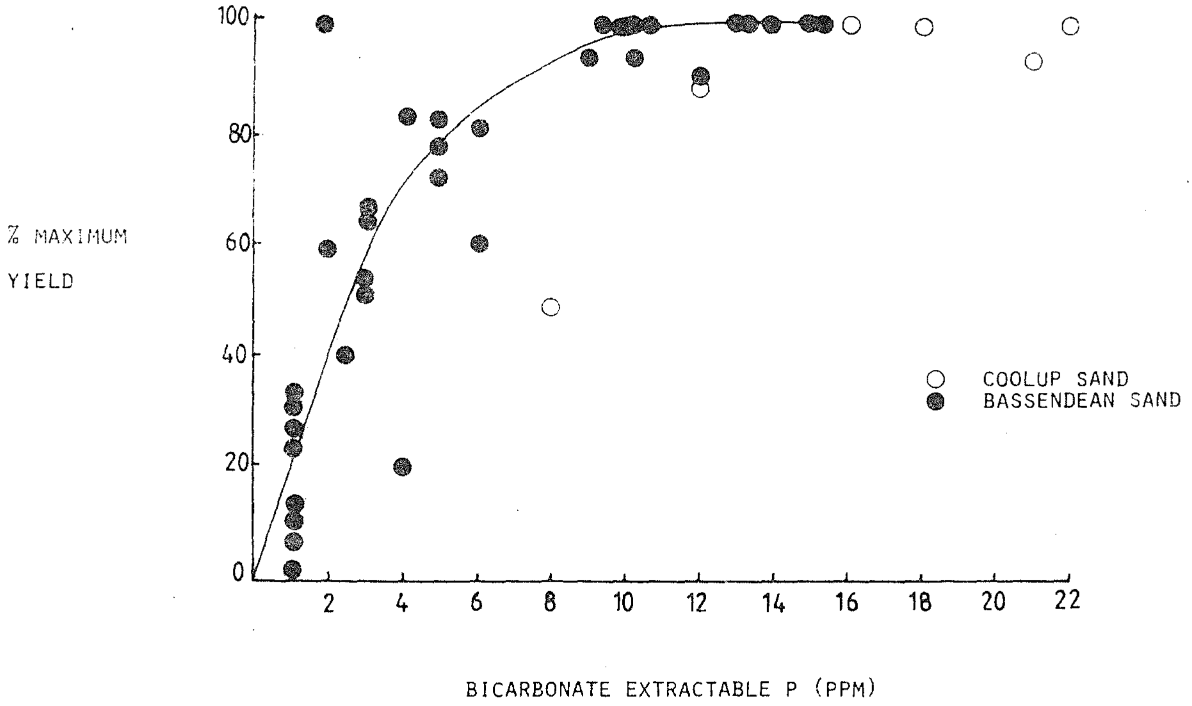
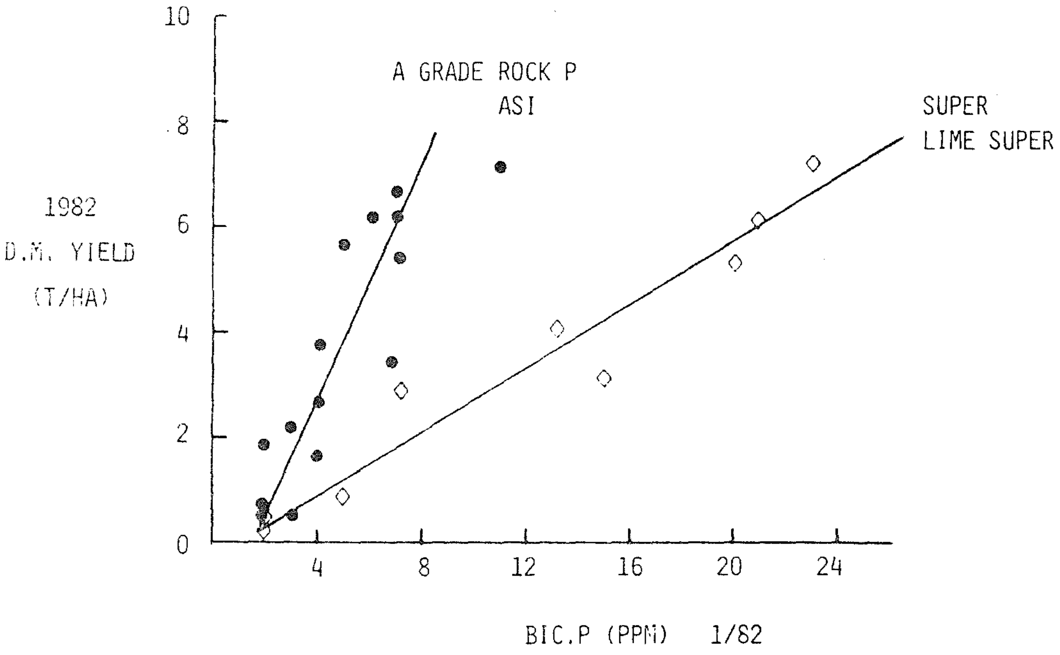


FIG **4** NEW LAND PEATY SAND SITE
YIELD VS. BIC.P YEAR 2



Predictions for Coolup sands are hampered by the lack of a well defined soil test calibration curve (due to a dearth of responsive sites for experimental work). Available data (Figure 3) suggest that 25 ppm is probably adequate as a cut off point for response on the Coolups. That is, the Mitscherlich 'c' coefficients for the soil test curve (related to P sorption) is approximately 0.40 on the Bassendeans, and 0.16 on the Coolups and will range between these two values for individual paddocks. Appropriate 'c' coefficients can be determined by using an objectively measured criterion related to P sorption (such as reactive iron) and scaling 'c' values between 0.40 and 0.16, allowing P rate recommendations to be made for the range of Peel-Harvey sandy soils without further extensive experimental work.

Soil test survey work (Russell) and calibration curve data indicate that because soil test levels on many paddocks are above those at which responses would occur, short term reduction in average P application rates of 60% (compared to 1982) on the Bassendean and Coolup sands would not reduce current pasture yields.

Despite the relatively well defined soil test calibration curve for Bassendean sands some problems remain in this area. Both bic and total P underestimate the residual value of past applications on organic sands (Joel), but tend to overestimate the value of recent very high P rate applications (relative to the established curve). This is interpreted as an indication of the relative availability of different soil 'pools'. Recent work has shown that on old land Joel sands 60-70% of total P is in an organic form, and similar proportions may be present in the bic P extract (normally only analysed for inorganic P). Sands with lower organic matter levels have lesser proportionate levels of organic P. (Apart from implications for the relevance of various soil analytical procedures, these findings have important implications for understanding the soil P cycles on the sands - see footnote*).

Other problems occur with soil testing after applications of various 'slow release' fertilizer sources. Bic P greatly underestimates the value of rock phosphate residues, and other extractants or additional calibration curves may be necessary if use of these sources (e.g. 'AS3') becomes widespread (Figure 4).

---

* As inputs of P in organic matter may reach 40 kg/ha/annum (though not all as organic P), and total soil organic P levels appear to rarely exceed 60 kg/ha (0-10 cm), organic matter will play a large rôle in the P nutrition of pastures, and in determining the fate (including 'leachability') of applied P. This is particularly evident when compared to experimental data which shows that 50 kg/ha total P (0-10 cm) on old land is adequate to produce maximum pasture growth on these soils.

Prediction of long term P requirements (maintenance rates)

Assuming an RVF of $\frac{1}{T+1}$, and a Mitscherlich 'C' coefficient of 0.10 for currently applied P, a long term reduction of about 40% in annual P application rate (as superphosphate, compared to a current rate of 16 kg/ha) is predicted to be achievable while still maintaining maximum pasture yield. However, at the cost/price ratio applicable to many enterprises on the sands, fertilizing for maximum production is not appropriate to achieve maximum economic returns (although > 60% of farmers are in fact currently fertilizing to maximum yield). In these situations, because of the nature of the relationship between P applied and pasture yield (Figure 1), available data indicates maximum long term economic returns can be achieved by cutting current annual P rates by 50% or more. In Table 3 estimates of maintenance P applications for various cost/price ratios and Mitscherlich response curve 'C' coefficients are presented as actual recommended P rates and as the percentage of the average current rate, (16 kg/ha). Available data (Morrison) indicates the cost/price ratios appropriate to the Joel and Coolup sands are in the range 1-2 (80% - 90% of maximum yield) and Gavin sands > 6 (uneconomic to fertilize at all).

TABLE 3

Estimates of rate of P required for maintenance of nominated pasture yield levels on Bassendean and Coolup sands. The three values of 'C' span the range of response curve coefficients believed appropriate for these soils

Cost/ price ratio	Pasture yield level appropriate (% maximum)	Annual maintenance P rate (as super) to achieve nominated pasture yield kg/ha/year			% of current common rate*		
		C=0.10	C=0.075	C=0.05	C=0.10	C=0.075	C=0.05
6	40	1.4	2.1	2.8	8	13	17
2	80	4.1	6.2	8.2	25	38	50
1	90	5.5	8.2	11.0	33	50	66
0.2	98	10.0	15.0	20.0	61	92	122

* estimated at 16 kg P/ha/annum

While the above provides useful first order estimates of possible reduction in P losses with more efficient use of currently available fertilizers, the sensitivity of the estimates to poorly defined parameters obviously means that such estimates should be treated with caution. In particular, problems are believed to exist as indicated with the response curve 'C' coefficient (currently estimated as 0.10, but possibly lower), the residual value function probably steeper than $\frac{1}{T+1}$ with superphosphate P), the method of maintenance rate estimation (not based on deep sand data) and the conversion of pasture to animal production. Accurate data from Bassendean and Coolup sands are essential to enable more reliable estimates to be made of actual reductions in P application rates appropriate on these soils. This work is currently in progress.

Other methods of establishing maintenance P application rates include using wholly empirical data from long term repeated rate field experiments (to be commenced 1984) and the use of a balance approach to P losses (replacement of P losses by fertilizer application, with assumptions about the asymptotic nature of soil P 'pools'). However, as estimates of losses from total P monitoring of field plots are extremely variable (Table 4) the latter approach cannot be used unless more accurate measurements of these losses are obtained, and necessary assumptions shown to be valid.

TABLE 4

Estimated losses of phosphorus from unfertilized plots over one year periods on deep grey sands. Losses were estimated from changes in total P content (0-10 cm)

	At 1981/82 (kg/ha)	At 1982/83 (kg/ha)	Δ P (kg/ha)	P removed as pasture (kg/ha)	Nett P loss (kg/ha)
Site 1	150	115	35	10	25
Site 2	110	85	25	5	20
Site 3	35	30	5	0	5
Site 4	150	75	75	20	55
Site 5	145	110	35	10	25
Site 6	75	55	20	5	15

2. Fertilizers of reduced water solubility ('slow release' fertilizers)

General considerations

The initial premise for the development of slow release fertilizers was that losses of water soluble P in the year of application accounted for the major P leaching losses from the sandy soils. Recent data from various sections of the catchment studies group (Birch, Ritchie) suggest that in fact major losses occur from previously fertilized soils without current P applications - that is from residual soil P 'pools', indicating that modification of source of P may achieve only relatively minor changes in total P losses as direct losses from fertilizer account for only a part of the total.

The pattern and rate of fertilizer dissolution will affect P leaching losses, the rate of incorporation into the various 'pools', and plant uptake. Use of slow release fertilizers aims to maximize transfer of applied P into plant and soil 'pools' which retain P against leaching. Dissolution rate must be fast enough to match plant requirements (as effectively as superphosphate, or with other relevant economic constraints) but slow enough to minimize leaching losses. Once incorporated into the soil P 'pools' leaching losses will be independent of initial source of P, unless the relative size of the 'pools', or the 'leachability' is also affected by the source.

TABLE

Sources of phosphorus used in experimental work.

Note: Source followed by year in Tables 6 & 7 refers to year of application

Abbrev -iation	Source	% of P as water soluble	 citrate soluble	 citrate insoluble	Total P content (%)
Super*	superphosphate) triple superphosphate)	84	9	7	10.0 19.7
LS*	lime reverted superphosphate (AFL)	9	50	41	5.4
LS2*)	lime reverted superphosphate (CSBP)	32	55	12	8.3
LS3*)	)				7.6
CS	coastal superphosphate)	17	71	12	7.2
AS1*)	partly acidulated rock	22	15	65	9.6
AS2)	phosphate (GRP(1)) +				13.1
AS3*)	elemental sulphur	20	13	66	9.8
GRP(1)* GRP(2)*	island A grade rock) phosphate)	<1	10	90	16.0
GRP(3)*	Duchess rock phosphate	<1	8	92	13.7
RR	'reactive' North Carolina rock phosphate				13.5
C-500*	calcined Christmas Island C grade rock phosphate	<1	66	33	14.0
C-ORE	Christmas Island C grade rock P.	0	0	100	11.2

* as analysed

Particle sizes	>20 μm	>106 μm
GRP(1)	77%	31%
GRP(2)	67%	13%
GRP(3)	73%	18%
C-500	79%	28%

N.B.:	
Clay	< 2 μm
Silt	2-20 μm
Fine sand	20-200 μm

TABLE 6

Effectiveness of various P sources relative to superphosphate applied in the year of trial establishment. RE was calculated from % P in tops where trials were non-yield responsive

P source*	83HA27	83HA26	82HA32		82HA31		82AL10		81AL6			81AL5			81KE2			81MA4			80AL2				80AL5			
	**	**																										
	1983	1983	82	83	82	83	82	83	81	82	83	81	82	83	81	82	83	81	82	83	80	81	82	83	80	81	82	83
Super 1980																					1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Super 1981									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0			1.1				1.6	
Super 1982			1.0	1.0		1.0	1.0	1.0		2.8	3.2		4.1	1.2		1.9			2.6	1.7			1.4				5.4	
Super 1983	1.0	1.0		1.6				-			6.3			6.3						6.6								
LS 1980																					0.8	1.1	0.8		1.3	1.1	2.1	
LS 1981									-	1.8	1.4	1.7	1.4	1.5	1.2	1.2		1.0	1.5	1.8								
LS 1982							1.1	1.1																				
LS2 1982			1.1	1.5																								
LS3 1982			1.3	1.8																								
CS 1983	0.9	0.6		2.1																								
AS1 1981									-	3.4	2.7	1.1	2.1	2.2	0.7	1.2		1.0	1.3	3.4								
AS1 1982							0.8	1.4																				
AS2 1981									-	0.9	-	0.3	0.7	0.4	0.6	0.5		0.6	0.5	1.0								
AS3 1983	0.8	0.8		1.5				-			4.0			5.5						3.2								
GRP(1) 1980																					1.1	0.8	1.1		1.3	1.4	2.2	
GRP(1) 1981									-	1.6	2.4	0.7	1.3	1.8	0.4	0.4		0.4	0.9	1.7								
GRP(1) 1982			0.8	1.3			1.3	1.0																				
GRP(2) 1981									-	1.9	2.1	0.8	1.3	1.5	0.5	0.5		0.6	0.7	2.0								
GRP(3) 1981									-	1.2	2.7	0.6	1.3	1.2	0.3	0.4		0.3	-	1.8								
RR 1982			0.5	1.3																								
C-500 1980																					-	-	0.8		1.2	1.5	1.7	
C-500 1981									-	2.1	3.2	1.2	1.1	1.5	1.0	0.7		0.6	1.1	1.0								
C-500 1982			0.5	1.3			0.7	0.7																				
C-ORE 1981									-	0.6	0.7	0.2	0.1	0.1	0.1	0.1		0.3	0.1	0.1								

** Coolup sands. All other trials are on deep grey sands.

TABLE 7

Estimated % of applied P recovered from the soil

	83HA27		83HA26		82HA32			82HA31	82AL10		
	6/1983		6/1983		1/83	6/83		1/83	12/82		
	0-5	0-10	0-5	0-10	0-10	0-5	0-10	0-10	0-5	0-10	0-25
Super 1980											
Super 1981											
Super 1982					17			6	38	36	68
Super 1983	63	69	34	44		20	22				
LS 1980											
LS 1981											
LS 1982									49	95	94
LS2 1982					33			15			
LS3 1982					34			23			
CS 1983	80	68	32	48		32	31				
AS1 1981											
AS1 1982									66	101	89
AS2 1981											
AS3 1983	75	61	67	56		64	46				
GRP(1) 1980											
GRP(1) 1981											
GRP(1) 1982					71			57	84	79	147
GRP(2) 1981											
GRP(3) 1981											
RR 1982					101			51			
C-500 1980											
C-500 1981											
C-500 1982					110			64	88	89	112
C-ORE 1981											

	81AL6						81AL5						
	1/82			12/82			6/81	1/82			12/82		
	0-5	0-10	0-25	0-5	0-10	0-25	0-10	0-5	0-10	0-25	0-5	0-10	0-25
Super 1980													
Super 1981	27	41	77	10	30	72	65	30	62	111	23	59	98
Super 1982				39	39	49					28	55	93
Super 1983													
LS 1980													
LS 1981	74	127	155	38	38	70	130	50	78	141	34	61	54
LS 1982													
LS2 1982													
LS3 1982													
CS 1983													
AS1 1981	107	133	206	46	90	107	71	30	58	121	23	34	54
AS1 1982													
AS2 1981	59	154	224	49	58	25	-	38	80	109	56	52	67
AS3 1983													
GRP(1) 1980													
GRP(1) 1981	111	157	234	95	125	102	102	71	97	121	27	40	37
GRP(1) 1982													
GRP(2) 1981	51	77	138	31	67	128	83	41	93	117	35	37	63
GRP(3) 1981	74	113	184	32	121	175	99	51	82	134	40	61	56
RR 1982													
C-500 1980													
C-500 1981	83	124	185	63	79	133	72	54	98	113	25	36	41
C-500 1982													
C-ORE 1981	77	114	173	76	55	61	105	72	119	182	54	72	103

	81KE2						81MA4					
	1/82			12/82			1/82			12/82		
	0-5	0-10	0-25	0-5	0-10	0-25	0-5	0-10	0-25	0-5	0-10	0-25
Super 1980												
Super 1981	31	58	117	11	21	65	43	80	91	32	50	29
Super 1982				26	45	65				39	39	53
Super 1983												
LS 1980												
LS 1981	39	74	144	59	45	69	66	115	130	44	44	34
LS 1982												
LS2 1982												
LS3 1982												
CS 1983												
AS1 1981	54	99	168	55	46	57	73	165	190	90	55	30
AS1 1982												
AS2 1981	21	70	126	55	24	69	96	171	146	29	41	22
AS3 1983												
GRP(1) 1980												
GRP(1) 1981	54	103	173	78	48	98	119	212	213	72	77	76
GRP(1) 1982												
GRP(2) 1981	68	131	233	68	85	57	64	96	78	90	49	33
GRP(3) 1981	44	117	152	35	11	46	86	177	179	38	33	31
RR 1982												
C-500 1980												
C-500 1981	68	127	213	56	73	75	96	157	153	46	52	76
C-500 1982												
C-ORE 1981	66	121	169	49	39	87	96	160	145	47	58	17

	80AL2					80AL5				
	1/81	1/82	12/82			1/81	1/82	12/82		
	0-10	0-10	0-5	0-10	0-25	0-10	0-10	0-5	0-10	0-25
Super 1980	47	38	9	39	66	31	0		3	0
Super 1981		11	19	31	70		17	0	7	3
Super 1982			21	40	83			36	44	39
Super 1983										
LS 1980	78	50	26	52	65	72	102	31	90	41
LS 1981										
LS 1982										
LS2 1982										
LS3 1982										
CS 1983										
AS1 1981										
AS1 1982										
AS2 1981										
AS3 1983										
GRP(1) 1980	71	60	84	73	110	49	66	38	93	42
GRP(1) 1981										
GRP(1) 1982										
GRP(2) 1981										
GRP(3) 1981										
RR 1982										
C-500 1980	66	64	60	71	113	69	53	34	31	42
C-500 1981										
C-500 1982										
C-ORE 1981										

Prediction of the fate of applied P is vital to an understanding of the long term implications of the use of 'slow release' fertilizers. Ideally, a plant uptake model should be used to match plant requirements and P release patterns, and work is current in this area. Data from new land experimental sites (nil growth on nil P plots) shows that $<$ 20% of P applied as any source is actually plant utilized in the year of P application, indicating large leaching losses, incomplete fertilizer dissolution, and/or the relative capacity of the competing processes to immobilize P.

Laboratory data

Initial data from the study of dissolution rates and processes of different P sources has shown large differences in leaching losses from the various sources during intense leaching in sand filled laboratory columns (Figure 5). Loss rates were higher from CSBP coastal super than from AFL lime super or 'AS3', though less than from ordinary superphosphate, confirming field data. The effects of incubation time and other factors affecting dissolution and leaching rates are under further investigation.

Field data

(a) Agronomic effectiveness

Field data are comprehensively presented in Tables 5 to 7. As measured by agronomic effectiveness, AS1/AS3 and the lime supers were approximately equivalent to superphosphate in the year of application on the Bassendean and Coolup sands, and had a higher residual value in subsequent years (data for Bassendean sand only - Tables 6,8). Other sources were generally less effective. These results mean that less phosphorus can be applied to achieve the same level of growth, but exactly how much less depends on the shape of the current response curve, and the residual function for each source, as previously discussed for estimation of fertilizer requirements. Available data on residual value of super, AS1/AS3 and lime super are presented in Table 9.

TABLE 8

Effectiveness of various 'slow release' fertilizer relative to superphosphate

Fertilizers all applied in year 1

Year	Super	AS1/AS3	Lime Super (AFL)	LS3/Coastal Super (CSBP)
1	1.0	0.8 (0.5-1.1)	1.2 (0.8-1.7)	1.0 (0.6-1.3)
2	1.0	1.9 (1.2-3.4)	1.4 (1.1-1.8)	1.8
3	1.0	2.8 (2.2-3.4)	1.3 (0.8-2.1)	-

Relative effectiveness = Ratio of slopes (Yield or % P on P applied

TABLE 9

Rate of reduction of agronomic effectiveness (residual value function) for super, AS1/AS3 and lime super

Note: (1) each source expressed relative to effectiveness in year of application (year 1)
(2) effectiveness measured relative to fresh super each year
(3) comparisons valid only within sources

	Super			AS1/AS3			LS (AFL)		
Site	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3	Year 1	Year 2	Year 3
1	1.0	0.44	0.16	-	-	-	-	-	-
2	1.0	0.22	0.16	1.0	0.45	0.32	1.0	0.21	0.16
3	1.0	0.32	0.15	1.0	0.50	0.50	1.0	0.60	0.28
4	1.0	0.52	-	1.0	0.86	-	1.0	0.50	-
5**	1.0	0.79	0.71	-	-	-	1.0	-	0.75
6	1.0	0.30	0.19	-	-	-	1.0*	0.87*	-

Relative effectiveness obtained as for data in Table 8.

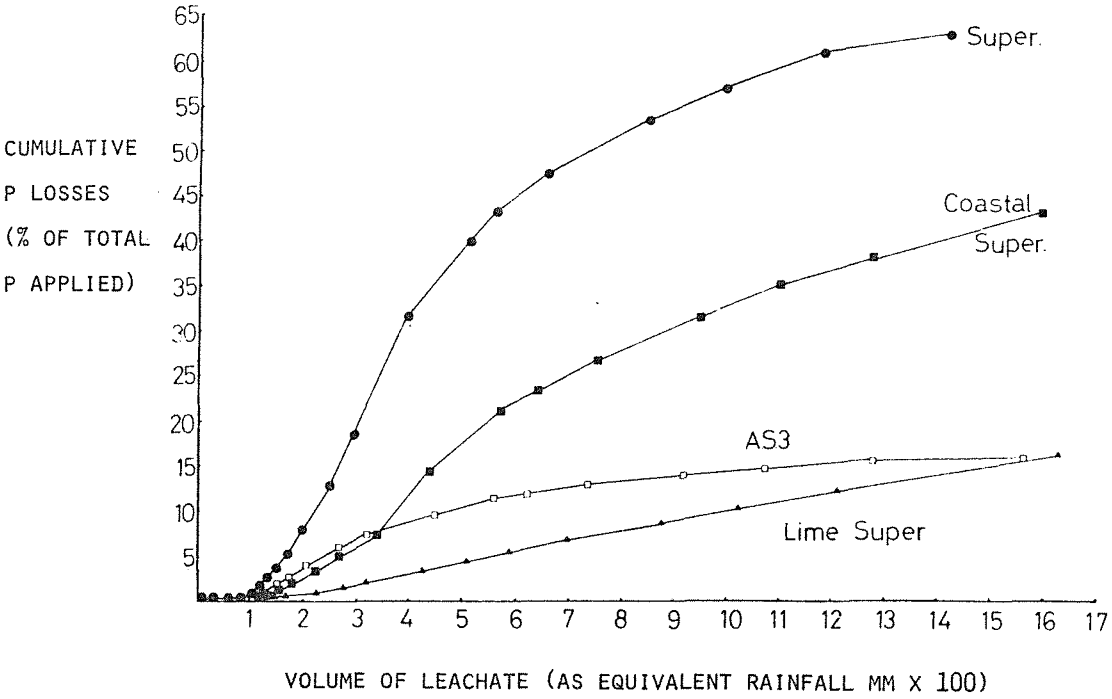
* CSBP LS3
** - ?

(b) Leaching losses

Estimated leaching loss data are difficult to interpret, and very variable. Apparent losses of super varied between 0% and almost 100% in year 1 (depending on site, and depth of sampling) but were generally greater than from the less soluble sources. Problems are obvious with some of the data (e.g. recoveries > 200%). On some sites (81AL6, 1981; 82AL10, 1982) sources with agronomic effectiveness equal to super had greatly reduced leaching losses from the top 25 cm of soil, but at others (81AL5) all recoveries were about 100%. On some sites losses from all sources were high (82HA31).

Data for years following the year of application show extreme variation. At some sites (81AL6, 81MA4) C-ORE, a source of extremely low water solubility and agronomic effectiveness, showed large apparent losses. As the rock phosphate sources are predominantly in the fine sand particle size range (> 90% of particles > 20 μm) vertical particulate losses are unlikely. Re-analysis of samples has shown consistent results. Generally, the data indicate that in year 2, differences in recovery of applied P between the various sources is relatively small, consistent with complete dissolution and incorporation into the various soil 'pools' in year 1, and losses in year 2 as a function of the size of these 'pools'. However, this hypothesis is difficult to reconcile with differences in residual value of the sources as measured by bic P (data not presented) and with the agronomic data in Tables 6, 8 and 9. Until a better understanding is reached of the soil chemical behaviour of P from the various sources, prediction of long term field leaching losses will remain difficult.

FIG 5 SAND LEACHING COLUMN EXPERIMENT



Simulation predictions

Theoretical estimates of losses are extremely sensitive to the actual size of leaching losses from soil P 'pools'. The results of calculated reductions in P losses from maintenance pastures using a P balance approach, assuming that all losses from the dissolving fertilizer occur in the year of application and all residual P subsequently enters soil 'pools', are presented in Table 10 for two fertilizers of differing dissolution characteristics. Changing from a fertilizer with 40% loss in the year of application to one with a 10% loss, reduction in total soil losses range with product removal losses from 27% to 41% of the appropriate maintenance rate at constant 'pool' losses of 5 kg/ha/annum. (i.e. more P must be applied to replace losses, and this leaches as a function of source). If 'pool' losses are lower, or are reduced with change in fertilizer type, greater reductions can be achieved, but no actual data is available on which to test these calculations.

TABLE 10

Changes in projected leaching losses with a change in P source from super (40% loss from the fertilizer) to a slow release source (10% loss)

Losses are expressed as % reduction of losses from maintenance super rates (Note: Maintenance rates are different for different 'pool' and product losses)

(Simulation only)

	SOIL P 'POOL' LEACHING LOSSES (kg/ha/annum)					
Product Removal Losses		Constant			Changing with P source	
(kg/ha/annum)	0	2	5	10	5 to 2	2 to 1
2	75	33	27	24	69	64
5	75	44	34	28	70	67
10	75	53	41	33	71	69

Sulphur

The provision of sulphur in a P fertilizer designed to replace superphosphate for maintenance dressings has previously been identified as a vital factor in farmer acceptance of modified fertilizer strategies (Yeates, Russell). Though of reduced P solubility, coastal super does not contain elemental sulphur, believed to be an appropriate source of S. 'AS3' has been developed specifically as a P and S source for maintenance pastures and 1983 field data (not presented) have confirmed its effectiveness as an S source. Effectiveness as a P source should be similar to 'AS1', which has been experimented with in the field since 1981. The degree of improvement of 'AS3' over coastal superphosphate as a P and S source for pastures should become more evident with time (from field and laboratory work). Major improvements over 'AS3' are not expected within the initially specified constraints of the study, but work will continue in this area.

SUMMARY AND CONCLUSIONS

Scope exists for phosphorus drainage losses from the sandy soils of the Peel-Harvey catchment to be reduced without reducing agricultural productivity, but the exact magnitude of the reductions cannot currently be estimated with certainty. With farmer cooperation, and use of an objectively based P recommendation system, fertilizer application rates may be reduced to optimum maintenance rates resulting in a minimization of P leaching losses. An improved recommendation system based on soil testing has been developed to help achieve this aim, but recommendations can be further refined with better definition of phosphorus response curves and residual value functions on the sands. Further reductions in P losses appear possible with the use of P fertilizers of lower water solubility than superphosphate, but many unknowns are still associated with the long term effectiveness of these sources in achieving reduced losses. Farmer acceptance of new fertilizers will depend on attractive pricing, availability and physical properties, and, as with reduced P applications, on the provision of sulphur in a suitable form to replace S in superphosphate.

Crude estimates of potential reductions in P losses which may be achieved are sensitive to many factors. Additionally, although it has been assumed that reductions in loss rates will equal reductions in application rate, this assumption may not be valid. (Ritchie group, ongoing work). However, from data available a 40% reduction in losses with the use of appropriately reduced application rates of superphosphate, and a further reduction of 20% (one third of the super maintenance rate) with the use of 'slow release fertilizers' (i.e. maximum of 60%) appears possible if phosphorus fertilizer applications are limited to those optimal for maximum economic return. However, both error associated in these estimates and the uncertainty of the level of adoption of changed practices makes this maximum figure unlikely to be achieved, and actual reductions may be considerably less. How long it will take for the estimated reductions to have an impact on the estuary algal problem, and how big the impact is likely to be is addressed in other papers.

FACTORS AFFECTING PHOSPHORUS LOSSES FROM SANDY SOILS

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Introduction

It is well known that phosphorus losses from sandy soils in the Peel-Harvey Catchement area are a major source of the P which causes algal blooms in the inlet and estuary. However, the effect of soil properties, environmental conditions and management practices on the extent of losses is not so fully understood. These are important aspects in determining whether leaching losses can be reduced sufficiently to prevent algal blooms and still maintain plant production. Consequently, work was initiated to investigate the effect of the above factors on phosphorus losses, the pools of phosphorus in sandy soils and the fluxes between them.

Phosphorus Reactions in Soils

When phosphorus enters the soil a variety of reactions can occur. Fig. 1 illustrates these reactions and the four main phosphorus pools that can exist. Each pool may be subdivided into fast and slow cycling sections and the phosphorus may either be in the organic or inorganic form.

Individually, each pool may be defined by its capacity (size), intensity (strength of binding P) and flux (rate of movement to and from the pool). The properties will depend upon the presence of different soil constituents, e.g. iron and aluminium oxides, organic matter, clay minerals. The amount of each type indicates the capacity, whereas each constituent will have a different intensity and flux to other pools.

Collectively, the major property to consider is the equilibrium between the pools. The forms of phosphorus in the soil do not exist as separate entities since there is continual movement of P from one pool to another. If there are no inputs or outputs from the system, the cycling between pools reaches a quasi-equilibrium. Inputs will favour an equilibrium shift towards the solid phases whereas outputs shift the equilibrium towards the liquid phase. The amount of P that moves will depend on the size of the individual pools. The speed of movement will be a function of the intensity of the reaction forming the pool and the extent to which the equilibrium is being disturbed.

Therefore, the state of the equilibrium between phosphorus pools in a soil will depend on the net effect of inputs and outputs and factors that affect them. In the Peel-Harvey Catchment area, there are regions of sandy soils where the equilibrium is continually being driven to the liquid phase by the loss of P by leaching.

Having established a somewhat arbitrary division of total phosphorus in soils and the equilibria between the pools, we shall now discuss some aspects that affect the state of the equilibria by considering factors that affect phosphorus losses.

Losses from Soil Phosphorus Pools

When rain enters a soil initially, some P will desorb or dissolve into the solution phase until a quasi-equilibrium is achieved with the solid phases. If rainfall continues, the bulk of the soil solution either moves down the profile or moves laterally in the first few centimetres after the soil becomes saturated. The removal of phosphorus in drainage waters and the replacement of the soil solution with further rainfall will cause more phosphorus to desorb, i.e. continuous rainfall shifts the equilibria in Fig. 1 towards the solution phase. The amount of phosphorus that is desorbed as the rainfall continues will be affected by several factors which are related to the soil itself and environmental and management considerations. Some of these factors are listed in Table 1.

Table 1. Factors affecting phosphorus losses from soils

Soil	Environmental	Management
Hydrous oxides	Rainfall	Fertilizer type
Organic matter	Storm interval	Fertilizer application rate
Clay fraction	Flooding	Fertilizer application method
Soil solution properties	Seasonal patterns	Plant growth
P content	Temperature	
Non-wetting properties		

The aim of our work has been to assess the importance of the factors mentioned above to see if phosphorus losses can be reduced sufficiently to prevent algal blooms and still maintain plant production. The results reported here refer to the deep peaty sands of the Joel soil type. We are also studying the yellow sandy duplex soils (Coolup) and the deep grey Gavin sands.

Modelling Phosphorus Losses in Sandy Soils

Because of the complex interaction between factors affecting phosphorus losses, we are currently developing a model to depict their overall effect. The model has evolved by constructing a base from consideration of soil factors. Subsequently, environmental and management factors have been added as optional variables. It is predictive rather than descriptive in nature because the approach has been to use laboratory data to estimate the parameters required rather than finding the curve of best fit to describe field data.

Since the model is still in the developmental stage, it will not be discussed in detail here. However, it will be used to illustrate the results. In order to demonstrate the feasability of the model, and the relevance of laboratory work to the field, predictions were tested by comparison with field data collected by Peter Birch and Nick Schofield. They measured the phosphorus load in drainage and runoff waters flowing from mini-catchment areas on the Joel soil type. The form of their data is particularly useful for comparisons because the load and flow measurements are made before any of the water enters the groundwater pool. This means that any complications due to groundwater flow or storage are eliminated. Birch and Schofield's data is expressed in terms of cumulative flow. Consequently, one cannot make an exact comparison of the predicted data with the field data because the relationship between rainfall and flow is uncertain, i.e. the flow after a certain amount of rainfall will not include the rain that has fallen the most recently. The disagreement between estimates of P losses by these two methods is greatest after low amounts of rainfall and decreases as the rainfall increases. This is because the lag between rainfall and the corresponding flow decreases as the wet season progresses. Fig. 2 shows the predicted loss. It is ∿25% less than that calculated from field data.

Short Term Effects on Phosphorus Losses

Short term effects refer to those occurring during one wet season only.

a) Total Soil Phosphorus Content

The amount of phosphorus lost per year increases as the total P content in the soil builds up (Fig. 3). More phosphorus is lost in the early rains but as the wet season progresses the loss decreases. This is because the rate of removal by leaching and runoff is greater than the rate of replenishment of the readily leachable pools.

b) Intervals Between Rainstorms

Fig. 4 illustrates that if the soil is saturated, and there is no application of fertilizer, intervals between rainstorms increase the P desorbed when the rains start again. It would appear that the major process occurring is the replenishment of phosphorus levels in the readily leachable pool during the pause between rainstorms. A seven day pause early in the season has a greater effect on losses than a similar pause near the end of the wet season. This is because the change in the amount of phosphorus lost not only depends on the length of the pause but also depends on the difference in the rate of removal of phosphorus and its replenishment from less readily leachable pools. The difference between these two factors increases as the season progresses, resulting in a decrease in the amount of phosphorus that can be lost.

c) Fertilizers

We have also investigated the losses that occur when fertilizers of different types and at different rates are added during the leaching period. The fertilizers studied and the percentages of water and citrate soluble P in them are given in Table 2. For the Joel soil type, the amount of P lost once rain starts again depends on the amount of readily soluble P (i.e. fertilizer type and application rate), adsorption, the amount of substrate available for microbial activity, and the time until rain starts again. If there is no pause in the rainfall after fertilizer application, the loss of phosphorus at all application rates is mainly governed by the dissolution rates of the three fertilizers and a small amount of adsorption (Figs. 5 and 6). For slightly longer pauses before rainfall recommences (1-2 days), the P lost decreases because of an initial microbial flush and further adsorption. As the pause lengthens, the P lost reaches a constant value, probably because the amount of available substrate becomes limiting and quasi-equilibrium is reached between the inputs and movement of P between pools. The changes are more obvious at high rates of P application because of luxury supply of phosphorus. At lower fertilizer rates, P supply as well as substrate availability may limit microbial activity, and so changes in P lost with time are not so great. With increasing time before rain starts again the difference in the amount of P lost from the three fertilizers decreases (Fig. 7).

Table 2. The percentage of total P that is water and citrate soluble in the fertilizers used in the study.

Fertilizer	Water soluble P	Citrate soluble P	(Water + citrate) soluble P
Superphosphate	80	10	90
Coastal Super	17	71	88
AS3	20	13	33

The observed loss is a net effect of dissolution versus assimilation and adsorption. The level of P lost will be maintained until the supply of readily leachable P by dissolution becomes limited by the application rate.

Long Term Effects on Phosphorus Losses

Long term effects consider factors acting over several winter and summer seasons. Preliminary results show that P in the readily leachable pools increases over the long hot summer. The increase is related to the total P in the soil at the end of the winter season, i.e. the more P left in the soil, the more that will move into the leachable pool over the summer months. This indicates that even though the flux between pools is not fast enough to replenish leachable pools on a daily basis of continuous rain, the fluxes are fast enough to move phosphorus if given a longer period before they are disturbed again by rain. If the total P remaining in the soil at the end of each wet season is large enough, the flux may be independent of supply for several summers until the total P has been lowered by a sufficient amount to limit the flux. This means that at the beginning of each wet season the readily leachable pool could contain the same amount each year until the total P limits flux.

As mentioned previously, losses from recently applied AS3 are far lower than losses from superphosphate and Coastal Super in the short term. Preliminary laboratory data (obtained by incubating soils at temperatures similar to those during summer) has shown that if the level of phosphorus from AS3 applications has built up (e.g. 3 x 18kg/ha), the summer break is a long enough pause for sufficient phosphorus to move into the readily leachable pool and subsequently cause greater losses than in the short term. These results have to be confirmed for longer time periods, higher temperatures and with a wider selection of soils.

Implications for Management

Our results have highlighted the following factors as important:

a) Weather Pattern

The results imply that the weather pattern plays an important role in P losses. The wet winters and dry summers help keep the phosphorus cycling between pools. Pauses in rainfall early on in the wet season can increase the P desorbed markedly since it gives the equilibrium time to re-establish itself. Similarly, the long hot summers provide sufficient time for the readily leachable pool to be replenished after the previous winter's loss.

b) Total Soil P Content

The amount of phosphorus lost is very dependent on the total level in the soil. The higher the total P, the more likely that large losses of P can be maintained over several years *even without fertilizer application.* The flux between phosphorus pools in the soil is sufficiently fast that the summer dry season is a long enough pause to allow replenishment of the readily leachable pool. Lower phosphorus losses will only occur when the flux becomes limited by the total P content. This means that *if fertilization ceased,* the time it would take before appreciable reductions in P losses were observed would depend on the total P content. For soils with total P contents of >70-100 ppm to a depth of 10 cm, it could be several years before the P lost each year started to decrease and then several years before it became negligible. Therefore, it would appear that run-down times will not be just a couple of years and a minimum of five years may be more realistic.

c) Fertilizer Type

Short Term

On old land, the use of fertilizers with low (water + citrate) soluble P reduces losses, but this may not prevent algal blooms. On new land, application of fertilizers similar to AS3 at rates <18kg/ha would lead to significantly lower leaching losses. However, plant growth might not be maintained.

Long Term

For both new and old land, if the application rates are kept the same, the loss of P from one applicaiton of low (water + citrate)soluble fertilizers will just be spread over a longer time period as more will be left behind in the soil. In the long term, therefore, the fertilizer with a smaller percentage of phosphorus in a readily leachable form (but the same total P content) will lose as much phosphorus as superphosphate but over a longer time period.

Summarizing, the short and long term behaviour of superphosphate and coastal super are similar even though the mechanisms may differ. The short term effects of AS3 are promising whereas the long term effects appear to be less encouraging.

d) Fertilizer Application Rate

Reduced application rates will reduce losses, but not sufficiently to prevent algal blooms. Previous data suggests that if the phosphorus loading in the Harvey River is <34 tonnes, no algal bloom will occur. If one assumes thatthis P comes primarily from about 17000 ha of soil, then a total loss of <2 kg/ha during the winter must be achieved to prevent algal blooms. Our present work indicates that *on established pastures*, applications of <10 kg/ha of all three fertilizers under investigation will not reduce losses to this level. Therefore, currently applied phosphorus is important in estimating the source of losses. It must be remembered though, that if the soil total P content is large, recently applied P may comprise only 40-50% of the total loss.

Possible Management Strategies

The points discussed above do not offer a quick agricultural solution to reducing phosphorus losses from soils under established pastures in the Harvey catchment area. However, there are long term strategies which would be mutually beneficial to both the farmers and those people who wish to use the recreational facilities of the Peel Inlet and Harvey Estuary.

Some long term strategies could be to:

1) Identify soils with high total P contents (>70-100 ppm?) and adequate P for plant production. No further additions of fertilizer should be added to these soils until the P content has been reduced to the minimum required to maintain plant production.

2) Change fertilizer to a less (water + citrate) soluble form.

3) Reduce application rates.

4) Change application method in effort to increase efficient usage by plants.

5) Improve soil test.

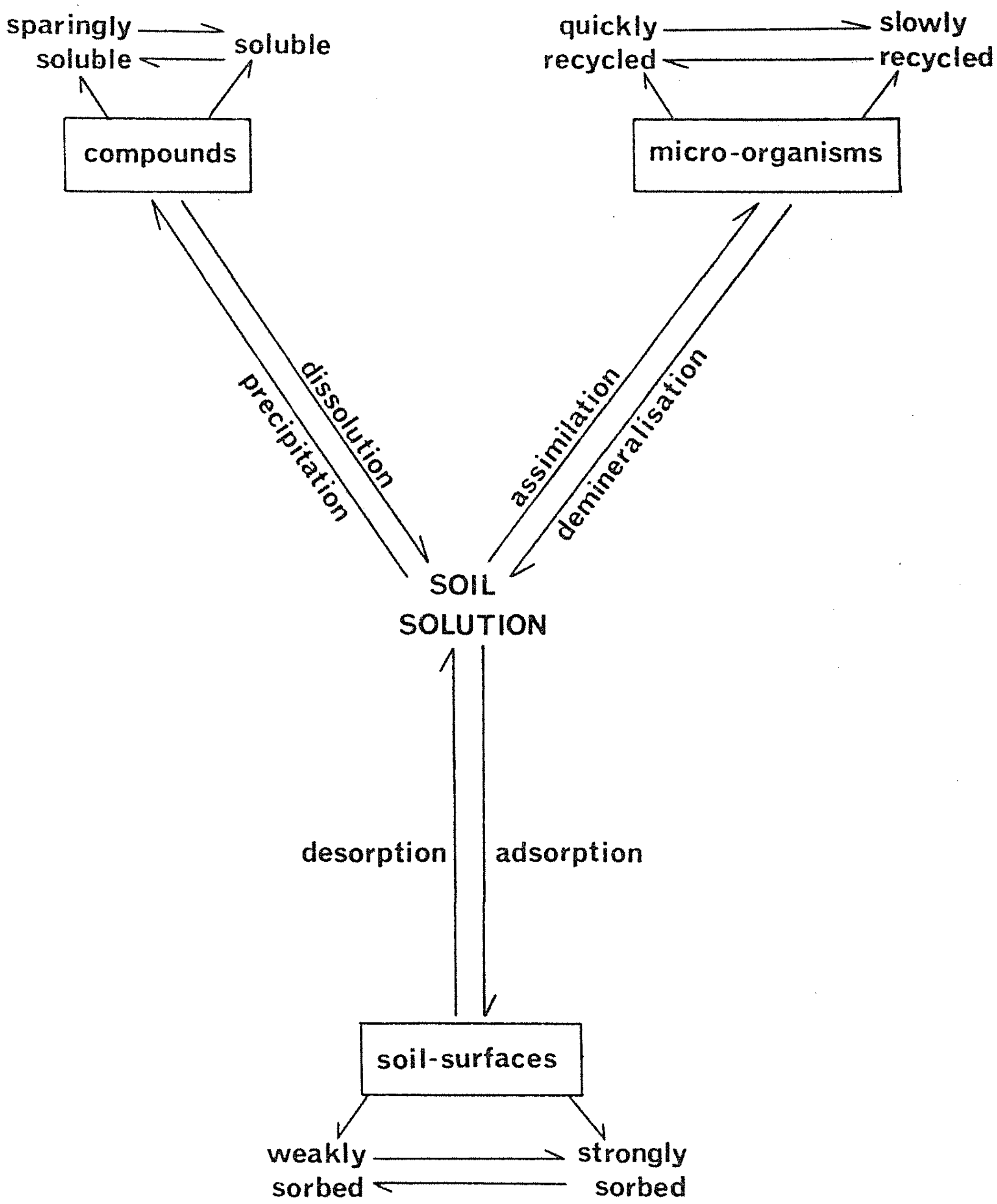

Fig. 1. Soil phosphorus pools (inorganic and organic).

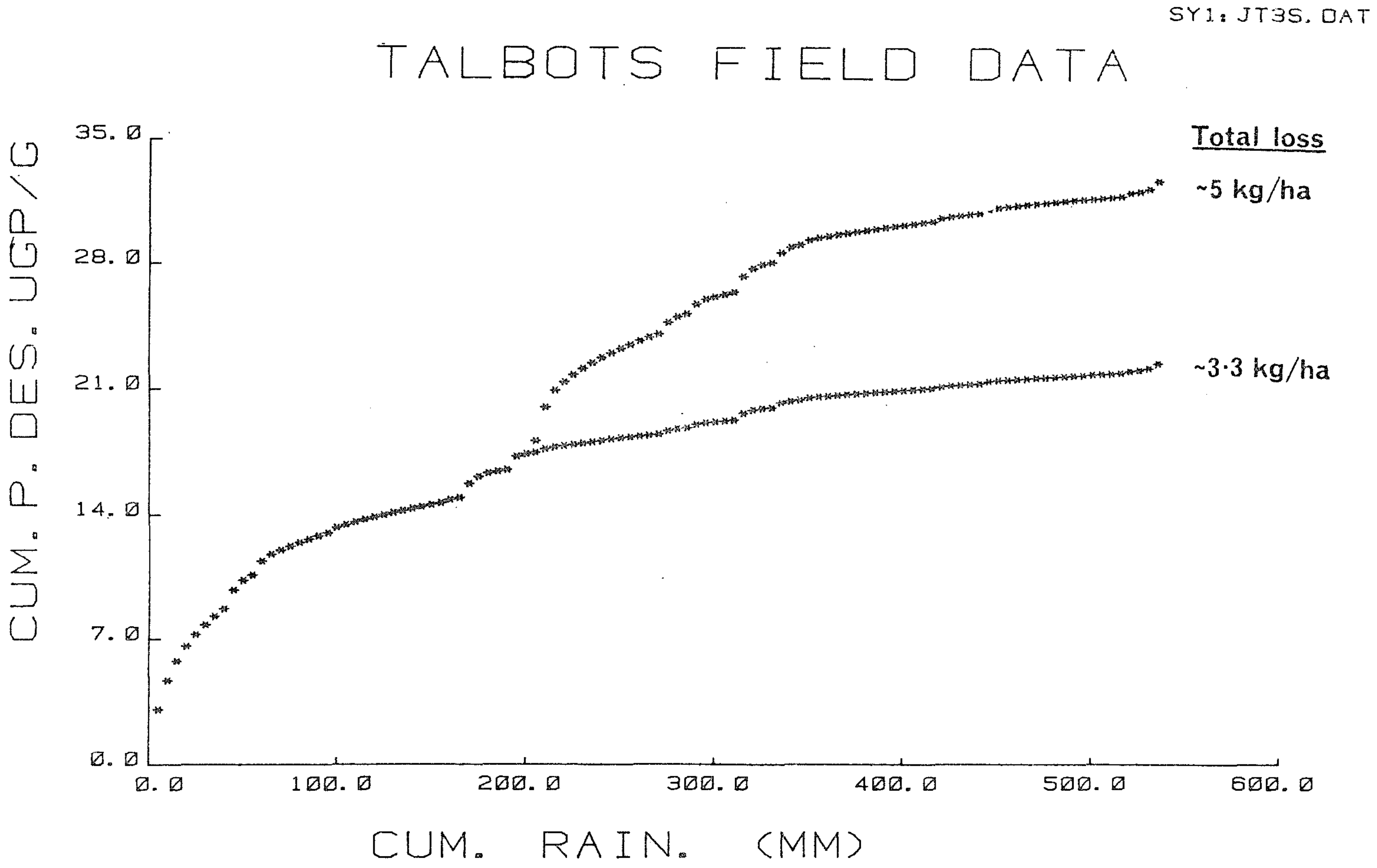

Fig. 2. Predicted phosphorus loss from the Talbot Field Trial in 1983 after 526 mm of rain.

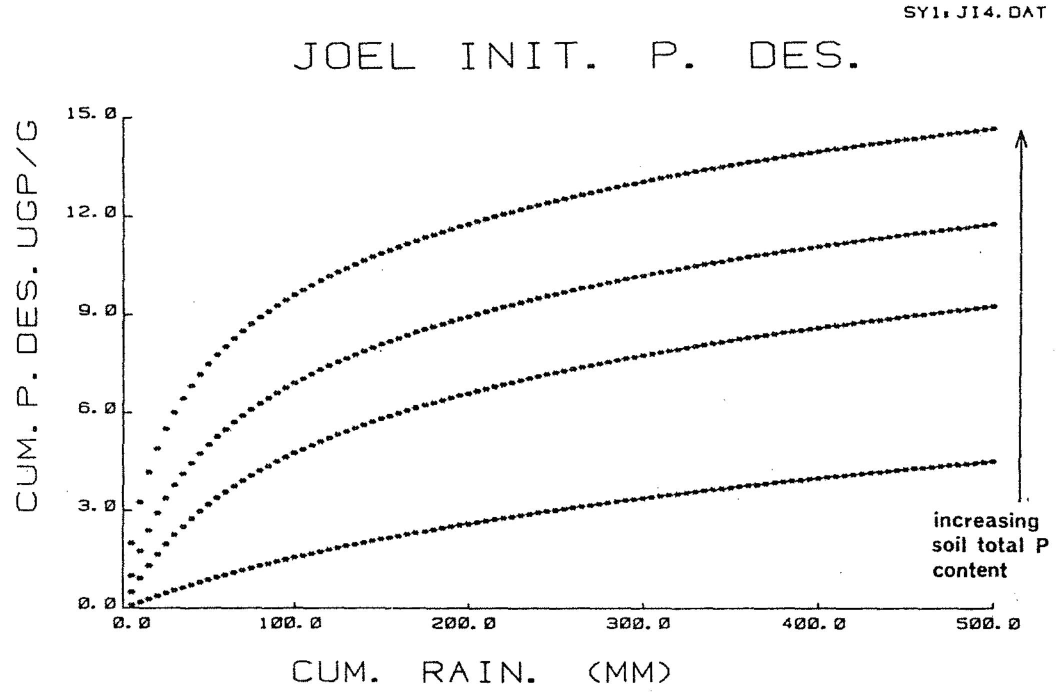

Fig. 3. The effect of soil total P content on phosphorus lost during the wet season.

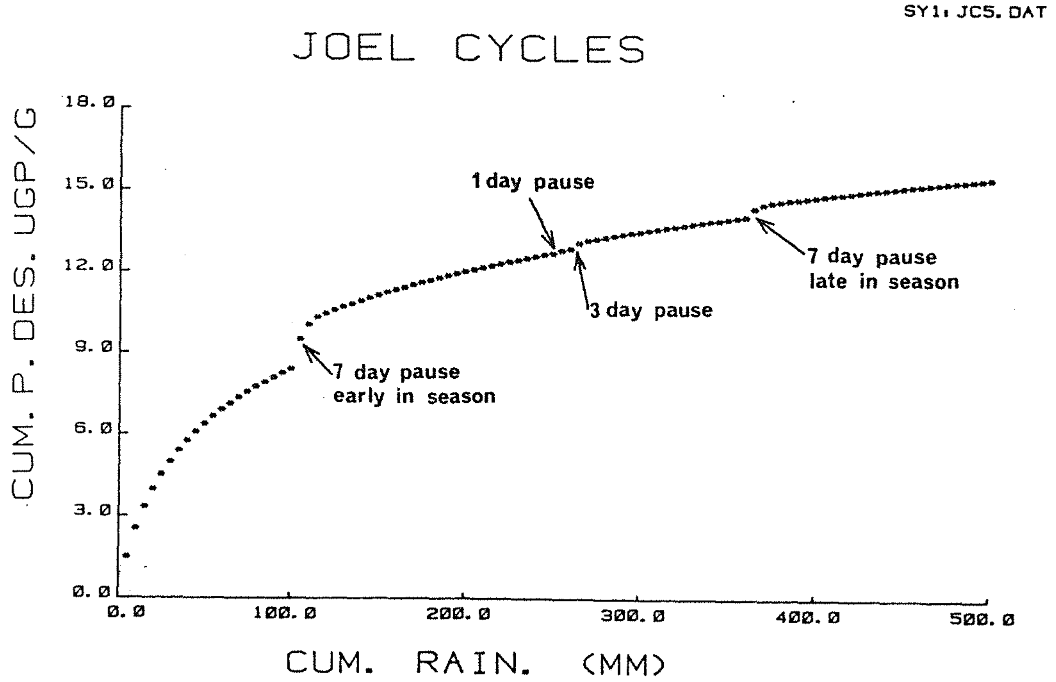

Fig. 4. The effect of different length pauses between rainstorms on P desorbed.

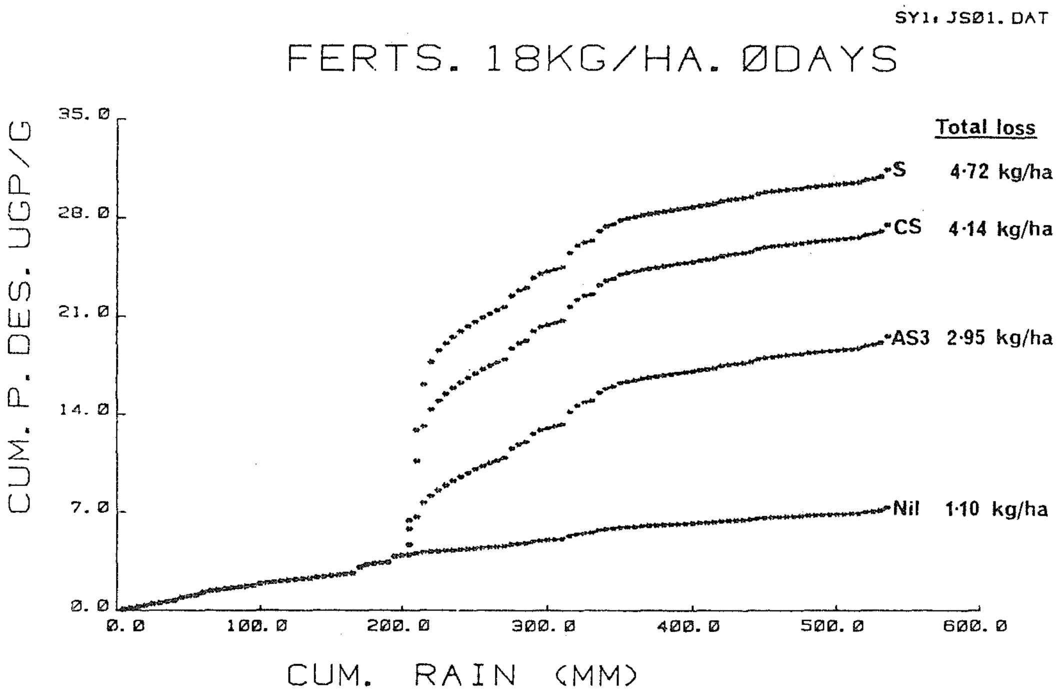

Fig. 5. Phosphorus lost after application at 18 kg/ha of three different fertilizers during continuous rain.

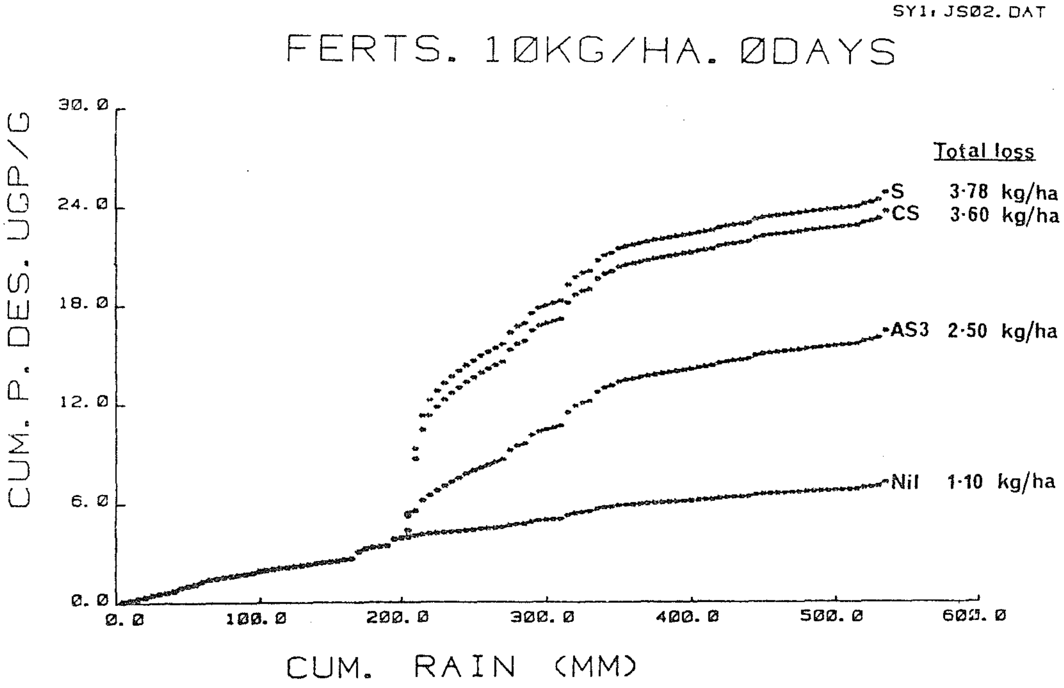

Fig. 6. As for Fig. 5 except application rate of 10 kg/ha.

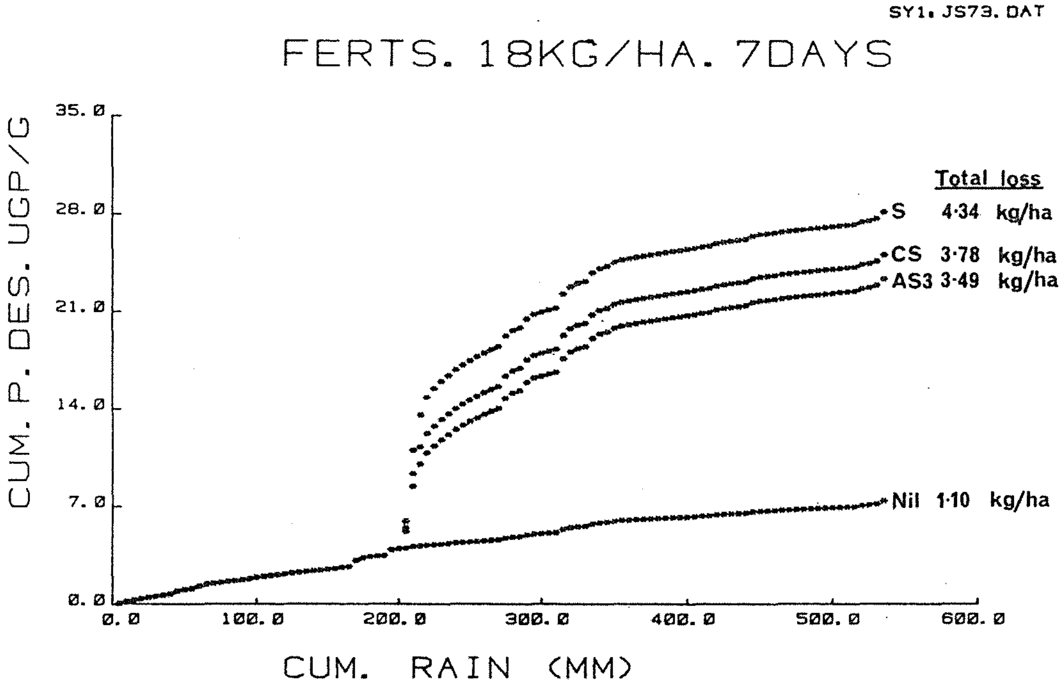

Fig. 7. Same as Fig. 5 except there is a 7 day pause in rainfall after application.

Determining phosphorus losses to drainage from currently applied superphosphate and coastal superphosphate fertilisers and from soil storage for different soil types in the Peel-Harvey catchment.

N J Schofield, P B Birch, G G Forbes, K W McAlpine, G M Bott

1. INTRODUCTION

The quantity of phosphorus leached from the landscape into drainage channels is likely to be a complex function of several factors, some of which are listed below:

rainfall characteristics
runoff characteristics
runoff components (flow paths)
drainage characteristics (e.g. density)
topography
land-use
applied fertilisers
fertiliser history (soil phosphorus storage)
time of fertiliser application and subsequent rainfall
soil physical and chemical properties.

The single factor being considered here as a means of reducing phosphorus leaching is applied fertiliser. Both the reduction of applied superphosphate and the introduction of a newly-developed slow-release fertiliser (coastal superphosphate) have been investigated. Another factor considered in the study is soil type as this is a major determinant of the phosphorus leaching rate. Field experiments have been carried out on the primary soil groups of the coastal plain, namely deep sands, duplex sand over clay and loams and clays (Figure 1).

The quantity of phosphorus stored in the soil from previous years of fertiliser application is also strongly correlated with leaching losses and this has necessitated extensive soil phosphorus testing. Climatical variables, especially winter rainfall total and its temporal distribution, will always strongly influence the actual amount of phosphorus leached from the landscape.

In order to manipulate the system from a management point of view, it is crucial to gain an understanding of the mechanisms of phosphorus and water movement and to quantify the individual transport components. Progress which has been made in this area is not reported in this paper.

2. PREDICTING PHOSPHORUS LOSSES TO DRAINAGE FROM DIFFERENT SOIL TYPES

Theoretically, if one could specify loss rates from particular soil groups, for given fertiliser application, soil phosphorus storage and runoff, it would be a simple matter to scale-up the results of small plot experiments to the management scale. This possibility, however, is made less attractive by the great variability of soils on the coastal plain and by complicating influences of the other factors listed above. Nevertheless, the soils of the coastal plain can be grouped into broadly differing soil types and this has formed the basis of the field experimental programme. The classification of major soil types, their extent and properties are summarised in Table 1.

Table 1: <u>The classification of major soil types of the Peel-Harvey catchment</u>

Soil Type	Extent in Harvey Estuary Catchment*		Properties
	ha	%	- deep sand profile up to ∿30 m
deep grey sands	14 300	22	- hard-pan (coffee-rock) often present near summer low watertable. - characterised by dunes (Gavin sands) and flats (Joel Sands) and interspersed by swamps (outcropping groundwater). - unconfined watertable close to surface. - sand has v. low P-adsorption capacity. Most P-storage in organic A horizon (∿10 cm) and on surface of coffee rock. - partly cleared for agriculture.
duplex soils of sands to sandy loams overlying clay	16 700	26	- surface soil 0-150 cm averaging ∿30 cm, usually with dark organic A horizon. - B horizon of low permeability clay. - very flat topographically (<1%). - moderate P-adsorption capacity. - virtually entirely cleared for agriculture.
ridgehill shelf soils - yellow and brown sands	4 650	7	

../Cont'd

Table 1: (Cont'd)

Soil Type	Extent in Harvey Estuary Catchment*		Properties
loams and clays	14 300	22	- heavy soils with v. high P-adsorption capacity. - embodies much of the irrigation district.
hills	13 900	22	- mostly uncleared - steep gradients - lateritic soils

* Harvey River plus Mayfields Drain catchments (these contribute over 90% of the phosphorus load to Harvey Estuary.

Three sub-catchments were established in 1982 to compare phosphorus leaching from the three main soil types in the coastal plain (deep sands, sand over clay, loams and clays). The locations of sub-catchments are shown in Figure 1 and their properties are listed in Table 2. To-date only the 1982 winter data are fully analysed for all three sub-catchments and these results (Table 3) will be used as a basis for discussion.

To determine the proportion of the total phosphorus contributed to the Harvey Estuary, we assume that the phosphorus loss to drainage from each catchment is typical of the soil type it represents. A prediction of phosphorus contributed by each soil type is then obtained by multiplying the loss rate by the area occupied by each soil type in the Harvey Estuary catchment (Table 4). The total phosphorus predicted is found to agree quite well with that measured in the Harvey River for the same period (57 tonnes) which accounts for about 85 per cent of the total input to the Harvey Estuary. On this basis it seems a reasonable management tool to scale-up the results of medium-sized experimental sub-catchments (1000-5000 ha) to predict phosphorus losses to drainage at the coastal plain scale (50,000-100,000 ha).

Table 2: Some Properties of the Soil Study Sub-Catchments

	Meredith	Mayfield (sub-G)	Samson Brook N. Drain
Soil type	deep sands	sand/clay	loams and clays
Area (km²)	52	10.65	18.0
% cleared	33%	∿100%	∿100%
Max. distance from outlet (km)	11.2	8.2	9.8
Max. width along long axis (km)	5.5	2.0	3.6
Drainage length (km)	27.3	16.1	28.4
Drainage density (km/km²)	0.55	1.51	1.58

Table 3: Summary of 1982 winter streamflow and phosphorus drainage loss (June-October 1982)

	Meredith	Mayfield (sub-G)	Samson Brook N. drain	Harvey River (mouth)
Streamflow ($10^6 m^3$)	4.6	1.97	4.0	130
Surface runoff (%)	41%	77%		
Subsurface runoff (%)	59%	23%	?	?
Rainfall at Waroona (mm)	707	707	707	707
Runoff/Rainfall	0.13	0.26	0.31	
Phosphorus load (tonne)	7.9	1.01	1.4	57
P-flow-weighted mean conc. (mg/L)	1.7	0.52	0.36	0.44
P load (kg/ha)	1.5(4.5)*	1.1	0.8	1.1

* P load/ha cleared

Table 4: Contributions of phosphorus from the major coastal plain soil types to the Harvey Estuary

Soil types	% of Harvey Estuary catchment	P drainage 1982 kg/ha	P contribution (tonnes)	(%) of total P
deep sands	22	1.5	21.5	36
duplex soils	34	1.1	23.5	40
loams and clays	22	0.8	11.4	19
hills	22	0.2	3	5
			TOTAL 59.4	

3. THE POTENTIAL FOR REDUCING PHOSPHORUS LOSSES TO DRAINAGE BY CHANGING FERTILISER PRACTICE: EVALUATION OF SUPERPHOSPHATE COASTAL SUPERPHOSPHATE AND NIL TREATMENTS

During the winter of 1983, experiments on deep sands and duplex soils have been conducted to evaluate the potential for reducing phosphorus losses to drainage by changing fertiliser practice, while at the same time maintaining pasture yield.

Deep Sands (Talbot's property)

A paired catchment study was undertaken to determine the effects of not applying phosphatic fertiliser to a deep grey sand whose soil test indicates adequate phosphorus for maximum pasture yield. The site chosen is shown in Figure 2 and the catchment properties are listed in Table 5. Both catchments are seen to be similar with respect to these properties. Additionally it is noted that the bicarbonate extractable soil phosphorus is slightly above the level required to give maximum pasture yield (according to recent plant response curves established by the Department of Agriculture). Thus this experiment is all the more meaningful since the main objective of the fertiliser programme is to achieve phosphorus availabilities at or near that required for maximum pasture yield and so knowledge of the response to different fertiliser treatments at this soil phosphorus level is crucial.

Due to the urgency of obtaining results, only a limited period of pre-treatment monitoring was possible. On July 19, superphosphate was applied to most of the South drain (see Table 6 for application rates). Substantial rains occurred a week later and a high concentration 'spike' (∿15 mg/L) was observed on the fertilised plot. The cumulative load-runoff graphs are shown in Figure 3. Prior to applying fertiliser, the flow-weighted mean concentrations of the two catchments were very similar (2-6 mg/L), indicating that a good pair had been chosen. After applying superphosphate, the loss rate from the South drain increased from 2.6 to 8.3 mg/L and then gradually declined to a value similar to the unfertilised North drain by the end of the winter. A summary of the results for the two catchments is given in Table 6. The runoff coefficients for the two drains are very similar, again indicating the similarity of the two catchments. Consequently, the flow-weighted mean concentration is a good indicator of the reduction in phosphorus leaching to drainage when no fertiliser is applied, this value being 30 per cent.

Table 5: Comparison of paired-catchment properties (Talbot's)

	North drain		South drain	
total area (ha)	22.2		38	
area cleared (ha)	19		27.2	
area of swamp	2.8 ha	(12.6%)	6.4 ha	(16.8%)
Gavin dunes	8.5 ha	(38%)	13.1 ha	(34%)
Joel flats	13.7 ha	(62%)	23.0 ha	(61%)
mean slope	0.515°		0.383°	
drainage length (km)	0.6		1.05	
drainage density (km/km²)	2.7		2.8	
	total P	bicarb. P	total P	bicarb. P
soil phosphorus tests (ppm)	71	10.5	59	8.5 - 9.5
kg/ha/10 cm depth	106.5	15.8	88.5	12.8 - 14.3
fertiliser history	>20 years		>20 years	
land-use	sheep grazing pasture		sheep grazing pasture	

Table 6: Paired-catchment results summary (deep sands: Talbot's)

		North drain	South drain
pre-treatment	total rainfall (mm)	218	218
	total runoff (10^6L)	8.2	15.8
	runoff/rainfall	0.17	0.19
	P load (kg)	20.8	41.6
	P conc (flow-weighted mean) mg/L	2.54	2.63

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Table 6: (Cont'd)

		North drain	South drain
	treatment	nil	5.4 ha at 20.7 kg P/ha 25.2 ha at 18.2 kg P/ha
post-treatment	total rainfall (mm)	357	357
	total runoff (10^6L)	50.3	82.1
	runoff/rainfall	0.64	0.61
	P load (kg)	89.1	219
	P conc (flow-weighted mean) mg/L	1.77	2.67
total period	total rainfall (mm)	575	575
	total runoff (10^6L)	58.5	97.9
	runoff/rainfall	0.46	0.45
	P load (kg)	109.9	260.6
	P conc (flow-weighted mean) mg/L	1.86	2.67
	P drainage/P applied	-	0.38
	P drainage/P storage (bic P)*	0.32	0.51
	yield (tonnes/ha) of pasture	5.72	5.12
	yield/yield (nil treatment)	1	0.90
	plant uptake (kg P/ha)	15.6	16.7

* bicarbonate extractable phosphorus

Duplex Soils

Three hillslope plots of 120 m x 35 m dimensions (Figure 4) were established on duplex loamy-sand/clay soils. In addition to the nil and superphosphate treatments, a newly-developed slow-release coastal superphosphate from CSBP was evaluated. Some of the properties of the individual plots are listed in Table 7.

Table 7: Properties of hillslope plots on duplex soils (Stacey)

	Plot 1		Plot 2		Plot 3	
area (ha)	0.42		0.42		0.42	
mean depth of soil horizons (A_1 (cm)	9.2		12.2		10.8	
(A_2 (cm)	18.4		16.9		38.3	
(B_1 (cm)	0.3		-		5.3	
slope (%)	.428°		.438°		.465°	
	total P	bicarb P	total P	bicarb P	total P	bicarb P
soil phosphorus tests (ppm)	150	38	140	36	130	34
kg/ha/10 cm	225	57	210	54	195	51
fertiliser history	>30 yrs		>30 yrs		>30 yrs	
land-use	sheep grazing pasture		sheep grazing pasture		sheep grazing pasture	

Cumulative graphs of phosphorus load vs runoff for the two fertiliser treatments compared with the nil treatment are given in Figures 5 and 6. In both cases the effect of adding fertiliser is apparent in increased concentrations of phosphorus in drainage. However, as compared to the deep sands (Figure 3), the higher flow-weighted mean concentrations are relatively short-lived.

The main results of the experiment are summarised in Table 8. The effect of the nil treatment was to reduce phosphorus leaching to drainage by 37 per cent over the winter period, as compared to the normal superphosphate application (200 kg/ha). The results for coastal superphosphate were complicated by significantly higher pre-treatment phosphorus concentrations from this plot as compared to the other two plots. For this reason two graphs are presented in Figure 6, one showing the actual data and the other adjusted to equalise the pre-treatment mean phosphorus concentration to that of the nil treatment. On the basis of the adjusted graph, the coastal superphosphate application resulted in a 28 per cent decrease in the flow-weighted phosphorus concentration as compared to normal superphosphate application. This value, however, is quite uncertain due to the nature of the adjustment described.

Table 8: Hillslope plot results summary (duplex soils, Stacey)

		Plot 1	Plot 2	Plot 2 (adjusted)	Plot 3
pre-treatment	total rainfall (mm)	325	325	325	325
	total runoff (10^3L)	332	420	420	467
	runoff/rainfall	0.24	0.31	0.31	0.34
	P load (kg)	0.167	0.280	0.212	0.213
	P conc (flow-weighted mean) mg/L	0.50	0.67	0.50	0.46
	treatment	superphosphate 18.2 kg P/ha	Coastal superphosphate 18.2 kg P/ha		Nil
post-treatment	total rainfall (mm)	388	388	388	388
	total runoff (10^3L)	832	1403	1403	1490
	runoff/rainfall	0.51	0.86	0.86	0.91
	P load (kg)	0.53	0.76	0.58	0.53
	P conc (flow-weighted mean) mg/L	0.64	0.54	0.41	0.36
whole period	total rainfall (mm)	713	713	713	713
	total runoff (10^3L)	1164	1823	1823	1957
	runoff/rainfall	0.39	0.61	0.61	0.65
	P load kg	0.70	1.04	0.79	0.74
	kg/ha	1.67	2.48	1.88	1.76
	P conc (flow-weighted mean) mg/L	0.60	0.57	0.43	0.38
	P drainage/P applied	0.09	0.14	0.10	-
	P drainage/P storage (bic P)	0.029	0.046	0.035	0.035
	yield (tonnes/ha) pasture	3.8	3.5	3.5	3.35
	plant uptake (kg P/ha)	12.4	13.1	13.1	11.1
	yield/yield (nil treatment)	1.13	1.04	1.04	1.0

4. COMPARISON OF PLOT RESULTS TO CATCHMENT RESULTS

The question of scaling-up small-scale plot experimental results to large areas is an important issue from the management point of view. Since data have been collected at three different scales (plot, micro-catchment, sub-catchment) this enables us to make direct comparisons for each soil type. Table 9 lists some of the pertinent parameters and 1983 results at the different scales. For the micro-catchments on the deep sands the drainage density and runoff coefficients are somewhat higher than for the Meredith sub-catchment. These factors may contribute to the higher phosphorus loss rates observed. Additionally, the high proportion of uncleared land on the Meredith sub-catchment substantially reduces the net catchment phosphorus loss rates.

On the duplex soils there appears to be fairly close agreement between the plot phosphorus loss values and those of the Mayfields catchment, despite differences in drainage density. This may indicate that the drainage density of the catchment is sufficiently high to effectively remove the high proportion of surface runoff evident on that catchment. Also, many of the farmer-made field drains were not included in the Mayfield sub-G drainage density calculation.

Table 9: Scaling comparisons for deep sands and duplex soils

		Microcatchments (Talbots)	Subcatchment (Meredith)
deep sands	area (ha)	38	5 200
	drainage density (km/km^2)	2.8	0.55
	runoff coeff.	0.45	0.17
	P conc (flow-weighted mean) from superphosphate application (mg/L)	2.7	1.2
	P export (kg/ha)	6.9	1.3 (4)*
		Plots (Stacey)	Subcatchment (Mayfield sub-G)
duplex soils	area (ha)	.42	1 065
	drainage density (km/km^2)	8.3	1.51
	runoff coeff.	0.54	0.50
	P conc (flow-weighted mean from superphosphate application (mg/L)	0.6	0.61
	P export (kg/ha)	1.7	2.3

* From cleared area

5. ESTIMATING POTENTIAL PHOSPHORUS DRAINAGE LOSS REDUCTION IN THE PEEL-HARVEY CATCHMENT

A gross estimate of the potential reduction in load to the Harvey Estuary can be made by extrapolating the paddocks scale results to the whole catchment and by assuming that phosphorus runoff from the control areas is indicative of runoff from paddocks receiving a maintenance dressing of slow-release fertiliser. The latter assumption may not be unrealistic since both control areas were at or above non-responsive soil test levels (confirmed by plant yield data) and could be rundown somewhat before a maintenance dressing would need to be applied.

Using these assumptions a long term potential reduction of 26 per cent is calculated (Table 10) if no reduction is achieved on the clays, loams and hills soils. These soils are at present fertilised at about twice the rate needed to maintain production. Therefore, some reduction in runoff of phosphorus will be achieved if these soils are fertilised according to soil tests. Even if the rate of reduction achieved is only about 50 per cent of that achieved for the duplex soils then a further four per cent overall reduction will be achieved, giving a total of 30 per cent. This figure could be further improved if the chemical nature of the phosphorus storage in the soil is altered by the long term use of slow-release fertilisers.

Since there are general similarities between the Harvey Estuary catchment and the Serpentine River catchment similar fertiliser management and similar reductions in phosphorus runoff should be achievable there.

Table 10: Potential long-term reduction of phosphorus inputs to the Harvey Estuary

Soil type	% P input	% reduction in field expts	% reduction for soil type area	% catchment P reduction
deep sands	36	30	30	11
duplex (sand/clay)	40	37	37	15
clay and loams	24	?	15*	4
			TOTAL	30

* estimated

6. EVIDENCE OF CATCHMENT-SCALE REDUCTIONS IN PHOSPHORUS DRAINAGE LOSS FOLLOWING DECREASED SUPERPHOSPHATE AND THE USE OF COASTAL SUPERPHOSPHATE

In 1983 a significant change in fertiliser practice on the Meredith catchment (5 200 ha) took place. In 1982, which may be considered typical of previous years fertiliser practice, 24 tonnes of phosphorus, almost entirely in the form of superphosphate, was applied to the catchment. In 1983, 6.2 tonnes of phosphorus as superphosphate and 10.2 tonnes as coastal superphosphate were applied. This change in fertiliser use corresponded to a reduction in the flow-weighted mean concentration of phosphorus in runoff from 1.7 mg/L to 1.2 mg/L. Thus, a 38 per cent decrease in phosphorus application saw a 29 per cent reduction in concentration in runoff. However, such a direct correlation between phosphorus application and runoff mean concentration must be considered against the background of annual variability and other influencing factors.

The 1983 reduction in flow-weighted mean phosphorus concentration in the Meredith catchment was also observed in the Harvey River, which decreased by 20% over 1982 and by 12% over the four year mean 1978-82 (Table 11).

Table 11: Flow-weighted mean phosphorus concentrations for Harvey River

Year	Flow-weighted mean phosphorus concentration (mg/L)
1978	0.38
1979	0.39
1980	?
1981	0.39
1982	0.44
1983	0.35

7. IMPLICATIONS

1. Predicting phosphorus losses to drainage on the basis of soil types

On the basis of the 1982 data, the concept of scaling-up results from medium-sized experimental catchments (1000-5000 ha) to predict phosphorus losses to drainage from different soil types appears to be a useful management tool. However the validity of undertaking the same exercise for micro-scale experiments is questionable.

2. Reducing phosphorus losses to drainage from deep sands by modifying fertiliser application

Reducing fertiliser application to zero on deep grey sands which have non-responsive soil test levels has the potential to reduce phosphorus leaching to drainage by about 30 per cent in one year, without affecting pasture yield.

The high proportion of phosphorus drainage loss to soil bicarbonate extractable phosphorus (0.32) indicates that significant reductions in further years of no fertiliser application may be possible, but this could be at the expense of pasture production.

3. Reducing phosphorus losses to drainage from duplex soils by modifying fertiliser application

Reducing fertiliser application to zero on sand over clay duplex soils with non-responsive soil test levels has the potential to reduce phosphorus leaching to drainage by about 37 per cent in one year, without significantly affecting pasture yield. The use of coastal superphosphate in the same situation could effect a reduction of 28 per cent. However, these figures are subject to uncertainty due to natural differences in runoff characteristics and phosphorus leaching rates on the experimental plots.

4. Estimating catchment reduction in phosphorus drainage loss

On the basis of scaling-up small experimental site results, a net reduction of phosphorus drainage loss (in terms of flow-weighted mean concentration) of about 30 per cent could be achieved in the long-term whilst maintaining agricultural production.

A substantial decrease in superphosphate application and its replacement by coastal superphosphate in the Meredith catchment in 1983 reduced flow-weighted mean phosphorus concentration by 29 per cent compared to 1982. A 20 per cent reduction was also observed for the Harvey River but these figures are subject to other influencing factors.

5. Rainfall-runoff influences

The actual phosphorus loading of the Estuary will continue to vary almost proportionately with total runoff. In this respect it is worth noting that only once in the last five years has average runoff been attained.

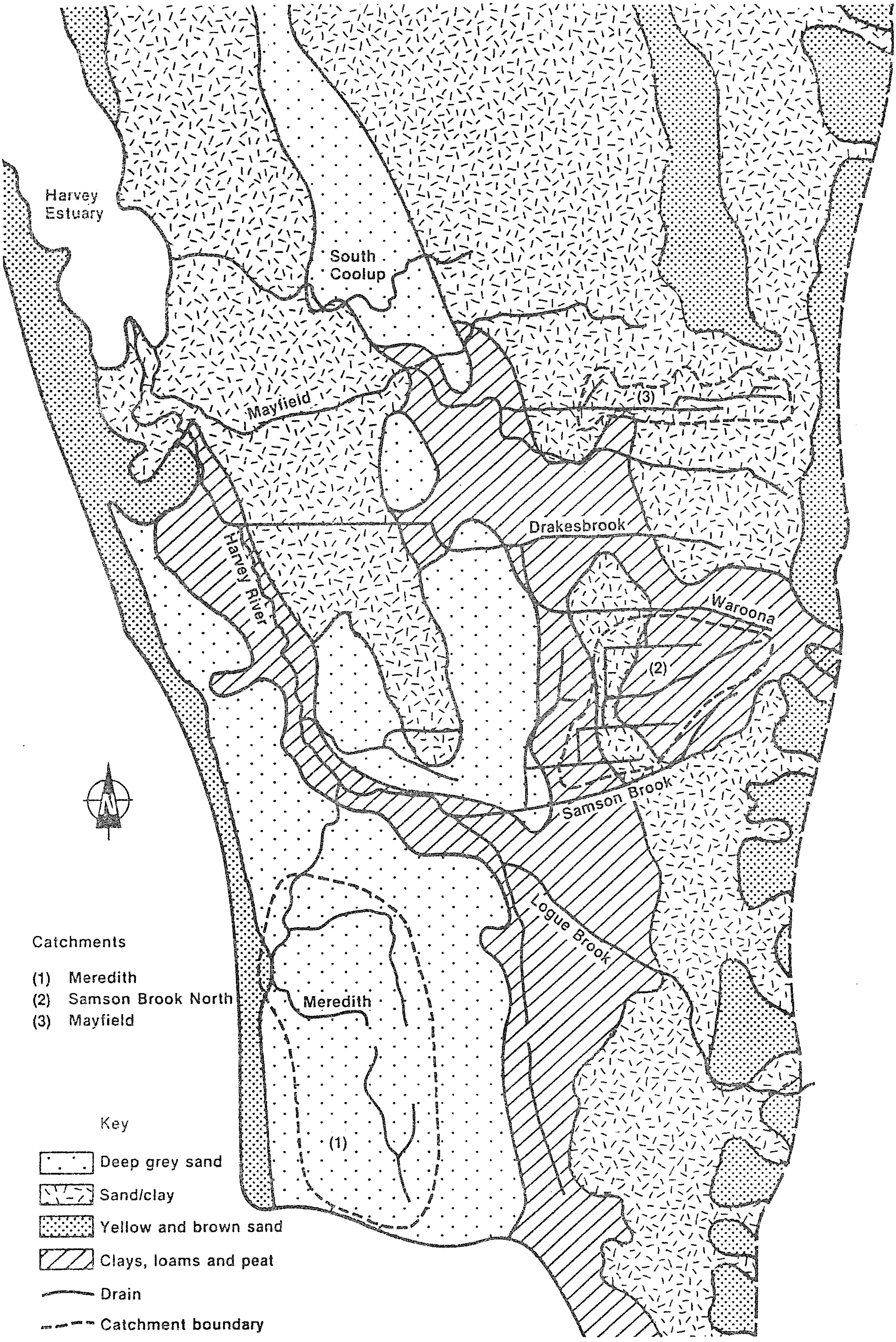

Figure 1 : Primary soil groups of the coastal plain with drains and their catchments superimposed.

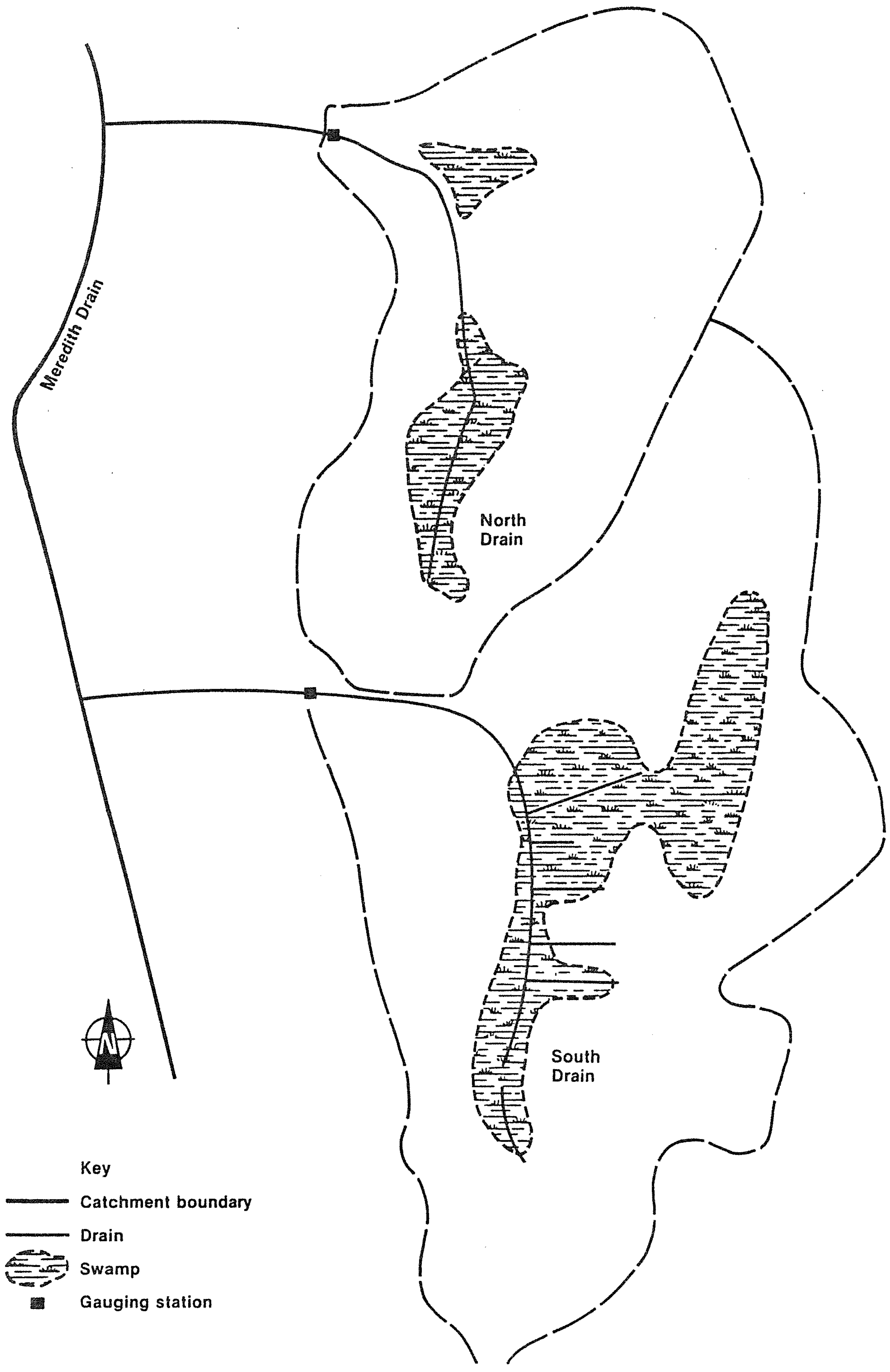

Figure 2 : Gauging station locations in the paired catchment study on the deep grey sand.

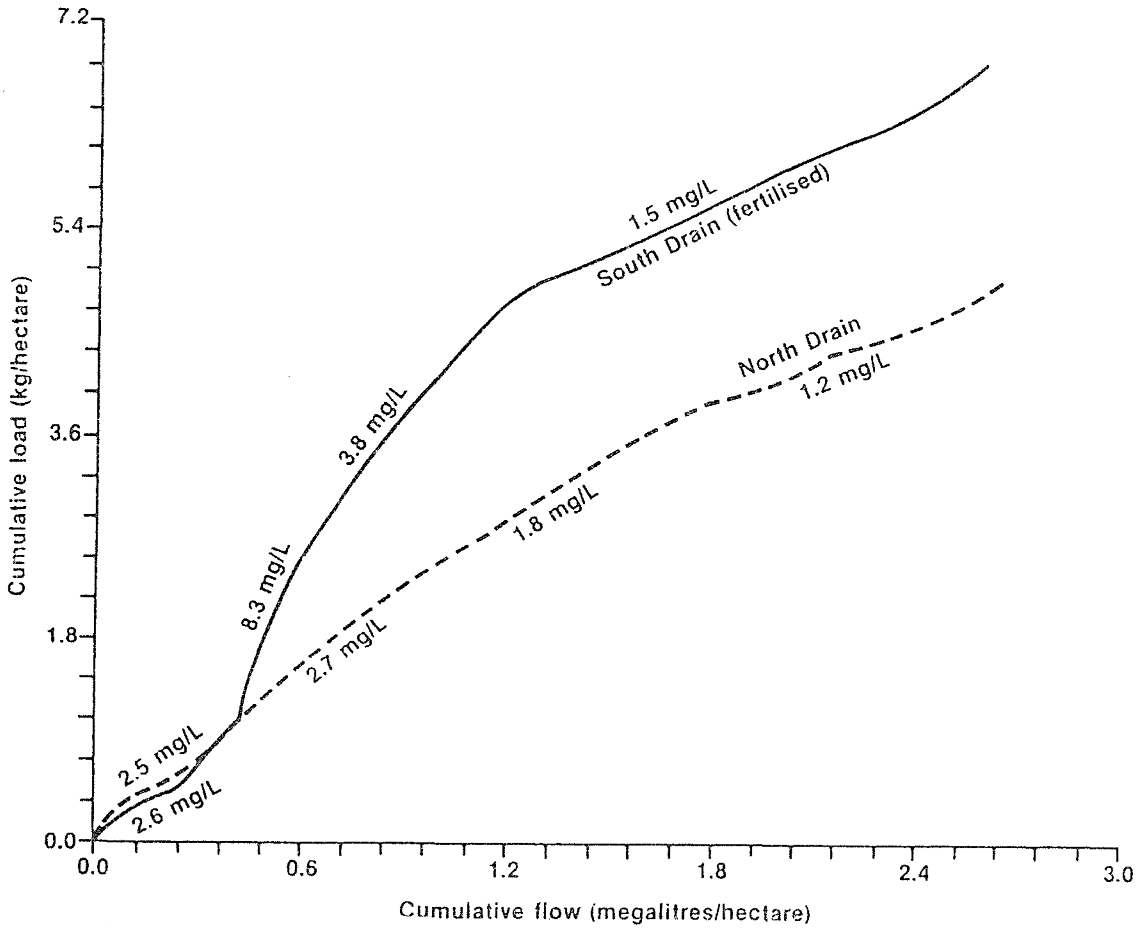

Figure 3 : Cumulative phosphorus load versus cumulative flow for superphosphate and nil treatments on deep sands.

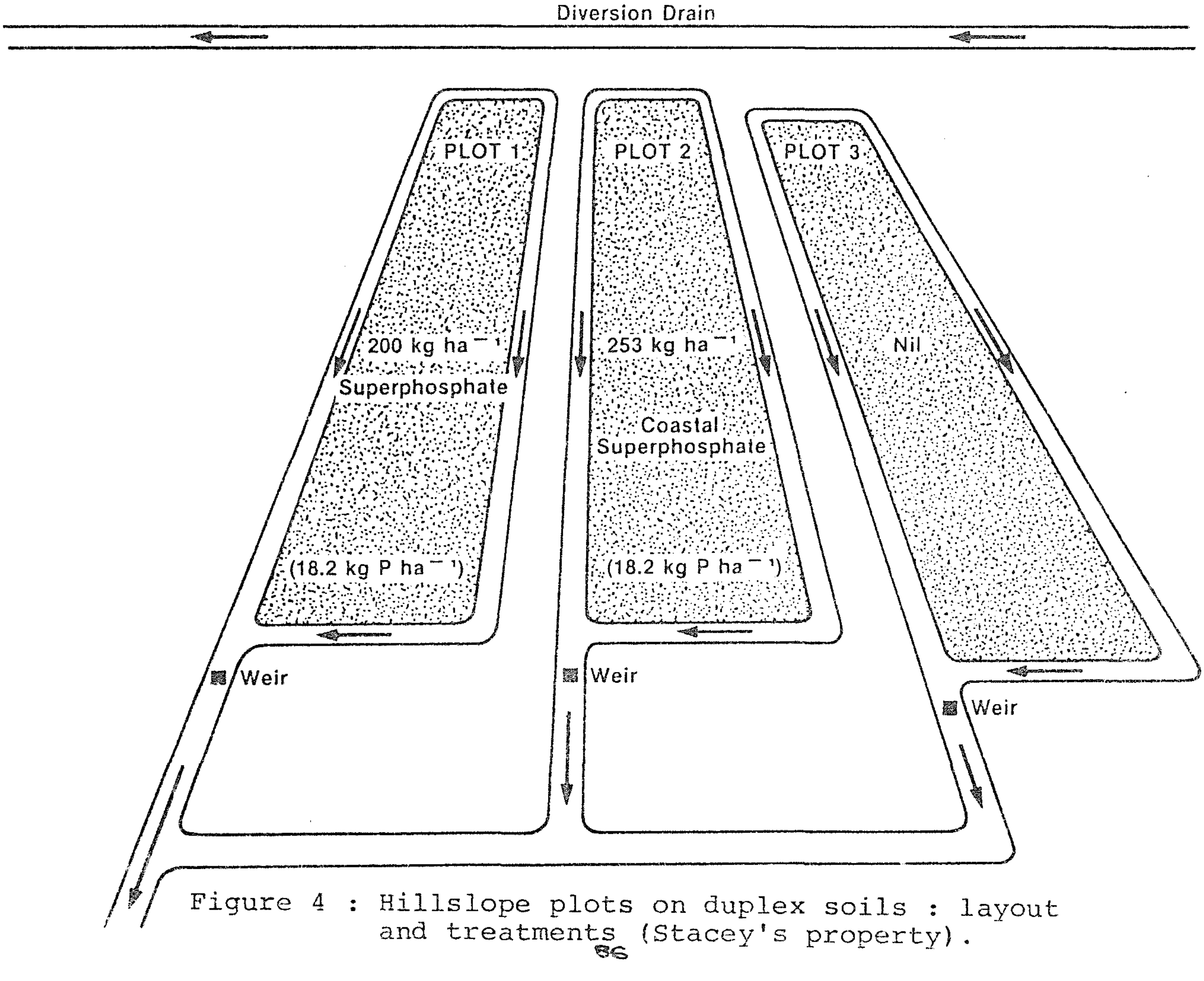

Figure 4 : Hillslope plots on duplex soils : layout and treatments (Stacey's property).

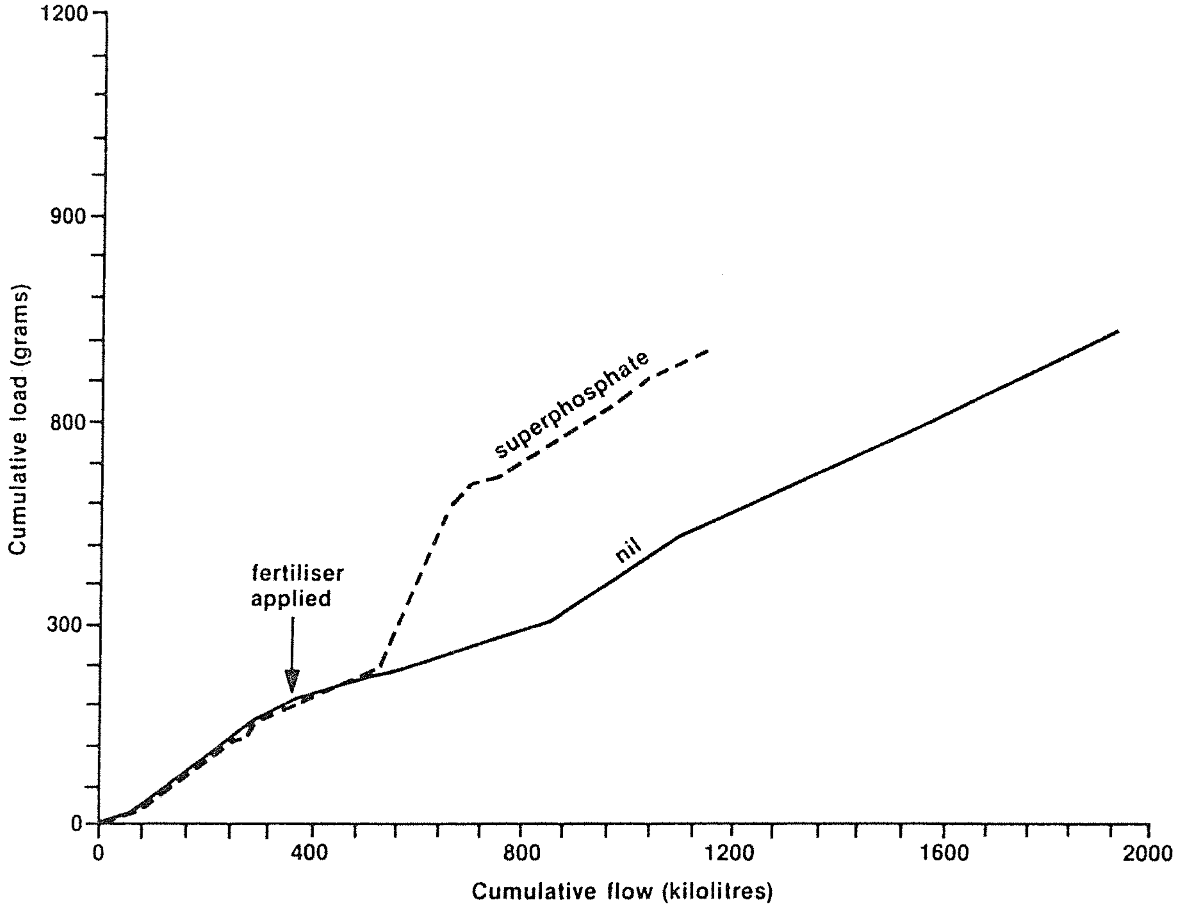

Figure 5 : Cumulative phosphorus load versus cumulative flow for superphosphate and nil treatments on duplex soils.

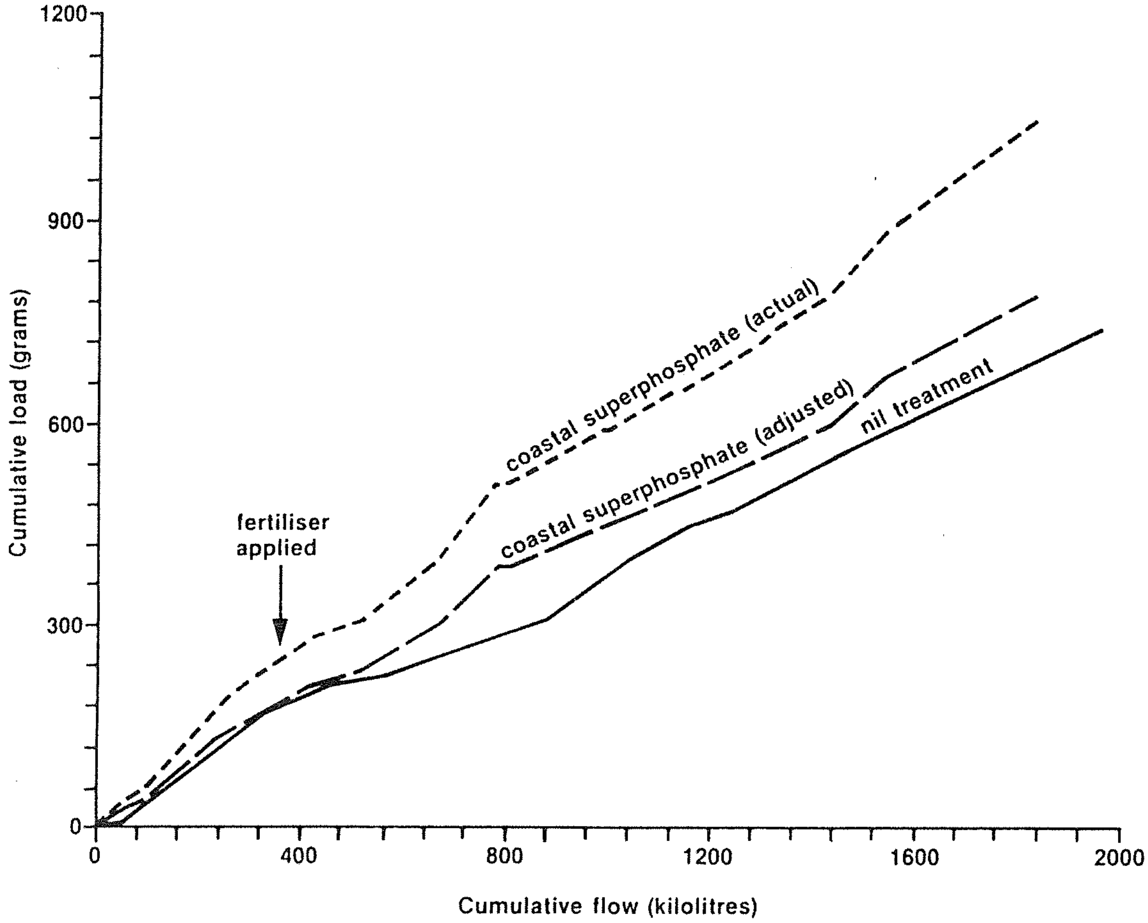

Figure 6 : Cumulative phosphorus load versus cumulative flow for coastal superphosphate and nil treatments on duplex soils.

GROUNDWATER SURVEY - DRAINAGE RESPONSE

ERIC BETTENAY*, MAURICE HEIGHT* and DENIS HURLE+

*CSIRO Division of Groundwater Research
+Denis Hurle and Associates

INTRODUCTION

Movement of phosphorus to the Peel-Harvey system via regional groundwater flow and via base of flow to drains is one part of a story. It needs to be integrated with surface, and near-surface, flows (Nick Schofield), and storage and release of P from surface and subsurface soil horizons (Gerry Ritchie).

In this paper we attempt to summarise the current state of knowledge on the importance of groundwaters. Both published and unpublished works have been drawn on, and we are grateful to those who have allowed us to quote their as yet unpublished data. Much data has been collected from recently installed wells. This data, which generally covers a period of less than one year is provisional, and has not been rigorously checked or subject to detailed examination.

REGIONAL GROUNDWATER

1. Water Movement

- Black and Rosher (1980) looked at an area to the east and north-east of the Peel-Harvey system. Gradients are similar to surface gradients, and flatten towards the estuaries. Gradients average about 1:1000 with a saturated hydraulic conductivity K_s of $5m^3/day/m^2$ (5 m day $^{-1}$) estimated. They estimated flows direct to the estuary and showed that about 1% of P input may come from groundwaters.

- Alan Deeney (GSWA; private communication) indicates an overall groundwater slope of 1:800, and a K_s of 5-10 m day^{-1} for aquifers in this area generally. Movement is to the west to Peel Inlet, and to the north-west towards Harvey Estuary.

- Iain Cameron (Murdoch University; private communication) has measured K_s in packed laboratory columns, for two deep sand profiles of the Bassendean Association, and finds:

Jandakot sand, 0.20 cm, K_s = 9.6 m day^{-1} rising to 24.4 m day^{-1} by 50 cm.

Gavin sand 0.20 cm, K_s 7.8 m day^{-1} rising to 33.3 m day^{-1} by 50 cm.

- For Merredith drain catchment in the Bassendean Association (see Fig 1), groundwater gradients, based on swamp heights which are an expression of the groundwater surface, are about 1:1500 with a fall to the north-west to the Harvey Estuary. Again the groundwater surface approximates the ground surface. Using a K_s of 50 m day^{-1} (unpublished CSIRO data for similar sands in the Gnangara Mound), the calculated general flow rate is 0.1 m day^{-1}. It would thus take 250-300 years for groundwaters to move from near the divide south of Riverdale Road to the Merredith drain gauge site at Johnston Road (approximately 10 km).

2. P levels

- Black and Rosher used an average figure for total P of 0.48 mgL^{-1} for groundwater in bores east and north-east of the estuary.

- Deeney more recently estimates an average figure of about 0.1 mgL^{-1} for the Peel-Harvey area.

- In waters from a grid of bores, from the scarp near Cookernup to the Harvey River Drain, CSIRO has measured ortho-P levels from 0.0-0.27 mgL^{-1}. These are within the range generally encountered in surface drains for Coolup, Dardanup and Wellesley soils.

- Near the groundwater surface in Bassendean sands, P levels as high as 26 mgL^{-1} have been encountered, but at depth levels fall to very much lower values (see later).

3. Conclusions

- It would seem that the Black and Rosher estimates for total P inputs to the estuaries via groundwater are of the right order. Their estimates of P concentrations may be generally high. Both P concentrations and K_s may be higher for Bassendean sands, but in the Merredith drain area gradients are not as steep.

- By contrast surface flow, or flow via open drains may be very rapid. It would take about 0.2 days for water to travel the 10 km, from near the Merredith drain divide to the Johnston Road gauge site, in a straight drain (say 0.5 days via the present Merredith drain).

- Merredith drain has a permanent flow fed by groundwater base flows. Flow rates, both as groundwater or surface flow, will be faster adjacent to sinks - particularly drains - due to the steeper gradients developed.

- Losses from Coolup types will be largely via surface or near surface flows (see Nick Schofield).

DETAILED GROUNDWATER STUDIES

Detailed groundwater studies are being carried out at Eastcotts (80 m grid of wells) remote from a major drain, and at Talbots (100 m grid of wells) adjacent to Merredith drain. Both sites are within the Bassendean association. Only the Talbots data has been analysed to date.

1. Water Movement

- A grid of fully slotted wells was inserted into the top ± 1 m of the watertable at the end of autumn. Groundwater contours have been generated from periodic water table measurements.
- There is a general flow direction from the south-east to the north-west. This is the same direction as the regional flow, but flow rates to drains are faster due to greater gradients (up to 4 m day^{-1} compared to 0.1 m day^{-1} for regional flow).
- Figure 1 shows groundwater contours prior to the winter rains (25 May 1983), and Figure 2 shows groundwater contours at a maximum after rains (7 September 1983).
- There is a close correlation between surface contours and groundwater contours.
- Groundwater levels rise between approximately 1 to 2 m with winter rains. The greatest rises are under the small dunes, which are also the areas remote from drains.
- Water levels rise to above the surface in some low lying areas, when water would move to the drains via surface flow.
- There is no apparent difference in groundwater response to rain between areas adjacent to either the north or south paddock drains.
- Perennial flows in Merredith drain indicate a groundwater input. The north and south paddock drains are seasonal. Surface flows contribute at times although the drain hydrographs are not as peaked (spikey) as those for drains in Coolup type soils (see Nich Schofield).

2. P levels

- P concentrations are measured in water entering recently pumped wells and so are considered to be a composite of water to the slotted depth.
- Concentrations rise in some wells as water levels rise. Those wells which rise to, or near the surface in winter generally have higher P concentrations than those in which the water table is deeper (see Fig 3).

- Increased P concentrations with time does not necessarily mean that concentrations at the surface are the highest. There may be a bulge profile as reported last year in Joel tube wells (see Fig 4).
- P concentrations in, on and under the coffee rock are low.
- Visual inspection of P contour data (see Fig 5) shows that obvious hot spots stay pretty much in place. It is unlikely that P applications to the south paddock drain have affected the north drain.

3. Conclusions

- Water levels rise to, or above, the surface in winter thus generating surface flow. There are large spatial differences in P concentrations, both between sites and with depth.
- Hot spots stay in place, and areas remote from drains are not much affected.
- The area adjacent to Merredith drain has low P concentrations, but there are swamp soils with a higher clay content near the surface.
- Drains may have an effect, in removing P, of up to 25 m on either side. This would not show up well on the current grid.
- Increased concentrations in groundwaters as wells rise may result from waters rising into zones where larger amounts of P are stored as organic P, or as mineral P in the unsaturated zone.
- If P additions are reduced then areas close to drains should be depleted of P. Removal of P from hot spots remote from drains will take much longer. This should mean that drains will flow at a reduced P level once the excess soil store is removed from near drains.

MODELLING

The groundwater levels at Talbots will be modelled numerically to match the observed levels so that groundwater flow rates can be calculated for use in a solute transport model. An additional component needed for a solute transport model is the sorption characteristics of the soils.

FUTURE REQUIREMENTS

- Better characterisation of aquifer materials - since we are using Gnangara K_s - by means of pump tests with nests of observation wells.
- Determine influence of coffee rock hard pan on water movement and P movement.

- Install further wells to determine total P storage in groundwater at depth.
- Install further tube wells to determine shape of P profile above hardpan (? Bulge profile).
- Obtain better idea of movement of groundwater to drains by means of more detailed grids of wells.
- Determine flow rates in drains.
- Further analysis of existing data, and testing model against data.
- Correlate with other groundwater models, and integrate with P absorption - desorption models.

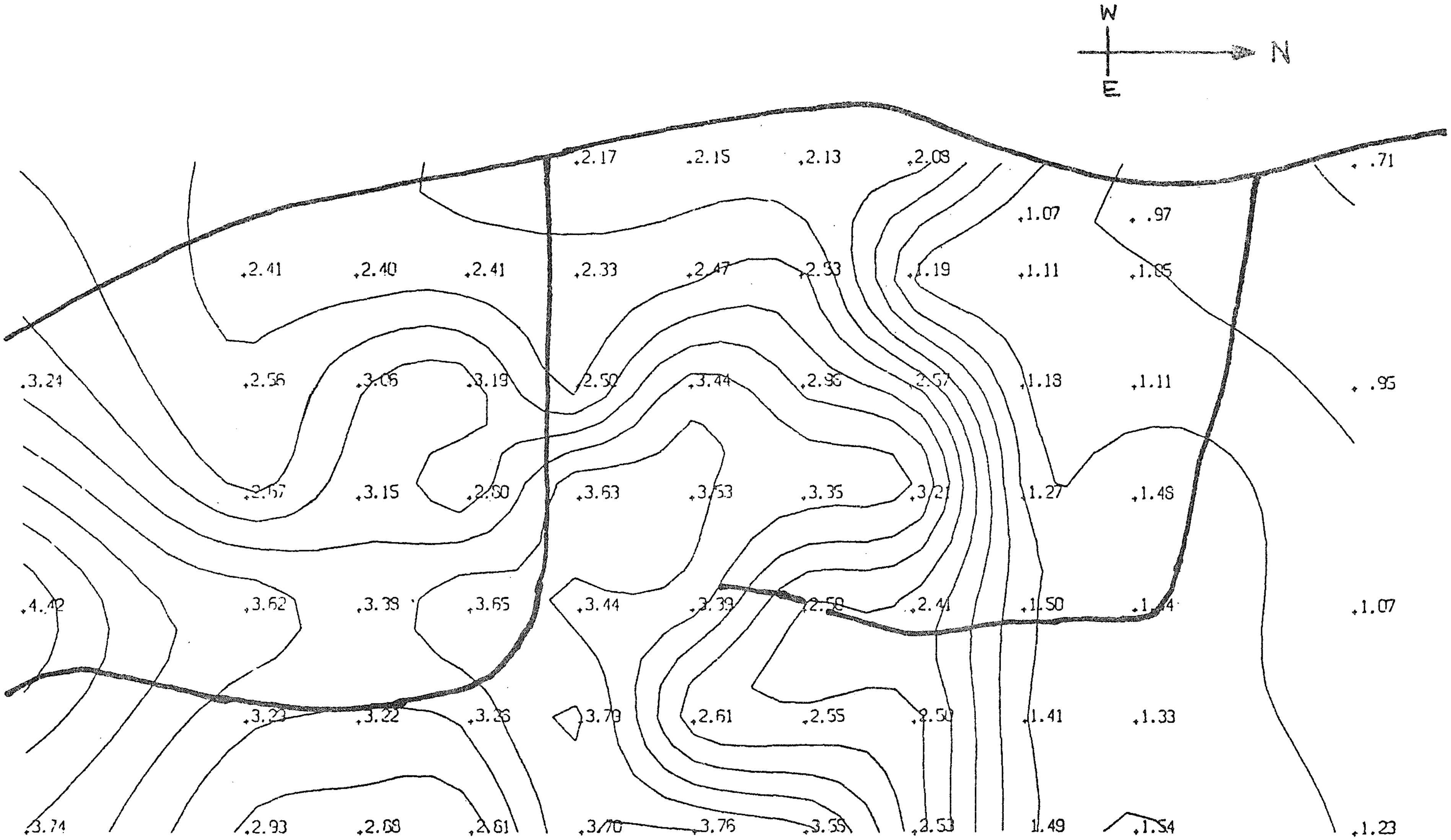

FIGURE 1: Relative levels of groundwater - Talbots
25/05/83, 0.25m contours.

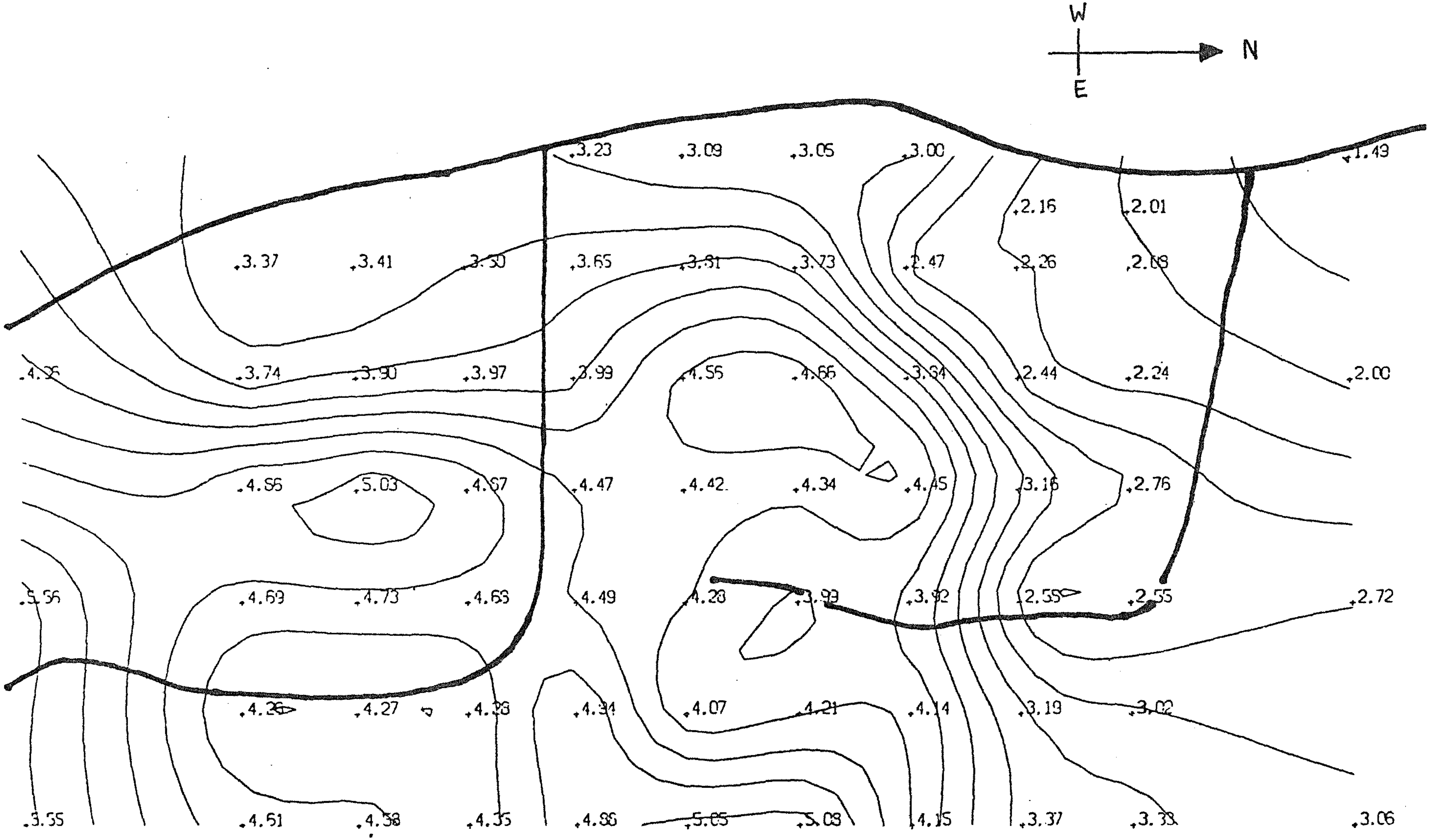

FIGURE 2: Relative levels of groundwater - Talbots 07/09/83, 0.25m contours.

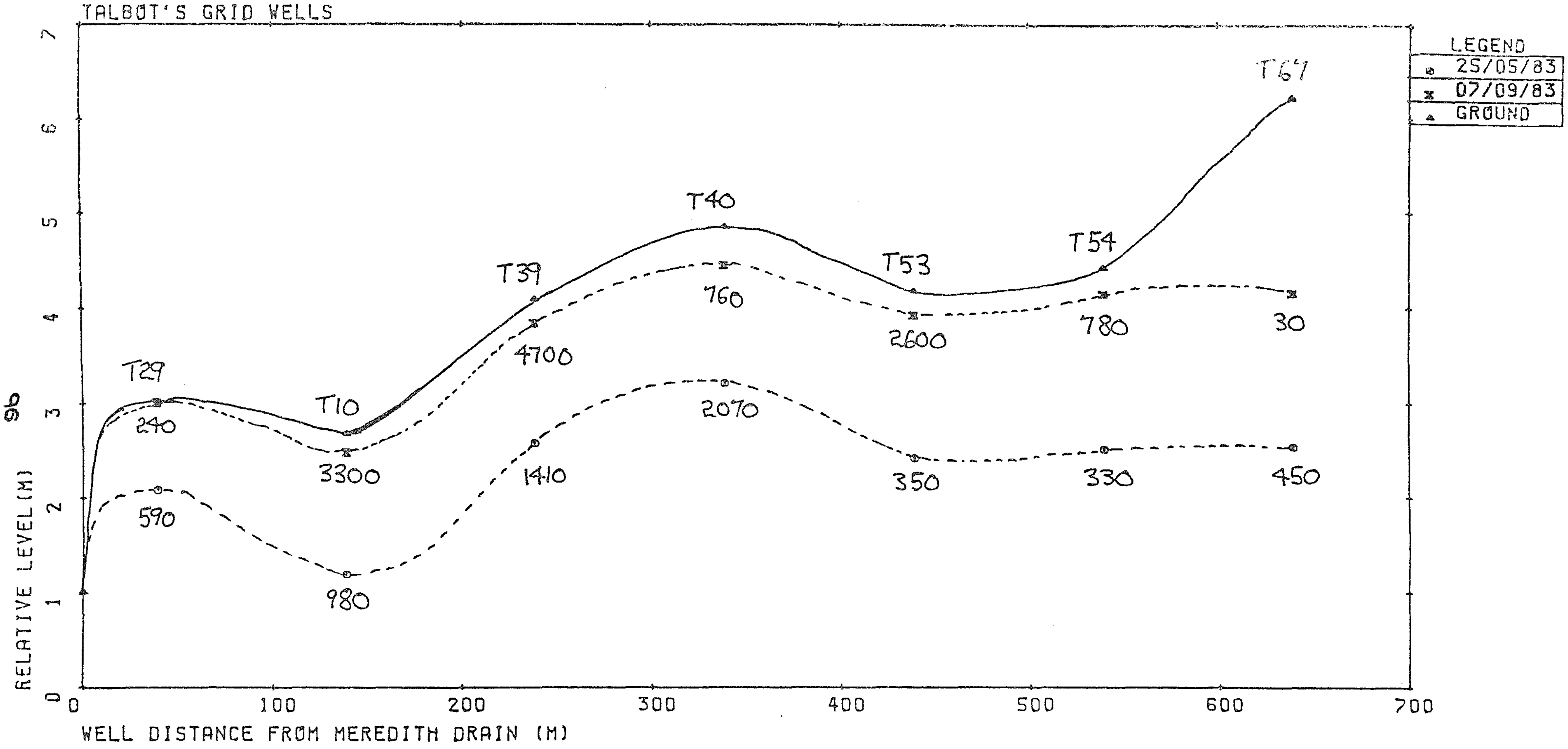

FIGURE 3: Relative heights of groundwater on two dates at Talbots.

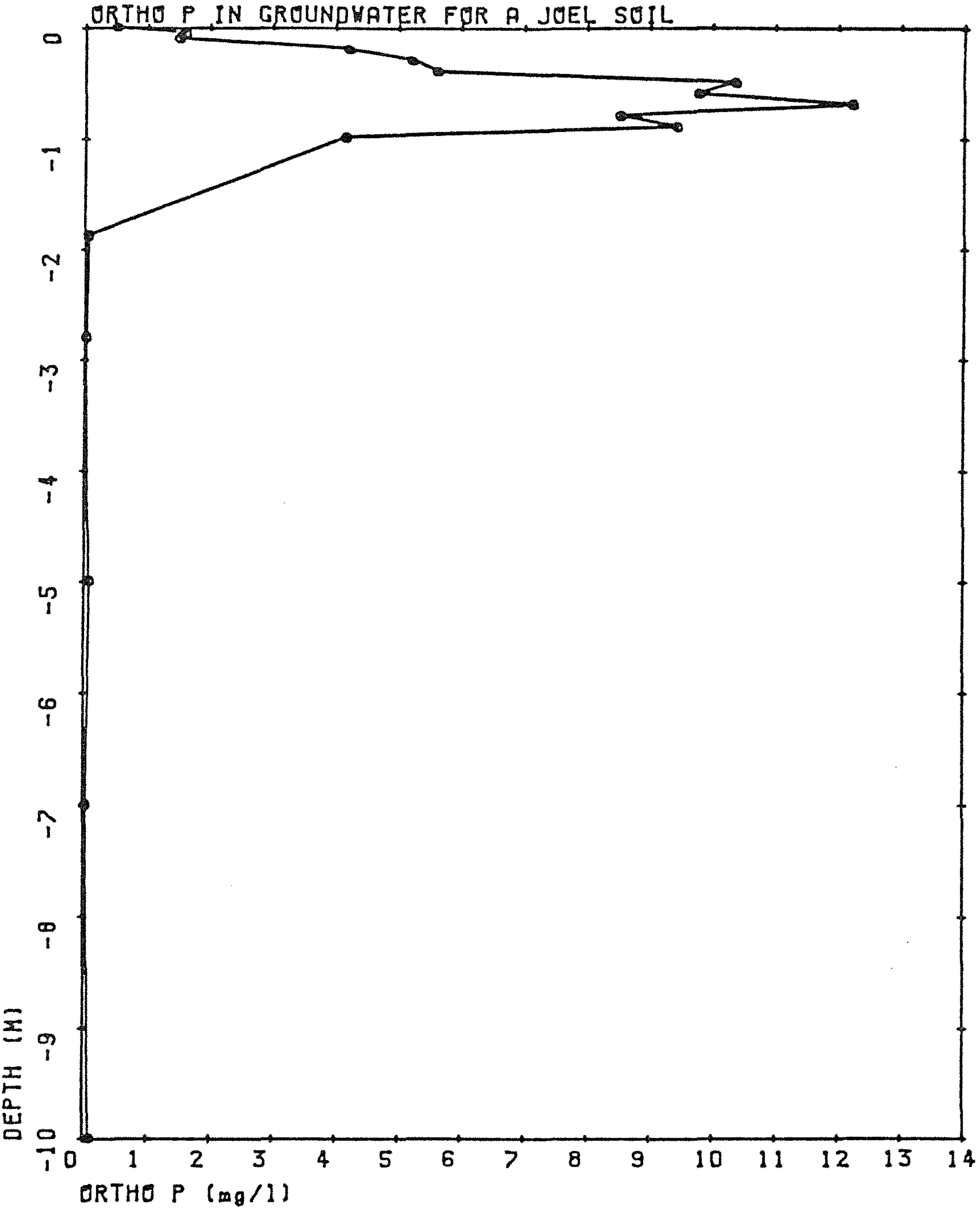

FIGURE 4: Ortho P in groundwater for a Joel soil

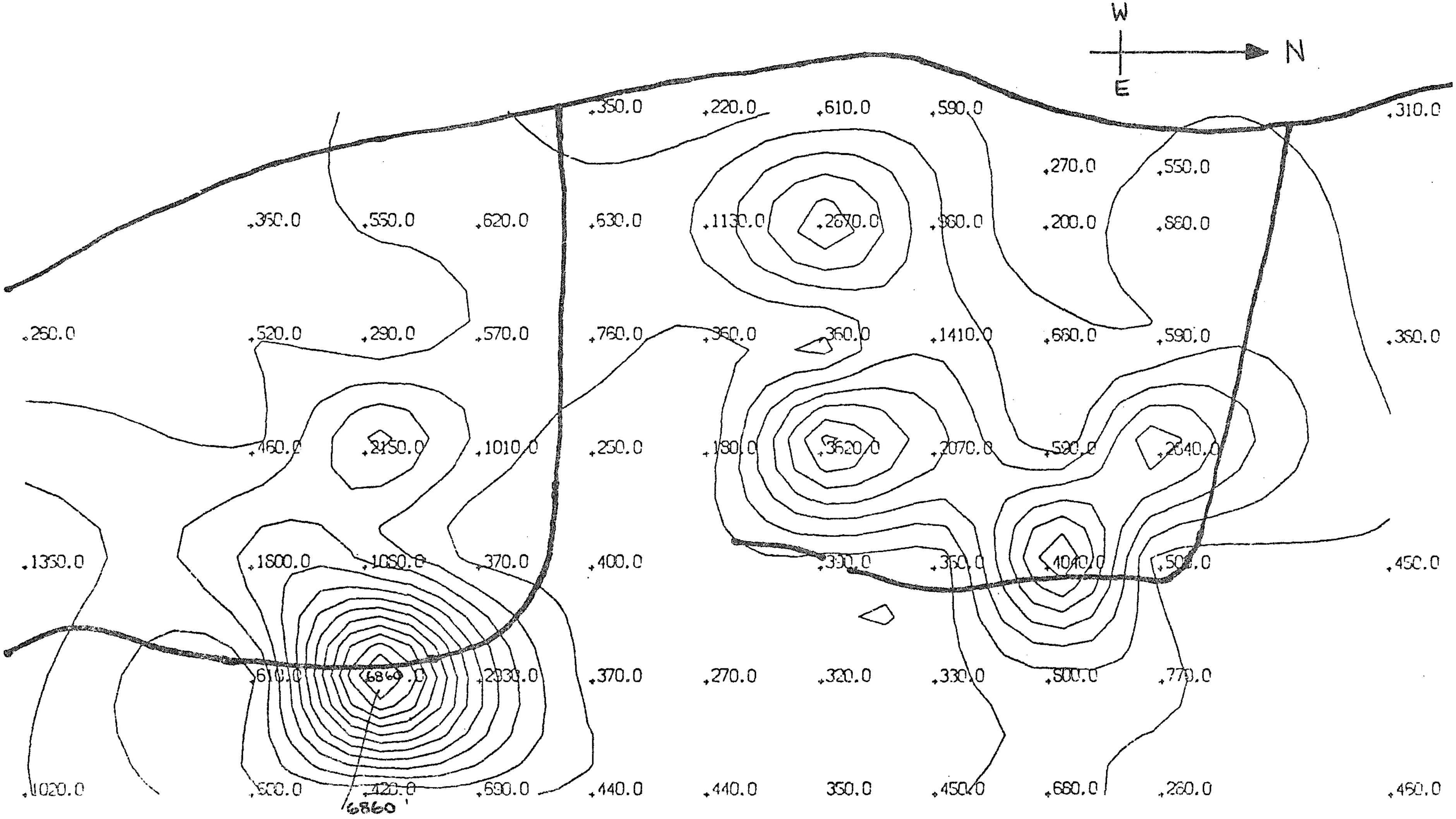

FIGURE 5: P concentrations of groundwater -
Talbots 25/05/83, 500 ug/l contours.

FERTILIZER MANAGEMENT - SUMMARY

by
P B Birch

What the fertilizer management option aims to achieve is maintenance of present agricultural production whilst minimising losses of P to drainage.

This situation will exist when pools of P in the soil have built up by fertilization to a level which just maintains present production. The only fertilizer which then needs to be added is that required to replace product and leaching losses. No further nett addition to the surface soil pools need take place.

Many farmers appear to have inadvertantly gone beyond this point by applying about 18kgP/ha (1 bag/acre) year after year and have continued to build up soil levels well beyond those needed, and in the process, have caused unnecessarily high losses to drainage and to unavailable soil pools.

In order to determine how much fertilizer use can be reduced and still maintain production without further adding to the surface soil pools we need a good knowledge of the overall chemistry of phosphorus in the soil and patterns of plant growth. Gerry Ritchie and co-workers have shown us how phosphorus in soils can be divided into four main pools and that these pools tend to be in equilibrium with each other. The size and nature of these phosphorus pools and the fluxes between the pools depends on numerous soil, environmental and management factors as has been outlined. Inputs of phosphorus to the system will favour an equilibrium shift towards the solid phase (as occurs with excessive fertilization) whilst outputs (leaching and product removal) shift the equilibrium to the liquid phase.

In the coastal plain system we have a wet winter and spring when plant growth takes place and when P is removed from the solution phase into plants or by leaching. During the long hot summer and autumn the solution phase can re-equilibrate with the solid phases, provided the total soil P pool is relatively large (as appears to be the case on many farms).

Within this scenario, John Yeates and David Deeley have looked at the residual value of fertilizers and the nature of yield response curves. From this they estimate that the present average application rate of superphosphate could be reduced by about 40% and still maintain production with no further nett additions to the surface soil P pools. This would lead to a 40% reduction in leaching losses. A further potential reduction of 20% (total 60%) is possible by using appropriate slow-release fertilizers. This is because these fertilizers add P into less available pools, reducing the rate of release enabling more P to go into plants and less into leaching.

These findings have been supported by those of Nick Schofield and Eric Bettenay and Collaboraters. Paddocks which are near or possibly slightly above maintenance P levels lose about 30-40% less P to drainage than those which receive an unnecessary dressing of phosphate at current rates applied by farmers. This work also reconfirmed the importance of soil type for P losses (sandy soils lose most).

Another important factor appears to be drainage density. About 99% of P enters the estuary via saturated overland flow or near sub-surface drainage into agricultural drains. This means the more drains per unit area we have, the greater the proportion of leached P that could be transported into waterways and ultimately the estuary.

Obviously these findings are provisional - results not yet fully processed and for many experiments we only have one year's data - and there can be big variations from year to year.

Further work is needed in several areas as has already been outlined. The most important ones include

(1) Better knowledge of residual values of fertilizers and yield response curves.

(2) Further development of models which predict P losses in the various soil systems

(3) Longer term studies of the paired catchment experiments and the movement of P in shallow groundwater.

(4) Better characterisation of aquifer materials by means of pump tests.

Overall, it seems that if we are to maintain the present level of agricultural productivity in the coastal plain with its leaching sands and extensive network of drains then we can only expect an average reduction in drainage losses of about 30-40% (possibly up to 60%) with the wise use of fertilizers. Any newly developed fertilizers will have to be easy to spread, economical and have a higher ratio of S:P than ordinary superphosphate.

Further reductions in P runoff would be possible if productivity was reduced below maximum. For example, if productivity was reduced to 70% of maximum, use of P could be reduced by about 80%, with a similar reduction in runoff losses. A detailed economic analysis of this type of approach is required to determine how the extra benefits of further reductions in P runoff compare with the extra costs of reduced agricultural production.

CHANGING FARMER'S ATTITUDES AND PRACTICES

Bill Russell
Officer-In-Charge
Department of Agriculture, Harvey

Over the past twelve months, farmers in southern catchment areas have been subjected to an almost barrage of information on what has gone wrong with the estuary and what probably has to be done to correct it. It has been made clear that farmer practices are the major cause of the problem, even if the farmers are not being blamed for the state of the estuary. The majority of farmers accept this but a few are still disputing the facts as presented by the study group.

There is a general recognition that part of the solution will be for farmers to alter their fertiliser practices, but there is as yet little sign of a large scale change in attitude. It is possible that the non-farming community has been led to expect a more rapid improvement in the condition of the estuary as a result of changes in farmer fertiliser practices than will in fact be possible.

Three reasons for slow adoption of new fertiliser practices by farmers are:

1. It is unusual for a large number of farmers to make major changes in longstanding practices in a short time, even when the change can be demonstrated to be beneficial. It is more likely that they would try the new recommendations on part of the farm for a year or two before adopting them for the rest of the farm.

2. For many farmers, the changes proposed were not physically possible in that the alternative fertilisers suggested had to be applied by special machines at an extremely difficult time of the year.

3. Continuing media reports about farmers needing to change fertiliser practices to solve the problems of the estuary, the inference being that farmers will have to change to help solve somebody else's problem and that the recommendations being made are at least partially politically influenced.

Slow-Release Fertilisers

Coastal Super and Coastal Super:Potash 3:2 were the only 'slow-release' fertilisers used by farmers this year. The 87 farmers who replied to the survey used a total of 317 t Coastal Super and 249 t Coastal Super:Potash 3:2. Of this, 226 t of Coastal Super and 220 T Coastal Super:Potash 3:2 were used by farmers on Bassendean Sands. Overall, about 70% of farmers on Bassendean Sands used a 'slow-release' fertiliser on at least part of the property. This is a rapid adoption of a new fertiliser. Very little 'slow-release' fertiliser was used by farmers on other soils.

Adoption of Recommendations

Farmers whose properties were soil sampled last summer were surveyed for their response to the recommendations made on the basis of the soil test. Forty per cent of the farmers said that they followed the recommendations completely, 9% thought that they were too low and 16% thought that they were too high.

The major reasons for not following the recommendations were:

- finance
- convenience
- credibility

1. Finance - about 14% of farmers reported that they thought the recommendations were too expensive to follow completely. I suspect that this related mainly to the amount of potassium recommended.

2. Convenience - about 20% of farmers gave inconvenience as the major reason for not adopting the recommendations. There were probably two main aspects to this:

   (a) gypsum has to be spread in winter using special spreaders.

   (b) on many farms, no two paddocks had the same soil test for phosphorus and potassium. This meant that each paddock had its own recommendation. While the 'next best' option usually overcame most of the problems, some farmers didn't like the idea of having to go over their paddocks two or three times with different fertilisers. In some cases, a small area of the farm had a different recommendation from the rest and this was usually ignored.

In some cases farmers who normally buy their fertiliser from Kwinana were not prepared to go to Picton to pick up a bit of Coastal Super for an area of deep sand on the farm. This will probably be a continuing problem.

3. Credibility - about 9% of farmers thought that the recommendations were too low to give good results - particularly on hay paddocks. All we can hope for in these cases is that the farmers will try the recommendation on at least part of the farm to satisfy themselves that they don't need to keep applying the phosphorus rates they have been used to.

The results simply reinforce what we already knew - until we get a sulphur fertiliser which can be applied before mid winter, there is little chance of getting a substantial reduction in the amount of phosphorus applied. Existing fertilisers are an extremely convenient way of applying three essential plant nutrients - phosphorus, potassium and sulphur. Until the alternatives can be demonstrated to be at least as convenient, and no more expensive, there is little incentive for farmers to change.

The newly developed fertiliser AS3 looks promising but there is still no announcement that it will be commercially available next year, it will probably cost a lot more per tonne than existing fertilisers and it doesn't contain any potassium. As with Coastal Super this year, the questions are:

- will there be sufficient demand for AS3 to justify producing the full range of mixes which farmers have become accustomed to?

- will they be available from Picton as well as Kwinana?

These are questions only the companies can answer but they have a bearing on the likely farmer acceptance of a new fertiliser. There could be a case for some Government assistance to reduce the on-farm cost of AS3 to a more attractive level.

An alternative would be to supply gypsum in a more attractive form so that it could be spread with existing machinery at a more convenient time of year. There appear to be substantial technical problems to overcome before this option becomes feasible.

A 'spreadable' gypsum is a very attractive proposition; 50% of farmers indicated that they would use it as a source of sulphur if the cost could be held down to about $4.50/ha. This is about three times the current cost of Kwinana gypsum and compares with $22.00/ha to use superphosphate as a source of sulphur.

About 20% would use AS3 and 3% would continue to use super, even if soil test showed that phosphorus was not required in the short term. In the long run, phosphorus will be required on these soils but there is no hope of running down existing high soil P levels until we get a better sulphur fertiliser.

The problem we have is that we are dealing with a relatively small market. We really cannot justify producing a big range of fertilisers and still expect the cost to be reasonable. It may be that we have to settle on a fertiliser which supplies P, K and S and accept that one or more of the nutrients will be over-supplied on some farms in some years.

Carrot or Stick

The issue of legislation to force farmers to adopt 'better' fertiliser practices has been raised and has to be faced.

Farmers, like any other group in the community, do not like the idea of being forced to change established practices especially to solve somebody else's problem. The carrot is much better than the stick.

Hopefully, we can convince the majority of farmers that it is in their own best financial interests to adopt the new fertilisers being produced. Coastal Super was quite widely used on the Bassendean Sands this year, in spite of the higher cost and reported handling problems.

Until we have settled on a 'best bet' P and S fertiliser for catchment soils, have demonstrated that its use will reduce P run-off while maintaining production and have given farmers the opportunity to use it voluntarily, I don't believe that it would be fair to consider the use of legislation to enforce its adoption. The cost of legislation to enforce the use of soil testing and new fertilisers would be high, both in severely damaging relations with farmers and in the financial cost of collecting and analysing the samples and getting the recommendations back to farmers.

To ensure that the soil samples were collected properly, they would have to be collected by the Government and arrangements made to have them analysed. Even allowing for the fact that an area probably only has to be sampled every 2 or 3 years, there are a lot of farms in the Peel Inlet - Harvey Estuary catchment and only a few months of the year in which the samples can be collected. If farmers collect the samples themselves, there is the risk that the most infertile area on the farm - or on somebody else's farm - will be sampled. A recommendation made on the basis of this type of sample would be meaningless.

In the long run, legislation may have to be considered to bring about the required changes. Legislation already exists in soil and water conservation areas which would restrict what a farmer can do on his property if it can be shown that the community as a whole would benefit from the restrictions. With the current concern over land degredation, the possibility of placing restrictions on what can be done on a farm has been accepted. The community is obviously being affected by the problems in Peel Inlet - Harvey Estuary and farmers have a big part to play in solving the problem.

Farmers have a lot to gain from the work being done on local soils and it will probably be in their own financial interests to adopt the new fertilisers. I hope we are a long way off even thinking about the use of legislation.

The Potential of Natural and Artificial Wetlands for Phosphorus Removal from the Harvey Catchment

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INTRODUCTION

The major aim of this study was to assess various management options involving wetland filters. These included:

1. Fringing agricultural drains with wetland plants.
2. The use of artificial wetlands at the outlet of
    (i) swamps; and
    (ii) major drains.
3. The use of artificial wetlands at point sources.
4. The diversion of runoff through existing wetlands.

These options can be divided into two types - those employing artificial wetlands to remove phosphorus from agricultural areas (options 1, 2 (ii) and 3) and those involving natural wetlands (options 2 (i) and 4). These two categories will be discussed in turn.

ARTIFICIAL WETLANDS IN AGRICULTURAL AREAS

To assess these management options the design of the artificial wetlands required for each option was drafted, investigations were made to determine phosphorus uptake of experimental wetlands, and data collected by others in the Catchment Studies Group on flow rates and phosphorus concentrations of water in the drainage system and on point sources was used.

Design

In the first option aquatic plants, for example sedges, were to be planted along the border of the drainage canal thus intercepting surface and sub-surface flow into the drain (Fig. 1 below).

The depth of sand beneath the plants was to be 0.5 m deep so that all water flowing across the coffee rock layer would be intercepted by the root system of the wetland plants.

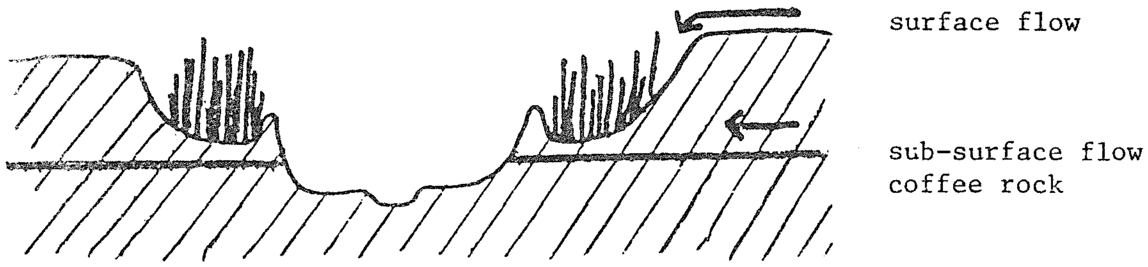

Fig. 1: Design for wetland filter along agricultural drains

The second option, to use artificial wetlands at the outlet of swamps and major drains, would require that water be spread in a shallow film (approximately 0.3 m deep) over a wide area of artificial wetland, as this provides the best environmental conditions for phosphorus uptake.

In the third option, point source effluent would be passed into a bed of wetland plants. This reservoir could have a pump to maintain optimal flow rates and water depth in the wetland filter.

Investigations

Experiments were carried out to examine the effect of flow rate on the ability of an aquatic plant and two substrates to remove phosphorus from water. The plant used was Lepidosperma longitudinale (or Common Sword Sedge). This plant was found to have a high productivity and phosphorus content in its natural environment. The substrates used were peat collected from one of the wetlands in the catchment and Bassendean sand collected adjacent to a drainage canal.

In these experiments four treatments, Lepidosperma/peat, Lepidosperma/sand, peat only and sand only, were placed into 48 ℓ containers. Water of known volume and phosphorus concentration was added to these containers and a similar volume was siphoned from the bottom of the container and assayed for total phosphorus.

INFLOW			OUTFLOW			
FLOW RATE L.M^{-2}.DAY	P CONCENTRATION MG.L^{-1}	P LOADING MG.M^{-2}.DAY	% REDUCTION LP*	LS	P	S
2.4	20	42	91	92	50	59
12.0	11-20	120-150	DECREASED OVER EXPERIMENT			

*LP = LEPIDOSPERMA/PEAT LS = LEPIDOSPERMA/SAND P = PEAT S = SAND

Fig. 2: Experimental data.

The results of the experiments are shown in the table above. At a flow rate equivalent to 2.4 ℓ m^{-2} day^{-} treatments containing Lepidosperma could reduce a phosphorus concentration of 20 mg ℓ^{-1} by 91-92%. Substrate only treatments were less effective. Flow rates of 12 ℓ m^{-2} day were too high for efficient nutrient removal by the experimental wetlands and rates of reduction decreased over the period of the experiment.

Assessment

Option 1: Fringing agricultural drains with wetland plants.

Humphries and Croft calculated the volume of flow from various catchment areas under different rainfall events.

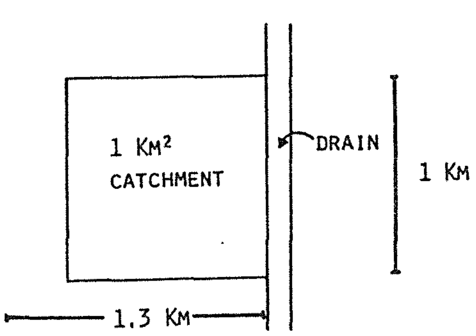

Fig. 3: 1km^2 catchment.

For example, consider a 1 km^2 catchment bordered by 1 km of drain (Fig. 3). It can be calculated that after 10 mm of rain 3100 ℓ of water will flow through into each metre of drain. If the drain were lined with a 2 m strip of wetland plants the loading rate would be 1550 ℓ m^{-2} day^{-1} as compared to 2.4 ℓ m^{-2} found to be satisfactory in the experiments. To achieve a loading comparable to that used in the experiment the wetland filter would need to be 1.3 km wide!

Phosphorus concentrations in the catchment were much lower than those of the experiment, 0.25-4.5 mg $ℓ^{-1}$ compared to 11-20 mg $ℓ^{-1}$ in the experiment. However, due to high flow rates phosphorus loadings were 70 times greater in the field than in the experiment. Hence both phosphorus and hydraulic loading on the drain verge suggest the use of wetland filters would be unsuccessful.

Option 2 (ii): The use of artificial wetlands at the outlet of major drains.

Calculations made by Croft, using the experimental wetland filter flow rate of 2.4 ℓ m^{-2} day^{-1}, estimate that treatment of the Harvey Main Drain with an assumed flow of 200,000 ML over a 15 week period would require a 794 km^2 wetland filter; almost the area of the Pinjarra-Waroona-Harvey coastal plain drainage area. Treatment of a smaller drain with a particularly high phosphorus loading, e.g. the Meredith Drain, would require an 18 km^2 wetland filter at a flow rate of 43 ML day^{-1}. Although the phosphorus concentration of the drainage water is much lower than that of the experimental solutions, at these high flow rates this option does not appear feasible.

Option 3: The use of artificial wetlands at point sources.

Information on point sources collected by Croft suggests that there are few areas which might be treated by wetland filters.

Piggery effluent was recommended for treatment, pigs producing an effluent volume of 3 m^3 $pig^{-1} yr^{-1}$ or 2.9 kg P pig^{-1} yr^{-1}. Calculations using the experimental data suggest a piggery containing 2000 pigs would require a wetland filter 0.7 ha in area. Implementation of a wetland filter would require further work on design detail and the efficiency of phosphorus retention. The significance of point sources as a source of phosphorus on a catchment basis is not known. If point sources are not found to be a significant contributor then management of them is less important.

NATURAL WETLANDS

The wetlands studied in the Harvey Catchment were in the Meredith Drain subcatchment. They are characterised by deep lake basins (2 m deep) surrounded by a band of wetland vegetation. Neither the depth of these lakes or the underlying anaerobic sediments is conducive to phosphorus removal from the water column and hence any nutrient removal would predominantly take place in the peripheral band of vegetation.

In farmland areas much of this vegetation has been cleared, and the lakes act as collection sites for phosphorus-rich water. A comparison of phosphorus loadings in farmland and reserves (where fringing vegetation remains intact) gave mean phosphorus concentrations of 5.2 mg ℓ^{-1} for farmland and 0.1 mg ℓ^{-1} for reserves.

During winter many of these swamps overflow releasing phosphorus-rich water to the drainage system. This may provide a significant source of phosphorus to the estuary and a number of options to reduce this input have been suggested:

(i) reintroduce the natural fringing vegetation;

(ii) introduce an artificial wetland at the site of outflow (option 2 (i));

(iii) reduce outflow of the swamps.

Assessment

(i) This is a long-term option. Replacement of fringing vegetation would reduce flow and the amount of phosphorus entering the swamp, but the phosphorus already present in the lake water and sediments is unlikely to be substantially reduced in the next few years.

SWAMP NUMBER	MEAN LAKE AREA (HA)	FLOW RATE DURING OVERFLOW $L.DAY^{-1}$	EXPERIMENTAL FILTER FLOW RATE $L.M^{-2}.DAY^{-1}$	AREA OF WETLAND REQUIRED (HA)
1	1.5	66,820	2.4	2.8
2	10.0	463,440	2.4	19.3

Fig. 4: Area of wetland filter required to treat outflow from swamps

(ii) The area of artificial wetland required to treat the outflow of swamps can be estimated using the flow rate of the successful experimental filter. Two examples are given in Fig. 4 and in each case a wetland filter twice that of mean lake area would be required. This does not appear practical, although it must be noted that phosphorus concentrations in the swamps were lower than the experimental solutions and hence higher flow rates might be used to calculate the area of wetland filter required to treat swamp overflow.

(iii) Reducing the outflow of swamps could be achieved by physically blocking the site of overflow or increasing evapotranspiration by planting trees around and in shallow swamps. Physical blocking is unlikely to be popular with farmers who would lose land to subsequent flooding. Planting trees has been successful but this is a long-term option.

Option 4: The initial management option to direct runoff through existing wetlands does not appear feasible. Many wetlands in the catchment are located in farmland and have insufficient fringing vegetation to maintain phosphorus concentrations at acceptable levels at the present rate of runoff without further loading.

CONCLUSION

A number of management options involving wetland filters to remove phosphorus from water in the Harvey Catchment were assessed. The most promising of these was the use of wetland filters at point souces, and work on the practical aspects of implementation and an assessment of the importance of point sources as a contributor of phosphorus to the estuary is recommended. Assessment of option 2 (i) was made difficult due to differences in flow rates and phosphorus concentrations between experimental and field data. Further work to clarify the relationship between flow rate, phosphorus concentration and wetland filter efficiency is envisaged.

PROSPECTS FOR REDUCING PHOSPHATE LOSS AND IMPROVING PRODUCTIVITY ON SANDY FARMLAND USING NEUTRALISED BAUXITE RESIDUE

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Introduction

The problem for the Peel-Harvey Estuary is to reduce the input of phosphate coming from fertiliser applied to farms in the catchment. Neutralised fine bauxite residue has the capacity to greatly improve phosphate retention on sandy farmland. There is thus potential for maintaining productive nutrient inputs, while reducing output to drainage (Barrow, 1982). Neutralised residue can also improve the productivity of sands by increasing water retention and reducing water repellance.

Wagerup Alumina Refinery is best placed to supply residue to the sandy soils contributing the majority of phosphorus to Harvey Estuary. Waste gypsum (calcium sulphate) from the superphosphate industry and copperas (ferrous sulphate) from titanium dioxide manufacture both effectively neutralise alkaline bauxite residue (Barrow, 1982; Ho, unpublished). Productive use or co-disposal of wastes mitigates the need for large storages and long-term management.

Barrow (1982) and Ward (in press) have shown that productive pastures can be grown on gypsum amended bauxite residues. Large-scale field implementation can now be evaluated.

Methods

In field experiments, alkaline fine residue was mixed with 5-10% waste gypsum to reduce the pH, filtered, dried, shredded and incorporated into free draining Gavin and wet Joel series sands at between 200 and 2000 t/ha. The amended and control soils were sown with medic and sub-clover legume pasture supplied with 80 kg/ha of phosphate. In a separate experiment phosphate rates from 5 to 240 kg/ha were applied to pasture established on Gavin sand amended with 1000 t/ha of residue.

Tube wells and field lysimeters were used to check the concentrations of phosphate and other leachates draining from amended sands to which up to 270 kg/ha of phosphate had been added. No pasture was sown on the lysimeters. Average annual dressings are normally of the order of 20 kg/ha phosphate.

Residue neutralisation with copperas and the adsorption of phosphate by residue mixed with gypsum or copperas was measured in the laboratory at Murdoch University.

Costs and returns were based on commercial rates for earthmoving and agriculture. Land values could be regarded as conservative. Areas of potential treatment were considered to be the deep sands (Bassendean series) and sands over clay (Coolup series).

Productivity

On Gavin sand, legume pasture production was increased significantly in the first year with any level of residue amendment. (Figure 1, Ward, unpublished data). Increased productivity is likely to be maintained on treated soils in subsequent years while untreated sites can be expected to slip back to the 0.3 t/ha level recorded by Roberts (1966) due to soil water repellance and nodulation problems interferring with the re-establishment of legumes. On a normally wet Joel sand, addition of residue also improved yields (Figure 2, Ward unpublished data).

On Gavin and Joel sands amended with 1000 t/ha of residue, increasing phosphate addition up to 40 kg/ha P increased the dry matter yield of legume pasture. Between 40 and 240 kg/ha P, no significant change in productivity occurred.

Phosphate Retention Capacity

From the available field data, 1000 t/ha of residue reduces the percentage phosphate lost by Gavin sand at least to the level of a clay/loam soil (Table 1, Summers unpublished data; Birch, unpublished). This occurs without any export of P as agricultural produce. Studies by Ho et al (Unpublished) showed that 200 t/ha should in fact be sufficient to retain the 40 kg/ha of P required in the first year.

Residue neutralised with copperas (pH 7.8) has even higher phosphate adsorption capacity (Ho et al, unpublished). As the residual alkalinity is leached out in the field, the declining pH will favour increasing phosphorus adsorption. Appropriate annual P doses, determined by soil test, would avoid increasing P losses with time.

If the P loss rates of deep sands and sands over clay are reduced to those of the clay/loams then a 52% reduction in total P loss to the estuary would accrue (Croft, pers. comm.). Table 1 indicates that the P loss rate measured for sandy soil amended with 1000 t/ha residue is indeed similar to that for clay/loam. In practice, rates as low as 200 t/ha may suffice.

Thus phosphate losses from sandy soils amended with neutralised bauxite residue can be reduced to levels which parallel the clay/loams. This effect seems sustainable through time. Pasture productivity can be increased at the same time on the Bassendean sands. If copperas were used as the neutralising agent, another waste product would be effectively utilised.

Treatment Area and Timing

Annual fine residue production from Wagerup will be 850,000 t from 1984. Residue suited to soil amendment could be produced from 1987.

If 90% of the sandy soils in the Harvey Estuary catchment are cleared, an upper limit on the area needing residue amendment is 28,000 ha. If the supply of copperas fixes the rate of production then the 430,000 t/annum of neutralised residue produced would cover this area at 200 t/ha over 13 years. Use of gypsum as well would reduce this to 7 years. If continued growth in residue production from Wagerup parallels projected growth in the world alumina market then the available area could be treated at 1000 t/ha over 14 years if both copperas and gypsum were used for neutralisation.

Commencing 1987 between 7 and 14 years would be needed to treat the sandy soils of Harvey Estuary catchment with bauxite residue.

Costs and Returns

Costs:
Components of the cost of residue application have been divided into groups (Table 2). There is scope for sharing of the costs consistent with the perceived benefit to each participating party. These might comprise the State, residue producers and Farmers.

The key points are that average distribution and application costs are almost invariable with application rate. The average cost of residue supply translates to a fixed cost per tonne of residue.

Returns:

Given increased pasture productivity and small savings in residue storage and management, there will be increased returns from treatment of sandy soils with residue (Table 2). A value might also be put on a clean estuary.

Returns were apportioned into capital appreciation of treated land and the net present value of increased productivity over time. A figure for the increased capital value of treated land was calculated assuming that the difference in price of two soil types is proportional to the difference in productivity. Weighting the increases in production above, by area affected, yields an average capital appreciation of $431/ha over all cleared sandy soils (Table 2).

Annual returns from legume pasture were calculated assuming sheep grazing only is practised. This converts to a net present value of $810/ha for all future production, using an annual discount rate of 10%.

Total cost will depend on the area requiring treatment whereas annual cost depends on the rate of treatment. If all cleared sandy soils required treatment over 14 years the cost for production and application would range from $3.2m to $4.7m/annum with returns of $2.5m/annum. The cost for transport would be $0.9m to $4.5m depending on application rate.

Phosphate Removal from Drains

Bauxite residue has been investigated for removing phosphorus and heavy metals from waste waters directly (Miko et al, 1973). A purpose built treatment plant is feasible for removing phosphorus from high concentration sources like the Meredith Drain using bauxite residue neutralised with 7% copperas. Using all available copperas, approximately 40 tonnes of phosphorus could be removed from the Harvey Estuary inflow annually. A capital cost of $16m is estimated with annual operating costs of $2.5 m.

The neutralised, washed and phosphorus enriched residue settled from the drainage water would be even more suitable for sandy soil amendment than material produced at the refinery. It would also be centrally located in the area of need. Operation of a treatment plant would make a valuable immediate partial contribution to phosphate removal from Harvey Estuary while soil amendment was progressively undertaken.

TABLE 1.

ANNUAL PHOSPHORUS BUDGETS

Site	Soil Type	Phosphorus As P (% of applied P) P Applied	Agriculture Export	Loss to Drainage	Store
Meredith Drain*	Deep Sands	100	28	25-31	41-48
Samson Bk. N. Drain*	Clay/Loam	100	20-32	4-5	62-73
Summers † Lysimeter	Gavin Sand	100	0	55	45
Summers † Lysimeter	Gavin Sand+ 1000 t/ha Residue	100	0	4	96

* Data from Birch, 1983.

† Unpublished data of Summers

TABLE 2.

COSTS FOR SOIL AMENDMENT WITH BAUXITE RESIDUE ($/HA)

	Action	Items	Residue Rate (t/ha) 200	500	1000
COSTS	Residue Production	Neutralising Agent Recovery and loading	176	440	880
	Transport	Trucking (23 km)	448	1120	2240
	Distribution	Road Construction & Maintenance.	1080	1110	1160
		Distribution on Farms.	500	500	500
	Application	Incorporation, Agricultural costs.	320	320	320
RETURNS		Capital Appreciation*	-	-	431
		Net Present Value of increased future prodn*	-	-	810

* Estimated average value of all soil types.

Figure 1
FIRST YEAR PASTURE YIELDS
ON AMENDED GAVIN SAND
(Unpublished data of Ward)

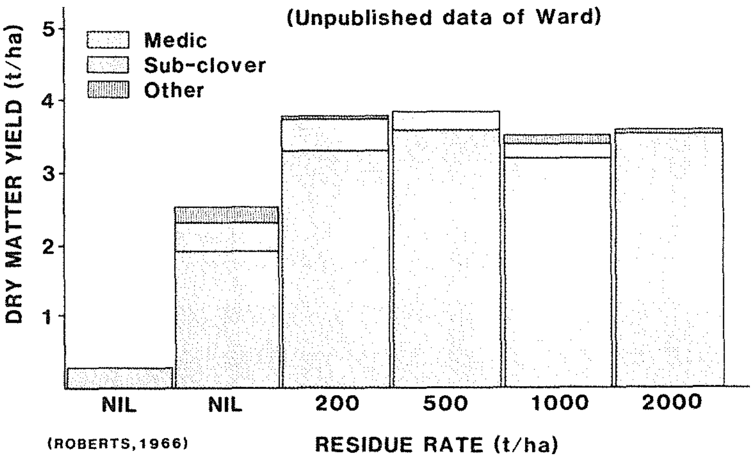
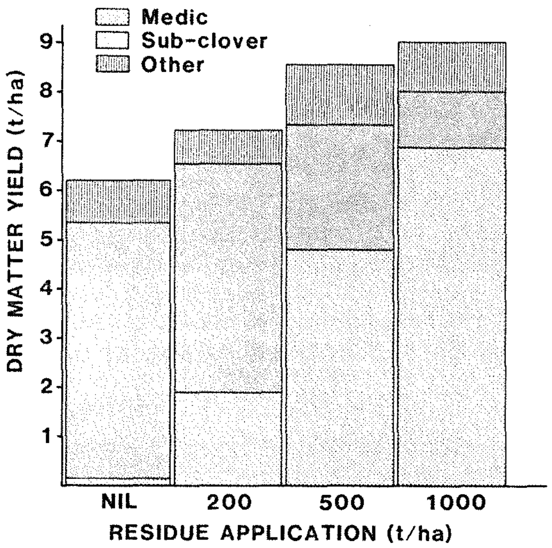


Figure 2
FIRST YEAR PASTURE YIELDS
ON AMENDED JOEL SAND
(Unpublished data of Ward)



Additional Studies

Pasture regeneration and nutrition in the second and subsequent years is being checked on Joel, Gavin and Coolup soils.

It is important that phosphate retention, leachate quality and erosion characteristics of treated farmland be checked at the field scale. This would require co-operative effort between Alcoa, the Department of Conservation and Environment, the Department of Agriculture and landholders. A proposal is being prepared for such a trial to be conducted in 1984 which will require resources from each of the above if it is to proceed.

Summary & Conclusions

The addition of neutralised bauxite residue to sandy soils can make a major contribution to controlling phosphorus loss at its source, before it enters the Harvey drainage system. Over 50% of the phosphorus load from the one in five year flow event could be accounted for by amending the Bassendean and Coolup soil types with residue. Depending on the area and rate of treatment, from 7 to 14 years, commencing 1987, would be required to complete residue application. If contractors were used, little or no additional capital expenditure would be required. If the maximum area (28,000 ha) were treated over 14 years, distribution and application costs would be between \$3.2m and \$4.7m with returns of \$2.5 m. Additional costs of \$0.9m to \$4.5m would be incurred to transport the neutralised bauxite residue.

If a treatment plant using bauxite residue to remove phosphorus from drainage waters was commissioned,35% reduction in phosphorus output would immediately occur. Start up date could be 1987. Estimated capital cost is \$16m with annual operating costs of \$2.5m.

Bauxite residue amendment of sandy soils is an attractive proposition for control of phosphate losses to Harvey Estuary. The challenges are to define how equitable cost-sharing arrangements can be worked out between producers of the residues, the State and Farmers and how best to arrange the logistics of distribution.

The advantages are the amount of phosphate which can be retained on the farm, pasture productivity increases on Bassendean sands and effective use of bauxite, gypsum and titanium dioxide wastes.

It will be important to demonstrate the effectiveness of residue in the real farm situation. Joint Government and Industry support is necessary to achieve this.

Acknowledgements

Alcoa would like to acknowledge the Departments of Agriculture and Conservation and Environment, Government Chemical Laboratories, CSBP and Farmers Ltd for the supply of gypsum, the Alcoa - MWA Red Mud Research Group at Murdoch University and Messers Walmsley and Summers whose co-operative efforts made this work possible.

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AN ECONOMIC COMPARISON OF ALTERNATIVE STRATEGIES FOR REDUCING EUTROPHICATION IN THE PEEL-HARVEY ESTUARY

D. MORRISON, B. MATTINSON AND D. PANNELL
WADA FEBRUARY 1983

Summary

This paper is concerned with comparing the cost efficiency of various strategies for reducing the phosphate pollution of the Peel Harvey estuary. Strategies compared include those which would operate within the catchment area to reduce phosphate export and engineering strategies which would act directly upon the estuary. The former involve changing from present agricultural practice, specifically an alternative fertilizer strategy, forestry options which involve the phasing out of agriculture and soil amendment by the incorporation of bauxite residue. The latter involve major public works, either a new channel from the estuary to the sea at Dawesville or a barrage.

Benefits and costs of various strategies are quantified, summed and discounted to provide net present values (NPV's) from the points of view of farmers, the whole community and Government. The only benefits not quantified are those resulting from reduced phosphate pollution. However each strategy's cost effectiveness in reducing phosphate pollution is accounted for by calculating NPV's per unit phosphate reduction.

Findings are only indicative because of the uncertainty of data. There is a need to generate improved data and to update this study as better data become available. Nevertheless results from the study provide a prima facie case for adoption of the alternative fertilizer strategy and/or a forestry option if the yield and price claimed for *Eucalyptus globulus* can be attained. The alternative fertilizer strategy is to be preferred in so far as it would be effective sooner and its cost efficiency is based on more certain data.

Results indicate that other strategies are, by comparison, expensive means of reducing phosphate pollution. Private pine enterprises based on *Pinus pinaster* would be adopted by farmers in the catchment only if Government were to pay them substantial compensation for income foregone. Government pines, both production and protection enterprises, would involve expensive land purchase which would not be sufficiently offset by income from *Pinus pinaster*. Conditional lease back to agriculture could recoup more of the costs of Government land purchase than pines although even this option is likely to be expensive. Bauxite residue incorporation would involve expensive treatment, transportation and incorporation costs which would not be compensated for by major increases in agricultural income. This strategy could be justified only if it involves major benefits to ALCOA, to the extent that ALCOA would be prepared to pay around 90% of transport and incorporation costs in addition to residue treatment costs. Engineering options require substantial Government investment (net present costs of $21 m for the Dawesville channel and $50 m for the barrage) without being offset by a direct economic benefit other than pollution reduction.

The requirement that there is a 70% reduction in estuarine phosphate necessitates a major non-catchment strategy in addition to a within catchment strategy. The 70% reduction would be achieved at least cost by the Dawesville channel in combination with the alternative fertiliser strategy and/or *E. globulus*.

CONTENTS

Note: The following Appendices, not included in this version of the paper, are available on application to the authors:

Appendix 1 Cost Benefit Analysis

Appendix 2 Data and Calculations for Present and Alternative Strategies

    2.1 Present Land Use
    2.2 Alternative Fertilizer Strategy
    2.3 Bauxite Residue Incorporation
    2.4 Production Forestry - Pines
    2.5 Production Forestry - *E. globulus*
    2.6 Protection Forestry

1. Introduction

Two important, complex and related questions posed by eutrophication of the Peel-Harvey estuary are:

* To what extent should Peel-Harvey eutrophication be reduced?

* How should this reduction be achieved?

This paper is concerned with only the latter question. It requires comparisons of the cost efficiencies of various strategies for reducing eutrophication. The strategies compared are based on changing practices and land use in critical catchment areas of the Peel-Harvey estuary as well as two engineering strategies formulated by the Public Works Department.

Phosphate originating from present agricultural enterprises on the deep grey and duplex sands of the Harvey River catchment, is the major cause of eutrophication. It follows that one approach to the eutrophication problem is treatment at its source, either by modifying present agricultural practices or by adopting alternative land uses. Possible modifications to agricultural practices include reduced application of phosphate fertilizer, use of a less water soluble form of phosphate and bauxite residue incorporation to increase phosphate fixation. Alternative land uses examined are various forestry options which are effective to the extent that they require less application of phosphate fertilizer and limit the export of phosphate already in the soil.

There are costs associated with both modification of agricultural practices and adoption of alternative land uses. Some of these are explicit costs such as the costs of:

- Researching and extending alternative fertiliser practices
- Transporting and spreading phosphate fixing bauxite residue
- Establishing a forest plantation.

In the case of changing land use the opportunity cost of agricultural production foregone, although implicit, is equally important. This cost is offset to at least some extent by benefits from the new land use.

In this paper the costs and benefits of various strategies for reducing phosphate export are estimated. They are used firstly to investigate whether there is sufficient incentive for farmers to adopt an alternative practice, secondly to identify an economically optimal strategy (or strategies) from the point of view of society as a whole and thirdly to examine costs to Government of the various strategies.

2. Method

In this paper benefits from reduced eutrophication of Peel-Harvey estuary are not estimated. Rather, the question addressed is:

> 'Given the assumption that reduced eutrophication is desirable, what is the cheapest method of achieving an "adequate" reduction?'

An adequate reduction is assumed to be 70%. There is no attempt to identify the optimal reduction. Limitations in the scope of this paper as a result of this assumption are discussed in section 5.

2.1 Procedure

Alternative strategies for reducing eutrophication are defined. For some strategies, "conservative" and "optimistic" scenarios or outcomes are considered. The various strategies are compared using the technique of Cost-Benefit Analysis (CBA). CBA compares costs with benefits to determine which strategy has the greatest net benefit or smallest net cost for the same level of benefit. Consistency with respect to time is achieved by the use of discounting, a technique by which future benefits and costs can be converted to their Net Present Value (NPV).

Standard CBA is used in this analysis, benefits and costs over the next 90 years being discounted to the present and summed. In keeping with standard practice in CBA only direct benefits and costs are accounted for although some indirect effects are discussed.

Initially CBA is conducted using costs and benefits to farmers of alternative land use strategies. These are compared with costs and benefits of agricultural practices currently undertaken in the catchment to determine whether there is a financial incentive for farmers to adopt a low phosphate exporting land use.

Secondly CBA is conducted considering costs and benefits from a community wide point of view. A broader range of alternatives, including engineering options and bauxite residue incorporation, is considered. Again, current agricultural practice is the benchmark with which alternatives are compared. Net receipts from agriculture are treated as an opportunity cost (i.e. a benefit foregone) to society in those strategies involving replacement of agriculture. This enables comparisons with other strategies in which agriculture is retained. NPVs are calculated and expressed per percentage reduction in estuarine phosphate level.

Thirdly, NPVs and cost efficiencies are calculated from the Government's point of view. The same strategies are considered as in the second part of the analysis.

2.2 Current Agriculture and Alternative Strategies

Strategies involving alternative land use are based mainly on soils of the Bassendean Association (deep grey sands) of the Harvey River catchment because they are the source of more phosphate export per hectare than any other soil type. Some strategies can be extended to Duplex soils of the Harvey River catchments, the other major source of phosphate export.

2.21 Current Agriculture

Continuation of present agricultural practices provides a basis for comparison with other strategies, both with regard to the level of phosphate exported and the magnitudes of costs and benefits.

There is already a large amount of data on present land use from surveys. It is known that nearly all this land is farmed in conjunction with a home property usually located several kilometres to the east (W.K. Russell, pers. comm.). In order to collect more detailed economic data a farm survey was conducted. 8 farms were selected as being representative of all farms on the Bassendean Association (deep grey sands) which makes up 22% of the Harvey River catchment. These eight farms constitute 75% of the farmed area of the Merredith Drain catchment and 20% of the farmed area of Bassendean sands in the Harvey River catchment. The survey was designed to collect information on current land use, intended future land use and productivity on each of the three soil types (Joel, Transition and Gavin) of the Bassendean Association. Findings from the survey indicate that land is currently used for sheep, beef or dry dairy cows (as part of a wholefarm dairy enterprise). Gross margins (profit per marginal hectare) are calculated for each soil type-enterprise combination, weighted according to the area of each found in the survey and extrapolated to the total area of Bassendean Association in the Harvey River catchment. Profit is defined to include those labour costs and fixed costs which are directly attributable to farming this block rather than simply spreading all labour, fixed and overhead costs over the whole farm.

It is assumed that this weighted gross margin is the best available indication of agricultural profitability into the future. This assumption is made since there is no reason to expect substantial changes in price relativities within agriculture, nor changes in technology used by agriculture nor major changes in the area of cleared land in the Harvey river catchment. The last expectation is based on survey results which indicate that the most productive land has been cleared, that little further clearing is planned and that few major changes in land use are planned.

2.22 Alternative Fertilizer Strategy

This strategy involves the least change from current agricultural practice. Its rationale is that currently used super phosphate is not the most suitable fertilizer because it provides phosphate in a form which is too water soluble and it encourages farmers to put on particularly high rates of phosphate in order to meet sulphur requirements. Consequently this strategy consists of a package of research into and extension of fertilizers with a higher sulphur content and a lower level of water soluble phosphate than superphosphate. It involves no other change to current agricultural practices. The CBA includes the continuation and expansion of this research and extension package as well as the direct costs and benefits of alternative fertilizer practice.

Although the alternative fertilizer is more expensive per tonne, a lower rate of application is required for the same growth response, the net result being a saving of $1.76/ha/year. Against this benefit are the costs of research and extension.

In estimating the phosphate export reduction resulting from this strategy (and subsequently its cost effectiveness) it is assumed that the alternative fertilizer would achieve a 40% reduction in phosphate export from the catchment within 4 years (J. Yeates and P. Birch, pers. comm.). This strategy is assumed to have its effect over both the Bassendean Association and the Duplex soils.

A high rate of adoption by farmers is expected because:

(i) The high allocation of resources to extension.

(ii) Farmers have already exhibited a willingness to adopt alternative, low phosphate exporting fertilizers (W. Russell, this publication).

(iii) Adoption of the fertilizer would not involve an increased expense to farmers.

A benefit from this strategy which is not included in calculations is the applicability of research results to areas other than the Harvey River catchment.

2.23 Bauxite Residue Incorporation

This strategy involves the incorporation of high phosphate fixing bauxite residues into the sandy soils of the Bassendean and Coolup Associations within the Peel-Harvey catchment (W.H. Tacey, this publication). Agriculture would continue as at present, but applied phosphate would be retained in surface soil and consequently would not be exported via ground water to the estuary. Costs additional to standard agricultural costs incurred under this strategy are:

- bauxite residue treatment transport and incorporation costs;
- research costs;
- the cost of extension to farmers.
- the cost to farmers of applying manganese fertilizer
- the cost of production foregone when the residue is first applied
- the cost of reseeding pasture

A benefit is the saving to ALCOA from using this waste disposal method compared with the present method. Although it has been claimed by ALCOA that bauxite residue incorporation may increase farm productivity, there is some dispute over the extent and value of this increase. J. Yeates (personal communication) has claimed that residue incorporation may not increase farm production because on the main phosphate exporting soil types (Joel sands from the Bassendean Association and all Duplex soils) there would be little or no increase in pasture production. Moreover Yeates proposed that if there were any increase in pasture production it would be only at spring time so that it would not enable a proportionate increase in stocking rate and profit.

In this paper two scenarios are examined for this strategy. The first is a conservative scenario, based on Yeates, which assumes that bauxite residue incorporation has no effect on pasture growth for the agriculturally important Joel sands, but it does effect the Gavin and Transition sands (soils of minor importance) to the extent claimed by ALCOA. Under this scenario, given the minimal gain and additional costs that bauxite residue would involve (e.g. reseeding correction of manganese deficiency) farmers would not willingly pay for the treatment. Costs would have to be borne by Government and ALCOA. The second scenario is more optimistic allowing for the yield response claimed by ALCOA. An allowance is made for the benefit to ALCOA of reduced waste disposed costs in both scenarios. For the optimistic scenario it is assumed that this benefit is equal to the full cost of residue treatment plus one third the cost of transport and application. For the pessimistic scenario this benefit is assumed to account for residue treatment costs only.

A 60% reduction in phosphate export from the Bassendean Association (resulting in a 26% reduction from the whole catchment) is assumed to be the result of adoption of this strategy under either scenario (J. Yeates, pers. comm.).

2.24 Production Forestry-Pinus pinaster

Under this strategy current agricultural production would be replaced by production plantations of Pinus pinaster, resulting in lower phosphate application, interception of groundwater phosphate and lower water tables, all of which would contribute to reduced phosphate export. Based on Forests Department advice it is assumed that conversion to production forestry of all developed agricultural land in the catchment would proceed over a 20 year period, five per cent of current agricultural land being replaced each year.

Within this strategy alternative programmes based on 30, 45 and 60 year production cycles are examined. Costs and benefits of these strategies are estimated for Government and private pine production. Yields, prices and costs were supplied by the Forests Department. An earlier set of data supplied by the Forests Department has been revised by them since the recent Peel-Harvey Symposium (November, 1983) resulting in higher yield and price estimates for this paper.

It is assumed (based on Forests Department advice) that pines on the Bassendean Association would reduce the present level of phosphate export from the Harvey River catchment by 23% and that this maximum effect would be achieved five years after planting is completed.

2.25 Production Forestry - Eucalyptus globulus

This strategy involves replacement of existing agriculture with commercial plantations of Eucalyptus globulus for pulp. Again the assumed conversion period is 20 years.

Data for this strategy were provided by West Australian Chip and Pulp Company and the West Australian Forests Department.

In addition to direct benefits and costs an allowance has been made for research and extension expenditure because of the insufficiency of information about this strategy.

The initial response of West Australian Forest Department employees to this strategy was that it was significantly inferior to pines and not worth investigating. This opinion was later revised on inspection of E. globulus stands already growing on the Bassendean Association. However there is still uncertainty over what yield would be obtained. Consequently two yield scenarios (conservative and optimistic) are examined. In the conservative strategy a yield of 20 m^3/ha/year is assumed. The optimistic assumption is for 25 m^3/ha/year.

It is assumed, on Forests Department advice, that E. globulus on Bassendean sand would ultimately reduce phosphate export from the catchment by 23% and that this maximum effect would be reached 5 years after planting is completed.

2.26 Protection Forestry - Pinus pinaster

This strategy consists of planting pines to achieve the quickest reduction in phosphate export from current agricultural land. A sooner reduction of phosphate export (as compared with production forestry) would be achieved by planting over a shorter period (1 year), planting more trees per unit area and adopting a 100 year growth period before clearing and replanting. In formulating the strategy, commercial considerations are secondary to the environmental protection objective. Consequently this strategy would not be attractive to private investors, but it is an option for Government.

For this strategy yields are lower and production is delayed relative to production forestry. Yields, prices and costs of this strategy were supplied by the Forests Department.

It is assumed, again based on Forests Department advice, that protection forestry on the Bassendean Association would ultimately reduce total phosphate export by 23% and that this maximum reduction would be achieved 6 years after planting is completed. Because planting would be completed in 1 year, the total time to maximum effect would be only 7 years.

2.27 Engineering Strategies

Two engineering strategies are considered; a barrage crossing at Heron point and a channel to the ocean at Dawesville (see Vodanovic, this publication, for details of these strategies).

In this study the cost of the barrage is underestimated because creation of a polluted lake behind the barrage is costed only with regard to land lost to the lake, not the social cost of creating a highly polluted lake.

Phosphate reductions in the estuary as a result of these strategies were estimated by P. Birch as 40% for the channel and 100% on the downstream side of the barrage. On the upstream side the barrage would cause an increase in phosphate concentration. For this purpose of cost efficiency comparison it is somewhat arbitrarily assumed that the barrage has a net effect equivalent to a 70% reduction in estuarine phosphate. Costs and timetabling of the strategies were provided by the Public Works Department (PWD)(see Vodanovic (1983)).

3. Results and Discussion

3.1 From the Farmer Perspective : Profitability of Alternative Land Uses

Figure 1 shows NPVs of various phosphate reducing strategies as functions of discount rate. In the range 3% to 5% discount rate, regarded as most appropriate for this comparison, agriculture is clearly more profitable than any of the options involving pines. It follows that there is no financial incentive for farmers to convert from agriculture to pine production. Assuming 4% as the appropriate discount rate, results show that farmers would have to be compensated about $1,000/ha (or alternatively $41/ha/year) to convert to pines. In reality a payment greater than this may be required because of:

* The unattractive cash flow provided by pines because they do not generate income for the first 11 years. This could be overcome by an annuity payment scheme (see Treloar, 1984).

* Farmer preference to continue farming for non pecuniary reasons. This reflects not only farmer conservatism but also a rational preference for retention of the land use they know most about and for which yields and prices are known with greater certainty.

The poor economic performance of pines compared to other options relates directly to Forests Department data indicating that this is a relatively poor location for pines. Pines do not grow as well on the Bassendean sands as on most other south-west soils and pine production has to be based on Pinus pinaster, a species with a lower yield and a lower value product than the preferred Pinus radiata.

Figure 1 shows that growing E. globulus for pulping would be more profitable for farmers than either pines or agriculture within the 3% to 5% range of discount rates. However, data on E. globulus yields and product prices are open to question because of the unavailability of yield data for Western Australia and the uncertainty of future prices. Nevertheless, even under the pessimistic scenario, based on low estimates of yield (from sources other than W.A. Chip and Pulp Co.), the NPV is still considerably higher than pines and slightly higher than agriculture.

This finding suggests that there may be sufficient profit potential to encourage farmers to convert from agriculture to E. globulus. At a 4% discount rate and given the pessimistic scenario, the NPV of E. globulus is $544/ha higher than agriculture (the equivalent of an annual payment of $22/ha). However, as with pines, there are reasons not represented in the NPV why farmers may choose to retain agriculture. Consequently the difference in NPV's may not be sufficient incentive for farmers to convert to E. globulus although it at least provides a prima facie case for further investigation and consideration of this option.

3.2 From the Community Perspective : Cost Efficiencies of Alternative Strategies

Table 1 shows Net Present Values (NPVs) to the whole community of the different strategies. NPVs are also expressed per unit reduction in phosphate export.

Figure 1: Net Present Value to the Farmer of Alternative Land Uses

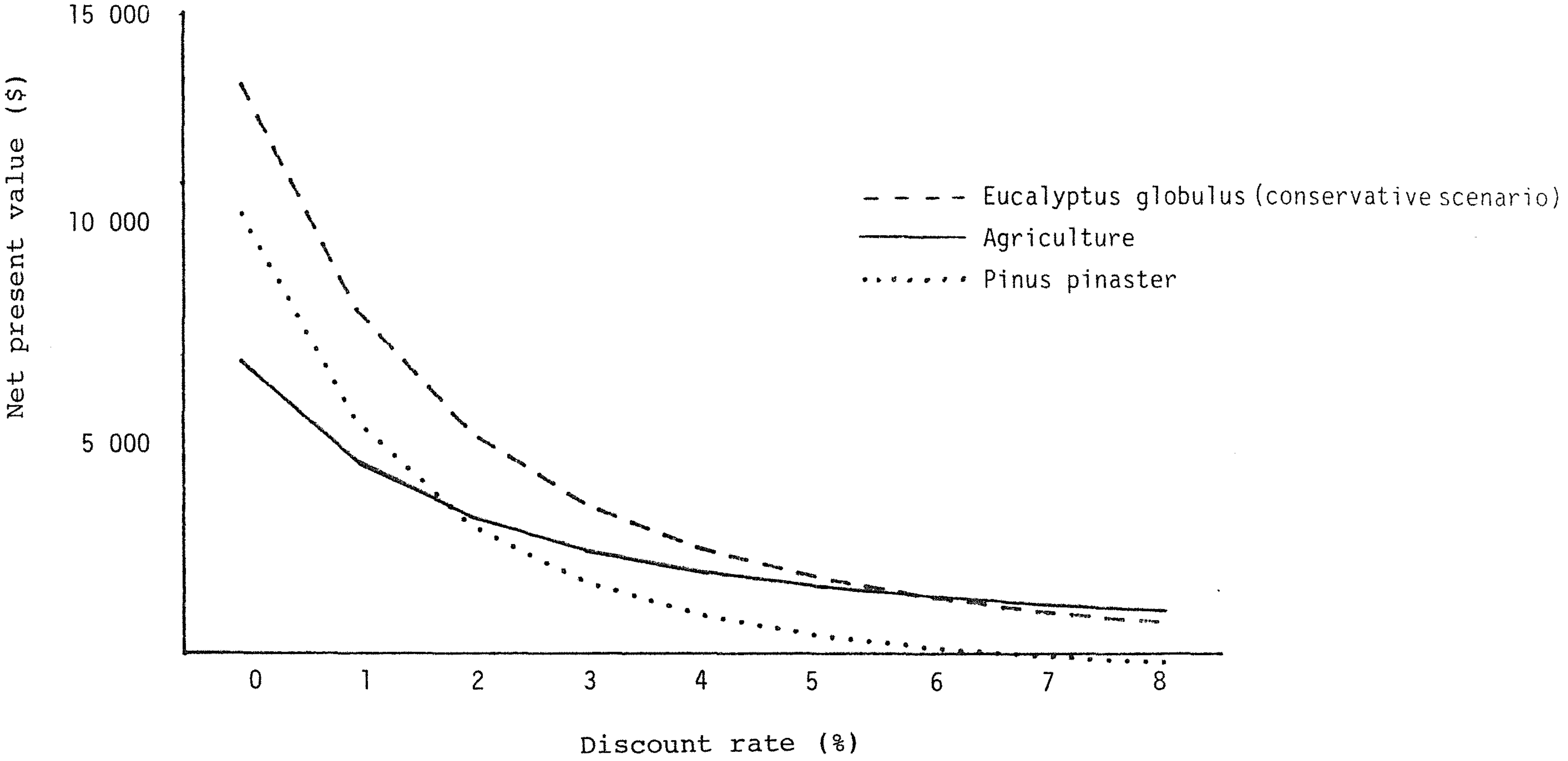

Table 1: Net Present Values and Cost Efficiencies of Different Strategies for Eutrophication Reduction

	AGRICULTURE		LAND USE CHANGE				ENGINEERING	
	Alternative Fertilizer[1.]	Bauxite Residue Incorporation	Eucalyptus globulus	Pines Private 45 yr cycle	Pines Government 45 yr cycle	Protection Forestry (pines)	Barrage	Channel
Net Present Value ($ m at 4% discount)	0.8	-24.6[2.] to - 8.1[3.]	3.6[2.] to 8.8[3.]	-8.9	-13.8	-30.9	-50.0	-21.0
Percentage Reduction In Estuarine Phosphate	40	26	23	23	23	26	74	40
Cost Efficiency ($'000 per % reduction in phosphate)	20.0	-945.0 to -313.2	156.5 to 380.6	-386.3	-599.8	-1168.7	-714.4	-525.0
Delay to Maximum Effect (years)	6	16	25	26	26	9	5	5

1. This includes the cost of the alternative fertiliser strategy over Duplex soil as well as the Bassendean Association. Other scenarios refer to the Bassendean Association only.

2. Estimate from conservative scenario.

3. Estimate from optimistic scenario.

4. This strategy would be equivalent to reducing phosphate export by 100% to most of the estuary but increasing its markedly in the rest of the estuary. Therefore the percentage reduction allowed for here is somewhat arbitrary.

The E. globulus and alternative fertilizer strategies are the only ones with a positive NPV. For E. globulus this reflects the fact that it is a more profitable land use than present agriculture. Even in the case of the most pessimistic scenario the NPV is about $3.6 m for conversion of Bassendean sands to E. globulus. It follows that this strategy generates an income per unit phosphate reduction; in the case of the pessimistic scenario $156,500 per percentage reduction in phosphate. Although absence of local data on production and price uncertainty for wood pulp require cautious use of this finding, there is at least a strong case for further research into the productivity of and market for E. globulus.

The alternative fertilizer strategy has the next highest NPV and the only other positive NPV at $800,000 or $20,000 income per percentage reduction in phosphate. This net benefit reflects the gain from the improved efficiency of agricultural production which is also derived from this research. Thus fertilizer research and extension expenditure is a highly cost efficient strategy. This finding may be regarded as more reliable than that for E. globulus because it involves continuation of the present land use and implementation of a strategy which has already been partly researched, rather than a radical change in land use to an alternative which has not been researched.

By comparison with the E. globulus and the alternative fertilizer strategy, other strategies are very expensive. NPV's for production pine forestry on Bassendean sands range from -$8.9 m for private commercial pine production in a 45 year cycle to -$30.0 m for protection forestry. Expressed in terms of cost efficiency these strategies range from almost $400,000 to $1.25 m per percentage reduction in phosphate export. Although all production forestry options cost considerably less in total than the Dawesville channel (the least expensive engineering strategy) only the private pine options (30, 45 and 60 year cycles) cost less per percentage reduction in phosphate. The least costly of these, the 45 year cycle is about $400,000 per percentage reduction compared with $525,000 for the channel. The 30 and 60 year cycles cost $508,000 and $463,000 respectively.

At face value it may seem surprising that the pine strategies did not rate more favourably because pines are a land use which generates income to offset costs whereas engineering strategies for instance, only incur costs. However this superficial view does not account for opportunity costs which are important for pines. When discounted to the present, profits from Pinus pinaster fall well short of profits from the agriculture they displace, whereas agricultural profits are of course retained under alternative fertilizer and engineering strategies.

It is feasible that pines could be more profitable than assumed and agriculture slightly less so. A small change in assumed pine yield or product price could make even government pines as cost efficient as the Dawesville channel. However, yields and prices which seem implausibly high for Pinus pinaster, are required to make any of the pine strategies approach the cost efficiencies found for the alternative fertilizer strategy or E. globulus.

The bauxite residue treatment is also a relatively expensive means of reducing phosphate export. Cost estimates for this strategy vary widely from a NPV of about -$8 m for the optimistic scenario based on data provided by ALCOA, to about -$24 m for the conservative scenario based on an alternative data source[1]. Even if the optimistic scenario is accepted, (based on the data provided by ALCOA and allowing for substantial cost disposal savings) the cost efficiency is not high at more than $300,000 per percentage reduction in phosphate export. This is more expensive than the alternative fertilizer and E. globulus. Under the conservative scenario it is clearly less cost efficient than production pines or engineering strategies.

Results for the bauxite residue strategy may not be in accord with some expectations because the plan has at least a superficial appeal. Bauxite residue is a pollution problem in its own right so that by transporting and spreading it two pollution problems are reduced and some increase in agricultural production may be gained along the way. However treatment, transport and incorporation of the residue are extremely expensive at around $2,250/ha; about twice the market value of the land. Production increases as a result of this treatment are very large on Gavin and Transition sands but these soils are unimportant agriculturally, constituting less than 20% of the agricultural land and not much more than 2% of agricultural production on the Bassendean Association. Moreover they contribute very little of the export phosphate. The response is modest to negligible on the Joel sands which constitute more than 80% of the agricultural land and contribute most to the phosphate export problem.

Bauxite residue incorporation can rate as a highly cost efficient strategy only if there are enormous savings to be made by ALCOA from the use of this method of residue disposal above the cost of their next best disposal method. This saving would have to be much greater than that allowed for in the optimistic scenario - i.e. much greater than the full cost of the residue treatment plant plus one third of the transport and application cost. For this strategy to be as cost efficient as the alternative fertilizer strategy, the waste disposal saving would have to cover full treatment costs and the major part of the transport and application costs. ALCOA has not yet provided information on alternative disposal costs, but this level of saving seems unlikely.

Cost efficiency is not the only consideration relevant to the choice of the best strategy. Government is also concerned with reducing eutrophication as soon as possible. Table 1 shows that there are substantial delays to maximum reduction of phosphate export. Only engineering, protection forestry and alternative fertilizer strategies would achieve their maximum effect in less than 10 years. Bauxite residue application and all production forestry strategies reach their maximum effect later. In the case of bauxite residue this is

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[1] J. Yeates, research officer W.A.D.A.

because the rate of application is limited to the rate at which residue becomes available so that substantial delay is unavoidable. For production forestry, it is feasible to achieve maximum effect sooner but this has to be traded off against the greater expense of a more rapid tree planting schedule. In private forestry it is unlikely that the planting would be achieved sooner unless there is an extension programme and a financial scheme to overcome scarce income in the early years (see Treloar, 1984, for discussion on an appropriate financial scheme).

Simultaneous consideration of the cost effectiveness and minimum delay shows that some strategies can be categorised as inferior[1]. This is clearly the case for production forestry options based on pine because they are considerably more expensive than E. globulus or the alternative fertilizer strategy without providing sooner phosphate reduction. Protection pine is not inferior to E. globulus because although much less cost efficient, it would be effective sooner. However, it is clearly inferior to the alternative fertilizer strategy being less cost efficient without being effective sooner. Assuming that the effect of the barrage is equivalent to a 70% reduction in phosphate export, the barrage is considerably less cost efficient without providing phosphate reduction any sooner than the channel. It is thus inferior to the channel. This process of elimination leads to two strategies within the catchment, E. globulus and the alternative fertilizer strategy, and one engineering strategy, the Dawesville channel. If a 70% reduction in phosphate export is accepted as the appropriate goal then none of these strategies is sufficient in itself. Catchment strategies based solely on Bassendean sands are far from sufficient and remain insufficient even when extended to the Duplex sands. It would be necessary to have some combination of a catchment strategy and the Dawesville channel to meet the requirement for a 70% reduction in phosphate export. The alternative fertilizer strategy or E. globulus or some combination of these would be the least cost catchment strategy which in combination with the Dawesville channel would provide the least cost means of achieving the 70% reduction.

These results are only indicative of what might be the best strategy because of the uncertainty of data, because the analysis has not identified the optimum combination of strategies and because decision makers may wish to consider other objectives. There are a number of aspects of data uncertainty. Some of these arise from the fact that the major sources of data may have some interest in the outcome of the study. For example ALCOA provided data on bauxite residue, the PWD provided data on the engineering options, the Forests Department provided data on pines, W.A. Chip and Pulp Co. provided data on E. globulus and the W.A. Department of Agriculture provided data on the alternative fertilizer strategy.

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[1] Where there is more than one objective a strategy is defined as inferior to another when it scores lower on at least one objective and higher on none.

In the case of strategies in which the data were provided by private companies alternative sources of data were consulted. Nevertheless there is uncertainty as to the cost of some strategies; in particular forestry and engineering. For the former both yield and future price data have a high degree of uncertainty, whereas only very approximate estimates are provided for the latter. In those strategies assuming voluntary change in land use or practices by private land owners there is some uncertainty as to whether land owners will make changes to the extent expected. If co-operation proceeded slower than expected it could be affected by Government intervention at a later date via a financial incentive or legslation. (The former would not affect NPVs because it is a transfer payment). There is further uncertainty in that the effect of each strategy on phosphate export reduction has only been roughly estimated.

Employment is an objective which Government may wish to consider in addition to the cost efficiency and timeliness of strategies in affecting phosphate export reduction. Although this objective has not been researched it warrants some discussion.

It is likely that the engineering strategies would add most to employment, although the increase would not be long term. The bauxite residue treatment is likely to add less to employment but it would increase it for a longer period. Alternative fertilizer, bauxite residue incorporation, and the engineering stratgies are favourable in that they result in additions to current employment without reducing current agricultural employment. Converting from agriculture to forestry may increase net employment slightly . This would be especially likely in the case of the Bassendean Association because at present it is not intensively worked but treated as runoff blocks. The alternative fertilizer strategy provides for additional research and extension officers and may result in some slight expansion in employment in fertilizer production.

3.3 From the Government Perspective : Cost to Government of Alternative Strategies

Table 2 shows the discounted present costs to Government and the cost effectiveness of Government expenditure for each of the phosphate reduction strategies. For some strategies the NPV from the community's point of view becomes the Government cost discounted to the present. Clearly this applies to the cost of engineering projects. It also applies to private forestry (except E. globulus) and bauxite residue incorporation if Government is expected to compensate farmers for their reduced income or pay those costs above the benefits to farmers and ALCOA. Government forestry is slightly different because the cost to Government is the cost of land purchase rather than the opportunity cost of agriculture. The alternative fertilizer strategy and E. globulus are also different because it is assumed that Government would not seek to recoup some of its cost by charging the farmers for the services so that increased profit would accrue entirely to farmers.

Inexpensive options from the Government point of view are E. globulus and the alternative fertilizer strategy which would cost Government $400,000 and $700,000 respectively. (These are present values, costed out precisely from an actual plan in the case of the alternative fertilizer strategy, but a rough estimate for E. globulus). Expressing these in terms of this cost efficiency to Government, both cost about $18,000 per percentage reduction in phosphate.

Other strategies involve considerably greater expense to Government than these two. Engineering and protection forestry are the most expensive strategies with discounted costs to Government of $21 m for the Dawesville Channel, $30 m for protection forestry and $50 m for a barrage. In addition, for each of these, costs would occur within a short period, compounding the difficulty of financing them.

Bauxite residue incorporation is also relatively expensive although Government expense would be spread over many years. Even if we assume the increase in productivity claimed by ALCOA, we assume the farmer is willing to pay for it and we assume ALCOA is prepared to pay for bauxite residue treatment plus one-third of transport and incorporation costs, the Government would still have to pay the present equivalent of $300,000 per percentage reduction in phosphate. From the data in Table 2 it can be deduced that ALCOA would have to be willing to pay at least 90% of transport and incorporation costs (in addition to its presumed payment of all residue treatment costs) for this strategy to approach the cost efficiency of the alternative fertilizer strategy from the point of view of Government.

Private pine production is moderately expensive requiring Government expenditure equivalent to a discounted present cost of $9 m to compensate farmers. Government run forestry would result in a net cost to Government which is almost twice that of private pines because of greater Government expense running pines and the expense of land purchase.

Assuming that 70% is the "required" reduction in phosphate level the best combination of strategies from the Government viewpoint would be the Dawesville channel in combination with E. globulus and/or the alternative fertilizer strategy. The present value of the expense of these projects to Government is around $22 million.

Table 2: Net Present Values and Cost Efficiencies of Government Expenditure on Different Strategies for Eutrophication Reduction

	AGRICULTURE			LAND USE CHANGE				ENGINEERING	
	Alternative Fertilizer[1.]	Bauxite Residue Incorporation	Purchase and Lease back	Eucalyptus globulus	Pines Private 45 yr cycle	Pines Government 45 yr cycle	Protection Forestry	Barrage	Channel
Net Present Value to Government ($ m at 4% discount)	- .7	- 24.6[2.] to - 8.1[3.]	- 6.1	- .4	- 8.9	- 16.4	- 29.4	- 50.0	- 21.0
Cost Effectiveness to Government ($'000 per % reduction in phosphate)	-18.0	-945.0[2.] to -313.2[3.]	-469.5	-18.0	-386.2	-713.5	-1144.4	-500.0	-525.0
Government Role	Research and extension	Subsidisation of bauxite residue transport and incorporation	Land purchase offset by leasing back	Research and extension	Compensation of farmers for less profitable enterprise	Land purchase offset by growing pines	Land purchase offset by growing pines	Public Works project	Public Works project

1. This includes the cost of the alternative fertilizer strategy over Duplex soil as well as the Bassendean Association. Other scenarios refer to Bassendean Association only.

2. Estimate from conservative scenario.

3. Estimate from optimistic scenario.

A further option to Government not discussed in 3.2 is that of purchasing land and leasing it back conditionally to farmers. The condition would be that the land, if used for agriculture, must be fertilized as prescribed by Government. It would thus have a very similar NPV to that for the alternative fertilizer strategy regulation costs replacing extension costs. There would be greater certainty of farmer co-operation to be traded off against the farmer preference for voluntary co-operation rather than compulsory conditions. Although the NPV would be about the same as the alternative fertilizer strategy, discounted present costs to Government would be higher, $6.1 m versus $.7 m, reflecting the fact that the income from lease does not offset the expense of land purchase. Nevertheless, if the Government is to purchase land, results in Table 2 indicate that it is more cost efficient to lease it back to agriculture rather than to plant it to pines.

4. Conclusions

The decisiveness of conclusions drawn in this paper is limited by the uncertainty of data used in calculations. In particular, there is a problem of relying on data provided by sources with vested interests. It follows that:

(1) Findings are only indicative so that any conclusions should be interpreted cautiously.

(2) There is a need for research to generate better data.

(3) There is a need to update this study in the light of better data.

Nevertheless, assuming that a 70% reduction in estuarine phosphate is required, this study provides a prima facia case for:

(i) the alternative fertilizer strategy and/or a highly productive private forestry strategy based on E. globulus for the catchment, plus

(ii) the Dawesville channel.

This conclusion is consistent with findings from the point of view of farmers, the whole community and Government.

Farmer Perspective

The high profitability of Eucalyptus globulus suggests that there is adequate financial incentive for farmers to convert from agriculture to forestry without Government subsidy. However the data used in this analysis is sufficiently unreliable to conclude only that further independent research into productivity of and markets for E. globulus is warranted.

If this research supports the above finding, a programme to extend this to farmers will be appropriate.

Given the anticipated yield and product price of Pinus pinaster, pines are not profitable enough on the Bassendean Association to encourage voluntary conversion to forestry by farmers. Government subsidy equivalent to at least $41/ha/year would be necessary to make conversion profitable for farmers.

Community Perspective

(i) E. globulus and the alternative fertilizer strategy are by far the most cost efficient strategies for reduction in phosphate export. The latter although slightly more expensive, is based on more reliable data and is likely to be effective sooner. By comparison other strategies - pines and engineering are highly expensive means of reducing phosphate export; protection pines and the Heron Point barrage being particularly expensive. Bauxite residue incorporation is a highly expensive method of reducing phosphate export unless there are substantial benefits to ALCOA not accounted for in this study.

(ii) When objectives of cost efficiency and minimum delay are considered, results indicate that all catchment-based strategies are inferior to either E. globulus or the alternative fertilizer strategy. This implies that the best practice for the catchment sands is either one of, or a combination of these strategies. The requirement that there is a 70% reduction in phosphate export means that a major non-catchment strategy is also needed. With respect to cost efficiency and minimum delay, the best non-catchment strategy examined is the Dawesville channel.

Government Perspective

E. globulus and the alternative fertilizer strategy are also the most cost efficient strategies from the Government perspective because they involve only relatively small research and extension costs. Other strategies require high Government expenditure: Privately run pines would require a substantial farmer subsidy (net present cost is around $9 m) whereas Government pines are more expensive still (net present cost around $16 m) because they require expensive land purchase which would be only slightly offset by returns. If Government purchases the land it is likely to recoup more by conditionally leasing it back to agriculture. Engineering options involve substantial public works expenditure (net present cost $21 m to $50 m). Bauxite residue incorporation requires substantial subsidy from Government (net present cost in the range $8 m to $25 m) unless ALCOA benefits considerably more than assumed. ALCOA would have to be willing to pay at least 90% of bauxite residue transport and incorporation costs (in addition to its presumed payment of all residue treatment costs) for this strategy to approach the cost efficiency of the alternative fertilizer strategy.

The requirement that phosphate export is reduced by 70% means that another major strategy is required in addition to the within catchment strategy. In accord with the findings from the community perspective the preferred strategy from the Government perspective would be the Dawesville channel. Dawesville channel and either one or a combination of the 2 cost efficient catchment strategies would cost Government around $22 m (net present cost) less than 5% of which is attributable to the catchment strategy.

5. Need for Further Work

Several areas for further work have been identified.

The first is the need for research to obtain more reliable estimates of yields, costs and prices associated with the various strategies. As better information becomes available this study should be updated.

The second is the need for improved estimation of the phosphate export reduction resulting from each strategy.

The third is the need to extend the costing for the E. globulus and bauxite residue strategies to the Duplex soils.

The fourth is the need to derive an optimum level of reduction in phosphate export rather than an analysis which starts with an arbitrary 70% standard. In the optimum strategy phosphate would be reduced only to the extent that marginal benefits from phosphate reduction exceed marginal costs. An optimum could be derived by building an economic model which would quantify cost as a function of the percentage reduction in phosphate export. As a next step this could, if there is sufficient accurate data, be converted to cost as a function of the frequency of algal bloom. Ultimately estimation of the benefit from less frequent algal blooms (although difficult to estimate) could be compared with costs in order to derive the optimum.

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PEEL HARVEY ESTUARINE SYSTEM

Study Symposium, November 28-29, 1983

DRAINAGE DIVERSION OPTIONS

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1. INTRODUCTION

Throughout the day the various speakers have produced data indicating that many of the catchment management options on their own could not guarantee a reduction in phosphorus transported by the Harvey Drainage System to non-bloom levels.

It is therefore necessary to consider the options available for storing and diversion of this drainage water to ensure that controlled amounts of phosphorus only, enter the estuary.

2. THE OPTIONS

2.1 Several diversion options were given preliminary investigation, noted and discarded as competitive concepts. These include:

(a) A barrage at Point Grey and disposal system to the ocean;

(b) A barrage at Herron Pt and diversion to Harvey River Diversion by pipe and lined channel;

(c) Diversion of parts of the farm area drainage to Harvey River Diversion;

(d) Redirection of flows from the upper reaches of the Harvey River to the Harvey Main Drain, away from the existing Harvey River Diversion, to increase flushing of Harvey Estuary.

2.2 The other drainage diversion options, that were recommended for more detailed evaluation, all required a barrage to provide a storage of water and a better set of inflow data on which to estimate the system discharge rate, either pumped or by gravity.

2.3 The barrage site selected was from Herron Point to Island point. The heights of barrage investigated were 3, 4.5, 5.5 and 6.5 metres with storage depths of 1.5, 3,4, and 5 metres respectively.

2.4 The areas inundated by the storage waters behind the various barrage heights are:-

Barrage Height (metres)	Area Inundated (hectares)
3	500
4.5	1400
5.5	2300
6.5	3000

2.5 Before any option could be examined, reliable flow data was required. This was limited to flows gauged in 1982. This has recently been expanded to include 1983 records but even with this information it was not considered sufficient to produce reliable probabilities of overtopping. Nevertheless the 1982 flows were used as a base year and a report was prepared acknowledging the limited data and the fact that 1982 flows may ultimately prove not to be representative of conditions on which to base final design. The preliminary diversion structures were sized using the 1982 data.

2.6 The order of costs estimated on this basis are shown on the attached table Fig. 1. The apparent least cost option appeared to be a low lift pumped flow through a tunnel and pipes from a 4.5 metre high barrage. Allowing for 10 years of operation and maintenance at $0.33 M per year the total estimated cost of the option is $25.7 M.

The required pump discharge rate for this option is 5.8 m^3/sec or 0.5 x $10^6 m^3$/day.

2.7 It must be remembered here that the flow considered was only 1982 conditions. When the annual inflow for 1982 is placed on a recently produced diagram, Fig. 2, showing estimates of catchment response as an annual inflow sequence based on 47 years of rainfall data, it becomes a very ordinary event. The barrage woud be frequently overtopped in wetter years if the pumping rate of 0.5 x 10^6 m^3/day was adopted. Obviously some better estimates of the likely regularity of overtopping of the barrage were necessary, and some level of acceptance of failure had to be established.

3. CRITERIA FOR ANALYSIS OF SPILL VOLUMES

3.1 After personal communication with C Croft and Dr R Humphries it was agreed that the diversion works should not permit overspill to the estuary greater than 100 x $10^6 m^3$ more frequently than 1 in 5 years. This volume was estimated to be the threshold of spill before bloom conditions occurred.

3.2 Using this criteria, a coarse attempt to produce an historic sequence of inflows into the estuary was carried out by R. Harvey, and from it was obtained a rough statistical estimate of the annual volumes spilt into the estuary through the barrage spillway using specific pump discharge rates from the storage.

It was soon realised that the higher level barrages were required to bring down the pumping rates to manageable levels. Barrage heights of 4.5, 5.5 and 6.5 storing water depths of 3,4 and 5 metres respectively were evaluated.

The results were included in a report which contains documentation of the statistical estimates of the volume of spill by simulating on a daily basis an impoundment with a calculated inflow and peak diversion rate, whether by pump or gravity system. The effects of rainfall and evaporation directly on the impoundment was included in the inflow calculations.

4. COMPARISON OF COST ESTIMATES BASED ON DERIVED FLOW ESTIMATES

4.1 Applying this new derived flow estimation to the least cost options examined for 1982 conditions resulted in the following required pumping or discharge rates. These rates allow for the spill to be limited to less than 100 x $10^6 m^3$ in 80% of years.

Height of barrage metres	Stored depth metres	Pumped or Discharge rate m^3 per day
4.5	3	2.5×10^6
5.5	4	2.0×10^6
6.5	5	1.6×10^6

4.1 It should be noted here that the 1982 conditions required a pumping or discharge rate of 0.5 x $10^6 m^3$ per day but did not meet the spill criteria. As the pumping rates rise then the Capital and operating costs rise accordingly. The barrage cost remains the same for the respective heights discounting spillway variations.

4.3 Based on results of the preliminary investigations the only drainage diversion options to be estimated for the new discharge rates were a barrage combined with

(a) a gravity tunnel
(b) low level pumping through pipes and tunnels
(c) high lift pumping over the hills through pipes

Consequently the 1982 conditions least total cost of $25.7 M for a low lift pumping system discharging through pipes and tunnels from a 4.5 metre barrage has now to be compared with a total cost of $59 M for the increased required discharge rate of 2.5 x $10^6 m^3$ per day to satisfy spill criteria.

4.4 However, if a 6.5 metre high barrage approximately 4 kilometres long is considered then the required pump discharge rate drops to 1.6 x $10^6 m^3$ per day and reduces the total cost of the low lift option to approximately $49 M.

5. THE DISPOSAL SYSTEM SELECTION

5.1 From the total cost estimates calculated using the overspill criteria, see Fig 3, it is quite significant that regardless of the barrage height used a combination of low lift pumping through tunnels and pipes to the ocean produces the least cost estimates. The main reason for this is the high annual operating and maintenance costs of high lift pumping schemes.

5.2 Gravity tunnels in all situations produced the highest capital costs and were not competitive even allowing for 10 years of operating and maintenance costs on all pumping schemes. It should be stated here that the actual site tunnelling rates may vary from those used in the estimates but the rates used were based on similar tunnels constructed through sand covered limestone coastal dunes at Bibra Lake and Beenyup. Some reductions may be gained if tunnelling conditions are found to be favourable, but this can only be evaluated after much detailed investigation along the route.

5.3 Some problems may also develop at the ocean - discharge point and attention in the design phase will be necessary.

5.4 Some features of the least cost options:

Barrage Length	4 kilometres
Barrage Height	6.5 metres
Depth of Water Stored	5 metres
Spillway Length	300 metres
Barrage Base Width	52 metres
Pump Discharge Rate	1.6 x $10^6 m^3$/day (4 pumps)
Pumping Head	10 metres
Tunnel Size	3 metres dia. for 2.7 kilometres
Pipes	3 x 1800 mm RC for 3.8 kilometres
Annual Operating Cost	$0.55 M
Total Cost (10 Years)	$49 M

5.5 A barrage height of 6.5 metres increases the stored water surface area to 3000 hectares. These inundated lands stretch 7 kilometres upstream from the Estuary along the Harvey Main Drain or approximately 2.5 kilometres south of Clifton Road bridge.

6. IMPLICATIONS FOR MANAGEMENT

If a diversion option is eventually adopted the following implications need to be considered by management.

6.1 A high Capital Cost.

6.2 A recurring annual operating cost.

6.3 Possible failure to restrict flows 1 year in 5.

6.4 Extensive geological investigations are required for tunnelling feasibility and costs can be verified.

6.5 A large surface area will remain during the storage cycle which may produce *Nodularia* and other algal products.

6.6 Although apparent regulation of phosphorus into the estuary can be achieved by diversion, the problem still remains unsolved on the catchment. Work should not cease on phosphorus control on farmed areas.

6.7 Resumption of houses may be necessary in some cases as a result of the state of the inundated land.

6.8 All designs and estimates developed in this phase of the study are based on very sketchy data and should only be used as guides in the selection of the management options rather than accurate estimates.

6.9 A continuation of funding for monitoring flows in the drainage systems is required to extend the reliable data base and permit confirmation of the derived flow sequence estimates used in the study.

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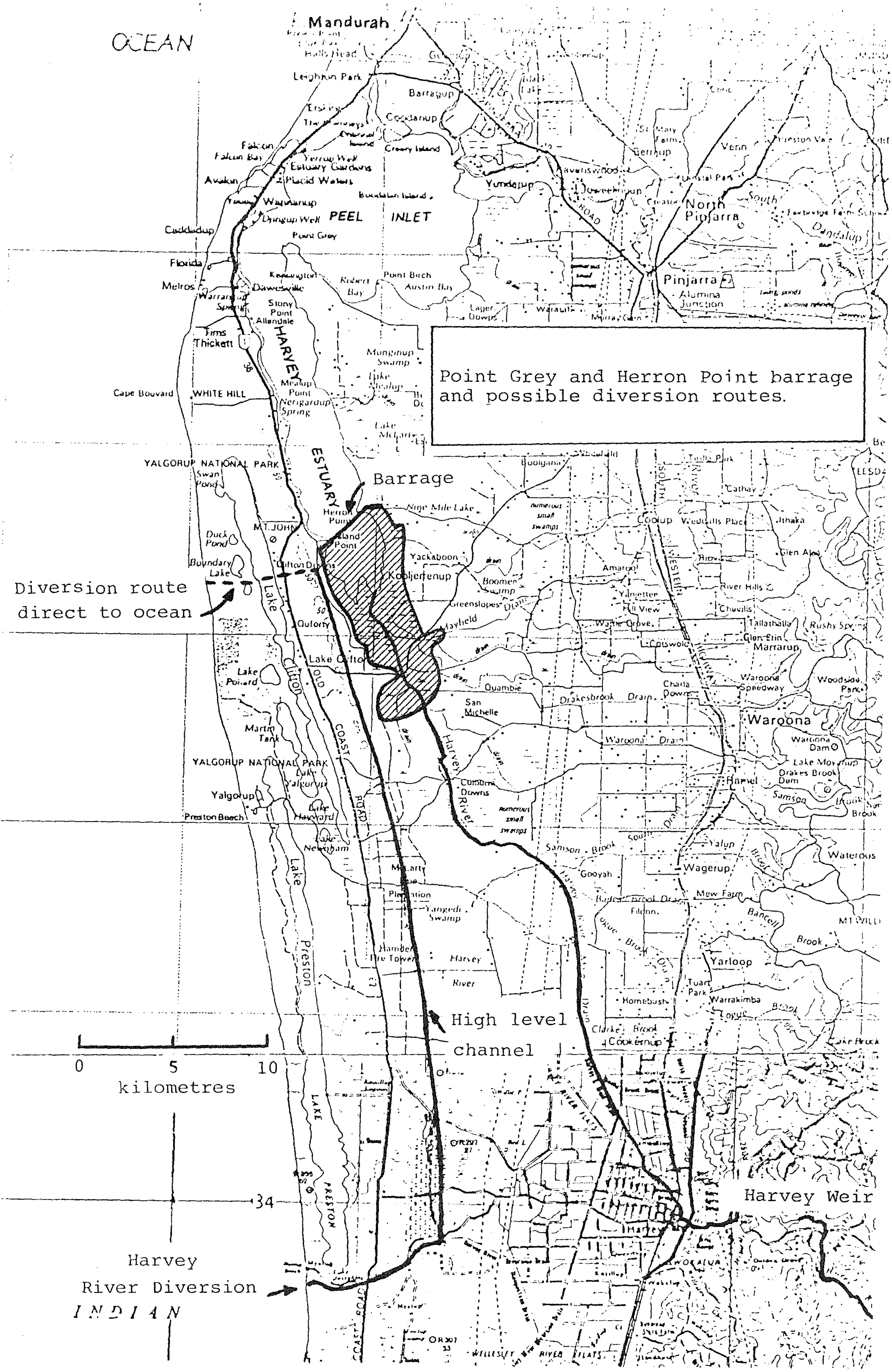

Point Grey and Herron Point barrage and possible diversion routes.

OPTION	CAPITAL COST $	ANNUAL PUMP COSTS (OP.& MAINT.) $	TOTAL COST (10 YRS) $
1. Diversion to Ocean from Harvey Estuary (1.5 m Storage Depth)			
PUMPING OVER HILLS	19.99×10^6	1.19×10^6	31.89×10^6
GRAVITY FLOW	45.17×10^6	-	45.17×10^6
LOW LEVEL PUMPING	22.90×10^6	0.29×10^6	25.8×10^6
2. Diversion to Ocean from Harvey Estuary (3.0 m Storage Depth)			
PUMPING OVER HILLS	17.36×10^6	1.4×10^6	31.36×10^6
GRAVITY FLOW	30.08×10^6	-	30.08×10^6
LOW LEVEL PUMPING	22.40×10^6	0.33×10^6	25.7×10^6
3. Diversion to Harvey River Diversion from Harvey Estuary			
(1.5 m Storage Depth)			
ALONG DRAINAGE PATHS	49.06×10^6	1.19×10^6	60.96×10^6
IN HIGH LEVEL CHANNEL	19.17×10^6	1.19×10^6	30.36×10^6
(3.0 m Storage Depth)			
ALONG DRAINAGE PATHS	33.60×10^6	1.4×10^6	47.6×10^6
IN HIGH LEVEL CHANNEL	20.00×10^6	1.4×10^6	34.0×10^6
4. Diversion of Flow from Part of Farm Area to Harvey River Diversion			
OPEN CHANNEL	1.62×10^6		1.62×10^6
5. Re-Direct Flows from Upper Reaches of Harvey River to Peel Inlet			
HARVEY RIVER MAIN DRAIN	9.77×10^6		9.77×10^6

FIGURE 1: PRELIMINARY INVESTIGATIONS - 1982 FLOWS
SUMMARY OF COSTS (26.4.83)

FLOW INTO HARVEY ESTUARY
PERCENTILE RANKING

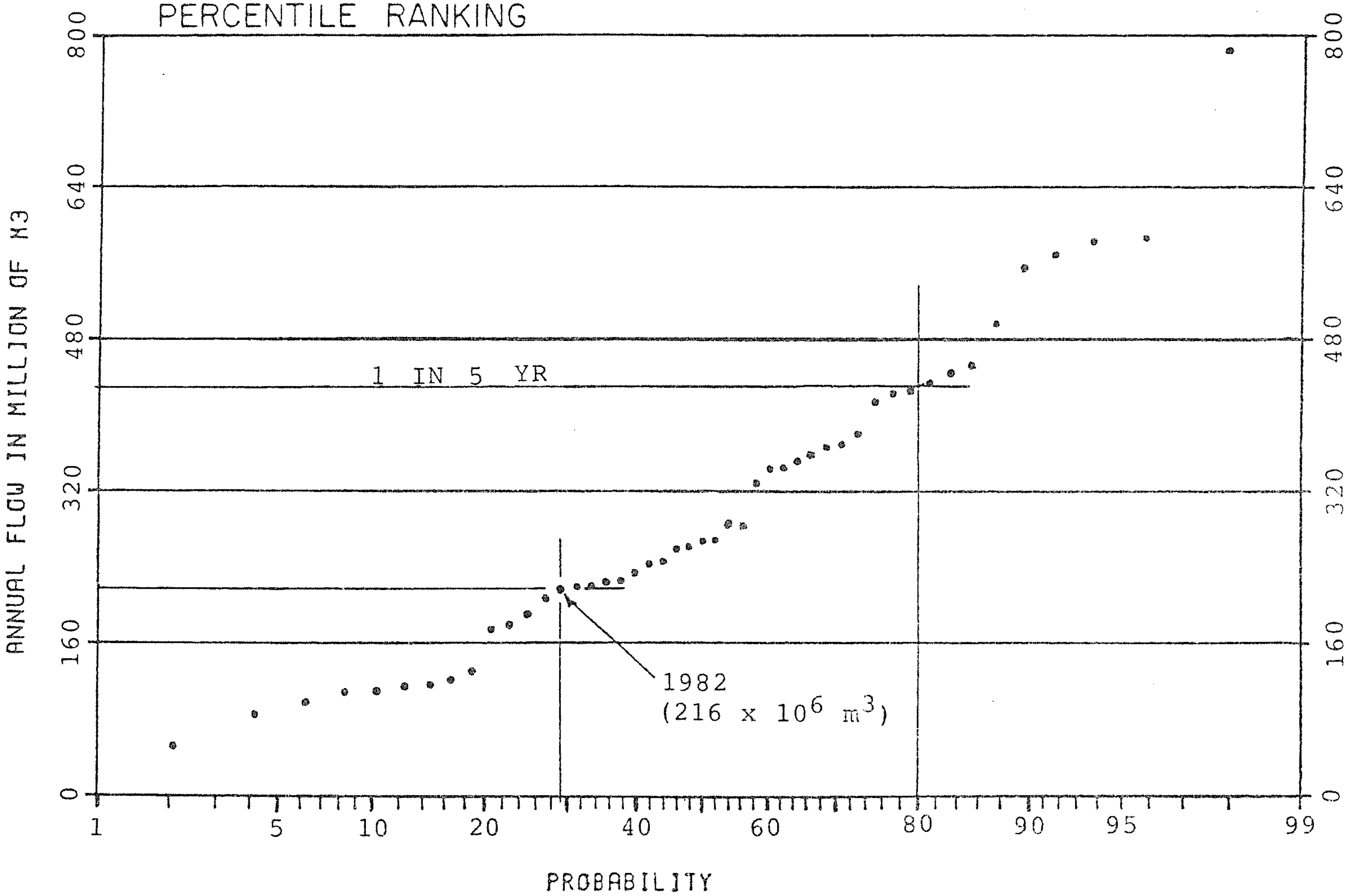

FIG.2 ESTIMATED CATCHMENT RUNOFF RESPONSE TO 47 YEARS OF RAINFALL DATA (JAN 1936 - DEC.1982)

DATE PLOTTED : 05/03/83
WATER RESOURCES SECTION
PUBLIC WORKS DEPARTMENT, W.A.

OPTION	CAPITAL COST $	ANNUAL PUMP COSTS (OP.& MAINT.) $	TOTAL COST (10 YRS) $
1. Diversion to Ocean from Harvey Estuary (3.0m Storage Depth)			
PUMPING OVER HILLS	52×10^6	3.2×10^6	84×10^6
GRAVITY FLOW	108×10^6		108×10^6
LOW LEVEL PUMPING	52×10^6	0.7×10^6	59×10^6
2. Diversion to Ocean from Harvey Estuary (4.0mStorage Depth)			
PUMPING OVER HILLS	47×10^6	2.9×10^6	76×10^6
GRAVITY FLOW	100×10^6		100×10^6
LOW LEVEL PUMPING	44×10^6	0.6×10^6	50×10^6
3. Diversion to Ocean from Harvey Estuary (5.0 m Storage Depth)			
PUMPING OVER HILLS	44×10^6	2.2×10^6	66×10^6
GRAVITY FLOW	89×10^6		89×10^6
LOW LEVEL PUMPING	43×10^6	0.6×10^6	49×10^6

FIGURE 3: PRELIMINARY INVESTIGATIONS - 1 IN 5 YEAR OVERSPILL CRITERIA - SUMMARY OF COSTS (May 83)

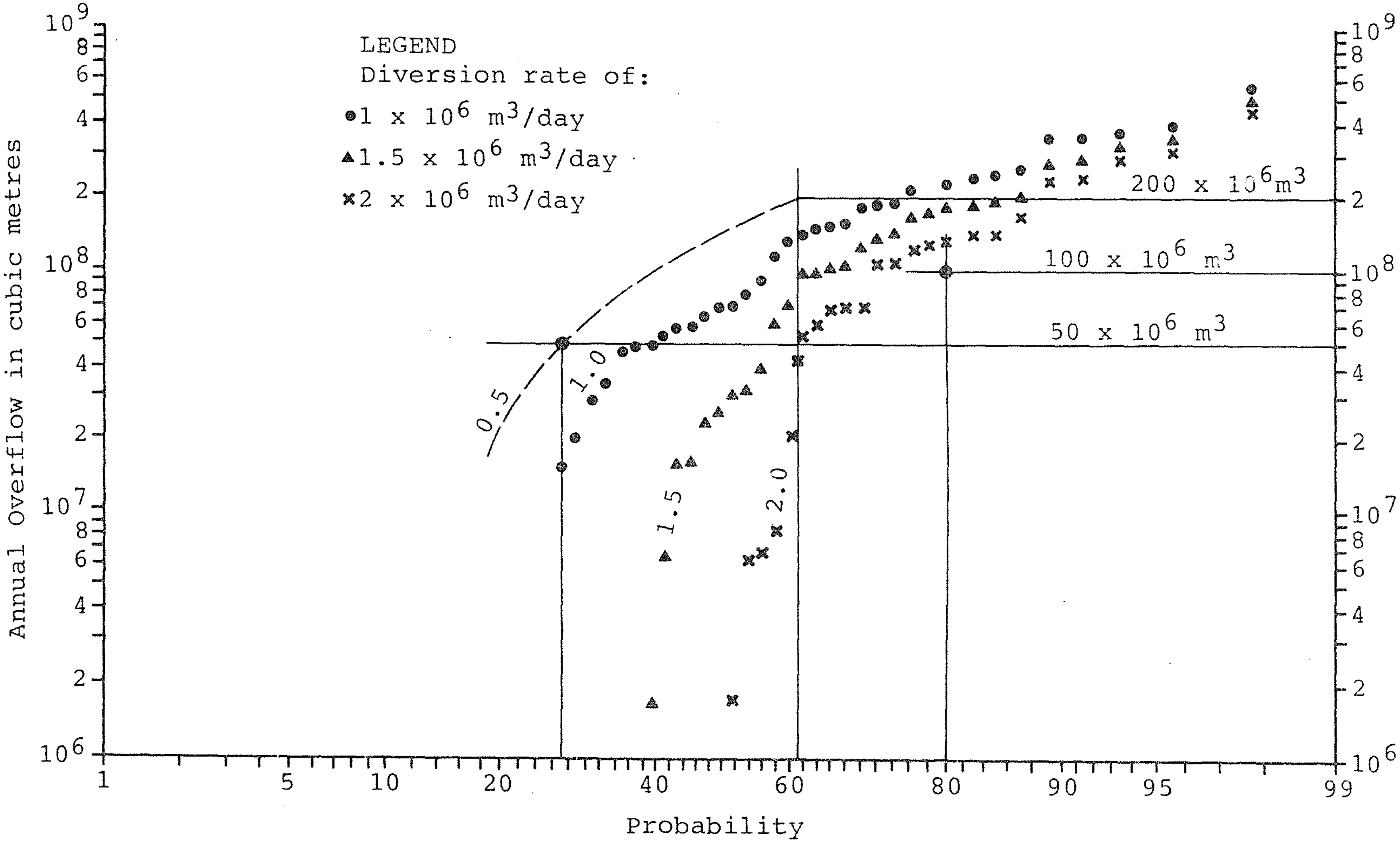

FIGURE : Overtopping of a 3m barrage.

SUMMING UP OF DAY I OF THE 1983 PEEL-HARVEY STUDY SEMINAR

NORM HALSE

In my summing up I will go chronologically through the day's proceedings, because it has been set out in a well-structured way and I see no reason to depart from it. The first two speakers, John Yeates and Gerry Ritchie, were both concerned with soil and plant uptake as they affected phosphorus drainage input into the estuary system. Everyone believes that modifications to this part of the system are likely to play some part in the eventual solution, which makes it extremely important.

John Yeates discussed the social problem as to whether farmers should be fertilising their lands to maximum production. We are concerned with this because John postulated that there is to be no reduction in production and he has worked on the basis that farmers would be fertilising to about 98 per cent of maximum production. According to David Morrison's estimates of profitability they should be putting on lower rates than this. There may be justification in looking differently at fertilising for best overall land use. Instead of fertilising for optimum economic production, perhaps we should look at how much production farmers would lose if they fertilised at lower rates. Those of you who are familiar with fertiliser response functions know that you can reduce fertiliser rates well below economic optimum production and lose very little money because your cost of fertiliser is declining simultaneously with your production.

People who are concerned with the agricultural phosphorus inputs in this system have been trying to make changes on a cost-free basis, no loss of production and no cost to the farmers or the government. They may be restricting the scope of their solutions by adopting this approach.

In these two first papers, it seemed to me that there was a difference between the two authors in their opinion of what would happen in a situation where you had infinitely aged phosphorus in the soil. I think Gerry's system suggested that you would always be getting leaching from high soil phosphorus levels, whereas John seemed to expect that leaching would depend on the forms of phosphorus present in the soil. Gerry Ritchie suggested that in wetting and drying cycles there would always be phosphorus movement into water soluble forms. I think this is something that they should enveavour to resolve but I may have been wrong in concluding there was an inconsistency.

The next two papers are on the very important topic of subsurface and near surface saturated water flow which moves the phosphorus from where the farmers want it to where the population of Mandurah doesn't want it. Nick Schofield and Eric Bettenay both discussed different aspects. Eric had been making field observations on what happens under natural conditions, whereas Nick Schofield reported experiments in which the system was manipulated. This work has led to the most interesting suggestion that drainage density itself may have a real and long-term effect on phosphorus loss from the soil system (not just a short-term difference). I believe that this work should be pursued. Given the availability of waterlogging tolerant pasture cultivars I believe that farmers would be happy to reduce drainage efficiency for a lot less than 10 million dollars.

Bill Russell talked about what changes have occurred in farmer practice in response to the traditional extension methods of the Department of Agriculture, which tries to persuade farmers.

The Department treats farmers with reverence, and that is very proper for such a poor but honest group as the Department of Agriculture, but there are other methods. It may well be that we could use high pressure mind-bending techniques on farmers with advantage, persuading them to do the right thing in their own interests. This may be one of the ways in which additional funds could be used to modify the phosphorus input part of the system. We could spend more money to get a much higher acceptance than normal, once we are confident of the proper field practices to be followed.

Jane, in her paper, gave us a very clear answer to the question on the value of biological filters. It was quite clear that although these wetland sinks may have value in particular situations, such as point sources of pollution, they will not solve the problem of fertiliser phosphorus input into the Peel-Harvey Inlet. One thing about Jane's solutions, where they are applicable, was that they would make people interested in water fowl, and water fowl themselves, very happy.

The next solution, which Warren Tacey presented, was one that would make ALCOA very happy. If we were able to solve the fertiliser phosphorus input using red mud from alumina refining it would make us all happy. It seems so logical and pleasant to be able to bring two problems together and have them cancel each other out. However, there would be quite a cost in doing this - due to the large amount of material to be transported. In discussion at the end of Warren Tacey's paper, John Yeates raised the possibility that there still may be problems in the long-term if we did amend the soil with bauxite residue. This related to earlier discussions about the nature of phosphorus in the soil and how much of it is going to be lost to leaching in various situations (fortunately it appears that subsequent consideration has led to the conclusion that the red mud additions could prevent phosphorus leaching permanently).

David Morrison's paper, on alternative land use in the phosphorus intake area, was a most valuable one because it provided a baseline cost comparison for any overall package of solutions. He set out to see what was the cost of removing the problem by buying the land out of agriculture and compared this cost with the cost of alternative solutions. He had difficulty with forestry as alternative land use because the first set of costs and returns were quite uneconomic and it was perhaps unfortunate that he had to speak before he had finished his survey. Nevertheless it was a valuable discussion; some of the points that were raised warrant more careful examination, not only from the economic point of view but from the point of view of forestry practice. I thought myself that this possibility of putting some of the land to an alternative use could well contribute to the final solution. Although the pine forest option doesn't look very profitable, the government may be wanting to plant pine forests and if they decide to plant them in the phosphorus intake area, instead of somewhere else, it may contribute substantially to the solution of this problem.

A major difficulty, that we are going to discuss tomorrow, is what to do with partial solutions. If you have got two partial solutions that are giving you perhaps a 55 per cent solution for about a quarter of the cost, you have got a problem. Do you forget about them or do you look for a third alternative partial solution to add to them? I think tomorrow's job has been made more difficult today because new possibilities have come up - as modifications of solutions already investigated. I thought myself, as a result of listening to today's proceedings, that the fertiliser work must go ahead, it is almost certain to be a part of any solution. I think that work should also continue on drainage intensity associated with further work on phosphate movement in saturated water flow near the surface. I think

David Morrison has showed us how valuable it is to have an economist thinking with us about these problems and I think further economic studies are warranted not only to complete his own study but perhaps to also assist with some of the others. If a management package is agreed tomorrow which needs further detailed examination there may well be the time to do some of the other work which I have suggested has arisen from today's discussions.

Macroalgae, phytoplankton and nutrients

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Macroalgae

The Peel-Harvey study was initiated in 1977 to determine the cause of the excessive growth and accumulation of macroalgae in Peel Inlet. Since the mid-1960's large masses of macroalgae have accumulated on the shores of Peel Inlet, where they decompose and emit a nauseous stench and foul formerly clean beaches.

A number of grid surveys have been carried out since 1978 to monitor macroalgal biomass and estimated total biomass is shown in Fig. 1. Peak macrophyte biomass was 66,000 tonnes dry weight in March 1979. There was a dramatic decline in biomass in late 1979 mainly due to the loss of Cladophora. Total biomass has remained close to 10,000 tonnes dry weight since October 1982, but qualitative estimates of macrophyte biomass in 1983 suggest that total biomass would have been close to 10,000 tonnes dry weight. Even at these levels the macroalgae still present an ongoing management problem for the Peel Inlet Management Authority. Clearing of the beaches in the Coodanup and Cox Bay areas alone costs approximately $70,000 per year.

Cladophora was the dominant macroalga until late 1979 (Fig. 1). Chaetomorpha was virtually absent in 1978 and its estimated biomass was 430 kg dry weight. In the 6 months between September 1978 and March 1979 its biomass had increased to almost 10,000 tonnes dry weight. Chaetomorpha was the dominant macroalga until late 1982 and in 1983 Ulva, which was virtually absent in earlier years, was the dominant alga. These changes in species dominance probably reflect changing conditions.

One possible cause of the decline in macroalgal biomass since 1978 is increased turbidity. Gordon et al. (1981) found that light penetration to the floor of the estuary was one of the important limiting factors for Cladophora growth. Table 1 shows that there has been a significant increase in turbidity during the summer months, the main macroalgal growth period, since the summer of 1977-78. The increase in turbidity has largely been

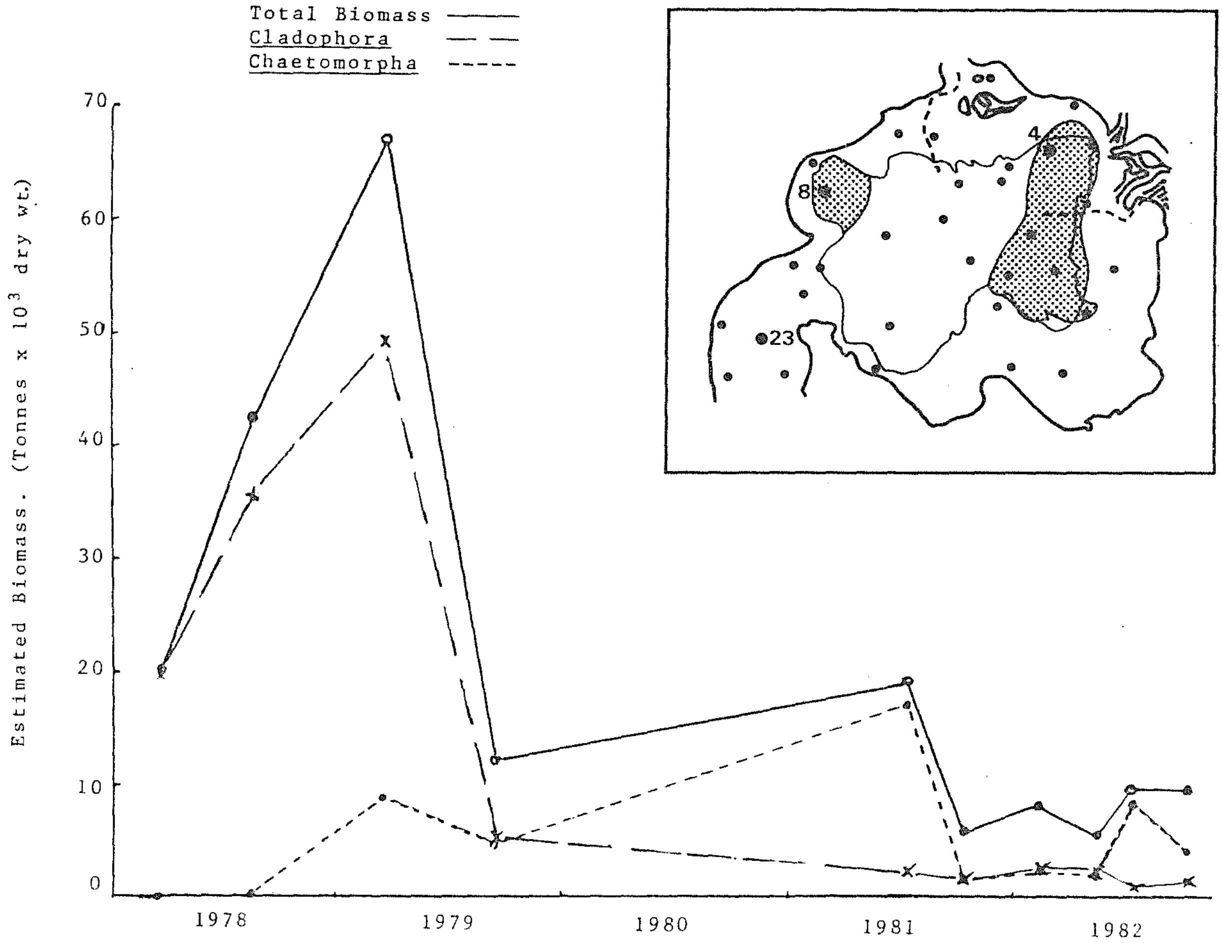

Figure 1. Variation in total macrophyte biomass, Cladophora biomass and Chaetomorpha biomass in the Peel-Harvey estuarine system. Inset: Location of the sampling sites and principal macroalgal growth areas (stippled) in Peel Inlet.

Table 1 Mean attenuation coefficient for the period November to April

Year	Attenuation Coefficient (E m^{-1})	
	Peel	Harvey
1977 - 78	0.39	0.50
1978 - 79	0.56	1.31
1979 - 80	0.49	0.52
1980 - 81	0.93	1.58
1981 - 82	1.01	1.64
1982 - 83	0.60	1.25

brought about by increased phytoplankton biomass in the water column. A reduction in turbidity due to a decrease in phytoplankton levels will probably lead to an increase in macroalgal biomass and much greater beach fouling than experienced in recent years.

Another possible reason for the reduction in macroalgal biomass since 1978 is reduced nutrient loading to the system. There are two major (macroalgal growth) sites in Peel Inlet (Fig. 1). The macroalgae on the eastern side of Peel Inlet probably rely on nutrient input from the Murray and Serpentine Rivers, while the main nutrient source for the western population in Cox Bay is probably the Harvey. Since 1975, except for 1981 when flow was average, Murray River flow, and hence nutrient input, has been well below average and the nutrient load to the eastern growth site greatly reduced. The nutrient supply to the Cox Bay growth site has probably increased in recent years due to the sedimentation and decomposition of *Nodularia* flushed from the Harvey Estuary. Fig. 2 shows the change in *Cladophora* and *Chaetomorpha* biomass at three sites in the Peel-Harvey system. Macroalgal biomass declined dramatically at site 4, a deep site on the eastern side of Peel Inlet, in late 1979 and has not recovered. At site 8, a shallow site in Cox Bay, biomass has gradually declined since 1978, and at site 23, a deep site in the northern end of the Harvey Estuary, biomass did not decline until early 1982 following the massive *Nodularia* bloom of 1981/82. The above results imply that some other factor or factors besides the reduction in light reaching the estuary floor were important in accounting for the decline in macroalgal biomass because the biomass in the northern Harvey, the most turbid of the three sites, did not decline until early 1982.

Implications for management

1. The macroalgae still present an ongoing management problem and should be considered in any overall management strategy for the Peel-Harvey system.

2. Macroalgal biomass is not being monitored at the present time and regular monitoring needs to be carried out so that the success and effects of any management strategies can be assessed.

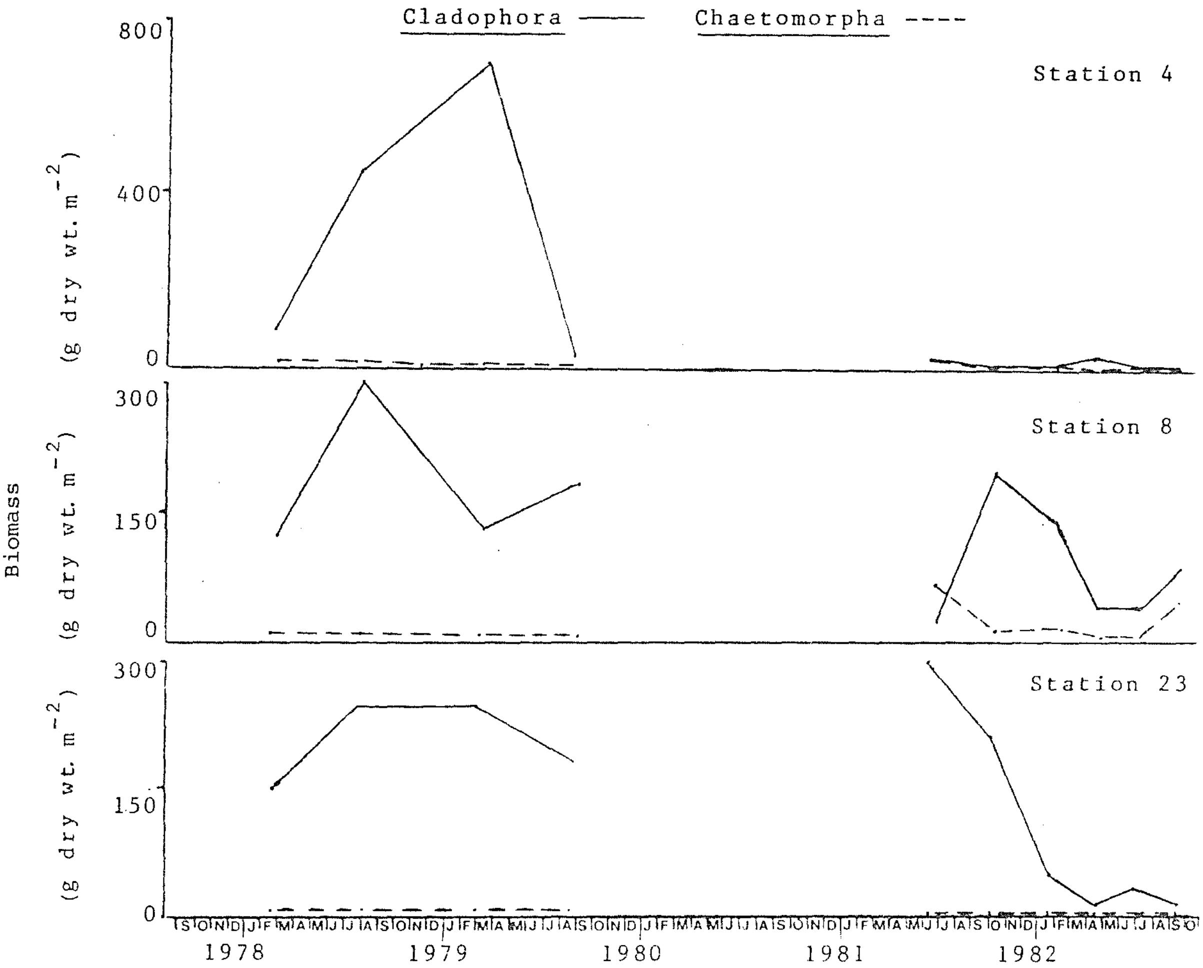

Figure 2. Variation in Cladophora and Chaetomorpha biomass at sites 4, 8 and 23. (Location of the sites is shown in Fig. 1).

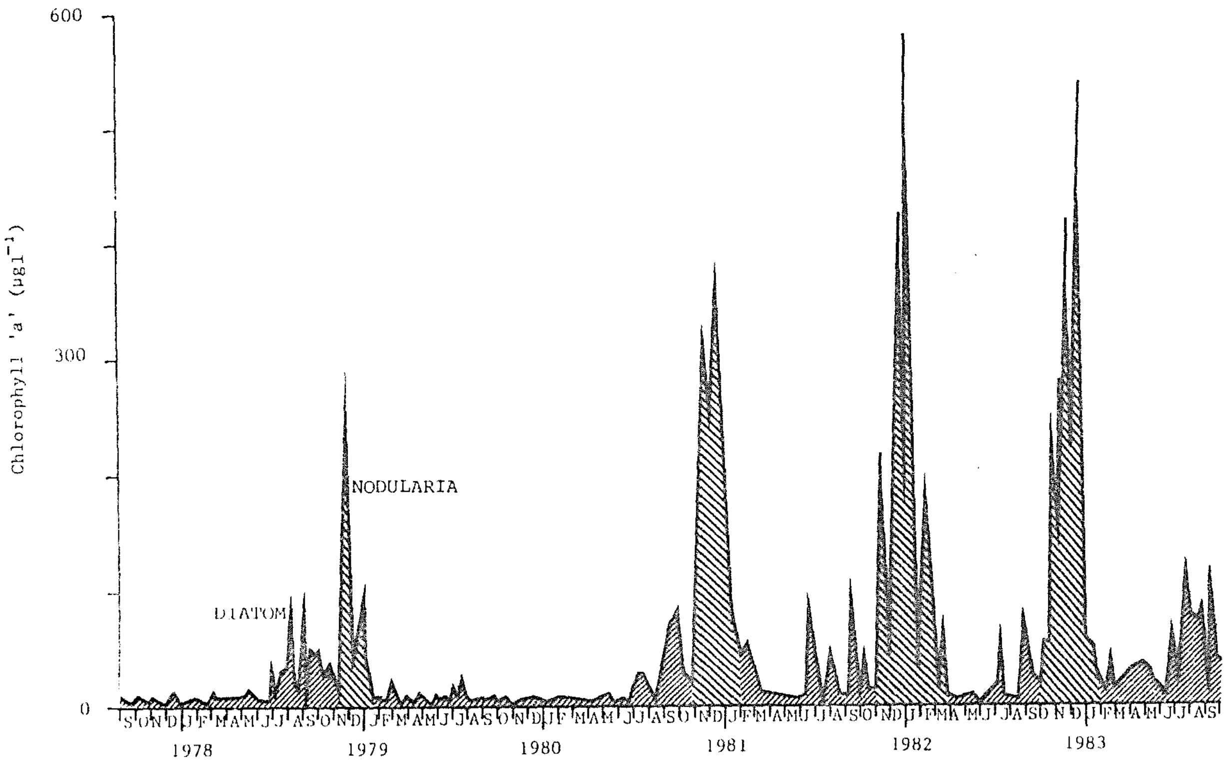

Figure 3. Harvey Estuary mean surface chlorophyll 'a'.

3. A reduction in turbidity will probably lead to an increase in macroalgal biomass and beach fouling.

Phytoplankton

In this section the relationship between nutrient input and phytoplankton is assessed and some possible factors that could account for the succession from diatom-dominated blooms to *Nodularia* blooms are outlined.

Harvey Estuary mean surface chlorophyll 'a' concentration is shown in Fig. 3. Chlorophyll 'a' is an estimate of phytoplankton biomass. Diatom blooms occur most winters following river flow. The diatom blooms are replaced by massive *Nodularia* blooms in spring, and in later years progressively greater diatom blooms have followed the collapse of the *Nodularia* blooms. In 1978 there was a short-lived bloom, a larger bloom in 1982, and this year there was a persistent bloom following the collapse of the *Nodularia* bloom up until the onset of river flow in late June.

In 1982 and again this year, following the collapse of the *Nodularia* blooms there have also been blooms of a benthic species of *Oscillatoria*. The *Oscillatoria* bloom was much worse this year than the previous year. On calm days large mats of *Oscillatoria* float to the surface and these are blown to the shores where they rot.

Table 2 shows that there has been a significant increase in post-*Nodularia* bloom chlorophyll 'a' levels in recent years. This suggests that the amount of available N and P recycling from the sediments has increased since 1978.

Table 2 Mean Harvey chlorophyll 'a' for the period March - May

Year	Chlorophyll 'a' ($\mu g l^{-1}$)
1978	6.5
1979	3.5
1980	3.6
1981	9.0
1982	17.8
1983	24.7

Fig. 4 shows mean Harvey surface salinity overlain by chlorophyll 'a'. The diatom blooms immediately follow river flow. The largest Nodularia bloom followed the winter with the lowest minimum salinity. The Nodularia blooms collapse when salinities reach about 30 $^{o}/oo$. The effect of the summer floods of 1982 are clearly seen in Fig. 4. The Nodularia bloom had started to collapse when the floods in January 1982 reduced salinities and brought in a new supply of phosphorus, and the Nodularia bloom responded.

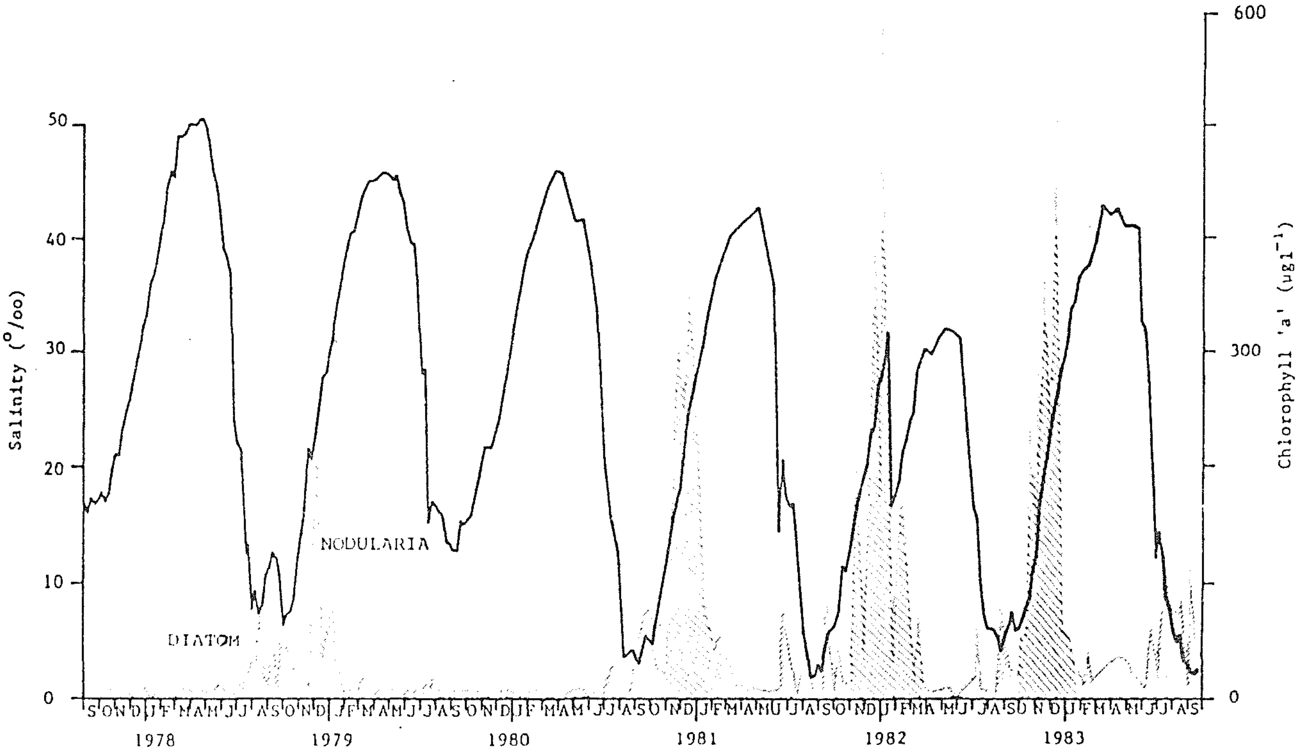

Figure 4. Harvey Estuary mean surface salinity and mean surface chlorophyll 'a'.

Fig. 5 shows surface ammonium-nitrogen levels and chlorophyll 'a'. Ammonium levels are usually high in winter due to sediment release. The collapse of the N-fixing Nodularia blooms was followed by a large release of ammonium in the early bloom years, due to the decomposition of Nodularia. The smaller post-Nodularia bloom peaks of ammonium in recent years is due to uptake by the larger phytoplankton biomass present. Ammonium levels were high in the winter of 1979 when there was only a very small diatom bloom. Nitrogen was unlikely to have been limiting phytoplankton growth at this time. Surface organic nitrogen levels are shown in Fig. 6. The peaks are due to Nodularia blooms and there appears to have been an increase in the levels of organic nitrogen since 1978.

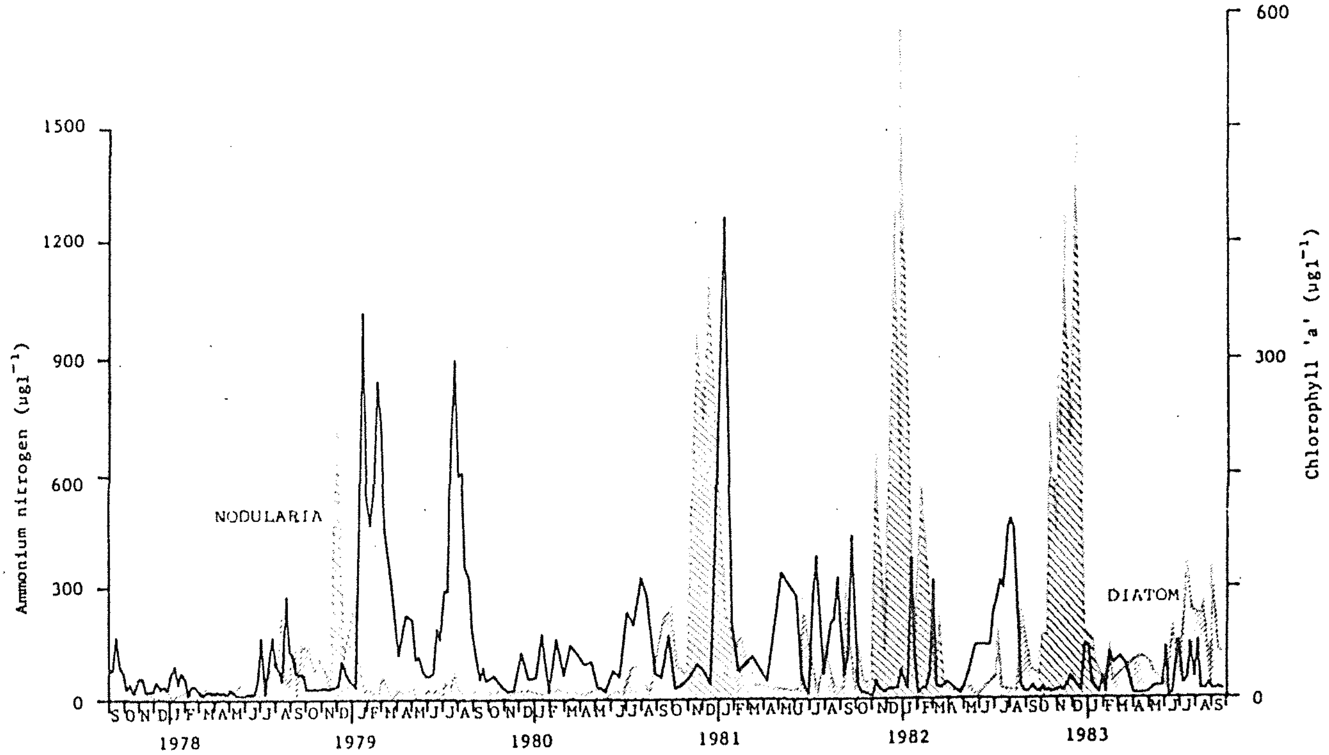

Figure 5. Harvey Estuary mean surface ammonium nitrogen and mean surface chlorophyll 'a'.

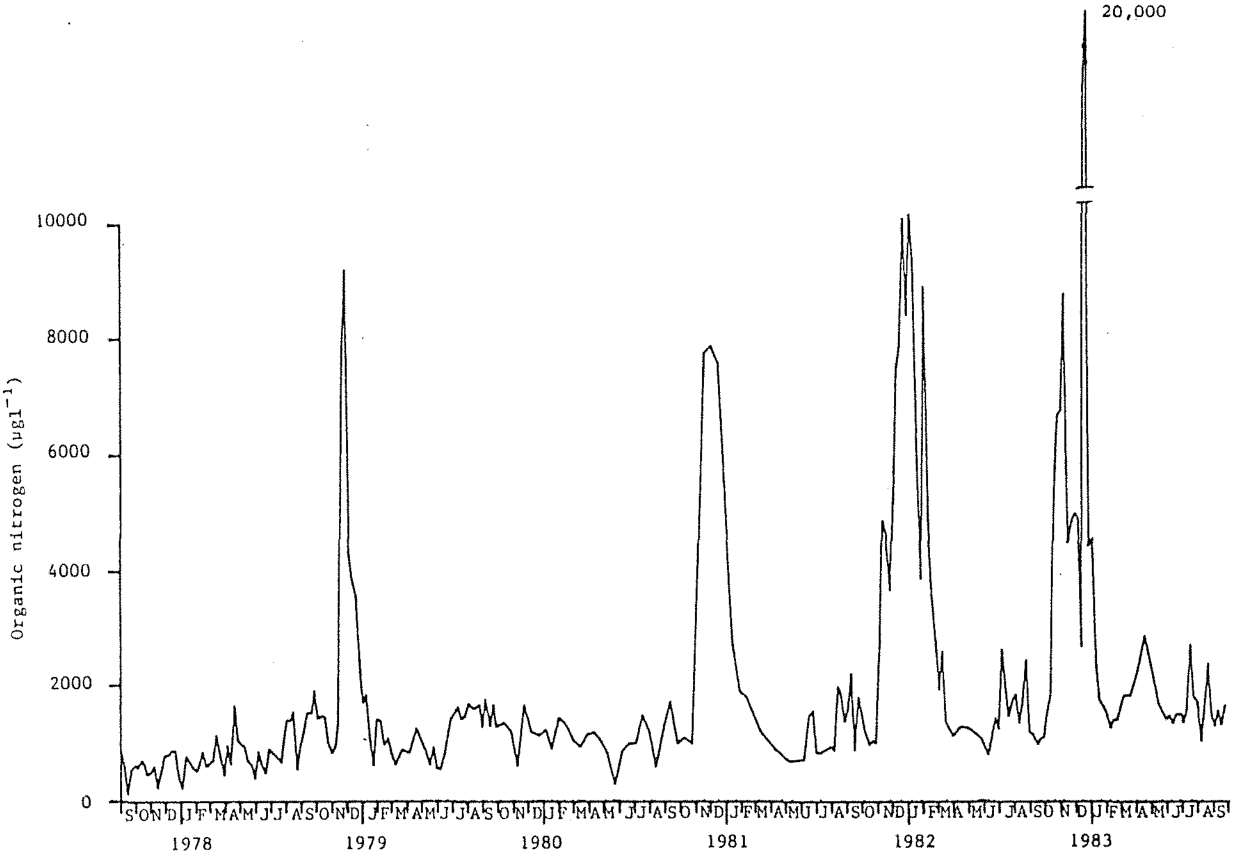

Figure 6. Harvey Estuary mean surface organic nitrogen.

Surface phosphate levels and chlorophyll 'a' are shown in Fig. 7. Phosphate levels are relatively low until the onset of river flow in winter and the diatom blooms follow almost immediately, the Nodularia blooms occur some 12 weeks later. The largest Nodularia bloom followed the winter with the largest phosphate load.

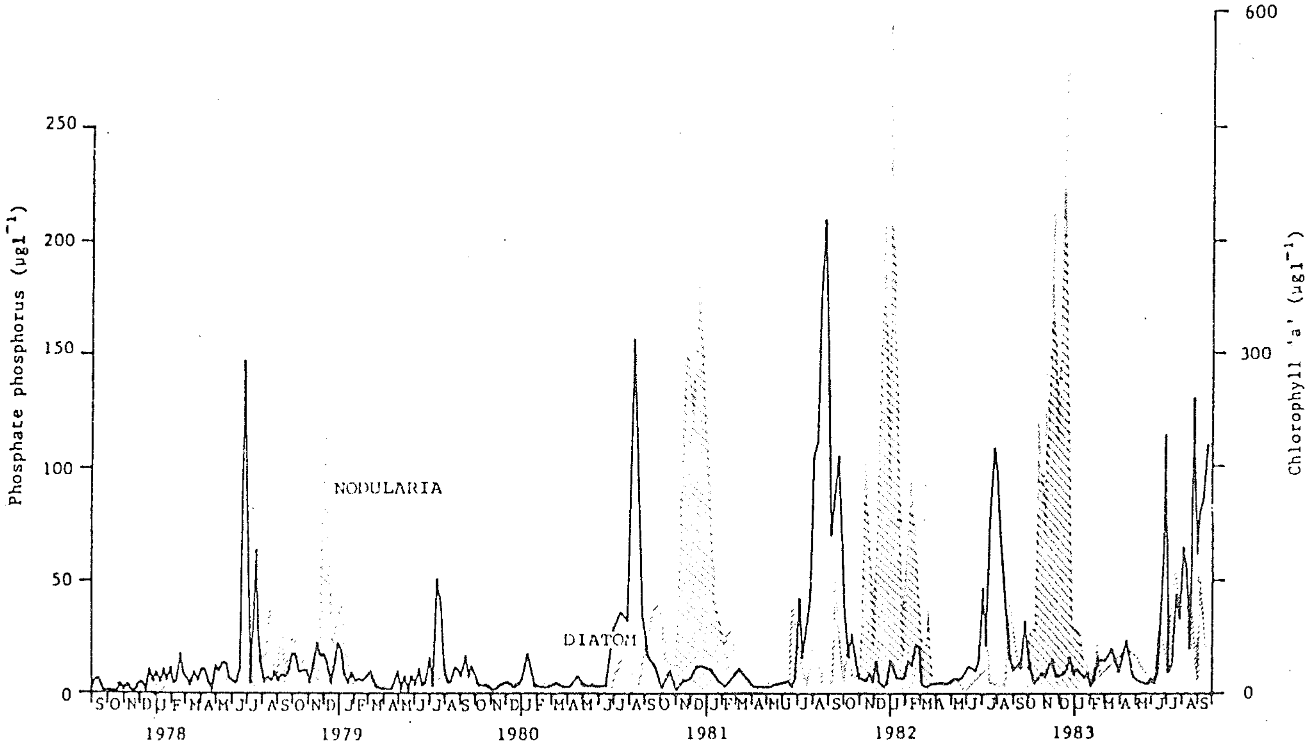

Figure 7. Harvey Estuary mean surface phosphate phosphorus and mean surface chlorophyll 'a'.

No significant blooms were recorded in 1979. There was a very small diatom bloom but no Nodularia bloom. The explanation for this is the reduced phosphorus input in 1979, due to well-below average rainfall. As has been shown, nitrogen was unlikely to have been limiting phytoplankton growth at this time. The relationship between the phosphate load and the magnitude of the Nodularia bloom is clearly shown in Fig. 8, in which the maximum mean Nodularia chlorophyll 'a' concentration is plotted against the Harvey River phosphorus load. This clearly shows the relationship between the current year's river phosphorus load, and the magnitude of the following Nodularia bloom.

Surface 'organic' phosphorus levels are shown in Fig. 9. The peaks are due to the Nodularia blooms and like nitrogen there appears to have been an increase in levels since 1978.

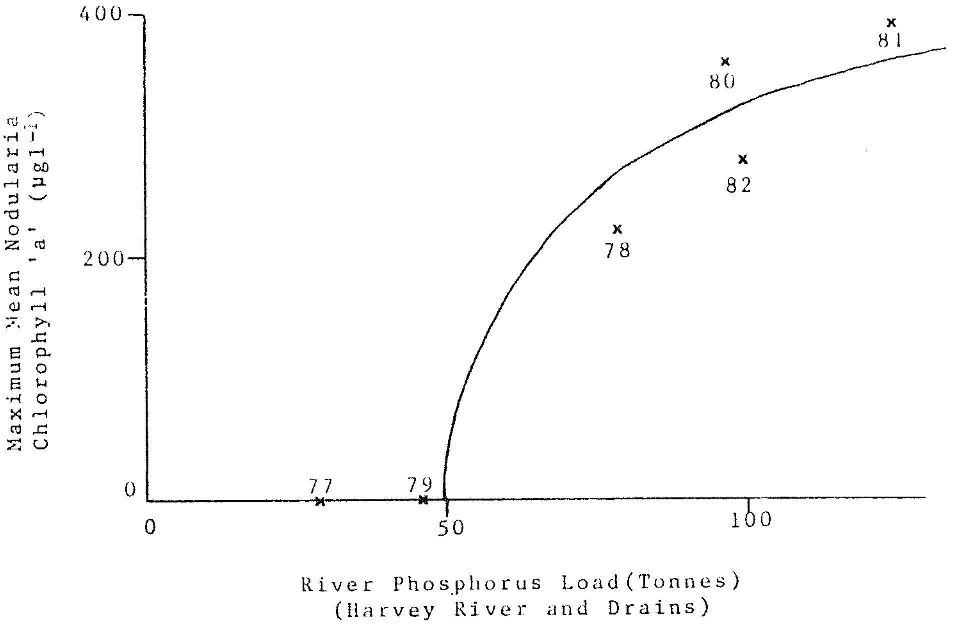

Figure 8. Harvey Estuary maximum mean <u>Nodularia</u> chlorophyll 'a' concentration plotted against river phosphorus load.

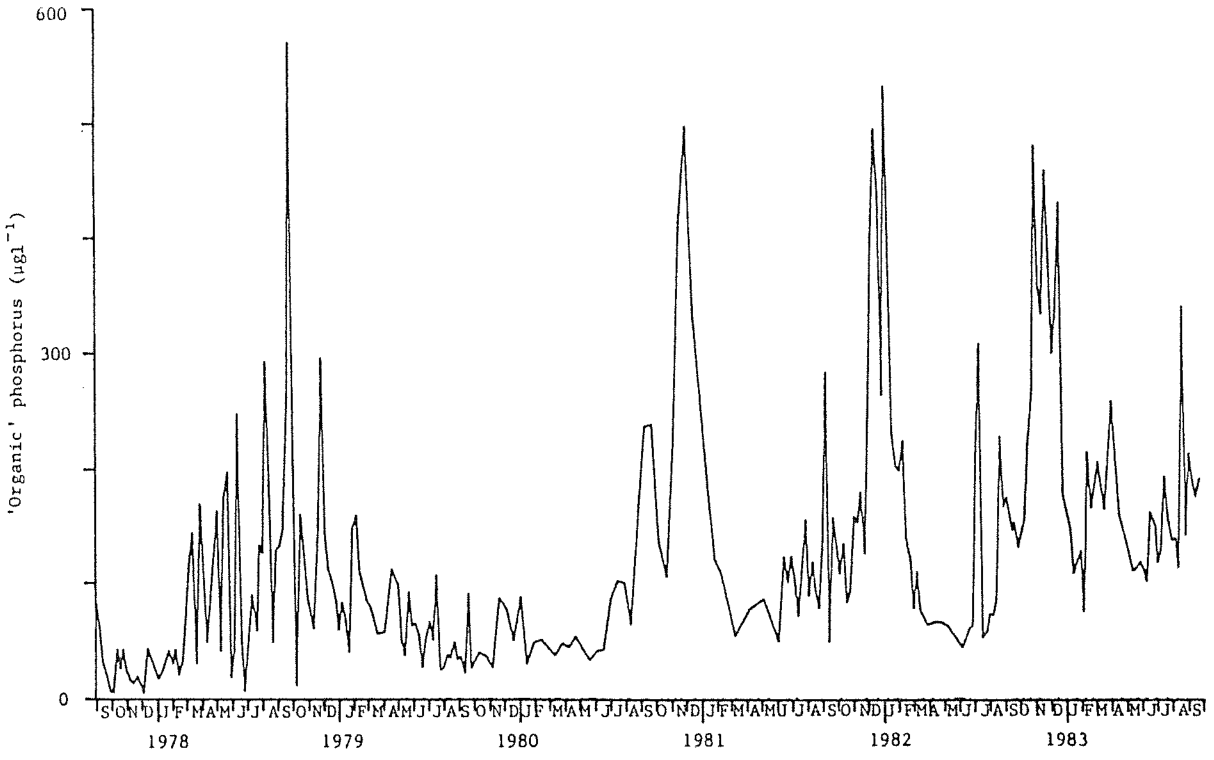

Figure 9. Harvey Estuary mean surface 'organic' phosphorus.

There are several factors that could account for the succession from diatom-dominated blooms to Nodularia blooms.

Temperature probably limits Nodularia growth during the winter period when the diatoms bloom. Nodularia is a thermophilic alga. Hubel and Hubel (1980) state that a minimum temperature of 17°C is required for the mass growth of Nodularia. Water temperatures have risen to 20°C before Nodularia first becomes conspicuous in the Harvey.

Nitrogen-fixing blue-green algal growth potential is increased by a low inorganic nitrogen to phosphorus ratio. However, when conditions are suitable for sediment phosphate release, large amounts of ammonium are also released from the sediments, up to 200 mg NH_4-N m^{-2} day^{-1}.

Silicon depletion has often been shown to be responsible for the collapse of diatom blooms. Silicon recycles at a much slower rate than either nitrogen or phosphorus. Silicate levels do decline at the time of the diatom blooms. However, levels rarely reach limiting proportions.

Selective grazing by zooplankton has often been suggested as a cause for diatom to blue-green succession. Zooplankton biomass peaks in spring at the time of diatom to blue-green succession, and diatom biomass falls to low levels at this time (Fig. 10). Zooplankton biomass crashes once Nodularia has become dominant. These data suggest selective grazing of diatoms by the zooplankton, which avoid the much larger Nodularia filaments, may be an important factor in accounting for the collapse of the diatom bloom and the dominance of Nodularia.

Once dominant, Nodularia restricts diatom growth as a result of shading, nutrient depletion and carbon-dioxide depletion. The collapse of the Nodularia blooms is probably brought about by a combination of the following factors, high salinity, photo-oxidation and nutrient depletion.

The available data suggest that at the present time the development of the winter diatom blooms (and the following Nodularia bloom) depends upon phosphorus from the current year's riverine input.

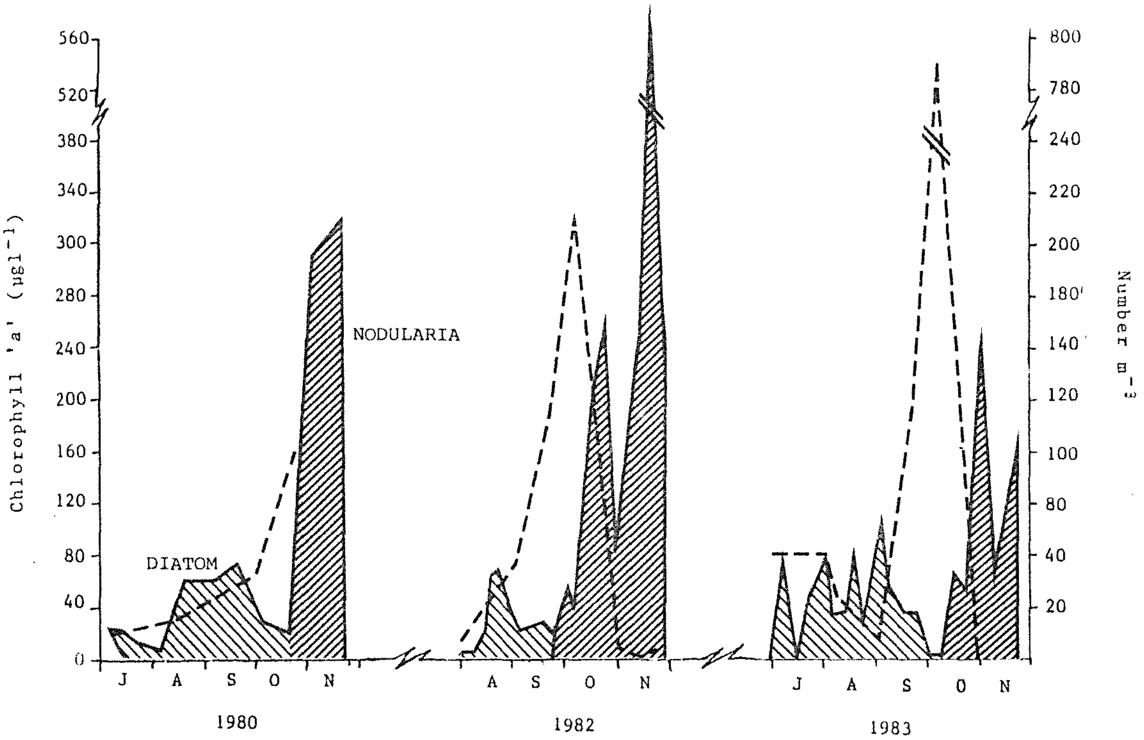

Figure 10. Surface chlorophyll 'a' and zooplankton biomass (number $m^{-3} \times 10^{3}$) at site 1 in the middle of the Harvey Estuary.

The magnitude of the Nodularia bloom is limited by phosphorus, but in winter, the period of major phosphorus input to the system, its growth is limited by temperature.

Nodularia, therefore, relies on recycled phosphorus from the current year's riverine input. The winter diatom blooms which immediately follow river input offer a mechanism by which phosphorus is trapped, sediments out, and becomes available for Nodularia growth when conditions are more favourable. The sediment supply of available phosphorus is not large enough to support a Nodularia bloom unless it is supplemented and enhanced by the collapse of the diatom bloom.

The long-term data suggest that the phosphorus store in the sediments and the recycling of available phosphorus is increasing, and in the future the sediment supply of phosphorus may be large enough to support a Nodularia bloom without any additional riverine input.

Implications for management

1. The data clearly demonstrate the relationship between the magnitude of the Nodularia bloom and the current year's riverine phosphorus input.

2. The long-term data show that there has been an increase in phosphorus, nitrogen and chlorophyll levels since 1978. This suggests that the Harvey has continued to deteriorate since 1978.

3. The obvious solution would be to substantially reduce the input of phosphorus to the system; this has the advantage that it would help solve both the macroalgal and Nodularia problems.

Phosphorus Retention in the Harvey Estuary

In this section some preliminary results of a study carried out in July-August 1983 are presented. The major aims of the study were to determine the amount of phosphorus that is trapped in the Harvey Estuary in a normal flood event, and to determine the major mechanism by which the phosphorus is trapped for later utilization by blue-green algae.

Mean hourly wind speed and direction recorded at Fremantle during the study are shown in Fig. 11. Prior to the commencement

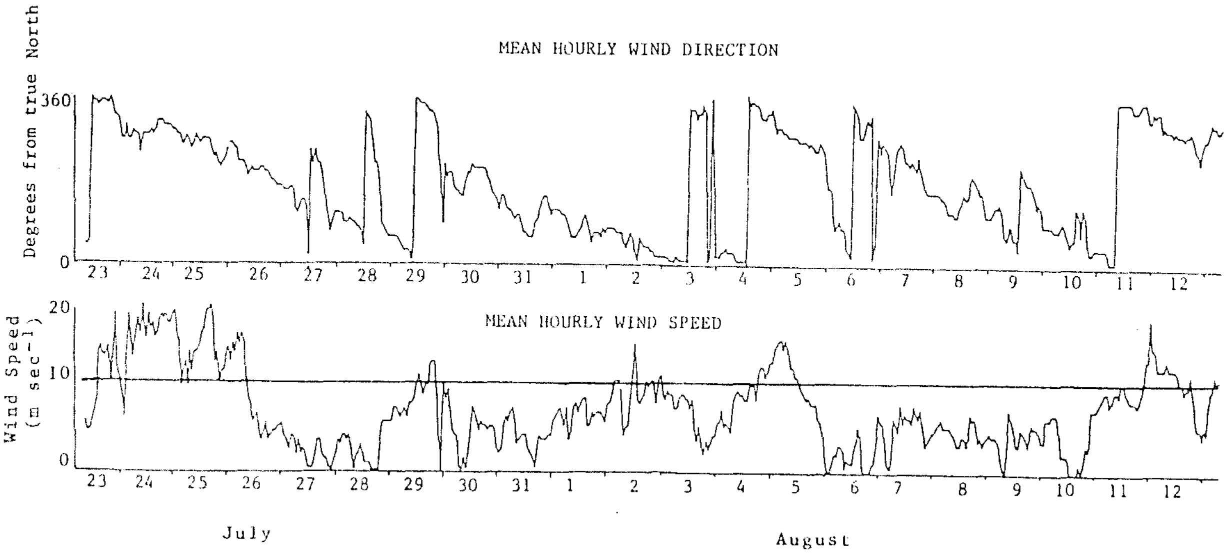

Figure 11. Wind speed and direction for the period 23.7.83 to 12.8.83. (Recorded at Fremantle).

of sampling on the 26th July strong winds and heavy rain were recorded along the S.W. coast due to the passage of a low pressure system over the coast. During the course of the study there were several occasions when the mean hourly wind speed exceeded 10 m sec^{-1} (Fig 11).

As a result of the heavy rain recorded in the Harvey catchment on the 24th and 25th July there was a large flood event at the start of the study (Fig. 12a). Harvey River flow on the 26th July was the highest of the winter. Two further, but much smaller, flood events were recorded during the course of the study.

The Harvey River was sampled daily to determine the phosphorus concentration of the river water (Fig. 12b). Phosphate phosphorus (soluble reactive phosphorus) was the dominant form of phosphorus in the river water, it accounted for 70-80% of the total phosphorus concentration.

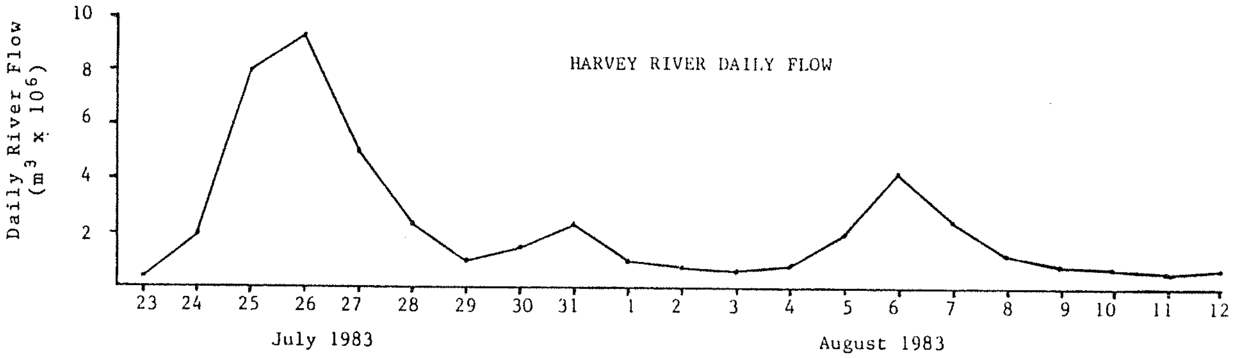

Figure 12a

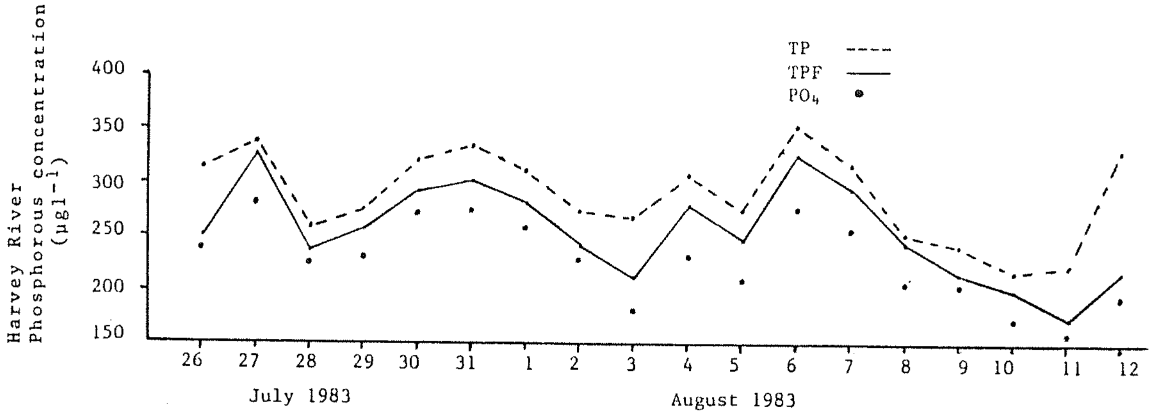

Figure 12b.

Figure 12. Harvey River (a) daily flow and (b) phosphorus concentration for the period 23.7.83 to 12.8.83.

The suspended solids concentration, a measure of the amount of particulate material suspended in the water column, for the Harvey Estuary during the study is shown in Fig. 13a. The peaks were due to strong wind events which caused resuspension of the bottom sediments. Fig. 13b shows the daily Harvey River and Harvey Estuary phosphate load during the study. On the days that strong winds were recorded, and hence an increase in the suspended solids concentration due to the resuspension of the bottom sediments, the Harvey Estuary phosphate load decreased. This was due to adsorption of phosphate phosphorus onto the suspended sediment particles and the subsequent sedimentation of these particles. However, during the calm periods in between the strong wind events, when bottom oxygen levels dropped, phosphate phosphorus was released from the sediments and there was an increase in the Harvey Estuary phosphate load (Fig. 13b). The increase in the Harvey Estuary phosphate load could not be accounted for by input from the Harvey River. Thus, while the sediments were capable of trapping phosphate phosphorus this was later released to the water column.

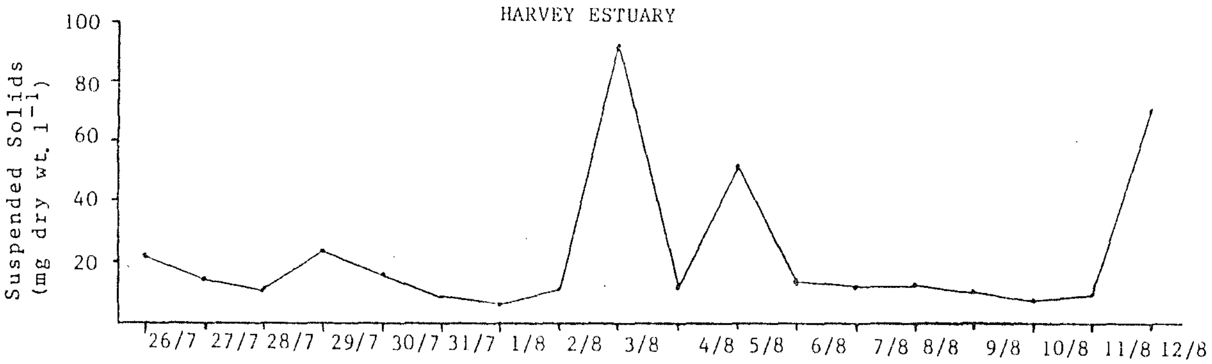

Figure 13a.

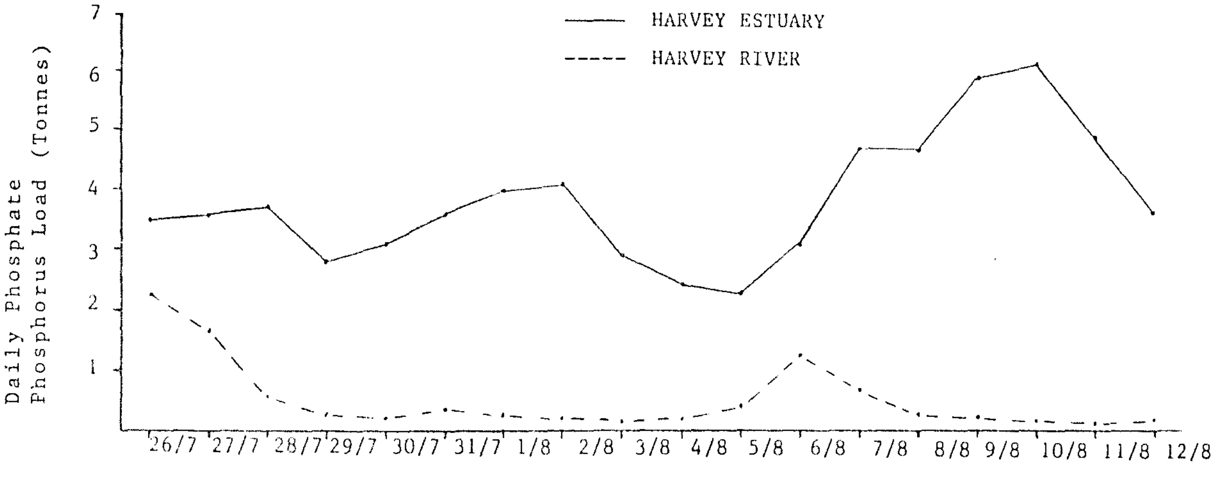

Figure 13b.

Figure 13. (a) Harvey Estuary suspended solids concentration
(b) Harvey Estuary and Harvey River daily phosphorus load.

Typical surface salinity and phosphate phosphorus contours for the study period are shown in Fig. 14. The phosphate distribution was related to salinity. Phosphate levels in the northern half of the Harvey Estuary were below reliable detection limits, almost all of the phosphate had been removed from the water column by the phytoplankton.

Fig. 15 shows surface phosphate contours for the 12th August 1980 and 31st July 1983. On both occasions there was a flood event of similar magnitude 6 days prior to the data being collected.

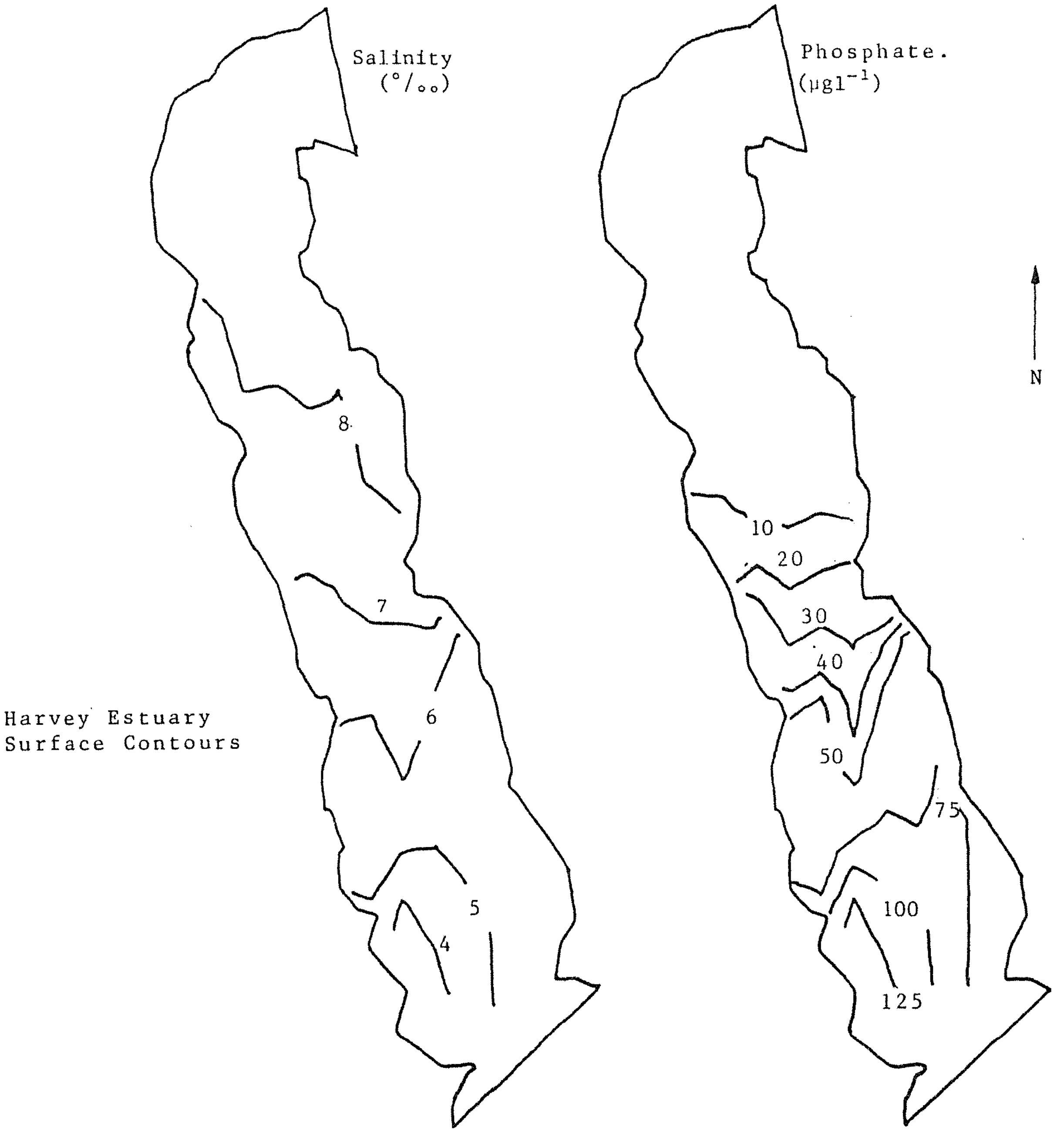

Figure 14. Harvey Estuary surface salinity and phosphate phosphorus contours on 6.8.83.

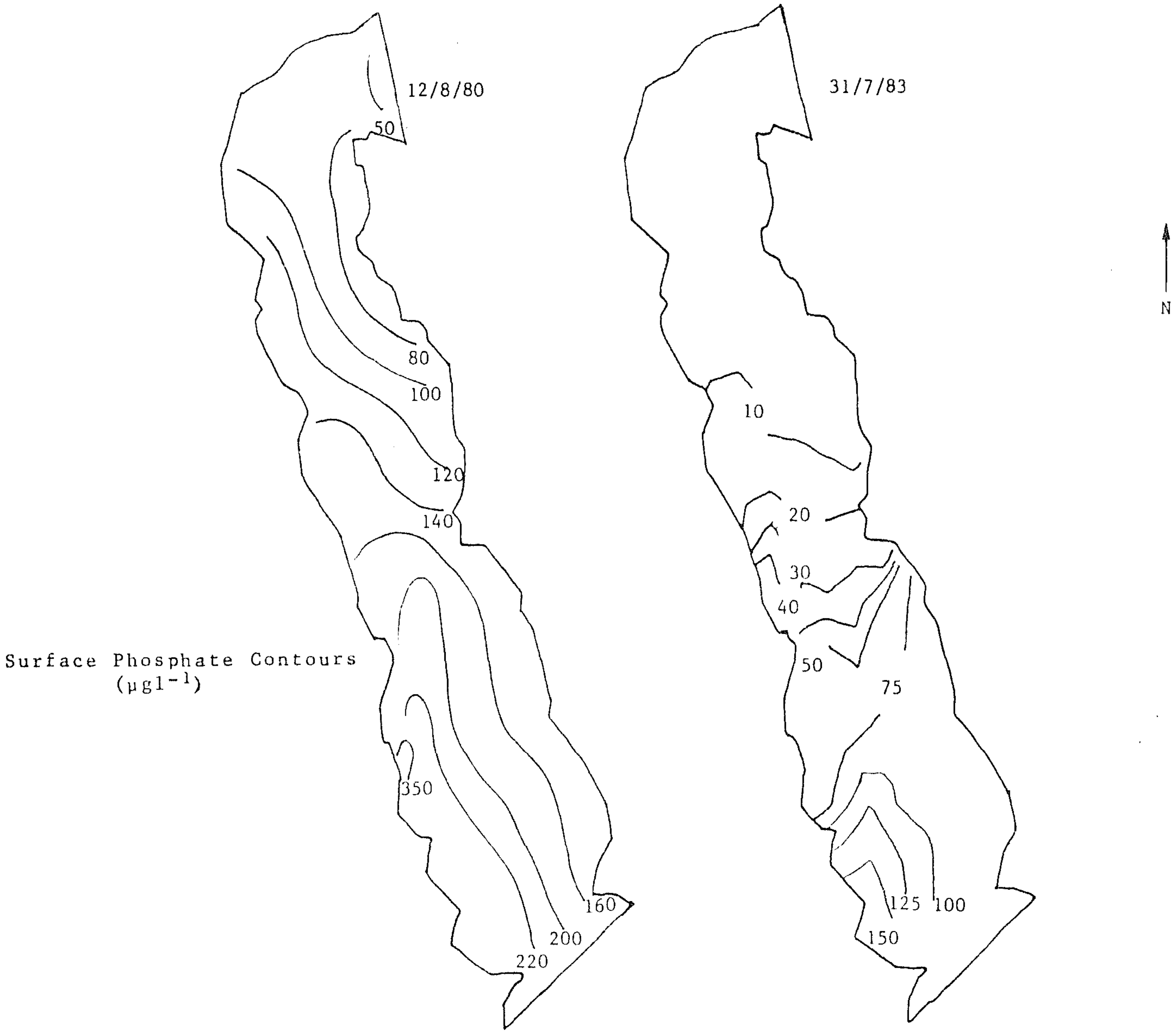

Figure 15. Harvey Estuary surface phosphate contours.

There is a large difference between the two occasions in surface phosphate levels in the northern end of the Harvey Estuary. The major difference between the two occasions was that phytoplankton levels in the 1983 study were approximately 10 times those in the 1980 study.

A salt budget for the Harvey Estuary for the study period was calculated from a water budget, and this was compared with the observed salt loss. Table 3 shows that the observed salt loss was approximately 650,000 tonnes, and the calculated salt loss based on the water budget was approximately 630,000 tonnes.

TABLE 3. PRELIMINARY SALT BUDGET FOR THE HARVEY ESTUARY FOR THE PERIOD 26-7-83 TO 12-8-83

OBSERVED SALT LOSS (TONNES) x 10^3	SALT LOSS CALCULATED FROM WATER BUDGET (TONNES) x10^3
654	626

These two values are comparable. This implies that the water budget was a reasonable approximation of the water exchange between northern Harvey and Peel Inlet during the study. Using the water budget a phosphorus budget was calculated for the Harvey Estuary for the study period (Table 4). With the adjustment for the difference in water level of 18 cm between the beginning and end of the study, the budget shows that almost all (99%) of the phosphate phosphorus which entered the Harvey during the study was trapped by the phytoplankton. Up to 75% of the total amount of phosphorus which entered the Harvey during the study was retained in the Harvey.

Implications for management

1. Phytoplankton were the major mechanism of trapping phosphorus in the Harvey Estuary during this study.

2. Almost all of the phosphate phosphorus, the dominant form in which phosphorus enters the Harvey via river flow, which entered the Harvey during the study was trapped by the phytoplankton.

3. Up to 75% of the total amount of phosphorus which entered the Harvey during the study was retained in the Harvey.

4. Due to increasing phytoplankton levels in the Harvey Estuary in recent years, phosphorus retention has also probably increased.

TABLE 4. PRELIMINARY PHOSPHORUS BUDGET FOR THE HARVEY ESTUARY
FOR THE PERIOD 26-7-83 TO 12-8-83

RIVER PO_4-P LOAD (tonnes)	RIVER T.P. LOAD (tonnes)	PO_4-P LOST FROM HARVEY ESTUARY (tonnes)	T.P. LOST FROM HARVEY ESTUARY (tonnes)	PO_4-P RETAINED IN HARVEY ESTUARY (tonnes)	T.P. RETAINED IN HARVEY ESTUARY (tonnes)
9.57	11.94	0.16	5.81	9.41 (98%)	6.13 (51%)
*		0.08	3.04	9.49 (99%)	8.90 (75%)

*Water Level Adjustment

PO_4-P = PHOSPHATE PHOSPHORUS

T.P. = TOTAL PHOSPHORUS

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IN-ESTUARY STUDIES AND THEIR RELEVANCE TO MANAGEMENT:

THE SEDIMENTS AND THE MOVEMENT OF PHOSPHORUS

By Denis Kidby, John Gabrielson, and Christina Huse

SUMMARY: The movement of phosphorus is discussed in terms of transfer between the sediments and the water column. An analysis of mechanisms is performed in terms of the forms of phosphorus present, primary and secondary mechanisms of transfer either to or from the sediments, and the conditions which are conducive to the various transfer mechanisms.

An indicative model for phosphorus transfer from the Harvey Estuary is explained in terms of its parameters and the application of the model. The model examines the influence of riverine phosphorus loading and variation in flushing rates on the net movement of phosphorus to the ocean. The model indicates the extent to which the net transfer of phosphorus is driven by biological assimilation. The model predictions are also relatable to recent studies on sediment phosphorus depletion by biological assimilation.

An increased summer flushing rate is indicated to profoundly increase the rate of run-down of the sediment phosphorus bank.

1. Introduction The present purpose is to explain the role of mechanisms of phosphorus transfer to and from the sediments and to present the results of an indicative model for the transfer of phosphorus out of the Harvey Estuary.

1.1 Macro-exchange between hydrological components The steps in the chain of events leading to the high P status of the waters and sediments of the Peel/Harvey system are: (i) movement of P from catchments areas to rivers and drains; (ii) transfer of P from rivers and drains to the Peel/Harvey; (iii) failure of ocean exchange to adequately flush P from the Peel/Harvey.

1.2 Micro-exchange within the Peel/Harvey The net exchange process of consequence to the problem of excess P in either or both of the sediment and the water column is the exchange between the water column and the sediments. The division of P between sediment and water column is of fundamental importance because only the water column P can be lost to ocean exchange.

1.3 Components of water column P For the present purposes it may be most useful to simply distinguish between P free in solution and P not in free solution or sedimentable P.

1.4 Components of sedimentable P Within this category it is useful to distinguish between living and non-living material. Living primary producers tend to stay in the water column longer than non-living material (although there are notable exceptions such as diatoms). They are therefore potentially good vehicles for the export of P to and from the Ocean.

1.5 Mechanisms of sediment - water column exchange. The simplest categorization of P movement is to consider this as moving in either of two directions, viz., either from the sediments or to the sediments. This approach is used in the following discussion as an aid to clarity rather a denial of the complex equilibria involved in many of these mechanisms.

The major question which is being addressed is: which mechanisms influencing net P retention are likely to be most important?

2 ANALYSIS OF MECHANISMS OF PHOSPHORUS MOVEMENT

2.1 Biological asimilation of orthophosphate Biological assimilation of water column P (Table 1.1) is sufficiently rapid to be a significant P trap where the flushing rate is low and growth is rapid.

2.2 Precipitation of Orthophosphate Precipitation of water column P (Table 1.2) would be expected to be too rapid to be influenced by either biological assimilation or flushing rates. Oxygen levels and pH would be expected to be frequently conducive but both calcium and iron might be expected to be limiting. Nevertheless, the response of sediments to oxygenation implicates this as a significant mechanism.

2.3 Exchange of orthorphosphate The contribution of sediment exchange capacity to the uptake of ortho-phosphate (Table 1.3) is greatly influenced by pH and chloride levels but may generally be expected to contribute to the retention of incoming phosphorus at all times. It should be noted that while the exchange characteristics of the sediments may have a significant bearing on how much is taken up, they may not greatly influence the amount let go by the sediment in response to biological assimilation. This is because the threshold for P uptake by most organisms is much lower than the equilibrium point concentrations for exchangeable P in these sediments.

2.4 Phosphatase activity Organic posphorus in solution, while rarely in high concentration is a necessary intermediate in the recycling of phosphorus following biological assimilation. The reason for this is that few, if any, organisms can take up, for nutritional purposes, organic phosphates. In the Peel/Harvey system there would appear to be relatively high levels of phosphatase and it is concluded on this basis that this would not normally be limiting (Table 1.4).

2.5 Precipitation of organic phosphorus The mechanism and speed at which poorly soluble salts of organic and inorganic phosphates are formed are sufficiently similar to suggest that organic phosphate would also be a significant contribution to the poorly soluble P component of sediments (Table 1.5).

2.6 Sedimentation of non-living insoluble material While much of the riverine P input is orthophosphate in solution the non-biological particulate phosphorus level (Table 1.6) in the Harvey Estuary in particular is frequently significant. More important than the contribution to the P load of the water column is the contribution of this fraction to the rate of P transfer between water and sediment. Thus it is seen as being more important as a fluxing mechanism than as a suspended load.

2.7 Sedimentation of biomass The water column primary producer of biomass (Table 1.7) varies in its potential for sedimentation according to species, age, and the influence of light and dissolved gas levels. The points to be made here are the following:

2.7.1 Many species do spend long periods in the water column before sedimenting.

2.7.2 Many species concentrate intracellular P to high levels.

2.8 Assimilation from the intenstitial solution The sediment interstitial solution (Table 2.1)and in particular the solution closely surrounding particles are significant from a mechanistic viewpoint because all transfers between the particulate fraction and the bulk solution are subject to these environments. At or near to particulate surfaces, concentration of many of the most important species will differ greatly from that in the bulk solution. Redox potential and pH in particular are likely to be lower, and solutes in general are likely to be higher at or near sediment particle surfaces.

The surface and near-surface chemistry of the sediment particles is a critical determinant of the transfer of P from the sediment to the water column. However, despite the mechanistic significance of surface chemistry this probably does not play a significant role in limiting the movement of P from the sediment to the water column provided that this transfer results from biological assimilation. The reasons for this have already been elaborated upon (Section 2.3).

All species are probably capable of reducing sediment phosphorus to acceptably low levels.

It is possible to conclude that the primary producers which concentrate high intracellurlar P levels from very low extracellular P levels, and which remain in the water column for long periods, have the potential to rapidly deplete sediment P. This view is supported by studies on phosphorus depletion of sediments by biological assimilation.

2.9 Assimilation of exchangeable orthophosphate Exchangeable orthophosphate (Table 2.2) does not undergo net transfer unless the solution concentration is very low or the salt or pH levels are high. The significance of this is that at moderate salinity levels and normal pH the net exchange of orthophosphate from the sediments is not favoured unless some secondary mechanism such as biological assimilation is withdrawing phosphate from the water column.

Thus sediments will generally lose phophorus only to assimilation in the water column.

2.10 Assimilation of precipitated phosphorusPrecipitated phosphorus (Table 2.3) is a significant fraction as evidenced by the large release of phosphorus from sediments subjected to anaerobic treatment. The low oxygen associated with bloom collapse will assist in the release of this form of phosphorus. The raised pH associated with the bloom collapse will tend to have the opposite affect on low solubility P salts.

2.11 Mineralization Mineralization rates of phosphorus (Table 2.4) will vary according to the organisms involved. Microbes such as *Nodularia* being rapidly mineralized while macrophytes such as *Cladophora* are relatively slow to break down. The ultimate step in mineralization, phosphatase catalysed hydrolysis of phosphate esters, would appear unlikely to be limiting in this system.

2.12 Grazing and Predation While the role of grazers and predators (Table 2.5) is not clear, it is apparent that these play no major role in the movement of phosphorus from the sediment to the water column under bloom conditions.

2.13 Resuspension All forms of sediment phosphorus are subject to resuspension (Table 2.6). In most cases the periods of resuspension will be too brief to result in a net loss to the ocean. However, even brief periods of resuspension will be of importance in facilitating the transfer of phosphorus by other mechanisms.

3 AN INDICATIVE MODEL FOR PHOSPHORUS TRANSFER FROM THE HARVEY ESTUARY

3.1 Aims of the model The model examines the influence of several variables on the net movement of phosphorus from the Harvey Estuary. Of particular interest are effects of riverine phosphorus loading, flow volume, and flushing rates.

The details of the model parameters, equations, and constants employed, are provided in Appendix 1.

3.2 Harvey River phosphorus loading and phosphorus retention. The result of varying the Harvey river P loading (concentration varied and constant flow volume) is seen in Figure 1.
The relative lack of response to low level loading (20 tonnes) suggests that the reduction of present loadings of ca. 60 tonnes

by even as much as two thirds may not reduce the long-term trend of sediment phosphorus enrichment.

3.3 Harvey River volume and phosphorus retention The response to an increased river volume flow (Figure 2 is limited to a less than one third reduction in retained P for a three-fold increase over recent (ca. 200 x $10^6 m^3$) flow volumes. This result suggests that even substantial increases in river flow volume will not arrest the long term-increase in sediment phosphorus levels.

3.4 Water Column retention rate and phosphorus retention The examination of this influence is not, in any strict sense, related to the independent variables encountered in this system. However, the water column retention rate is conceptually useful in certain areas of analysis, eg, determination of flux directions.

Figure 3 shows the effect on retention of P for retention rates of 0.25 to 1.5. Thus at a retention rate of 1.2 (where 1/6 of the water column P is derived from the sediment) there is a net depletion of ca. 13 tonnes of phosphorus.

3.5 Background phosphorus and phosphorus The background phosphorus of the estuary reflects the sum retention total of all the influences upon free phosphorus levels in the water column of the estuary. The reason for examining this influence was to assess whether or not a reduction to sea water P levels (ca. 26 mg m^{-3}) would have a significant influence on P retention. The extremely flat response curve (Figure 4) is perhaps not surprising since the sediments can only be depleted to the extent that the water column is loaded with phosphorus, and the most significant loading for purposes of net P loss in the system is biomass rather than background P.

3.6 Winter flushing rate and phosphorus retention Even a two - to three-fold increse in summer flushing rate (assuming the present summer flushing rate to be ca. 0.08) has a profound influence on the retention of phosphorus (Figure 6). A run-down of sediment P is indicated to be rapidly effected by an increase in the range three- to five-fold.

This influence may be attributed to high water column P loads during the summer. The length of the summer period is also of significance. The model has been used to indicate the effect seen in only the first year. However, so long as available sediment P levels remained high the depletion rate would be significant.

3.7 Summer flushing rate and phosphorus retention Even a two - to three-fold increase in summer, flushing rate (assuming the present summer flushing rate to be ca. 0.08) has a profound influence on the retention of phosphorus (Figure 6). A run-down of sediment P is indicated to be rapidly effected by an increase in the range three - to five-fold.

This indluence may be attributed to high water column P loads during the summer. The length of the summer period is also of significance. The model has been used to indicate the effect seen in only the first year. However, so long as available sediment P levels remained high the depletion rate would be significant.

3.8 Applicability of the model The present model is considered to have both heuristic and indicative value. The model is sufficiently general to be of application to the Peel Inlet also, but in this latter case, it would be necessary to segregate the water column and sediments into more than one mixed compartments. This should present no great difficulties but would certainly produce some complex interactions.

4 Conclusions and Recommendations A brief review of the compartments and mechanisms of phosphorus movement to and from the sediments has been presented. The relative importance of various transfer processes for P has been assessed.

An indicative model suggests that a relatively modest increase in summer flushing rate should rapidly run down the sediment phosphorus bank. Even significant depletion of riverine P loading is indicated to have relatively little effect on the rate of phosphorus build-up in the estuary.

It is recommended that the model be further developed in order to improve its value as an indicative technique.

TABLE 1 MECHANISMS OF MOVEMENT OF PHOSPHORUS FROM WATER COLUMN TO SEDIMENT

	FORM OF PHOSPHURUS		PRIMARY MECHANISM	SECONDARY MECHANISM	CONDUCIVE CONDITIONS
1.1	ORTHOPOSPHATE	→	BIOLOGICAL ASSIMILATION		GROWTH
			↘	SEDIMENTATION	MORIBUND CALM
1.2	ORTHOPHOSPHATE	→	PRECIPITATION		OXYGEN ↑ pH↑ Ca^{+2},Fe^{+3}↑
1.3	ORTHOPHOSPHATE	→	EXCHANGE		WATER COLUMN Pi↑ Cl^{-1}↓ pH↓
1.4	ORGANIC PHOSPHORUS	→	HYDROLYSIS TO ORTHOPHOSPHATE		PHOSPHATASE↑
			↘	(1 - 3)	
1.5	ORGANIC PHOSPHORUS	→	PRECIPITATION		OXYGEN↑ pH↑ Ca^{+2},Fe^{+3}↑
1.6	PARTICULATE PHOSPHORUS (NON-BIOLOGICAL)	→	SEDIMENTATION		CALM
1.7	PARTICULATE PHOSPHORUS (BIOMASS)	→	SEDIMENTATION		MORIBUND CALM

TABLE 2 MECHANISMS OF MOVEMENT OF PHOSPHORUS FROM SEDIMENT TO WATER COLUMN

	FORM OF PHOSPHORUS	PRIMARY MECHANISM	SECONDARY MECHANISM	CONDUCIVE CONDITIONS
2.1	INTERSTITIAL SOLUTION →	BULK SOLUTION TRANSFER		STIRRING
		↘	BIOLOGICAL ASSIMILATION	GROWTH
2.2	EXCHANGEABLE →	EXCHANGE		WATER COLUMN Pi↓ Cl^-↑ pH↑
		↘	BIOLOGICAL ASSIMILATION	GROWTH
2.3	PRECIPITATED →	DISSOLUTION		OXYGEN↓ pH↓ Ca^{+2}, Fe^{+3}↓
		↘	BIOLOGICAL ASSIMILATION	GROWTH
2.4	BIOMASS PHOSPHORUS (MINERALIZING) →	HYDROLYSIS TO ORTHOPHOSPHATE	↗	P:N RATIO↓ PHOSPHATASE↑
2.5	BIOMASS PHOSPHORUS (NON-MINERALIZING) →	BIOLOGICAL ASSIMILATION (GRAZING)		GRAZERS↑
		↘	BIOLOGICAL ASSIMILATION (PREDATION)	PREDATORS↑
2.6	ALL OF ABOVE (1-5) →	RESUSPENSION		STIRRING

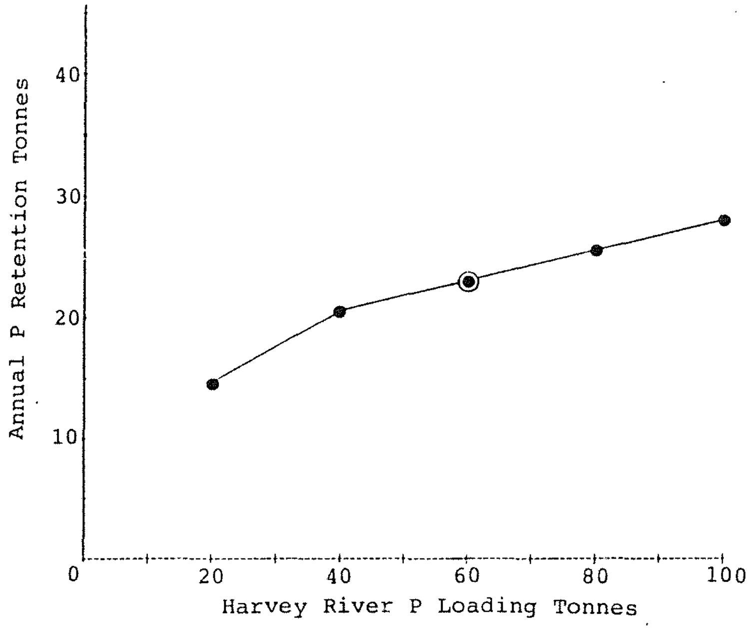

FIGURE 1 : Harvey River P loading vs. P retention

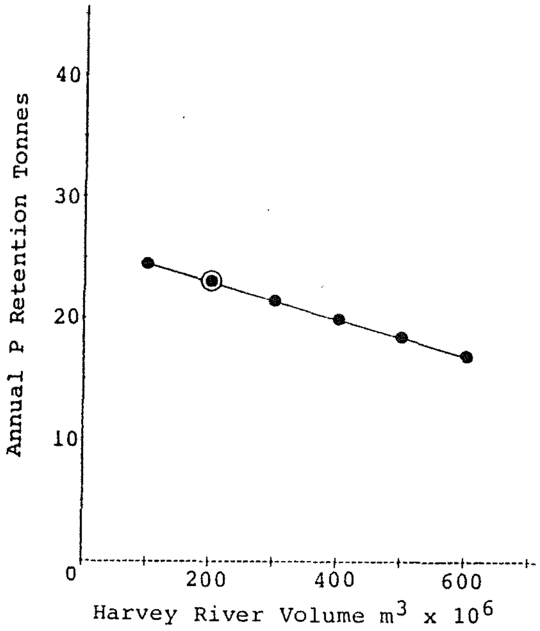

FIGURE 2 : Harvey River volume vs P retention.

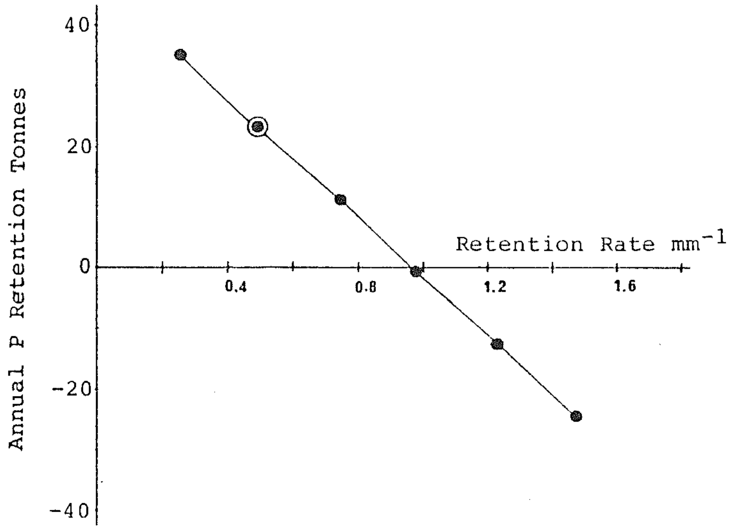

FIGURE 3 : Retention rate vs P retention

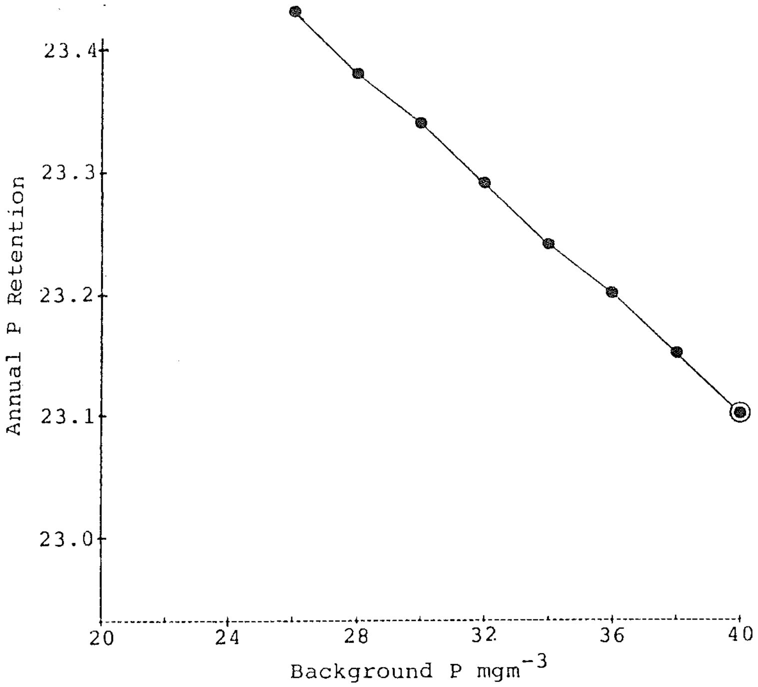

FIGURE 4 : Background P vs P retention

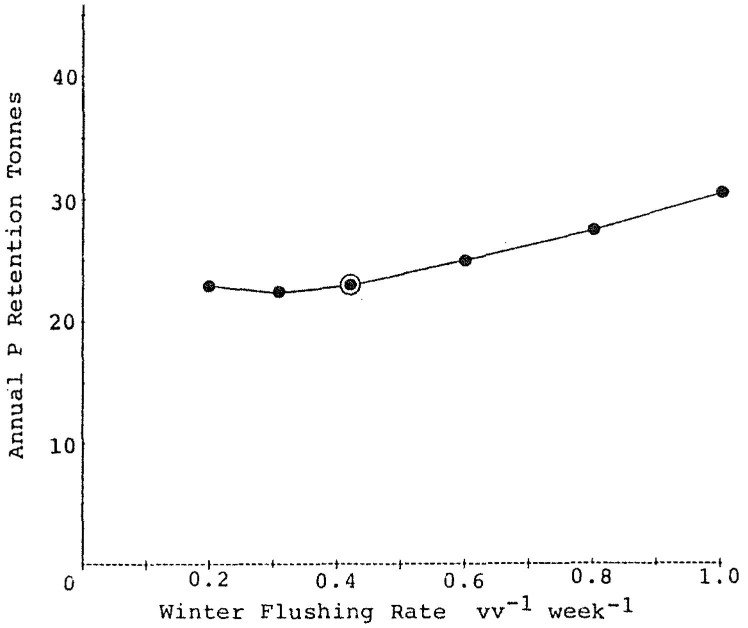

FIGURE 5 : Winter flushing rate vs P retention.

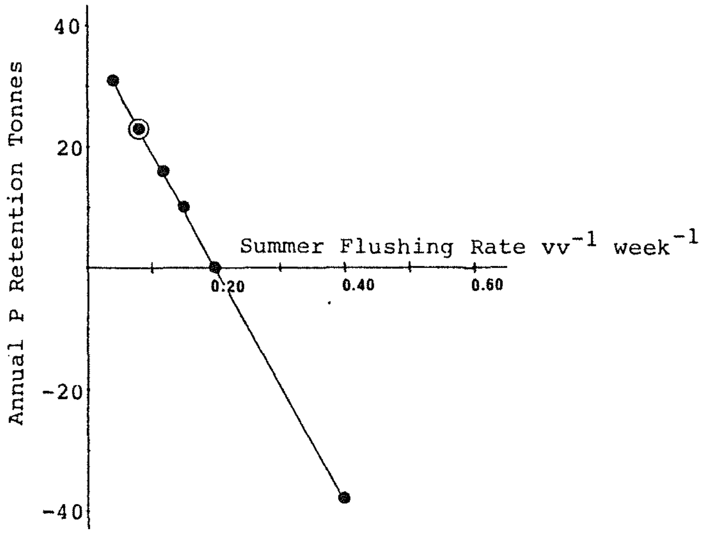

FIGURE 6 : Summer flushing rate vs P retention

APPENDIX 1

MODEL PARAMETERS

A = Harvey River total phosphorus concentration, mg m^{-3}

B = Harvey River loading, tonnes

C = Harvey Estuary water column retention rate during winter period, M M^{-1}

C1 = Harvey River flow volume, m^{3} x 10^{6}

C2 = Mean winter flushing rate, V V^{-1}week^{-1}

C3 = Time during which mean winter flushing rate, C2, is operative, weeks

C4 = Phosphorus concentration of sea water, mg m^{-3}

C5 = Mean winter water column phosphorus contributed from estuarine sources mg m^{-3}

Chla = Chlorophyll *a*, mg m^{-3}

D = Mean winter water column phosphorus in the Harvey Estuary from all sources, mg m^{-3}

E = Winter phosphorus loss from Harvey Estuary through flushing exchange with sea, tonnes

F = Loss of phosphorus during winter as a percentage of Harvey River loading, %

G = Peak summer phosphorus concentration in Harvey Estuary, mg m^{-3}

H = Peak summer phosphorus load in Harvey Estuary, tonnes

H2 = Mean summer flushing rate, V V^{-1}week^{-1}

/contd....

H3 = Time during which mean summer flushing rate is operative, weeks

I = Ratio of peak summer biomass phosphorus to phosphorus retained in Harvey Estuary in winter, $M\ M^{-1}$

J = Mean summer phosphorus concentration in Harvey Estuary, $mg\ m^{-3}$

K = Summer phosphorus loss from Harvey Estuary through flushing exchange with sea, tonnes

L = Nett annual retention of phosphorus in Harvey Estuary, tonnes

MODEL EQUATIONS

$$B = \frac{A \times C1}{1000} \qquad \ldots\ldots\ 1$$

$$D = C \left\{ \frac{C1 \times A + 56 \times C5 + (C2 \times C3 - C1)C4}{56(C2 \times C3 + 1)} \right\} \qquad \ldots\ldots\ 2$$

$$E = 0.056 \times C2 \times C3 \times D - (0.056 \times C2 \times C3 - \frac{C1}{1000} \qquad \ldots\ldots\ 3$$

$$F = \frac{E}{B} \times 100 \qquad \ldots\ldots\ 4$$

$$G = 1.4(9.1 \times B - 256) \qquad \ldots\ldots\ 5$$

$$H = 0.056 \times G \qquad \ldots\ldots\ 6$$

$$I = \frac{H}{B-E} \qquad \ldots\ldots\ 7$$

$$J = 0.2 \times G + 30 \qquad \ldots\ldots\ 8$$

$$K = 0.056 \times H_2 \times H_3 \times (J - 26) \qquad \ldots\ldots\ 9$$

$$L = B - (E + K) \qquad \ldots\ldots\ 10$$

CONSTANTS EMPLOYED IN EQUATIONS

Equation 2. 56 = Harvey Estuary volume x 10^{-6}

Equation 3. 0.056 = Harvey Estuary volume x 10^{-9}

Equation 5. 1.4 = $\frac{G}{Chla}$

(Derived from a proposed relationship between peak summer phosphorus and chlorophyll a levels associated with *Nodularia* blooms, where chl a = mg m^{-3} chlorophyll a)

/contd....

9.1 = gradient terms of a proposed linear function relating B and chlorophyll *a*

-256 = intercept term of the above linear function

Equation 8. 0.2 = proportion of summer peak biomass phosphorus contributing to the summer period mean phosphorus level

30 = basal phosphorus concentration over summer period, $mg\ m^{-3}$

Equation 9. 0.056 = Harvey Estuary volume x $10^{-9} m^3$

26 = Sea water phosphorus concentration, $mg\ m^{-3}$

CYANOBACTERIA IN THE PEEL-HARVEY ESTUARY WITH PARTICULAR REFERENCE TO NODULARIA, PHOSPHORUS AND MANAGEMENT.

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Nodularia spumigena Mertens is the major species of nuisance cyanobacteria in the Peel-Harvey estuarine system. Many others are present, but only three genera occur or have occurred in nuisance proportions: Oscillatoria, Anabaena, and Microcystis. The Oscillatoria species that occurs is a benthic species and, therefore, is not a serious problem except in retaining nutrients in the estuary. The Microcystis and Anabaena species that occur are primarily freshwater species. Since none of the favoured management options will decrease the salinity, these species are not serious potential risks. This paper will be limited to the problem of Nodularia.

In order to assess any management options, we must first understand how Nodularia will respond to the changes these measures would bring about. The aspects of Nodularia which are of most significance in assessing the management options for the Peel-Harvey Estuary will be discussed.

There are three stages in the Nodularia life cycle which must be considered separately with respect to possible control mechanisms: 1. bloom initiation involving akinete germination, 2. the bloom, including initial rapid growth and stationary phases, and 3. bloom decline.

1. Bloom initiation.

The effects of light, temperature, salinity, phosphorus, nitrogen and iron on akinete germination have been determined. It is considered that massive germination of akinetes in the surface sediments requires a significant exposure to light, >16^{o}C, <20 ppt salinity , >10 ug PO_4-P/l, and <500 ug NH_4-N/l. Within these bounds, the timing and distribution of Nodularia blooms has been very consistent (Tables 1, 2). In 1979, the primary missing factor appears to be PO_4-P. High phosphorus events occurred in July '79 and January '80, but salinities were high. Hence, no bloom occurred. In both 1981-82 and 1982-83 there were prolonged periods during which Nodularia germination could have taken place, especially in the Harvey Estuary. These periods extended well into the blooms, and could have contributed to the overall size and length of the blooms. It is also interesting to note that the January '82 flood created conditions suitable for germination at a time when the bloom was declining. There was subsequent regrowth of the bloom, part of which may have been due to recruitment of germinating akinetes from the sediments.

2. Bloom growth and stationary phases.

Once a Nodularia bloom is established, it remains at a more or less constant standing biomass (Fig 1). However, in situ studies indicate that Nodularia maintains a growth rate in the estuary which is similar to that obtained in P-enriched laboratory cultures (Fig 2). Figure 3 demonstrates the growth of the Nodularia in a bloom (growth rate 0.25 day^{-1}), the biomass losses from the bloom, and the recycling of phosphorus from decomposing biomass back into the standing biomass. The minimum amount of phosphorus which must be given up by the sediments in order to maintain the standing biomass can be estimated. During a bloom, the sediments are continually being depleted of phosphorus, with the most rapid depletion occurring early in the bloom (Fig 4). Recycled phosphorus becomes more significant as the bloom progresses. From laboratory studies, the current phosphorus status of the Harvey Estuary sediments appears to be such that they could support blooms without any further phosphorus inputs. Figure 5 indicates that phosphorus was much more limiting at Station 1 during the 1981-82 bloom than during the 1982-83 bloom. Nodularia at Station 4 was also severely phosphorus limited in 1982-83. However, the condition of the Peel Inlet with respect to phytoplankton also appears to have deteriorated in the past year (Figs. 6,7). Never the less, in the laboratory, Nodularia biomass increases proportionally to the amount of added phosphorus.

3. Bloom decline.

The factors which could affect the decline of Nodularia blooms are nutrient depletion, salinity, light, temperature, carbon dioxide, and pathogens, grazing, or competition. In the field, the declines of blooms have been very well correlated with salinities at or above 30‰. Under laboratory conditions, however, Nodularia grows above 30‰, albeit at a reduced rate. It is likely that high salinities and nutrient depletion, in combination with high light and temperatures, and CO_2 depletion in surface "scums" leads to the rapid declines observed. At 30 ppt salinity, no akinete germination can occur to "re-seed" the bloom.

4. Implications for management.

Management options which address themselves to decreasing the phosphorus concentrations in the estuary, or increase the salinity will have the following effects:

1. they will shorten or eliminate the time during which sediment akinetes can germinate,
2. they will shorten the time during which rapid growth can occur,
3. they will bring forward the time when conditions will result in bloom decline.

TABLE 1: Conditions for germination of akinetes.

Parameter	No Germination	Maximum Germination
Orthophosphate-P (uM)	0	1 (31mg/l)
Nitrate-N (uM)	-	0->720 (10mg/l)
Ammonia-N (uM)	>70 (980ug/l)	<40 (560ug/l)
Iron (uM)	?	>30 (5mg/l)
Temperature (^{o}C)	12-15	20-25
Light (uE/m^{2}/sec)	0	>9
Light exposure time (h)	<12	>50

TABLE 2: Dates when bottom water conditions were appropriate for akinete germination, 1978-1983.

Station	31	1	58	2	7	4
Year						
1978	ND	010,24	ND	010	-	010,24
1979	S25	-	-	-	-	-
1980	010 - N1	S23 022	-	-	-	-
1981	A25 S15-027 F2-9/82	A25 S22 013-27 F2,9/82	A25 S22 F9/82	S22- 013	A25	A25 S15
1982	A31 S21-12 N16-23	A31 S21-05 026-N2	A17,31 S28 012	S21-28	S21-28	A31 S28
1983	S13-27 04-11	S13-27 04	S13-27 04-11	S20-27 04	S20-27	S13-27 01

A=August S=September 0=October N=November F=February

*Blooms reported: 15/11/78, 23,29/10/80, 27/10/81, 1,7/09/82, 4/10/82.

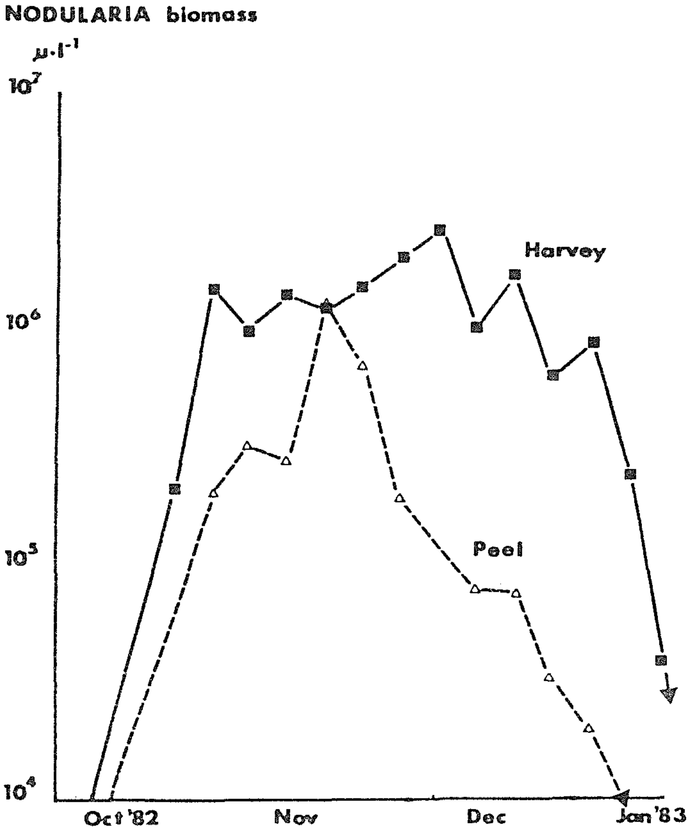

FIGURE 1. Mean <u>Nodularia</u> biomass (length.l^{-1}) in the Peel Inlet and <u>Harvey</u> Estuary between October '82 and January '83, surface to bottom integrated samples.

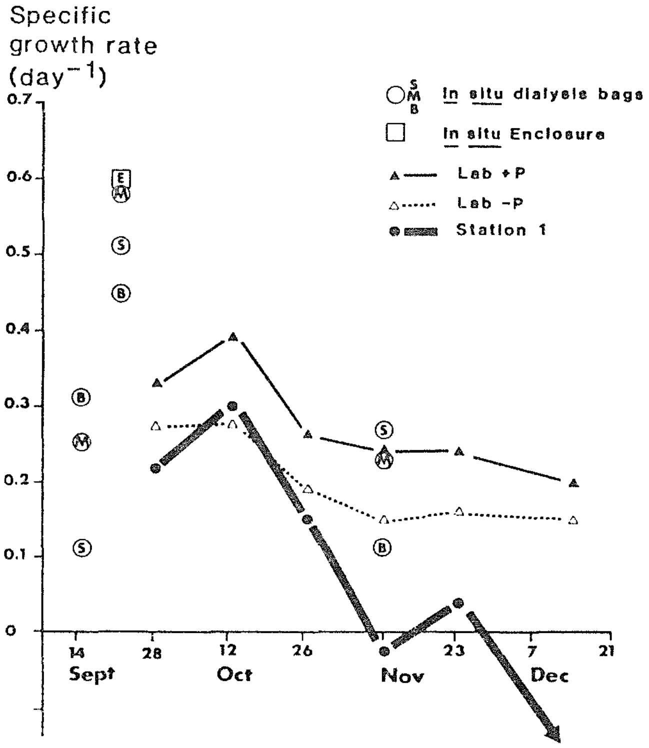

FIGURE 2. Specific growth rates of <u>Nodularia</u> in <u>in situ</u> and laboratory studies, and apparent growth rate of the <u>Nodularia</u> bloom between September and December 1982.

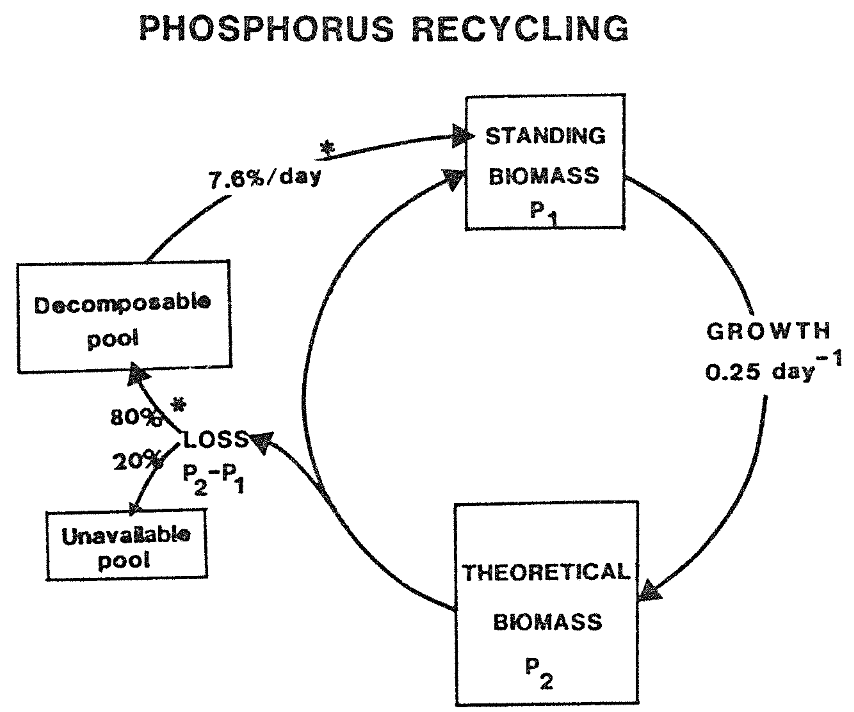

FIGURE 3. Phosphorus recycling during a Nodularia bloom.

* Data taken from Birch, P.B. and J.O. Gabrielson, 1983, Cladophora growth in the Peel-Harvey estuarine system following blooms of the cyanobacteria Nodularia spumigena. Bot. Mar. (in press).

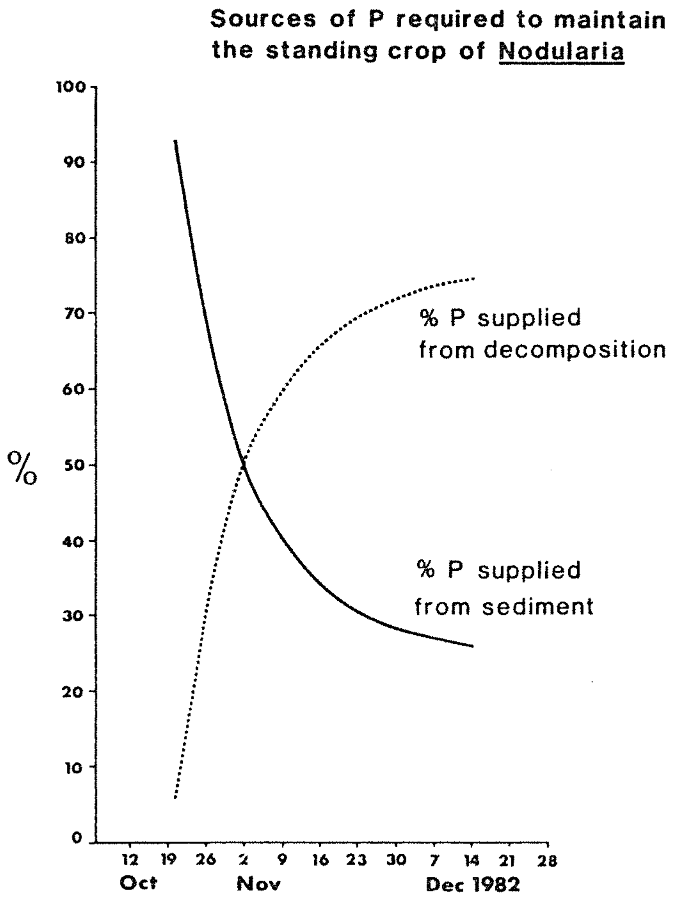

FIGURE 4. Estimated relative supply of phosphorus to the Nodularia bloom from sediments and Nodularia decomposition.

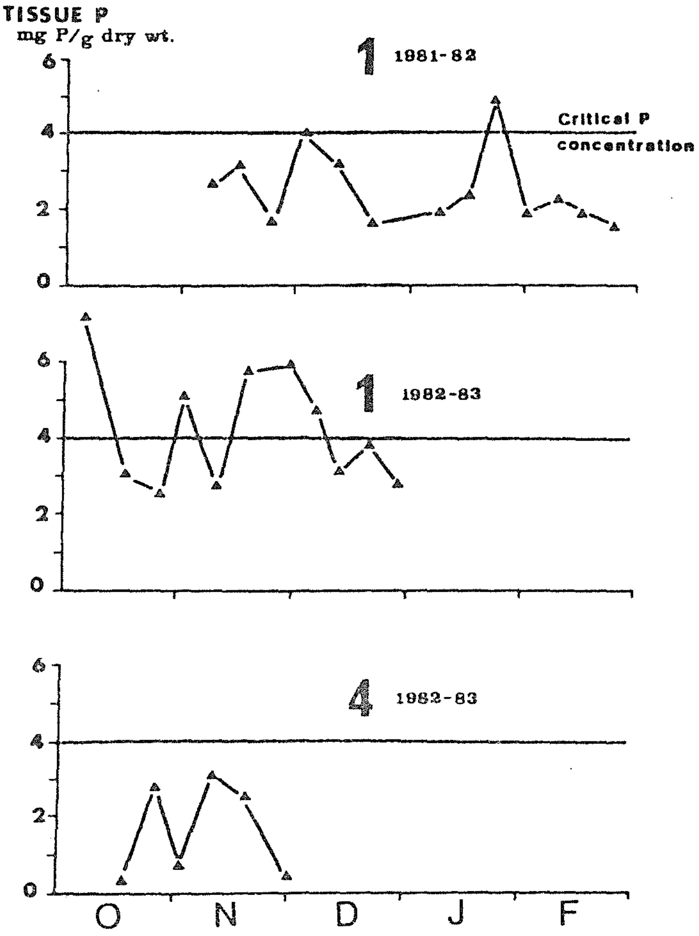

FIGURE 5. Tissue phosphorus concentrations in surface samples of *Nodularia* at Station 1, 1981-82, and Stations 1 and 4, 1982-83.

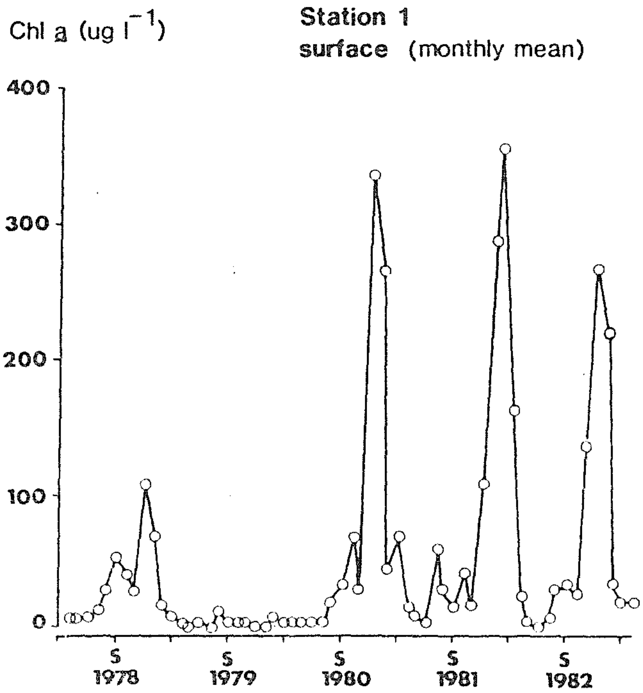

FIGURE 6. Mean monthly chlorophyll a concentrations in surface waters at Station 1, from 1978 to 1982.

Data from Waterways Commission and Botany Department, U. of W.A.

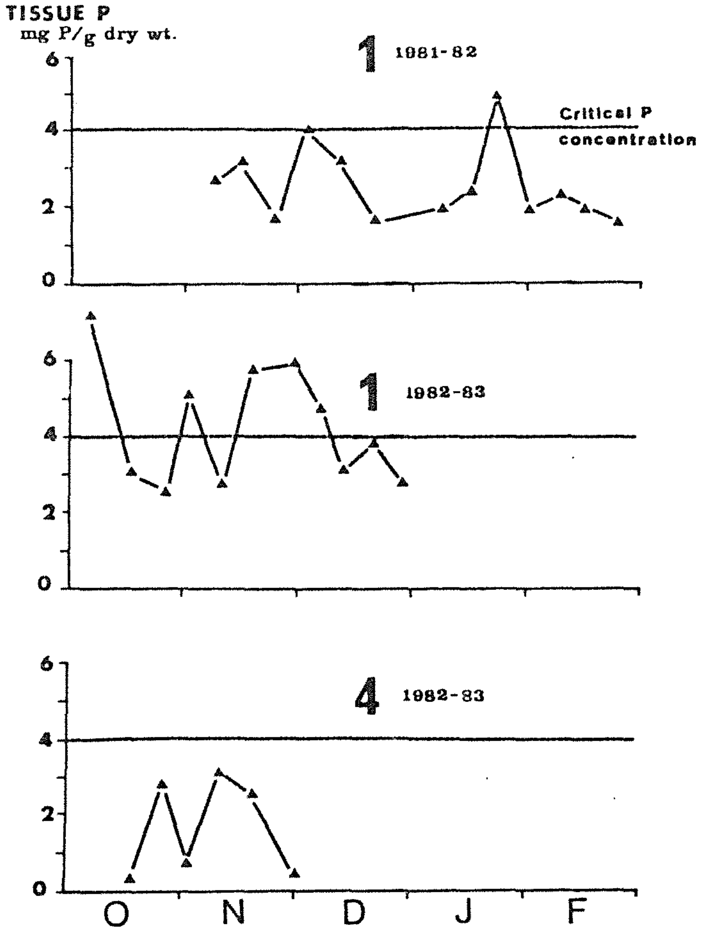

FIGURE 5. Tissue phosphorus concentrations in surface samples of Nodularia at Station 1, 1981-82, and Stations 1 and 4, 1982-83.

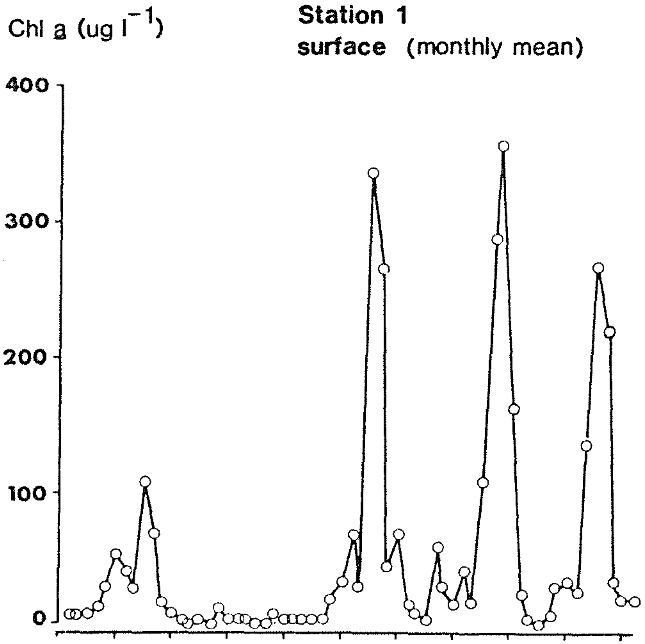

FIGURE 6. Mean monthly chlorophyll a concentrations in surface waters at Station 1, from 1978 to 1982.

Data from Waterways Commission and Botany Department, U. of W.A.

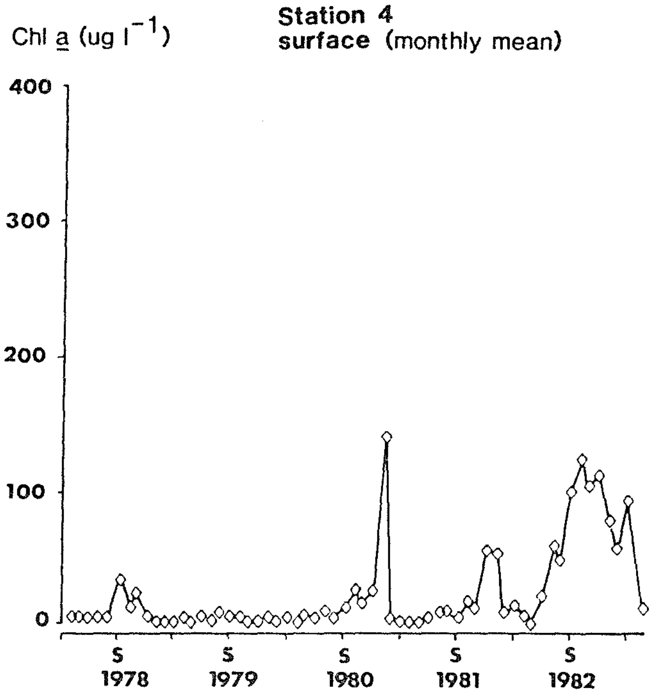

FIGURE 7. Mean monthly chlorophyll a concentrations in surface waters at Station 4, from 1978 to 1982.

Data from Waterways Commission and Botany Department, U. of W.A.

PEEL-HARVEY ESTUARY

Fish and the Fishery

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Introduction

The initial work on the fish fauna and the blue manna crab in the Peel-Harvey estuarine system, which commenced in April 1979, was aimed at elucidating the patterns of distribution, abundance and growth of the different species (Potter *et al.*, 1983a; in press). At the same time, the data on the commercial fish catches for the last 40 years were subjected to detailed analysis to ascertain whether any changes in catch during the 1970s could be related to the increased growth of macroalgae (Lenanton *et al.*, in press). More recent work has focussed on determining whether *Nodularia* has an effect on the fish fauna either through inducing changes in behaviour or by causing mortality (Potter *et al.*, 1983b).

The Fish Fauna

Beach seines, gill nets and otter trawls were used during 1979-81 to sample extensively the fish fauna of the Peel-Harvey estuarine system. Approximately 145,000 individuals were caught, representing 29 families and 55 species. The Clupeidae, Teraponidae, Mugilidae, Apogonidae, Atherinidae and Gerreidae were the dominant families, each contributing more than 8% to the total catch (total 86.2%). Seasonal catch data and length-frequency distributions were used to help clarify the way in which the estuary was utilised by fish. Nine of the fifteen most abundant fish species were marine species which entered the estuary for variable periods, while the other six were represented by populations in which the individuals were capable of passing through the whole of their life cycle within the estuary. In order of abundance, the nine marine species were the sandy sprat or whitebait (*Hyperlophus vittatus*), six-lined trumpeter (*Pelates sexlineatus*), yellow-eye mullet (*Aldrichetta forsteri*), sea mullet (*Mugil cephalus*), common blowfish (*Torquigener pleurogramma*), long-finned goby (*Favonigobius lateralis*), Ogilby's hardyhead (Pranesus ogilbyi), devil fish (Gymnapistes marmoratus) and western sand whiting (Sillago schomburgkii), while the six species with estuarine populations were the gobbleguts (Apogon rueppellii), elongate hardyhead (Atherinosoma elongata), Wallace's hardyhead (Atherinosoma wallacei), cobbler (Cnidoglanis macrocephalus), Perth herring (Nematalosa vlaminghi) and yellow-tailed trumpeter (Amniataba caudavittatus). The extent and seasonality of the distribution of the species within the estuary and associated river systems varied considerably. Our data also showed that marine species were represented predominantly by individuals in their first or second year of life and that in general fish tended to move further away from the shallow banks near the shore with increasing age and size. Comparisons of the fish fauna of the Peel-Harvey were made with those of Cockburn Sound and the estuary of the Swan-Avon in Western Australia and with Botany Bay in eastern Australia. These comparisons showed that the incidence of large piscivorous fish was lowest in the Peel-Harvey system.

The blue manna crab

Various aspects of the biology of the blue manna crab, Portunus pelagicus, were investigated using samples collected regularly by beach seine, gill net and otter trawl. Whereas crabs were widely dispersed throughout Peel Inlet, Harvey Estuary and the saline regions of tributary rivers during the summer and autumn, they were found mainly near the estuary mouth in the winter and spring. Since our data suggest that P. pelagicus prefers salinities of 30-40‰, the above changes in distribution are apparently related to the marked seasonal variation in salinity which results from the very seasonal pattern of rainfall. The number of ovigerous crabs in the estuary were greatest in January and February. The mean carapace length and number of eggs of ovigerous females were 110 mm (range 85-157 mm) and 509,433 (range 270,183 - 847,980) respectively. *P. pelagicus* started to reach the minimum legal size for capture (carapace width 127 mm) in the summer when they were approximately one year old and left the system in large numbers in the following winter when they were 15-20 months old. These features explain why the fishery for *P. pelagicus* is highly seasonal, with the vast majority of crabs being taken between January and May. As crabs approached the end of their first year of life, the ratio of females began to exceed that of males, apparently as a result of the movement of males out of the system and the legislation against the capture of ovigerous females.

The fishery

Comparisons were made between the catch statistics for the commercial gill and haul net fisheries of the Peel-Harvey system and that of the large neighbouring Swan-Avon estuary. The results indicate that during the 1970s the abundance of fish in the Peel-Harvey system rose as a result of the effects of nutrient enrichment, which included a massive increase in macroalgae (*Cladophora* sp. and *Chaetomorpha* spp.). In terms of mean monthly catch per boat per annum, which is shown to be a good reflection of the annual catch per unit effort, the total fishery increased by 1.8 times from 738 kg in the ten years prior to 1969 to 1,327 kg between 1970 and 1979. The comparable values for the three most important commercial species, i.e. the yellow-eye mullet (*Aldrichetta fosteri*), sea mullet (*Mugil cephalus*) and cobbler (*Cnidoglanis macrocephalus*), increased by 1.9, 2.1 and 3.3 times respectively. This contrasts with the situation in the nearby large Swan-Avon estuary which has not seen prolific macroalgal growth but whose fishery uses the same techniques and is exposed to similar market demands. Thus, in the Swan-Avon the mean monthly catch per boat for the total fishery increased in the 1970s by only 1.2 times and no significant change occurred in this parameter for the important sea mullet and cobbler. Length-frequency data showed that all three species grew rapidly in the Peel-Harvey estuary, with the result that most individuals had reached the minimum legal length for capture within two years. In the case of the sea mullet, this length was sometimes achieved by the end of the first year of life. Since growth rates of the main fish species in the Peel-Harvey were similar to those in the Swan-Avon, the increase in weight of fish caught is probably attributable to a rise in fish abundance rather than a faster growth rate. While the rise in abundance may reflect a greater food availability, it could also represent a decline in predation from the large, local, piscivorous bird populations as a result of the development of extensive macrophyte cover.

Effects of *Nodularia*

Our data indicate that dense blooms of the blue-green alga *Nodularia spumigena* affect fish and crab populations in the Peel-Harvey system. For example, the numbers of fish were generally very low at sites in which chlorophyll *a* level, an excellent indicator of *Nodularia* density during the late spring and summer, was above 100 $\mu l\ l^{-1}$ Moreover, commercial fishermen have recorded greatly reduced catches in *Nodularia*-affected areas and dead fish and crabs were found in regions where *Nodularia* was very dense. While the effects of this blue-green alga apparently led to death in the case of some bottom-living species in the most affected parts of the system, more active species moved into regions where *Nodularia* was virtually absent.

Current work is examining the relationship between *Nodularia* blooms and the commercial catch. This study involves an analysis of the fishermen's commercial log books which have been designed to distinguish catches taken in different parts of the system. It also involves the chartering of two fishermen to determine the areas in which commercial sized cobbler and yellow-eye and sea mullet are found in the Peel Inlet and Harvey Estuary during Nodularia blooms.

Conclusions

For the following reasons, the introduction of a cut between the Harvey Estuary and the sea, without the construction of a plug between the Peel Inlet and Harvey Estuary, is likely to have beneficial effects for the fishery.

1. It adds an additional entry point to the Peel-Harvey system for the juvenile stages of marine teleosts and crustaceans which form the basis of the commercial and recreational fisheries.
2. The reduction in Nodularia in the Harvey Estuary will remove what appears to be the major reason for the decline in crab numbers and fish catches in this part of the Peel-Harvey system during those periods when the cyanobacterium reaches high levels.
3. The reduced period of very low salinities in the Harvey Estuary will mean that large crabs will remain longer in this part of the Peel-Harvey system.

In contrast to the above beneficial effects, a reduction in macroalgae in Peel Inlet as a result of reduced phosphorus input may lead to a slight reduction in fish catches. However, it is relevant to note that a very viable commercial fishery operated in the Peel-Harvey prior to the massive outbreak in macroalgal growth.

It should be noted that if management plans call for continual dredging of the current Entrance Channel, this will almost certainly reduce the numbers of fish and crabs migrating into Peel Inlet.

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Overview of "In-Estuary" Studies

by A.J. McComb

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I would like to address four main areas:

1. Why controlling phosphorus will improve the estuary.
2. Quantitative relationships between phosphorus loading and *Nodularia*, and their management implications.
3. Levels of macroalgae in Peel Inlet.
4. What will happen to the system if phosphorus loading is reduced.

1. The Importance of Phosphorus

I thought it would be useful to spend a little time on this topic because if we are not convinced that increased phosphorus loading has been responsible for the estuaries problems, and that reducing phosphorus levels will improve the estuary, we would have to jettison a number of management options, including all the work on fertilizers. I am also aware that a number of persons attending the conference were not involved in the first phase of the Peel-Harvey project, the "in-estuary" work, and may appreciate a brief overview of this important topic.

The evidence has come from the following areas:

1.1 General grounds

1.2 Nutrient limitation algal assays

1.3 Nitrogen-to-phosphorus ratios

1.4 Timing of blooms

1.5 Statistical correlations

1.6 Nitrogen fixation by blue-greens

1.7 Phosphatase enzyme measurements

1.8 *Cladophora* growth studies

1.9 Tissue concentrations

1.10 Systems analysis

1.11 Catchment origin of phosphorus

1.1 General grounds

All plants, whether they be crop plants, seagrasses, macroalgae, diatoms or blue-greens, require essentially the same range of widely-studied and well-understood essential elements - "macroelements" required in large amounts, and "microelements" or "trace-elements" required in small amounts. Of the macroelements, nitrogen and phosphorus are particularly important in aquatic systems because, though required in large amounts for plant growth, they are usually present at very low concentrations in natural waters. Further, it is the concentrations of just these two elements which are typically increased dramatically as a result of man°s activities. It follows that where unusually large amounts of plant material occur in a water body, whether they be macroalgae or phytoplankton, the problem has been brought about by nutrient enrichment or "eutrophication", involving enhanced levels of nitrogen and phosphorus.

Of these two elements, phosphorus is especially important when management is being considered. If nitrogen levels were reduced, but phosphorus still remained high, one would select in favour of those organisms in the environment, including certain blue-greens such as Nodularia, which are capable of "fixing" their own nitrogen, derived from nitrogen gas in the atmosphere. This would restore the level of available nitrogen in the aquatic system, and the effect of management would be negated. If on the other hand phosphorus were reduced, and nitrogen levels ignored, then because there is no course of phosphorus comparable to nitrogen fixation, the amount of plant biomass would fall.

There are of course complications - phosphorus may be less critical than nitrogen in marine embayments where nitrogen-fixing organisms are less prominent, and it is always possible that some other element may be found to limit plant growth in a particular situation. Nevertheless this "armchair analysis" provides a compelling argument for the suggestion that prolific plant growth in an aquatic system, with its unsatisfactory consequences, will be found to be due to eutrophication involving high levels of nitrogen and phosphorus, and that reduction in phosphorus availability will lead to a reduction in the amount of plant material.

1.2 Nutrient limitation algal assays

In these, water samples from the estuary, containing natural levels of nutrients and phytoplankton, are returned to the laboratory and incubated for a few days under light and temperature conditions similar to those of the field; nutrients can be added to the flasks and their effects on growth monitored. In Fig. 1, it can be seen that the "controls", samples to which no additions had been made, supported relatively low levels of phytoplankton. The levels did not significantly increase after addition of phosphate; on this occasion, and at the site sampled, phosphorus availability was not "limiting" growth. On the other hand, addition of nitrogen, in the readily-available form of ammonia nitrate, lead to a spectacular increase in the amount of plant biomass supported, providing evidence for nitrogen limitation in the natural water. Once nitrogen is available at a high level, it is not surprising to find that phosphorus becomes limiting; under these conditions the further addition of phosphorus lead to still higher levels of phytoplankton. Significantly, this level of plant material was not increased by the further addition of all the other essential elements, and certain vitamins, required for phytoplankton growth. Thus the assay provides evidence that it was indeed nitrogen and phosphorus, and not some other element, which was controlling the amount of plant material in the water; and that on this particular occasion the level of nitrogen was limiting.

To sustain maximum growth, plants require nitrogen and phosphorus in a ratio of about 15:1. The water used in the assay illustrated had a ratio of about 5:1 (of available, or inorganic nitrogen and phosphorus, calculated by atom), suggesting that nitrogen may be at a growth-limiting level, and this is confirmed by the assay results. The water used in the assay summarised in Fig. 2 was 30:1, suggesting phosphorus limitation; and the results are similar to those of Fig. 1, except that on this occasion addition of available phosphorus, alone, supported a higher level of plant biomass than the control.

1.3 Nitrogen-to-phosphorus ratios

The assay results give us some confidence in using the ratios between the available forms of nitrogen and phosphorus, obtained in routine sampling, as a guide to growth limitation by nutrients in the field. Suffice to say that the observations are generally consistent with the suggestions outlined earlier (1.1 above). The ratios are typically high, indicating phosphorus limitation, except when the Harvey River flows, when the input of phosphorus causes the ratio to become very low, indicating nitrogen limitation, and setting the scene for a subsequent blue-green bloom. Nevertheless, as Rod Lukatelich has pointed out, the diatoms have "first call" on the nutrients under these winter conditions.

1.4 Timing of blooms

Important diatom blooms occur after river flow brings in high phosphorus levels. At other times of year, or in years of low river flow, there may be high levels of available nitrogen, released from sediments and decomposition. However, these do not result in phytoplankton blooms; phosphorus addition is required for bloom stimulation.

1.5 Statistical correlations

Statistical analyses of the amount of variation in chlorophyll levels in the water, which can be explained by measured environmental factors, are considered with the importance of nitrogen and phosphorus.

1.6 Nitrogen fixation by blue-greens

The very occurrence of *Nodularia*, and its highly active nitrogen fixation, is entirely consistent with the interpretation given earlier (1.1 above).

1.7 Phosphatase enzyme

This enzyme is responsible for breaking down complex organic forms of phosphorus into phosphate, which is readily availble for uptake and utilization by plant cells. Produced by a range of microorganisms including at least some phytoplankton, it is important in water bodies where phosphorus availability limits plant growth; as Anne Huber and Denis Kidby have found, it is readily detected in waters of the Peel-Harvey system.

1.8 Cladophora growth studies

Extensive laboratory studies have defined the nutrient, light, temperature and salinity requirements of this macroalga. Field measurements show that when light and temperature are adequate, phosphorus is often present at growth-limiting levels.

1.9 Tissue concentrations

A comparison between the levels of nitrogen and phosphorus measured in algal samples from the field, and those developed in laboratory cultures, shows that tissue nitrogen levels in the field are usually adequate to support high growth rates. On the other hand, phosphorus is often present in those tissues at levels which would be quite insufficient to maintain a high rate of growth.

1.10 Systems analysis

Modelling of the growth of phytoplankton and macroalgae in Peel Inlet, carried out by Bob Spear, George Hornberger and Bob Humphries at the Centre for Resource and Environmental Studies (CRES), Australian National University, showed that the behaviour of these biological components of the system can be simulated by realistic manipulation of phosphorus inputs; comparable work with nitrogen could not simulate the observed behaviour of the system.

1.11 Catchment origin of phosphorus

The origin of phosphorus in the catchment has been extensively documented, as repoted in part at this meeting. It was first cystallized in the numerical analyses and modelling carried out by the CRES group, under the direction of Peter Young.

All of this information is at last consistent with, and in many cases offers evidence for, the hypothesis that high levels of phosphorus loading from the catchments are responsible for the unacceptable levels of phytoplankton and macroalgae in the system.

2. Phosphorus loading and Nodularia blooms

Having accepted this conclusion, we may next ask if there is a quantitative relationship between some measure of the amount of phosphorus arriving in Harvey Estuary in a particular winter, and the amount of *Nodularia* which grows in the subsequent summer.

Fig. 3 shows the relationship between the peak concentration of the *Nodularia* bloom each summer, and the minimum salinity reached in the estuary in each preceding winter. The minimum salinity is a reflection of the volume of water entering from the river system, and so indirectly a measure of the amounts of phosphorus transported by that water. The relationship is a close one. When the relationship was first plotted there was no figure for 1982, and so the level of chlorophyll expected in that year was read from the graph, using the minimum 1982 salinity, and the prediction placed in writing to the Waterways Commission. The prediction turned out to be very accurate. The correlation, and the confirmed predictive ability of the relationship, leads us to the firm expectation that the maximum level of the bloom which is developing in 1983 will be equal to the highest experienced so far.

Fig. 4 is the relationship between the same measure of Nodularia chlorophyll, and the maximum concentration of phosphate reached in the estuary water each preceding winter. Here the relationship is again close, curving at higher phosphate concentrations; it would not be surprising to find that at very high phosphorus loads there may be reduction in the proportion of phosphorus trapped in the estuary, and so a tapering off in the elationship between these two measures. The relationship can again be used for prediction, with the same expectation for 1983 as derived from minimum salinity.

Fig. 5 shows the dependence of Nodularia on river phosphorus load. There is clearly a close relationship, which is essentially the basis for the relationships shown in Figs. 3 and 4. It is less use in a predictive way because, unlike minimum salinity and maximum phosphate, the river load cannot be computed until flow data are available late in the year.

It is hardly necessary to emphasise that close relationships like those shown in the figures do not in themselves prove the dependence of Nodularia on phosphorus loading; that conclusion was reached on quite other grounds (section 1 above), and a casual relationship between the two is assumed.

3. Implications of the relationship between Nodularia and phosphorus loading

It is useful to use the relationships shown in Figs. 3-5 as a basis for considering a number of other matters, especially in relation to management.

3.1 Monitoring

The relationships are clearly close, with useful predictive capacity, and it will be important to monitor these properties as management proceeds, and the biological properties of the system change as phosphorus levels fall.

3.2 Relationship to complexities of the ecosystem

We should bear in mind that in looking at such gross correlations, we are standing well back from the data, and from the complexities of the real world. The parameters graphed in the figures are separated in time by 2-3 months, and Rod Lukatelich and Anne Huber have, as they explained, been exploring the complex mechanisms by which phosphorus input is translated into Nodularia bloom. Anne has emphasised the complexity of deciding which factor may be limiting Nodularia growth at a particular time. There is a temperature and salinity "window" in the year when

Nodularia growth can occur - within that window, the level of Nodularia biomass reached is controlled by the amount of phosphorus available in the ecosystem.

3.3 Significance of annual loading

The amount of Nodularia biomass reached in a particular year is determined by the amount of phosphorus loaded into the system in the previous winter, and not on the amount of phosphorus accumulated over the years in the sediment. That is, the figures indicate that if next winter there were no phosphorus input, there would be no Nodularia bloom the following summer. We may want to be somewhat more guarded than that - as Denis Kidby has explained, one can demonstrate that the sediment has the potential to sustain at least a second major bloom, and this has een taken into account in the management study. But importantly, stopping phosphorus entering the estuary would stop Nodularia blooms in the short term, while stopping fertilizer application onto the land surface would be followed by some years of phosphorus export from the accumulated soil reserves. And so if phosphorus fertilizer application were reduced, the rate of phosphorus "rundown" from the catchment would control the rate of improvement in the estuary, and not he amount of phosphorus accumulated in the estuarine sediment. We may futher conclude that dredging out the surface sediment would not be a profitable control measure.

3.4 Level of phosphorus reduction required

The relationships suggest that to achieve Nodularia control it is not necessary to eliminate phosphorus loading, but to reduce loading to that which was seen in 1979.

3.5 Nodularia and phosphorus levels before 1978

The relationships have held between 1978 and 83, and so it is pertinent to ask what happened before this period, as there have certainly been high river flows, high fertilizer application rates and (presumably) high phosphorus loads into the estuary. Now Peter Birch has used estimated river flows (derived from Robert Harvey s analysis of flow/rainfall relationships) to infer phosphorus loads in previous years. According to those estimates no bloom would have been expected in 1977, and none was observed in field sampling undertaken in that year as part of the early Peel-Harvey study. Both 1976 and 1975 would not have carried blooms, but blooms would be expected for 1974 and 1973. In fact, blue-green bloom swere recorded in both those years by the Government Chemical Laboratories in their regular quarterly sampling of the estuary, and by Rob Rippingale (WAIT) for 1974. High pH values in Government Chemical Laboratories records in some earlier years were also indicative of bloom occurrence.

One cannot therefore reject the suggestion that the relationships have held for a number of years before this study, but that blooms did not attract much attention; and that there was not a sudden deterioration in conditions in 1978.

3.6 Further deterioration in the estuary

The relationships have clearly held for a considerable time, and in this sense the estuary is no "worse" than in 1977, and perhaps 1973. However, suggestions of a deteriorating situation come, as Rod Lukatelich has pointed out, from generally increasing levels of chlorophyll and nutrients during the year, and the occurrence of blooms of diatoms and other blue-greens after the *Nodularia* bloom, which are lasting for longer periods. And Denis Kidby has emphasised the magnitude of sediment-phosphorus accumulation. In the Peel, there have been more blooms, and consequently, poorer light penetration through the water.

If nothing is done, one can speculate that there will be increasing dominance of phytoplankton, with prolongation of blooms throughout the year. In addition, we may reach a stage where the relationships develop because of accumulated phosphorus in the sediment, rather than on a particular annual phosphorus load.

4. Macroalgae in Peel Inlet

The question of light penetration leads naturally to a consideration of the macroalgae. The study was initiated because of the macroalgal problem in Peel Inlet, where the main nuisance alga was *Cladophora*. This bottom-dwelling (benthic) plant depended on light penetration through the water column in summer, and nutrients released from decomposing alga and sediments below; a bank of nutrients topped up by sedimenting phytoplankton and the associated faecal pellet of zooplankton grazers. As Rod Lukatelich has mentioned, light penetration in the Peel has fallen, and there has been a marked decline in macroalgae, with a shift to dominance by genera other than *Cladophora*. This fall is presumably related to the decrease in light penetration, though changes in nutrient levels may have a supplementary role.

It might be noted in passing that the input of phosphorus which is particularly important to sustain plant biomass in Peel Inlet, is largely derived from the coastal plain catchments of the Serpentine and Murray rivers, rather than the Harvey, emphasising the need for control of phosphorus from those catchments. It will also be important to monitor the levels of macroalgae as management proceeds.

5. Consequences of phosphorus reduction

A reduction of phosphorus loading - and the term is used here to embrace both a reduction in input from the rivers and an increase in flushing to the ocean - would lead to an immediate reduction in the level of blue-green blooms. In Harvey estuary this will probably lead to some expansion in seagrass populations, which occur at present in the shallows, and some increase in macroalgae. However, their expansion will be limited because water clarity will continue to be severely affected by the wind-stirring of light sediments; this resuspension is an important factor in the ecology of Harvey estuary.

In Peel Inlet, a reduction in blooms will lead to significantly better light penetration, and a consequent increase in macroalgae. At a later stage, and the timescale is not clear, a continued reduction in phosphorus loading will lead to relatively more prominence by seagrasses, which are widely distributed in the Inlet, and are generally regarding as more desirable than the macroalgae.

As far as the fisheries are concerned, Ian Potter has explained that the increase in macroalgae has been accompanied by an improvement in the catch of fish, and it might therefore be supposed that there will be a reduction in catch if the macroalgae are reduced. Some would argue that a reduction in catch is a price one must pay for an improvement in the estuary. There is, it could be argued, an analogy with agriculture - one may have on the one hand a high yield from a fertilized farm carrying introduced pasture, or on the other a low yield from a pastoral lease carrying natural vegetation; in the estuary, one might aim for a high yield from a fertilized fish pond with attendant eutrophication problems, or a lower, sustainable yield from an essentially "natural" ecosystem. Fortunately, the argument seems to be somewhat irrelevant. Any reduction in fish catch in Peel Inlet through the loss of macroalgae would be offset by the improved environment for fish and crabs in the Harvey.

In conclusion, there is no evidence to suppose that there has been an irreversible deterioration in the biology of the estuarine system. If phosphorus levels are reduced we may confidently look forward to a rapid reduction in the blue-green problem, and a longer-term reduction in the macroalgal problem, without, it would seem, any significant reduction in the harvesting of fish and crabs.

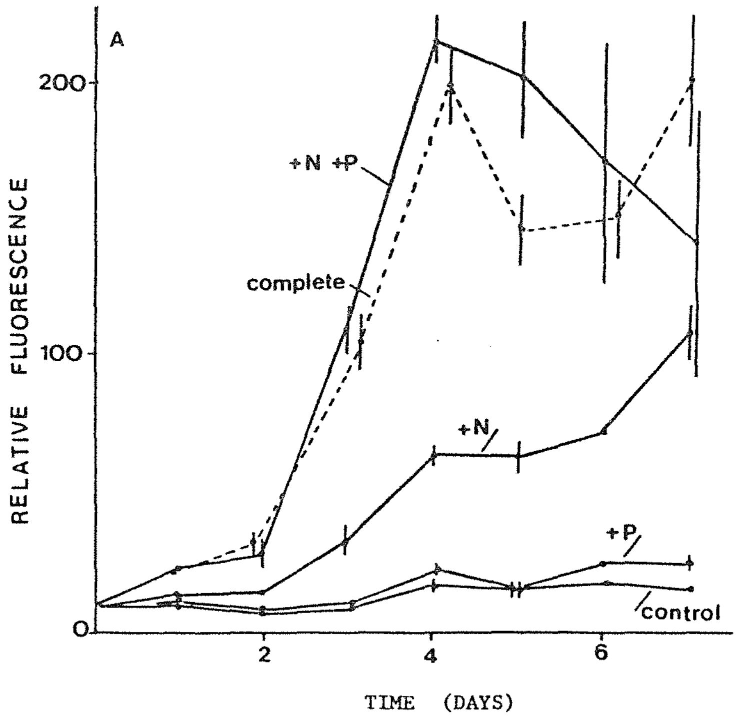


Fig. 1 Nutrient limitation algal assay, using water from the Peel-Harvey estuary with a nitrogen to phosphorus ratio (calculated from atomic weight ratios of inorganic nitrogen and orthophosphate) of 5:1. The vertical scale is chlorphyll fluorescence, measured with a Turner Designs fluorometer. (Data of R.J. Lukatelich.)

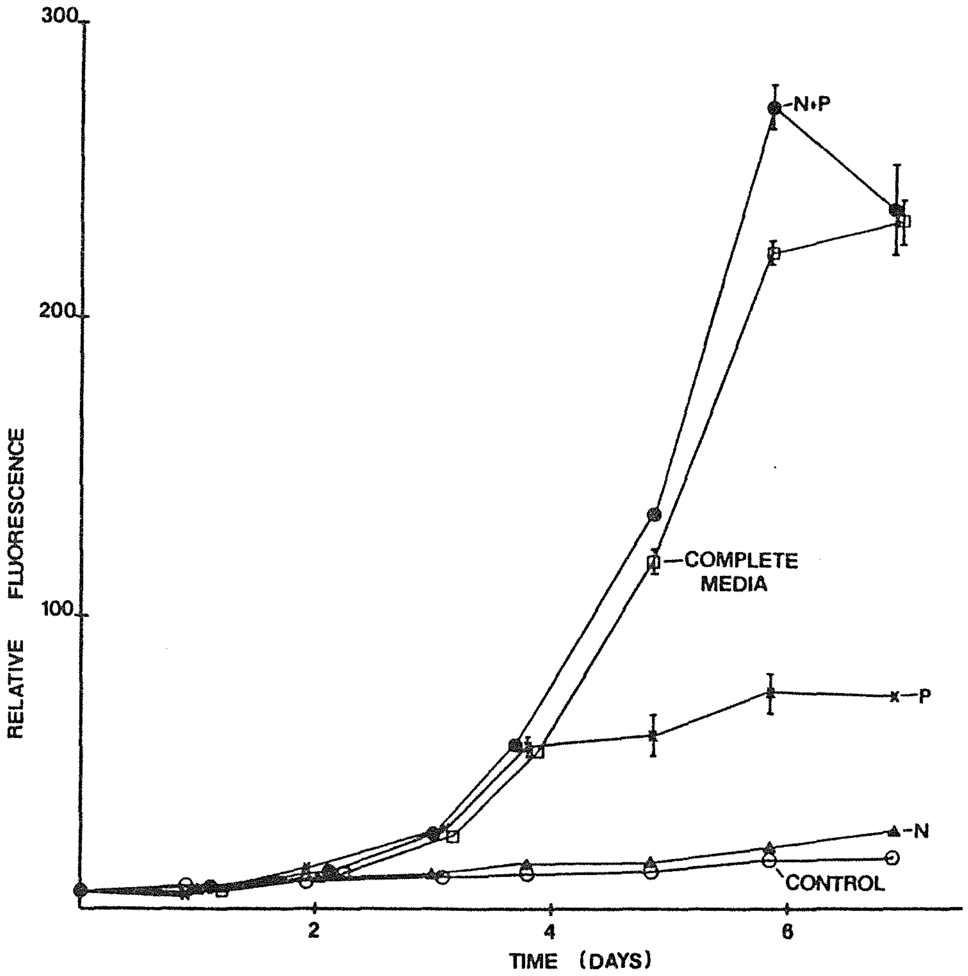


Fig. 2 Nutrient limitation algal assay, using water from the Peel-Harvey estuary with a nitrogen to phosphorus ratio of 30:1. Other details in Fig. 1. (Data of R.J. Lukatelich.)

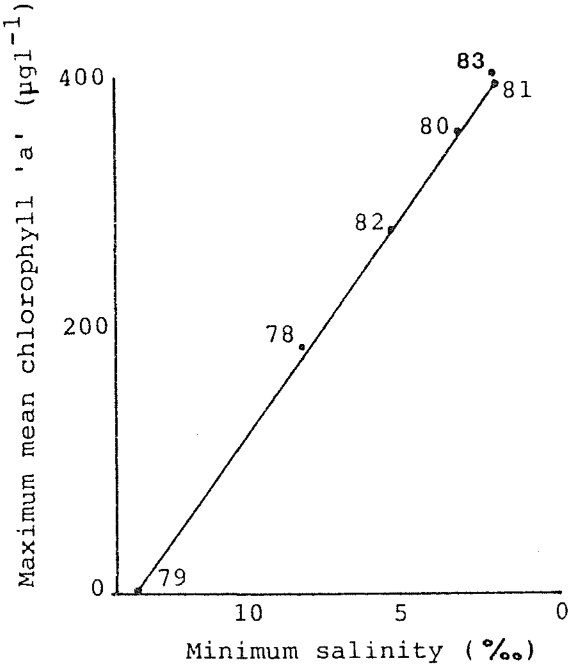


Fig.3 The relationship between the summer maximum Nodularia chlorophyll concentration (averaged between surface and bottom water) and the minimum salinity recorded in the estuary each preceding winter. (Data of R.J. Lukatelich.)

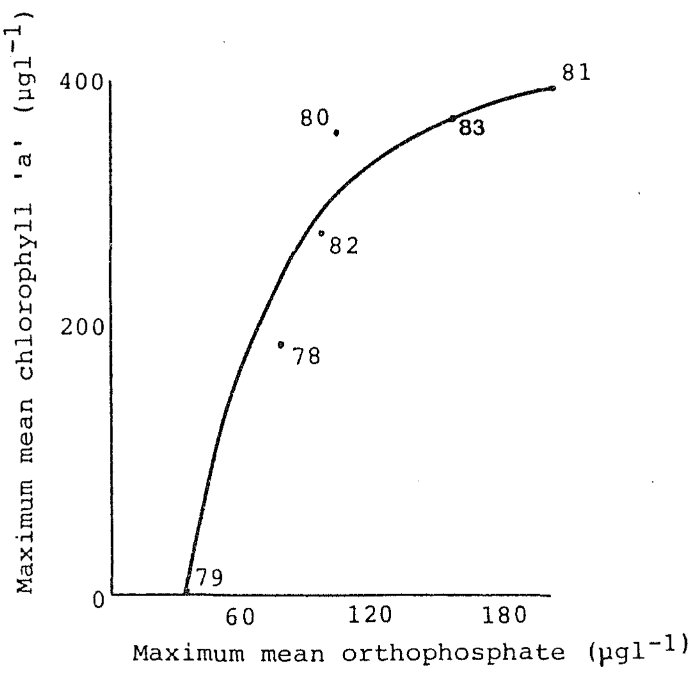


Fig. 4 The relationship between the summer maximum Nodularia concentration and the maximum orthophosphate concentration recorded in each preceding winter (both averaged between surface and bottom water). (Data of R.J. Lukatelich.)

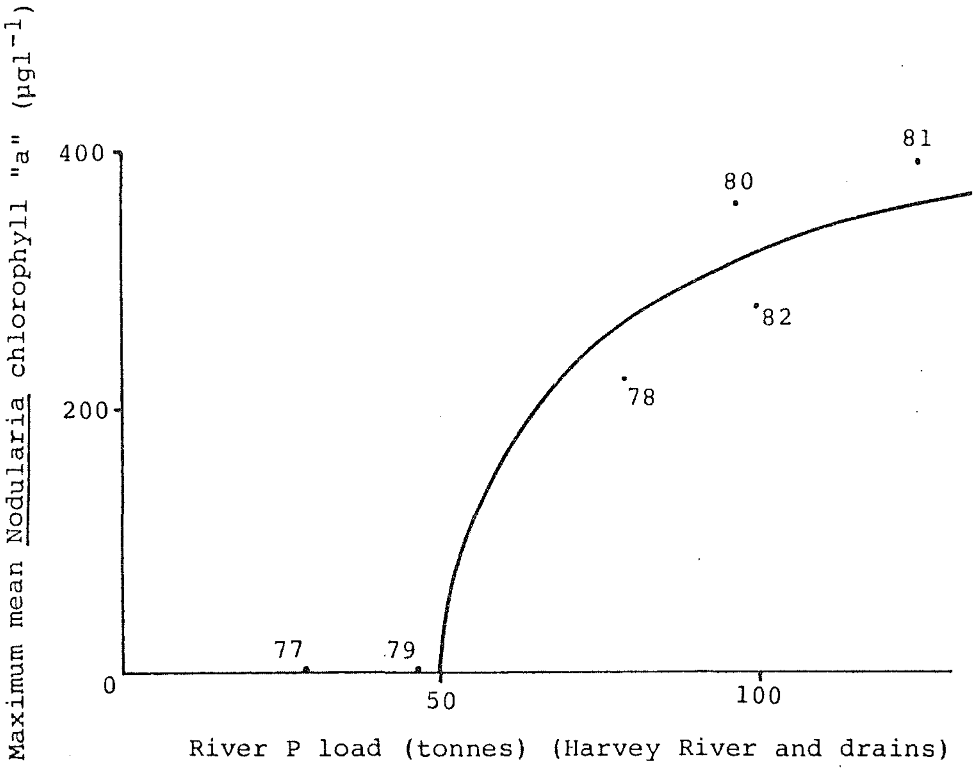


Fig. 5 The relationship between the summer maximum Nodularia concentration (averaged between surface and bottom water) and the total load of phosphorus entering the Harvey Estuary by river and drain flow each year. (Data of R.J. Lukatelich and P.B. Birch.)

DISCHARGE TO THE OCEAN

Mike Paul
Supervising Engineer, Coastal Investigations
Harbours and Rivers Branch, Public Works Department

Over the past year, the Public Works Department has investigated various engineering concepts which, if implemented, would increase the discharge of nutrients to the Ocean and thereby improve water quality within the Peel-Harvey Estuarine System.

These investigations have included an examination of cost effectiveness for the following dredging and flow training options:

(i) several different alternatives for widening and/or deepening of the existing Mandurah Ocean Entrance Channel, as shown in Figure 1 and Table 1,

(ii) a combination of dredging and flow training works between the Murray River mouth and the Mandurah Ocean Entrance Channel, as shown in Figure 2,

(iii) dredging works to create a new channel between Harvey Estuary and the Ocean at Caddadup, both with and without complete separation of the Peel and Harvey estuarine basins by reclamation to 'plug' the existing flow channel between Point Grey and Ward Point, as shown in Figure 3.

Detailed conceptualisation of the various schemes, probable construction techniques and estimated costs were determined by officers of the Harbours and Rivers Branch (ref. 1). The water quality and hydraulic effects were determined from mathematical model studies carried out by the Centre for Water Research, University of Western Australia, as part of a core project sponsored by the Public Works Department (refs. 2 to 11).

The mathematical models adopted for purposes of these investigations include:

(i) the one dimensional DWOPER flood routing model - used to simulate water levels and flow velocities between the Murray River mouth and the Ocean,

(ii) the two dimensional RAND water quality model - used to simulate water circulation and exchange within the Estuarine System, under the influence of defined tide and wind conditions.

The DWOPER Model was used to examine the effects of dredging works on tidal flows and discharge of a 100 year Murray River flood. The RAND Model was used to calculate the concentration of Peel, Harvey and Ocean water at points throughout the Estuarine System after 14 days of water circulation under "normal summer" and "normal winter" patterns of wind and tide. The results were presented in the form of concentration maps, as typically shown in Figure 4. Also, rates of water transport calculated over a 14 day period were used to determine estimated flushing times, or the time over which all estuary water would be replaced by ocean water if the replacement rate continued at a similar rate to that existing over the first 14 days of water circulation.

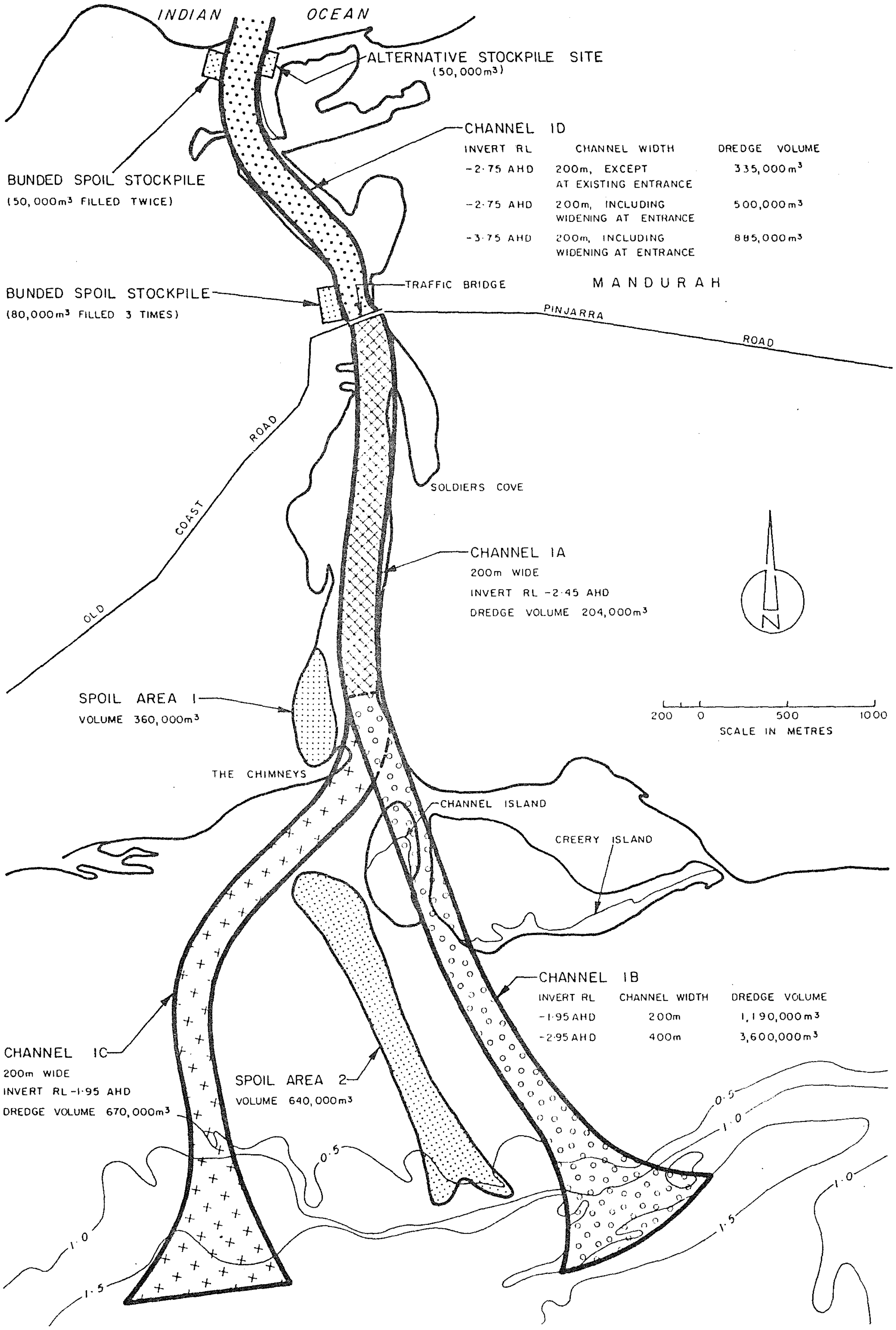


Figure 1 -- - Proposed dredging alternatives for the Mandurah Channel

Table 1 -- Mandurah Ocean Entrance Channel
Summary of Channel Improvements by Dredging
July 1983 Costs

DREDGING OPTION	CHANNEL 1A		CHANNEL 1B		CHANNEL 1C		CHANNEL 1D		PROJECT DURATION ONE DREDGE ONLY MONTHS	DREDGING * COST
	DEPTH m AHD	WIDTH m	DEPTH m AHD	WIDTH m	DEPTH m AHD	WIDTH m	DEPTH m AHD	WIDTH m		
A	-2·45	200	-1·95	200					17	$2 300 000
B							-2·75	UP TO 200 m	6	$1 100 000
A + B	-2·45	200	-1·95	200			-2·75	UP TO 200 m	23	$3 400 000
C	-2·45	200	-1·95	200			-2·75	200	24	$3 900 000
D (EAST)	-2·45	200	-1·95	200			-3·75	200	29	$5 200 000
D (WEST)	-2·45	200			-1·95	200	-3·75	200	25	$4 600 000
F	-2·45	200	-2·95	400			-3·75	200	54	$8 700 000

* EXCLUDES MOBILISATION/DEMOBILISATION COSTS WHICH WOULD COST UP TO $150 000 PER DREDGE

Estimated costs for the alternative Mandurah Ocean Entrance Channel dredging options are summarised in Table 1, whilst estimated flushing times and the corresponding Improvement Factors (relative to existing conditions) are shown in Table 2 for both "normal summer" and "normal winter" conditions. These indicate that the largest proposed Mandurah Channel Improvements (i.e. dredging option F at an estimated cost of $8 700 000) would result in a Flushing Time Improvement Factor of the order 1.47 to 1.60 for the Harvey Estuary.

The proposed combination of dredging and flow training works between the Murray River mouth and the Mandurah Ocean Entrance Channel were shown to have some value in reducing the retention of nutrients introduced to Peel Inlet from the Murray River, but little value in improving the quality of water in the Harvey Estuary.

Estimated flushing times and corresponding Improvement Factors for the proposed new channel between Harvey Estuary and the Ocean are included in Table 2 for comparison with results on the Mandurah Channel improvements. These indicate that the largest proposed Harvey Estuary to Ocean Channel (i.e. 1.5 km long x 200 m wide and excavated to a depth of 4.5 m below AHD, at an estimated cost of $25 000 000) would result in a Flushing Time Improvement Factor of the order 2.47 to 3.37 for the Harvey Estuary when the 'plug' is in place. Of the engineering concepts investigated, the proposed new Harvey Estuary to Ocean Channel is best able to improve water quality within the Peel-Harvey Estuarine System.

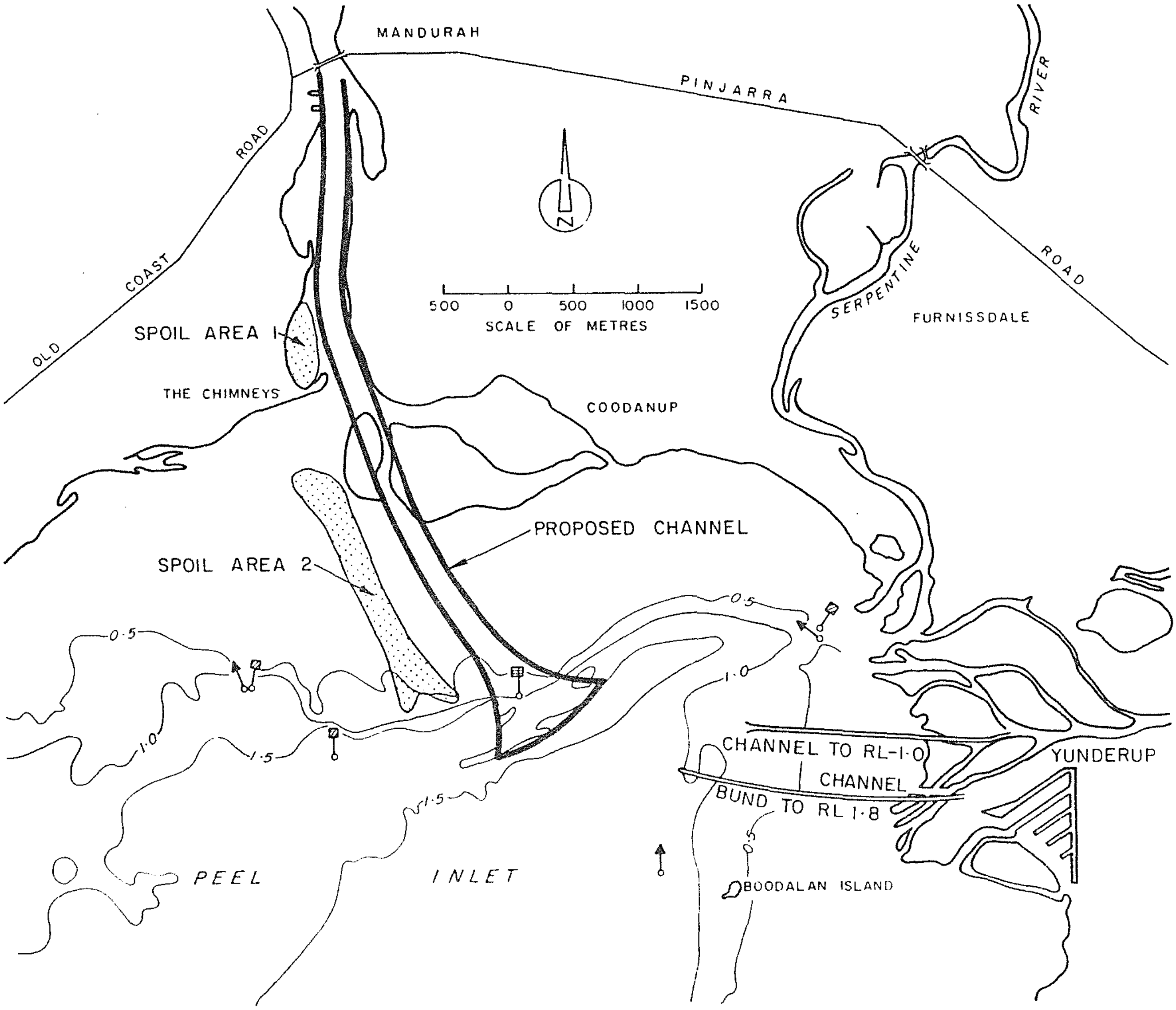


Figure 2 -- Proposed dredging and flow training works between the Murray River mouth and the Mandurah Ocean Entrance

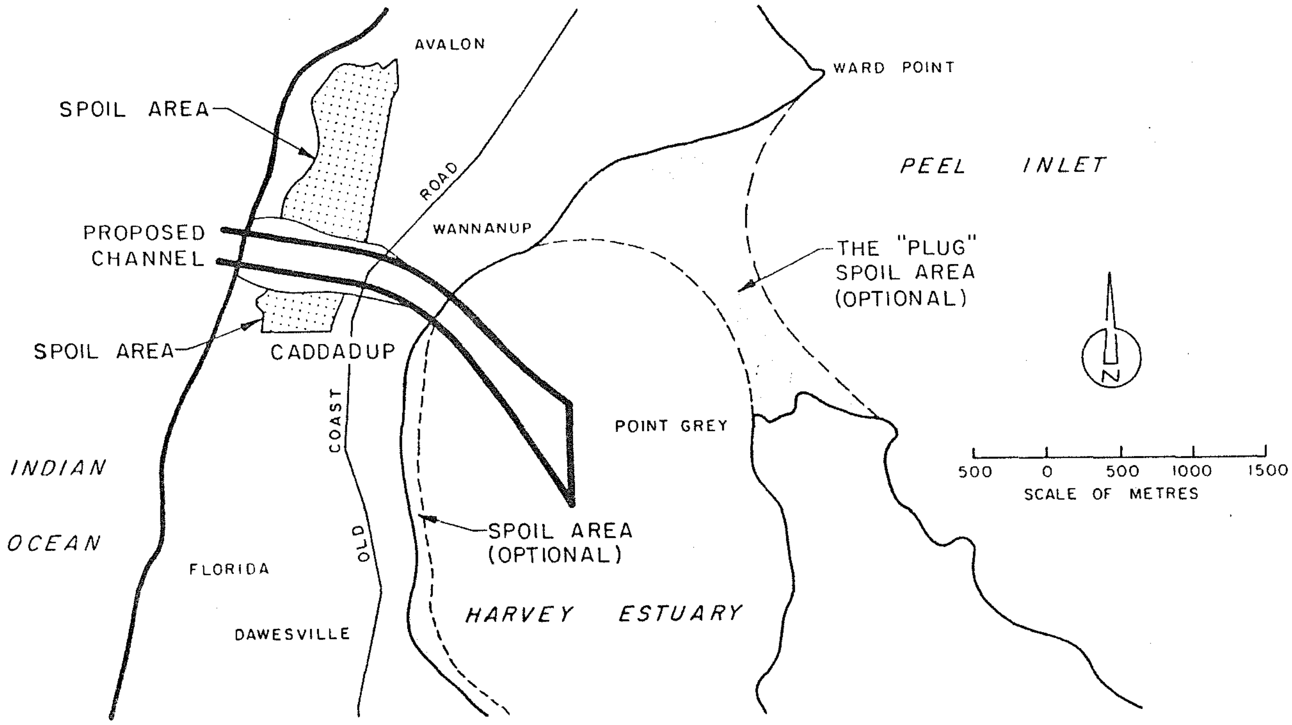
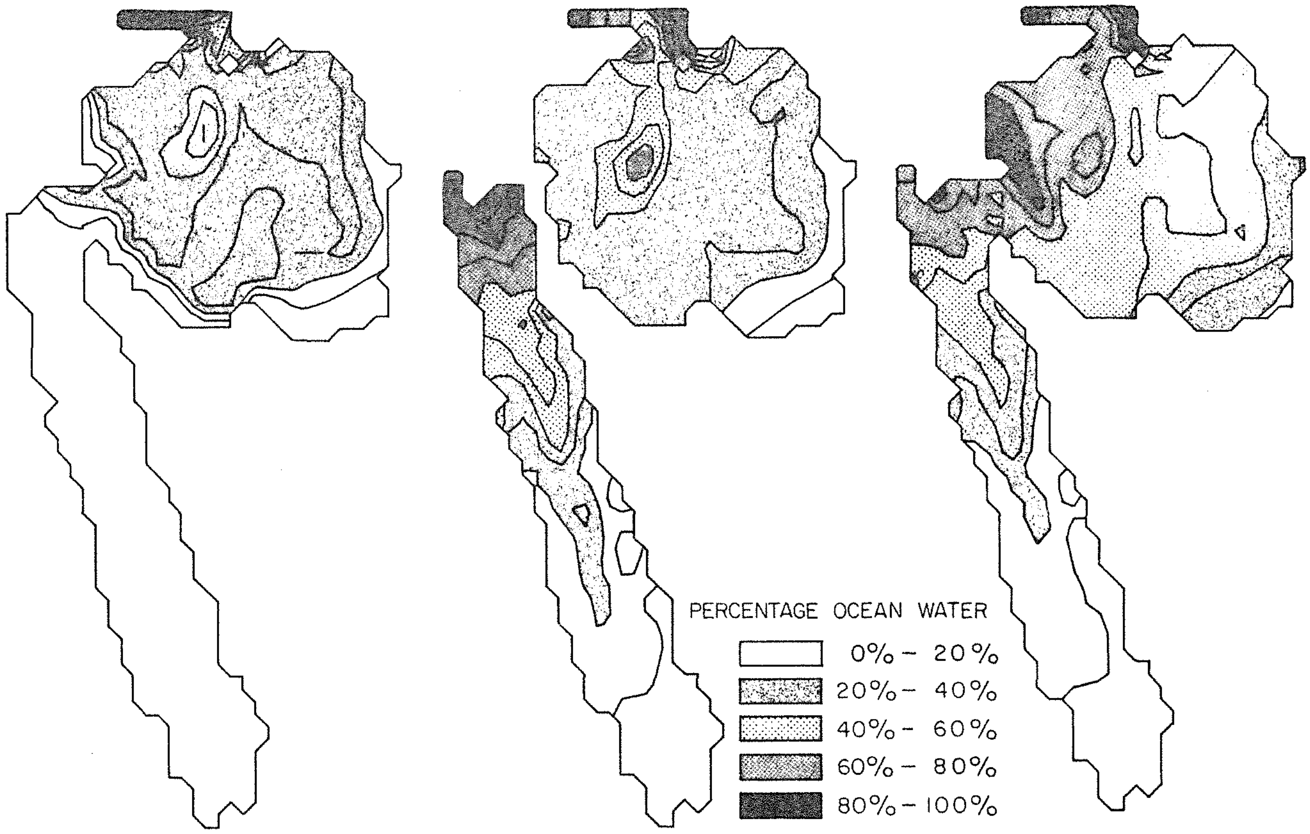


Figure 3 -- Proposed new channel between Harvey Estuary and the Ocean at Caddadup



A. EXISTING B. NEW OCEAN CHANNEL WITH "PLUG" C. NEW OCEAN CHANNEL WITHOUT "PLUG"

Figure 4 -- Typical concentration maps showing the displacement of Peel/Harvey water by Ocean water, after 14 days, under "normal summer" conditions

Table 2 -- Peel/Harvey Estuarine System - Channel improvements by dredging Comparison of Estimated Estuary flushing times

FORCING CONDITIONS	LOCATION OF CHANNEL IMPROVEMENTS	DREDGING OPTION	FLUSHING TIME (DAYS)		FLUSHING TIME IMPROVEMENT FACTOR	
			HARVEY	PEEL-HARVEY	HARVEY	PEEL-HARVEY
"NORMAL SUMMER" TIDE AND WIND	MANDURAH OCEAN ENTRANCE	EXISTING	128	103	1·00	1·00
		D (EAST)	85	69	1·51	1·49
		D (WEST)	84	62	1·52	1·66
		F	80	47	1·60	2·19
	NEW HARVEY TO OCEAN CHANNEL	WITHOUT 'PLUG'	46	38	2·78	2·71
		WITH 'PLUG'	38	43	3·37	2·40
"NORMAL WINTER" TIDE AND WIND	MANDURAH OCEAN ENTRANCE	EXISTING	84	47	1·00	1·00
		D (EAST)	59	38	1·42	1·24
		D (WEST)	59	35	1·42	1·34
		F	57	33	1·47	1·42
	NEW HARVEY TO OCEAN CHANNEL	WITHOUT 'PLUG'	42	29	2·00	1·62
		WITH 'PLUG'	34	31	2·47	1·52

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THE SOCIAL SCENE

Dr S R Shea - Deputy Shire President - Shire of Mandurah

INTRODUCTION

I believe the Peel-Harvey Study represents one of the most fascinating and challenging scientific exercises in the area of land and marine resource research that I am aware of.

I am particularly envious of the way in which it has been possible to bring together so many scientists from different disciplines to work on the problem. While it is true to say that scientists working by themselves can make a significant contribution in any area, I strongly believe that progress towards solutions of ecological problems will only occur when we have developed the ability to work together as a team. Over the years that I have been involved in scientific research I believe that the problem associated with getting scientists to work together were far greater than those involved in solving the technical questions that were confronting us. I have often asked Ernest Hodgkin how he has been able to achieve this positive interaction with so many scientists but he hasn't yet been able to tell me - perhaps therein lies the answer.

I also feel apprehensive about talking about - the social scene - not only because of the unfortunate connotations but also because I certainly have no professional expertise - in the social sciences.

Nonetheless in the years that I worked as a scientist dealing with a range of forest problems I became convinced that although there was no question that understanding the physical and biological processes which affected the ecosystem which had been disturbed are an essential prerequisite to solving the problem - such research no matter how successful will have little impact unless there is a corresponding understanding of the processes affecting the social factors which invariabily are associated with the ecosystem problem.

An important corollary of this is that elucidation of these social questions are as difficult or even more difficult than the scientific ones. I might say that I formulated these views from the perspective of a scientist. My experiences as a shire councillor have only re-inforced them.

Increasingly, of course, many scientists are recognising this fact. But I know of no situation where the problem is being addressed adequately. The purpose of address this afternoon is:

- firstly to put the proposition to you that your own study is no exception
- secondly to suggest why and how these social questions could be tackled

- and finally, and hopefully with your help, suggest ways in which the government could assist your study which would permit the social environment to be adequately catered for.

Implicit in my opening remarks was a suggestion that one of the reasons why scientists have difficulty addressing the social questions is the disdain which many of us have for social science - "social scientists, heaven forbid, they are only one step from politicians." Many scientists are not happy unless they can present the results of their endeavours in some complex mathematical equation or at least in a statistically validated graph. Of course there are many aspects of the social environment which can not be easily quantified.

You would undoubtedly be pleased to know that in my analysis of the social scene I have, at great personal cost, attempted to quantify some of these factors which I believe have a profound bearing on the Peel Inlet Study. I present the results of my personal research in the following graphs.

1. Seasonal fluctuations in Mandurah's index of faith in scientists.

2. Relationship between number of retired farmers in the community and faith in scientists.

3. The relationship between community concern for environmental problems and the distance from the problem.

4. Relationship between popularity of solution and impact on unemployment.

5. Shire Council decision making capacity.

6. Relationship between funds that are available for research and the majority of a local government member.

WHY SHOULD WE CONSIDER THE SOCIAL ENVIRONMENT?

After all funds are limited and wouldn't they be better spent on understanding the scientific basis for the solution of the problem. I readily concede that we shouldn't sacrifice our capacity to understand the science of the system at the expense of cheap public relations exercises.

But I believe there is a very strong interaction between the social, physical and biological environments that you are studying.

I believe the option of ignoring the social environment to enable maximum resources to be devoted to scientific studies is not only not sensible but not feasible.

Let me give specific examples -

1. Firstly social factors are important because this study and the management treatments that will flow from it are carried out for and are being paid for by the community. It may appear trite but I believe that we are normally obliged to inform the community what we are doing, what progress is being made, and what are the prospects for obtaining a solution to the problem.

2. Apart from this moral obligation to inform of the community, it is simply good sense to consider the social environment because to a large extent the amount of funds that are available is very much determined by community attitudes.

3. But social factors can have even more specific implications to your work. I believe that whenever we depart from a rational approach to resolving ecological problems we are in serious trouble. But anybody who was present at the public meeting held on the foreshore at Mandurah early this year, organised by a people's action committee to save the estuary, would agree with me that we should not under estimate the danger of populist groups gaining public support for simplistic but potentially disastrous approaches to solving the estuary problem.

   At that meeting, and many others I have attended, I have heard scientists personally denigrated and the scientific approach to solving the problem ridiculed.

4. Finally, and this list is by no means complete, part of the mechanism by which most the desirable options can be implemented involves a very significant consideration of social factors.

I can use a topical issue to illustrate this point by simply pointing to the costs that the companies who propose to develop canals in Mandurah are incurring simply because of their total neglect of social factors when they were planning the developments.

Quite clearly such options as the reduction of phosphorus input and channel cuts can only be implemented successfully if we recognise the significance of the social element in their implementation.

THE SOCIAL STRUCTURE OF THE AREA

I intend to elaborate on some of these points I have raised, but before doing so let me give you a laymans thumb nail sketch of the social and political environment in the Peel Harvey area.

Quite clearly there are two broad social compartments each with its own particular relevance to the problem. Firstly there is an obvious rural component represented in the Shires of Waroona, Harvey and Murray. The people in these Shires who are relevant to the study are the farmers. Secondly in the urban area, represented by the Mandurah Shire, the social environment is much more complex. Traditionally Mandurah has been a retirement village and basically a poor man's holiday resort. The community structure still strongly reflects this. For example there are still proportionally a large number of retired people and many people still use Mandurah as a low cost holiday resort.

Notwithstanding this, in the last five to ten years there has been a dramatic change in the number and composition of residents in Mandurah. The nature of the business community, particularly the tourist industry, has generated very significant changes in the social environment. For example the coming of Alcoa has meant that the town has become partly an industrial dormitory. As a consequence a greater proportion of the town is composed of younger people many of whom have children approaching the age when they will need a job. The larger community has generated a number of small business operations; hence the town is much more sensitive to levels of economic activity.

This sensitivity is amplified by the fact that, because Mandurah is growing rapidly, there are inevitably severe swings in the business environment for the individual small entrepreneur, which are superimposed on the normal business cycle.

For example last year the town reached the size which attracted a large shopping complex. The establishment of the K-Mart (with 48 check out points) has had a disastrous affect on the small business in the central Mandurah area.

Superimposed on top of these changes, there have been dramatic swings towards the development of "up market" type holiday resorts. The Atrium complex is just one of the many existing or planned tourist resorts. The canal developments are just another extension of this type of damand.

What all these changes mean, of course, is firstly that the significance of the eutrophication problem to the local community, and the State, is far greater than it would have been had Mandurah remained the sleepy holiday retirement village.

That is not to say that I under rate how distressing the problem is to retired people in the town. Some have invested their savings in their retirement home in locations near the estuary and now find, in some extreme cases, that for periods of the year they are unable to use them because of the stench from the estuary.

Nor am I endorsing the trend towards the "up market" intensive tourist development which in some cases could be carried out at the expense of what I regard as a unique environment. But these changes are inevitable and it must be recognised that we must evaluate them, if we are to understand the significance of the social environment.

I will complete my thumb nail sketch of the social environment by describing briefly the political scene. There are only two lower house seats which are relevant - Murray-Wellington which is, as you would expect, a safe conservative seat and the newly formed seat of Mandurah. Originally Mandurah was part of the Murray electorate and Mandurah until the last elections had consistently been held by the Liberal Party with a very large majority. At the last elections a swing in excess of nine percent saw the seat change to a Labor candidate with a majority of 57 votes. The seat was won on preferences of a candidate whose platform was based on the estuary issue.

As far as local government is concerned I think most people would be aware that the Mandurah Shire Council currently reflects two distinct points of view - a pro-development group (representing the business sector of the community) and a more conservation orientated group which reflects the retired community and those younger people in the community who are concerned about retaining the Mandurah lifestyle and who are less dependant on the local business environment for employment.

SPECIFIC EXAMPLES OF THE RELEVANCE OF THE SOCIAL ENVIRONMENT TO THE PEEL-HARVEY STUDY

I would like now to elaborate on some of the specific areas where the social environment is directly relevant to the Peel-Harvey Study.

1. There will be few people at this symposium who would not agree that reduction of phosphorus input is of critical importance and they would also agree with Bill Russell's proposition that it would be disastrously counter productive to use coercive methods to achieve this. Quite clearly we need to have the farmer on side if we are to successfully implement the desired fertiliser regimes. I do not in any way wish to denigrate the work that Bill Russell is doing or the work of other participants in this symposium who have been working with farmers in the catchment areas. But as Bill has already stated, and it is my own personal observation, that farmers already feel that they are being labelled as polluters and fear that they may be penalised for the benefit of the rest of the community.

I put it to you very strongly that once that perception becomes entrenched in the farming community the task of changing farmer practice will become very difficult to achieve, even if such practices may have a net benefit to the individual farmer.

Quite frankly I don't think this particular problem is being addressed adequately, by field demonstration, etc., to convince farmers of the scientific basis for desirable fertiliser regimes. But over and above the scientific extension work there is, for lack of a better term, the need to address the psychology of farmers in order to ensure that they are receptive to what the scientists are proposing.

The importance of the social factors associated with the rural sector of the community are obvious. But social factors in the urban sector may be equally important. If for example the channel option becomes essential local planning procedures could obviously be very important.

I can't help but be disturbed by the proliferation of developments of various types around the estuary. One of the reasons for my concern is simply that they seem to be based on the premise that the existing problem will be readily solved or that people occupying these developments will adjust to it. Personally if I invested upwards of $100,000 in my dream home on a canal I would not be very pleased if the canal water was bright green and stinking for two to three months of the year.

Obviously such developments will lead to greater pressure on both State and Local Government to solve the problem. But if in fact we can't solve the problem within a reasonable time span no matter what the government does, what then?

Apart from the fact of the effect of estuary conditions on these developments, it is possible that their very location may put a physical constraint on implementing a desirable management option.

IMPACT OF THE PROBLEM

I would like to now discuss one of the most important constraints on implementing the most desirable management options - the cost.

Obviously in your study you have recognised this and papers in this conference have included an estimate of the direct cost of implementation of the particular option being discussed.

But these figures only represent one side of the balance sheet. To put them in perspective we also need to have some idea of what costs would be incurred over the time period that the estuary problem remains unsolved.

This is of course a difficult task because many of the costs are intangible. But none-the-less we could make a ball-park estimate of direct cost of not solving the problem.

For example, the K-Mart at Mandurah have kindly provided me with the gross turnover figures for the month of April this year. In April 1983 K-Mart took $2,300,000 into their cash registers. Now it so happens that for other reasons they have a very accurate estimate of the percentage of their customers that are not normally residents of Mandurah - 75 per cent. If we were to assume that a bad bloom in the estuary deterred half of those people from coming into Mandurah over a three month period every summer one could estimate that a reduction of $2,000,000 gross takings of this business in one year could be attributed to the estuary problem.

Similarly one could estimate the cost to a canal developer who had invested $100,000,000 and, as a consequence of the estuary problem, could only sell his land at half the rate.

My point is that we cannot possibly evaluate the cost of management options unless we know the costs of the alternatives. One alternative is to do nothing and all alternatives have various time factors associated with them.

If we add to these directly quantifiable costs the intangible costs which I have referred to, the cost of some of the options which are being considered may not be as formidable.

COMMUNICATION

Many of the problems I have spoken about which are based on social factors would be less difficult if the people who make up the social environment in the Peel-Harvey area made their decisions on a rational basis. In other words if they were fully informed.

Once again I stress that what has been done in the form of pamphlets and newspaper articles and more recently a film are excellent. It is not what has been done that is at fault just that in my opinion there has not been enough of it.

I am confident that I am right because I am constantly in contact with members of the community who discuss the Peel-Harvey problem and I find it is the exception to find the person who has even a basic understanding of the problem. Most, however, are very prepared to offer their solution which frequently reflects their ignorance.

You may well ask why is this so, given that there has been a fair effort to communicate.

Firstly - I believe that we grossly underestimate the difficulty of communicating the substance of a complex scientific study to an audience which is largely unfamiliar with science and is virtually saturated with competing information.

eg. simply by using the symbol P instead of the world phosphorus in a diagram explaining P uptake by diatoms means that half the population of Mandurah won't understand the diagram.

e.g. a parallel example is the fact that we as scientists tend to accept as the norm that equally reputable scientists can have different interpretations of basic processes and that as information becomes available the method by which we hope to achieve control of a problem and the prognosis can change quite rapidly. But the average citizen in the street doesn't have the concept. As a consequence the option to dredge the inlet, because it was suggested, as it should have been, at an early stage of the study, as an option which needed to be examined, was seized on by the peoples group to save the estuary as the answer which could easily be funded if we didn't have to pay all these fancy scientists.

The second reason why we are not succeeding, and it follows from the first, is that we are not devoting enough resources to the problem and the special skills, which are not often found in scientists, to effectively cope with what is a major public education problem.

I think it is ironic that my letter box is literally stuffed each week with coloured brochures urging me to buy from local stores yet we have only just started using the same technique and at a far lesser intensity to communicate about the eutrophication problem.

In concluding I anticipate that you may respond to many of the points that I have raised by denying that they are the responsibility of scientists. I am sympathetic to this preposition to a degree. None-the-less I hope you do not dispute that the social environment is very relevant to the Peel-Harvey Study.

There may be some questions as to who is responsible for handling the social and political aspects of the Peel-Harvey eutrophication problem but clearly they are important and must be addressed. I believe it would be a tragedy if the excellence of your scientific endeavours is wasted because of a neglect of the social environment.

Postscript - Recommendations for Management

Ernest P Hodgkin

Following the Symposium careful consideration was given to what recommendations should be made to Goverment with respect to management and further necessary study. In making these recommendations special attention was given to the findings of the Humphries-Croft study (DCE Bulletin 165 of 1984) and the recommendations arising from this. (Summarised by S J Robinson pp 3-10).

The report presented to Cabinet in February 1984 stated the principal aim of management to be to reduce the algal nuisance to acceptable levels without further damage to the estuarine environment, and if possible without loss of production of the estuarine fishery and of agricultural production in the catchment.

'Acceptable levels' of algal abundance were defined as:

. Blue-green algal blooms should not occur more often than once in five years, that is only in years of well above average rainfall.

. Large green algae should not cause fouling of beaches near populated areas.

The report stated that these objectives could be achieved either by:

. control measures; measures designed to contain the problem by assaulting the algae themselves, without attacking the cause of the problem, by weed harvesting and possibly by the use of algicides:

or

. preventive measures; management measures designed to reduce the eutrophic condition which causes the algal problem by reducing the input of phosphorus to the estuary or by increasing phosphorus loss from it.

Specific recommendations were as follows:

1. Weed harvesting

Both offshore harvesting and beach removal of algae to be continued as long as is necessary in order to prevent fouling of beaches adjacent to populated areas. The effectiveness of these measures in reducing the weed problem must be monitored by periodical surveys of weed growth areas.

2. Application of algicides

Further investigation of the potential of algicides (especially terbutryn) for control of both blue-green and green algae be undertaken. Assessment of possible dangers associated with the use of such algicides must also be undertaken.

3. Modification of agricultural fertilizer practices

It is recommended that the methods which have so far only been employed on an experimental scale in the catchment of Harvey Estuary should be implemented forthwith in the entire coastal plain catchment of the Peel-Harvey estuary. This is both because it will substantially reduce the input of phosphorus to the estuary and because of the improvement it can make to agricultural practices on sandy soils of the catchment of the estuary, and elsewhere in the State. Implementation is urgent so that the maximum effect can be achieved in 1984. It is recognised that the 30 to 40% reduction in phosphorus input to the estuary, that this measure can achieve in 3 to 5 years will, by itself, only reduce the frequency and intensity of algal blooms. Long-term management can only be achieved by a combination of this measure and increased flushing to the sea.

4. Amendment of leaching soils with bauxite residue

It is recognised that this measure has the potential to reduce the quantity of phosphorus leached from sandy soils by improving the phosphorus and water retaining capacity of the soils. It is recommended that ALCOA and the Department of Agriculture be encouraged to continue research on this technique.

5. Changes in current land use

It is recommended that further evaluation of this measure be undertaken because it has supplementary value as a means of reducing leaching of phosphorus to drainage from the Bassendean sands, more especially from the Gavin sands from which there is poor economic return under present conditions. It is unlikely to be applicable to more productive sandy soils, but these should nevertheless be considered in any study.

6. Treatment of rural point sources

It is recommended that continued support be given to research into the potential of this measure for treatment of nutrient-rich point sources.

7. New channel from Harvey Estuary to the ocean

Further evaluation of this measure is recommended because, with Option 3 it offers the best prospect for long-term management of the present eutrophic condition of the estuary. If this is done in 1984-85, construction could be started in 1986, with two years to completion. (This assumes there will be no delay due to land acquisition).

Investigation is required to establish the optimum location and dimensions of the channel which would minimise construction costs consistent with producing the required effect on the estuary. This should include further estuary modelling as well as investigation of the geology of the proposed site of the cut.

In addition to evaluation of the engineering aspects, investigation is required of possible deleterious effects of the predicted change in tidal regime (from 'barometric' tides of 5 to 15 days to daily tides) on the biota of the estuary, and particularly with respect to problems which may arise as a result of the more frequent exposure of large areas of the marginal shallows. Also the effect of the channel on flood levels and storm surge need to be assessed.

8. Enlarging the Mandurah channel

This measure aims primarily to reduce the availability of phosphorus to algae in Peel Inlet by increasing flushing of estuary water to the sea and hence to reduce weed growth. It would have very little effect on the retention of phosphorus in Harvey Estuary and consequently only minimal effect on blue-green (*Nodularia*) problems there.

Implementation of this measure as a means of managing the eutrophic condition of the estuary is not recommended, unless the new channel from Harvey Estuary to the sea is rejected in which case further evaluation of this measure is desirable.

9. Clearing controls

In order to prevent any exacerbation of the eutrophic condition of the estuary a moratorium should be placed on further clearing of land on the coastal plain.

10. Restrictions on new drainage

It is recommended that further investigations be undertaken to ascertain the relationship between drainage density and phosphorus discharge. These investigations would form part of the surface run-off monitoring and evaluation program that would be undertaken as part of the modification of agricultural practices (3).

PHOSPHORUS MOVEMENT THROUGH SANDY SOILS AND GROUNDWATER IN THE PEEL HARVEY CATCHMENT AREA

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INTRODUCTION

A primary aim of our research is to establish within a defined catchment area actual migration or dispersion of phosphorus applied as phosphated fertiliser through the catchments soil structure and associated groundwater. Phosphorus moves through soil and groundwater with rainfall water as its carrier medium. An understanding of phosphorus movement therefore requires an understanding of how rainfall water moves through the catchment area. This understanding can be derived from a study of the hydrology (including groundwater hydrology) of the catchment. A quantification of the hydrologic cycle over the catchment is necessary to determine the amount of water lost to the atmosphere from evaporation and evapotranspiration, the amount of water flowing as surface run-off and the amount infiltrating through the soil and eventually to the groundwater.

An understanding of the movement of phosphorus through soils and groundwater also requires an understanding of how phosphorus interacts with soil, how it is adsorbed, precipitated and perhaps desorbed from soil and how the adsorption of soil for phosphorus is affected by time.

Finally, we have to combine our understanding of the hydrology and soil chemistry components so that we have a coherent overall picture of the phosphorus movement, especially since phosphorus removal by soil is known to be time dependent. Our work concentrates on providing the link between the groundwater hydrology and soil chemistry components through a modelling technique incorporating both. Though we will rely and make use of results available in the hydrology and soil chemistry areas of the project, we will also conduct laboratory experiments that will provide values for the parameters of our model.

In its initial stages the laboratory work will consist of establishing phosphorus breakthrough curves, a phosphorus adsorption - desorption - dispersion pattern together with initial time dependent adsorption characteristics for each defined soil over its various horizons. We make use as a framework for our experiments and the interpretation of the experimental results a model incorporating the movement of P through soil by convection, hydrodynamic dispersion and time dependent P adsorption by the soil.

From these laboratory determined parameters we will set up a working model which will be able to predict phosphorus movement through a defined catchment of the Peel Harvey Estuarine System. The experimental results presented here are preliminary estimates of these parameters required by the proposed model.

EXPERIMENTAL

In an endeavour to simulate field conditions within the laboratory samples of Jandakot and Gavin soils from the Bassendean soil association were collected within the catchment area (Bettenay, pers. comm. 1984), over three different horizons (A - ground surface to 20 cm, B - 20 cm to 80 cm and C - 80 cm to 150 cm). In situ bulk densities were determined at least at two levels across the profile. Samples were also taken from the hard pan commonly known as coffee rock.

Dispersion coefficient

The dispersion coefficient D was determined from phosphorus breakthrough curves where phosphorus was not adsorbed by the soil. A superimposition technique was used to find D from the experimental data by comparing the breakthrough curves with curves computed from values derived by Brenner (1962) at different B_e values, Figure 1.

Adsorption isotherms

A series of batch tests were conducted on each soil horizon to establish the adsorption isotherms for phosphorus. The tests were done in a shaking water bath at 30°C over a period of 24 hours. Some tests were also performed at 48 and 96 hours. A soil:solution ratio of 1:3 was used, solution samples were 0.01 M with respect to calcium chloride and contained phosphorus in the range 0.5 to 200 $mg\ell^{-1}$ P added in the form of KH_2PO_4. At the end of each time period samples were filtered on a 0.45 μ millipore filter and the filtrate analysed for phosphorus.

Phosphorus Breakthrough Curves

Adsorption - a phosphorus solution containing 40 $mg\ell^{-1}$ P in 0.01 M $CaC\ell_2$ was allowed to flow through each soil horizon at its natural infiltration rate until the inflow and outflow concentrations became equivalent. A fraction collector collected the outflow which was analysed for phosphorus.

Desorption - a solution containing potassium nitrate at 40 $mg\ell^{-1}$ K in 0.01 M $CaC\ell_2$ was allowed to flow through each soil horizon at its natural infiltration rate until the outflow concentration of phosphorus approached zero.

RESULTS

Table 1.

Property / Horizon	Jandakot Soil			Gavin Soil			Coffee Rock
	A	B	C	A	B	C	
Bulk Density kgm^{-3} ρ_B	1330	1470	1470	1340	1450	1510	1650
Particle Density kgm^{-3} ρ_P	2390	2620	2640	2450	2600	2620	2480
Porosity	0.44	0.44	0.44	0.45	0.44	0.42	0.33
Hydraulic Conductivity K md^{-1}	9.7	24.4	21.3	7.9	25.7	33.3	
Pore velocity x 10^{-4} V ms^{-1}	2.02	5.55	4.45	1.63	5.55	6.93	
Dispersion Coefficient D m^2s^{-1}	$8x10^{-6}$	-	-	$6x10^{-7}$	$3x10^{-6}$	$3x10^{-6}$	
Brenner Number B_e	2	-	-	20	15	15	
Freundlich Relationship $s = mc^n$ m	4.6	9.3	32	-	-	-	800
n	0.53	0.38	0.33	-	-	-	0.36

DISCUSSION

Bulk density, particle density and hydraulic conductivity

The dispersion coefficient values of between 0.6×10^{-6} to 8×10^{-6} m^2/s at pore velocities of between 2×10^{-4} to 7×10^{-4} m/s are comparable to values reported for sands (Klotz *et al*, 1980). A value of 4×10^{-8} m^2/s was obtained by Mathew *et al* (1982) for Bassendean sand from Canning Vale at a pore velocity of 1.5×10^{-5} m/s.

Adsorption Isotherms

Batch tests conducted over a limited range of phosphorus concentrations and soil:solution ratios have revealed a wide range of characteristics for various soils. The Gavin or deep grey sands have shown no ability to retain phosphorus; however more testing is required varying the soil:solution and time to confirm this initial experimental work. The Jandakot soil horizons together with a coffee rock sample provide the only source of phosphorus adsorption capacity within the catchment area. Jandakot soils show an increasing affinity for phosphorus with depth especially within the C horizons, Figure 2. The adsorption isotherms follow the Freundlich relationship fairly closely. In a similar manner the coffee rock layer shows even a greater affinity for phosphorus and exhibiting a time dependent capacity for phosphorus adsorption. The time dependent adsorption is expected to occur with Jandakot soils as well.

Breakthrough Curves

The phosphorus breakthrough curves illustrate the range of interactions of phosphorus and soils in the transport of phosphorus through soils with differing adsorption properties. These soils have shown:

(i) no adsorption with phosphorus; transport due to convection and dispersion only, Figure 3,
(ii) adsorption with both convection and dispersion, Figure 4, and
(iii) time dependent adsorption, Figure 5.

These differences are of importance when considering the movements of phosphorus from the point of application, through the soil and groundwater to drains and rivers.

FUTURE WORK

Future work should be directed towards field and laboratory investigations. The field programme, which is carried out by CSIRO, should be directed towards estimation of the extent of the coffee rock layer together with an accurate description of the catchment soil profile. Groundwater movement within a defined catchment should also be accurately quantified.

The laboratory programme will concentrate upon further column and batch experiments to obtain the parameters required for the phosphorus-groundwater model of the catchment area.

In terms of management of phosphorus in the Peel Harvey Catchment our work has shown that we ought to be looking for ways of modifying the groundwater hydrology regime to take advantage of the adsorption capacity of coffee rock for phosphorus. It appears that in summer months long contact times between water and the soils (including coffee rock) is large and management of phosphorus by soil adsorption is feasible since adsorption already takes place. In the winter months we need to modify the flow regime to move away from the present regime towards the summer flow regime.

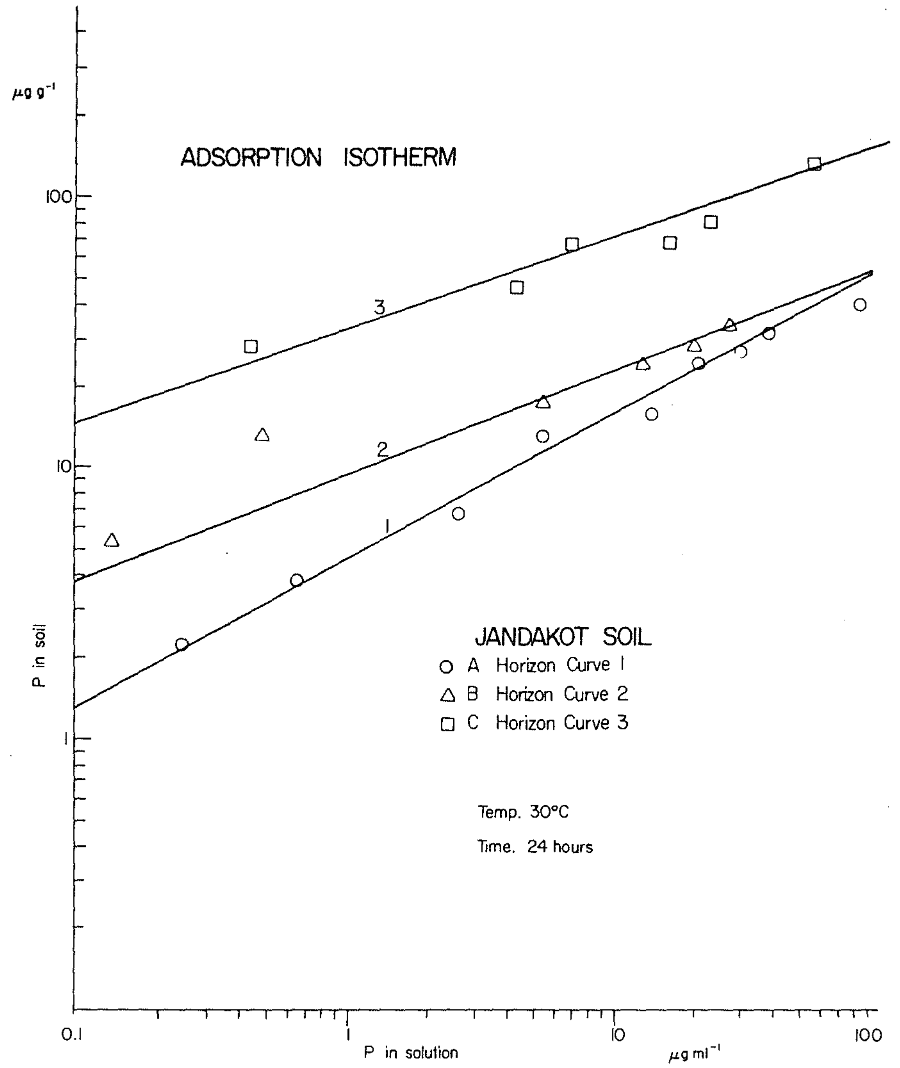

Figure 1.

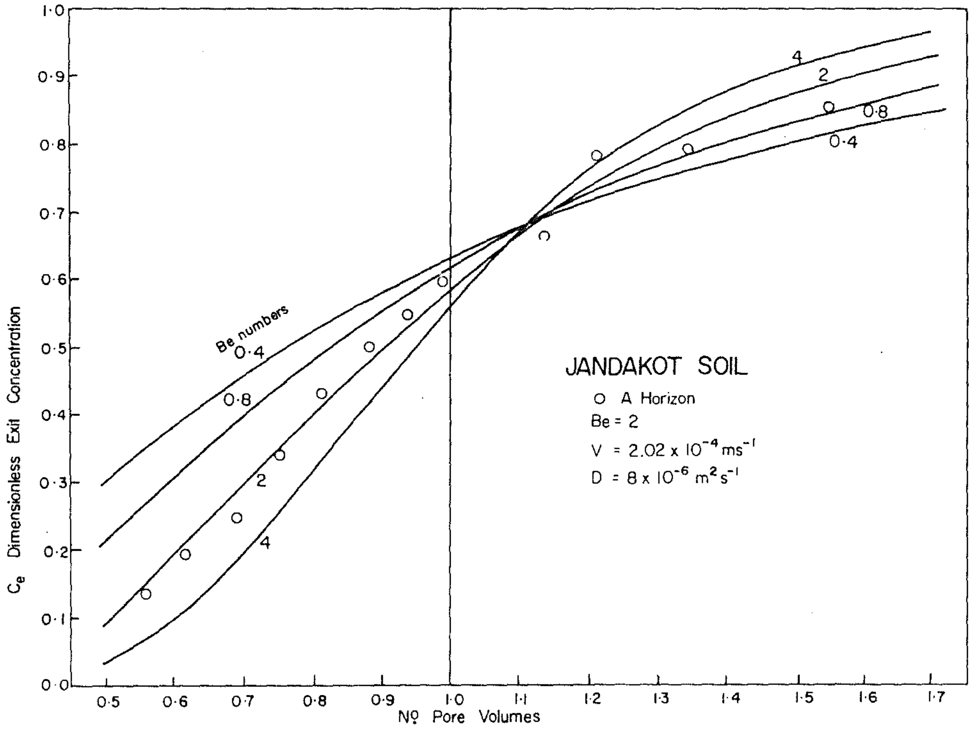

Figure 2.

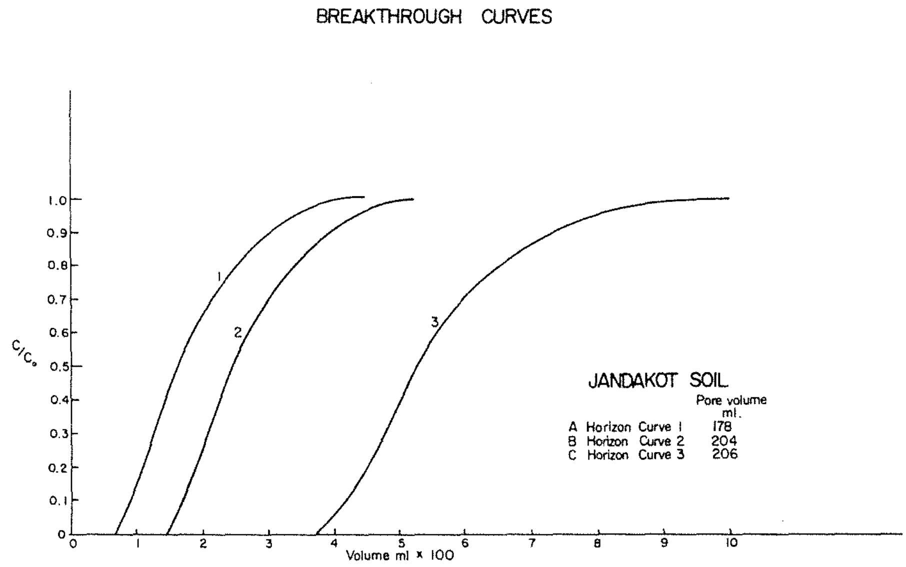

Figure 3.

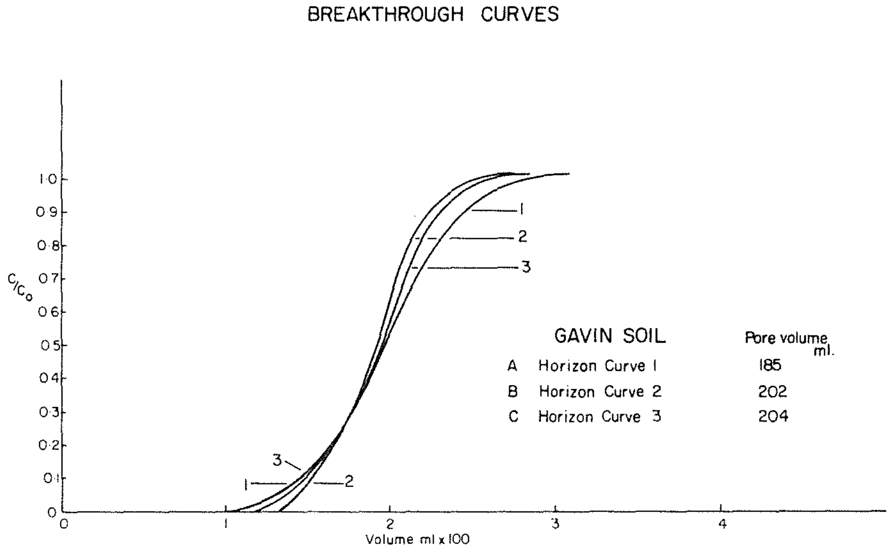

Figure 4.

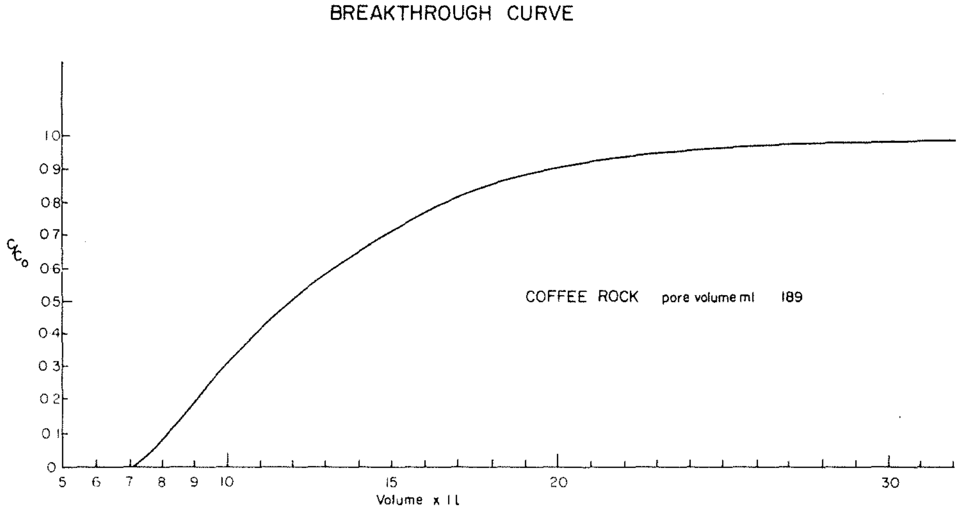

Figure 5.

PEEL-HARVEY ESTUARINE SYSTEM STUDY

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