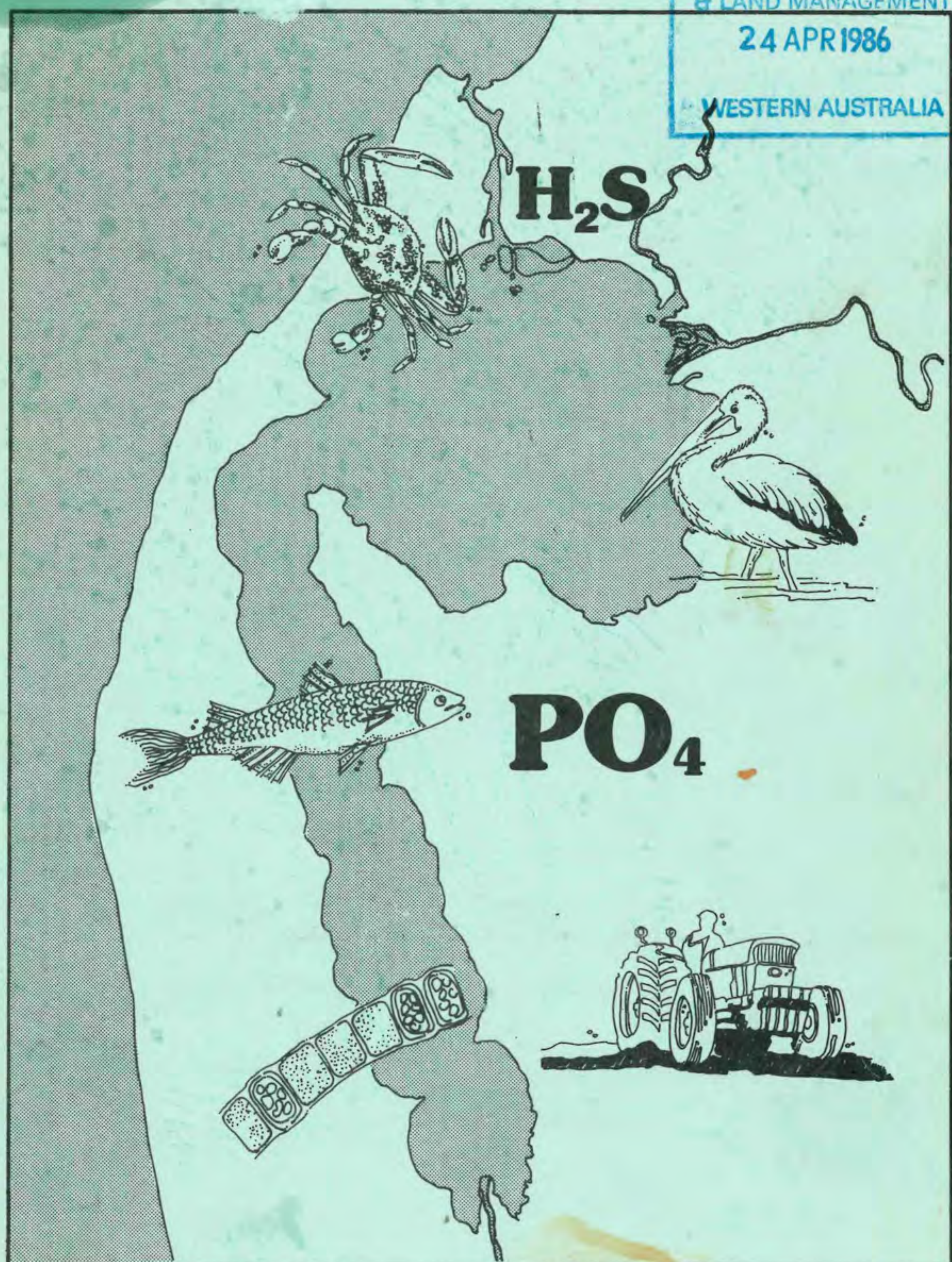
PEEL-HARVEY ESTUARINE SYSTEM STUDY
MANAGEMENT OF THE ESTUARY



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PEEL - HARVEY ESTUARINE SYSTEM STUDY:

MANAGEMENT OF THE ESTUARY

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DEPARTMENT OF CONSERVATION AND ENVIRONMENT

BULLETIN 195

ERRATA

Delete last paragraph of page 146 and Table 2 (top of page 147) and replace with ...

Typical segment flushing times for an average tidal range are given in Table 2 as calculated from the usual definition of flushing time in tidal cycles (Dyer, 1973, p 110).

$$T = \frac{V_o + P}{P} \quad \text{(tidal cycles)}$$

where V_o is the segment low tide volume and P, the intertidal volume

V_o = plan area x D (D = the low water depth)
P = plan area x ΔH (ΔH = the tidal range)

Example.
For $A_{plan} = 3.10^6$ m^2, D = 1.5 m and ΔH = 0.1 m

$$T = \frac{(3.10^6)\ (1.5 + 0.1)}{(3.10^6)\ (0.1)}$$

= 16 tidal cycles

The method shows the independence of the flushing time on the segment area (cancellation) hence, on the basis of a uniform rise and fall of water level over the whole estuarine system per tidal cycle, the flushing figure can be taken as quite representative of the flushing time for the Peel and Harvey basins.

	Segments (sections)	Flushing time in tidal cycles (days)	
		No Dawesville Channel	With Dawesville Channel
Peel side of Channel	10-11	14	5
	12-13	14.5 (30)	5 (10)
	14-15	12	4.5
Harvey side of Channel	17-18	17	5.7
	21-22	16.5 (50)	5.7 (17)
	25-26	15.3	5.5

( ) estimated Peel and Harvey basin flushing times

TABLE 2: Segment flushing times based on volumetric exchange

1985 PEEL-HARVEY ESTUARINE SYSTEM SYMPOSIUM

Introduction Day 1

Ernest P. Hodgkin

This is the third Symposium we have had since starting Phase 2 of the Peel-Harvey study in 1982. The first, in December of that year, reviewed progress reports of the early investigations which aimed to determine how the estuary could be managed.

At the second, in November 1983, we saw the results of the first efforts to reduce the load of phosphorus coming into the estuary. These were very encouraging but pointed to a number of deficiencies in the methods being employed and how these could be remedied.

We also had the results of a number of studies which gave a better understanding of what goes on in the estuary itself, particularly with respect to what happens to phosphorus once it enters the estuary.

The Symposium also had the results of the assessment of potential management measures made by Bob Humphries and Chris Croft (DCE Bulletin 165). They came up with the radical new proposal for a second channel to the sea, the Dawesville Channel, in order to reduce phosphorus retention in the estuary sufficiently to achieve the management objectives.

As a result of the deliberations of the Symposium a list of recommended management measures was given to Government with a 'preferred strategy' which we envisaged as necessary if the algal problems, and in particular the *Nodularia* problem, were to be solved quickly. This was given publicity in Bulletin 170 of May 1985.

The Dawesville Channel was a key element of this strategy. This radical and costly solution could not be put to the EPA without a great deal more information as to what it would achieve in respect to the algal problems, but also what else it would do to the estuarine ecosystem and of course details of where, how and at what cost it would be constructed.

Oddly enough, no-one asked us to find out what the response of the public would be to such a major undertaking, especially what the local residents thought about it. However, as you can see from tomorrow's program, this aspect has not been neglected.

During the past year there has been great progress on all fronts, particularly on the measures to reduce the wasteful loss of phosphorus being used to fertilize crops on the coastal plain and on assessing the effects of the proposed management measures on the ecosystem.

This year, as in 1983, our program is divided into discussion of these two main areas: the catchment and the estuary. Again, on the basis of the reports we have, we will now have to make recommendations as to the management measures we believe should be adopted.

Obviously, from the scientific point of view we will not have enough information for us to be able to cross our hearts and say: 'these are the perfect solutions to the estuary's problems'.

There are still a lot of unknowns and in respect of some I am sure we would all feel more comfortable if we had more adequate data. However, recommendations now have to be made and we must be content with levels of uncertainty which would be unacceptable in a more rigorously scientific investigation.

This is in no sense derogatory to the first class scientific work which has contributed to our understanding of the estuary and its problems, the quantity and quality of which is evidenced by the long list of scientific publications. This is a clear bonus from a study which is primarily directed towards solving a practical problem.

At this point, it is relevant to note what I know is painfully obvious to the speakers: that they cannot here give adequate accounts of their work in the time available. I assure them that there is no lack of interest in the more scientific aspects of their work and hope there will be other venues at which the full story can be told.

The papers to be presented over these two days range over a wide spectrum of topics, from determining the rates of movement of water and phosphorus through the various soil types, to what the public thinks about the estuary and its problems. But the objective of all must be to indicate what the findings contribute to judgments about management.

On this first day we are concerned with matters relating to determining how best the plant nutrients can be reduced at source, primarily on farmlands of the coastal plain.

In this area we are already well into the management stage, Phase 3, of the study and are beginning to see what the fertilizer modification campaign, based on the soil testing program and use of New Coastal Super, can achieve by way of reducing the input of phosphorus to the estuary both in the short term and for the continued, long term well being of the estuary. Also, of course, for the future of agriculture in the catchment.

Important areas of ignorance noted at previous symposia include: the rate and volume of water moving through the different soil types, the behaviour both of the applied fertilizer phosphorus and of the store of phosphorus that has accumulated in the soils, and, most important, the time over which the soil stores will continue to contribute to run off to the estuary and in what quantity.

On all these points today's speakers will contribute valuable new data, data that is derived from a variety of field experiments, subject to the vagaries of the weather and human interference. This is backed up by laboratory studies designed to speed up what goes on in the field and to determine more precisely the nature of the processes involved

In previous symposia considerable emphasis was laid on the different soil types and the way they behave in respect to the release and retention of phosphorus and its availability to crops. If this receives less attention today, it is not because it is no longer important, rather, I suspect, because there is little new to add.

However, it is well to recall the significance of the soil types to budgeting phosphorus input to the estuary. Our earlier superficial emphasis on the prime importance of the Bassendean sands was put into perspective by Jim Barrow two years ago when he suggested that the Collup soils were likely to present us with the more serious long term problem.

How much phosphorus do each of the three major soil types contribute to input now? And how are these contributions likely to change over the next five, ten or twenty years? In this respect, the data from Peter Birch's sub-catchment monitoring is clearly most valuable, though as you will learn, he has had his share of problems in interpreting the data.

In deference to Eric Bettenay, it is only fair to point out that 'three' is a gross simplification of the complexity of soil types depicted on the soils map of the coastal plain so that we are very much in the position of suck it and see, waiting to see what the fertilizer modification program will achieve in this complex situation.

For obvious reasons most attention has been given to management measures which will produce quick results by reducing the immediate loss of phosphorus to drainage and ensuring the maximum rate of run down of the soil phosphorus store. But it is still necessary to consider the long term future of the catchment's influence on the welfare of the estuary.

On the one hand we need to know what changes there may be which will affect the nutrient supply and, on the other hand, whether we can suggest any modifications to present practices which can reasonably be expected to contribute to a reduction in input to the estuary. These questions are the focus of the third session today.

In concluding this introduction, let me hark back to one item of the second session today. It is concerned mainly with the development and proper use of fertilizers apppropriate to coastal plain soils and the results of their application.

These new methods would never have been adopted so widely and so successfully but for the efforts of the Extension Services of the Department of Agriculture in explaining to farmers the benefits to them from accepting recommendations made on the basis of the soil tests. All the work involved in developing new fertilizers would have been of little use if farmers could not have been induced to adopt them.

To quote John Yeates: "The major challenges in the future are to increase the level of adoption of the 'new' strategies, and then maintain a high level of adoption."

I sincerely hope this can be achieved by persuasion; by persuading farmers to adopt measures which are to their advantage as well as to the advantage of the estuary. We, and especially the Department of Agriculture, are opposed to any form of compulsion.

Lastly, on behalf of the Project Team, Peter Birch, Ron Black and myself, I want to thank the speakers for the hard work they have put into making this Symposium a success.

PLOT AND SMALL CATCHMENT STUDIES OF PHOSPHORUS LEACHING TO SURFACE DRAINAGE IN RESPONSE TO SUPERPHOSPHATE, NEW COASTAL SUPERPHOSPHATE AND NIL FERTILIZER TREATMENTS

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INTRODUCTION

The overall objective of the field hydrological experiments has been to determine the extent and period over which phosphorus input to the Peel-Harvey Estuarine System can be reduced by modifying fertilizer practices on the coastal plain without reducing agricultural production. In addition to answering this comprehensive management question, the experimental programme has attempted to quantify the components of the water and phosphorus budgets and also to give an insight into phosphorus transport mechanisms. The technical side of the study is only reviewed briefly in this paper, where emphasis on management considerations is required.

Field experiments have now been in operation from 1 to 3 years. In addition to quantifying the effects of different fertilizer treatments on phosphorus leaching to drainage, some attempt has been made to define the immediate impact of the new fertilizer regime as well as the longer term impact. This often amounts to a division between the contribution of the treatment and of the soil phosphorus store.

The paper begins with some pertinent facts about the Peel-Harvey catchment, then discusses the experimental approach before proceeding to describe the 1984 results. At the conclusion a summary of the major management findings is presented.

SOME PERTINENT FACTS

1. The highest proportion of phosphorus entering the Peel-Harvey System is from surface drainage of the Peel-Harvey catchment. Approximate proportions of the various components are given below:

Source	Proportion (%)
rivers and drains	68
marine	30
urban	~ 1
rainfall	~0.5
deep groundwater	0.3

2. Most of the phosphorus in surface drainage is leached from sandy soils of the coastal plain. Figures for phosphorus input (load) to the Harvey Estuary (via the Harvey River and drains entering the Estuary) for each major soil type are shown below:

	Harvey Estuary	
	% area	%P input
deep sand	22	36
sand over clay	33	40
other (loams, clays)	45	24

It is apparent that sandy soils of the coastal plain contribute about 76% of the total phosphorus load but only occupy 55% of the area. The reason for this fact is that sand has a low phosphorus adsorption capacity and releases phosphorus at a faster rate than texturally finer soil types.

3. For annual phosphorus loads and flows at the large scale, there is a good correlation between load and flow. Another way of expressing this is that flow-weighted mean concentration of phosphorus is fairly constant over time:

$$\overline{P}conc = \frac{\text{total load}}{\text{total flow}} = \text{constant}$$

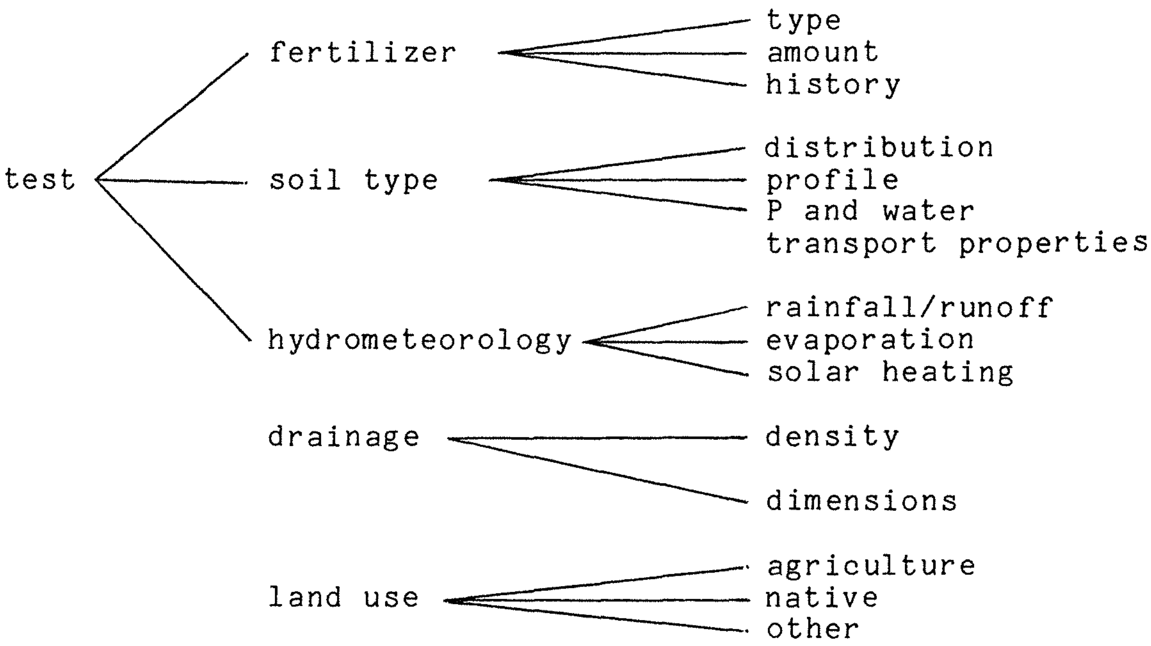
As an example, for Harvey River winter flows, over the period 1977-83:

$$\overline{P}conc = 0.41 \pm 0.06 \text{ mg/L}$$

The apparent constancy in $\overline{P}conc$ has made this parameter a particularly useful tool in attempting to quantify the effects of different fertilizer treatments.

METHODOLOGY OF FIELD EXPERIMENTS

The amount of phosphorus leached to drainage in any one year is dependent on a wide range of factors, some of the major ones of which are listed below:



At the outset of the study it was assumed that the first three major factors are most significant and amenable to field experimentation. That is, it was required to quantitatively determine the effects of different fertilizer treatments for the major soil types over a range of climatical conditions. Superphosphate fertilizer has been applied to the agriculturally developed land of the coastal plain at the fairly consistent rate of '1 bag to the acre' (18kg P/ha) in accordance with the Department of Agriculture guidelines until the recent fertilizer modification programme. The amount of phosphorus accumulated in the soil depends primarily on the soil type and the number of years of application. The soils of the coastal plain have been divided into a small number of broad groups (Fig. 1) for the purpose of siting field experiments and extrapolating results. Both the water and phosphorus movement mechanisms are quite diffent in each soil type. The hydrometeorology factor is tested by operating experiments over a number of years during which a range of conditions will occur. The distribution of rainfall and runoff appears to be very significant in determining phosphorus leaching (see Birch et al., Ritchie et al. this bulletin).

In addition to the range of factors discussed above, phosphorus leaching is subject to 'scale variability', that is the effects of different spatial scales. This problem is particularly relevant to extrapolation of results and has been overcome to

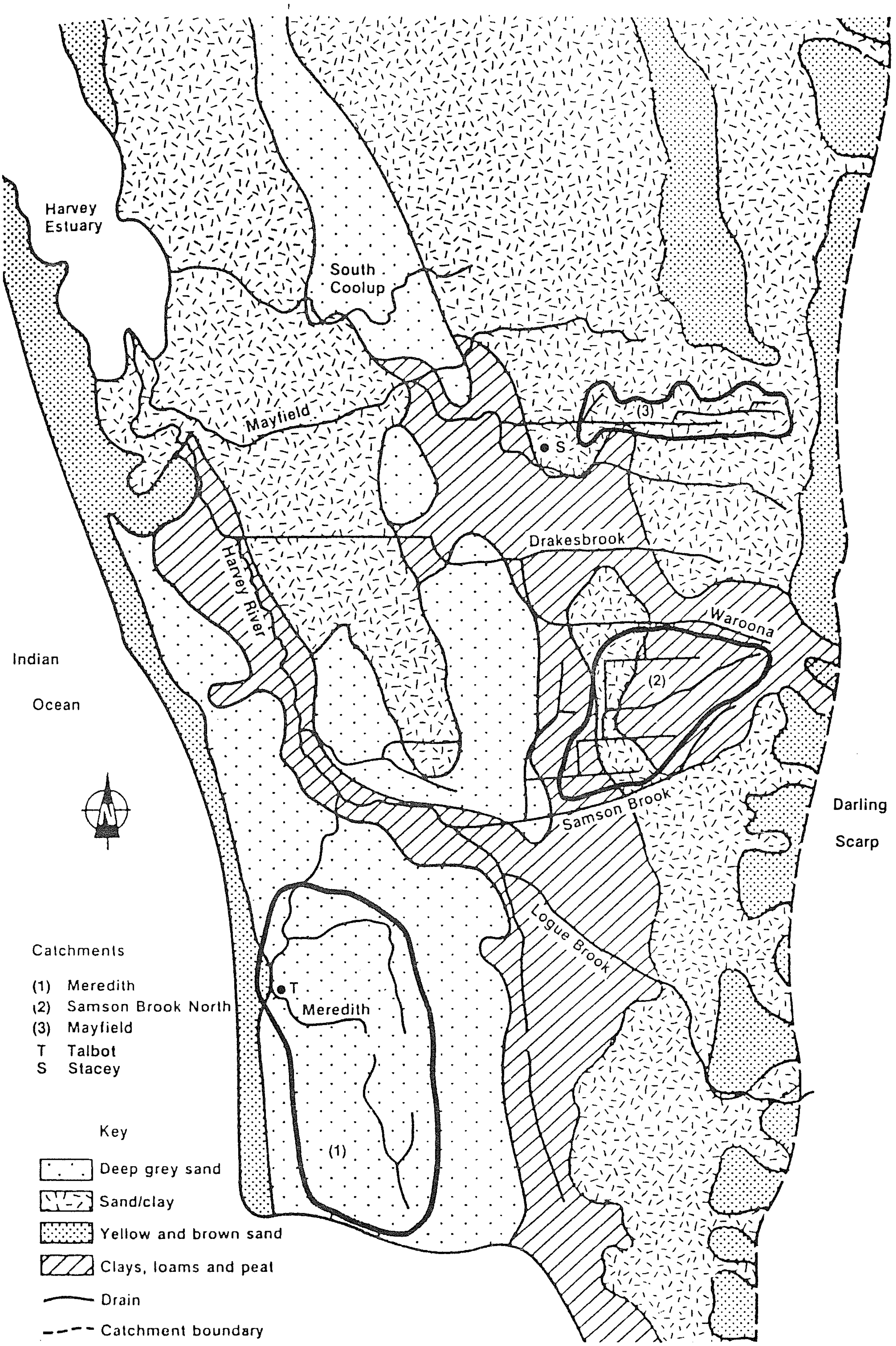


Figure 1 : Primary soil groups of the coastal plain with drains and their catchments superimposed.

some extent by conducting experiments at a range of scales, from small plots to large river catchments. The small scale is naturally useful for testing different fertilizer treatments, whereas large catchments are essentially a monitoring exercise, assessing widespread changes in fertilizer practices. The scales and types of experiment are listed below and the locations of sites referred to in the text are shown in Fig. 1.

Small Scale (.4 - 40 ha)

- paired and triple plots/microcatchments
- measure effects of different fertilizer treatments on different soil types

Intermediate Scale (1000 - 5000 ha)

- single catchments
- measure $P_{applied}$ and $P_{drainage}$ on different soil types

Large Scale (900 - 8000 km^2)

- large river systems
- estimate $P_{applied}$, measure or estimate $P_{drainage}$

RESULTS

The presentation of results is divided between experiments occurring on deep sands and sand over clays (or duplex soils). Data on Samson Brook North catchment (based on loams and clays) is not yet available for the 1984 period.

Deep Sands

As mentioned previously, deep sands occupy a large area of the coastal plain and also contribute phosphorus to drainage at the highest rate. The movement of phosphorus and water through deep sands is significantly different to other soil types. On the broad inter-dune flats, groundwater lies permanently close to the surface. At the onset of winter the water table is typically 1 m below the surface, but during winter the water table rises close to the surface and in major storm events overland flow occurs. It is calculated that approximately 40% of drain flow is derived from overland flow and the remainder is primarily shallow groundwater flow.

Three experimental sites have been established on deep sands, namely Talbot (paired microcatchment study), Caratti (triple microcatchment study) and Meredith (intermediate scale catchment). Each study is discussed seperately in the following.

Talbot's study

A higher level of investigation has taken place at Talbot's site than any other due in part to the high rate of phosphorus leaching from deep grey sands. The principal aims of this study have been to compare superphosphate and nil treatments, to quantify water and phosphorus budgets and to investigate water and phosphorus movement.

The properties of the Talbot catchments are described in detail by Bettenay *et al*. (this bulletin). In general the paired catchments are thought to be representative of the deep grey sands with an appropriate distribution of soil types (primarily gavin dunes and joel flats) and not atypical drainage. The site has been fertilized for 16 years and used for sheep grazing pasture. Soil tests indicated that the catchments have a soil phosphorus store beyond the non-responsive pasture yield limit.

The results of comparison of fertilizer treatments are summarized in Table 1. The comparison is made over three periods: pre-treatment, post-treatment and total runoff period. At the outset of the experiment the pre-treatment data indicated that the catchments were well matched (on the basis of similar $\bar{P}$concs). For the post-treatment 1983 period, $\bar{P}$conc was 34% lower under the nil treatment. However, over the following summer the swamp vegetation of the South catchment was sprayed with herbicide and killed, releasing an unspecified quantity of phosphorus. This is reflected in the significantly higher $\bar{P}$conc of the South catchment in 1984. However, if the pre-treatment contribution of the swamp is represented by the differences between its 1984 and 1983 values, then the post-treatment differences between nil and superphosphate treatments is 38%. This slight further reduction compared to 1983 is also indicated by comparing 1984 and 1983 nil treatment values, which show a 3% reduction. However, it is likely that such small changes are well within the variability of the system and quantitative conclusions should not be drawn at this stage.

Table 1 : Comparison of fertilizer treatments on Talbot's paired catchments

	1983		1984	
	North	South	North	South
	nil	superphosphate 18.2 kg P/ha	nil	superphosphate 18.2 kg P/ha
pre-treatment				
runoff (10^3m^3)	7.9	15.1	8.6	8.1
P load (kg)	20.1	39.1	18.4	32.3
$\bar{P}$conc (mg/L)	2.54	2.58	2.14	3.98
post-treatment				
runoff (10^3m^3)	50.6	82.8	13.7	16.8
P load (kg)	89.8	218.4	22.4	80.9
$\bar{P}$conc (mg/L)	1.78	2.68	1.64	4.83
total period				
runoff (10^3m^3)	58.5	97.9	22.3	24.9
P load (kg)	109.9	257.5	40.8	113.2
$\bar{P}$conc (mg/L)	1.88	2.66	1.83	4.55
pasture yield (tonne/ha)	5.72	5.12	3.95	4.04
Pplant (kg/ha)	15.6	16.7	8.60	11.12

key P load means phosphorus load
Pplant means phosphorus in plant tops
$\bar{P}$conc means flow-weighted mean concentration
nil means basal fertilizers only

Of additional interest in this experiment is the apparent decline in phosphorus taken up by plants under nil treatment in 1984 compared to 1983. This amounts to a relative decline of 16% but is not reflected in pasture yield.

Substantial progress has been made in quantifying components of the phosphorus budget. This is discussed in some detail in the summary by Birch (this bulletin) and only the main points are considered here. Table 2 shows the phosphorus budgets for the North and South catchments for 1983, and compares the quantities involved to the total soil phosphorus store in the top 10 cm of the soil. It is apparent that under nil treatment the North catchment is undergoing a net depletion of phosphorus whilst the South catchment is undergoing a net accumulation of phosphorus of a similar magnitude. Both quantities, however, are relatively small compared to the total soil phosphorus store. This fact may not be pertinent, though, to the rate of decrease of $\bar{P}$conc, which may be related more to the length of the period of nil application.

Table 2 Phosphorus budgets for North and South catchments in 1983

	North	South
P applied (kg/ha)	0	15.01
P drainage (kg/ha)	-4.95	-6.86
P ag. export (kg/ha)	-1.71	-2.14
P ground store (kg/ha)	-6.66	+6.06
P soil (kg/ha/10cm depth)	103.3	78.6

Additional work has been undertaken to quantify the amount of phosphorus that has accumulated in the soil profile since superphosphate application began. To do this, the phosphorus stored in the soil was measured on Talbot's South catchment (fertilized site) and on an adjacent virgin site. In addition, the total phosphorus applied as fertilizer, lost as drainage and exported in agriculture were estimated. The results are given in Table 3.

Table 3 Long-term phosphorus budgets

total phosphorus applied as fertilizer	(kg/ha)	304
agriculturally exported phosphorus	(kg/ha)	-66
phosphorus exported in drainage	(kg/ha)	-126
soil accumulated phosphorus	(kg/ha)	-112
	balance	0

Although there are a number of assumptions and approximations in deriving the above figures, it is apparent that the amount of phosphorus accumulated in the soil can be sensibly accounted for by the application of superphosphate over the period of 15 years. As regards distribution in the profile, 56% of the soil phosphorus (on a single joel South catchment profile) was found to occur in the first 30 cm.

Caratti study

A new research site was established in 1984 for the purpose of replicating Talbot's experiment and to test the new coastal superphosphate fertiliser. Three adjacent microcatchments of area approximately 5 ha were established on the property of Caratti. Following a pre-treatment monitoring period, three treatments of nil phosphorus, superphosphate and new coastal superphosphate were applied. The results of the experiment are summarised in Table 4. The interpretation of the results in this case has been made more difficult by the apparent pre-treatment differences in flow-weighted mean concentration between the plots. In addition plot 1 drains considerably more water because it is lower lying and adjacent to a swamp. At this stage no conclusions can be drawn from the relative effects of the treatments.

Table 4 Comparison of fertilizer treatments on Caratti's property (1984)

	Plot 1	Plot 2	Plot 3
treatment	superphosphate 18 kg P/ha	NCS* 18 kg P/ha	nil
pre-treatment			
runoff ($10^3 m^3$)	6.3	1.2	2.1
P load (kg)	29.7	6.5	7.7
$\bar{P}$conc (mg/L)	4.75	5.61	3.78
post-treatment			
runoff ($10^3 m^3$)	9.3	8.5	7.3
P load (kg)	31.4	30.4	20.4
$\bar{P}$conc (mg/L)	3.39	3.57	2.81
total period			
runoff ($10^3 m^3$)	15.5	9.6	9.31
P load (kg)	61.1	36.8	28.12
$\bar{P}$conc (mg/L)	3.94	3.82	3.02
pasture yield (tonne/ha)	3.64	3.97	3.71
Pplant (kg/ha)	10.8	12.7	11.1

* NCS = new coastal superphosphate

Meredith catchment

Meredith catchment has an area of about 5000 ha of which approximately 2000 ha are cleared. It is located primarily on deep grey sands and has provided the highest mean phosphorus concentration in drainage. Accurate monitoring of this catchment commenced in 1982 and the adoption of new fertilizer recommendations began in 1983. The results of three years of monitoring are shown in Table 5. In 1983 and 1984 the flow-weighted mean phosphorus concentration was significantly less than 1982 (~30%) and some of this decrease is assigned to the adoption of new fertilizer practices. A precise measure of the change, however, is unobtainable because there is only data for one 'pre-treatment' year. It is also noteworthy that 1984 was a relatively low runoff year and this would have some effect on phosphorus leaching to drainage.

Table 5 Annual phosphorus loads from Meredith catchment

year	runoff (10^3m^3)	P load (kg/ha)	$\bar{P}$conc (kg/ha)	*Papplied (kg/ha)
1982	4612	1.53	1.72	19
1983	6422	1.46	1.18	15
1984	3196	0.76	1.22	11

* approximate figures at this time

Sand Over Clay (Duplex) Soils

Although a large portion of the coastal plain Peel-Harvey catchment is termed sand over clay in the broad soil classification, in reality there is a tremendous variability across the area. However, very significant areas of essentially sandy soil overlying or grading to a clay at 0.2 - 1.0 m depth undoubtedly exist, and this gives rise to differences in hydrology as compared to the deep grey sand. On the duplex soils, water tends to perch above the low-permeability clay horizon following early winter rains. Since much of the area is exceedingly flat, drainage through the upper aquifer is slow and most of the drain flow (approx. 80%) comes from overland flow when the upper aquifer is fully saturated. Drain flow in this area is ephemeral since there is no deep groundwater input.

Three small-scale experiments are being conducted on the duplex soils (Stacey, Hodgson and Jenkin) and one intermediate sized catchment is being monitored (Mayfield sub-G). The results of these experiments are discussed in the following.

Stacey experiment

On Stacey's property 3 hillslope plots of 0.4 ha were established in 1983 and treatments of nil phosphorus, (new) coastal superphosphate and superphosphate fertilizers were applied. The results of the experiment are summarised in Table 6. In 1983 there was an apparent significant reduction in $\bar{P}$conc on the nil treatment in comparison to the superphosphate but the magnitude of the effect was not sustained in 1984. This may in part be due to a large storm event which followed the 1983 treatment, leaching freshly applied fertilizer into the drains. Such an event did not occur in 1984. The pre-treatment $\bar{P}$conc of plot 2 was significantly higher in 1983 than the other two plots but this difference increased drastically in 1984 and remains unexplained. Overall the variability in behaviour of these plots has confounded a quantitative interpretation of the results. As far as pasture is concerned the yield has decreased in plot 3 (nil treatment) with respect to the other plots but this has been identified as a result of waterlogging of the lower slope and not the fertilizer treatment.

Table 6 Comparison of fertilizer treatments on Stacey's property

	1983 Plot 1	1983 Plot 2	1983 Plot 3	1984 Plot 1	1984 Plot 2	1984 Plot 3
treatment	super	CS*	nil	super	NCS	nil
pre-treatment						
runoff ($10^3 m^3$)	.33	.35	.47	.73	.46	.60
P load (kg)	.15	.22	.20	.27	.48	.20
$\bar{P}$conc (mg/L)	.44	.63	.42	.37	1.05	.34
post-treatment						
runoff ($10^3 m^3$)	1.02	1.37	2.16	.53	.44	.50
P load (kg)	.64	.80	.76	.24	.24	.17
$\bar{P}$conc (mg/L)	.63	.58	.35	.46	.55	.33
total period						
runoff ($10^3 m^3$)	1.35	1.76	2.63	1.26	.91	1.10
P load (kg)	.79	1.02	.96	.51	.73	.37
$\bar{P}$conc (mg/L)	.58	.59	.36	.40	.80	.34
pasture yield (tonne/ha)	3.8	3.5	3.4	4.6	5.1	3.9
Pplant (kg/ha)	12.4	13.1	11.1	14.3	17.7	10.2

* coastal superphosphate is an early version of NCS

Hodgson's and Jenkin's experiments

These experiments consist of 2 sets of four 200 m^2 plots with treatments of nil, superphosphate, lime, lime and superphosphate. Observations of soil water phosphorus concentrations and pasture yields have been undertaken but the data have not yet been adequately processed for inclusion in this report.

Mayfield sub-G catchment

Mayfield sub-G is part of the Mayfield drain catchment and has been monitored since 1982. It is about 1000 ha in area and is almost entirely cleared for agriculture. The results of the monitoring are given in Table 7 and Fig. 2.

Table 7 Annual phosphorus loads for Mayfield's sub-G catchment

year	runoff ($10^3 m^3$)	P load (kg/ha)	$\bar{P}$conc (mg/L)	*Papplied / Papplied (1982)
1982	1956	0.95	0.52	1
1983	3749	2.14	0.61	.89
1984	2497	0.63	0.27	.55

* figures approximate at this time

Adoption of new fertilizer practices was not significant in this catchment until 1984. In 1983 $\bar{P}$conc increased slightly over 1982, perhaps reflecting the high runoff of that year. 1984, however, saw a dramatic reduction in $\bar{P}$conc to nearly half of its 1982 value. This reduction would not be entirely related to the reduction in phosphorus applied, but to some extent represents the 'background variability' of the system.

DISCUSSION

Flow-weighted mean phosphorus concentration ($\bar{P}$conc) appears to be the best measure of the effectiveness of a fertilizer treatment. However, there appears to be significant variability in this parameter, particularly at small scales. For this reason several years of pre-treatment data would be necessary to reliably identify the effect of a given treatment. However, the urgency of obtaining results has restricted the pre-treatment period to a few months at the small scale and to one or two years at the intermediate scale. As a result there is little information on the variability of these systems under long term use of superphosphate. The only exceptions are in the multiple plot/catchment studies where one treatment is superphosphate, but these have not yet been monitored long enough for an assessment of their variability. Thus, at this stage, there is

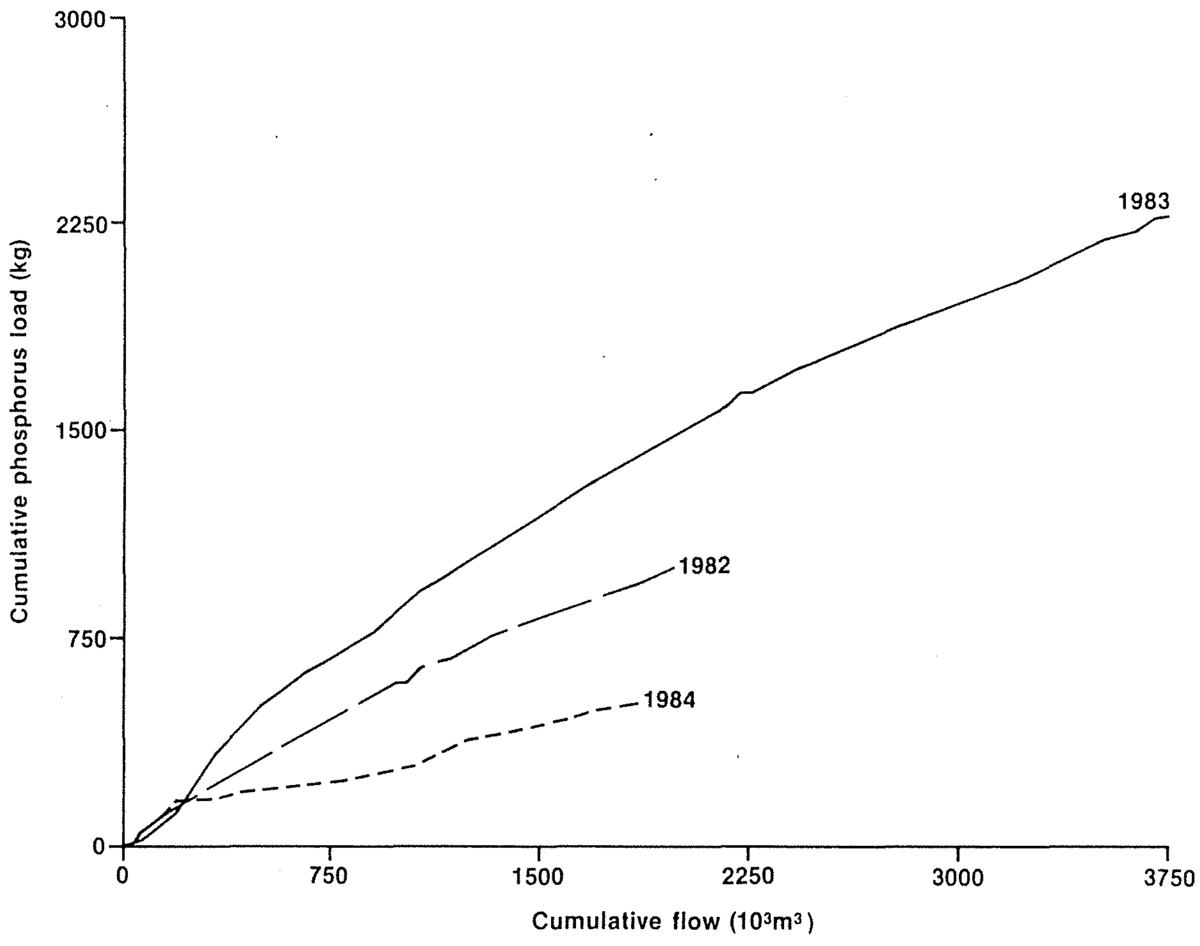


Figure 2: Cumulative phosphorus load versus cumulative flow for Mayfield sub-G catchment.

some difficulty in quantitatively interpreting results. One exception is perhaps Talbot's experiment, where the two catchments appear to be well matched. The results of the second year, however, were spoilt by the killing of swamp vegetation in one catchment with the consequent release of an unquantifiable amount of phosphorus.

CONCLUSIONS

1. In 1983 it was concluded that the adoption of recommended new fertilizer practices would cause a fast initial reduction of flow-weighted mean phosphorus concentration (up to 30%) entering the estuary. After the initial impact, there would be a much slower rate of reduction corresponding to a rundown of phosphorus stored in the soil. The 1984 data generally supports this picture but there is less certainty on precise figures.

2. The amount of phosphorus leached into drainage each year is highly variable. However, there is a good correlation between phosphorus load and flow for the Harvey River on an annual basis, i.e. flow-weighted mean phosphorus concentration is approximately constant over time. At the smale scale, however, even this parameter is variable and this has confounded the interpretation of some experiments. Several years of monitoring should establish qualitative, if not quantitative trends.

3. There has been no significant reduction in pasture production under any of the fertilizer treatments imposed.

4. Conclusions on the effectiveness of the fertilizer programme in reducing phosphorus input to the estuary should be judged on the full range of research activities (in addition to this field programme).

THE PHOSPHORUS DISCHARGED BY GROUNDWATER TO THE PEEL INLET - HARVEY ESTUARY SYSTEM, WESTERN AUSTRALIA

A. C. Deeney
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ABSTRACT

Excessive algal growth in the Peel Inlet-Harvey Estuary System (the Inlet), due to the input of phosphorus derived from fertilizer, has been a problem since the late 1960s.

Groundwater discharges from an anisotropic unconfined aquifer to the Inlet. A flow-net analysis has been used to estimate the discharge, directly from throughflow and indirectly as baseflow, from the six catchments comprising the groundwater catchment area of the Inlet.

Phosphorus concentrations at the water table range from less than 10 µg/L to more than 3000 µg/L whereas in the deeper groundwater concentrations generally do not exceed 200 µg/L. Fertilizer is the major source of phosphorus at the water table and in the deeper groundwater phosphorus is largely derived from marine sediments.

Approximately 0.4 tonnes and 7.2 tonnes of phosphorus are discharged to the Inlet by groundwater throughflow and baseflow respectively. In comparison with the total phosphorus input of approximately 146 tonnes/annum, these small quantities do not contribute significantly to the eutrophication of the Inlet.

INTRODUCTION

LOCATION

The Peel Inlet-Harvey Estuary System (the Inlet) occupies an area of approximately 133 km^2 located about 70 km south of Perth. A narrow peninsula separates the Inlet, which has an average depth of 1 m from the Indian Ocean and a narrow channel at the northern end allows limited circulation of seawater.

The groundwater discharging to the Inlet, directly from throughflow and indirectly as baseflow, is derived from a catchment area of approximately 1600 km^2 extending from Serpentine in the north to Harvey in the south and from the Darling Scarp in the east to within a few kilometres of the coast in the west (Figure 1).

PURPOSE AND SCOPE

Eutrophication of the Inlet first became apparent in the mid 1960's (Lukatelich, 1984). Excessive algal growth, caused by the input of phosphorus derived from fertilizer (Birch, 1984), has been a problem since then. The relative quantities of phosphorus discharged to the Inlet in surface water and in groundwater were therefore a matter of concern particularly in the longer term.

Estimates of the quantities of phosphorus discharged to the Inlet by groundwater throughflow and in baseflow in the main rivers are given in this paper together with an assessment of their significance to the management of the system. These estimates are based on a flow net analysis and the measured concentrations of phosphorus in a large number of bores. The area north of Mandurah is not discussed in detail since

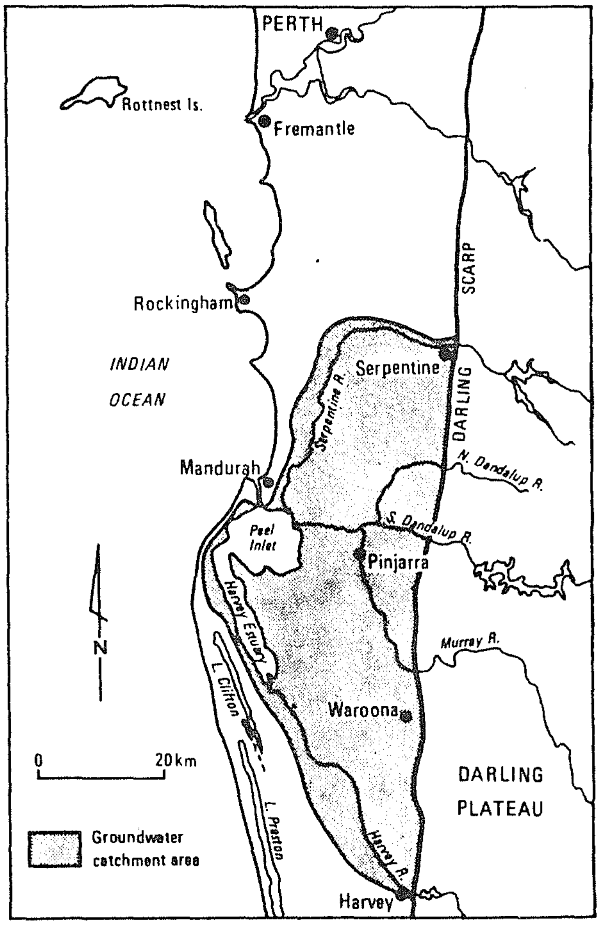

Figure 1. Locality map

groundwater from this area discharges to the Serpentine River as baseflow and has been assessed by Davidson (1984). A detailed description of the geology and hydrogeology of the Cainozoic sediments of the coastal plain between Mandurah and Bunbury is given by Deeney (in prep.).

CLIMATE AND LAND USE

The area has a Mediterranean climate, with hot dry summers and cool wet winters. The average annual rainfall is about 900 mm along the coast increasing to about 1100 mm along the Darling Scarp. Rainfall generally exceeds evapo-transpiration during the five months, May to September.

Most of the land has been cleared for agriculture, and in the Harvey-Waroona area pastures are irrigated using water from a number of dams east of the Darling Scarp. The remainder consists of small areas of native vegetation and urban areas, the largest being Mandurah.

PHYSIOGRAPHY AND DRAINAGE

The area lies on the Swan Coastal Plain where the physiography is dominated by three sets of stabilized dunes parallel to the present coastline with lakes and swamps in the low lying interdunal depressions (McArthur and Bettenay, 1960; McArthur and Bartle, 1980). The Spearwood Dunes (Tamala Limestone on Figure 2) form prominent parallel ridges reaching a maximum altitude of 70 m above sea level, and the easternmost ridge forms a distinct scarp separating them from the low hills and

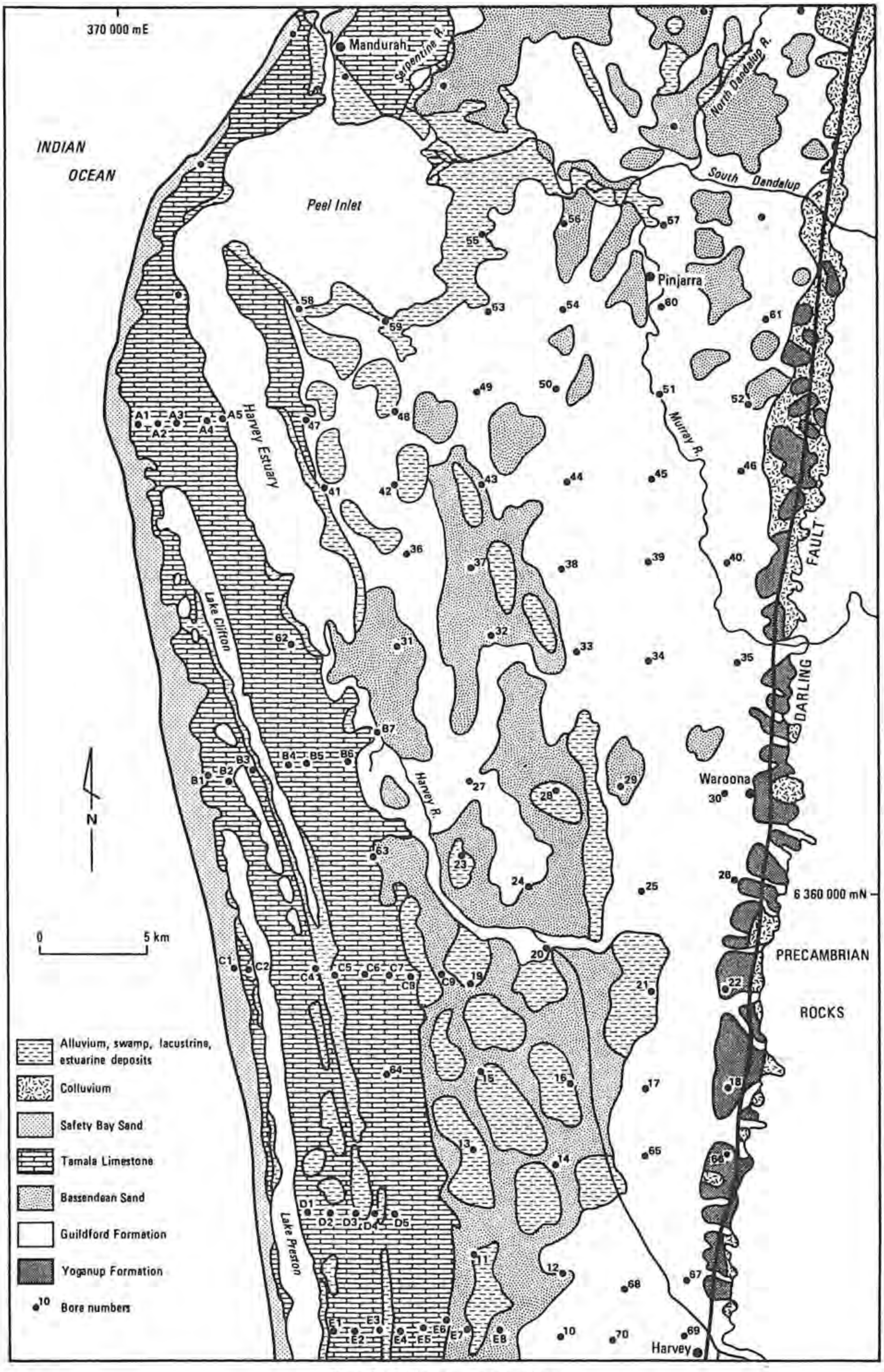

Figure 2. Geology and bore locations

swamps of the Bassendean Dune System (Bassendean Sand on Figure 2) in the central part of the coastal plain. The Quindalup Dunes are confined to a coastal strip a few kilometres wide (Safety Bay Sand on Figure 2).

The area is drained by the Serpentine, Murray and Harvey river systems, flowing from the Darling Plateau to the Inlet. Numerous drains have been constructed to lower the water table in the central part of the coastal plain. The majority of these discharge into the rivers, however a few flow directly into the Inlet.

Most of the runoff occurs during winter in response to rainfall and the low flows in the rivers during the summer consist predominantly of groundwater discharging as baseflow.

DRILLING, TESTING AND SAMPLING

A network of 151 bores were drilled at 74 sites, on a 4 km grid, to investigate the Cainozoic sediments on the coastal plain between Mandurah and Bunbury (Figure 2). Bores were designed to sample groundwaters from the base of the Cainozoic sediments, the water table, and from an intermediate level where it was thought, on the basis of lithology, that there were significant variations in the aquifer characteristics and the groundwater chemistry.

Five abstraction bores were drilled at selected sites and screened over the same interval as the adjacent deep investigation bore. A short pumping test programme was carried out at each site using the adjacent investigation bores as observation piezometers.

A detailed chemical sampling programme was carried out between April and August 1983 which included field measurement of unstable parameters. In addition, 19 of the bores drilled during an earlier investigation (Commander, 1984) and 12 private bores located north of the Murray River and west of the Inlet were sampled (Figure 2).

GEOLOGY

The area lies within the Perth Basin, which contains about 8000 m of Phanerozoic sediments (Playford and others, 1976), and is bounded in the east by the Darling Fault and the Precambrian rocks of the Yilgarn Block.

The stratigraphic units comprising the Cainozoic succession have been described by many authors including Allen (1976, 1977), Commander (1984), Davidson (1984), and Playford and others (1976). The stratigraphic succession and a summary of the lithology of each unit is given in Table 1.

The Cainozoic sediments, range in thickness from about 10 m to 90 m, rest on a gentle westward sloping erosional surface, and unconformably overlie a thick sequence of Mesozoic sediments on the coastal plain and Precambrian rocks along the Darling Scarp (Figure 3). They comprise a flat lying sequence of interbedded sand, silt and clay. The clay content generally decreases in a westerly direction and the basal sediments in the central part of plain are of marine origin. Aeolian sand and limestone occur in the west (Figures 2 and 3). Along the northwestern margin of the area these sediments unconformably overlie the Rockingham Sand which occupies a channel incised into the Mesozoic sediments and is of Quaternary age.

TABLE 1. STRATIGRAPHY

AGE	FORMATION	MAXIMUM THICKNESS (m)	LITHOLOGY	REMARKS
CAINOZOIC Quaternary (Holocene)	Alluvium, estuarine, lagoonal and swamp deposits	15	Sand, silt, clay, peat	Deposits often contain abundant organic material
	Colluvium	15	Lithic sand, silt, clay, laterite debris	Grainsize ranges from coarse pebbly sand on the Scarp to silty sand at the foot of the Scarp
	---------- Unconformity ----------			
	Safety Bay Sand	50	Sand	Sand is calcareous and unlithified
	---------- Unconformity ----------			
(Pleistocene)	Tamala Limestone	90	Limestone, sand, subordinate marl	Predominantly of aeolian origin, basal section mainly composed of marine and lacustrine sediments
	---------- Unconformity ----------			
	Bassendean Sand	15?	Sand	Forms a thin cover over most of the Guildford Formation
	---------- Unconformity ----------			
	Guildford Formation	25	Clay, sand	Individual beds are not persistent. Clay content decreases westwards
	---------- Unconformity ----------			
	Jandakot Beds	24	Sand, silt, clay	Forms the basal unit of the Cainozoic succession in central part of the plain, is generally fossiliferous, and is of marine origin
	Yoganup Formation	10+	Sand, minor clay	A shoreline deposit occurring discontinuously along Scarp
	---------- Unconformity ----------			
MESOZOIC	Various	-	Sand, siltstone, clay, shale	

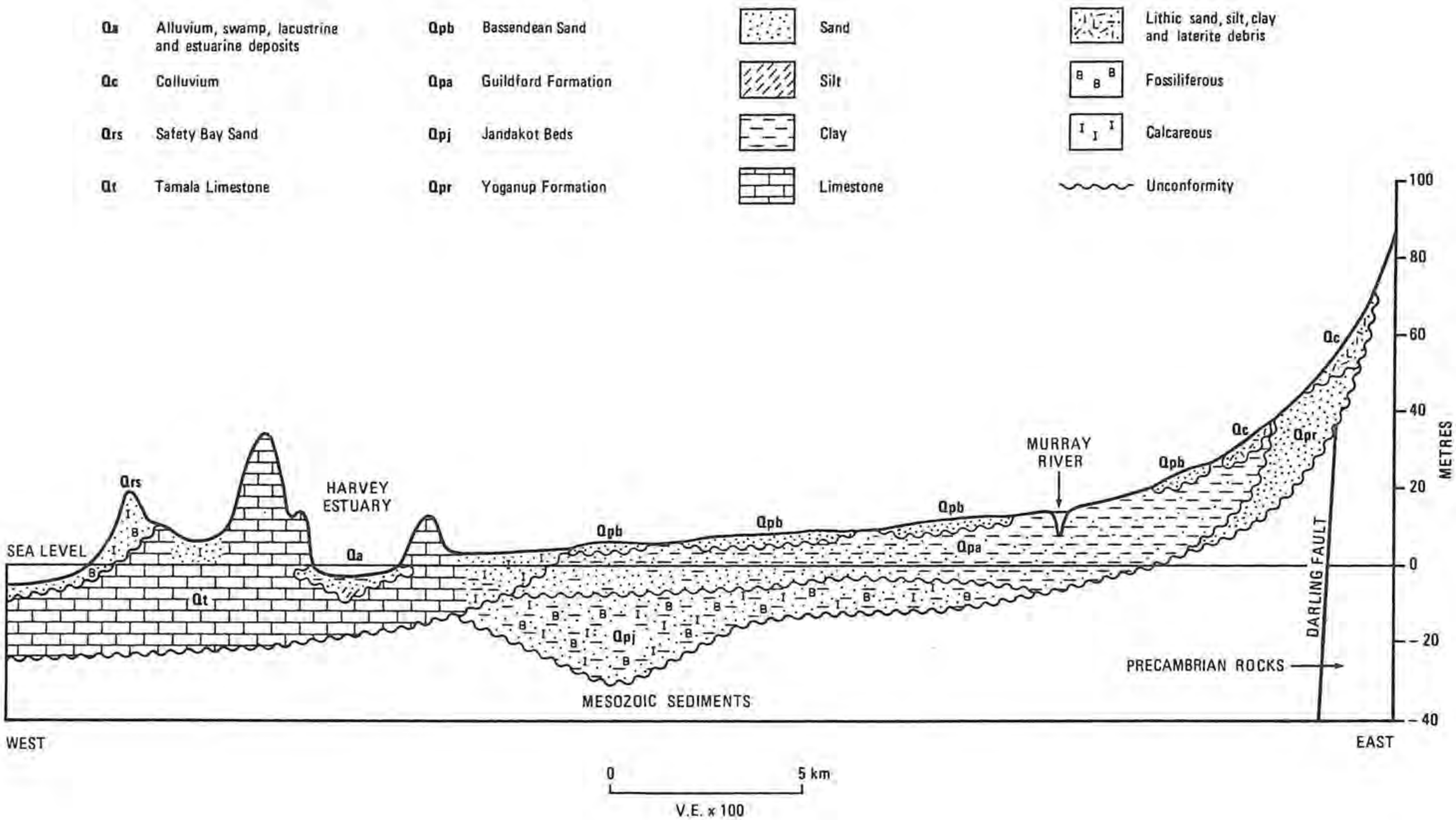

Figure 3. Diagrammatic section of the Cainozoic sediments showing lithology

HYDROGEOLOGY

CAINOZOIC AQUIFER

The Cainozoic sediments form an anisotropic unconfined aquifer extending westwards from the Darling Scarp to the coast. Generally, the aquifer is underlain by impermeable sediments, though locally, significant downward leakage occurs, particularly into the Rockingham Sand which forms a separate aquifer containing brackish groundwater.

The water table fluctuates seasonally and intersects the ground surface in many parts of the area during winter. The seasonal variation in level ranges from less than 0.5 m in the west to more than 4 m in the east and is generally about 1-2 m. Significant variations in potentiometric head occur between the water table and the base of the aquifer. They range from less than 0.1 m in the west to more than 5 m in the east.

The saturated thickness of the aquifer is 20-30 m throughout most of the area except where it decreases close to the Darling scarp. Aquifer transmissivities, which were estimated from lithological data and also obtained from pumping test analysis, range from 10 $m^3/d/m$ to 500 $m^3/d/m$.

West of a zone extending about 5 km inland from the coast and including the Peel Inlet and the Harvey Estuary, only thin lenses of fresh groundwater occur above saline groundwater (Figure 4). The groundwater salinity throughout most of the remainder of the area is fresh ranging from 100 to 1000 milligrammes per litre, total dissolved solids (mg/L TDS). Groundwater in zones adjacent to the major rivers and in the Harvey-Waroona irrigation area is generally brackish with salinities in the range 1000-10 000 mg/L TDS.

The aquifer is recharged by percolating rainfall, imported irrigation water, runoff from the Darling Plateau and upward leakage from the underlying sediments. However, a large proportion of infiltration is lost by evapo-transpiration. Groundwater discharges to the Inlet, the river systems and drains, the underlying sediments, and the Indian Ocean (Figure 4). Abstraction is insignificant in the area.

GROUNDWATER CATCHMENTS

The water table configuration is strongly influenced by the rivers and extensive drains (Figure 5). The hydraulic gradient is low over most of the coastal plain and increases adjacent to the Darling Scarp, the Harvey Mound and the discharge areas. Potentiometric heads generally increase with depth, indicating upward flow, in the discharge areas, and decrease with depth, indicating downward flow, away from these areas.

The area shown in Figure 5 has been divided into nine groundwater catchments bounded by groundwater divides or bounding flow lines whose positions are inferred from the water table configuration. Groundwater throughflow from the Inlet-Estuary East, Inlet-Estuary West and Coodanup catchments discharges into the Inlet across a saline interface. Groundwater discharges as baseflow in the rivers and drains from the Serpentine, Murray and Harvey catchments. Only the southern part of the Serpentine catchment is shown in Figure 5. Groundwater from the remaining three catchments discharges into the Indian Ocean, coastal lakes and Harvey diversion drain, and therefore they do not form part of the groundwater catchment area of the Inlet.

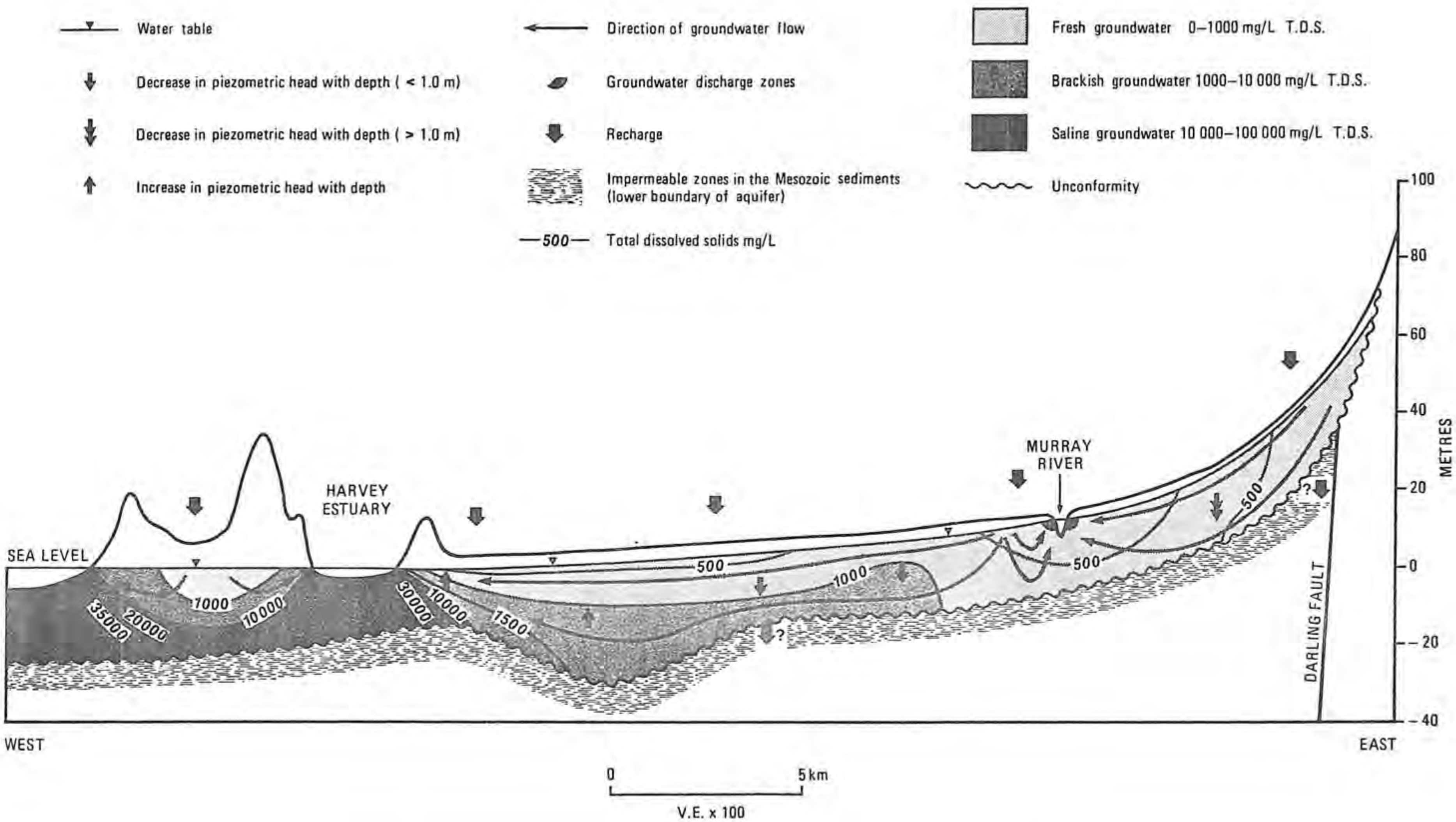

Figure 4. Diagrammatic hydrogeological cross-section showing salinity contours and directions of groundwater flow.

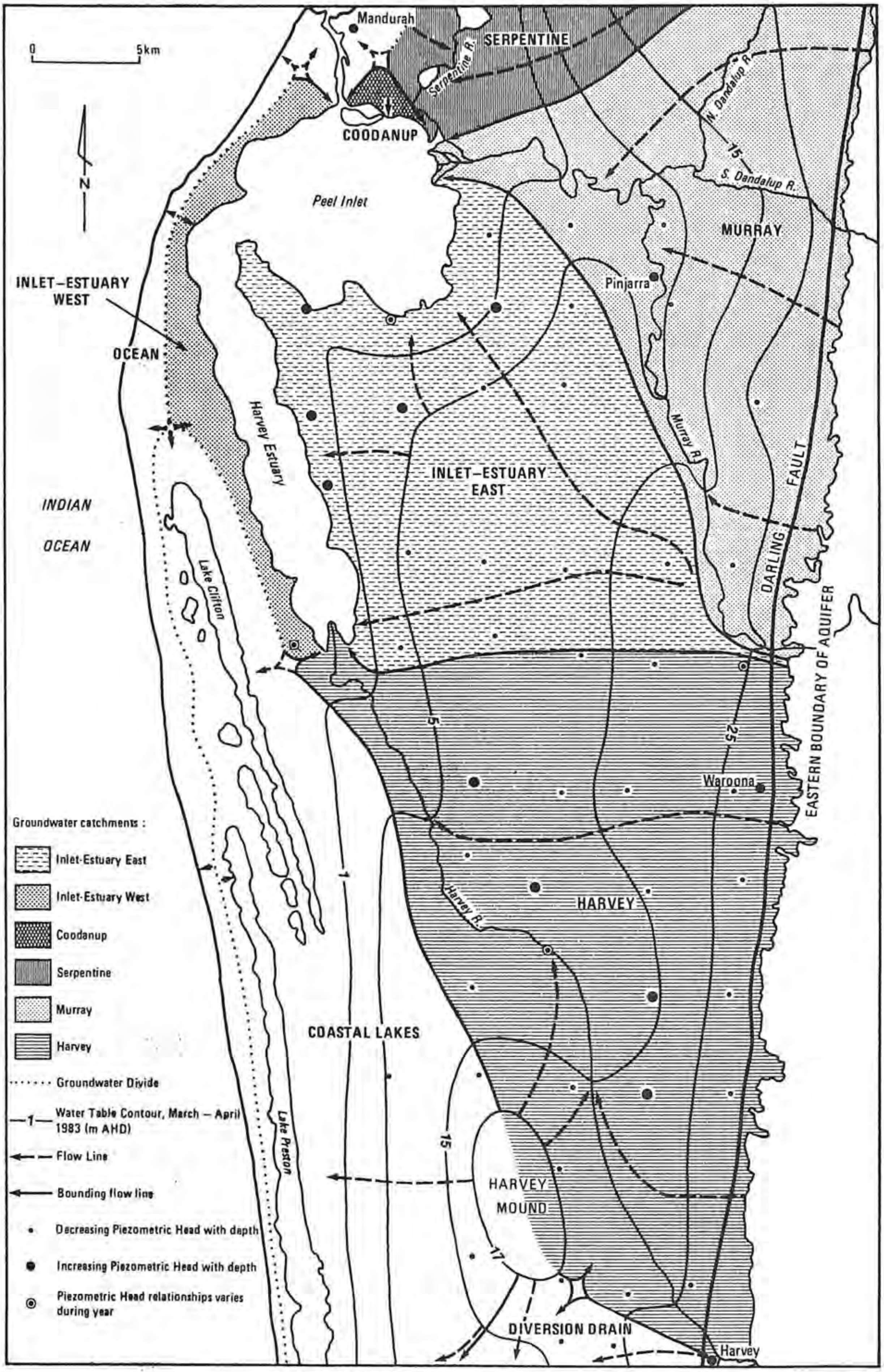

Figure 5. Groundwater catchments

GROUNDWATER DISCHARGE TO THE INLET

A flow-net analysis, based on a comparison of the flow rates obtained using the Darcy equation and the chloride balance, has been used to estimate the groundwater discharge from each catchment except the Inlet-Estuary West and Coondanup catchments. The groundwater discharge from these catchments has been estimated as a percentage of the average annual rainfall using the chloride balance, since there was insufficient water level data available to draw contours. The results are given in Table 2.

The total groundwater throughflow, discharging directly to the Inlet, is estimated to be 5.6 x 10^6 m^3/annum. The volume of groundwater discharing indirectly to the Inlet as baseflow in the rivers and drains is estimated to be 45.7 x 10^6 m^3/annum. The groundwater throughflow is insignificant compared to the average inflow from the major rivers, which includes baseflow, and is estimated by Birch (1984) to be approximately 560 x 10^6 m^3/annum.

PHOSPHORUS CONCENTRATIONS IN GROUNDWATER

SOURCES OF PHOSPHORUS

The phosphorus present in groundwater is derived from two distinct sources. Phosphatic fertilizers are used extensively and are undoubtedly a major source of phosphorus. The basal marine sediments of the Cainozoic succession often contain significant though generally minor amounts of phosphate in the form of, phosphatised shell and teeth fragments consisting of apatite minerals, and of pebbles of collopohane cemented sandstone and siltstone. This material was probably incorporated in the Cainozoic sediments during reworking of the underlying Mesozoic sediments. Traces of detrital apatite derived from the erosion of Precambrian rocks east of the Darling Fault probably also occur throughout the Cainozoic succession.

Generally, phosphorus occurs in groundwaters only in the form of inorganic orthophosphate and concentrations rarely exceed 30 microgrammes per litre (μg/L). Agricultural drainage waters exhibit much higher total phosphorus concentrations but the phosphorus in these waters may be present in dissolved and suspended forms and as orthophosphate, polyphosphate and organic phosphate (Stumm and Morgan, 1970).

Investigations of the Cainozoic sediments of the coastal plain near Perth, in rural areas where little or no fertilizer is applied, have shown that concentrations of phosphorus in the deeper groundwaters often exceed 30 μg/L and range from 20 μg/L to 250 μg/L.

In the groundwater catchment area of the Inlet the basal sediments are similar to those near Perth, and therefore, background levels of phosphorus in the deeper groundwaters may also be in the range 20 μg/L to 250 μg/L. However, background levels at the water table are unlikely to exceed 30 μ/gL since the sediments in the upper part of the Cainozoic succession contain very little phosphate.

PHOSPHORUS CONCENTRATIONS AT THE WATER TABLE

Phosphorus concentrations at the water table are variable ranging from less than 10 μg/L to more than 3000 μg/L (Figure 6). South of the Murray River, phosphorus concentrations generally exceed 50 μg/L except in the central part of the Inlet-Estuary East groundwater catchment and along the eastern margin of the Murray, and Harvey catchments. Concentrations in excess of 100 μg/L are found in the Murray, Inlet-Estuary

TABLE 2. GROUNDWATER DISCHARGE AND PHOSPHORUS FLUX TO THE PEEL INLET - HARVEY ESTURY SYSTEM

Groundwater Catchment	Area of Catchment (km2)	Discharge Area	Estimated Throughflow or Baseflow (10^6 m^3/annum)	Flow-Weighted Average Concentration of Phosphorus (µg/L)	Estimated Phosphorus Flux (tonnes/annum)
		Throughflow			
Inlet-Estuary East	300	Inlet-Estuary	3.1	100	0.3
Inlet-Estuary West	43	Inlet-Estuary	2.3	50	0.1
Coondanup	4	Inlet	0.2	50	0.01
			Total 5.6		Total 0.4
		Baseflow			
Serpentine	480	Serpentine River System	11.1	150	1.7
Harvey	456	Harvey River System	19.6	190	3.7
Murray	305	Murray River System	15.0	120	1.8
			Total 45.7		Total 7.2

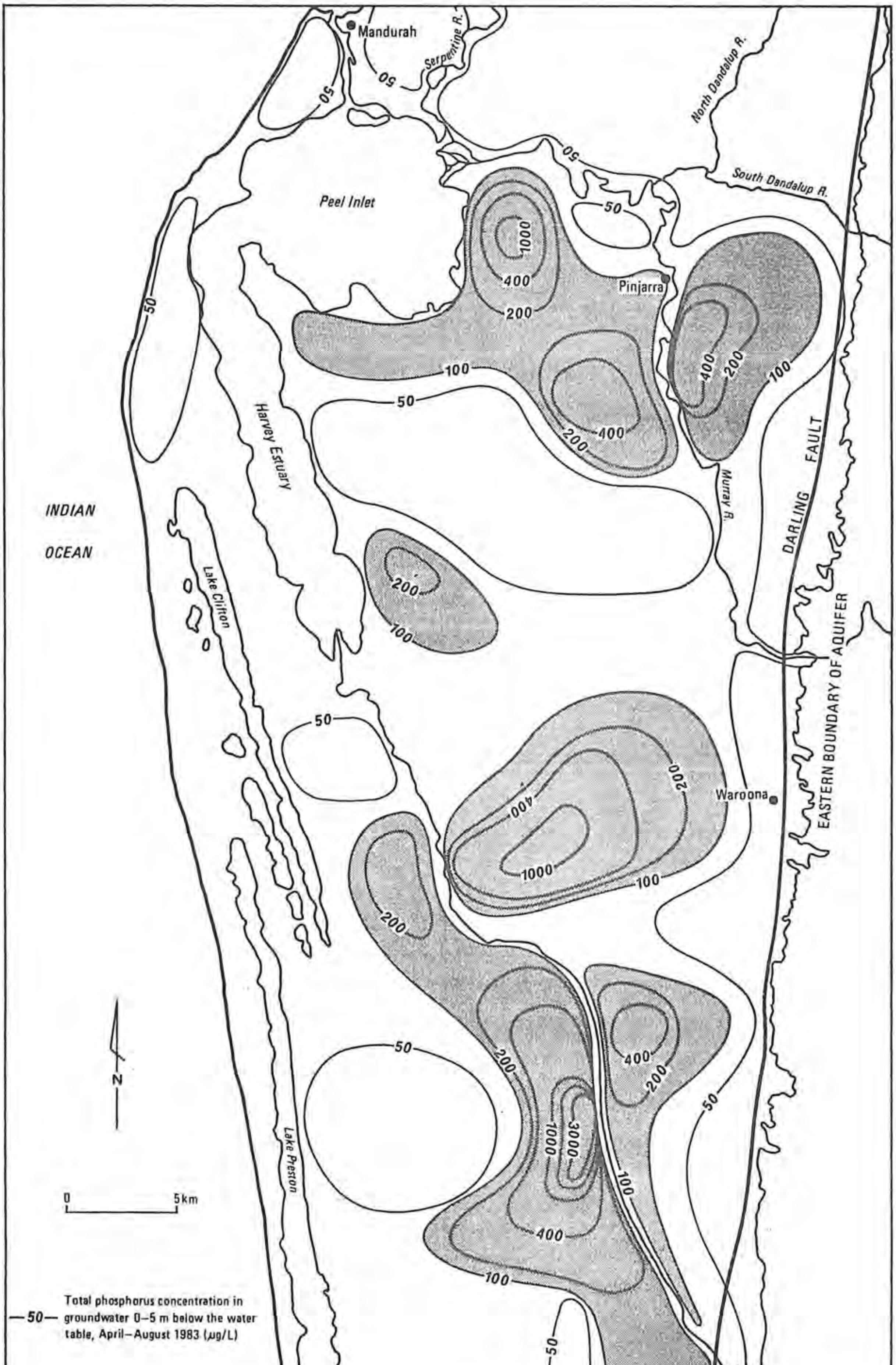

Figure 6. Phosphorus concentration in groundwater at the water table

East and Harvey catchments, and the highest concentrations occur adjacent to the Harvey River.

Fertilizer is the major source of phosphorus at the water table and three factors are thought to influence its distribution. The rate of fertilizer application varies according to land use and the perceived fertilizer requirements of particular pastures. There is a marked variation in the lithology, particularly in the clay content, of the Cainozoic sediments. Consequently, the amount of phosphorus adsorbed by the sediments and the quantity of phosphorus leached to the water table varies considerably. The phosphorus concentration does not increase down hydraulic gradient suggesting that phosphorus is being removed from groundwater by adsorption and baseflow in the drains and rivers.

PHOSPHORUS CONCENTRATIONS AT THE BASE OF THE AQUIFER

The distribution of phosphorus in the deeper groundwater is more uniform than at the water table and concentrations generally do not exceed 200 µg/L (Figure 7).

The zone in which concentrations exceed 100 µg/L coincides with the area in which marine sediments, namely the Jandakot Beds, underlie the Guildford Formation (Figure 7). There is little similarity between the distribution of phosphorus at the water table and at the base of the aquifer except in the area east of the Murray River. This suggests that the phosphorus in the deeper groundwater is largely derived from the basal sediments and not from fertilizer.

East of the Murray River, the aquifer is thin, the Jandakot Beds do not occur except in a small area immediately north of Pinjarra, and potentiometric heads decrease with depth. The distribution of phosphorus at the base of the aquifer is almost identical to that at the water table probably as a result of downward flow in the aquifer.

PHOSPHORUS DISCHARGED BY GROUNDWATER TO THE INLET

The estimated phosphorus flux to the Inlet from each of the groundwater catchments is given in Table 2. Generally, the phosphorus flux, obtained using the equation given below, has been calculated for individual flow cells adjacent to the discharge zones and the results added together to give the total for each groundwater catchment.

$$Fp = \frac{Q(P_W + P_b)}{2 \times 10^{-9}}$$

where F_p = Phosphorus flux (tonnes/annum)
Q = Groundwater flow (m^3/annum)
P_W = Total phosphorus concentration at the water table (µg/L)
P_b = Total phosphorus concentration at the base of the aquifer (µg/L).

The phosphorus flux from the Inlet-Estuary West, Coondanup and Serpentine catchments has been obtained by multiplying the total throughflow by the average concentration of phosphorus in each catchment, since detailed information concerning the concentrations of phosphorus was not available.

The Harvey catchment contains the highest flow-weighted average concentration of phosphorus and contributes the largest quantity of phosphorus to the Inlet (Table 3).

Approximately 0.4 tonnes of phosphorus is discharged to the Inlet annually by groundwater throughflow. In comparison, the rivers discharge about 146 tonnes/annum (Birch, 1984) and baseflow contributes approximately 7.2 tonnes/annum to this figure.

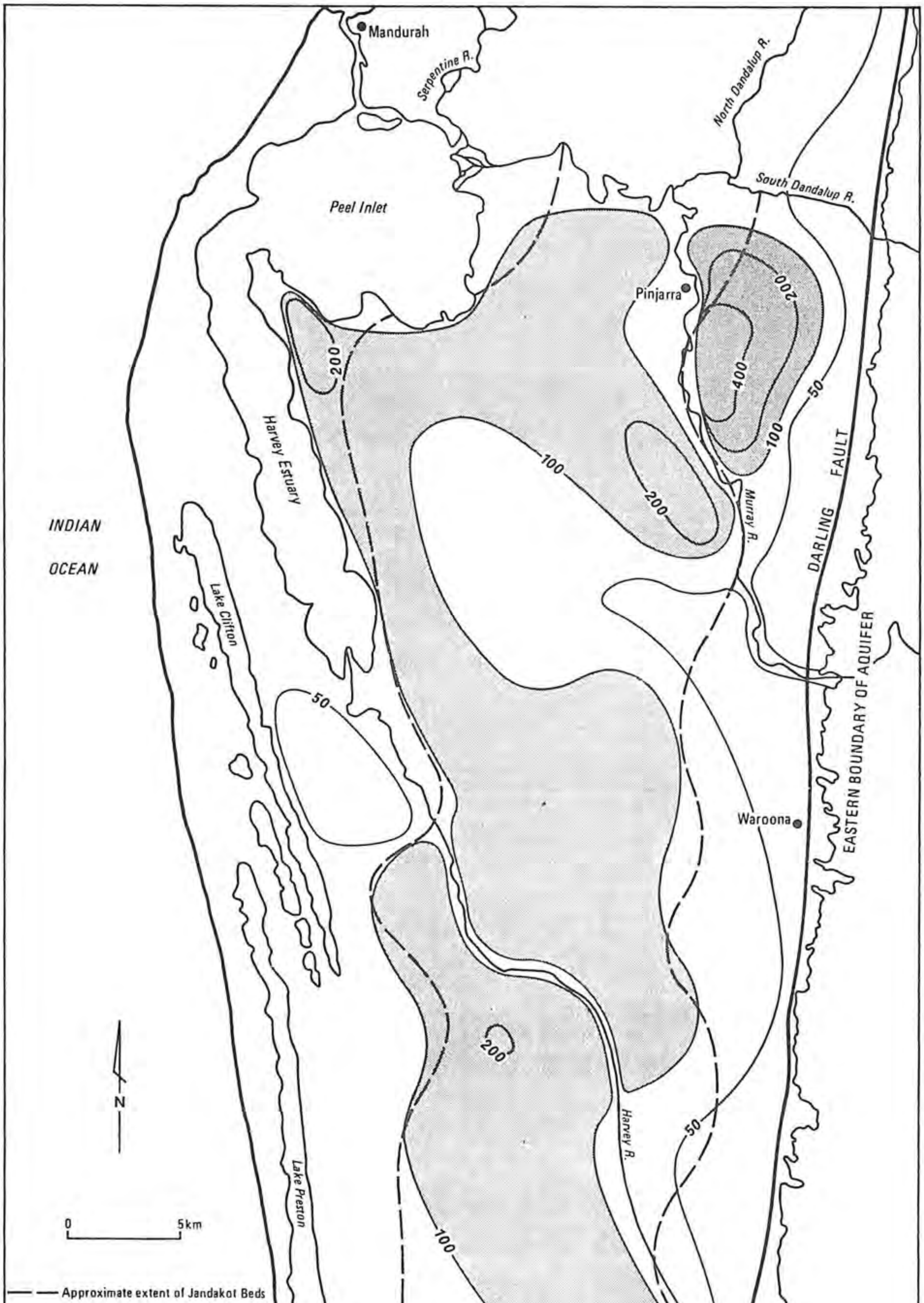

Figure 7. Phosphorus concentration in groundwater at the base of Cainozoic aquifer

CONCLUSIONS

The groundwater catchment area of the Peel Inlet-Harvey Estuary System has been divided into six catchments, separated by bounding flow lines or groundwater divides. Groundwater discharges to the Inlet directly from throughflow or indirectly as baseflow in the rivers and drains, and the flows from each catchment have been estimated using a flow-net analysis.

Groundwater throughflow of approximately 5.6 x 10^6 m^3/annum is less than 1% of the average annual inflow from the river systems which includes a baseflow component of approximately 8%.

A detailed chemical sampling programme has shown that phosphorus concentrations at the water table are extremely variable ranging from less than 10 µg/L to more than 3000 µg/L adjacent to the Harvey River. The major source of phosphorus is fertilizer and three main factors influence its distribution, variation in the rate of fertilizer application, varying degrees of adsorption by the sediments, and discharge of phosphorus to the drains and rivers.

The distribution of phosphorus in the deeper groundwaters is more uniform and generally bears little similarity to the distribution at the water table. Phosphorus in the deeper groundwaters is thought to be largely derived from phosphate contained in the basal marine sediments. East of the Murray River, the distribution of phosphorus at the base of the aquifer is almost identical to that at the water table, probably as a result of downward flow in the aquifer.

Approximately 0.4 tonnes of phosphorus is discharged annually to the Inlet by groundwater throughflow and this represents 0.3% of the total phosphorus input. Baseflow contributes approximately 7.2 tonnes per annum which is about 5% of the total phosphorus input.

The quantity of phosphorus discharged by groundwater does not constitute a significant factor in the development of suitable management strategies for the Peel Inlet-Harvey Estuary System. This situation is unlikely to change in the future since low flow rates limit the phosphorus input.

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PEEL-HARVEY ESTUARY STUDY
GROUNDWATER STUDIES, SITE SPECIFIC

by

E. BETTENAY, D.H. HURLE and M.I. HEIGHT

1. INTRODUCTION

This report summarises the findings of the groundwater studies group and integrates work that has been carried out during 1983 and 1984, both separately and conjunctively, by the following personnel:

- CSIRO Division of Groundwater Research
  - Mr Eric Bettenay
  - Mr Maurice Height
  - Mr Wally Russell

- CSIRO Division of Mathematics and Statistics
  - Dr Tony Grassia

- Department of Conservation and Environment
  - Mr Phillip Bayley

- Denis Hurle and Associates
  - Mr Denis Hurle
  - Field Technicians

The summary study reported here relates to two study sites within the Bassendean soil association of permeable grey sands, namely Talbot's (Karinga Downs) and Eastcott's, although the report has been concentrated on the paired catchments at Talbot's farm. A full report is in press (Bettenay, Hurle and Height, in press)*.

The aim of these studies has been to obtain groundwater response to rain, and other climatic variables, in order to determine pathways and

* Reference. Bettenay, E., Hurle, D.H., and Height, M.I. (in press). Peel-Harvey Estuary Catchment Studies: Groundwater Investigations. Department of Conservation and Environment, Perth, Western Australia, Bulletin No. 188, March 1985.

rates of water movement to drains, and ultimately to the estuary, as a basis for interpreting catchment studies of water and phosphorus loss.

2. THE MONITORING PROGRAMME

2.1 Groundwater Response

Assessment of the first two years of data collected from the experimental Talbot's farm site (see Figure 1) has given detailed insight into defining and quantifying the major processes of subsurface water movement and its contribution to surface water runoff.

Results of the monitoring programme have yielded estimates of groundwater storage increases of about 300 mm over the 1983 winter period compared to measured rainfall of about 470 mm.

Groundwater level increases (see Figure 2) resulted in flooding in much of the low lying Joel swamp soil areas of the site. This was seen to result in surface flow and groundwater flow to the shallow drains discharging from the lower areas.

2.2 Hydraulic Testing

Hydraulic testing of the groundwater systems at two sites within the Bassendean association was undertaken during 1984. Results from this indicated that the deeper aquifer below the coffee rock (see Figure 3) had high transmissivity and the potential to transport large amounts of water (and phosphorus) to sink areas. Pumping however, could not induce any leakage of shallow groundwater (containing the phosphorus) through the coffee rock.

2.3 Groundwater Phosphorus

Assessment of groundwater phosphorus concentrations (see Figure 4) has enable determination of the spatial distribution, and the time variation in phosphorus storage within the saturated soils.

Generally, high phosphorus storage was encountered in the SW 2 swamp soils where concentrations of up to 32 mg l^{-1} were recorded. These areas are generally inundated during winter. Concentrations in the Joel series were lower, rarely exceeding 7 mg l^{-1} and in SW 1 swamp soils adjoining the Meredith drain, and in the higher

Gavin soils, concentrations were generally low, rarely exceeding 3 mg l^{-1}.

Phosphorus storage within the groundwater (see Figure 5) was estimated to increase from summer to the end of winter, being more related to groundwater storage increases rather than to concentration changes. Estimated storages were generally of the order of about 1 kg ha^{-1} to 15 kg ha^{-1} the lower estimates being on the north catchment in areas adjacent to the Meredith drain.

These estimated storages are considerably less than the total inorganic and organic phosphorus storages of the Bassendean soils. Note that typical phosphorus application rates are 18 kg ha^{-1} yr^{-1}.

No significant changes in groundwater phosphorus storage were observed following superphosphate application to the south drain catchment in 1983 and 1984, however large temporal variations in phosphorus concentrations were noted following groundwater rising to the soil surface.

In summary, assessment of phosphorus redistribution within the groundwater has shown the complexity in describing the physical processes involved and their variability in space.

This is apparently due to the interaction of 'fixed' phosphorus and 'mobile' phosphorus stores and their relationships to variations in soil properties and seasonal hydrology of the shallow soil system.

3 MODELLING

The detailed definition of water processes resulting from this study has resulted in the formulation of process-based groundwater/surface water flow model. This model has been used to simulate the hydrological responses on the Talbot's site and is capable of predicting:

- groundwater recharge/discharge.
- groundwater storage changes.
- unsaturated soil water storage change.
- groundwater flow to drains and swamps.

- surface water flow to drains.
- rates of horizontal redistribution given detailed site characteristics and seasonal climatic data.

The model has been calibrated by comparison of predicted results with recorded hydrological responses in winter 1983.

Preliminary modelling results indicated that groundwater level changes can be predicted to within 20%, and cumulative drain discharges were predicted to within about 25% of those observed over the first 82 days of the 1983 winter flow period.

Further improvement in matching observed responses will be achieved by developing the recharge relationships used in the model, and by comprehensively adjusting the spatial estimations of hydraulic parameters in relation to soil types and landscape positions.

The development of a process based model and its subsequent calibration to real field hydrology in this manner gives the researcher greater insight into identifying and quantifying the unmeasured mechanisms dominant in the hydrological system.

The water flow model is seen as a forerunner to the development of a phosphorus transport model. This model will be based on empirical relationships describing:

- the relationship between 'fixed' phosphorus in the soil profile and mobile phosphorus in the soil water, and rates of soil water movement.

- release of phosphorus from applied superphosphate to rainfall infiltration, plant uptake, and to 'fixed' soil storage.

- phosphorus status in unsaturated soil profiles under varying conditions of climate, soils and hydrology.

It is expected that the large variability observed in phosphorus responses in a field situation may causes some problems in simulating farm behaviour in terms of phosphorus stores and phosphorus discharge to drain flow under different management practices.

4. IMPLICATIONS

Some catchment practices which may reduce farm phosphorus export are apparent from the results of this study.

First, it is apparent that the total farm water (and phosphorus) yield to drain flow in any season, is highly dependent on, apart from rainfall, the depth to groundwater before the onset of winter rains. Hence if groundwater levels were reduced by one metre during the summer season, then it would require about an extra 100 mm of rain to occur prior to groundwater intersection of the surface, waterlogging and subsequent surface flow. The ability to achieve this would be dependent on the logistics of being able to lower water table levels, and how to do it (e.g. by using deeper rooted summer pasture, trees, or summer irrigation from the shallow groundwater).

Second, drainage of internal swamps by discharging water of high phosphorus concentration to main drains is apparently a major source of nutrient to the estuary from the Bassendean association. Discharging the swamps on to soils which have the potential to adsorb phosphorus (e.g. SW 1 soils), if practical, would have the twofold benefits of reducing total phosphorus export and retaining phosphorus on the higher productive farm areas. Irrigation of these areas may be a practical solution. In summary, options relating to management of shallow groundwater to minimise surface flow need to be evaluated.

5. FURTHER STUDIES

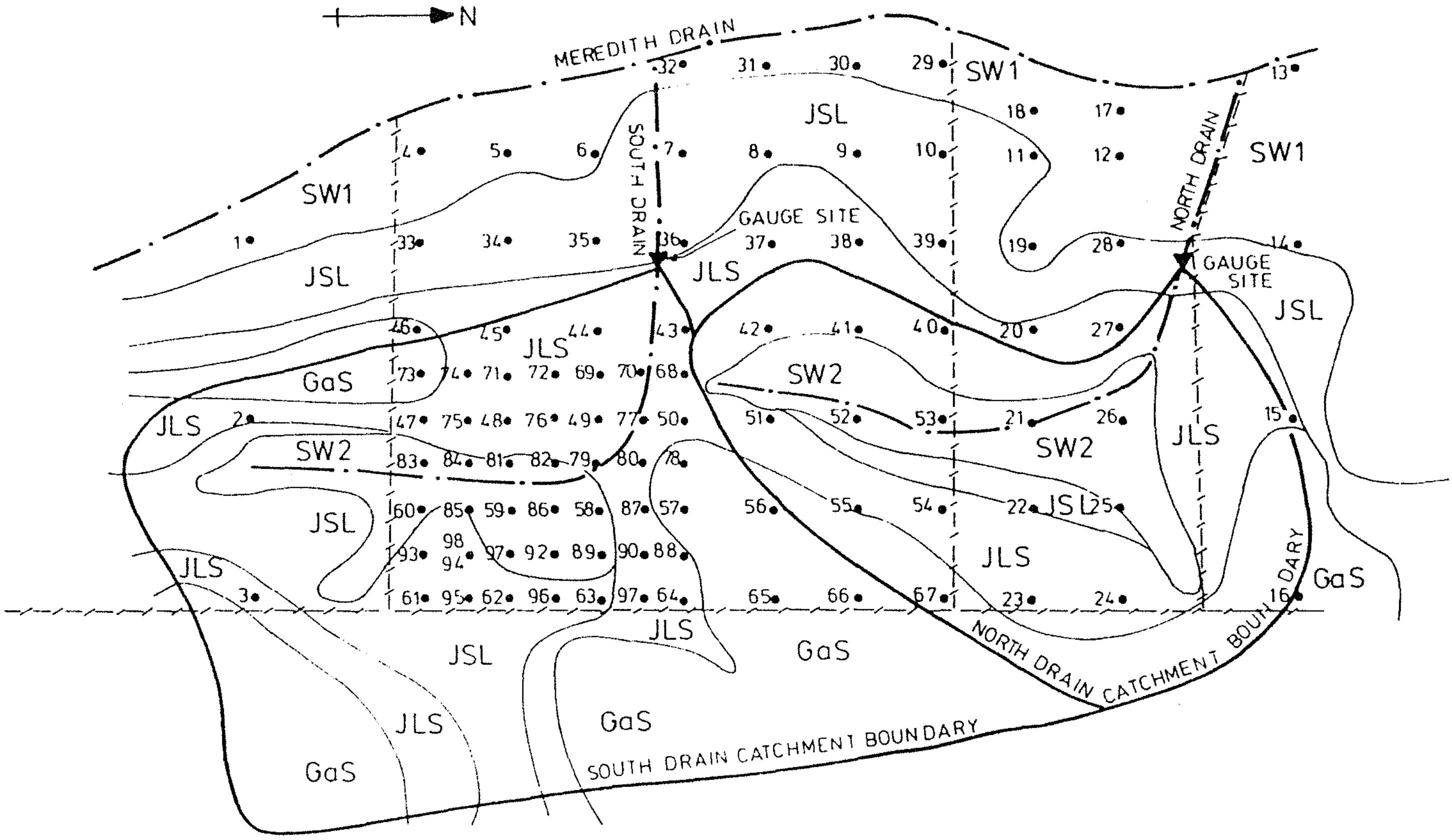
Future work to be undertaken in the groundwater studies programme is involved with examining the rundown of soil phosphorus on the untreated north catchment compared to the south catchment.

Particular studies should be undertaken. It is necessary to identify the presence and depth of the confining coffee rock over the entire Talbot's site. It is anticipated that this can be achieved by shallow seismic techniques using existing CSIRO equipment. As well as achieving these objectives the study should result in the development of these techniques so that they can be applied to other (study) areas. This would save considerable costs in drilling.

A study needs to be undertaken to determine the hydraulic properties of the shallow, above coffee rock, aquifer and the variability of these parameters in terms of soil types etc. Ideally, infiltration tests and constant head permeameter techniques could be evaluated and carried out in both summer and winter.

It is planned that the group will undertake groundwater aging studies to determine rates of water flow between the various aquifer sequences in different landscape positions. This may be achieved by tritium analysis, carbon dating or by application of radioactive phosphorus.

It is recommended that, following final acceptance of the surface water modelling results, a detailed review of (or workshop relating to) the possibility of modelling phosphorus transport processes, be undertaken. This will involve liaison with other groups within and outside the Peel-Harvey Project. It should result in the formulation of a conceptual understanding of phosphorus redistribution such that a computer based model will be developed. The model should ultimately be capable of predicting the results of varying phosphorus management practices on pasture production, phosphorus storages on farmland, and phosphorus discharge to drain flow. This work would be carried out conjunctively with laboratory and field trials such as the Talbot's study, and should not be considered short term.



LEGEND

—·—	DRAIN
——	SURFACE CATCHMENT BOUNDARY
-----	SOIL TYPE BOUNDARY
43 •	OBSERVATION BORE NUMBER
—/—/—	FENCE LINE
▼	GAUGE SITE

SOIL TYPES

Ga S	GAVIN SAND
JSL	JOEL SANDY LOAM
JLS	JOEL LOAMY SAND
SW 1	SWAMP 1
SW 2	SWAMP 2

FIGURE 1 TALBOT'S SITE
SOIL MAP AND MONITORING
INSTALLATIONS

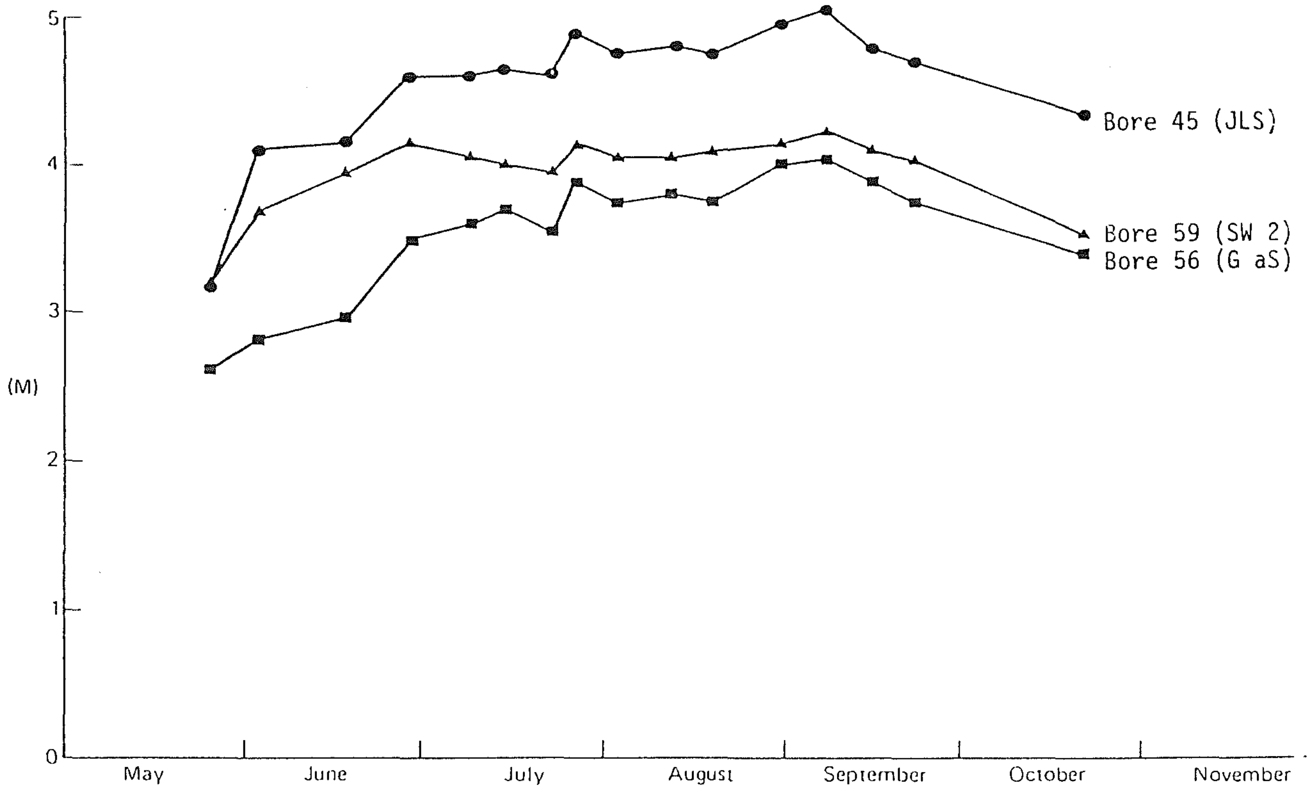


FIGURE 2. TYPICAL GROUNDWATER RESPONSES ON MAJOR SOIL TYPES

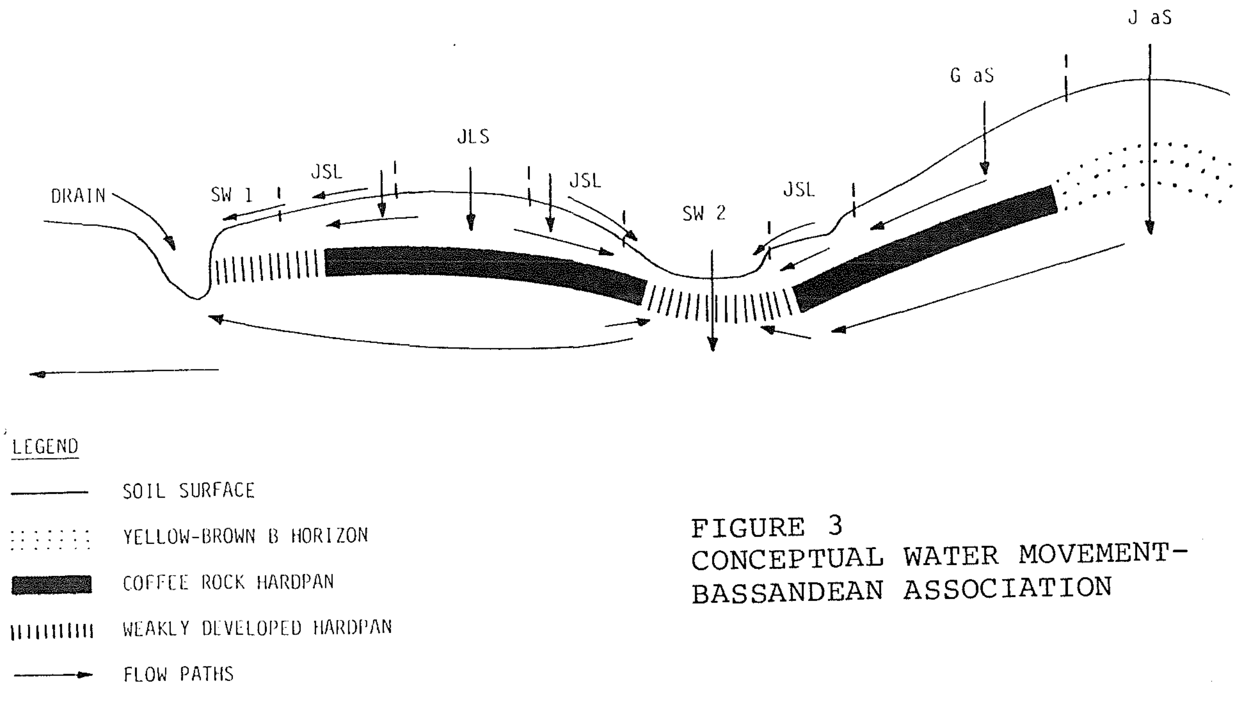


FIGURE 3
CONCEPTUAL WATER MOVEMENT-
BASSANDEAN ASSOCIATION

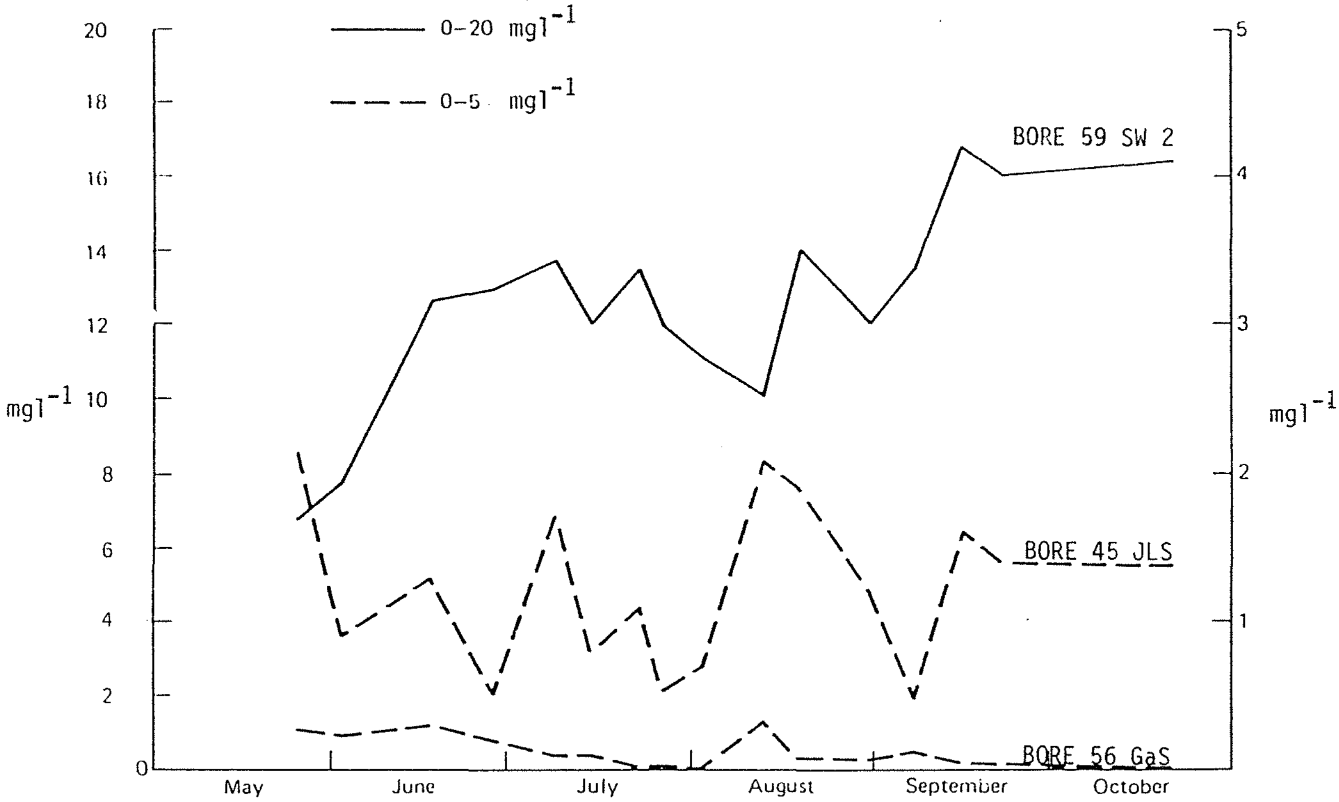


FIGURE 4. PHOSPHORUS CONCENTRATIONS IN BORES

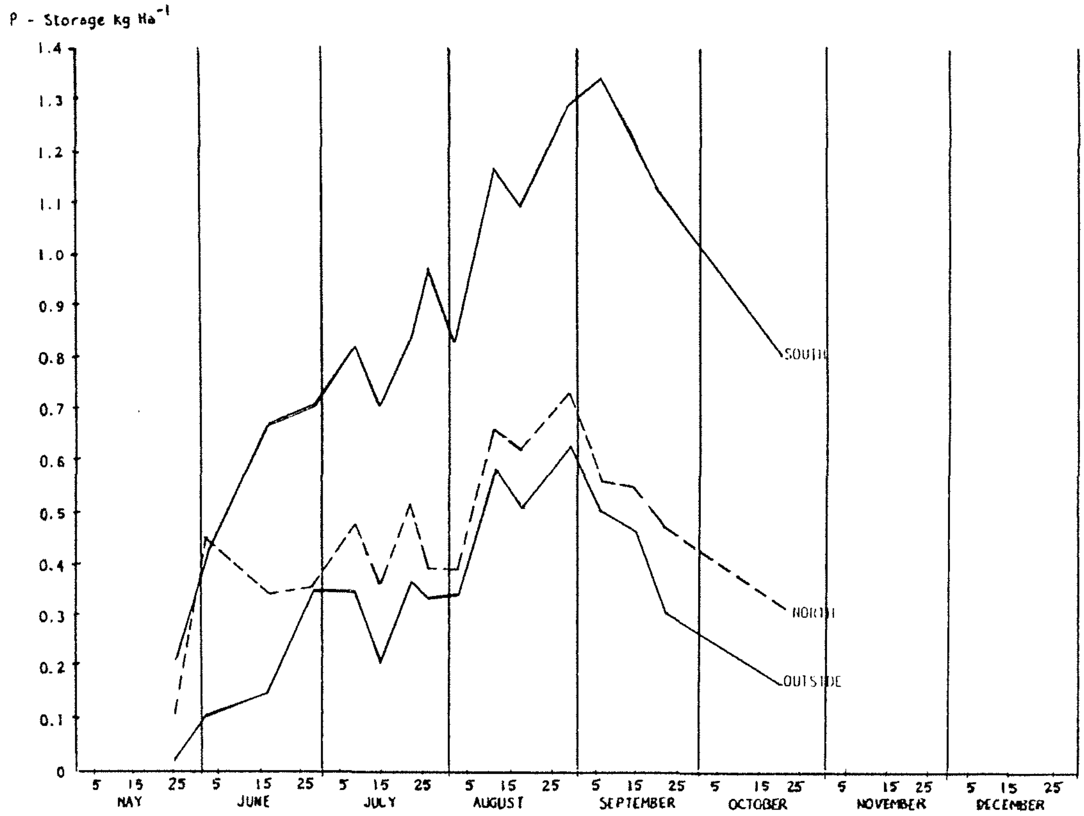


FIGURE 5
1983 MEAN PHOSPHORUS STORAGE IN GROUND WATER ABOVE HARDPAN ($kgHa^{-1}$)

LONG TERM PHOSPHORUS LOSSES FROM DEEP GREY SANDS AND DUPLEX SOILS

by

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INTRODUCTION

Continued application of superphosphate to deep sands and duplex soils used for pasture production in the Peel-Harvey catchment area has led to a steady build-up of phosphorus levels in excess of plant requirements. Since the main aim of the catchment management group is to minimise losses whilst maintaining plant production, two of the strategies that need to be implemented to achieve this aim are:-

(1) To run down phosphorus levels in soils.

(2) To maintain plant available phosphorus in soils at a level just adequate to maintain plant growth without causing another detrimental build-up in the soil phosphorus store.

If phosphorus fertilization of soils was ceased, it is not known how long they would be able to maintain plant growth and what the associated reduction in phosphorus losses would be. Similarly, little is known about the long term consequences of regular applications of less soluble fertilizers such as New Coastal Superphosphate (NCS).

It would take many years to improve our knowledge in this area if we were to rely on field experiments alone. Time is limited, however, and so laboratory-based experiments have had to be used to investigate the long term phosphorus losses from fertilized and unfertilized soils. Leaching studies have been designed to assess:-

(a) how long it would take to run down plant available phosphorus in the deep grey sands (Joel) and duplex soils (Coolup) to levels just sufficient to maintain plant production;

(b) the annual phosphorus loss from soils at maintenance levels;

(c) the long term phosphorus losses and gains from soils continually fertilized with NCS and ordinary superphosphate.

For each soil and a given set of environmental conditions, long term cycling and losses will be affected by:- (a) the level and form of native phosphorus; (b) the level and form of added phosphorus; and (c) plant uptake. Each factor must be studied individually before imposing the others into the system so that one can clearly differentiate between their separate effects and establish their relative importance. The results described here examine the effect of (a) and (b) separately and then in combination under a constant set of environmental conditions. Because of lack of time we have not yet progressed to the effect of plant uptake.

EXPERIMENTAL DESIGN

In order to achieve results within a reasonable time period certain assumptions and compromises have had to be made.

The soils have been subjected to 10 consecutive cycles designed to simulate the annual weather pattern of the coastal plain. Higher soil temperatures were used to reduce incubation times so that more than one cycle could be achieved within twelve months. Each cycle consisted of a wet period during which 850 mm rain was applied to the soil (i.e. winter) followed by a drier, hot period (i.e. summer). The phosphorus in several soil pools was measured at the end of each "winter" and "summer" period for each cycle as well as the phosphorus load of the leachate from the winter period.

The experiments were designed such that phosphorus losses were measured from the top 10 cms of the soil and could have occurred by infiltration, sub-surface lateral flow or overland flow. The actual values for losses and gains are higher than would occur in the field because of the absence of plants in our experiments. In most cases, however, it is the relative values that are of concern. Even so, we need to have some estimate of rundown times and so when looking at absolute losses these represent the *minimum* time for a given set of environmental conditions.

LONG TERM PHOSPHORUS LOSSES FROM UNFERTILIZED SOILS

Long term leaching studies were carried out on Joel and Coolup soils which initially contained phosphorus in excess of plant requirements.

The most important rundown time to be considered is the time required to reduce plant available phosphorus in unfertilized soils to levels just adequate for maintaining plant growth. Plant available phosphorus (i.e. bicarbonate extractable) levels of 8 and 18 ppm are considered adequate to maintain pasture production on deep grey sands and duplex soils respectively (Hodgkin *et al.*, 1984).

An estimate can also be made of the time taken to run down excessive P levels so that the associated loss does not cause algal blooms. Until now, algal blooms have not occurred when the phosphorus loading of the Harvey River is <34 tonnes (Birch, 1984) which approximates to a <2 kg/ha loss from all the deep sands and duplex soils in the Harvey catchment area (Ritchie *et al.*, 1984). Even though lower phosphorus losses from agricultural land may not *eliminate* algal blooms because of sufficient P supplies within the estuarine ecosystem, reducing the phosphorus load of the winter input can help to *reduce* magnitude of *Nodularia* blooms (Lukatelich, 1984).

Finally, run-down times can also be estimated for the time taken to achieve a 50% reduction in phosphorus losses.

Joel Soils

Phosphorus losses from unfertilized, deep grey sands exponentially decreased with time (Fig. 1). The annual loss of phosphorus from the higher P soil decreased markedly in the first four years followed by a much more gradual decrease in loss. For the lower P soil, the annual loss decreased more gradually but was still exponential in nature.

Fig.1

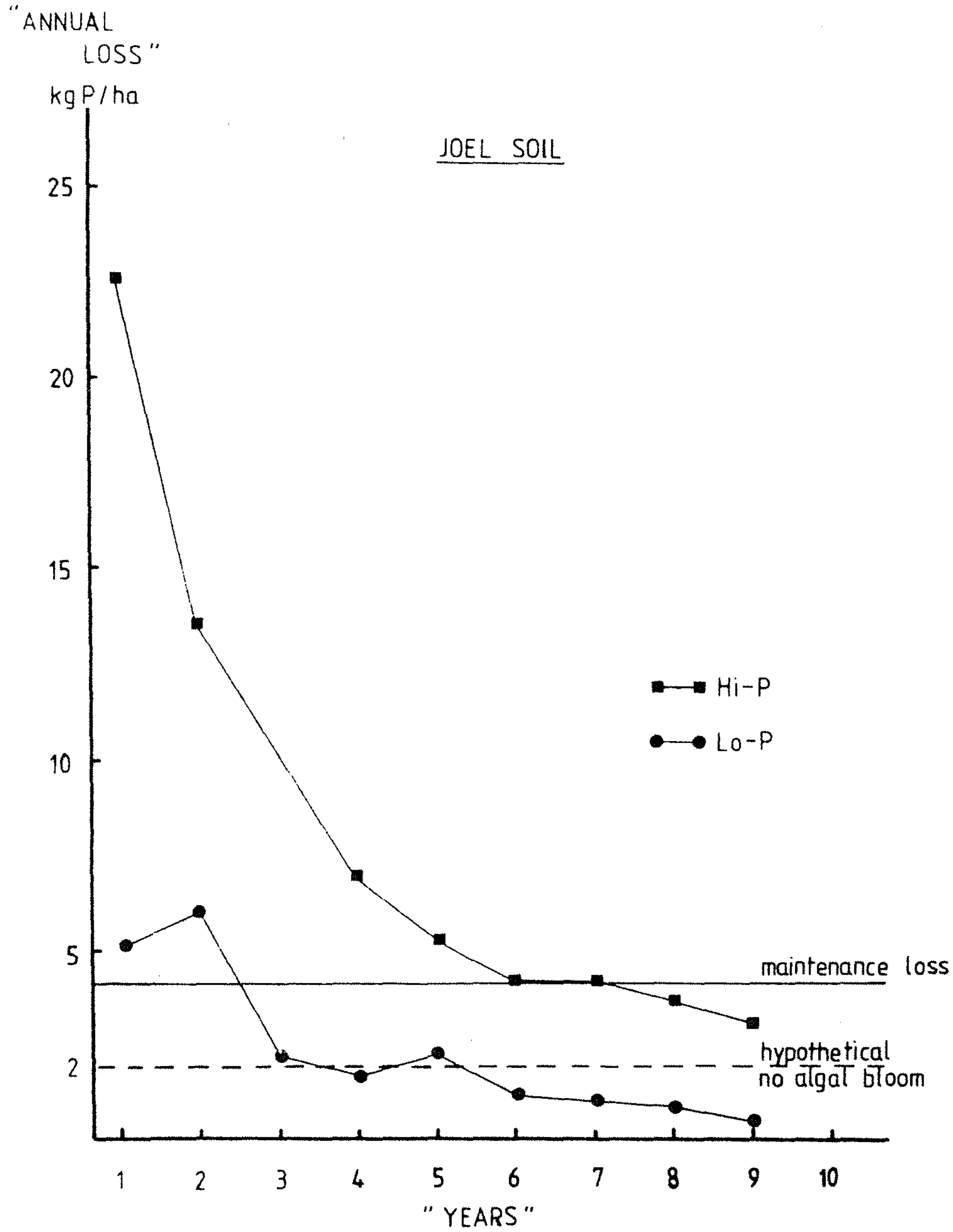

Fig. 1. Variation in the annual loss of phosphorus (kg/ha) with time (yrs) since fertilization of deep grey sands ceased.

The shape of the curves in Fig. 1 suggests that one curve may be used to represent the decline in P lost with time since the curve for the lower P soil appears to be an extension of the higher P Joel curve. One curve was also found to be adequate to explain water soluble P levels in Joel soils during winter (Ritchie *et al.*, 1984).

For a given set of environmental conditions, the amount of plant available phosphorus at the end of summer was found to be linearly related to the amount of phosphorus lost in the following wet season (Fig. 2). Therefore, if the plant available P level of a soil is measured at the end of summer, the relationship in Fig. 2 may be used to estimate the amount of phosphorus that would be lost in the following year. Having established the soil's current ability to lose P, Fig. 1 may then be used to estimate how long it would take to run down the P in that soil to maintenance requirements if the levels were originally more than adequate. Examples of estimates of run-down times are given in Table 1 for deep grey sands containing different initial levels of plant available phosphorus. An extensive survey carried out by the Department of Agriculture indicated that ∿60% of the soils they sampled fell into these groups (Hodgkin *et al.*, 1984).

The annual phosphorus loss associated with the maintenance phosphorus level was found to be approximately 4 kg/ha. The loss will probably be higher than that observed in the field because of the absence of plants. Another aspect of the size of the loss is that the major source of phosphorus in the soil is ordinary superphosphate. Lower losses would probably be observed if the major source was changed to NCS.

The results indicate that a minimum run-down time of approximately four years is required to achieve maintenance P levels for soils with an initial plant available phosphorus level <20 ppm. In the field, this time would be longer because the recycling of phosphorus through plants would slow down its rate of loss by leaching.

Coolup Soils

The rate of loss of phosphorus from two Coolup soils with luxury levels of P for plant uptake did not change markedly over an eight year period (Fig. 3). Leaching losses from the soil with the higher P content did not begin to decrease until the fourth year. For the lower P soil, leaching losses actually increased slightly with time and then remained constant after the third year. The small changes in leaching losses demonstrate the major influence of the soil sorption capacity on the rate and level of P release.

In contrast to the Joel soils, there was no consistent relationship between bicarbonate-extractable P and the amount of phosphorus lost in the following wet season. Consequently, only limited estimates may be made of run-down times. It would appear that for soils with a bicarbonate P level >25 ppm, more than seven years of no fertilization are required before plant available phosphorus levels fall to 18 ppm or losses are reduced to <2 kg/ha. From the data available, it is still not possible to assess the annual phosphorus loss associated with the maintenance levels but it would appear to be <3 kg/ha.

Fig.2

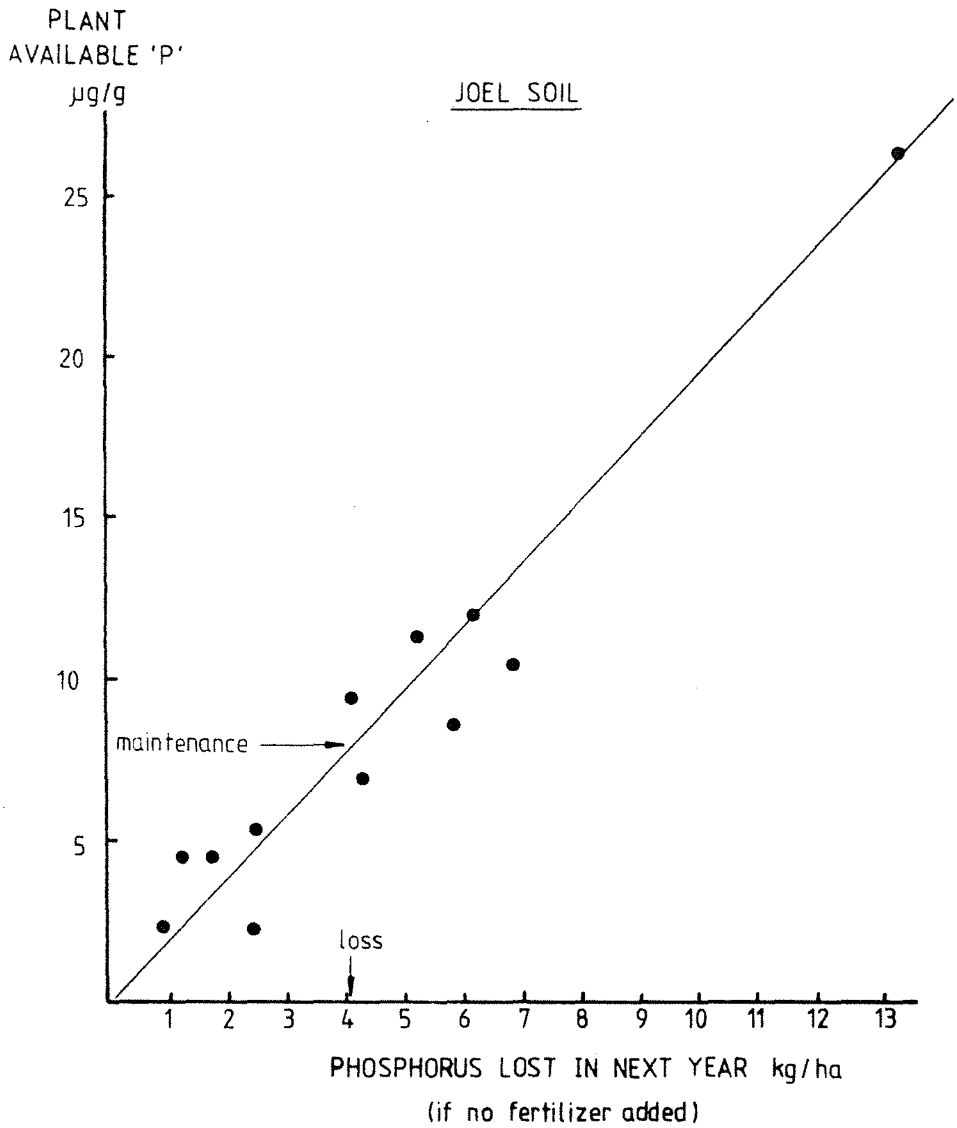

Fig. 2. Relationship between plant available phosphorus (mg/g) at the end of summer and the amount of phosphorus lost (kg/ha) during the following wet season if no fertilizer is applied.

TABLE 1

Phosphorus losses and run-down times from deep grey sands with varying levels of plant available phosphorus (i.e. bicarbonate extractable).

Plant available P (ppm)	Associated loss+ (kg/ha)	Minimum Run-down time to maintenance levels* (yrs)	% reduction in P lost	Minimum run-down time to achieve	
				50% reduction	annual loss 2 kg/ha
8 - 12	4 - 6	0 - 2	0 - 30	>4	>4
12 - 16	6 - 8	2 - 3.5	30 - 45	3 - 4	5 - 6
16 - 20	8 - 11	3.5 - 4	45 - 65	∿3	6 - 8
20 - 24	11 - 13.5	4 - 5	65 - 70	∿3	>8
24 - 28	13.5 - 16.5	5 - 5.5	70 - 75	∿3	>8

* Maintenance level is 8 ppm bicarbonate extractable P.

\+ Phosphorus lost in a following wet season of 850 mm continuous rain in the absence of plants.

Fig. 3

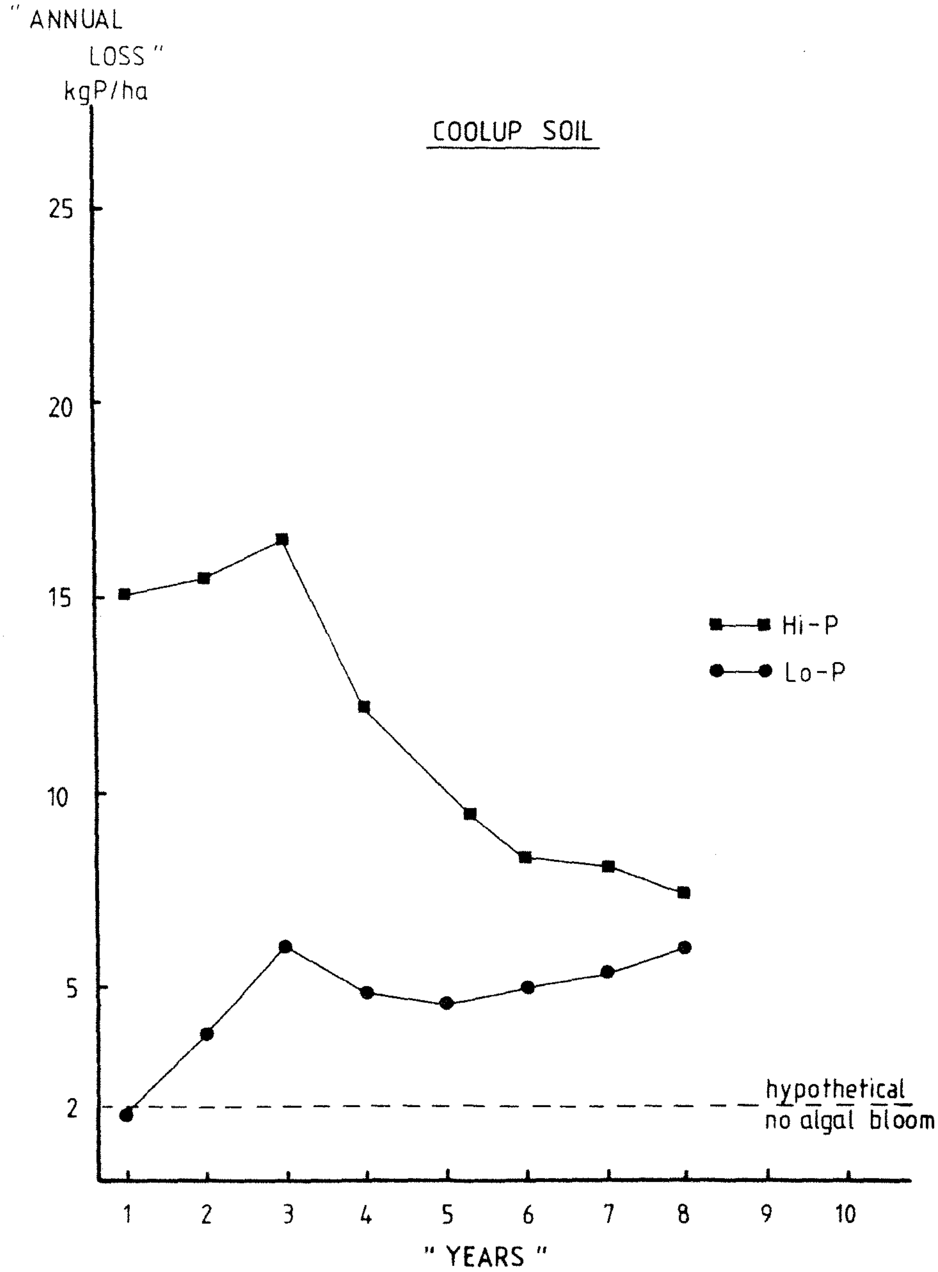

Fig. 3. Variation in the annual loss of phosphorus (kg/ha) with time (yrs) since fertilization of duplex soils ceased.

LONG TERM PHOSPHORUS LOSSES FROM FERTILIZED SOILS

Phosphorus losses from the same Joel and Coolup soils have also been monitored in the presence of various rates of New Coastal Superphosphate and superphosphate. The aims of these leaching studies were to assess the comparative P losses associated with the two fertilizers, the major factor controlling the level of loss and the long term effects on phosphorus pools.

Level of Loss

For both soil types, approximately twice as much phosphorus was lost from superphosphate as from NCS when compared at equivalent rates, but the loss was never <2 kg/ha. The % of fertilizer P lost by leaching decreased with increasing application rate in all cases except for superphosphate applied to the Coolup soil. Also, 2-3 times more fertilizer phosphorus was lost from the same source when applied to the Joel soil than when applied to the Coolup soil.

In the year of application, the addition of superphosphate and NCS to both soil types caused an increase in the amount of P lost which was linearly related to the amount of (water + citrate) soluble phosphorus added in the fertilizer. The relationship was independent of fertilizer source but not of soil type (Fig. 4).

Even though it is well established that less P is lost from NCS than from ordinary superphosphate, it is not known whether the differences in leaching losses will decrease with continued annual application. This could be caused by a greater build-up of P in the soil in the case of NCS application followed by its conversion to a more soluble form so that eventually just as much or more phosphorus may be lost from continued annual applications of NCS as from superphosphate.

It was found that the amount of fertilizer P lost from successive applications of NCS increased with time because P was not only being lost from the current application but also from previous additions. A similar observation was made for superphosphate except when the loss was nearly 100% in the case of Joel soils fertilized at rates <10 kg/ha.

For the Joel soils, the rate of increase in the amount of fertilizer P lost with time was greater than for superphosphate. Therefore, given enough time (15-20 years), and assuming the rate of increase remains the same, just as much phosphorus could be lost from NCS as from superphosphate. The implication of this result should be kept in perspective. Concurrent monitoring of the phosphorus soil pools indicated a steady build-up of P and that plant available P never fell below 8 ppm. This suggests that excessive phosphorus was being added to the soil and that annual applications are not necessary to maintain plant growth.

For the Coolup soil, the rate of increase in P lost from NCS is far lower than that for P lost from superphosphate, indicating that the above situation is unlikely to occur on the duplex soils.

Controlling Factors

Under constant environmental conditions, the solubility of the fertilizer appears to play an important role in phosphorus losses from Joel

Fig. 4

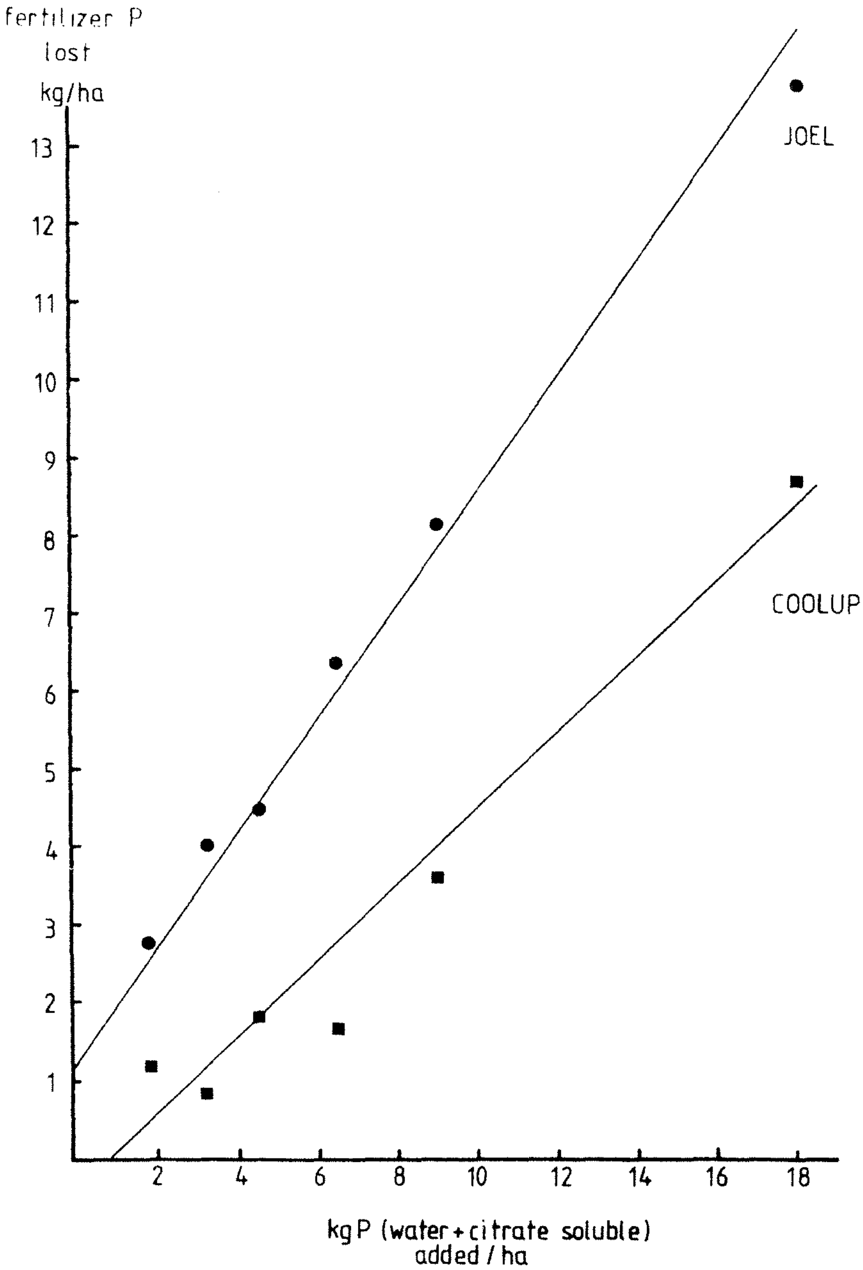

Fig. 4. Variation in fertilizer phosphorus lost (kg/ha) from Joel and Coolup soils with the amount of (water + citrate) soluble phosphorus added (kg/ha) in the fertilizer.

soils. On the other hand, adsorption by soil surfaces as well as fertilizer solubility are important in Coolup soils (Fig. 4).

Phosphorus Pools

When NCS was used as the phosphorus source on both soil types, there was a marked increase in the level of P in the inorganic acid-soluble pool in comparison to the unfertilized soil or a soil fertilized with superphosphate at an equivalent rate (Fig. 5).

DISCUSSION

Application to the Field

As mentioned earlier, the results reported here cannot be applied directly to the field because of the controlled environmental conditions used and the absence of plants. The most limiting factor of the environmental conditions imposed is probably the continuous "rainfall" during winter. Intervals between rainstorms can increase and decrease losses depending on their proximity to fertilizer applications and when they occur in the wet season (Ritchie *et al.*, 1983). The importance of the rainfall pattern has also been observed in relation to phosphorus loading of the Harvey River (Birch, pers. comm.). The later the rains occur, the greater the possibility for P to be taken up by plants rather than for it to be leached. This is particularly so for phosphorus applied as a fertilizer in the current year rather than for native phosphorus.

However, it is encouraging to note that the results are in agreement with the limited field data that is already available. For example, an experimental catchment of duplex soils (the Hodgson plots) which has not been fertilized for four years is behaving in a similar fashion to that predicted by our laboratory data for duplex soils, i.e. there has been no significant drop in leaching loss.

Frequency of Fertilizer Application

Even though the run-down times estimated by these experiments are not as quick as one might have hoped, they do show some positive advantages as far as frequency of fertilizer application is concerned. For Coolup soils, the pattern of leaching loss suggests that some highly fertilized soils may provide adequate P for plant growth for three years without further application. This is supported by the plant available P levels at the end of each summer cycle which were found to be >18 ppm even after six years of leaching. Once the soil P is run down to maintenance level, the observations made on losses from NCS applied to Coolup soils may be used to determine a more economical fertilizer strategy. The results indicated that a lower % of fertilizer P was lost when higher application rates were used, and the plant available P levels were maintained at >18 ppm. Therefore an application rate of 10 kg/ha once in three years may be adequate to maintain plant growth, minimise leaching losses and prevent the unnecessary build-up of P in the soil which will lead to an increased % of fertilizer P being lost each year.

A suitable fertilizer strategy for the Joel soil type is more difficult to assess because the contribution of plant uptake to decreasing leach losses is not yet known. However, it would appear that applications of 10 kg/ha will be needed to maintain adequate P levels and this is

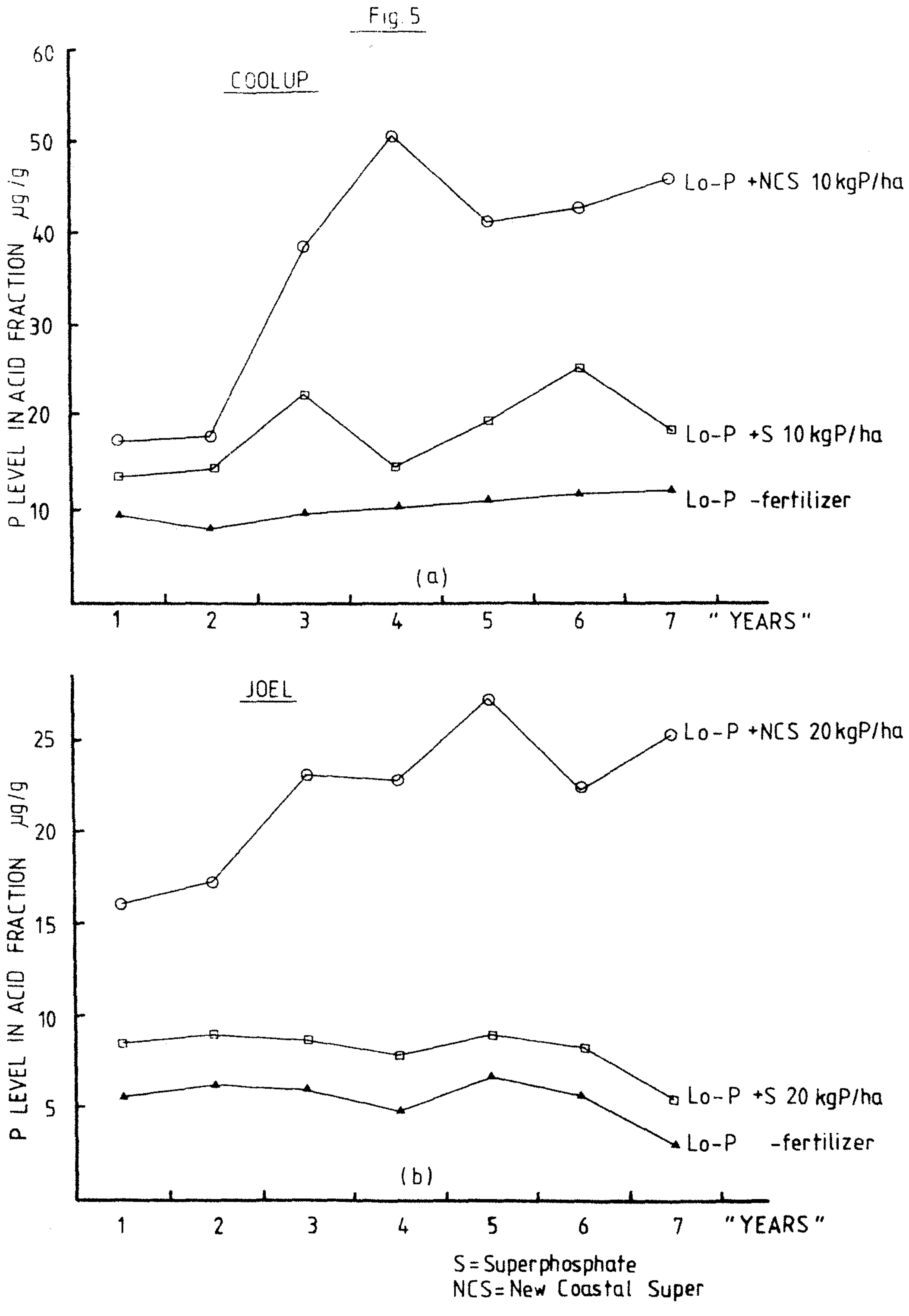

Fig. 5. Phosphorus levels in the acid-soluble soil fraction and their variation with time and application of different fertilizers.

associated with a loss of >2 kg/ha. However, annual application would probably be unnecessary and may in the very long term be detrimental.

IMPLICATIONS FOR MANAGEMENT

1. Run-down times

(a) To achieve "pasture maintenance" levels of P

Joel: A *minimum* of 2-5.5 years would be required to run plant available phosphorus down to 8 ppm for soils with initial levels of 12-28 ppm. The loss associated with maintenance levels would be ∿4 kg/ha if superphosphate was the phosphorus source.

Coolup: More than 7 years without fertilization appear to be required to run down plant available P to approximately 18 ppm from levels >24 ppm. A loss of <3 kg/ha would probably be associated with this P level if the fertilizer source was superphosphate.

(b) To prevent algal blooms

Joel: To achieve a phosphorus loss of <2 kg P/ha, it will take a minimum of 4-9 years for Joel soils with plant available P levels of 12-28 ppm.

Coolup: For soils with a bicarbonate P level >25 ppm, it will take more than 7 years to achieve a loss of <2 kg P/ha.

(c) To achieve a 50% reduction in phosphorus losses

Joel: For soils with a bicarbonate P level of 12-28 ppm, more than 4 years of no fertilization would be required to observe a 50% reduction in phosphorus losses.

Coolup: More than 6 years of no phosphorus application would be necessary for soils with a bicarbonate P of approximately 50 ppm.

2. Alternative fertilizers

(a) Size of reduction in phosphorus losses

A 50% reduction in phosphorus losses was observed when NCS was used as the phosphorus source instead of ordinary superphosphate on both soils.

(b) Major factor controlling extent of loss

Joel: Fertilizer solubility > environmental conditions >>> soil properties.

Coolup: Fertilizer solubility > soil properties > environmental conditions.

(c) Changes in soil phosphorus pools with NCS application

Joel: No changes except in very long term (>15 years).

Coolup: An increase in acid soluble pool due to insolubility of NCS.

(d) Long term effects of NCS

Joel: If NCS were applied at 10 kg/ha annually for periods >15 years, then the situation may arise that the overall loss could equal that from superphosphate at the same rate of P application. It is probably unnecessary to fertilize these soils every year with NCS.

Coolup: There would be a much more gradual increase in the percentage of applied NCS that is lost and it is unlikely that the loss would ever become similar to that which occurs with equivalent superphosphate applications. Annual fertilization with NCS would not be necessary once a maintenance P level was achieved.

POSSIBLE MANAGEMENT STRATEGIES

Joel Soils

(a) Identify soils with bicarbonate P >12 ppm and do not apply fertilizer for 3-4 years. Monitor soil P level after 3 years.

(b) For soils with bicarbonate P of <12 ppm, an application of 10 kg/ha of NCS every other year may be suitable for maintaining plant growth without causing an excessive build-up of soil phosphorus.

Coolup Soils

(a) Identify soils with bicarbonate P >25 ppm and do not apply fertilizer. Monitor soil P level every 3 years.

(b) For soils with "maintenance" P levels (approximately 18 ppm bicarbonate P), an application of 10 kg/ha of NCS once in 3 years would prevent an unnecessary build-up of soil phosphorus and still maintain adequate plant growth.

MANAGEMENT OF AGRICULTURAL PHOSPHORUS LOSSES FROM THE SOILS OF THE PEEL-HARVEY CATCHMENT

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Background

Large losses of phosphorus occur from the sandy soils of the Peel-Harvey catchment for three major reasons.

(i) The soils are porous and of low water holding capcity, and have extremely low phosphorus absorption properties. This leads to a high proportion of phosphorus applied in soluble forms being present in the soil solution, which, in turn leads to rapid water and P losses to the drainage system.

(ii) The seasonal nature of the cultivated annual agricultural species, in contrast to perennial plant species, creates a large 'hole' in the phosphorus cycle on the sandy soils. Over the summer and autumn period, when available P levels in soils reach maximal values (from soil and fertilizer P) these annual species have no capacity to utilize soil P. Large leaching losses can occur following autumn and winter rains, before plant roots are capable of absorbing significant quantities of P, and before tops become significant P 'sinks' (Figure 1). Additionally, water use by annual plants is low compared to perennial species, causing greater water percolation and P losses to drainage.

(iii) The quantity of P applied to the sandy soils of the catchment have in the past greatly exceeded that required by the agricultural system, and that which can be held by the system.

Strategies which have been examined to reduce the agricultural P losses from diffuse sources (c.f. point source losses) have concentrated on the factors outlined above. Work has been conducted on modification of soil properties ('red mud' incorporation) and, although this strategy may have future potential, it is expensive and logistically difficult. It is not considered a viable strategy at present. A related area, clearing and drainage policy, is currently under review.

The practical strategy which has evolved from research work on the Peel-Harvey and earlier studies satisfies the stated aims of the work - to reduce P losses while maintaining the current type and profitability of agriculture. It aims to minimize the amount of P being applied to the sandy soils (and so to minimize P losses), and to apply the P in a form more efficiently used on the sands by annual pasture species.

STRATEGIES TO REDUCE AGRICULTURAL PHOSPHORUS LOSSES

1. The use of fertilizers with phosphorus release patterns better matched to the requirements of annual agricultural species

Slow release P sources

The use of 'slow release' P fertilizers which, unlike superphosphate, are not readily water soluble, and release P at a slower rate over a longer period, aims to increase the efficiency of use of P fertilizers through increasing plant uptake and decreasing leaching losses of P compared to ordinary superphosphate. To be a suitable replacement for P in superphosphate on the catchment sands, 'slow release' P sources must be sufficiently soluble to provide adequate P for plants, but have lower leaching losses (and be economically and practically attractive to farmers).

Work conducted on 'leaching sands' since 1980 has identified several such P sources, the best of which is now commercially marketed as Coastal Superphosphate. Tables 1-3 present summarized data from up to 11 experimental sites on which the sources work has been conducted on pasture (not all sites for year 4).

A range of sources was found to have effectiveness similar to superphosphate (per unit of applied P) in the year of application, to have a higher residual value in subsequent years, and to have lower associated leaching losses for several years following application. In addition to its effectiveness as a P source, other criteria used for the commercial development of a slow release fertilizer were that it was to be attractive in price and readily available, could be readily granulated into a product physically suited to application, and that it could be formulated to supply sufficient sulphur for pasture growth (see below). That the pattern of P availability differs greatly between the sources is seen in the data from a laboratory leaching experiment (Figure 2).

By itself, the use of slow release P sources in place of ordinary superphosphate would be expected to have some impact on leaching losses, but over-fertilization with any P source will lead to excessive P losses. Though the initial premise for the research on slow release P fertilizers was that losses of water soluble P in the year of fertilizer application accounted for a major portion of P leaching losses from sandy soils, it is now clear from other work (Birch, Schofield, Ritchie) that currently applied P represents a third or less of the losses from old land pasture. That is, modification of the source of P will not in itself achieve large cuts in leaching losses, as loss from residual soil 'P' pools are dominant. Reducing these losses is therefore of major importance in reducing overall P losses.

In summary, research work conducted has shown that direct losses of P from fertilizers can be reduced, with slow release P sources, and (ultimately) application rates of P can be reduced (compared to super) as the slow release sources have a higher residual value. Exactly what this means for total P leaching losses is however unclear.

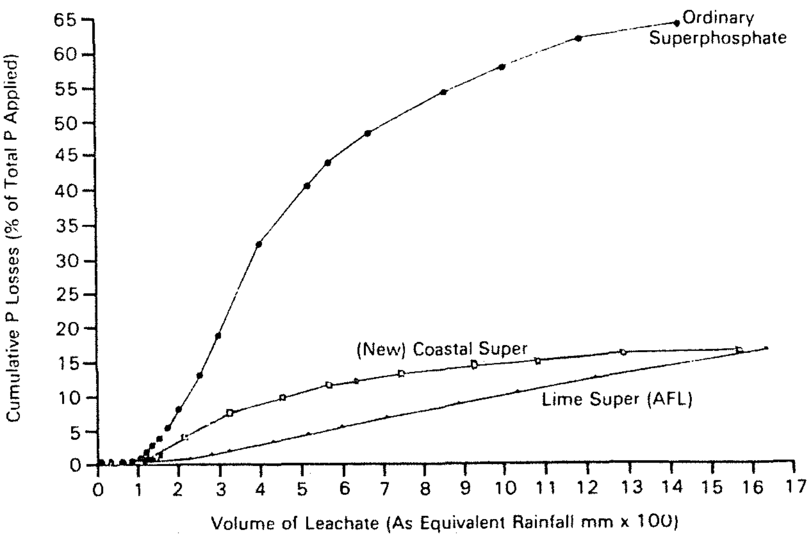

FIG 1. SEASONAL RAINFALL, PASTURE GROWTH AND POTENTIAL LEACHING PATTERN FOR HIGH RAINFALL AREA SANDY SOILS SUPPORTING ANNUAL SPECIES.

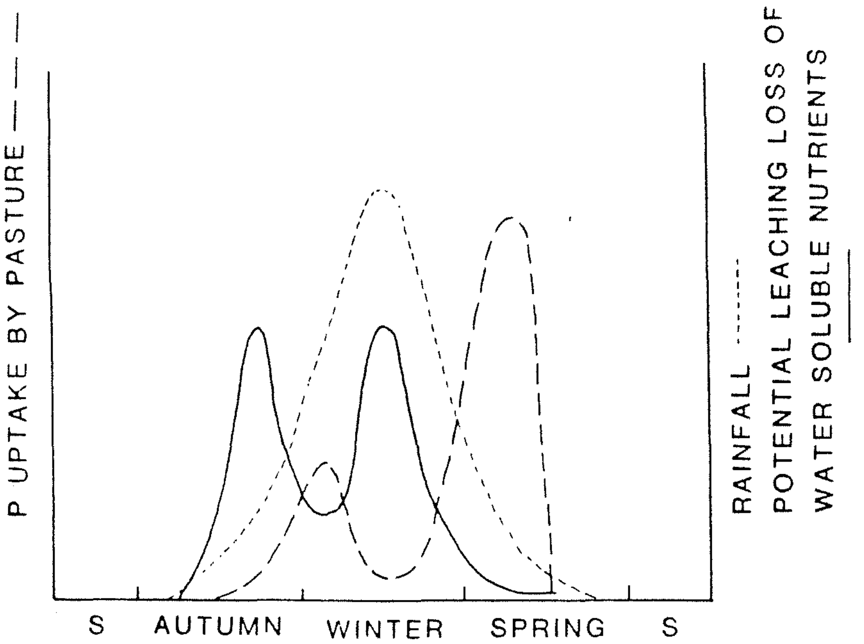

FIG 2. CUMULATIVE LEACHING LOSSES FROM P SOURCES APPLIED TO THE SURFACE OF A GAVIN SAND ON 30CM COLUMNS, AND SUBJECTED TO CONTINUOUS LEACHING.

Table 1: P and S content of the more effective fertilizers used in the P source work.

Source	Total P Content (%)	% of Total P Content as			Total S Content
		WS*	CS*	CI*	
Superphosphate	9.1	84	9	7	10.5
A grade island rock phosphate (<0.15 mm)	16.0	<1	10	90	0
(New) Coastal Super (experimental fertilizers AS1 & AS3 to the same formulation)	9.0	20	13	16	30
Calcined C-grade inland ore (<0.15 mm)	14.0	<1	66	33	0
Lime reverted superphosphate (AFL, N.S.W.)	5.4	9	50	41	8

* WS water soluble
CS citrate soluble
CI citrate insoluble

Table 2: Effectiveness of various P fertilizers in field experiments on pasture on deep grey sands over three years. Each figure is a mean of up to 11 sites (different for each source and year). Effectiveness was calculated by the initial slopes method on either yield (for yield-responsive sites) or % P (for non-yield responisve sites) and expressing data relative to the initial slope measurement for superphosphate applied freshly to new plots in the year of measurement. Figures in parenthisis are effectiveness relative to super applied in the same year as the sources. (NOTE: Data and analysis still incomplete.)

	Year 1	Year 2	Year 3
Superphosphate	1.00(1.00)	0.38(1.00)	0.19(1.00)
'A' grade island rock	0.70(0.70)	0.46(1.21)	0.35(1.84)
(New) Coastal Super	0.81(0.81)	0.66(1.74)	0.53(2.79)
Calcined island 'C' grade ore	0.87(0.81)	0.46(1.21)	0.39(2.05)
Lime reverted super	1.00(1.00)	0.41(1.07)	0.23(1.22)

Table 3: Mean estimated losses of P from the top 10 cm of soil following fertilizer application to pasture on deep grey sands. Losses were estimated from a regression line fitted to P recovered from 6 rates of application at each site. Data are for up to 11 sites (all fertilizer applied in year 1).
(NOTE: Data and analysis still incomplete.)

	Year 1	Year 2	Year 3
Superphosphate	59%	76%	79%
'A' grade island rock	0%	37%	43%
New Coastal Super	0%	54%	52%
Calcined C-ore	0%	40%	49%
Lime reverted super	9%	43%	45%

Time of application of P fertilizers

Another strategy for potentially better matching P release patterns to plant requirements is to delay application of soluble fertilizers until annual species have developed sufficiently to effectively utilize the applied P. Though this approach has been effective in some trial work, results have been variable, and can even be reversed in mild autumns (giving early rapid pasture growth and P uptake) followed by cold wet winters (when applied P can be lost more rapidly than from autumn applications - Table 4). Additionally, late application is logistically difficult for farmers. Overall though late application on average is likely to increase P utilization, it is unlikely to have a very significant effect on P losses by itself, and is generally unacceptable to farmers.

Table 4: Uptake by pasture of P applied as superphospate in the two years following application to sub-clover pasture on deep sandy soils in the high rainfall area (% of P applied)

P applied (kg/ha)	Site 1		Site 2	
	Early autumn	Winter	Early autumn	Winter
10	6	81	60	51
20	-	-	34	21
30	3	30	-	-

2. Precise definition of the phosphorus requirements of pasture on the sandy soils

General considerations

Applications of P fertilizer to catchment soils should not exceed those which will achieve optimum economic production. At these minimum rates total soil P levels are kept to the minimum required to maintain agricultural productivity on the soils, and fertilizer application is minimized, both factors which lead to the minimization of P loss to drainage.

To accurately define P requirements the parameters of response curves for currently applied P (Figure 3) and the residual value of past applications must be established. From these a prediction of P rate required to achieve a nominated level of production (determined by the prevailing economics - cost of inputs, quantity and price of outputs - and the response pattern to applied nutrient) can be made. A previously defined residual value function (RVF) or a calibrated (for different soils, environments and pasture species) P soil test is used to estimate the yield achievable without additional phosphorus fertilizer. With the economics of current P application, the optimum level of P fertilizer application for the current year can then be determined.

The shape of the response curve shown in Figure 3 indicates that a large proportion of the maximum yield achievable on any site is obtainable with a small application of fertilizer, but that a very large application is required to achieve the last growth increment. If soil test levels are high the response from current P application effectively commences high on the curve and increased growth is therefore only achievable with relatively large P inputs. It is economic only to fertilize to where marginal cost and returns are equal. On the better Peel-Harvey sandy soils used for beef or sheep grazing profit is usually optimized at only about 80-90% of maximum growth with respect to P (Matlinson, Morrison). Obviously any increases in the price of product dictates that P rates should be increased - of paramount importance to the future management of catchment P losses.

Of particular importance to the Peel-Harvey study is the determination of the long-term annual 'maintenance' rate of P fertilizer for pasture growth on the leaching soils. The maintenance rate is the minimum rate required to just maintain the optimum (from the cost/price ratio applicable) pasture yield on soils with near-adequate P levels by replacing P losses (leaching + product + any nett immobilization) from the available soil pool, and without increasing the nett level of available P.

Response parameters for currently applied P

Trial data on the leaching sand shows that Mitscherlich 'c' coefficients for P in superphosphate (and Coastal Super) are generally in the range 0.05-0.10. Variation appears due to seasonal factors, the components of which are not fully understood. A value of 0.10 is currently used the PHOSULK fertilizer recommendation model (see below). Values of 0.06 and 0.03 respectively are used on medium and heavy textured soils (reactive iron values 500-1000 and >1000).

Residual value function

If the residual value of past applications of superphosphate (or other P sources) could be accurately predicted for different situations, an RVF could be used to estimate the current value of previous P applications. However, research work has shown that both site and seasonal factors on apparently similar soils affect residual value as measured by bicarbonate-extractable (bic) P (Tables 5 and 6). This also complicates the calculation of optimal fertilizer rates, as the future value of current P applications should be taken into account in fertilizer recommendations.

Table 5: Changes in bicarbonate-extractable residual P (0-10 cm, ppm) over-time on nil plots and following superphosphate application to pasture on deep grey sands

						Superphosphate application, Year 0							
Site	Nil plots					30 kg/ha P				90 kg/ha P			
	Year					Year				Year			
	0	1	2	3	4	1	2	3	4	1	2	3	4
1	3	6	6	5	6	6	4	6	6	9	9	6	5
2	10	8	8	8	8	10	10	9	9	25	19	15	16
3	15	11	2	5		16	6	6		17	5	9	
4	2	2	2	2		5	3	5		15	9	12	
5	4	2	2	2		7	2	2		7	2	7	
6	12	15	12	10		19	10	10		21	17	24	

(Bic. P measured over summer)

Table 6: Site and seasonal effects on bicarbonate-extractable residual P (0-10 cm, ppm) one year after application of superphosphate to pasture on two deep grey sands

	Site 1				Site 2			
P rate (kg.ha)	Applied 1980 sampled 1980/81	Applied 1981 sampled 1981/82	Applied 1982 sampled 1982/83	Applied 1983 sampled 1983/84	Applied 1980 sampled 1980/81	Applied 1981 sampled 1981/82	Applied 1982 sampled 1982/83	Applied 1983 sampled 1983/84
0	10	8	8	8	6	6	5	6
10	10	13	11	-	9	5	10	-
30	10	11	14	-	6	6	8	-
90	25	30	28	18	9	7	18	11
180	36	26	26	27	9	11	25	18

(Bic. P measured over summer)

Because the RVF for P applied to the deep sands has not been well defined, superphosphate 'history' cannot be used to accurately estimate current P requirement. Reasons for the variability in RVF - probably the factors affecting the rate of leaching losses from currently applied P - are important in attempting to manage losses, and are currently under investigation.

Soil tests

Soil tests directly measure the current value of past P applications, and therefore can be used to estimate the additional P fertilizer required to achieve the optimum economic level of yield. However, soil tests must be calibrated to plant yield for different soils, environments and plant species before this can be done.

Recent research on the P leaching soils of south-west Western Australia has established a new series of P calibration curves for sub.clover based pastures (Figure 4). Previously used calibrations overestimated the bic. P level required for maximum pasture yield on permanent pasture, and resulted in excessive P recommendations and usage.

The shape of the calibration curve (the Mitscherlich function 'C' parameter) is a function of the P adsorption capacity of the soil, with heavier soils (higher reactive iron content) having lower soil test 'C' parameters (i.e. a higher test level is required to achieve maximum growth).

The new soil test 'C' values on sandy soils, existing values for heavier soils (Bowden, unpublished) and response curve data for P applied to pastures have been incorporated into the PHOSULK computer model (with S and K response data), which was developed in 1984 to make fertilizer recommendations for the pastured soils of the high rainfall areas of south-west W.A., particularly the Peel-Harvey catchment.

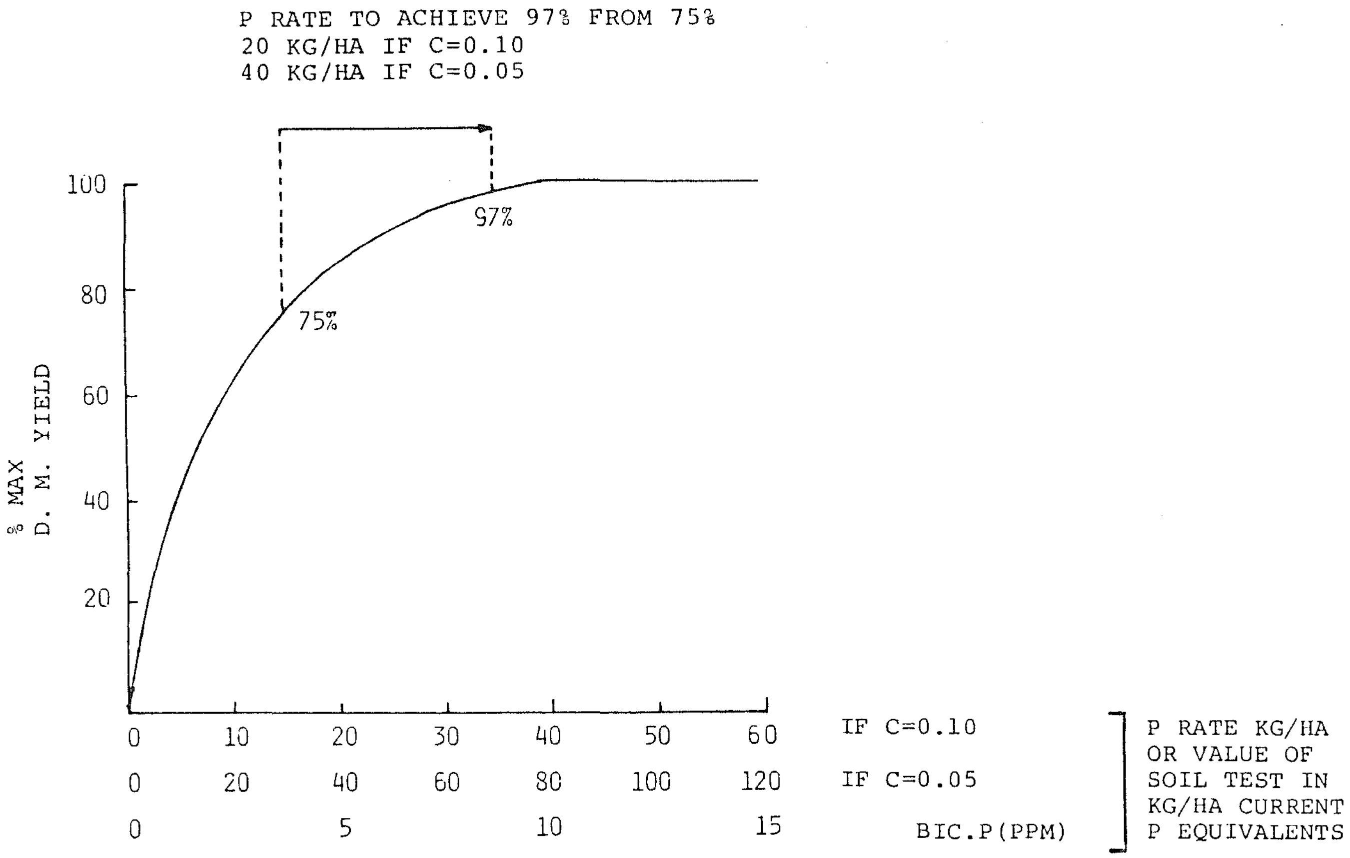

FIG. 3. PHOSPHORUS RESPONSE CURVE (MITSCHERLICH FUNCTION)

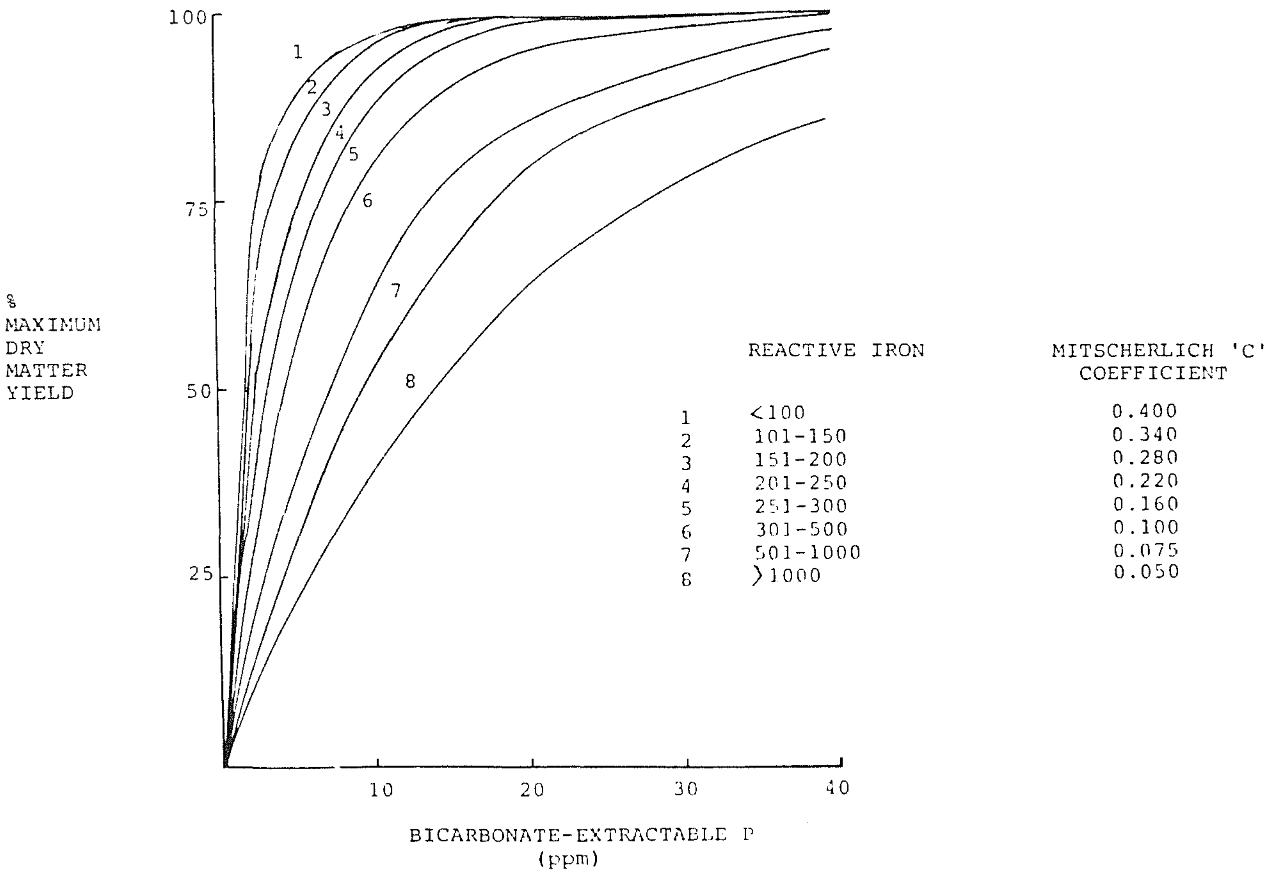

FIG.4 PHOSPHORUS SOIL TEST CALIBRATION CURVES
FOR HIGH RAINFALL AREA PASTURES

Prediction of long term P requirements

The long term 'maintenance' rate for pastures on the leaching soils will determine to level to which P losses from the soils can be reduced within the constraint of maintaining agricultural productivity. Data from which to directly estimate these rates are not available, though long term work was commenced in 1984. However, assuming maintenance rates to be about a quarter of that required to achieve the nominated proportion of maximum yield on new land (from limited data available in other situations), estimates have been made in Table 7 of annual maintenance rates as kg P/ha/annum, and as the percentage of the rate of P commonly used by farmers on the leaching soils prior to 1984 (16 kg P/ha), with figures for the relevant range of P response 'c' coefficient. With a 'C' coefficient of 0.10 for currently applied P, only a small reduction in pre-1984 annual P application rates (as superphosphate) is predicted to be achievable while still maintaining near-maximum pasture yields in the long term. However, at the cost/price ratio applicable to many enterprises on the sands (Joel and Coolup sands 1-2 - 80%-90% of maximum yield - and Gavin sands >6-uneconomic to fertilize at all), and because of the nature of the relationship between P applied and pasture yield (Figure 3), available data indicates maximum long term economic returns can be achieved by cutting current (< 1984) annual P rates by 50% or more (Table7).

Table 7: Estimates of rate of P required for maintenance of nominated pasture yield levels on Peel-Harvey sands. The three values of 'C' span the range of coefficients of currently applied P believed appropriate for the soils

Cost/ price ratio	Pasture yield level appropriate (% maximum)	Annual maintenance P rate (as super) to achieve nominated pasture yield: kg/ha/year C=0.10	C=0.075	C=0.05	% of current common rate* C=0.10	C=0.075	C=0.10
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 long-term reduction in P application rates (and therefore 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. Accurate data from Bassendean and Coolup sands are essential to enable more reliable estimates to be made of actual reductions in P application rates achievable on these soils. This work is currently in progress. Also crucial to the estimates is the cost/price ratio chiefly altered in practice by product price changes - which greatly alters the optimum P application rate.

The large reduction in P rates which could theoretically be achieved obviously represents a potential savings on fertilizer bills (compared to current expenditure) for those farmers with soil tests sufficiently high to require only maintenance P dressings. Such savings (without loss in farm profitability) are likely to be a powerful incentive for farmers to adopt modified fertilizer strategies.

Other methods of estmating maintenance P application rates include the use of a balance approach to P losses (replacement of P losses in product and in drainage, with assumptions about the asymptotic nature of soil P 'pools'). However, as field estimates of these losses are very variable (Table 8), this approach cannot currently be used unless more accurate data on these losses are obtained, and the necessary assumptions shown to be valid. More accurate estimates may be obtainable from long term experimental or paddock P balance data.

Table 8: Estimated losses of P from unfertilized plots on old land over one year periods on deep sands. Losses were estimated from changes in total P content, 0-10 cm

Site	P at year 0 (kg/ha)	Nett cumulative loss at the end of year 1 (kg/ha)	2	3
1	115	0	0	0
2	100	0	8	0
3	135	18	0	-
4	165	78	0	-

* Nett loss = change in total P from year 0 adjusted for P removal of 3 kg P/ha/annum as losses in animal products.

That difficulty has been experienced with maintenance rate calculations from the balance sheet approach is not surprising as drainage monitoring work (Birch, Schofield) shows <5 kg P/ha/annum to be lost - too small for accurate measurement in the short-term using total P analysis of soils. A further difficulty arises with P distribution down the soil profile ($>$10cm), which may only be partly available to plants.

Simulation predictions using P balances

Estimated changes in P applications rates theoretically achievable on old land pastures (and P leaching losses if assumptions of asymptotic P pools are accepted) by reducing rates to maintenance levels and by the use of a slow release P source (e.g. Coastal Super) in place of ordinary superphosphate are presented in Table 9. The data were generated using a simple simulation model, with the following assumptions.

1. Leaching losses of superphosphate in the year of application = 25% of P applied, and for the slow release P source = 10% of P applied, and are independent of the absolute rate applied.

2. All losses from the dissolving fertilizer occur in the year of application.

3. All losses in the second and subsequent years are from the 'available soil P pool', are independent of the source of P in year 1, and are dependant only on (maintenance) soil P levels and soil factors.

4. Asymptotic P pools. That is, maintenance rates do not result in a nett change in soil P, but only replace losses.

Table 9: Maintenance rates of P required as superphosphate and as slow release P, equally as agronomically effective as super (kg P/ha/annum).

SIMULATION ONLY

Product removal (kg P/ha/annum)		Soil P 'pool' leaching losses (kg P/ha/annum) 1	2	5
2	as super[1]	3.75	5.00	8.75
	as S.R.[2]	3.30	4.40	7.70
5	as super	7.50	8.75	12.50
	as S.R.	6.60	7.70	11.00
10	as super	13.75	15.0	18.75
	as S.R.	12.10	13.2	16.50

1 = ordinary superphosphate
2 = 'slow release' phosphate

Available data (Birch, Schofield) indicate that P leaching losses from currently unfertilized pastures with bic. P levels giving > 95% of maximum yield are in the range 1-4 kg P/ha/annum, which represents 60-70% of the total losses of soils fertilized with 16 kg P/ha/annum, and P product losses under beef and sheep grazing (c.f. hay, dairying) are less than 3 kg P/ha/annum. The simulation data from the P balance in Table 8 therefore indicate that P rates required for maintenance on the leaching sands are of the order of 50% of the currently applied rate, a similar conclusion to that reached from the estimates presented in Table 7.

To predict the total reduction in P leaching losses however, the soil P 'pool' losses associated with existing soil levels needs to be known, and compared with estimated maintenance loss rate. Field data are not available, but laboratory data (Ritchie) indicates that a linear, proportional relationship exists between bic. P levels and P losses. That is, if mean soil bic. P levels are currently twice that necessary for maintenance growth, 50% of current soil P losses can be eliminated by reduction of these levels to maintenance, and direct losses of fertilizer being applied to maintain these excessive losses can also be reduced. Again however, these estimates rely heavily on unvalidated assumptions.

The sulphur problem

The research programme, and the soil test results from the extension work (see below) clearly show that considerable potential exists for a reduction in the amount of phosphorus currently being applied to the Peel-Harvey catchment, without any loss of agricultural productivity. However, these reductions can only be achieved if adequate attention is given to the 'sulphur problem'.

In addition to P, superphosphate also contains sulphur (10.5%S) which unlike P, does not build up significantly over time from past applications. On sub.clover pastures on the sandy soils severe sulphur deficiency usually occurs within one year of cessation of applications of a sulphur-containing fertilizer. In the past many farmers have been unknowingly applying superphosphate primarily to prevent sulphur deficiency occurring, often mistakenly believing that growth reductions caused by leaving superphosphate off have been due to phosphorus deficiency. (Extension work indicates that farmers still do not fully appreciate the importance of sulphur for pasture growth).

One of the major problems confronting farmers wishing to follow soil test - based P advice has been how to apply sulphur in a form other than as superphosphate. Even in the severely leached soils P levels build up from past super applications, often leaving sulphur, on old pastures, as the main or only nutrient present in superphsophate which is actually required for one or more years.

Fine gypsum is a cheap source of sulphur, but is difficult to spread in late winter-spring when it is required for plant growth, and is generally not acceptable to farmers. Earlier applications are too rapidly leached to be effective for spring growth. The problem was partly overcome with the development of (New) Coastal Superphosphate, which contains a much higher S:P ratio than ordinary super, and has both S and P in a slow release form. The S:P ratio is adequate for maintenance of the soil status of both nutrients with annual application, applying about 9 kg P/ha with adequate S compared to about 16 kg P/ha for ordinary super, but Coastal Super still contains unnecessary P for high P soil test situations. Development of a suitable S-only fertilizer for pastures to allow high P soil levels to run down to maintenance levels (and so reduce soil P pool and direct fertilizer P losses) has proved technically difficult, but is still continuing.

Potassium

Potassium is another nutrient commonly required by pastures on the sandy soils, and supplied by traditional fertilizer mixes used in the catchment. Development of alternative fertilizers, fertilizer strategies and advice has had to cover this nutrient in addition to P and S. Unlike sulphur however, potassium is not an integral component of superphosphate, and so can be easily mixed with new or existing fertilizers in relevant proportions, if suitable equipment is available.

THE AGRICULTURAL EXTENSION PROGRAMME

The programme to modify current farmer fertilier strategies on all the coastal plain soils of the Peel-Harvey catchment using results of the research work outlined above was introduced in 1984, following a pilot study in 1983 and the commerical development of (New) Coastal Superphosphate in 1983/84. The 'package' presented to farmers is summarized in Figure 5. To encourage maximum farmer particpation, soil sampling, analysis and fertilizer advice was provided free of charge by the Department of Agriculture and the Government Chemical Laboratories.

Almost 4,000 soil samples were collected during summer 1983/84. The soil bicarbonate-extractable P results are presented graphically in Figure 6 (a)-(d). Overall, from soil P data and the economics of P fertilization, about 70% of the catchment paddocks were predicted not to require additional P in 1984. When weighted for the expected leaching from each class of soil, this represents a potential reduction of about 60% in direct losses from applied fertilizers (or about 20% of total losses if one third of all losses are direct fertilizer losses).

FERTILISER MANAGEMENT STRATEGY

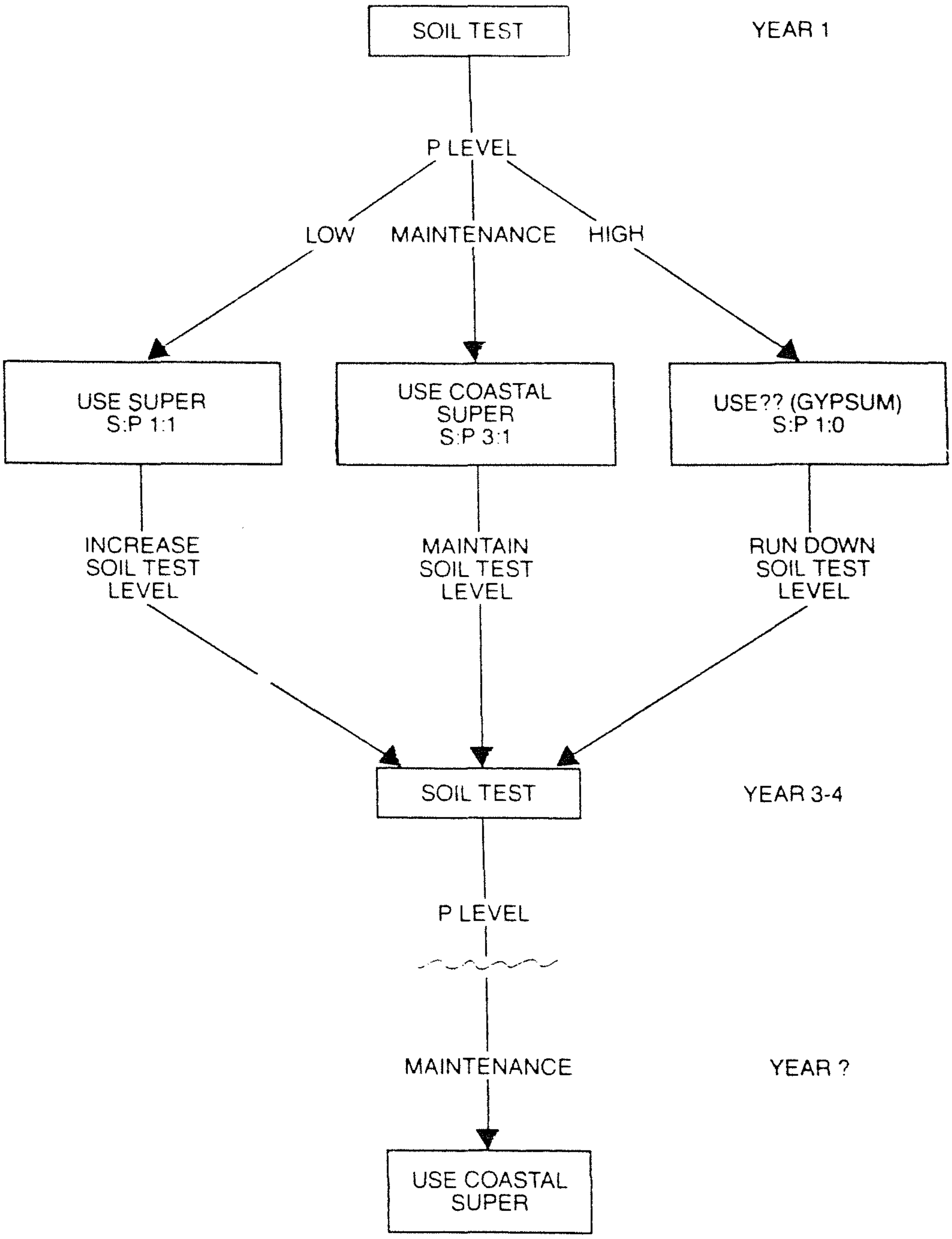

FIG 5. SUMMARY OF THE LONG TERM PEEL-HARVEY CATCHMENT FERTILIZER MANAGEMENT STRATEGY.

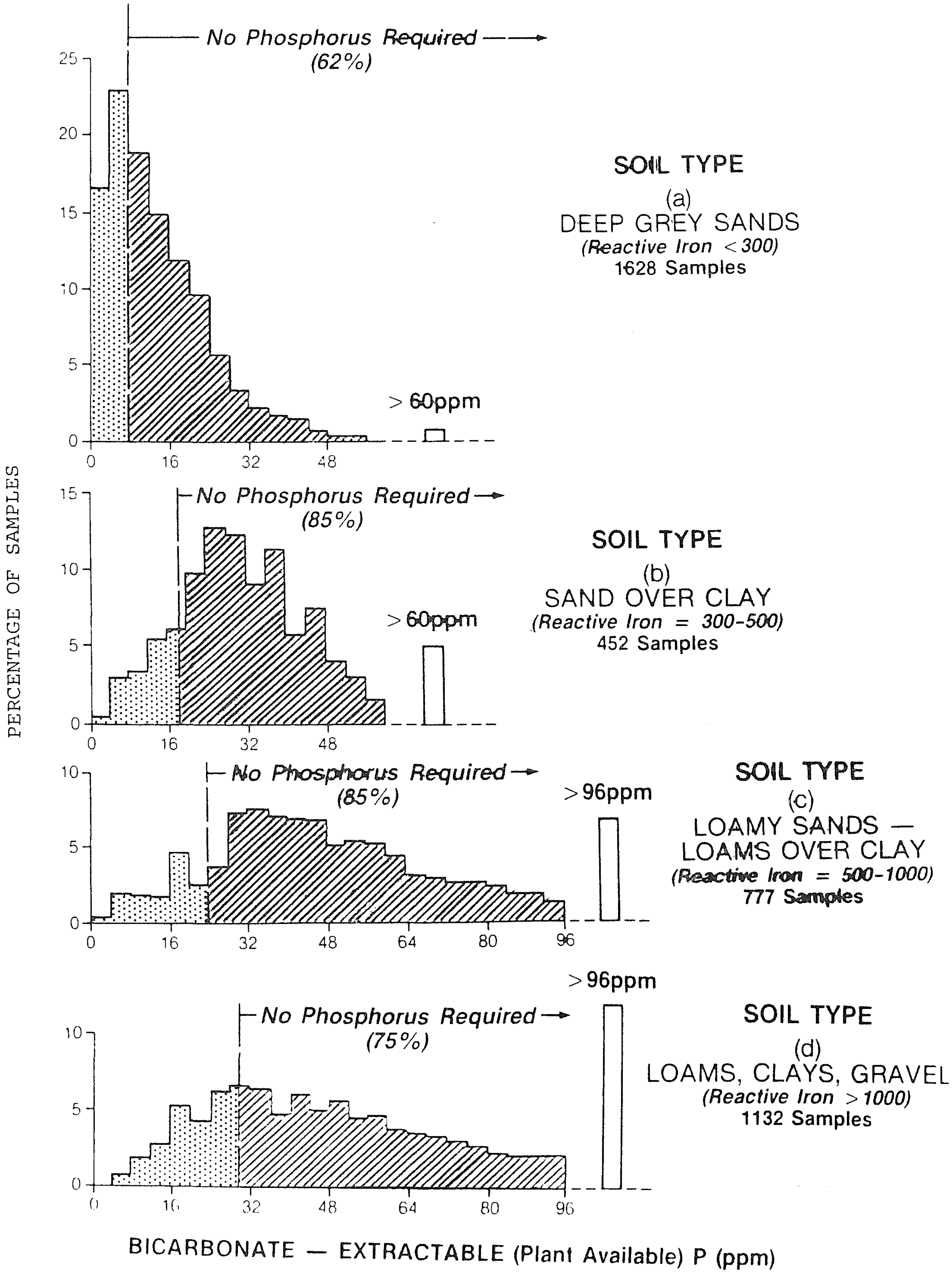

FIG 6 PHOSPHORUS SOIL TEST LEVELS FOR COASTAL PLAIN CATCHMENTS ON THE PEEL HARVEY ESTUARY, 1983/84

On the soils requiring additional P in 1984, it was estimated that the mean rate required was about 50% of that previously commonly applied. That is, if all P had been applied in 1984 according only to actual requirement, P losses would have been reduced by about 25% overall.

Farmer acceptance of the fertilizer modification campaign

A survey of 100 farmers was conducted during September 1984, to ascertain the level of acceptance of recommendations, and the type and quantity of fertilizer actually used. Eighty-nine farmers were advised to use fertilizers other than super on at least part of their farm, and this advice was followed by 67 of them. In most cases following the advice to use the modified strategies resulted in cost savings of about $2-$3/ha compared to traditional strategies, though in a number of cases the savings on P and S were offset by higher K recommendations.

Rates of fertilizers actually used per hectare were not determined in the survey, but from total tonnage used it was estimated that a mean of 1.01t of P was used on farms using super, compared to 0.69t/farm for farms using New Coastal Super. Assuming all farms were of equal size, this represents a total P application reduction (compared to 16kgP/ha/annum) of about 30% in 1984 - closely matching data obtained from CSBP on total P sales to the catchment. This figure is about half of that theoretically achievable in the short term from the soil test data obtained.

The sampling and advisory exercise has been repeated in 1985 and will possibly be carried out again in 1986. The long-term goal is to have all farmers following the soil test-based decision making process outlined in Figure 5 with very little Government involvement, and with the savings involved in permanently adopting the modified strategies as sufficient incentive for a high level of adoption. A major survey is planned for spring 1985 to determine farmer attitudes towards the programme, and to identify areas of research or extension required to make advice even more attractive to farmers.

SUMMARY AND CONCLUSIONS

The 1984 extension campaign clearly demonstrated that, given economic incentives and appropriate strategies, advice and encouragement, a high level of farmer co-operation in reducing agricultural phosphorus usage can be obtained. The major challenges in the future are to increase the level of adoption of the 'new' strategies, and to then indefinitely maintain a high level of adoption. To achieve these aims requires further improvement in the technical data available, a wider range of fertilizers to be available to allow farmers to closely follow advice (particularly a new S-only fertilizer) and guaranteed funding of the programme for an as-yet undetermined time. Of particular importance technically is the accurate definition of the minimum long term P application rates required to maintain optimum pasture growth on the range of 'leaching sands'.

The benefits to the estuary of the programme can still be only crudely estimated. The critical questions - how long will the soils with high phosophorus levels tke to run down to where maintenance levels of phosphorus are required, and what phosphorus loss rates will be associated with the run down and maintenance phases - have been addressed in other papers. From the field experimental results obtained to date, run down times of about 5 years (Joels) to more than ten years (Coolups) seem likely and long term reductions of about 40% in phosphorus application rates appear achievable within the constraints of the study. Better estimates will be obtained from the long term field experimental work.

NUTRIENT LOADING INTO THE PEEL-HARVEY ESTUARY

BY

P B BIRCH, G G FORBES AND G M BOTT

Nitrogen and phosphorus loads into the estuary from the Murray, Serpentine and Harvey Rivers have been measured by various methods and levels of accuracy since 1977. Full details of estimated loads, methods employed and an error analysis will be published shortly in DCE Bulletin 182. Therefore the purpose of this paper is to summarize only the main details of flows and loads. In addition, an analysis will be made of the effectiveness of the fertilizer modification programme on concentrations of phosphorus in river water and loading to the estuary.

Figure 1 depicts the boundaries of the Murray, Serpentine and Harvey plus drains catchments and Table 1 summarizes their annual flows, loads and flow-weighted concentrations for the period 1977-84. For 1984 measured data are available up to the first week of October and have been extrapolated for the rest of the year.

The flows and loads for the Harvey and Murray Rivers for 1984 were well below the study period (1977-84) average and for flows were well below the long term (40-50 year) mean and median. The Serpentine River was above the study period average in 1984 but below the long term average.

The below average flows for the Harvey and Murray Rivers in 1984 were caused by distribution of rainfall rather than low actual amount (Table 2). Rainfall was below average in the critical month of July but well above average in November following a relatively dry October.

It is interesting to note that for the study period the average rainfall has been within 10% of the long-term average, despite the very dry years of 1977 and 1979. However, the rainfall pattern has produced flows that have been about 30% below the long-term mean for the Murray and about 20% below the long-term mean for the Harvey and Serpentine, but only slightly below the median flows for all rivers. This reflects the skewed distribution of flows, particularly for the Murray River, where only one third of years are above the mean (Fig. 2). Therefore, one well above average flow in the Murray River (500 - 700 million m^3) and one near average flow in the next two years would turn the decade of flows (1977-86) into one fairly typical of the previous four.

Since flow-weighted concentrations of nitrogen and phosphorus are largely independent of annual flows and have been relatively constant for the Harvey and Serpentine Rivers, one would expect that, on average, loadings should be about 25% higher than they have been over the study period. But again allowing for the historical skewness in flow distribution, we would expect an increase in the average to be most likely brought about by one well above average and one near average flow in the next couple of years.

Another useful feature of the relative constancy of the flow-weighted concentrations of phosphorus from coastal plain drainage is in predicting the effect of the fertilizer modification program. However, when the phosphorus concentrations are plotted with their estimated 95% confidence intervals (Figure 3) it is seen that the anticipated effect of the program (a 30-40% reduction in concentration of coastal plain drainage in 3-5 years) can only be reliably detected in the Harvey River. Large errors in flow, load and flow-weighted concentration occur when significant (20%) proportions of the catchment are ungauged coupled with a weekly (or less) sampling frequency for concentration, as has been the case for both Murray and Serpentine Rivers, especially prior to 1979. When all of the catchment is gauged and weekly samples are taken the annual error reduces to about ±12%. This reduces even further to about ±3% when daily water samples are taken. Such is the case for the Harvey River since 1982.

Given the above, the 25% reduction in concentration for the Harvey River in 1984 compared to the 1977-83 mean is encouraging with the proviso that the 1977 concentration was also nearly 25% below the long term mean. Therefore, it is important to note that effects other than the fertilizer program could at times affect the flow-weighted concentration by a significant amount. The task at hand is, therefore, to evaluate the possible effects of both the fertilizer modification program and seasonal influences and to compare these with the observed effect.

Final statistics of the 1984 fertilizer use are not yet available but a preliminary estimate is that phosphorus application was reduced by about 40% and of that applied about 60% was as New Coastal Superphosphate (see Yeates, this Bulletin). This would reduce the direct fertilizer loss component of phosphorus runoff by 40% plus any further effect from New Coastal Superphosphate. According to Ritchie et al (see this Bulletin), leaching losses from New Coastal Superphosphate are 50% less than those from ordinary superphosphate. Thus the direct fertilizer loss in 1984 could have been reduced by:

$$40\% + \left(\frac{60\%}{2} \text{ of } 60\%\right)$$

$$\text{ie } 40\% + 18\% = \underline{\underline{58\%}}$$

It is difficult to estimate the fraction of direct fertilizer loss in total phosphorus runoff but paired catchment experiments indicate that it could be about 20% for sand over clay (and possibly also for clays and loams) and about 30% for deep grey sands. Given that the deep grey sands contribute about 40% of total runoff, the duplex soils 40% and the heavy soils 20% of total runoff, an approximate estimate of the reduction in phosphorus runoff and hence flow-weighted concentration in 1984 is:

$$0.60[0.58\ (0.20)] + 0.40\ [\ 0.58\ (0.30)]$$
$$= (0.07 + 0.07) \times 100\%$$
$$= 14\%$$

This compares with an observed reduction of 25% and suggests that some other seasonal factor such as apparently operated in 1977 could have also contributed. This aspect is under investigation and at present an important component appears to be the proportion of total winter (May-October) flow which occurs in May-July. Figure 4 shows that, on average, phosphorus concentration jumps from 0.24mg/L in May to 0.48 mg/L in June when the first significant runoff occurs i.e. a "first flush" effect. After that there is a steady decline each month to 0.17 mg/L in October. It was therefore hypothesized that those years with higher proportions of total flow in the first half of the season would have higher seasonal flow-weighted concentrations. This was tested by regressing the proportion of seasonal flow in May-July against the seasonal flow-weighted concentration which revealed a fair (r=0.77) correlation provided 1984 was omitted (Figure 5). The point for 1984 plots well below the regression line which suggests that for its distribution of flow the concentration was about 25% lower than that predicted by the regression equation. This in turn suggests that the observed decrease in concentration could have been caused by the modified fertilizer practices. However, other seasonal effects such as the proportion of high flow rates and incidence of dry spells still remain to be investigated. Even so as an interim conclusion we believe that the low concentration in 1984 was probably partly caused by modified fertilizer practices and partly by seasonal effects of flow, in particular the low flows in July.

Table 1. Annual flows and loads for nitrogen and phosphorus from the Harvey, Murray and Serpentine Rivers 1977-84, Data for 1984 are preliminary estimates and subject to minor revision.

	Harvey & drains		Serpentine		Murray		Total to Estuary	
	1984	(1977-84)	1984	(1977-84)	1984	(1977-84	1984)	(1977-84)
Flow ($10^6 m^3$)	202	(230)	156	(120)	237	(270)	595	(620)
P Load (Tonnes)	56	(86)	54	(42)	13	(23)	123	(151)
P Conc (mg/L)	0.28	(0.37)	0.35	(0.33)	0.055	(0.083)	0.21	(0.24)
N Load (Tonnes)	360	(380)	256	(210)	330	(610)	946	(1200)
NConc (mg/L)	1.8	(1.7)	1.6	(1.7)	1.4	(2.2)	1.6	(1.9)

Table 2. Comparison of annual runoff volumes and catchment rainfall for the Harvey, Murray and Serpentine Rivers for 1984 with the mean for the study period (1977-84) and the long-term mean and median.

	Annual Runoff in $10^6 m^3$				Annual Rainfall in mm		
River	1984	(1977-84)	Long Term		1984	(1977-84)	Long Term Mean
			Mean	Median			
Harvey & drains	202	230	300	270	1048	970	1010
Serpentine	156	120	140	130	975	901	996
Murray	237	270	380	280	638	651	650

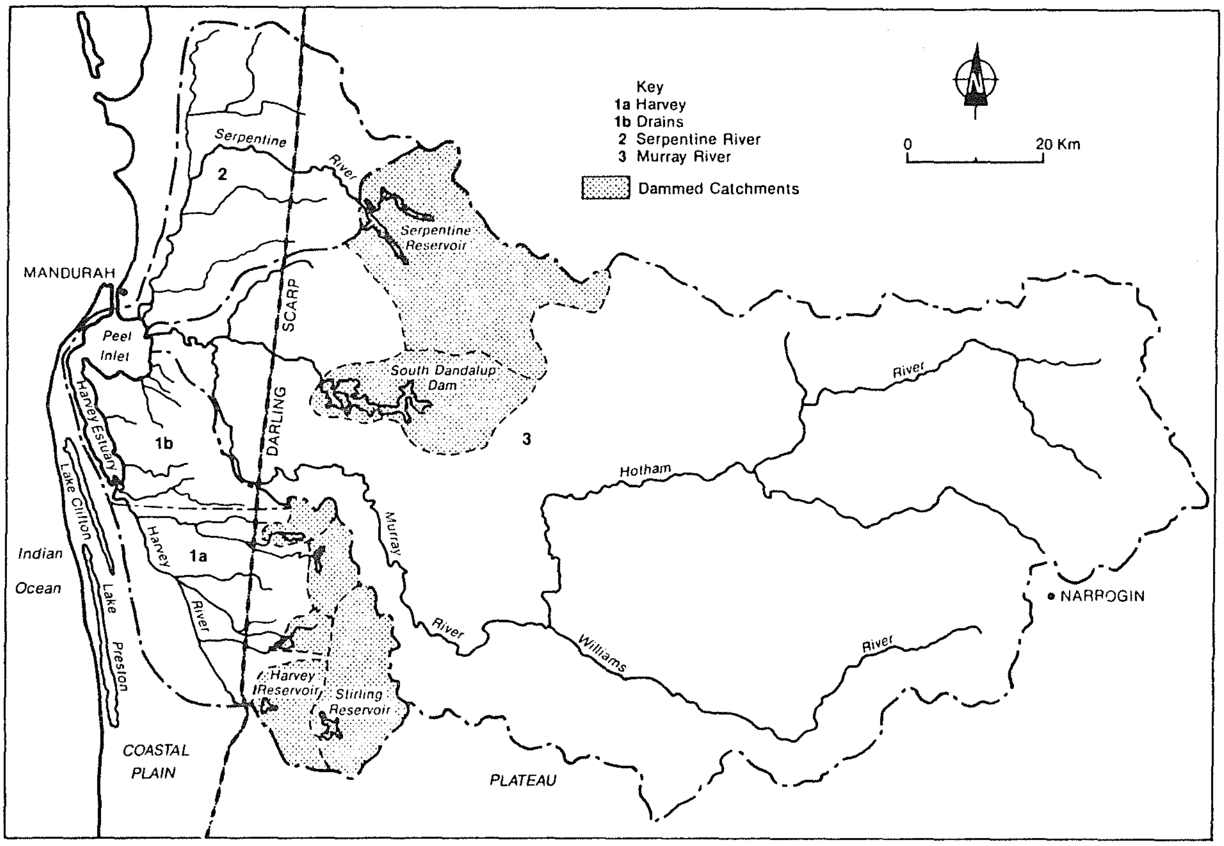

Fig 1 Catchment of the Peel Harvey estuary

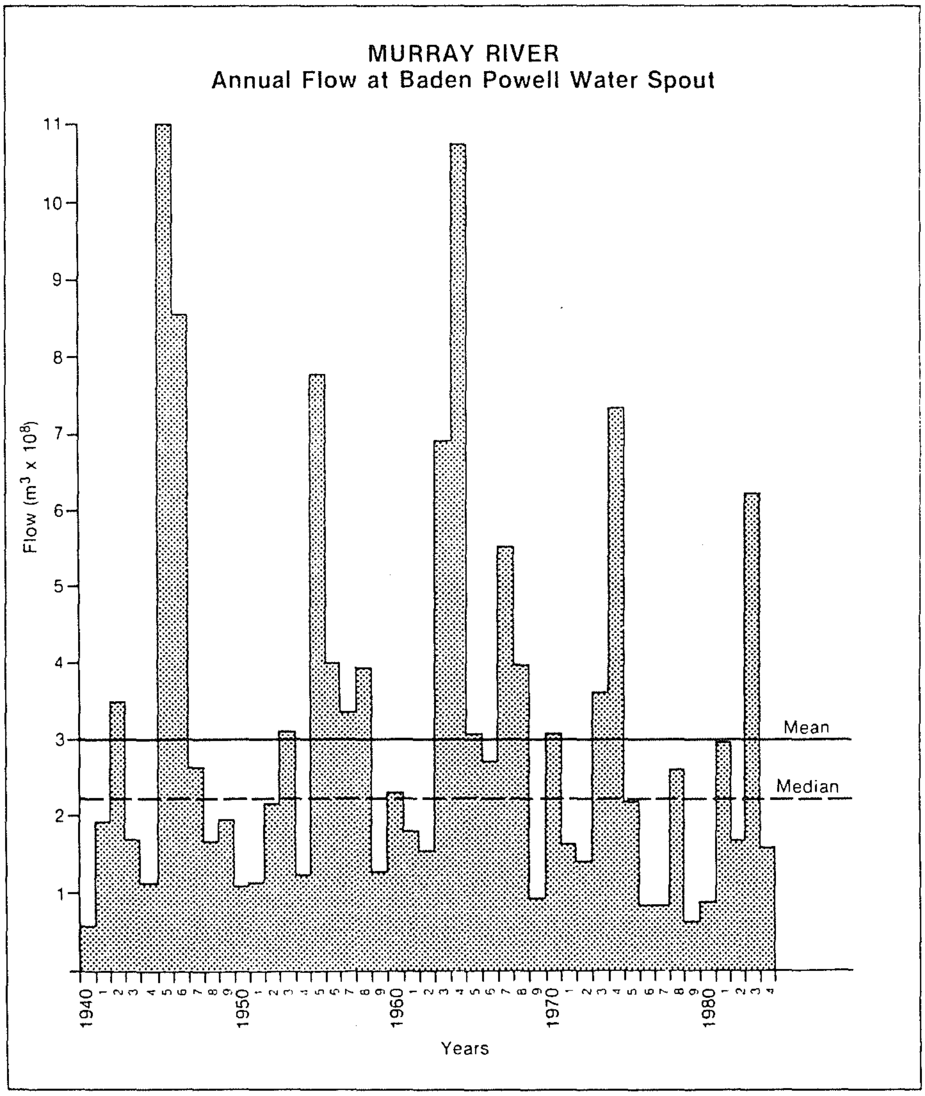

Figure 2 Murray River annual flows at Baden Powell Water Spout gauging Station (614006).

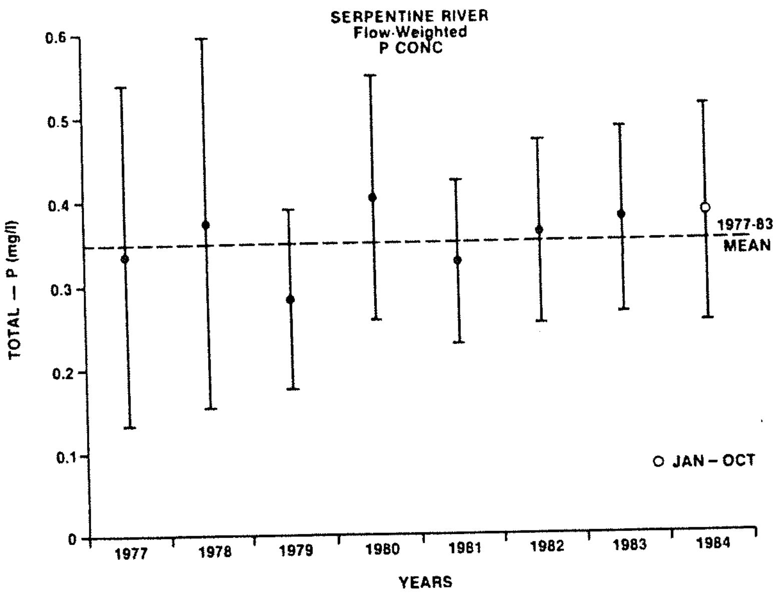

Figure 3 (a) Flow-weighted phosphorus concentrations for the Serpentine River with estimated 95% confidence intervals

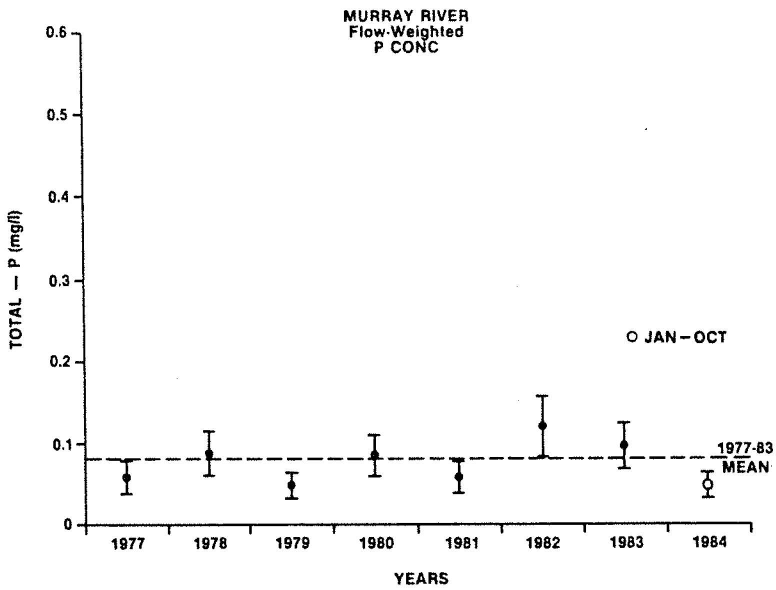

Figure 3 (b) Flow-weighted phosphorus concentrations for the Murray River with estimated 95% confidence intervals

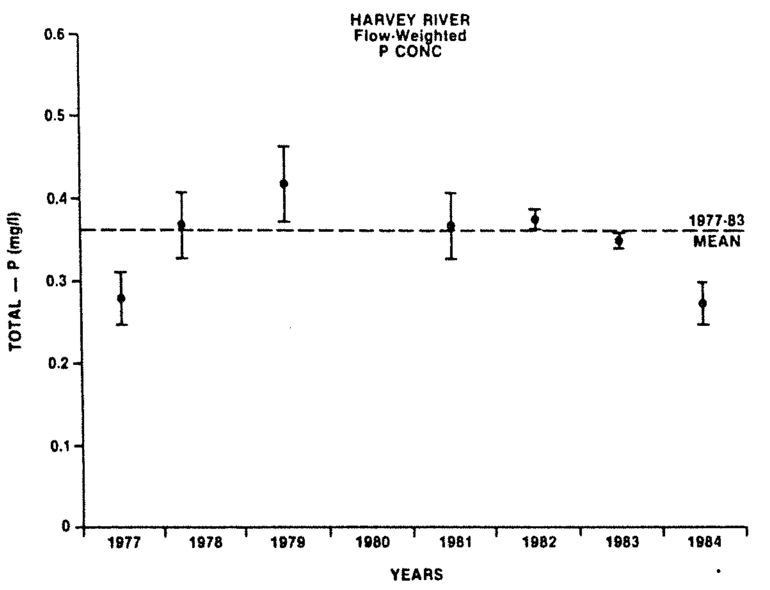

Figure 3 (c) Flow-weighted phosphorus concentrations for the Harvey River with estimated 95% confidence intervals

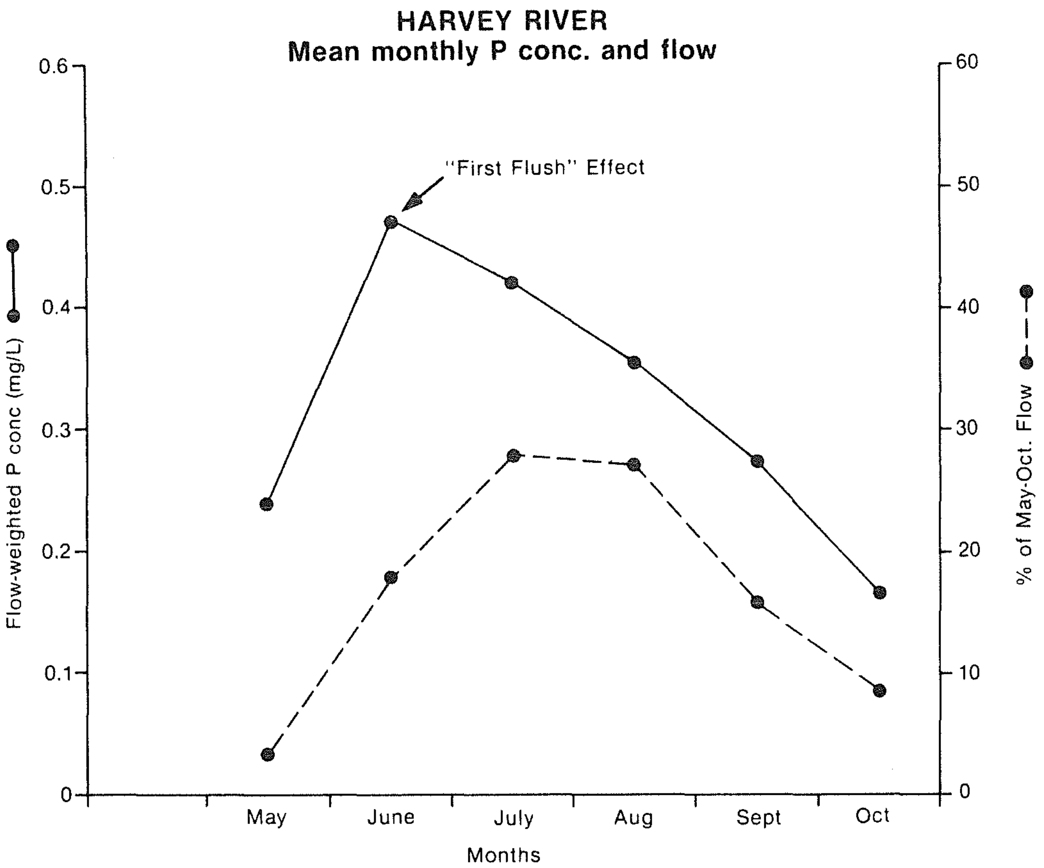

Figure 4 Average flow-weighted concentrations of phosphorus and proportion of flow for the months May - October for the Harvey River, 1977-84.

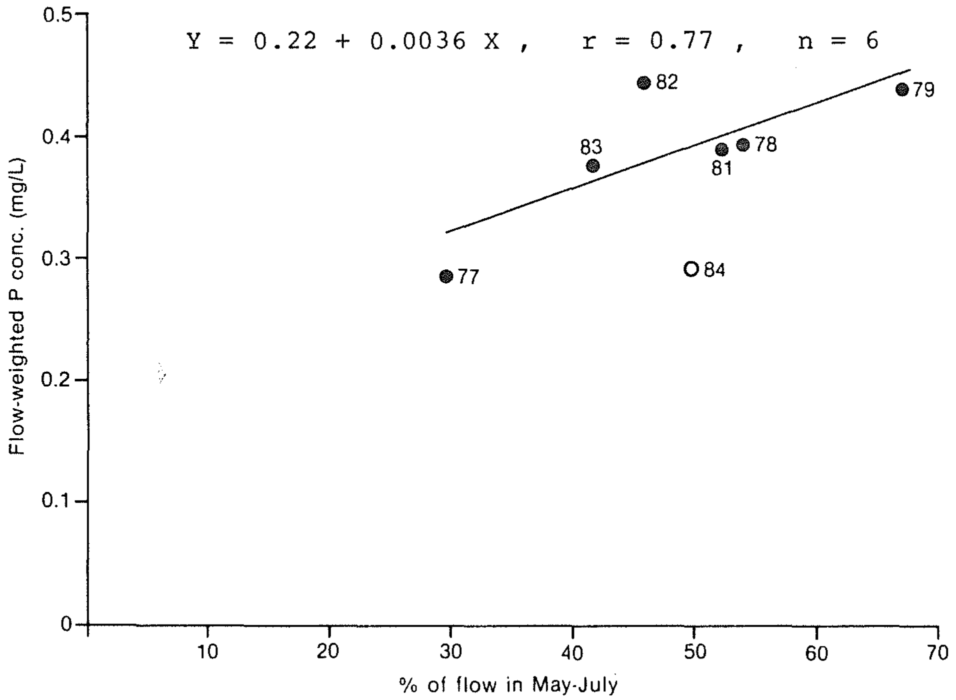

Figure 5 Regression of proportion of May - October flow in May - July in the Harvey River (1977-1983) on flow-weighted phosphorus concentration. The datum for 1984 was not included in the regression analysis.

"THE APPLICATION OF BAUXITE RESIDUE TO REDUCE PHOSPHATE LOSS IN THE PEEL-HARVEY CATCHMENT"

Don. J. Glenister, Manager-Residue Development, Alcoa of Australia Limited

ACKNOWLEDGEMENT

Research on the use of bauxite residue to amend sandy soils has been a team effort. Dr. Jim Barrow of CSIRO first suggested the idea and Sam Ward and other members of Alcoa's Environmental Department have set up and monitored the trials. Murdoch University has also carried out supporting research under the supervision of Dr. Guon Ho. The support of the Department of Conservation and Environment and the Department of Agriculture is also acknowledged.

INTRODUCTION

To overcome the seasonal algae problems which occur in the Peel Inlet and Harvey Estuary the flux of nutrients entering the waterbody via drains and rivers needs to be controlled. The current levels have to be reduced by 60 or 70 per cent and methods of controlling future inputs originating from alternative land uses in the catchments must be employed.

Research conducted by Alcoa over the past five years has confirmed that bauxite residue following neutralization by waste gypsum or ferrous sulphate can be mixed with sandy soils to improve moisture and fertilizer retention. This work was initiated following suggestions by Dr. Jim Barrow of CSIRO and early trials were aimed to demonstrate and measure the improved pasture yields from sandy soils following amendment with neutralized bauxite residue.

Improvements in phosphorus retention also suggested the method as a means of reducing the migration of fertilized applied phosphorus into the Peel Inlet-Harvey Estuary. A range of trials commenced over the past three years and continuing to date have been aimed at investigating the agronomic aspects of soil amendment and also to examine the method as a control strategy for the Peel-Harvey problem.

Last year's report by Warren Tacey summarised trials underway, described the methods utilised and discussed the feasibility, costs and timing of soil amendment as it applied to the Peel-Harvey problem. This brief report will summarise progress over the past 12 months and make some recommendations concerning the place that bauxite residue may play in the future management strategy for this complex problem.

GROWTH TRIALS

1984 was the second year of the small scale field trials on Gavin and Joel type soils in the Coolup area. Improvements in pasture yields were again measured on the Gavin type soils particularly at the higher residue application rates of 500-2000 tonnes per hectare. Legumes predominated on the amended soils whereas lower feed value grasses and weeds predominated on the unamended sand. The second year results on the Joel type soil were less encouraging. Yields were similar or slightly lower on the amended plots. Amendment of these soils should therefore be aimed at phosphorus retention rather than pasture improvement and therefore residue application rates would be low. Figures 1 and 2 illustrate the second year pasture growth results.

LEACHING TRIALS

Measurements of leachate properties from field columns set up in early 1983 continued during 1984. The results indicate that phosphorus leaching can be reduced by up to two orders of magnitude by bauxite residue amendment at rates of over 500 tonnes per hectare. Theoretically much lower rates should be sufficient to retain applied phosporus, however the practicalities of spreading and mixing need to be considered. Smaller scale column leaching experiments have also been carried out by Murdoch University under controlled laboratory conditions. Both gypsum and ferrous sulphate neutralized mud have been tested and the leachates characterised.

The environmental implications of soluble salts entering the ground water has not been considered at this stage.

LARGER SCALE FIELD TRIAL

Following the first year's data assessment from small scale field trials it was decided to proceed with a "form scale" trial in order to assess phosphate retention, leachate quality, erosion characteristics as well as crop performance and practical aspects of spreading and mixing. With assistance from the Department of Conservation and Environment and the Department of Agriculture a trial site was chosen on the Kielman property at Serpentine.

The area chosen was on a 22 hectare site from which two 8 hectare sub plots were defined for the comparative study (Figure 3). It was decided to delay residue incorporation for one year to enable the background condition of both plots to be studied. The surface drainage system was designed so as not to interfere with ground water flow. The paired catchments were divided by low bund walls which deflect surface drainage into a shallow drain and thence over a low V-notch weir.

The initial weir installation was found to lack sensitivity at low flows so it was replaced by a steeper V-notch. Flows of up to 15 m^3/hour were recorded from the Northern catchment. During 1984 both catchments were subjected to fertilizer application at a rate of 200 kg/ha (New Coastal Super). The measured total phosphorus loss via surface runoff from the Northern catchment was 1.8 kg/ha during the 1984 winter which is low when compared to values determined experimentally by Gerry Richie.

Ground water was sampled from a network of tube wells for phosphorus analysis and static ground water levels were monitored. The contour diagrams shown on Figures 4 and 5 show a reasonably well balanced condition between the two catchments. The proportion of well drained Gavin type sand and winter saturated Joel soil is also similar in each catchment.

Bauxite residue is currently being incorporated into the Northern catchment. The gypsum neutralized residue was produced at Kwinana for the purpose of the trial, solar dried, then excavated and trucked to the site. The material is being spread at a rate of 2000 t/ha on the Gavin sand and 500 t/ha on the Joel sand. The residue will be mixed into the surface soil using an elevating scraper and will be seeded and fertilized in the autumn.

Following incorporation a full comparative set of data will be obtained for both catchments from which the following assessment will be made:

- phosphorus loss
- hydrologic changes
- surface and ground water quality changes (dissolved salts, pH, suspended solids)
- crop productivity
- method for spreading and mixing residue into sand
- costs.

The large scale field trial will be assessed by the end of 1985 to determine the feasibility of the method as a means of improving agriculture on the poorer soils and/or controlling phosphate loss. Further studies on the longer term effects of soil amendment will continue on all the field trials for a number of years.

CONCLUSIONS AND RECOMMENDATIONS

- Prior work has shown that bauxite residue can be utilised to amend sandy soils to improve pasture production and prevent phosphate loss.

- The process of mixing bauxite residue into the topsoil may stabilise residual phosphorus present in the top 150-200mm of soil as well as intercepting newly applied phosphorus. Soil amendment is unique in this respect when compared to other management options.

  The efficiency of the treatment will depend upon mixing which is difficult to represent in the laboratory so further field trials are required to confirm the predictions.

- Column trials in the field and at Murdoch have helped to characterise the leachate quality from a range of red mud amended soils. Assessment of the effects of soluble salts entering the ground water and drainage systems, particularly at higher red mud application rates is required.

- Alcoa's Wagerup refinery is well located to provide residue for the Peel-Harvey catchments however changes in disposal practice will be required to produce suitable material. The acid effluent from the SCM plant could be utilised for neutralisation. A realistic minimum timeframe for implementation is five years.

- In 1983 the estimated cost of soil amendment was $4.00 to $5.00 per dry tonne of residue. These costs could not be supported by the alumina industry and large scale implementation would depend upon others supporting a significant proportion of the costs.

- Soil amendment is a large scale earthmoving operation and as such would be disruptive to local residents and the farmers concerned. In addition, changes in post amendment farming practice may be necessary. These aspects suggest difficulties gaining widespread acceptance with the present farming community. On the other hand, the method could be considered a prerequisite for redevelopment of the land for more intensive agriculture or other uses which may otherwise aggravate the present problems with the Estuary.

- Following completion of the large scale field trial this year, soil amendment should be reassessed to determine the scope of further work. Irrespective of additional work monitoring of all trial plots will continue to determine longer term performance.

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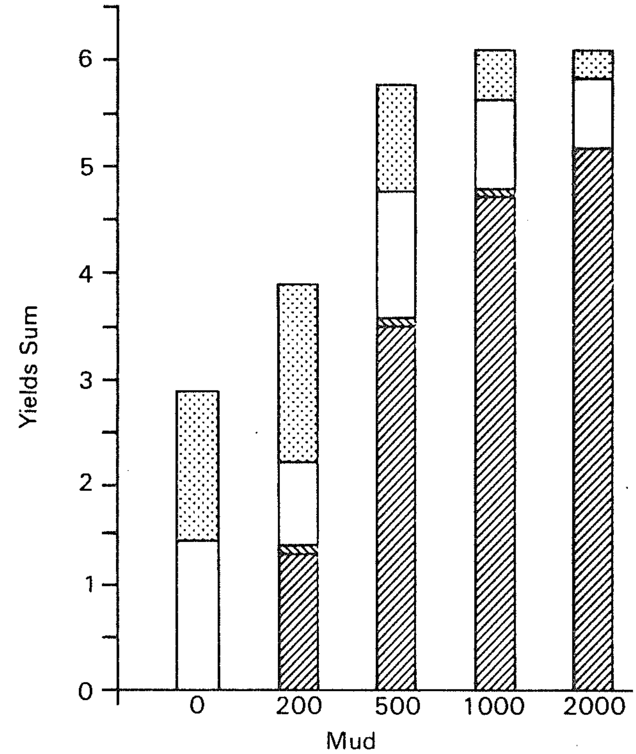

Figure 1. Growth Trial - Gavin Sand. 1984 yields T/Ha on Gavin Sand amended with different levels of red mud/gypsum (with Manganese Sulphate).

Legend: SPP Medic Sub-clover Weed Grass

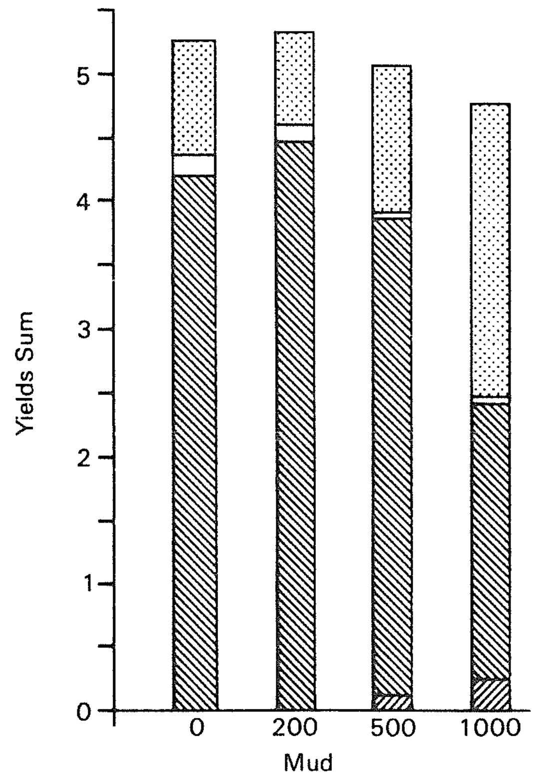

Figure 2. Growth Trial - Joel Sand. 1984 yields T/Ha on Joel Sand amended with different levels of red mud/gypsum incorporation at 2 x 100 Kg/Ha KCL application. (Pasture supplied in mid October four weeks after being evenly grazed to 5-10cm in height.)

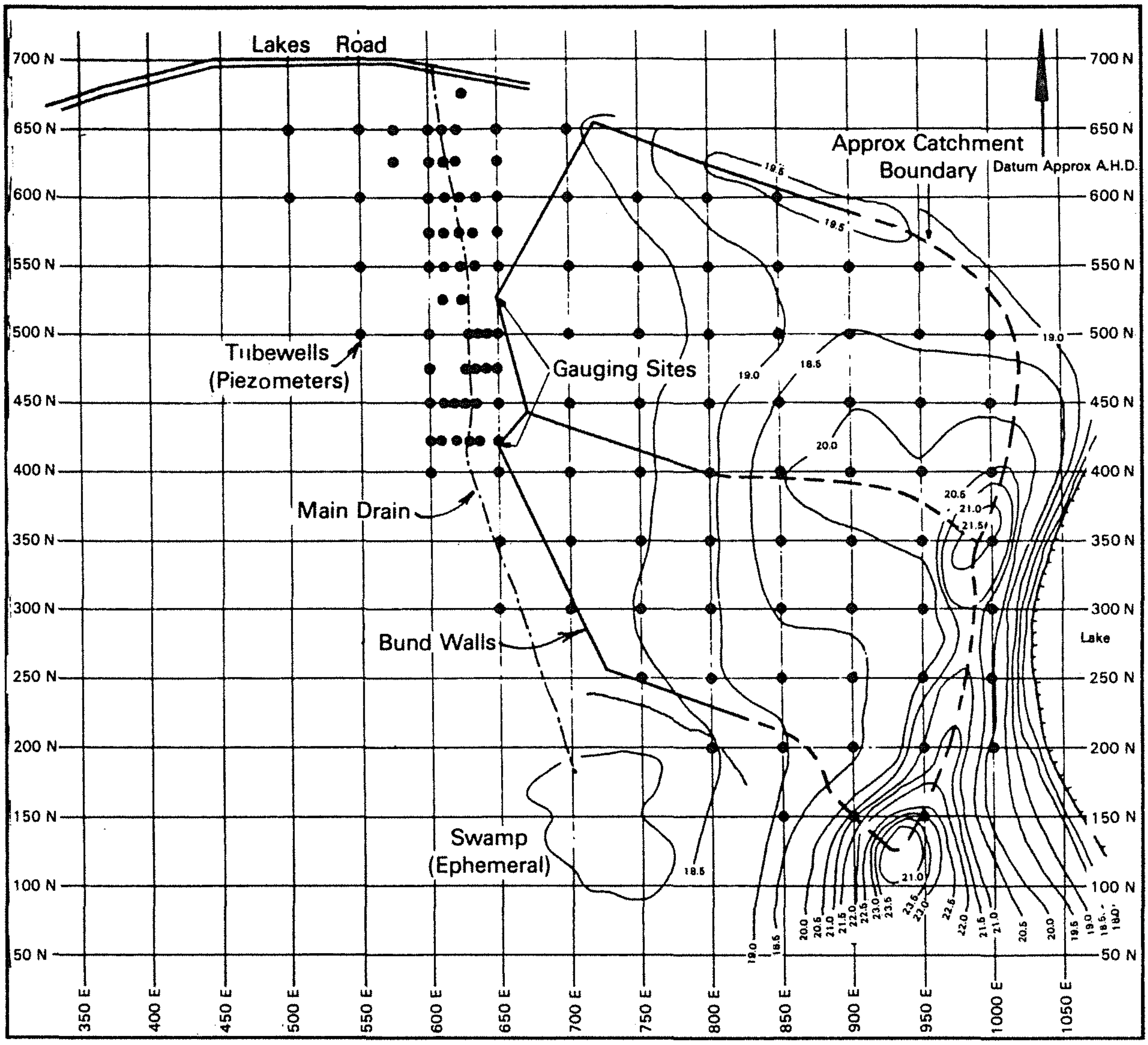

Figure 3: Plot Diagram, Kielman Trial, Serpentine

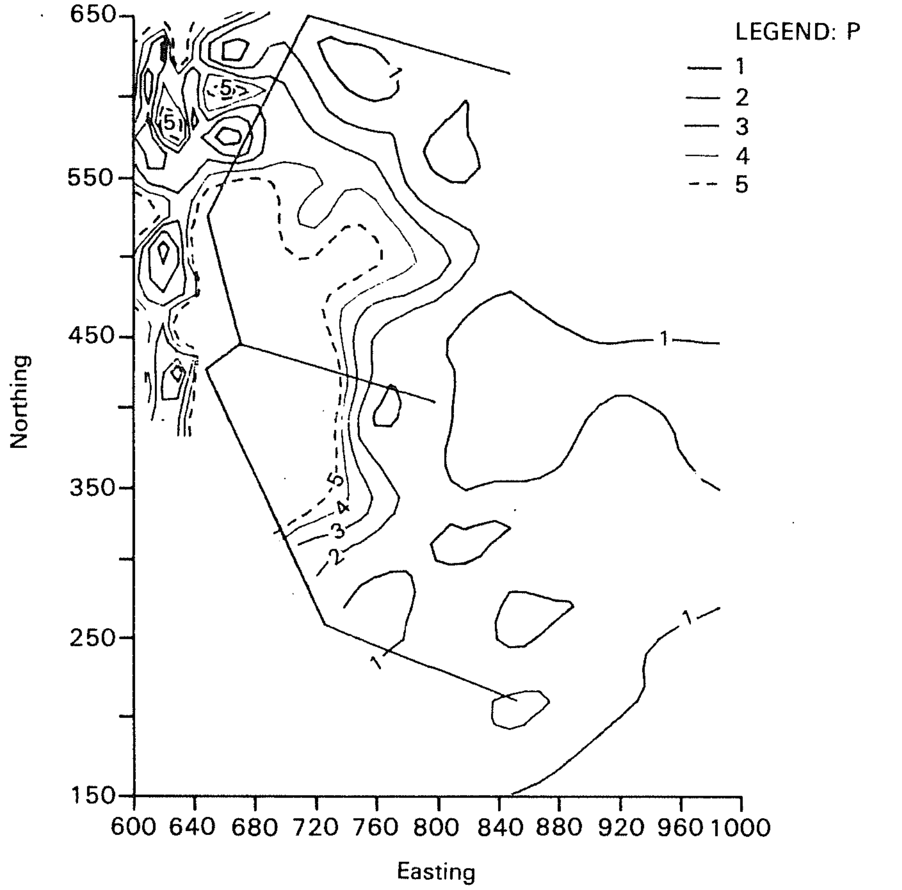

Figure 4. Plot of Phosphorus Concentration MG/L for 24 May 84. Data shown is for Deep Bores.

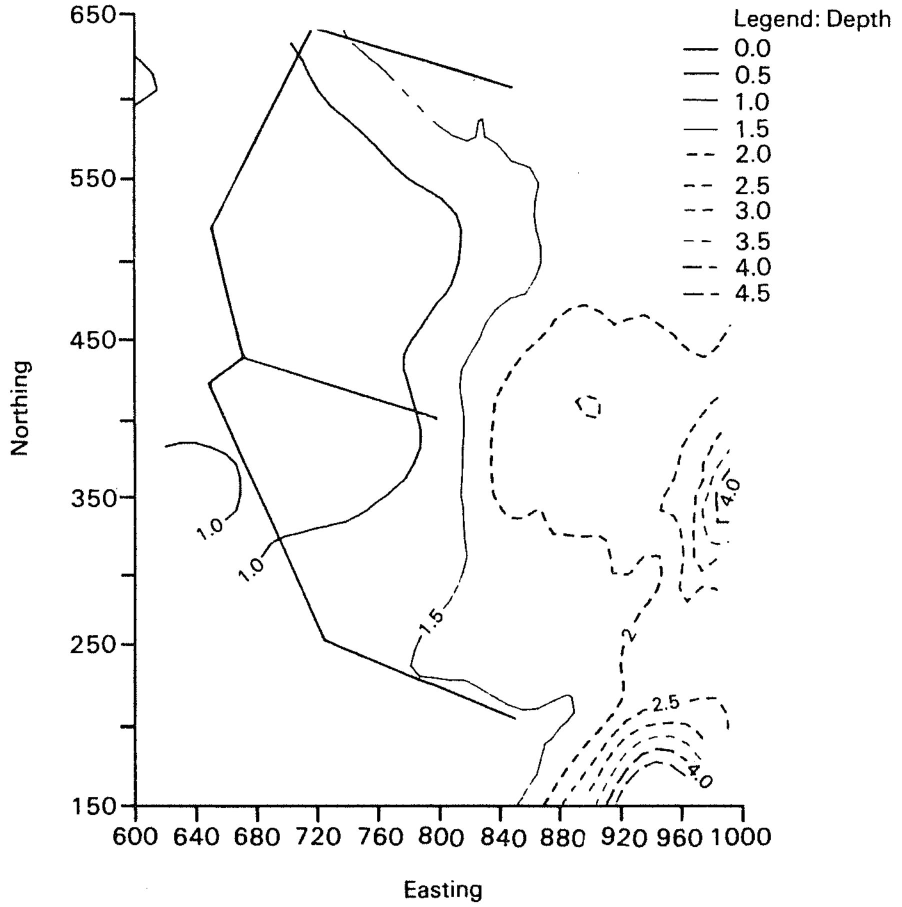

Figure 5. Plot of Depth from — 300m to Water for 23 Feb 84.

CONTROL OF RURAL POINT SOURCES IN THE PEEL-HARVEY CATCHMENT

Jane Chambers and Tim Wrigley*, Centre for Water Research (Botany Department), University of Western Australia, Nedlands WA 6009.

The major aim of this study was to assess the importance of eutrophic swamps and rural point sources in the transfer of phosphorus to the Peel-Harvey estuary. A survey was carried out of eutrophic swamps and several rural-based industries, and experiments are being undertaken on phosphorus uptake by artificial wetlands. It will be possible to use this information to pinpoint problem areas, and to design wetland 'filters' which may reduce the concentrations of phosphorus found in effluents derived from point sources.

EUTROPHIC WETLANDS

Approximately 200 wetlands exist in the Serpentine, lower Murray and Harvey River catchments. Of these, 69 were sampled at the end of the wet season in October-November 1984. At each swamp major nutrients were assayed, including ammonia, nitrate, orthophosphate, total phosphorus and total Kjeldahl nitrogen. A description of the vegetation of each wetland was recorded and a subjective ranking of 1-5 used to designate the state of degradation of each wetland, such that a ranking of 1 meant a natural wetland with a dense band of fringing vegetation whereas a ranking of 5 represented a wetland with little or no natural vegetation. Nearby drains and sites of overflow were also recorded both from fieldwork and study of topographic maps.

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Of the swamps sampled, 50% were in the Harvey River and associated drains catchment, 44% were in the Serpentine catchment, and the remaining 6% were in the lower Murray catchment. Of the 34 wetlands sampled in the Harvey catchment 7 wetlands had phosphorus concentrations greater than 1 mg l^{-1} (Fig. 1). The remaining wetlands in this catchment had phosphate concentrations ranging from 0.07 to 0.8 mg l^{-1} with a mean of 0.26 mg l^{-1}. The phosphate concentrations of wetlands in the Serpentine and Murray River catchments ranged from 0.06 to 0.8 mg l^{-1} with a mean of 0.17 mg l^{-1}.

It is useful to compare the data obtained from the survey with a table developed by Vollenweider (1971) to classify the trophic status of lakes (Table 1). This comparison relies on the concentrations of total phosphorus and inorganic nitrogen in the lake waters. With respect to total phosphorus 31% of wetlands fell into the eu-polytrophic status while 69% were polytrophic. However, when nitrogen alone was considered, because of the low inorganic nitrogen concentrations, all but 10 wetlands fell into the ultra-oligotrophic status. These 10 wetlands were represented in each of the other four categories.

Two wetlands were polytrophic and these were both located near the Peel-Harvey estuary, one next to the Murray River and one on the southern shore of Peel Inlet (Fig. 1). These two wetlands were the only ones with zooplankton blooms, perhaps indicating a relatively high algal productivity.

Despite the high phosphorus levels, the wetlands generally carry few phytoplankton, probably because of high concentrations of humic substances in the water; the low inorganic nitrogen levels may be due to microbial utilization. However, what concerns us here are the levels of phosphate in the wetlands, and whether they may lose significant amounts of this phosphorus to the estuary. As stated previously only 10% of the wetlands had phosphorus concentrations greater than 1 mg l^{-1}. Of those surveyed the highest concentration was the swamp near the Peel Inlet at 17 mg l^{-1}; the remaining six wetlands had concentrations around 2 mg l^{-1}. Total phosphorus levels were somewhat higher, phosphate representing 70-85% of the total phosphorus.

A study of the drainage from the surveyed wetlands revealed that 39% of swamps had drains running through or from them, 12% had drains nearby to which they might overflow, and 49% had no drainage. Wetlands with drainage are able to contribute phosphorus directly to the estuary by surface flow, while those without drainage are restricted to contributing by groundwater flow, if at all.

The majority of drains from swamps appear to flow only seasonally. During the survey carried out at the end of the wet season, only a few wetlands were contributing to drainage. Field data collected in the Meredith Drain subcatchment shows that swamps there overflowed in 1982 and 1983 but not in 1984. Tentatively, this suggests that swamp overflow may only be important in years of high rainfall.

An estimate of phosphorus export from the swamps can be made using data on overflow volumes collected in 1982 for the Meredith Drain subcatchment (Table 2). With an assumed swamp overflow of 10,000 m^3 per annum, using phosphate concentrations and drainage information obtained from the wetland survey, then from 90% of wetlands in the catchment a total of 200 kg of phosphorus would be exported to the estuary. The remaining 10% of wetlands (those having phosphate concentrations in excess of 1 mg l^{-1}) would export between 200 and 400 kg of phosphorus. This represents a maximum of 0.6

tonnes of phosphorus, less than 0.5% of the total average phosphorus input to the estuary, which was estimated as 143 tonnes per annum over the period 1977-1984.

Because the quantities of phosphorus being exported from the swamps are so low, it would appear that treatment of their effluent is not necessary.

It is interesting to note, however, that the majority of wetlands with phosphorus concentrations in excess of 1 mg l^{-1} had 'degradation rankings' of 4-5 (i.e. little or no natural vegetation). Correlation of phosphate concentrations and rankings showed that those wetlands with a ranking of 1 (natural wetlands) had a mean phosphate concentration of 0.03 mg l^{-1}, while those of ranking 5 had a mean concentration of 1.96 mg l^{-1}. However, variation within the rankings was high as phosphorus concentrations depend on the location of the swamp, i.e. whether it is in farmland and subject to fertilizer inputs.

POINT SOURCES

The Peel-Harvey catchment supports several rural-based industries including piggeries, sheep holding yards, intensive poultry farms, dairies, abattoirs and also has sewage treatment works. Of these, pigs, sheep, poultry and humans have been estimated to produce 122 tonnes of phosphorus per annum (Table 3). A large percentage of this amount is produced by a piggery and sheep-holding yard both in the Serpentine catchment, which produce up to 50 and 25 tonnes of phosphorus per annum respectively. Dairy cattle, numbering 17,500, produce an estimated 511 tonnes of phosphorus per annum; most of this is distributed over paddocks, and only a smaller proportion would be found in the milking sheds. Beef cattle and abattoirs are smaller contributors of phosphorus.

The accepted method of wastewater disposal used at the majority of these point sources is lagooning followed by spray irrigation. The prime purpose of lagooning is to reduce the BOD concentration of wastewater; a reduction in nutrient concentrations is a secondary consideration, although substantial reductions, particularly of nitrogen, can occur. Phosphorus is more difficult to treat in lagoons and spray irrigation of wastewater provides an opportunity for phosphorus to be absorbed in the soil or utilized by vegetation. Limitations arise with irrigation when:

1. wastewater is irrigated onto sparse natural vegetation or poorly managed crops, allowing little uptake of phosphorus;

2. rainfall increases runoff allowing nutrient-rich water to enter the drainage system;
3. excessive irrigation increases runoff.

The siting of several rural-based industries on Bassendean sands, which have a low capacity to absorb nutrients, accentuates the limitations of spray irrigation of wastewater.

The disposal of solid waste, which may contain up to 80% of the phosphorus in waste from a rural industry, may also pose disposal problems. Such waste is often used as landfill, but nutrients may be leached from this material into surface runoff and groundwater. At present, some solid waste material is used by farmers as fertilizer, but proper disposal of solid waste should be further investigated.

Current waste disposal methods appear to be inefficient in phosphorus removal from point source effluent. It is not known what proportion of the phosphorus load produced by point sources (more than 122 tonnes) is lost to groundwater or drainage to the estuary. This might well be investigated. The possibility of upgrading effluent at present used in spray irrigation, by flowing it through beds of wetland plants, is being examined. Experiments are being carried out to determine the efficiency of these biological filters to remove phosphorus from water at a range of phosphorus concentrations and flow rates as part of a research programme on phosphorus dynamics of wetlands. If it is found that wastewater disposal methods do require upgrading then this information can be used to design filters for specific point sources.

Although, at the moment, only two major point sources exist in the catchment these produce a large amount of phosphorus. There is clearly a possibility that other point sources may be established in the catchment, for example cattle feedlots, abattoirs and other piggeries. An increase in the number of point sources will increase the potential phosphorus export to the estuary and it is important that proper controls on the nutrient quality of point source effluent are instigated before this occurs.

SUMMARY

1. Eutrophic wetlands - 90% of the sampled wetlands in the catchment had phosphate concentrations less than 1 mg l^{-1}. Phosphate concentrations were generally higher in the Harvey catchment where 7 of the wetlands surveyed had phosphate levels greater than 1 mg l^{-1}. Approximately 50% of the wetlands were capable of contributing to drainage but phosphorus export from the swamps would be less than 0.5% of the total annual phosphorus export to the estuary. Treatment of wetland effluent does not appear necessary.

2. Point sources - Several point sources exist in the catchment, the most

important being a piggery and a sheep-holding yard in the Serpentine catchment which, together, produce up to 75 tonnes of phosphorus per annum. The total phosphorus production by point sources is more than 122 tonnes per annum. The methods of waste treatment at point sources need to be investigated in relation to their efficiency at removing phosphorus. Experiments on biological filters to improve point source effluent are being undertaken.

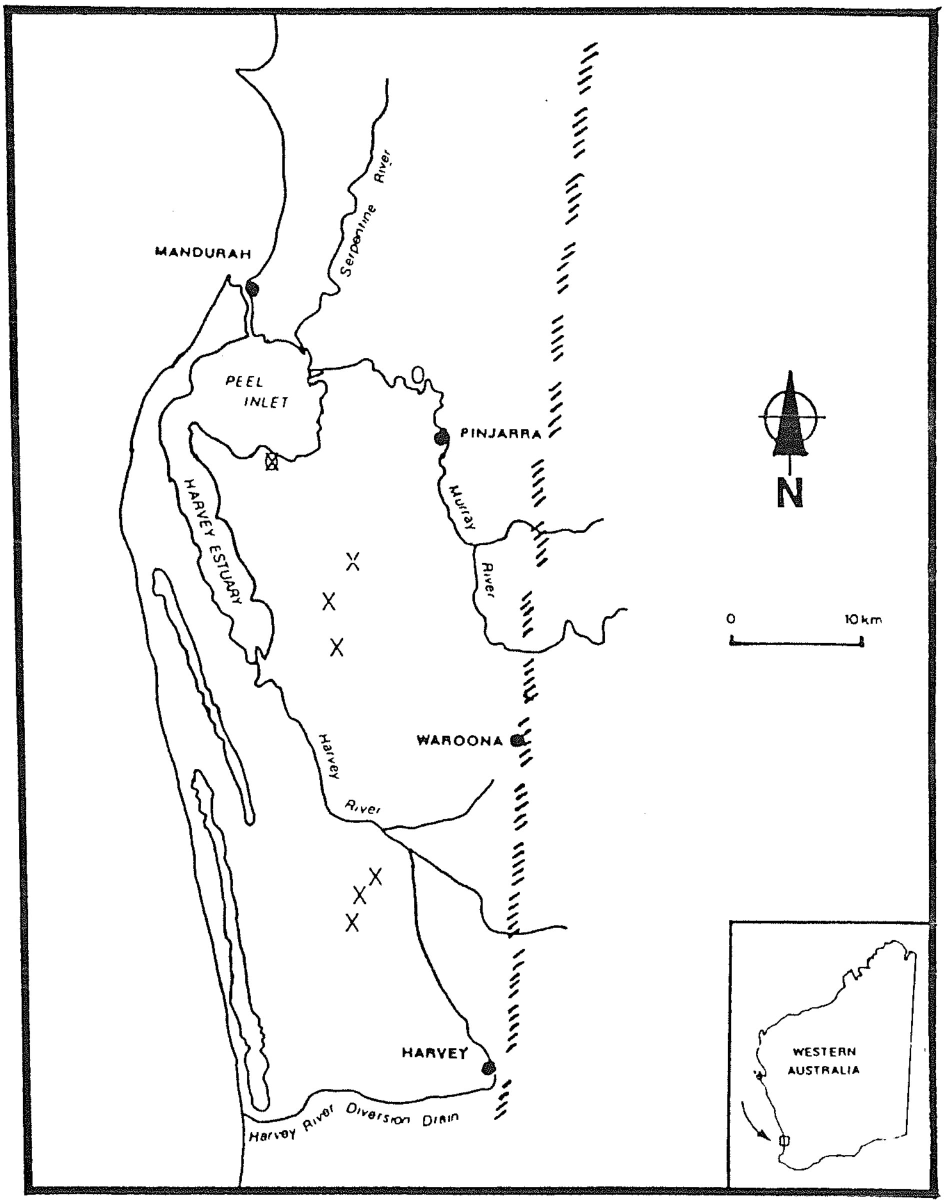

FIGURE 1 : LOCATION OF POLYTROPHIC WETLANDS AND WETLANDS WITH PHOSPHATE CONCENTRATIONS > 1 MG L^{-1}.

KEY : O - POLYTROPHIC WETLANDS

X - WETLANDS WITH PHOSPHATE CONCENTRATIONS > 1 MG L^{-1}

Table 1

A system for the classification of lake trophic status
Vollenweider R.A. (1971)

Category	Total Phosphorus ($\mu\ l^{-1}$)	Inorganic Nitrogen ($\mu\ l^{-1}$)
Ultra-oligotrophic	0 - 5	0 - 200
Oligo-mesotrophic	5 - 10	200 - 400
Meso-eutrophic	10 - 30	300 - 650
Eu-polytrophic	30 - 100	500 - 1500
Polytrophic	>100	>1500

Vollenweider, R.A. (1971). Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with particular reference to Nitrogen and Phosphorus as Factors in Eutrophication. Organisation for Economic Co-operation and Development, Paris.

Table 2

Calculation of possible phosphorus loss from swamps through overflow

Assuming 50% of wetlands overflow into drains

At 10,000 m^3 $annum^{-1}$

At $\bar{X}$ PO_4 conc of 0.26 mg l^{-1} - Harvey)
0.17 mg l^{-1} - Serpentine/Murray) 90% of wetlands
2-4 mg l^{-1} - Remaining 10 of wetlands

Then 90% of wetlands would export 200 kg PO_4 (total)
10% " 200-400 kg PO_4 (total)
600 kg PO_4 maximum

Table 3

Phosphorus production by point sources

Phosphorus production Tonnes P $annum^{-1}$	Point Source
63	Pigs (including a piggery producing 50 tonnes P $annum^{-1}$)
32	Sheep (including a sheep-holding yard producing 25 tonnes P $annum^{-1}$)
18	Sewage Treatment Works
9	Poultry Farms
122	

Data calculated from information assembled by Humphries and Croft (1983) for phosphorus production per animal. The figure does not include dairies, abattoirs, etc.

CONTROL OF CLEARING AND DRAINAGE

IN COASTAL PLAIN CATCHMENTS OF THE PEEL-HARVEY ESTUARY

BY

P.B. BIRCH

INTRODUCTION

Eutrophication of the Peel-Harvey Estuary has been primarily caused by a significant increase in the inflow of nutrient-rich water from coastal plain catchments. This has resulted from clearing for agriculture followed by the development of an extensive improved drainage system and finally the (unintentional) excessive use of phosphatic fertilizers on sandy soils. These factors combine to efficiently transport a vastly increased amount of phosphorus into the estuary. An initial analysis of old CSIRO data and study team data by Humphries and Henderson (1980) indicated that phosphorus input via the Serpentine River (and presumably the Harvey River) had increased by 5 to 10 times from the early 1950's to the late 1970's.

The network of drains on the coastal plain catchments was necessary for agricultural development because in its natural state it was characterised by extensive swamps and open water wetlands (clearing, of course, only added to the surface water problem). Therefore crops and pastures were flooded during winter and yields suffered. Viable agriculture could only develop if drains were built which would efficiently remove excessive standing water from paddocks within about 2 days after heavy rainfall in winter.

HISTORY OF DRAINAGE

The early drainage problems on the coastal plain resulted in demands from farmers which culminated in the Land Drainage Act of 1900. Prior to this drainage works were undertaken to a limited extent under the direction of the Manager of the Agricultural Bank.

The Land Drainage Act, 1900, provided for the declaration of Drainage Districts and the appointment of boards. These were to advise the Government on matters relating to the drainage of lands, levy rates for the maintenance of such works, and to provide a sinking fund and interest on the capital cost. The Government was empowered by the Act to spend up to $60,000 for the construction of main drains, etc.

From 1901 - 1907 drainage works were conducted by the Lands and Surveys Department, and by 1907 some 81 miles of drains had been completed. Some early successes were noted in the Department's records such as ... "the effect has been to transform the Harvey River into a clear and continuous waterway from being a mere succession of timber-choked pools connected by dense ti-tree swamps".

After 1907 drainage came under the control of the Public Works Department and drainage works continued. After World War I there was the Soldier's Settlement Scheme and in 1932 construction of the Harvey River Diversion Drain commenced, to be completed 4½ years later.

By 1940 most of the major drains had been constructed. Only the Hymus, Robert Bay, Mealup, Curtis and Meredith Drains were constructed after this date. However of significance has been the upgrading of design and reconstruction of the existing drains which has taken place since then.

Prior to 1950 drains were generally designed to discharge about 20 cu ft/s/1000 acres. From 1950 - 1967 this was increased to 35 cu ft/s/100 acres, and in 1967 to 70 cu ft/s/1000 acres, (D. Vodanivic, PWD, pers. comm.). This last change represents a 100% increase in the potential efficiency of the drains.

In 1968 a program of upgrading all the drainage systems in the South West was commenced to cater for the increased runoff due to farmlands development. Notable inclusions in these works were improvements to the Harvey River Main Drain (1970 - 77).

Thus the agricultural development of the coastal plain catchments has been one of gradual clearing associated with improvements in drainage to relieve local flooding and increase agricultural productivity.

However whilst a significant level of agricultural production has been achieved there have been negative environmental effects namely:

- more rapid and increased flow of nutrient - rich water into the estuary
- reduced area of wetlands and hence less places suitable for water fowl during summer.

THE PRESENT SITUATION

At present approximatley 90% of the coastal plain catchments have been cleared for agriculture and an extensive network of PWD drains has been constructed. Details of uncleared sandy land are given in Table 1.

EFFECTS OF FURTHER CLEARING AND DRAINAGE

If all the uncleared land was cleared and drained and it is assumed that it leached phosphorus at the same rate as the Harvey River catchment then increases in inputs to the estuary would be as follows:

(a) Deep grey sands 15,690 ha x 4 kg P/ha* = 63 Tonnes P

(b) Sand over clay 6,480 ha x 2.3 kg P/ha* = 14.9 Tonnes P

Total = 78 Tonnes P

* 4kg P/ha = loss rate from cleared area of Meredith drain, 1983.

** 2.3 kg P/ha = loss rate from cleared area of Mayfields "G" drain, 1983.

The total input of phosphorus to the estuary in 1983 was 206 Tonnes, thus the potential increase is up to 38% assuming the Meredith drain and Mayfields "G" drain to be representative of deep grey sands and sand over clay soils, respectively. However, the calculation also assumes that farmers do not modify their fertilizer practices on the newly-cleared land, thus the estimate is definitely on the high side. It also assumes that all of the land is worth clearing. Much of the land could be low quality Gavin sands and not worth clearing in the first place. Furthermore some of the uncleared land will be needed for stock shelter.

If an allowance of say 50% is made for poor soils and for stock shelter the estimated increase could be reduced to about 18%. Furthermore if farmers adopt sound fertilizer practices based on soil tests the estimated input could be reduced by another 50%, ie a total increase of up to about 9%.

However, all the above calculations further assume that the newly cleared land will be drained at the same density as the Mayfield and Meredith drains. There is evidence which indicates the density of drainage (the total length of drains per unit area) is an important factor in facilitating phosphorus loss to drainage. This is illustrated by the long-term flow records of the Harvey and Serpentine River catchments in Table 2.

The two catchments have almost identical areas, similar distribution of soil types and similar rainfall. However, the amount of runoff and phosphorus discharge in the Harvey catchment is about double that of the Serpentine catchment. That is on a unit area basis about twice as much water but with the same phosphorus concentration is discharged from the Harvey catchment. This is in almost exact proportion to the difference in drainage density in the two catchments. Therefore, it is reasonable to hypothesize that the greater number of artificial drains constructed in the Harvey catchment are facilitating a greater proportion of surface and sub-surface runoff relative to rainfall. This in turn facilitates of a greater loss of phosphorus from the store of phosphorus in the enriched pasture root zone (0-10cm). Presumably there is greater loss of water through evapotranspiration and to deep groundwater where the drainage density is less. For phosphorus, there is greater opportunity for both accumulation in top soil and/or deep leaching where drainage density is less. These effects are illustrated conceptually in Figure 1.

Taking all of the above into account then the final predicted increased input of phosphorus could be less than 9% if newly cleared land is not as extensively drained the Meredith and Mayfields "G" sub-catchments. Virtually no increase could occur if none of the newly-cleared land required drainage and was relatively remote from existing drains.

The only other way in which increases in phosphorus input could occur is if existing drainage networks are substantially upgraded. However, according to Senior Officers of PWD there is not expected to be much demand for this now given all the improvements which have already taken place between the early 1950's and the late 1970's.

RECOMMENDATIONS

Given the serious eutrophication problems of the estuary no further increases in phosphorus input from clearing and drainage of the catchment should take place. However in view of practical problems, any measures to control clearing and drainage should be only considered for adoption if a significant increase (more than 5 - 10%) in phosphorus input could occur. Present assessment indicates that significant increases may not occur but this is subject to several assumptions which need to be checked. It is therefore recommended that a small working group comprising of officers from PWD, Agriculture and DCE be set up to further evaluate effects of clearing and drainage and to develop long-term policies. Such policies would of course have to take into account the effects of the proposed Dawesville Cut should it be constructed. In the interim the Department of Agriculture should continue to encourage the maximum practical use and maintenance of existing uncleared areas for stock shelter, and any proposals for new drainage works should only proceed subject to the policies developed by the working group.

ACKNOWLEDGEMENTS

Text on the history was derived from notes by S Mollett. Helpful information was supplied by Messrs D Vodanovic, G Lloyd and A Middleton of the Public Works Department.

Table 1. Uncleared areas of sandy soils in coastal plan catchments[1]

Catchment	Deep Grey Sands (ha)	Sands Over Clay (ha)	Total	(% of Total Area)
Serpentine	11,300	2,100	13,400	(14.7)
Murray	990	2,100	3,090	(4.4)
Harvey & Drains	3,400	2,280	5,680	(5.7)
Total	15,690	6,480	22,170	(8.5)

1. Data supplied by C Croft and R Humphries

Table 2. Relationship between density of drainage and mean annual runoff in the Harvey and Serpentine River systems 1977-83.

	Harvey River[1]	Serpentine River
Undammed catchment (km^2)	990	910
Drainage density (km/km^2)	0.84	0.42
Long-term mean rainfall (mm)	1010	996
Runoff ($10^6 m^3$)	220	112
(m^3/ha)	0.22	0.12
Runoff/Rainfall (%)	22	11
Phosphorus discharge (tonnes)	80	38
(kg/ha)	0.81	0.42
Phosphorus conc. (mg P/L)	0.36	0.34

1. Including minor drains.

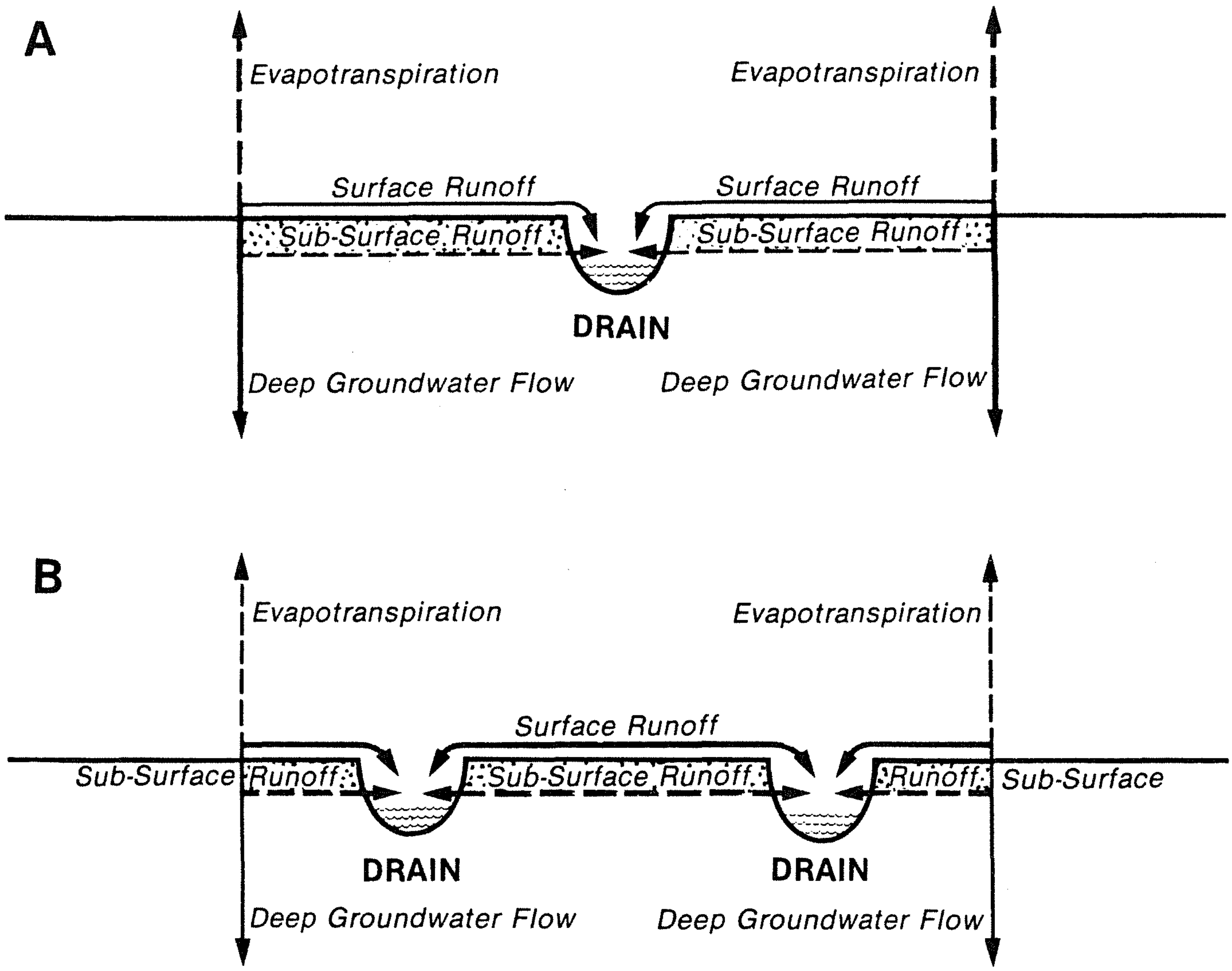

Figure 1 Conceptual model of effect of increased drainage density on runoff. It is hypothesised that with increased drainage density (Fig. 1B) that surface and near sub-surface runoff is greater whilst evapotranspiration and deep groundwater flow is lesser.

THE CATCHMENT MANAGEMENT PROGRAM - WHAT IT WILL ACHIEVE

by P B BIRCH

SUMMARY

The aim of the Catchment Management Program is to minimise phosphorus losses to drainage whilst maintaining and, if possible, enhancing profitability of agriculture on the coastal plain.

The major component of the strategy is the Fertilizer Modification Campaign but this will be aided by several supplementary measures. These include minimising or controlling phosphorus runoff from further clearing and drainage and from rural point sources. In addition planting *Eucalyptus globulus* for woodchipping looks potentially promising and could play a useful role in the long term (10-15 years). Spreading bauxite residue could also reduce phosphorus leaching in the long term but its future is in some doubt because of high spreading costs and pasture establishment problems on Joel sands.

The best available information at present suggests that the Fertilizer Modification Campaign can achieve a reduction in phosphorus runoff of up to about 20-30% in the short term (3 years) by minimising direct fertilizer runoff and by up to 60% in the long term (10 years) when the excessive reserves of phosphorus in the soil have been depleted. This assumes that the present high (80%) level of farmer co-operation is maintained and there are no major long-term changes in the economics of beef and sheep farming.

THE CATCHMENT MANAGEMENT PROGRAM - WHAT IT WILL ACHIEVE
by P B BIRCH

In its broadest terms the Catchment Management Program aims to minimise agricultural phosphorus losses to drainage through implementing appropriate management practices whilst maintaining and, if possible, enhancing profitability of coastal plain agriculture. The major management question which arises from this is by how much can phosphorus losses be reduced and how soon will this reduction be achieved? To answer this question we need to assess what each potentially viable management option can achieve and over what period.

At this time it is clear that the Fertilizer Modification Campaign will be the most practically effective measure and I will devote most of my remarks to this. Firstly, however, I would like to comment on the role of the supplementary measures.

SUPPLEMENTARY MEASURES

1) Bauxite Residues
The work done so far by ALCOA has demonstrated that neutralized bauxite residue can effectively retain applied phosphorus and improve water relations on the sandy ridges (Gavin sands). The measure also provides for disposal for two industrial wastes if the residue is neutralized by acid effluent from SCM (Laporte) at Bunbury or gypsum from CSBP. On the other hand we still know little of the ultimate fate of suplhate which will be leached from the residue and there are problems with establishing plants on the Joel sands. In addition the residue is costly to spread and large quantities would not be available for at least two years.

In view of these problems it is therefore not likely that this option will play a major role if the proposed Dawesville channel is constructed.

2) Control of Rural Point Sources
A major potential problem exists if more than a few percent of the phosphorus produced by intensive piggeries, feed lots and sheep yards enters drainage. For example one large intensive piggery produces about 50 tonnes of phosphorus per annum and the liquid waste is discharged onto Bassendean sands. The fate of this phosphorus and that from other major industries needs to be determined and if problems exist new techniques need to be developed. Using reed beds amended with bauxite residue appears to offer an effective method.

3) Control of Clearing and Drainage
There is potential for an increase of up to 38% in phosphorus loading to the estuary to occur if all the remaining sandy country on the coastal plain was cleared and drained. However this is most unlikely as at least some of the land will be too poor to clear and some is required as stock shelter. Using realistic assumptions an increase of less than 10% can be calculated.

However these assumptions need to be checked and long term policies determined by an inter-departmental working group. If increases in phosphorus loading of more than 5-10% are anticipated, controls on clearing and drainage should be considered but final judgements should take into account the effect of the proposed Dawesville channel.

4) Planting *Eucalyptus globulus*

Economic analysis suggests that planting *Eucalyptus globulus* could be profitable for farmers as an alternative to pasture but there is still some doubt about the validity of the data. Nevertheless there is sufficient good evidence to warrant further investigation. Planting these trees on key parts of farms could well provide a useful contribution to controlling phosphorus losses in the medium to long term.

The Fertilizer Modification Campaign

There are two ways in which phosphorus loss to drainage may be reduced by the Fertilizer Modification Campaign. Firstly, in the short term (2-3 years) a substantial reduction in direct fertilizer runoff could be achieved. Secondly in the long term (10 years) a further gain could be achieved from the gradual depletion of the excess store of phosphorus in soils.

This is illustrated in the phosphorus budgets of the Talbot and Stacey experimental sites (Figures 1 and 2) which typify the situation for deep grey sands and sand over clay soils, respectively, before the Fertilizer Modification Campaign. The budgets show that phosphorus has been applied at rates exceeding the combined losses from deep leaching, runoff and agricultural export. As a result phosphorus has been gradually accumulating in the top soil for many years and at present these reserves could sustain maximum growth of pasture for at least 3 years at the Talbot site and probably 5 years or more at the Stacey site.

The other major features of the budgets are a:

- runoff of phosphorus into drainage is three times higher from the deep sand site compared to the sand over clay site.
- The major part of phosphorus runoff at both sites is from the soil store rather than from direct fertilizer runoff.
- Approximately 34% of phosphorus runoff was derived from direct fertilizer loss at the Talbot site; 19% at the Stacey site.

Direct Fertilizer Runoff

A reduction in direct fertilizer runoff is possible because most farmers are now applying much more fertilizer phosphorus than is required. Soil surveys show that about 70% of paddocks require no added phosphorus for at least one year, and more likely for up to five or more years. Most of the farmers involved are presently applying 13-18 kg P/ha.

Estimating the reduction in phosphorus runoff from not applying 13-18 kg P/ha of superphosphate is difficult because the runoff depends on time of application, weather conditions and soil type and these factors vary from farm to farm and year to year. However limited experimental evidence as shown in Figures 1 and 2 suggests that direct fertilizer losses could account for up to about 20% - 40% of total phosphorus runoff. Even so to achieve this requires the availability of an appropriate sulphur fertilizer for sandy soils. In practice the required sulphur has been applied via superphosphate. Highest priority needs to be given to developing this fertilizer for commercial release next season.

In the long term all paddocks will require a maintenance application of Coastal Superphosphate. However leaching losses from this should be about 50% of that from superphosphate and the rate of application about 50% of present. Thus direct fertilizer losses of phosphorus could be reduced by 75% in the long term, ie about 15% - 30% of total runoff losses.

Reduction of the Excess Soil Store

As already stated most farmers have an excess store of phosphorus in their top-soil. The rate at which these over-fertilized soils can be depleted depends on:

- soil type
- fertilizer history
- type of agriculture
- type of drainage

Deep grey sands will tend to deplete more rapidly than sand over clay soils because their capacity to store plant-available phosphorus is less and they generally have a shorter fertilizer history. Fertilizer history is important because it reveals the total amount applied and the period over which applications have been made. Soils with long histories of over-fertilization will tend to have the largest store, but on the other hand the retained phosphorus which was applied many years ago is less available to plants than recently applied phosphorus.

The type of agriculture is important because, for example, cutting hay removes up to 10 - 12 kg P/ha per year whilst pasture grazing removes only about 2 - 4 kg P/ha per year.

The reduction in phosphorus runoff which will result from depletion of the excess store of phosphorus is not certain. It is of course reasonable to expect that less phosphorus runoff would occur because phosphorus concentrations in the soil solution should be less. No longer would there be the luxury levels of today which are in excess of plant demand.

Laboratory work on deep grey sands suggests that phosphorus leaching from typically over-fertilized paddocks (14 ppm bicarbonate - P) could be reduced by 40% after "depletion" to growth responsive levels of bicarbonate - P (8ppm). Further work needs to be done on the sand over clay soils before any reasonable estimate can be made. However, early laboratory results do show that reductions in leaching of up to 50% can be achieved albiet after long (5 - 10 year) "rundown" times. Therefore as a preliminary conclusion we can expect that phosphorus runoff will be reduced by up to 50% in the long term after the excess bank has been depleted. When this is added to a long term reduction of about 20% from direct fertilizer losses a long term total reduction of up to 70% appears achievable for sandy soils.

At present the heavy (clay and loam) soils contribute approximately 20% of the total phosphorus load to the estuary from the coastal plain. These soils too have been over fertilized and soil surveys show that 75% do not respond to added phosphorus. Whilst the depletion time for these soils would be very long at least the direct fertilizer losses can be reduced. These soils are naturally sufficient for sulphur so a reduction in phosphorus runoff could be achieved by simply not applying superphosphate. Limited evidence suggests that this reduction in direct fertilizer loss could be similar to that of sand over clay soils (ie about 20%) depending on seasonal conditions.

The total reduction possible therefore is:

$$(0.70 \times 0.80) + (0.20 \times 0.20) \times 100\% = \underline{60\%}$$

In summary therefore the best available information at present suggests:

- a reduction of up to 20% - 40% in 3 - 5 years
- a reduction of up to 60% in 10 years

These reduction rates assume continuity of the present high co-operation from farmers, the availability of appropriate fertilizers and no significant increases in phosphorus runoff from further clearing and drainage and from rural point sources. A further caution is sounded if a permanent increase in the profitability of beef farming occurs which may increase the pressure for higher fertilizer use.

The role of *Eucalyptus globulus* is not yet clear but, in the long term, it could complement the fertilizer campaign and at least give greater confidence for achieving the highest estimated reductions in phosphorus runoff, and possibly even add to these reductions.

Acknowledgements: I would like to thank all members of the Catchment Studies Group from whose work this report is derived. I would also like to thank Kevin McAlpine for his research into the phosphorus budgets.

Talbot Site (Deep Grey Sands)

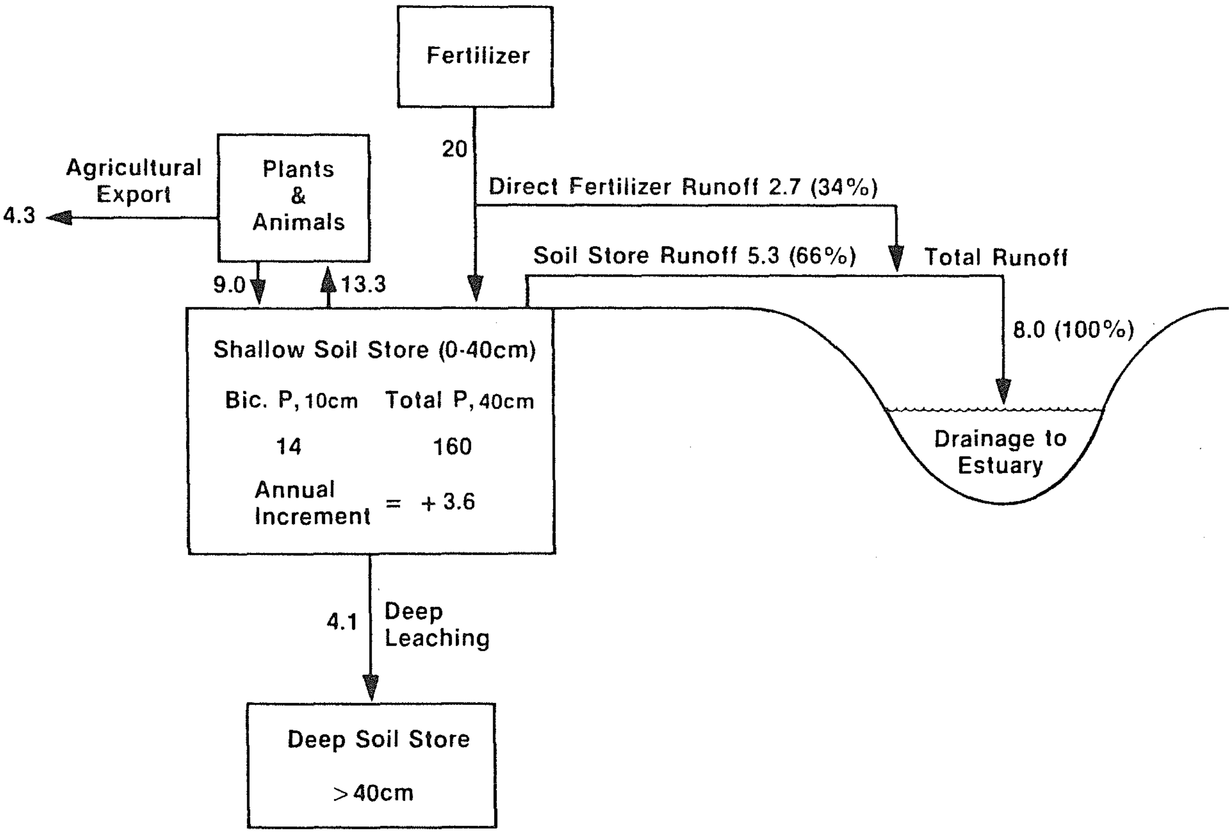

Figure 1. Total Phosphorus Budget in kg P./ha/yr

Stacey Site (Sand Over Clay)

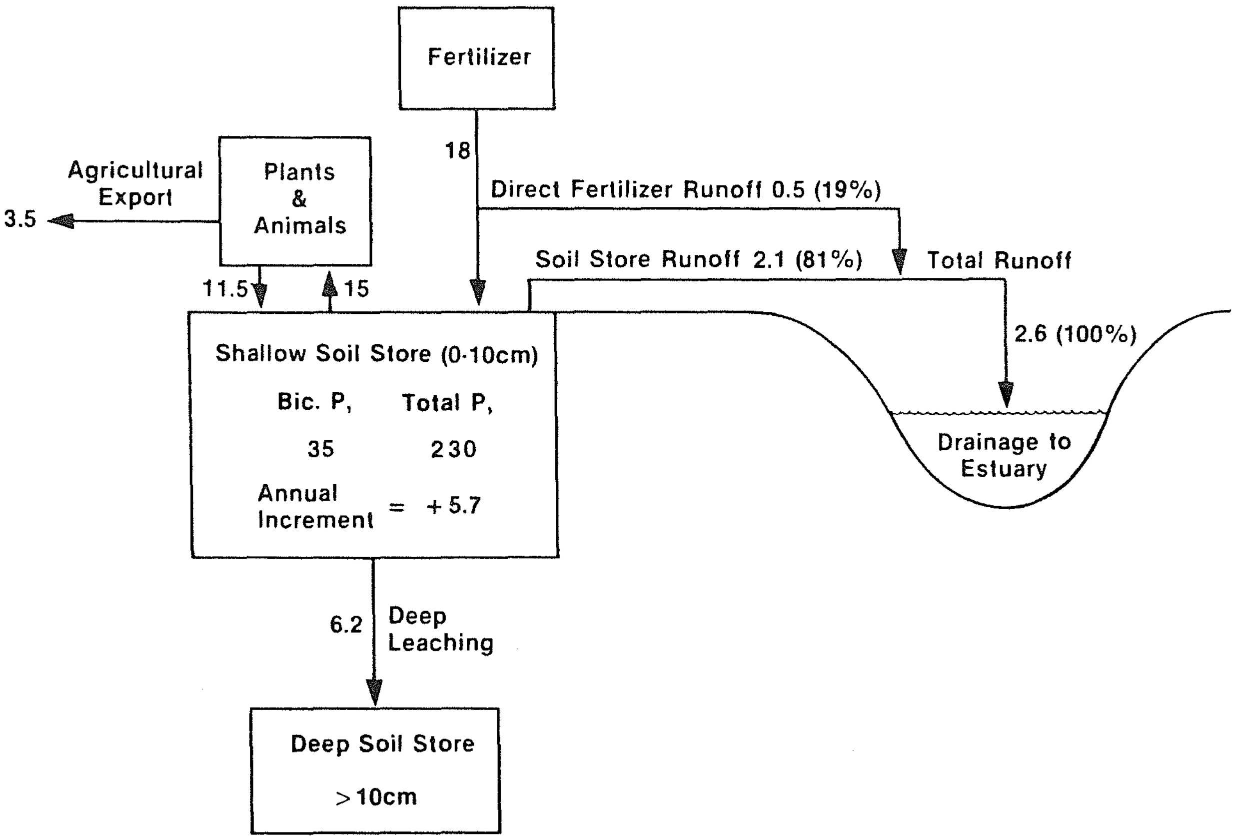

Figure 2. Total Phosphorus Budget in kg P./ha/yr

1985 PEEL-HARVEY ESTUARINE SYSTEM SYMPOSIUM

Introduction Day 2

Ernest P. Hodgkin

On this second day of the Symposium our aim is to review the proposed management measures for the estuary and decide both what we think they will achieve by way of reducing the algal problems and what other changes they will make to the estuarine ecosystem. We will also need to consider whether we believe these other changes will be beneficial or detrimental and, in the final session we examine their implications for the human population. It must be obvious to everyone here that the further we go along the chain from the phosphorus molecule and bulldozers to fish and birds the more difficult it is to predict what will happen to elements of the ecosystem - but this we have to do to the best our ability if we are to ensure that we make rational judgments about management.

When it comes to interpreting the potential response of the human population we are, of course, into a whole new dimension where the familiar scientific rules no longer apply.

Yesterday's discussions have given us a measure of by how much and how soon we can expect to decrease the input of phosphorus to the estuary. Now we have to assess how the ecosystem will respond to this reduced input. Will this reduced input of phosphorous be enough alone to tip the balance against the present excess of phosphorus input to the estuary over all losses? The 1984 experience (the big *Nodularia* bloom despite the small input of phosphorus) suggests to me that it wont be enough. So we have to examine very carefully the potential of other measures, especially the proposed Dawesville Channel.

First, I want to peddle a line which may seem irrelevant to solving the urgent problem of eutrophication, but it is one which I believe to be vital to a proper appreciation of the true nature of the estuary and what are the best long term solutions to its problems.

The history of eutrophication is a short one, and there is a much longer history of changes which have predisposed the estuary to this condition. Putting Peel-Harvey in the context of other estuaries of the south west it can be seen to be on the road to extinction through natural, geomorphological processes (Reference Hodgkin and Kendrick, 1984, DCE Bulletin 161) though construction of the training walls at the mouth (in 1967) have given it a slight reprieve. One can signal a number of turning points in the geologically short history of the estuary.

Even before the estuary was flooded by the rising sea level 6-7000 years ago the site of the proposed Dawesville Channel appears to have been blocked by a sand dune, which was subsequently lithified.

For a time Peel Inlet was a marine embayment, rather like Oyster Harbour today, with a rich invertebrate fauna.

Then rather abruptly about 3-4000 years ago exchange with the ocean became obstructed, just as has happened to other estuaries of the south west, and the diverse, more marine fauna was replaced by a restricted fauna, dominated by a few strictly estuarine species, albeit abundant in numbers of individuals.

From this time until 1967 there were occasions when exchange with the ocean was interrupted completely for several months at a time.

Drainage of the coastal plain, starting in 1900, followed by damming of the hills catchments and, from 1945, the addition of large doses of phosphorus, are man's contribution to deterioration of the ecosystem.

Even though the estuary was a 'healthy' one 40 years ago, it was already vulnerable to the impact of an unfamiliar large dose of plant nutrients. It is now even more vulnerable because of the demands of the rapidly increasing human population.

What then is or was the 'natural environment' of the Peel-Harvey estuary which we should be trying to conserve? Is it that of 1985, 1950, 1829, or perhaps 3000 years B.C.?

I suggest that if the Dawesville Channel is made it will convert one senescent estuarine ecosystem into two healthy estuaries. This, at the cost of having to manage geomorphological processes which, sooner or later, are going to have to be managed.

In the 1890s C.Y. O'Connor blew up the bar at the mouth of the Swan and dredged out the tidal delta to make the Port of Fremantle. This increased tidal exchange in the estuary of the Swan, which I am certain has greatly benefited the present estuarine ecosystem.

At this point it is perhaps well to say just what I understand by 'healthy' and 'unhealthy' as applied to the estuary.

I consider the Peel-Harvey estuary to be 'unhealthy' because primary production (or plant biomass) is so greatly in excess of secondary production (or the consumers) plus export to the ocean that there is a gross excess of plant biomass which cannot be recycled within the ecosystem without harm to it. (The result is too much hydrogen sulphide and too little dissolved oxygen in the water). In a 'healthy' ecosystem there is no such imbalance.

Having said that, let me emphasise what I am sure is familiar to most here, namely, that there are two distinct algal problems, which to some extent will require different solutions.

The problem of Nodularia blooms only dates from 1980. The blooms are seasonal epidemics of a single species of blue-green alga (bacteria).

Duration of the blooms is delimited mainly by physical environmental factors, temperature and salinity. (Fig 1).

The organism is independent of a river supply of nitrogen because of its ability to fix atmospheric nitrogen and probably for this reason has the edge over green algae and diatoms because of the low N:P ratio (in water from coastal plain rivers).

It is these factors and the geometry of the estuary which favour Nodularia more in Harvey Estuary than in Peel Inlet, though it flourishes in both.

The smell of Nodularia is nauseating, but shore accumulations present a relatively minor problem. However, collapse of the blooms causes serious depletion of dissolved oxygen and consequent death of the fauna.

Green algae, on the other hand, contribute the bulk of the weed accumulations which have been the major perceived problem of the estuary since the late 1960s.

Unlike Nodularia, the algal problem is endemic, with a number of species having replaced one another over the years (probably in response to the increasing phytoplankton blooms and consequent decrease in light available to benthic plants). They grow throughout the year, even though growth is slowed by low winter temperatures and reduced light.

In Harvey Estuary they are disadvantaged by the relatively low light levels there but flourish in Peel Inlet with its generally clearer water.

However, to quote Rod Lukatelich, "There is not [now] any significant correlation between river nutrient load and macroalgal biomass. Light [not phosphorus] is probably the limiting factor controlling macroalgal growth in Peel-Harvey". But there are still plenty of algae accumulating on the beaches.

Thus the estuary has two different diseases, with different aetiology and with differing significance according to the perspective from which they are viewed, and which in some respects require different cures.

Rob Atkins put it well the other day when he said: "In terms of the ecology of the estuary, Nodularia is the more important, but in respect to the response of the human population the macroalgae are the more important problem".

This brings me to the subject of management recommendations, and I think we will find as the discussions proceed that we are faced with a dilemma as to our priorities: for improving the eclogy or pleasing the people. They could require different measures, at least for a short term solution.

Fortunately, while it is our job to decide what the different management measures will achieve, it is not our responsibility to decide what will be done.

Yesterday the Minister reminded us of the management objective: to reduce the algal nuisance to acceptable levels without further damage to the estuarine environment.

'Acceptable levels' were defined as: Nodularia blooms should not occur more frequently than once in five years on the average, and weed should not foul beaches near populated areas.

The measures by which these can be achieved are listed in Bulletin 170. They have different proximate objectives; ameliorative, curative, or preventive, with different time tags on them and different contributions to make to solving the algal problems. How do we see the potential of these now, in the light of the 1984 studies?

Yesterday we discussed measures to reduce the phosphorus at source, today we have to assess what these and others can achieve and, especially, what the Dawesville Channel will do.

While we are concerned primarily with what these measures will do for the ecology of the estuary, you will remember that there were two constraints to the management objectives: that they should not cause loss of production to the fishery, or to agriculture in the catchment.

These are social judgments and it is interesting that on the ABC Science Show program (9 Feb, 1985) the spokesman for the Conservation Council questioned the validity of the second, but made no comment about the first.

The fertilizer modification campaign is designed to ensure no loss of agricultural production. It is much more difficult to predict how management measures will affect the fishery, if the acceptable levels of algal abundance are to be achieved.

The last session today is concerned with the social scence: how people view the estuary, the management measures, especially the Dawesville Channel, what their effect will be on the area, and also the economics of management.

It was not in our brief to consider such matters, but we do need to be aware of them, even if only because an ERMP will have to be prepared if the Dawesville Channel is to go ahead.

Such considerations should not affect our judgment about how best to solve the ecological problems of the estuary, but they will be certain to influence decisions elsewhere as to what will be done to solve them.

What I hope we will gain from today's discussions is a clearer picture of the advice we must now tender to Government as to the best way to clean up the algal problems of the estuary - that is the brief of the study team.

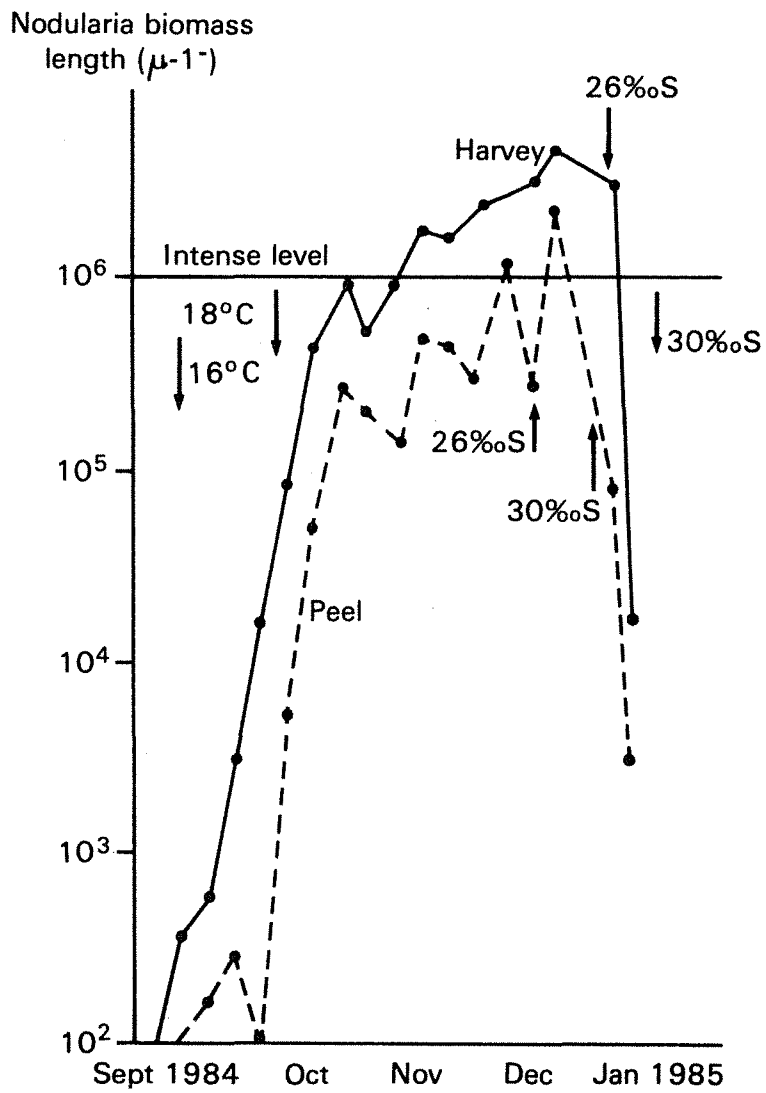

Figure 1. Mean Nodularia biomass in Peel Inlet and Harvey Estuary (surface to bottom integrated samples).

HARBOURS AND RIVERS BRANCH

PUBLIC WORKS DEPARTMENT

WESTERN AUSTRALIA

PEEL/HARVEY ESTUARINE SYSTEM - PHASE 3 STUDY

INVESTIGATIONS INTO THE DAWESVILLE CHANNEL OPTION

PAPER PRESENTED AT

SYMPOSIUM 19 & 20 FEBRUARY 1985

BY

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1. INTRODUCTION

In November 1984 the Department reported (Reference 1) on engineering investigations into alternative means of increasing nutrient discharge into the Ocean. This involved various schemes for dredging the Mandurah Channel, dredging and flow training works between the Murray River mouth and the Mandurah Channel, and the Harvey Estuary to Ocean Channel (or Dawesville Channel) concept.

In February 1984, the feasibility study of management options (Reference 2) came out in favour of the Dawesville Channel as one of eight preferred management options considered worthy of more detailed investigation and possible implementation.

Accordingly, over the past twelve months, the majority of the Department's Phase 3 Studies effort has been directed towards further investigation and refinement of the Dawesville Channel concept. However, some work has also been undertaken to further analyse data gathered on the alternative Mandurah Channel dredging options in order to assess the most cost effective strategy in the event that the Dawesville Channel does not proceed.

2. DAWESVILLE CHANNEL SITE

The Dawesville Channel site is located at the northern end of the Harvey Estuary (Figure 1). This is the only feasible location because of the reasonably short distance (1.5 km) between the Estuary and Ocean.

Other advantages of this site are that while most of the land is in private ownership the majority is zoned rural or at least has undergone very little urban development, and the average elevation of the land is low which reduces the volume of excavation to create the channel.

3. DAWESVILLE CHANNEL ALIGNMENT OPTIONS

Two channel alignments were considered throughout the investigation (Figure 2). The South Channel alignment is similar to the route considered in the Phase 2 Study and has the advantage of involving a smaller volume of rock excavation.

The North Channel alignment, however, is the preferred option because it involves a smaller total volume of material to be excavated, it provides for an entrance location which will enhance the natural bypassing of littoral sand, and it provides a better balance of land available for redevelopment between the north and south sides of the channel.

4. SCOPE OF INVESTIGATION

Engineering investigations into the Dawesville Channel were required to assess a number of different aspects of the proposal including:

- Ground conditions
- Ocean wave climate
- Littoral drift
- Channel flow velocities
- Tidal prism
- Channel stability
- Ocean entrance stability

- Effect on Mandurah Channel
- Effect on other public utilities
- Spoil disposal options
- Development opportunities
- Development costs

Channel flow characteristics and the tidal prism were ascertained from the results of the mathematical modelling conducted by the Centre for Water Research as part of the Phase 3 Study.

Other aspects of the Dawesville Channel proposal such as the estuary response are not discussed in this paper as they are more the concern of others who are reporting on the implications for the estuarine environment of constructing the Dawesville Channel.

Although the investigations of the last twelve months have considerably improved our knowledge, there are still some areas where further studies will be required for detailed design and tendering purposes if the Dawesville Channel is to proceed. These are dealt with separately throughout the paper and summarised in Section 15.

5. GROUND INVESTIGATIONS

The ground investigation programme commenced in August 1984 when survey lines were cleared. These can be seen in the aerial photo shown as Figure 1 and in the diagram shown as Figure 3. They were located to provide ground information along each of the alternative routes, the North and South Channel alignments.

The programme included the following activities:

- Seismic surveys along the centre lines of the two alignment options conducted by the Geological Survey of Western Australia.

- Diamond drill and auger core holes located along the centre lines.

- Penetrometer tests along the survey lines.

- Vibrocores in the estuary.

- A hydrographic survey together with hand probes to determine the bathymetry and to locate the rock surface of the near-shore ocean areas.

- Geological mapping of the land area by Geological Survey of Western Australia.

- Preparing a 10 metre grid of levels over the land area from photogrammetrically contoured plans.

The cores were logged and analysed by the Engineering Research Station of the Public Works Department and by the Geological Survey of Western Australia (Reference 3). The results of all the investigations showed the ocean entrance to consist mainly of moderately indurated limestone, the land area to be sand overlying slightly to moderately indurated sandstone and limestone, and the estuary material to be sand close to the shore changing to organic muds and clays towards the centre of the estuary.

An assessment of the degree of difficulty of excavating the varying types of rock through the land section found them to be either rippable using a D9 bulldozer with single tine or marginally diggable using a front-end loader.

For each of the channel alignment options the quantities of each type of material to be excavated are shown in Table 1 below. The quantities have been calculated assuming the channel to be 4.5 metres deep below Australian Height Datum (AHD) with a bottom width of 200 metres and side slopes of 1 in 5.

TABLE 1 QUANTITIES TO BE EXCAVATED (Cubic Metres)

		SOUTH CHANNEL	NORTH CHANNEL
1. Ocean Entrance			
	Sand	25,000	
	Rock	55,000	70,000
	Sub Total 1	80,000	70,000
2. Land Section			
	Sand	2,450,000	2,020,000
	Rock	1,610,000	1,840,000
	Sub Total 2	4,060,000	3,860,000
3. Estuary			
	Sand	340,000	340,000
	Mud and Clay	168,000	168,000
	Sub Total 3	508,000	508,000
Total Volumes		4,648,000	4,438,000

6. COST OF EXCAVATION

Based on a review of the ground information and recent large contracts involving similar conditions, Maunsell and Partners Pty Ltd developed a cost estimate for excavating the preferred North Channel option (Reference 4).

It was determined that the most economical method of excavating the channel would be to use a large cutter suction dredger; the total estimated cost of excavation being $17.5 million. However, if the ground could be adequately dewatered so that conventional land based plant could be employed efficiently then the estimated cost of excavation would reduce to $15.0 million.

The estimate of $17.5 million has been accepted for the budgetary cost purposes of this feasibility study. However, further ground investigations will be necessary if the Dawesville Channel option is to proceed. A practical trial to determine whether conventional land based plant can efficiently excavate the rock to the required depth together with more extensive coring of the land and estuary areas will be necessary for tendering purposes.

The excavation of a channel solely for flushing the estuary is all that can be provided within the estimate of $17.5 million. It was assumed that excavation spoil would be dumped as economically as possible in the low lying areas immediately adjacent to the channel. No provision has been made for compaction to provide a filled area suitable for redevelopment. In section 12 a proposal for ultimate development of the channel and the surrounding area is discussed.

7. OCEAN ENTRANCE AND CHANNEL STABILITY

The stability of a channel is affected by a number of natural forces acting upon it. Some of the major factors are littoral sand moving along the coast, wave climate at the ocean entrance, and tidal flows. Per Bruun (Reference 5) says that:

> "The stability of tidal inlets on littoral drift shores should be interpreted as a "dynamic stability" by which the elements involved attempt to maintain a situation characterised by relatively small changes in inlet geometry including location, planform, and cross sectional areas and shape".

Three simple criteria were used to indicate whether or not the channel will be stable. They are tidal flow velocity, the change in velocity with changing channel cross sectional area, and the ratio of tidal prism to littoral drift.

Per Bruun (Reference 5) suggests that the maximum flow velocity for a stable channel will be in the range 0.9 to 1.2 metres per second. Foster and Nittim (Reference 6) say "Australian inlets on the open East Coast indicate a range of 0.6 to 1.1 metres per second". The mathematical modelling work by the Centre for Water Research has predicted maximum velocities in the range of 0.8 to 1.2 metres per second which appear to be of the right order.

To determine the effect of varying the cross sectional area on the maximum velocities in the channel the mathematical model was run with the channel depth set at 4.0 metres, 4.5 metres, and 5.0 metres. For typical 14 day winter and summer periods the maximum daily ebb tide velocities were averaged and these mean velocities were tabulated for each channel depth. The results are shown in Table 2 below. Although the velocities are very similar there is a slight increase in velocity with decreasing depth, which is indicative of a stable channel cross section condition.

TABLE 2 STABILITY OF CHANNEL CROSS SECTION

CHANNEL DEPTH (m AHD)	MEAN MAX VELOCITIES (Ebb) SUMMER (m/sec)	WINTER (m/sec)
- 4.0	0.705	0.783
- 4.5	0.696	0.771
- 5.0	0.683	0.737

According to Per Bruun (Reference 5) the ratio of tidal prism to littoral drift is an important indicator of a tidal inlet's ocean entrance stability and the extent to which a sand bar is likely to form at the entrance. It is also an indicator of the overall stability of the channel.

Tidal prism (P) is the volume of water flowing through the inlet channel in a half tidal cycle during a period of maximum tidal range. Littoral drift (M) is the total volume of sand moving past the entrance during a full year. For diurnal tides, as is the predominant situation for this part of the coast, the resultant ratio must be halved. Per Bruun (Reference 5) indicates that stable inlets typically have P/M (P/2M for diurnal tides) ratios greater than 150 and unstable inlets which are characterised by shallow sand bars (such as Mandurah) have low P/M ratios of about 50. Ratios were calculated for the Dawesville Channel for three winter and three summer days covering a range of tides from large to small. Although the larger tides are of primary importance for determining stability it was wise to also consider the situation for periods of small tidal range. The calculated ratios (P/2M) are shown in Table 3 and these indicate good stability and the likelihood that there will be no predominant sand bar at the entrance.

Tidal prisms were calculated from the results of the mathematical modelling. Littoral drift has been very hard to determine but Foster and Nittim (Reference 6) concluded that "Longshore transport likely to result in siltation of the proposed channel is probably small". For this stability exercise a figure for littoral drift of 50,000 cubic metres per annum has been used and it is considered that this figure is conservative.

TABLE 3 CHANNEL STABILITY - TIDAL PRISM TO LITTORAL DRIFT RATIOS

Day	P/2M (Summer)	P/2M (Winter)
2	230	380
6	200	210
11	140	160

8. ENTRANCE TRAINING WALLS

The shape of the entrance training walls have been chosen to enhance natural bypassing of littoral sand and to minimise the penetration of ocean waves into the channel. Figure 4 shows the proposed shape of the North Channel ocean entrance.

The longer southern training wall is located on a reef spur with the head of the groyne located in about seven metres of water (below AHD). Its curved shape will cause ebb tide flows to accelerate against the southern training wall and this should allow any littoral sand deposited within the entrance to be transported in a northerly direction, where wave action could then carry it back onto the beach on the north side of the entrance. In this way natural bypassing of littoral material will be enhanced.

Although the South Channel ocean entrance alignment could be shaped in a similar manner it is somewhat disadvantaged by the reef spur referred to previously being immediately to its north. Firstly, the northerly movement of sand flushed from the entrance is likely to be retarded by the reef and secondly wave action around the reef area would present an increased navigation hazard for small craft using the entrance.

Limited bathymetric information and theoretical wave refraction analysis was used to provide the design information for the training walls. However, for detailed design and tendering purposes further hydrographic surveys and wave monitoring will be necessary.

9. EFFECT ON NORTHERN COASTLINE

Although the proposed channel's ocean entrance has been designed to enhance natural bypassing of littoral sand, the training wall is likely to trap a proportion of the nett northwards movement of sand for some years. On a coastline with wide sandy beaches one could expect the entrapment of littoral sands at the entrance to lead to erosion of the down-drift beaches.

However, as can be seen in figure 5, the coastline to the north of the channel entrance is controlled by rocky headlands every few hundred metres. Even if the littoral drift was interrupted, the coastline as far north as Mandurah could not recede to any appreciable extent because the rocky headlands act as natural groynes securing the existing beaches.

10. EFFECT ON MANDURAH CHANNEL

Results of the mathematical modelling by the Centre for Water Research show that neither the tidal flow velocities nor the flow rates in the Mandurah Channel will be affected to any appreciable extent by construction of the Dawesville Channel. The rate of siltation of the Mandurah Channel should not, therefore, become any worse if development of the Dawesville Channel proceeds.

11. ROAD BRIDGE

The Old Coast Road will need to be bridged across the Dawesville Channel. A concept plan for this bridge has been prepared by the Main Roads Department and is shown in Figure 6.

The 330 metre long two lane bridge and its associated roadworks are estimated to cost $4.4 million.

High natural abutments provide about 9 metres of clearance under the bridge for small craft. This should be adequate for most vessels which can be used on the shallow waters of the Harvey Estuary.

12. ULTIMATE DEVELOPMENT OF DAWESVILLE CHANNEL

Although the Dawesville Channel was concieved as a means of flushing the estuarine system and solving the eutrophication problem, it is difficult to contemplate a project of this magnitude without giving some consideration to further development opportunities for recreation and other purposes. With this in mind a Town Planning Consultant was engaged to advise on ultimate development of the channel and its environs to maximise the benefit to the public of developing the Dawesville Channel.

Figure 7 shows the marina and land development proposals contained in the preliminary concept plan (Reference 7) prepared by the consultant, Ralph Stanton Planners. The additional cost of further excavation and recontouring of the land area together with compacting fill areas to make them suitable for residential type development is estimated to be $7 million. This amount includes no allowance for marine retaining walls and boat mooring facilities, nor for any of the costs associated with subdivision development and services.

13. TOTAL COSTS TO DEVELOP THE DAWESVILLE CHANNEL

The estimated total cost of implementing the Dawesville Channel option on the favoured North Channel alignment is as follows:

	$ MILLION (Dec 1984)
Land Acquisition	2.2
Ocean Entrance Training Walls	4.0
Excavation and Reclamation	17.5
Bridging and Roadworks	4.4
Minor Works	1.0
Contingencies	1.0
Surveys and Supervision	0.9
	$31.0 MILLION

This estimate of $31.0 million is considered to be accurate within a tolerance of plus or minus 10 per cent.

As discussed in Section 12 the estimate above should be increased by $7 million to provide for ultimate development in accordance with the town planning consultants preliminary concept plan.

14. MANDURAH CHANNEL DREDGING

If the Dawesville Channel were not to proceed, an analysis of the various possible dredging combinations shown in Figure 8 has revealed (Reference 8) that the most cost-effective programme of Mandurah Channel dredging work comprises:

a) Dredging a channel 200 metres wide by 2.95 metres deep (below AHD) through the upstream delta, following Sticks Channel and involving 1,305,000 cubic metres at a cost of $3.4 million.

and

b) Dredging downstream of the traffic bridge to a depth of 3.75 metres (below AHD) involving 594,000 cubic metres at a cost of $3.2 million.

An attractive alternative is to proceed in stages by dredging both sections of the channel to depths which are shallower by one metre at an initial overall cost of $3.1 million.

Mandurah Channel dredging will not harm the Estuarine System, yet it would increase the navigable water area, create useable islands by spoil disposal, and increase the interchange of water between the Estuary and Ocean. It could be implemented more quickly than the Dawesville Channel, and monitoring its effects would provide information that could be used to check mathematical model predictions about implications to the estuarine system of developing the Dawesville Channel.

15. FURTHER INVESTIGATIONS REQUIRED

Before either the Mandurah Channel or Dawesville Channel proposals can proceed to the detailed design and tender stage further investigations will be required. For the Mandurah Channel some ground investigations and some further consideration of the most suitable and acceptable spoil disposal locations is required.

For the Dawesville Channel, however, far more investigation is required before reaching the tender stage. The work required includes:

a) More detailed ground investigations along the preferred channel Alignment.

b) Further hydrographic surveys.

c) Wave monitoring to determine the wave climate more accurately for design purposes.

and

d) Physical modelling of the entrance training walls.

To carry out these investigations and complete detailed design work, in order to progress this proposal to the tender stage, would take a further twelve months.

16. SUMMARY

Dredging of the Mandurah Channel in an initial stage costing $3.1 million would provide improved small craft navigation within the Channel and Peel Inlet, it would improve marine flushing of Peel Inlet, it would provide an opportunity to monitor the effects of relatively small dredging improvements on estuarine water quality during the detailed investigation and design phase for the Dawesville Channel, and it could proceed within a few months of approval.

The Dawesville Channel can be developed at a cost of $31.0 million to satisfy the needs for improved estuarine flushing. The coastline between the Dawesville Channel entrance and Mandurah would not erode, nor would Mandurah Channel siltation become any worse as a result of development of the Dawesville Channel. Siltation of the Dawesville Channel Ocean entrance should not be a problem. Further investigations are necessary to bring this proposal to the tender stage and these are likely to take up to twelve months.

A preliminary concept plan for the ultimate development of the Dawesville Channel designed to maximise public benefit from the Channel and its environs has been prepared. The additional cost of this proposal compared to the basic channel would be substantial with further excavation, recontouring and full compaction alone costing $7.0 million.

17. RECOMMENDATIONS

It is recommended that dredging of the Mandurah Channel in an initial stage costing $3.1 million should proceed immediately.

It is also recommended that detailed investigations and design for the Dawesville Channel should proceed immediately and, provided that the current investigations being reported by others confirm the Dawesville Channel as part of the preferred solution to the eutrophication of the Peel/Harvey estuarine system, it is recommended that the Dawesville Channel be constructed.

18. REFERENCES

1. PUBLIC WORKS DEPARTMENT, "Peel/Harvey Estuarine System - Phase 2 Study, Engineering Investigations, Dredging And Flow Training Options", Report No. CIS 83/3, November 1983.

2. DEPARTMENT OF CONSERVATION AND ENVIRONMENT, "Potential For Management Of The Peel/Harvey Estuary", Bulletin 160, February 1984.

3. J R GOZZARD, GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, "Harvey Estuary Ocean Channel Geological Assessment", Report EG 291, 1985.

4. MAUNSELL & PARTNERS PTY LTD, "Proposed Dawesville Channel Cost Estimate", February 1985.

5. PER BRUUN, "Stability of Tidal Inlets, Theory And Engineering", Elsevier Scientific Publishing Company, 1978.

6. D N FOSTER AND R NITTIM, WATER RESEARCH LABORATORY, UNIVERSITY OF NSW, "Sedimentation Aspects Of The Proposed Harvey Estuary To Ocean Channel - Stage 1", Report No 85/01, January 1985.

7. RALPH STANTON PLANNERS, "Dawesville Channel, Preliminary Concept Plan", February 1985.

8. PUBLIC WORKS DEPARTMENT, "Peel/Harvey Estuarine System - Phase 3 Study, Engineering Investigations, Dredging Of The Peel Inlet Ocean Entrance Channel", Report No CIS 84/4, June 1984.

FIGURE 1. SITE OF DAWESVILLE CHANNEL

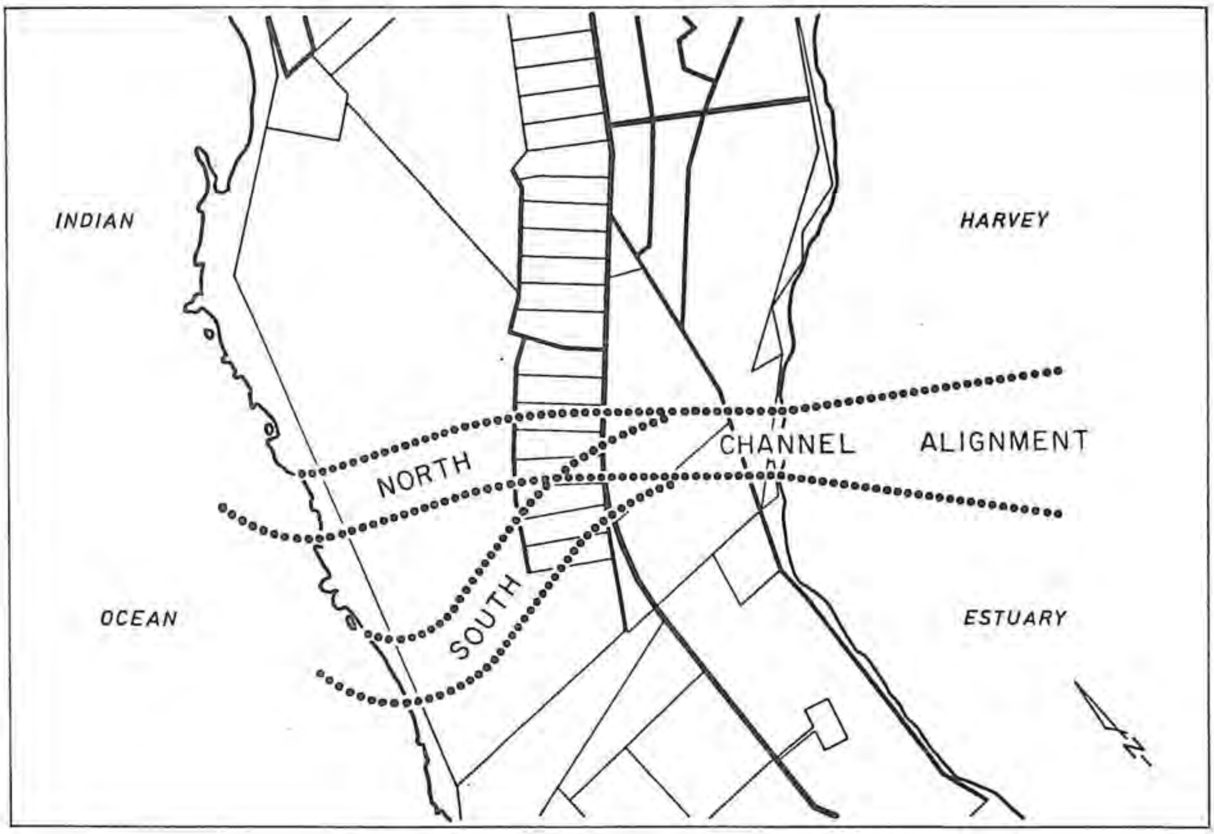

FIGURE 2. GENERAL ARRANGEMENT OF OPTIONS

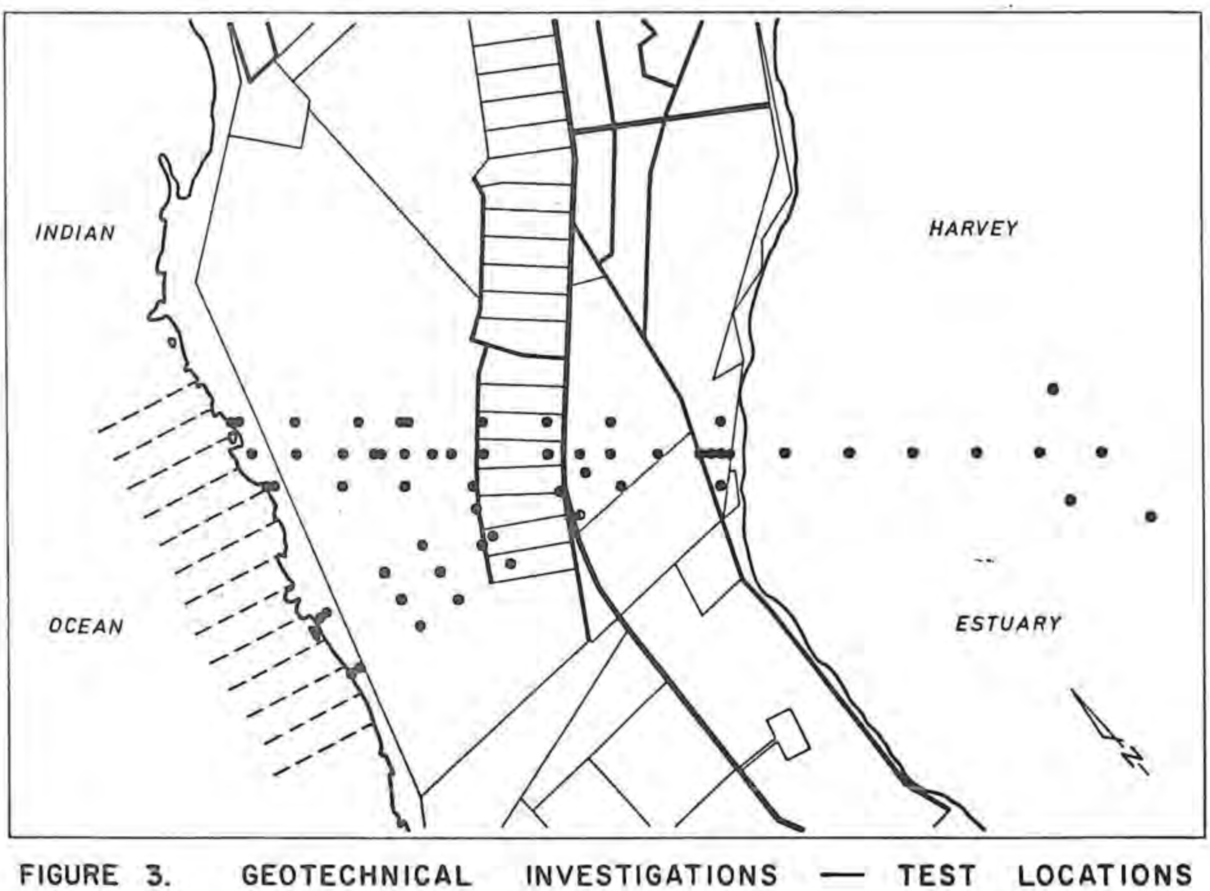

FIGURE 3. GEOTECHNICAL INVESTIGATIONS — TEST LOCATIONS

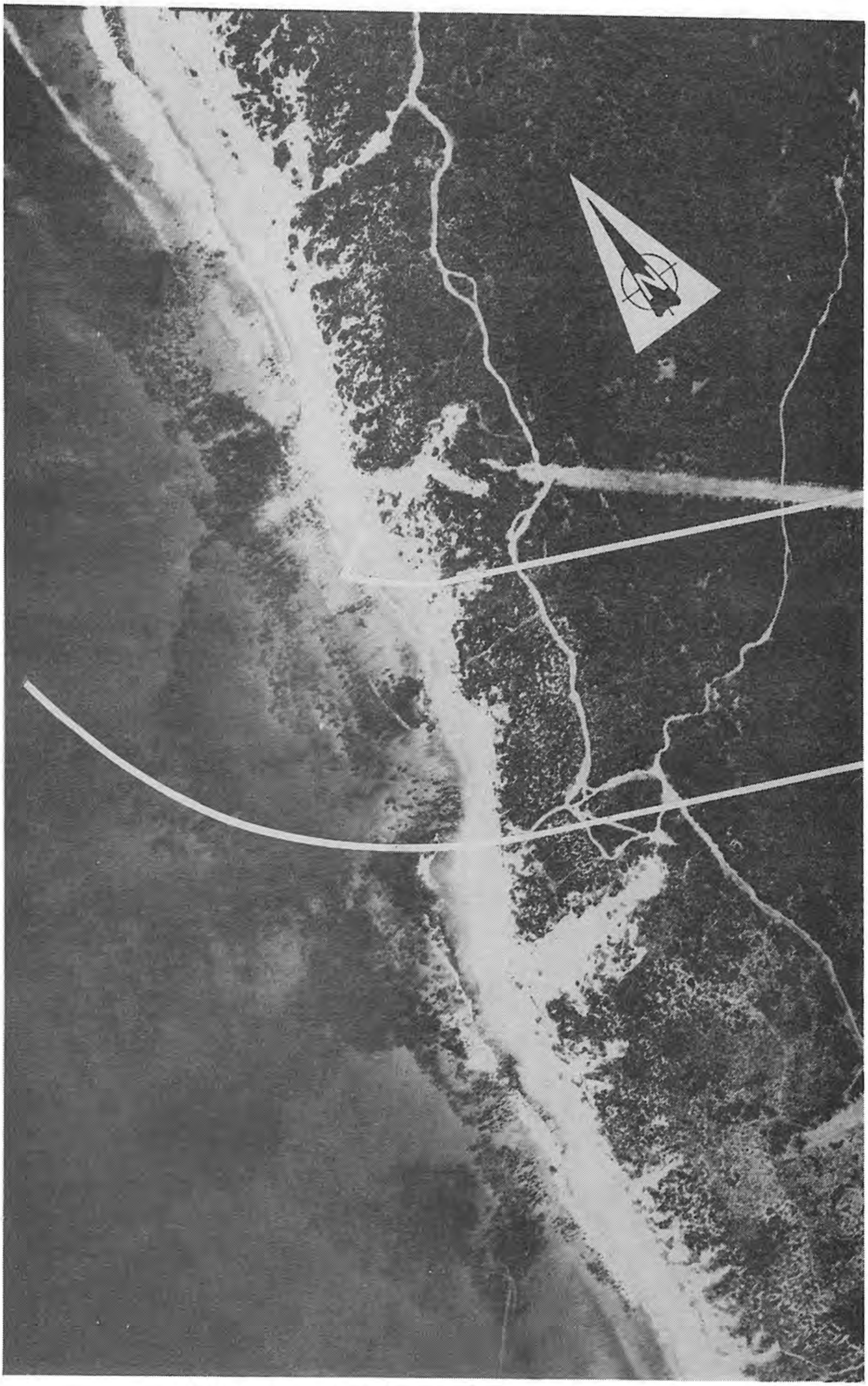

FIGURE 4. NORTH CHANNEL ENTRANCE

FIGURE 5. COASTLINE NORTH OF DAWESVILLE CHANNEL

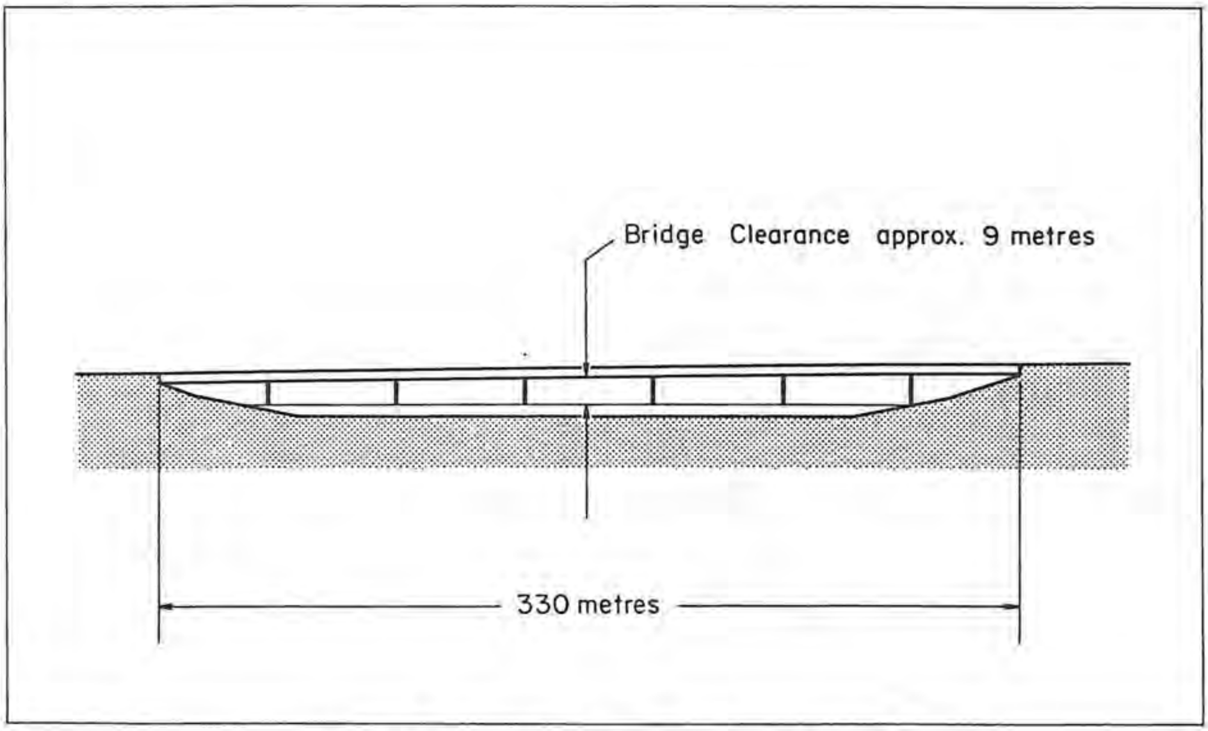

FIGURE 6. CHANNEL ROAD BRIDGE

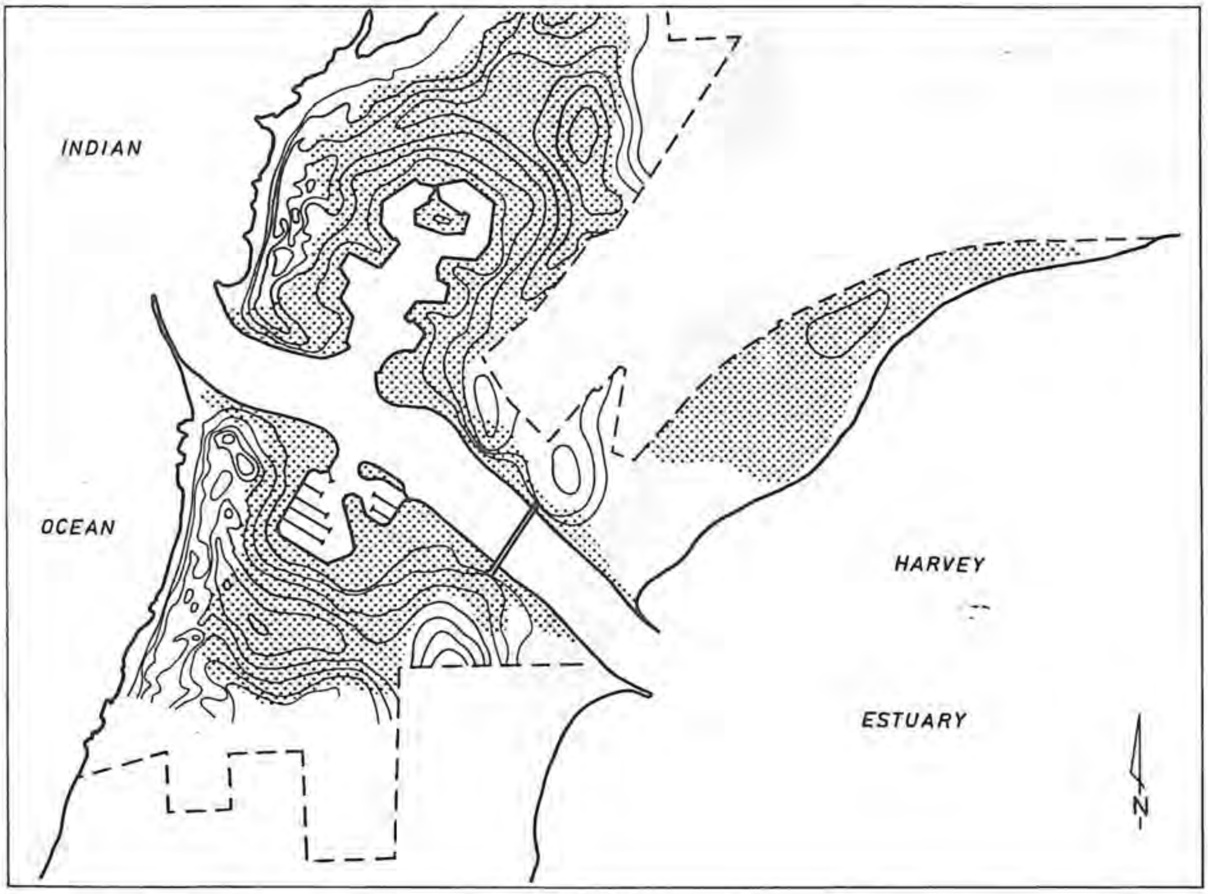

FIGURE 7. ULTIMATE DEVELOPMENT — CONCEPT PLAN

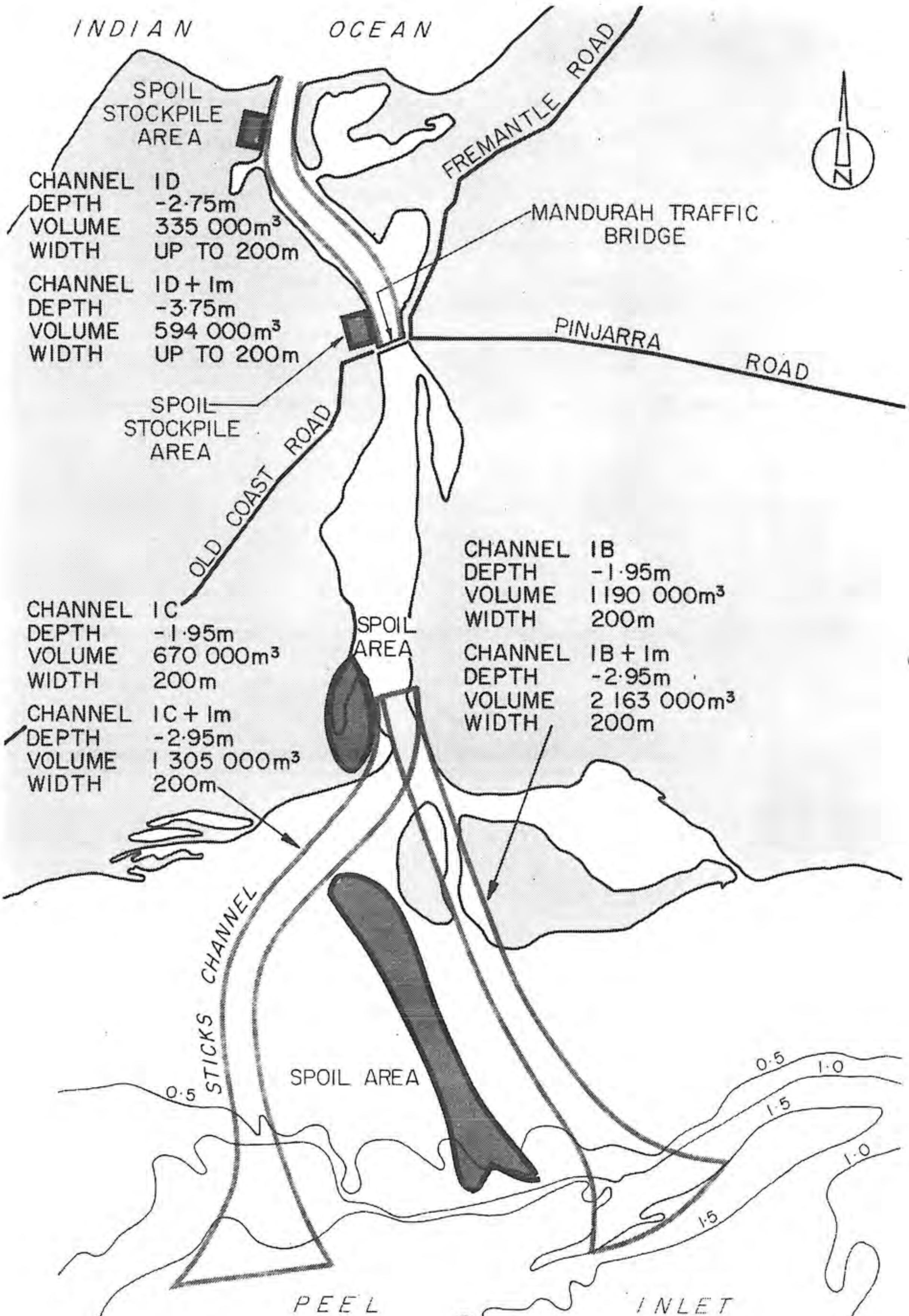

FIGURE 8. MANDURAH CHANNEL DREDGING OPTIONS

Department of Conservation and Environment

Report for Management

Modelling Studies of Dawesville Cut - Harvey Estuary

Project No. 84082

(Study Period : May 21st, 1984 - March 31st, 1985)

Submitted by: G.D. Tong
Computational Fluid Mechanics Int. Pty.Ltd.

for

Centre for Water Resarch,
Department of Civil Engineering,
University of Western Australia.

Also submitted as proceedings paper:

Hydrodynamic Modelling Studies,
Peel-Harvey Study Symposium,
Wednesday, 20th February, 1985.

Table of Contents

List of Figures

1. Introduction

The construction of a 1.7 km channel between the Estuary at Dawesville and the Indian Ocean has been proposed as an engineering option to be implemented concurrently with the new coastal plain superphosphate catchment management programme.

The aim of this study has been to investigate the changes in hydrodynamic characteristics of the Peel-Harvey Estuarine System should the proposed Dawesville Channel be constructed. Seasonal salinity and nutrient distributions, as a result of changes in hydrodynamic characteristics, are a part of the current brief but the drawing of inferences on biota response has been the topic of ecological investigations and is reported in the contributions of other members of the study team.

This report is to communicate the essential results of the hydrodynamic studies*. For further details the reader is referred to the companion Final Report.

*Results of hydrodynamic studies reported herein are from the one-dimensional network model. Additional results from the two-dimensional modelling investigation will be included in the Final Report.

2. Approach to Task

2.1 The Models

The approach to the task has been to establish three models to simulate the hydrodynamics of the Peel-Harvey system both with and without the proposed Dawesville Channel.

The first two of these models ESTRAFPH and TRIDENT are true hydrodynamic models which solve conservation equations for mass and momentum together with a transport equation for a scalar quantity such as a salt or nutrient concentration.

ESTRAFPH (Estuary River And Flood Plain Hydrodynamics) is a fully implicit one-dimensional link-node finite-difference model which has proved ideal for establishing the major hydrodynamic features of the system (tidal elevations, velocities and volumetric exchanges) for given ocean tidal signals and river inflows, with and without Dawesville Channel. The basic components of the model are described in Tong (1978). See Figure 1 for network discretisation of the system.

TRIDENT is a two-dimensional depth-averaged semi-implicit finite-element model set up to provide a further check on the hydrodynamics obtained from ESTRAFPH, to provide an estimate of tidal and wind driven circulation and to allow a second (finite-element) approach to the solution of the transport equation which proved difficult for the very small one-dimensional advective field (velocities) yielded by ESTRAFPH. It was considered worthwhile to pursue the additional complexities of a two-dimensional finite-element model with facility to include a time varying wind stress and an horizontal mixing coefficient. The successful solution of the transport equation for a conservative tracer would be the best indicator of flushing times for various segments of the system. TRIDENT has proved to require much greater execution time than anticipated and has only been run over a period of a few hours. Long term runs may be possible on the Cyber 205, CSIRO, Division of Computing Research, Canberra. These are being pursued.

The third model, SALTIE, is a mass balance model, again for a scalar quantity, based on volumetric exchange over any number of nominated tidal cycles (usually 1). The model includes the facility to correct the computed concentration for evaporation and rainfall/runoff effects at the end of each block of tidal cycles.

2.2 Model Calibration

ESTRAFPH was calibrated on the "as is" configuration (no Dawesville Channel) for two defined run periods which were adopted throughout the study as the representative Winter and Summer conditions.

Winter period : 0000 hrs 9th July, 1983 to 2400 hrs 22nd July, 1983.

Summer period : 1200 hrs 10th December, 1983 to 1200 hrs 14th December, 1984.

The model required very little calibration on the chosen friction factor, Chezy $38m^{1/2}s^{-1}$, ($n \approx 0.039$ for a water depth of $\approx$ 1m) to achieve observed tidal elevations throughout the estuarine system to within about 0.05m. Where discrepancies were larger, particularly at Ford, the observed elevations were uncertain to within 0.04m.

SALTIE again needed no calibration to produce the major characteristics of the late spring, summer and autumn periods of the recorded annual salinity time series. This record exhibits a strong periodicity for the five years of plotted data (1978-1982). The "dry" season (spring, summer, autumn period) of low freshwater inflows and high evaporation shows the quite regular trend of Peel and Harvey salinities "crossing-over" at ~ 40°|oo at the beginning of February from initial salinities of about 20 and 15°|oo respectively at the beginning of November. The model is best suited to this period. The predicted rate of rise of the salinity curve to the threshold salinity for nodularia growth, with Dawesville Channel, can therefore be viewed with confidence.

3. Results

3.1 Tidal Elevations

The winter and summer periods were simulated with the appropriate ocean tidal signals (Figure 2) and winter freshwater inflows (Figure 3).

3.1.1 Elevation plots (Figures 4a and 4b)

These show the computed elevations with (red) and without (blue) Dawesville Channel and the observed tidal response (green) for the "as is" situation at Chimneys, Dawesville and Ford. The marked increase in tidal elevation at the individual locations is evident.

Based on the tidal range response inside the Peel-Harvey compared with the range of the ocean signal (Warnbro) the model results indicate that the tidal range will increase from ~ 15-20% (without Dawesville Channel) to ~ 45-50% as a result of the Dawesville Channel for both summer and winter conditions. See Table 1.

In addressing the question of extent of flooding and drying of mud flats, the approach was to synthesise the astronomic signal by analysis of a 9-month record and to modulate that signal with a carrier wave to include barometric effects. Analysis of the difference between the synthesised signal and the recorded signal (what would be expected as the barometric effect) showed some 10-day periodicity rather than 14. The carrier wave was therefore given a 10-day period and the total signal fed into the model. The response throughout the system was plotted and finally the levels with a 10-day return period were plotted on a 1:25000 plan (Final Report).

		SUMMER				WINTER			
		No Dawesville Ch.		With Dawesville Ch.		No Dawesville Ch.		With Dawesville Ch.	
High range	Ocean	0.85				1.0			
	Chimneys	0.30	(35)	0.35	(41)	0.24	(24)	0.50	(50)
	Mid.Peel	0.12	(14)	0.35	(41)				
	Dawesville	0.11	(13)	0.35	(41)	0.15	(15)	0.45	(45)
	Ford	0.10	(12)	0.35	(41)	0.14	(14)	0.45	(45)
Mid range	Ocean	0.70				0.80			
	Chimneys	0.25	(36)	0.30	(43)	0.14	(18)	0.30	(38)
	Mid.Peel	0.09	(13)	0.30	(43)				
	Dawesville	0.08	(11)	0.30	(43)	0.08	(10)	0.30	(38)
	Ford	0.08	(11)	0.30	(43)	0.08	(10)	0.30	(38)
Low range	Ocean	0.30				0.30			
	Chimneys	0.15	(15)	0.20	(67)	0.07	(23)	0.15	(50)
	Mid.Peel	0.08	(27)	0.17	(57)				
	Dawesville	0.07	(23)	0.16	(53)	0.05	(17)	0.13	(43)
	Ford	0.06	(20)	0.16	(53)	0.05	(17)	0.12	(40)

( ) indicates percentage of ocean tidal range

Table 1 : Diurnal Tidal Range Inside Estuary (m)

The extent of flooding and drying, with and without Channel, were found to be much less than anticipated. This was certainly the case in the Harvey with lateral extents of only 10-30m involved. For the flatter sections of the Peel, distances of between 50 and 400m were found for the 10-day inundation extents but in no case did the Dawesville Channel increase these extents by more than about 100m.

The results are best indicated on the section lines 1, 2, 3, 4, 5 Ward Point-Point Grey and lines A, B, C, D, E, F on the PWD sections (Plan Nos. 55472-42,3) in Figures 5a and 5b.

3.2 Flushing Time Estimates

A first estimate of flushing times has been calculated (based on volumetric exchange) for different segments of the Estuarine System. These estimates, using volumetric exchange per tidal cycle lead to an underestimate of flushing time which could be low by 50 to 100%. The error is due to incomplete mixing and also, in the method, that the volumetric exchange/first tidal cycle is simply multiplied up. The volume of water exchanged per tidal cycle is the same but this is not the case for the mass of a conservative tracer.

Typical segment flushing times for an average tidal range* are given in Table 2.

An estimate of the flushing time for the separate Peel and Harvey basins can be obtained by summing the flushing times for the segments contained in each (Dyer, 1973, p.111). See Figure 1 for segment locations.

*An average internal tidal range, representative of the whole estuarine system, has been taken as 0.09m for no Dawesville Channel and 0.3m with Dawesville Channel. This is also an average representation for both winter and summer conditions.

DEPARTMENT OF CONSERVATION AND ENVIRONMENT

BULLETIN 195

ERRATA

Delete last paragraph of page 146 and Table 2 (top of page 147) and replace with ...

Typical segment flushing times for an average tidal range are given in Table 2 as calculated from the usual definition of flushing time in tidal cycles (Dyer, 1973, p 110).

$$T = \frac{V_o + P}{P} \quad \text{(tidal cycles)}$$

where V_o is the segment low tide volume and P, the intertidal volume

V_o = plan area x D (D = the low water depth)
P = plan area x ΔH (ΔH = the tidal range)

Example.
For $A_{plan} = 3.10^6\ m^2$, D = 1.5 m and ΔH = 0.1 m

$$T = \frac{(3.10^6)\ (1.5 + 0.1)}{(3.10^6)\ (0.1)}$$

$= 16$ tidal cycles

The method shows the independence of the flushing time on the segment area (cancellation) hence, on the basis of a uniform rise and fall of water level over the whole estuarine system per tidal cycle, the flushing figure can be taken as quite representative of the flushing time for the Peel and Harvey basins.

	Segments (sections)	Flushing time in tidal cycles (days)	
		No Dawesville Channel	With Dawesville Channel
Peel side of Channel	10-11	14	5
	12-13	14.5 (30)	5 (10)
	14-15	12	4.5
Harvey side of Channel	17-18	17	5.7
	21-22	16.5 (50)	5.7 (17)
	25-26	15.3	5.5

( ) estimated Peel and Harvey basin flushing times

TABLE 2: Segment flushing times based on volumetric exchange

Segments (sections)		Flushing time in tidal cycles (days) No Dawesville Ch.		With Dawesville Ch.	
Peel side of Channel	10-11	14		5	
	12-13	14.5	(90)	5	(30)
	14-15	12		4.5	
Harvey side of Channel	17-18	17		5.7	
	21-22	16.5	(150)	5.7	(50)
	25-26	15.3		5.5	

( ) indicates Peel and Harvey basin flushing times

Table 2 : Segment Flushing Times Based on Volumetric Exchange

The Peel and Harvey basic flushing times, obtained in this way, are given in parentheses.

The effect of the proposed Channel can thus be summarised as being an approximately 3-fold decrease in flushing time.

The associated water exchange through the main connecting channels per tidal cycle is given in Table 3.

		Without Dawesville Channel m^3	With Dawesville Channel m^3
Typical Winter	Mandurah Channel	7.4 10^6	9.4 10^6
	Peel-Harvey	3.5 10^6	10.0 10^6
	Dawesville Channel		16.8 10^6
Typical Summer	Mandurah Channel	5.5 10^6	6.3 10^6
	Peel-Harvey	3.5 10^6	6.4 10^6
	Dawesville Channel		15.6 10^6

Table 3 : Water Exchange per Tidal Cycle

These are the average Winter and Summer values proposed to be used in the annual (seasonal) salinity exercise.

The values show only a slight increase in volumetric exchange through the Mandurah Channel as a result of the Dawesville Channel but a large increase (> 100%) in volumetric exchange between the Peel and the Harvey.

The highly conveyant Dawesville Channel will carry volume flows per tidal cycle approximately twice those carried by the longer and more constrictive Mandurah Channel.

3.3 Seasonal Salinity Distribution

Figures 6a and 6b show average daily evaporation and streamflow respectively as a monthly variation over a 12 month period. Using this seasonal data, ocean salinities (36°/oo summer, 35°/oo winter) and the typical water exchanges per tidal cycle as given in Table 3, the comparative annual salinity series for Channel and no Channel conditions were computed. See Figures 7a and 7b.

The plotted results are self explanatory. Possibly the "cross-over" points of the Peel and Harvey salinities occur 2 to 3 weeks too early and would better be interpreted as occurring at the beginning of February (no Channel) and beginning of December (with Channel). The salinity level at this first "cross-over" event would be in the range 35-40°/oo. Perhaps the most important information arising from the results is the much greater rate of rise of salinity in the case with Dawesville Channel. If 30°/oo is taken as the threshold salinity for nodularia growth then the results confirm that this salinity is reached around mid-December for Harvey and in the latter half of November for Peel. In contrast such salinities can be expected to be achieved in both basins before mid-November with Dawesville Channel constructed.

The simulation technique, as expected, shows sensitivity to the major effects of evaporation and freshwater inflow. Although the computations have been performed on a daily time period (1 tidal cycle), daily evaporation and freshwater inflow information has been input to the model with a monthly variation. This has produced the monthly "scalloped" effect in the plots which is most pronounced over the winter (high inflow) months. The resulting trend, however, of a flatter curve and more saline conditions with Dawesville Channel is still considered to be a good indicator of the expected annual salinity distribution.

3.4 Salinity Characteristics of the Harvey

In Figure 8 the salinity data for the 5-day summer exercise period 10-14th December, 1984 is plotted at stations DAW (Dawesville) and MEA (Mealup) together with the wind data for that period.

The most important features to be noted are the following:

- the extremely close correlation between wind climate and the stratified/unstratified condition of the estuary
  - strong up-estuary winds - no stratification.
- the time for the stratification to mix down, 6-8 hours.
- a tendency for the estuary to quickly restratify even in this December period in which no significant freshwater inflows are entering.
- the restratification mechanism is by gravity currents from the more saline Peel - 0.1 m/s (about 4 km overnight) for the existing density difference between DAW and MEA ($\Delta\rho \approx 6°|oo$).
- there is a "toe" of relatively fresh water down at the extreme end of the Harvey (Ford) which would assist in a baroclinic return mechanism (gravity induced upper layer current) however the Peel contains sufficient saline water to restratify the Harvey for several months.
- the tendency for stratification in the Harvey will be enhanced by the Dawesville Channel and raises the question of comparing this increased stratification with the advective transport (flushing) under stratified conditions.

Figure 9 is a plot of the annual salinity in the Harvey (weekly readings) for 1978 which reinforces the persistence of the stratified condition.

4. Concluding Remarks

On the basis of the depth-averaged (for well-mixed conditions) computer simulation runs discussed earlier, the following concluding remarks regarding the effect of the proposed Dawesville Channel can be made.

It is expected that the proposed Dawesville Channel will provide the desired hydrodynamic performance to enhance the flushing characteristics of the system and to reduce the propensity of algal blooms with perhaps surprisingly little effect on the system's shoreline habitat. The predicted effects as a result of the Channel can be summarised as follows.

(i) An increase in tidal elevation response inside the estuary from 15-20% to 45-50% over the full range of ocean tidal signals (1m to 0.3m tidal range), summer and winter conditions. The 10-day flooding and drying extents will be quite restricted in the Harvey between 10m and 30m for the better defined areas and between 50m and 400m for the flatter sections of the Peel and upstream of Herron Ford.

(ii) Segment flushing times based on volumetric exchange for estuary segments will decrease from around 15 days to 5 days. This is an underestimate of flushing times mainly as a result of incomplete mixing. The segment flushing times also need to be aggregated to be representative of the basin. Flushing times of:

Peel 90 days (without Channel) and 30 days (with Channel)

and

Harvey 150 days (without Channel) and 50 days (with Channel)

are therefore considered to be more appropriate for both the Peel and Harvey basins.

(iii) Water exchange per tidal cycle through the Mandurah Channel will increase by some 15-20% as a result of the Dawesville Channel but the exchange between Peel and Harvey will increase by more than 100% particularly for the Winter condition.

(iv) The effect of the Dawesville Channel on the seasonal salinity series appears to be as anticipated. Certainly the rate of increase of salinity from Spring through to mid Summer is much greater with the proposed Dawesville Channel than without. Threshhold salinities of between 30 and 35°|oo for Nodularia growth will be reached within the first two weeks of November.

It should be kept in mind that the conclusions reached in this report are based on analyses of well-mixed conditions. The review of existing salinity data suggests that this assumption needs to be relaxed and that the transportive processes for a truly stratified situation need to be investigated for a better estimate of the hydrodynamics, particularly the flushing times and exchange between the Peel, the Harvey and the ocean.

5. Acknowledgements

The work has been carried out as a Centre for Water Research (CWR, University of Western Australia) research contract for the Department of Conservation and Environment (DCE), Project No. 84082.

The author wishes to acknowledge the support and cooperation of the steering committee and most helpful discussions with members of the study team, particularly Rod Lukatelich (CWR), Professor Jorg Imberger (CWR) and Ian Hutton (PWD), over the duration of the project.

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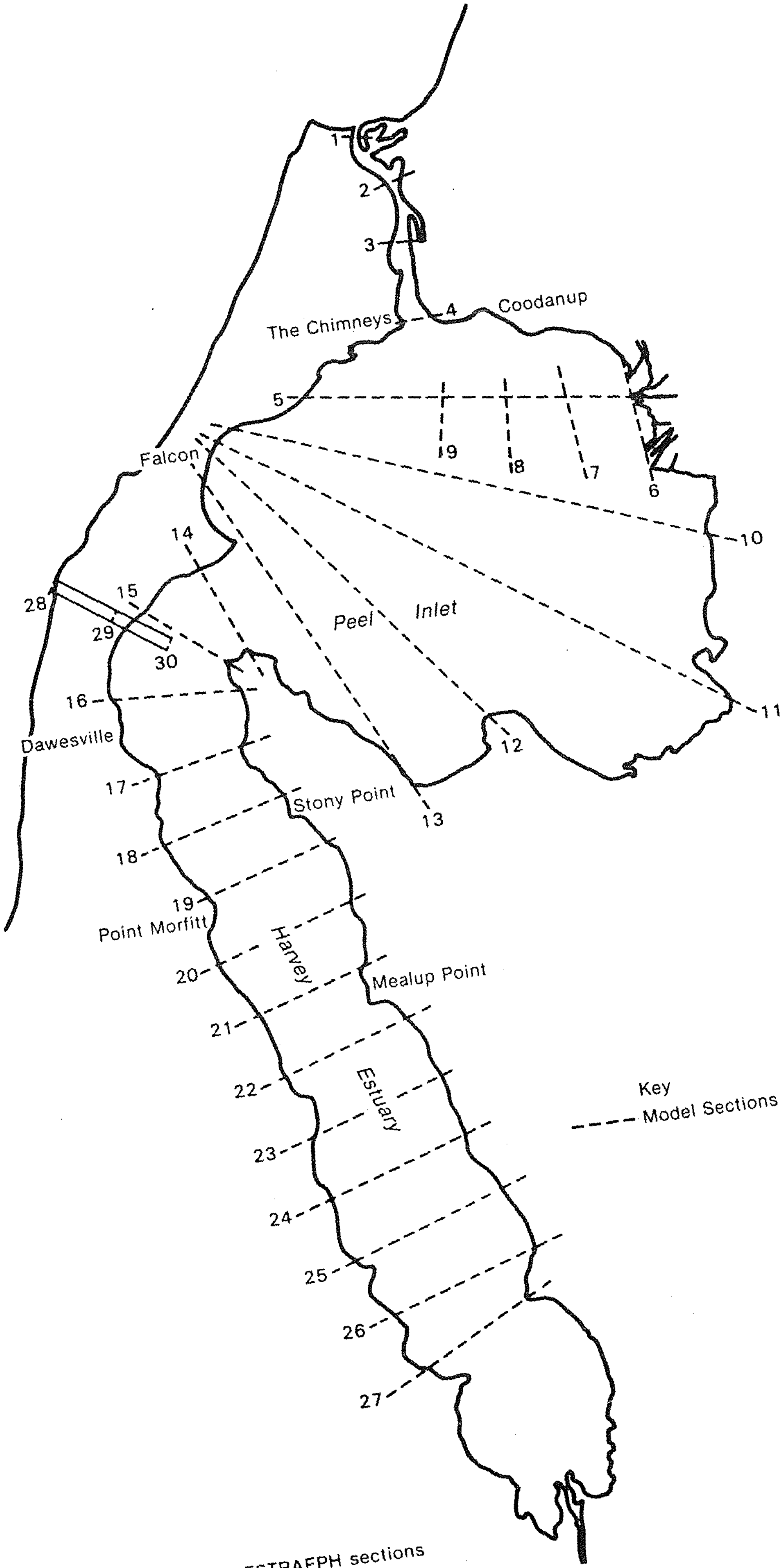


Figure 1 Outline Plan with ESTRAFPH sections

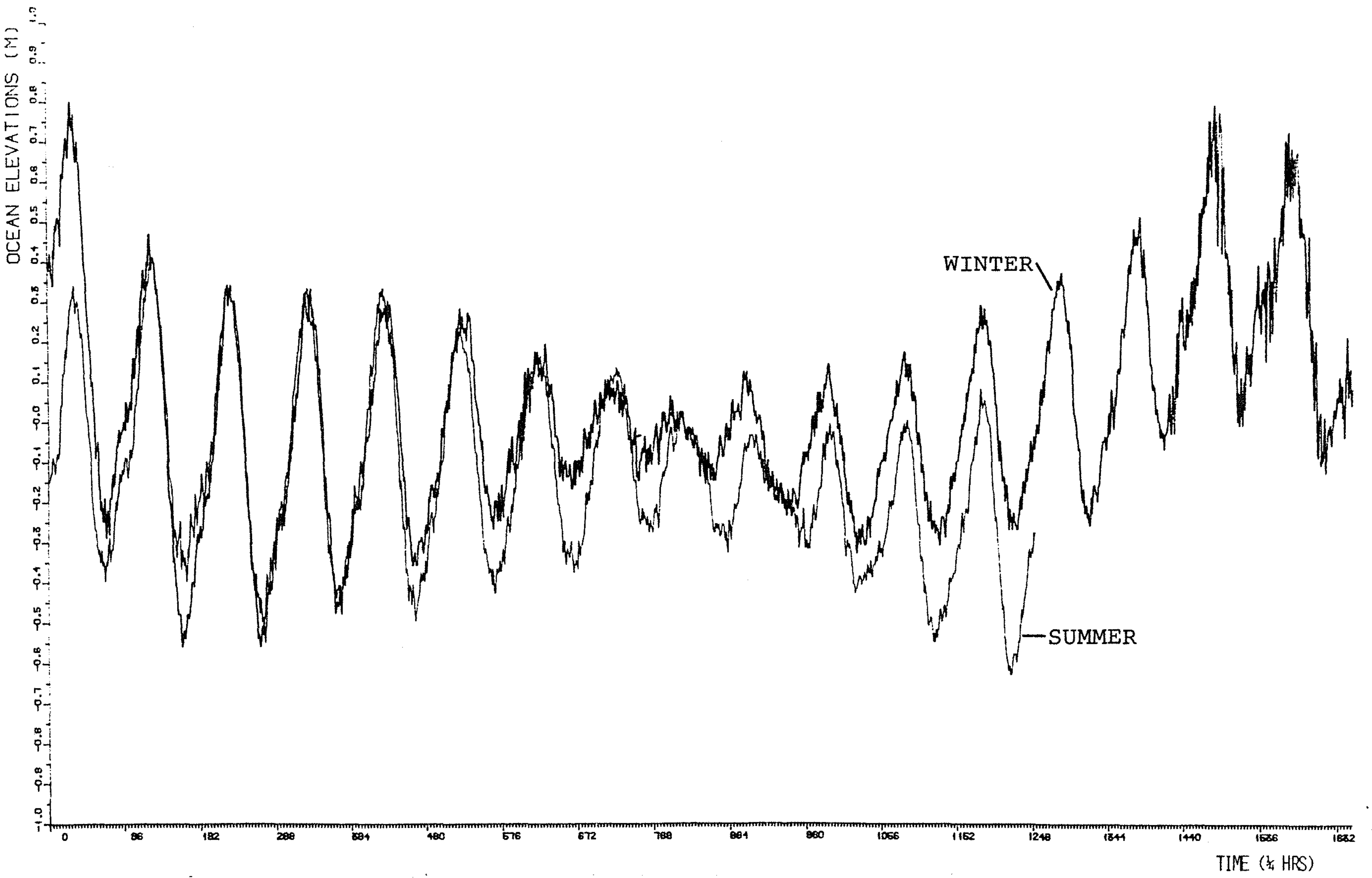
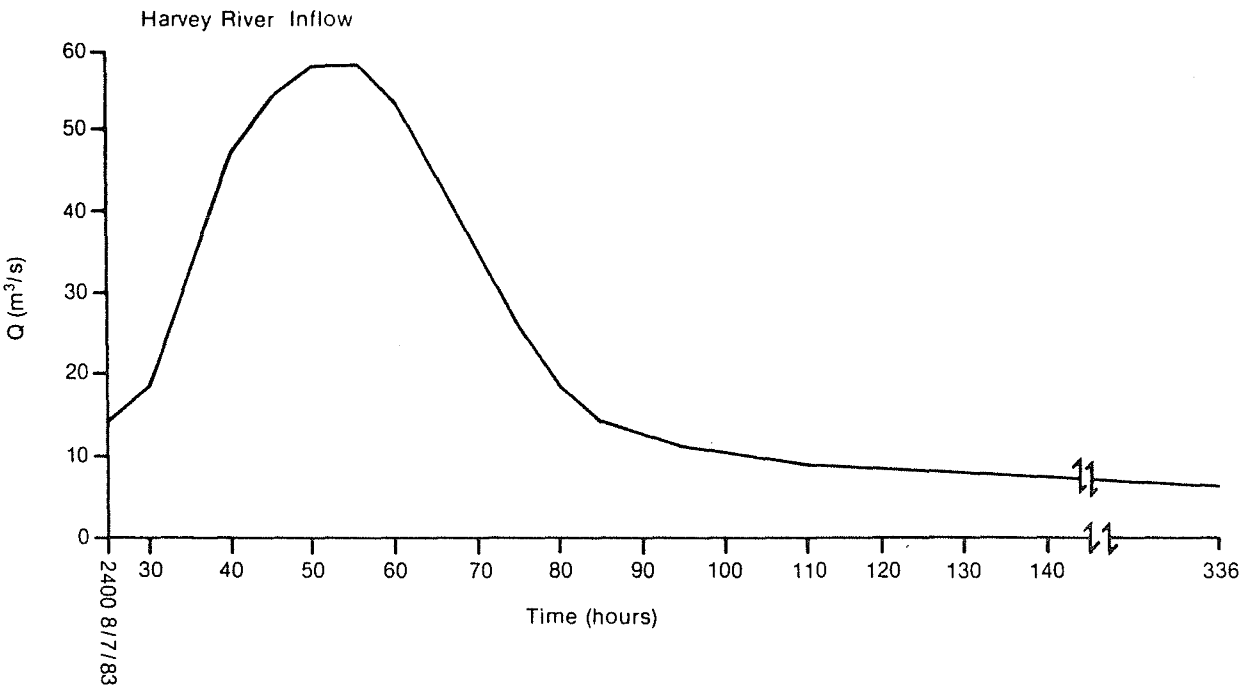


FIG. 2. Ocean Tidal Signals - Summer and Winter



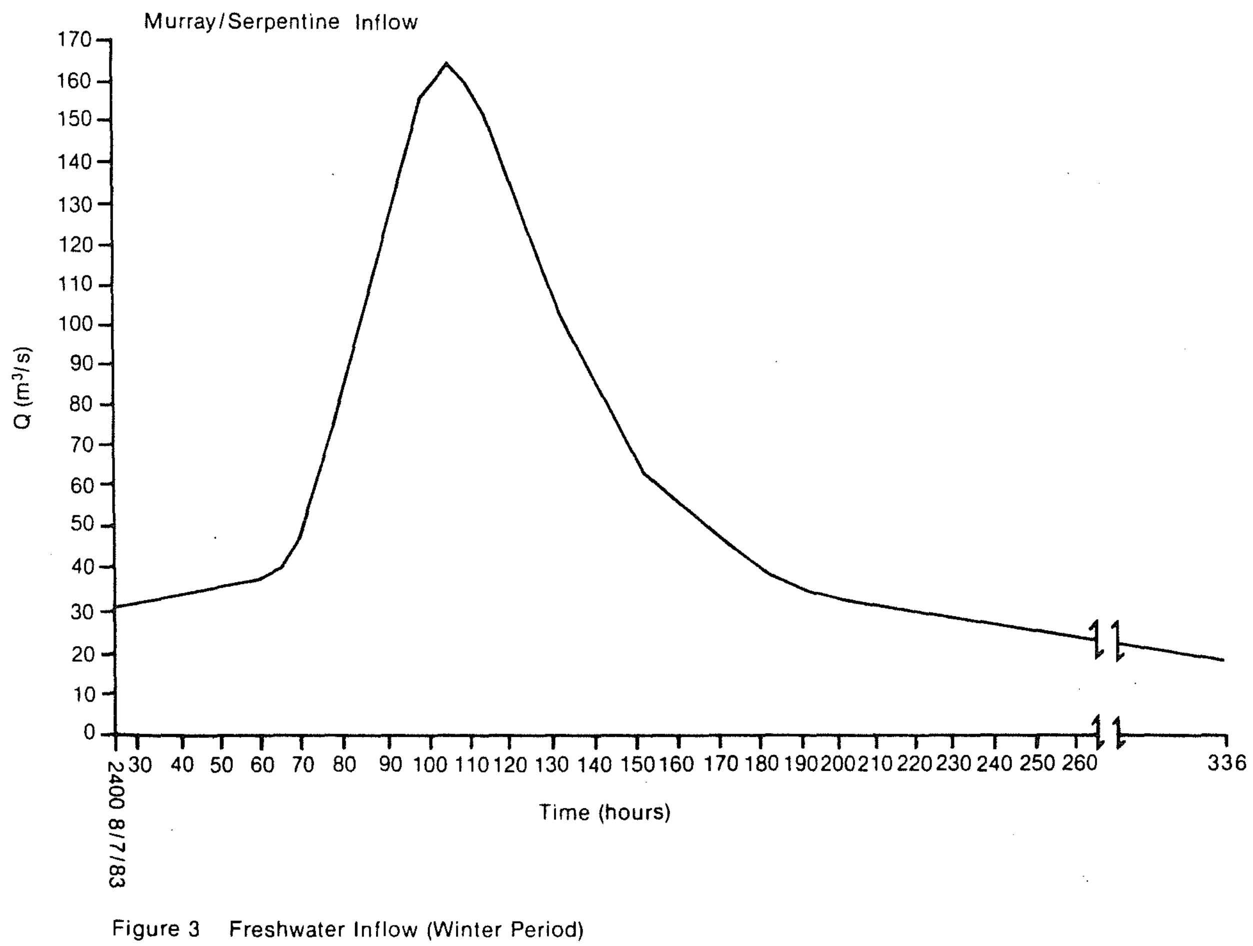


Figure 3 Freshwater Inflow (Winter Period)

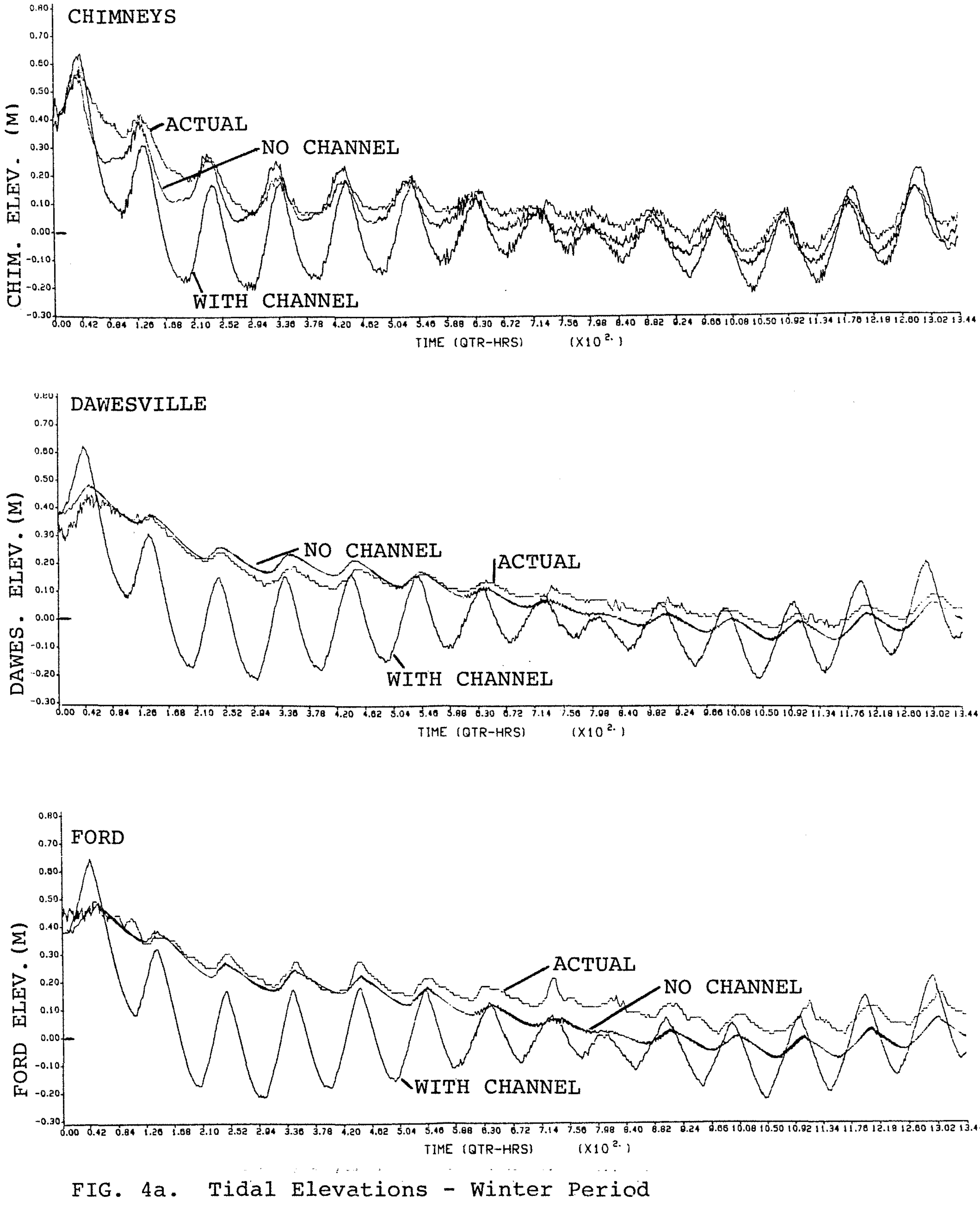


FIG. 4a. Tidal Elevations - Winter Period

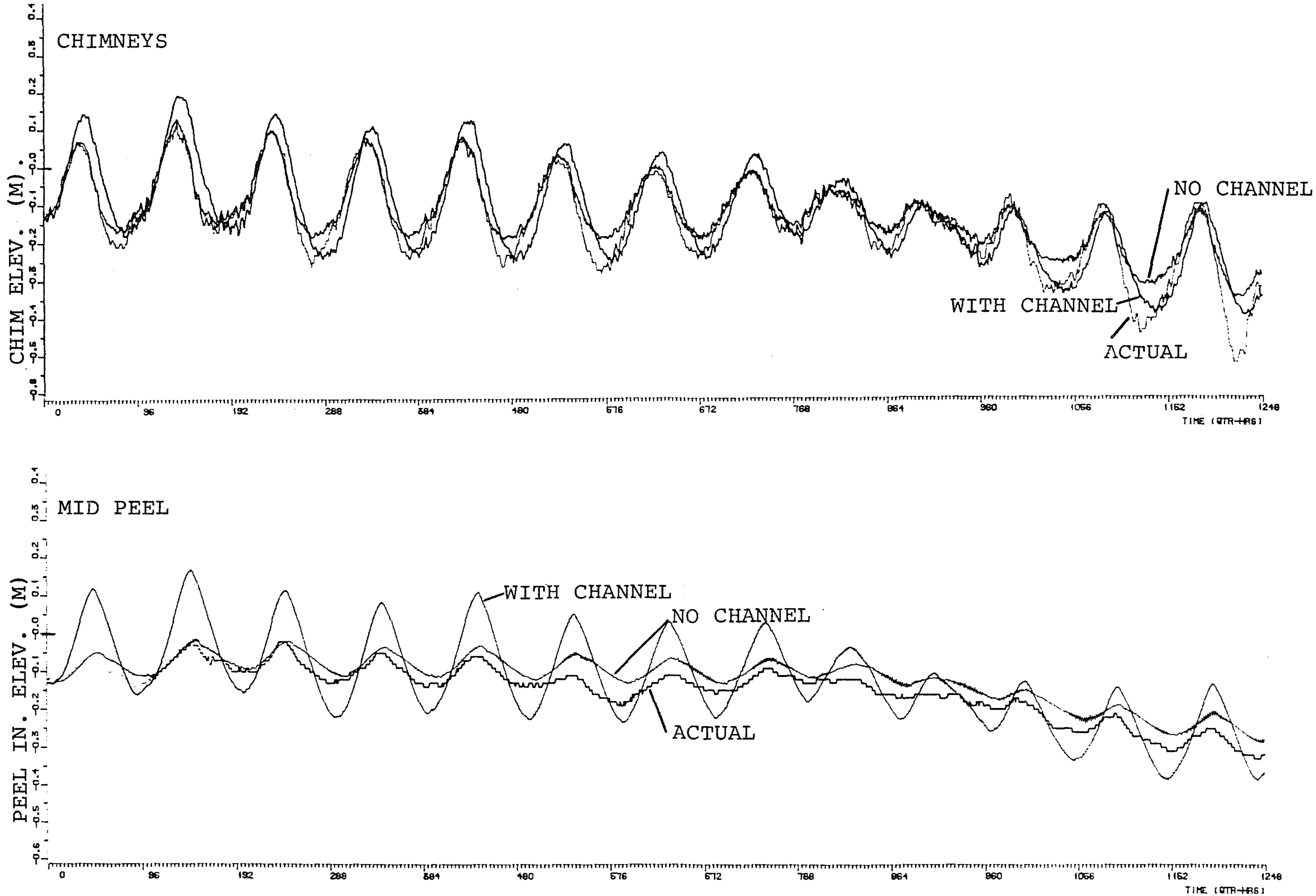


FIG. 4b. Tidal Elevations - Summer Period.

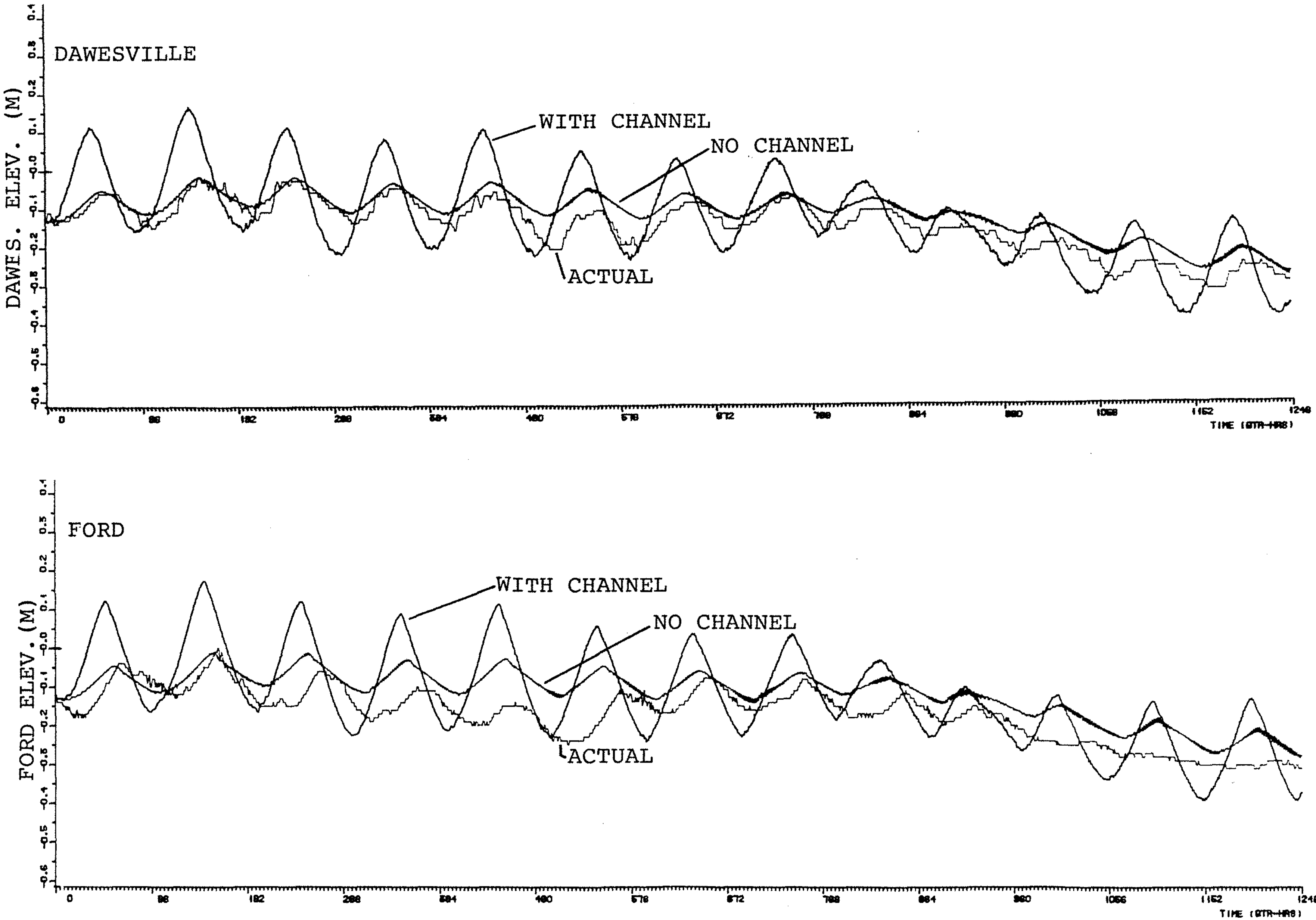


FIG 4b Tidal Elevations - Summer Period

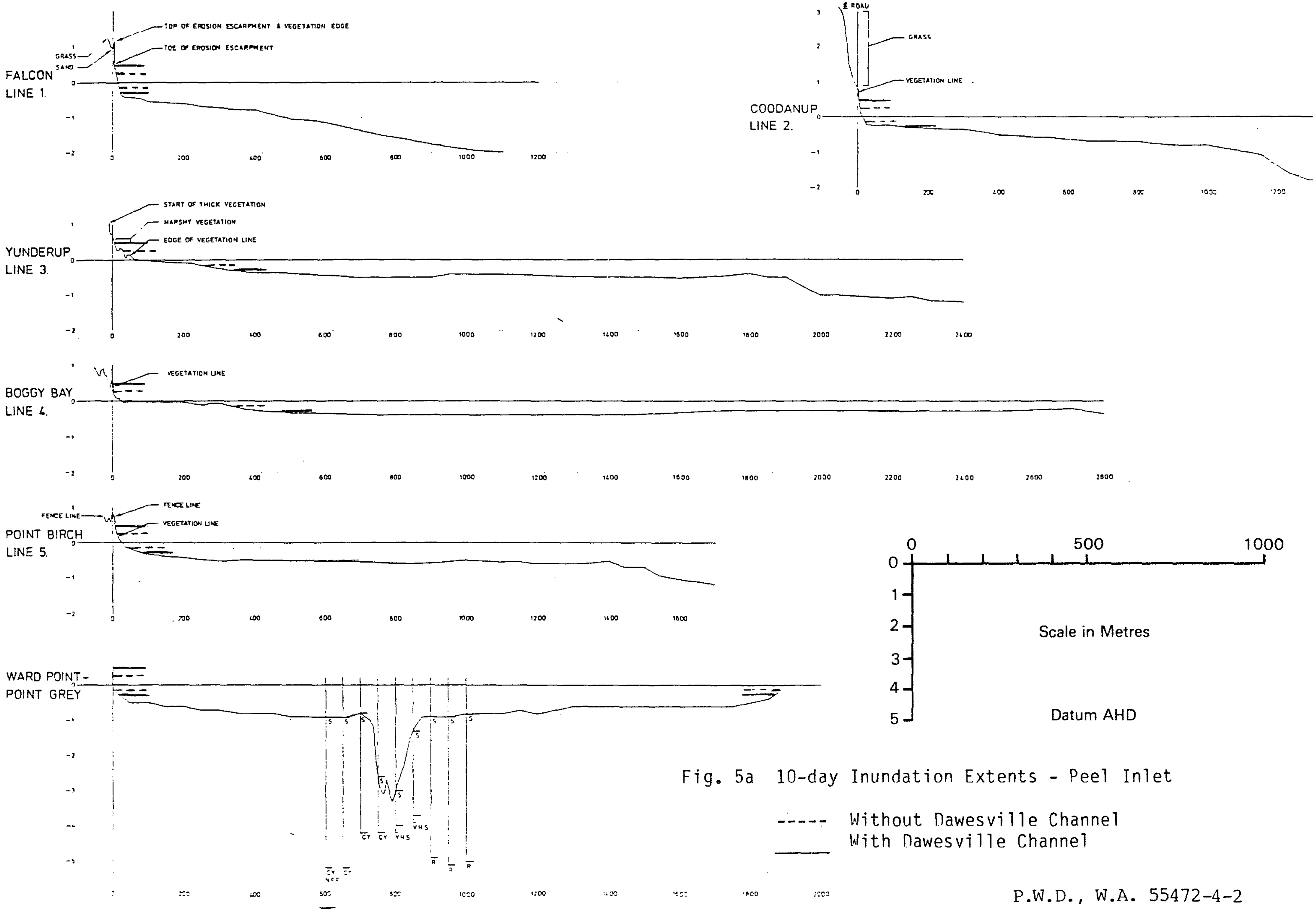


Fig. 5a 10-day Inundation Extents - Peel Inlet

----- Without Dawesville Channel
——— With Dawesville Channel

P.W.D., W.A. 55472-4-2

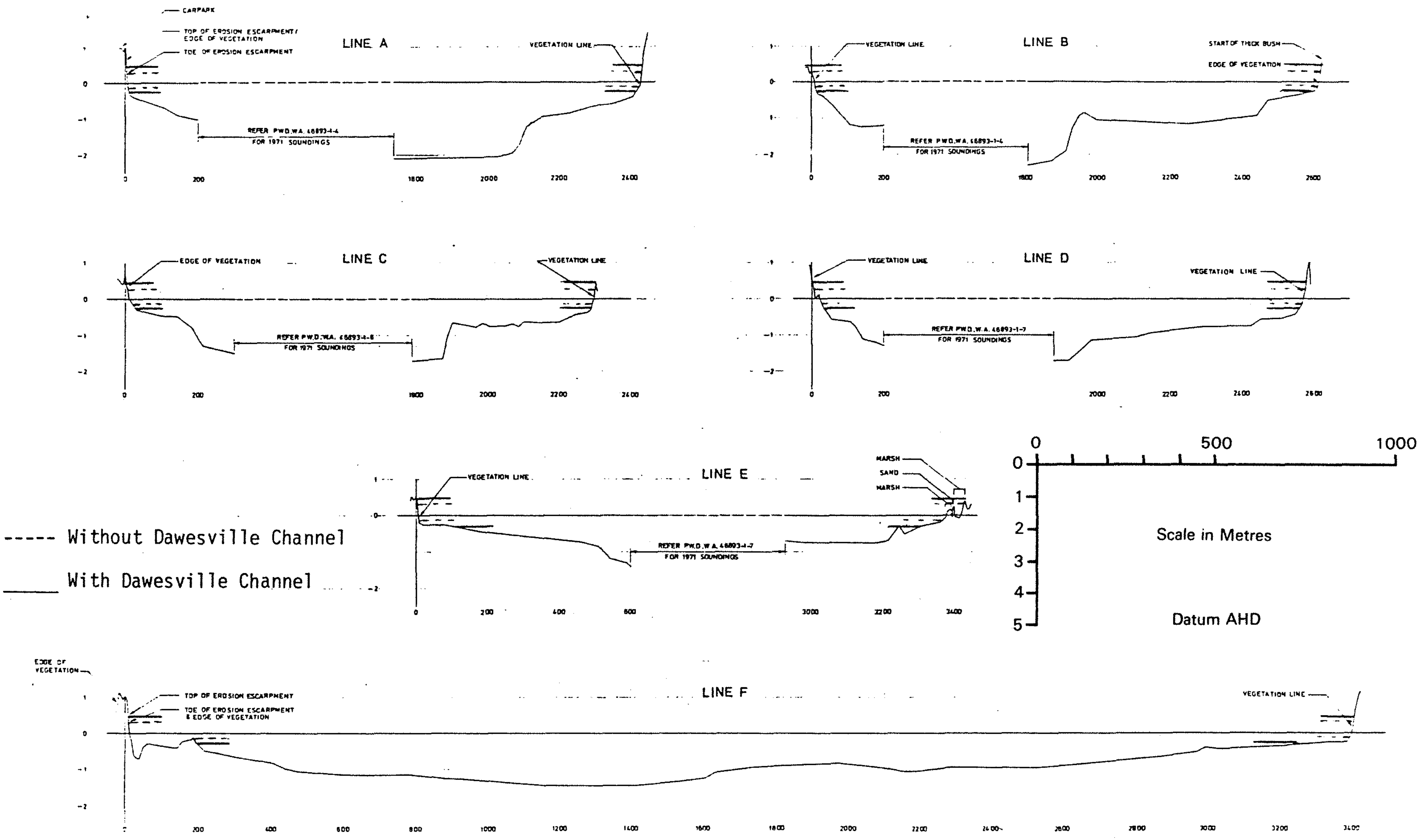


Fig. 5b 10-day Inundation Extents - Harvey Estuary

P.W.D., W.A. 55472-4-3

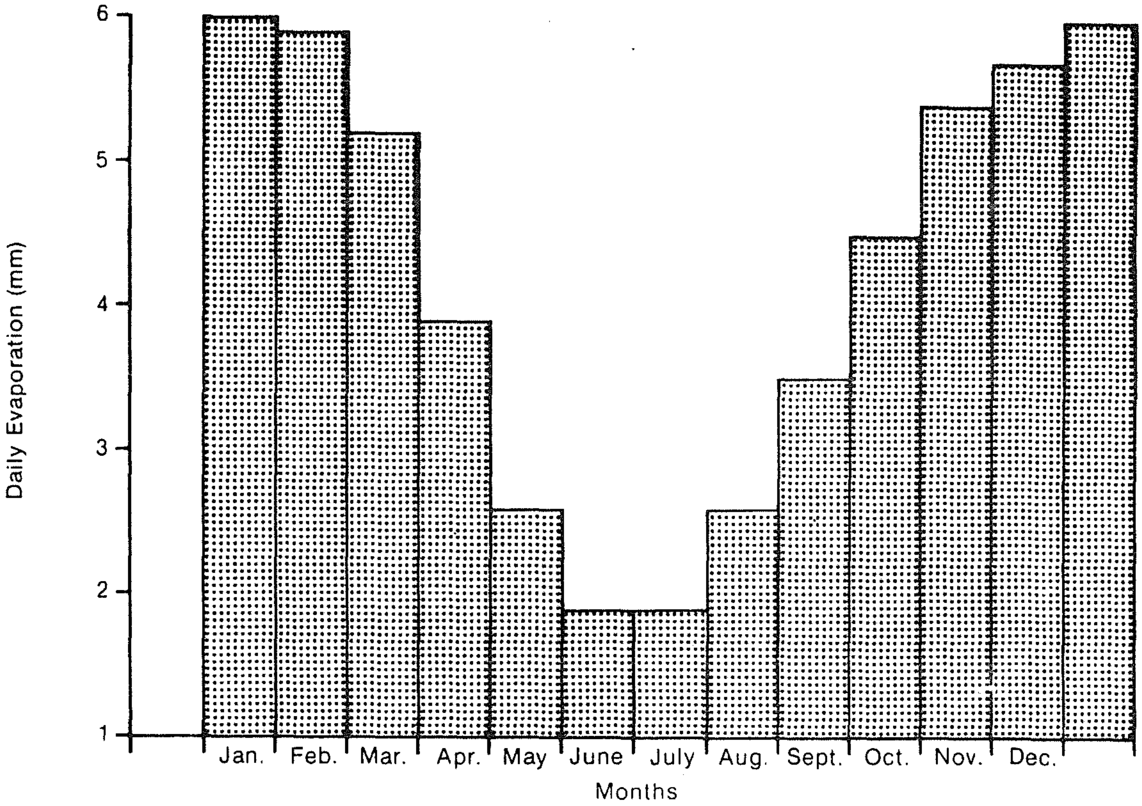


Figure 6a Daily Evaporation (mm)

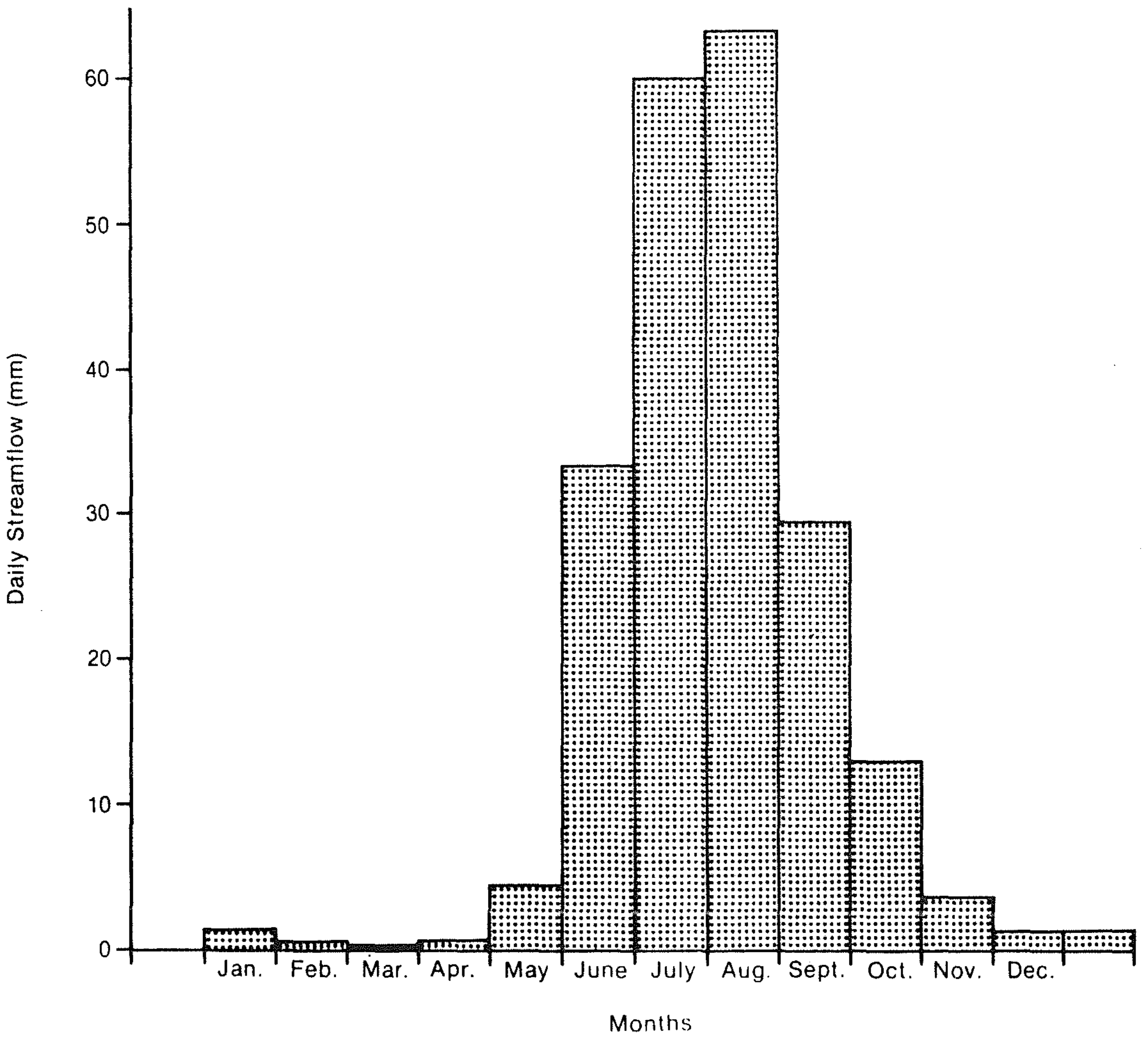


Figure 6b Daily Streamflow (mm)
(Murray/Serpentine and Harvey Rivers)

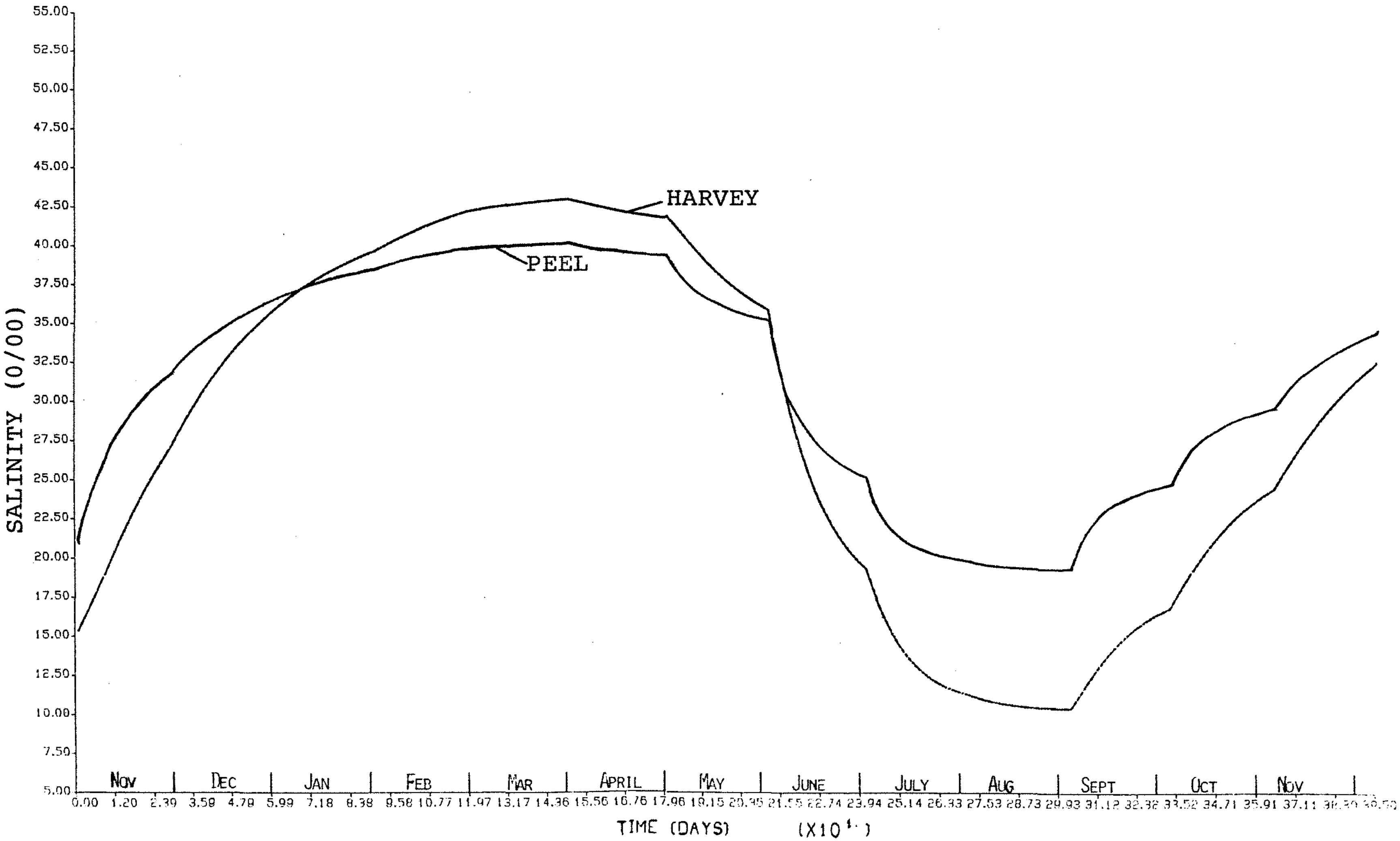


FIG. 7a Peel and Harvey Annual Salinity Series - No Dawesville Channel

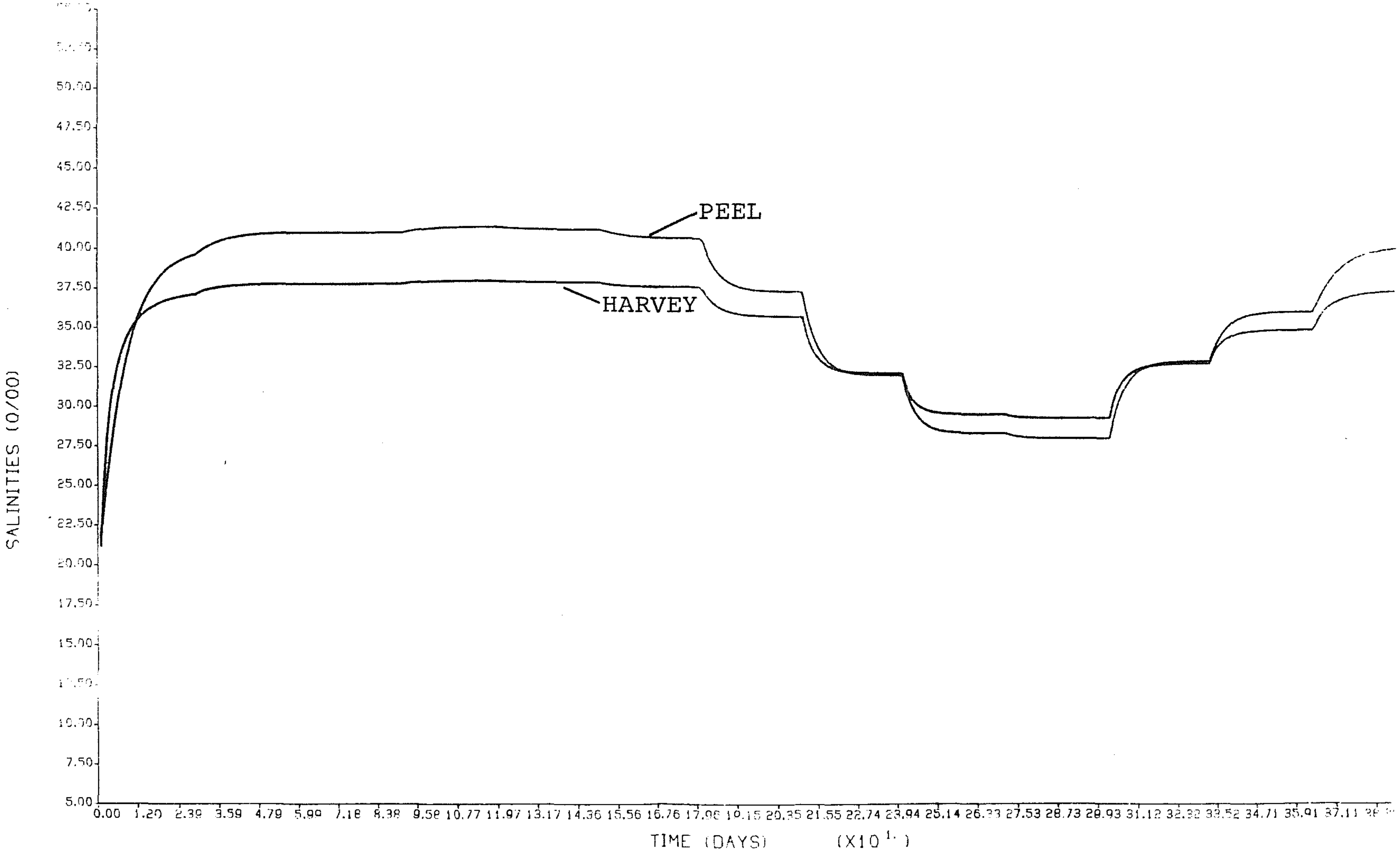


FIG. 7b. Peel and Harvey Annual Salinity Series - With Dawesville Channel

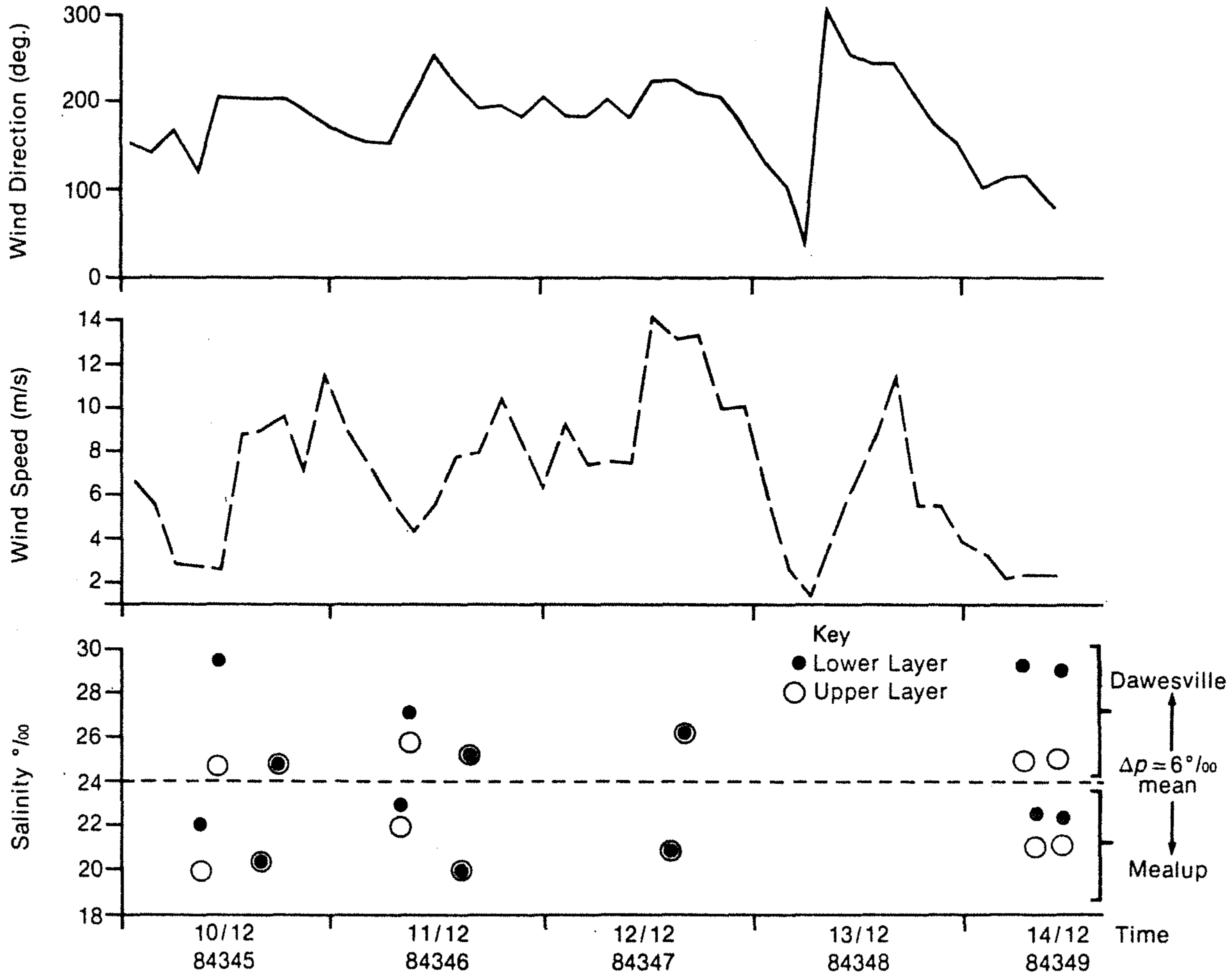


Fig. 8 Salinity and Wind Data — Summer Exercise
(Dawesville and Mid Harvey)

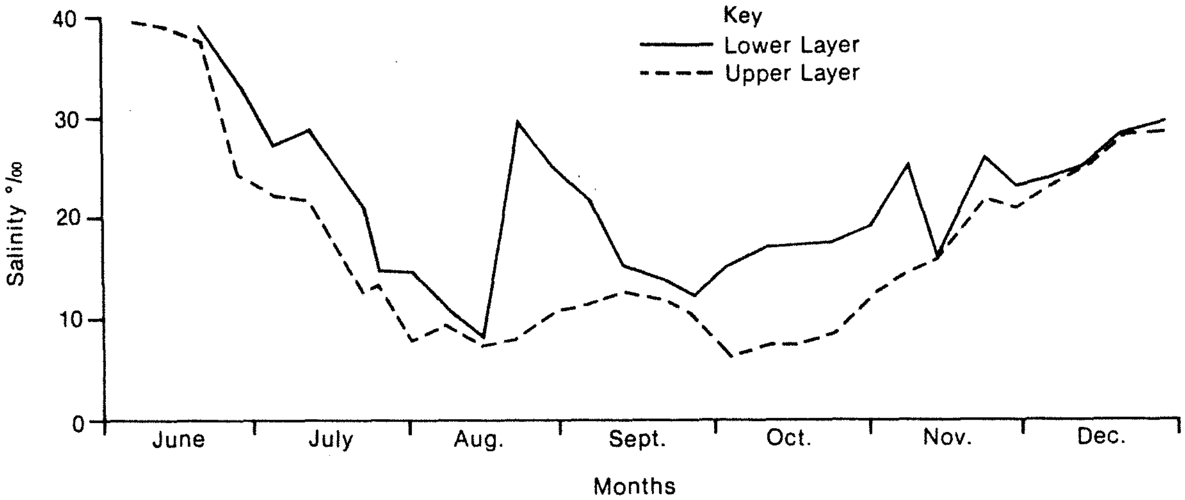


Figure 9 Annual (1978) Salinity Data for Harvey Estuary.

Macroalgal growth, phytoplankton biomass, zooplankton populations and the role of the sediments; present trends and possible effects of the proposed Dawseville Channel.

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Contents

1. Abundance and distribution of macroalgae

Introduction

Since the mid-1960's large accumulations of macroalgae have been reported in Peel Inlet, though not the adjoining Harvey Estuary. The most prominent macroalga has, until recent years, been the green *Cladophora*, and a considerable amount of work has been directed to understanding the response of this species to light, salinity and nutrients (Birch et al., 1983, Birch et al., 1981, Birch and Gabrielson, 1984, Gabrielson et al., 1983, Gordon et al., 1980, Gordon et al., 1981, McComb et al., 1981) The amount of this alga in the system reached 50,000 tonnes dry weight in 1979, but as detailed below, there has been a reduction in the size of the macroalgal populations and an alteration in species composition since that time. In recent years there has also been an increase in the size of the populations of *Nodularia* and other phytoplankton in the system.

During the course of the Peel-Harvey study, a number of estimates have been made of macroalgal biomass, and the purposes of this analysis were, firstly, to examine the time course of change in biomass in relation to environmental variables, so as to seek evidence for the reason for biomass fluctuations. Secondly, an examination was made of tissue concentrations of nitrogen and phosphorus. The tissue concentrations of nitrogen and phosphorus which limit the growth of *Cladophora* under otherwise optimum laboratory conditions are already known (Gordon et al., 1981). It was felt that such analysis of plants collected from the field would provide indirect evidence of nutrient limitation, and allow comparisons between populations from different parts of the system. Thirdly, the analysis would provide information about the possible effects, on macroalgae, of constructing a new channel to the ocean at the northwest corner of Harvey Estuary.

Biomass

Changes in total biomass are shown in Fig. 1. There are no biomass estimates for 1980 and 1983, but a large bloom of *Chaetomorpha* occurred in the system in 1980, the remnants of which were sampled in July 1981, and biomass has been conservatively estimated to have averaged 30,000 tonnes dry weight in 1980. In 1983 *Ulva* first became important as a component of macroalgal biomass, and total macroalgal biomass is estimated to have been about 15,000 tonnes in that year.

In Fig. 2, mean macroalgal biomass is plotted against mean attenuation coefficient in Peel Inlet for the period December to March each year, and the mean chlorophyll *a* concentration in the water column of Peel Inlet for the same period. Biomass was negatively correlated with attenuation coefficient ($r^2 = 0.90$) and chlorophyll *a* concentration ($r^2 = 0.85$). This suggests that the low macroalgal biomass in 1981 and 82 may have been due to increased light attenuation due to increased phytoplankton biomass. Tissue N and P levels do not suggest decreased nutrient availability during this period.

Peel mean chlorophyll *a* concentration in the post-*Nodularia* bloom period (March-May) has not altered significantly since the commencement of sampling in 1978 (Table 1), and so the decrease in macroalgal biomass in 1981 and 1982 was not due to increased post-*Nodularia* bloom phytoplankton levels in those years. The most important period appears to be December to March. The light data in Table 2 show that the mean attenuation coefficient for this period showed a marked increase in 1980/81 and 1981/82 compared to the other years.

The increase in chlorophyll *a* levels in the Peel in the December/May period (Table 3) in 1980/81 and 1981/82 was mainly due to the relatively large size of the *Nodularia* blooms in the Harvey. Table 1 shows that there has not been an increase in Peel chlorophyll levels in the post-*Nodularia* bloom period, and by early December salinities are generally too high in

Peel for the growth of Nodularia. Most of the Nodularia in the Peel at this time has been flushed from the Harvey. There does not appear to be any significant correlation between river nutrient load and macroalgal biomass. In earlier years, high nutrient loads were generally associated with high macroalgal biomass, but in recent years the relationship has not held. It is suggested that, although nutrient loading allowed the accumulation of a large macroalgal biomass in earlier years, the deteriorating light climate has inhibited macroalgal growth in recent years.

Changes in species composition

The alga dominating biomass has changed several times since sampling began. Cladophora was dominant in 1978 and 1979, but fell from an estimated 50,000 tonnes dry weight in March 1979 to 5,000 tonnes in September 1979; Cladophora biomass has not exceeded 5,000 tonnes since then.

Chaetomorpha became the dominant alga in 1980 and remained dominant until 1983, when Ulva became more prominent. In 1984 Chaetomorpha, Enteromorpha and Ulva have been co-dominant.

The change in dominance has probably been brought about by changing nutrient and light conditions. Water column nutrient levels (organic N and P) have steadily increased in both estuaries since 1978. The amount of light reaching the floor of the estuary, and the length of the growing season has decreased since 1980. Both Cladophora and Chaetomorpha are benthic algae, and require clear water so that sufficient light can reach the floor of the estuary for growth.

Enteromorpha is normally found in the shallows, at the water surface, where it grows epiphytically on other algae or seagrasses. In deeper water it forms large floating rafts. Ulva grows as large, thin sheets of thallus which may be attached to the bottom, and are suspended in the water column. Enteromorpha and Ulva may be better adapted to low light conditions because of their growth habit.

In terms of management the change in species dominance may cause some concern because both Enteromorpha and Ulva undergo large seasonal fluctuations in biomass, and decompose very rapidly once they are beached.

Tissue N and P concentrations

Tissue N and P concentrations are shown in Figs. 3 and 4. The critical concentration shown for comparative purposes is for Cladophora (Gordon et al., 1981). The sites chosen were 4, 5 and 14 to represent the eastern Peel populations, and 8 and 23 to represent Falcon and Dawesville (western Peel) respectively.

The results are consistent with earlier work (Gordon et al., 1981) in that the algae appear to be more P-limited than N-limited at all sites. The tissue N concentration rarely fell below the critical concentration at the Falcon and Dawesville sites. There appears to be no obvious trend in the tissue N data, except that the tissue N concentration appears to have fallen in 1984.

Tissue P levels do show a trend which is most obvious in the data for the western Peel populations. Tissue P concentrations were always below the critical concentration until October 1981 and they remained high throughout 1982. No data are available for 1983, but tissue P concentrations fell again in 1984. The tissue P concentration of the eastern Peel populations showed a similar (though not so obvious) trend.

There appears to have been a significant increase in tissue P concentrations in late 1981 and 1982 in the western Peel populations, and a similar but much smaller increase in the eastern populations. (As noted above, biomass of macroalgae was apparently limited at the time by low light intensities.) This increase followed the large P input in the winter of

1981 and the summer floods of January 1982, so there would have been more P available at this time. There is also some evidence of increased P recycling from the sediments in the Harvey following the winter of 1981 until December 1983.

Harvey mean chlorophyll a concentration for the period March to May inclusive was much higher in 1982 and 1983 compared with other years (see Table 1). Also in 1982 and 1983 there were large benthic *Oscillatoria* blooms following the collapse of the *Nodularia* blooms. Following the collapse of each *Nodularia* bloom there was a large release of ammonium nitrogen into the water column. Following the 1981/82 and 1982/83 *Nodularia* blooms there were only small increases in ammonium nitrogen concentration compared to the other bloom years.

In these years (1981/82 and 1982/83) the ammonium peaks may have been reduced because phytoplankton were able to utilize more of the ammonium as a result of the increased availability of P. The post-*Nodularia* bloom chlorophyll a levels were much higher in those years (Table 1).

N:P ratios in the waters of the Harvey Estuary (Fig. 5) also tend to support this suggestion of increased P recycling and availability. The N:P ratios following the 1981/82 and 1982/83 *Nodularia* blooms were much lower than those following the 1978/79, 1980/81 and 1983/84 *Nodularia* blooms. This may have been due to increased uptake of N by phytoplankton (as evidenced by the much higher chlorophyll a levels and occurrence of the *Oscillatoria* blooms) as a result of increased P recycling and availability, rather than a reduction in N recycling. The Peel N:P ratios also showed a similar trend but it was much less pronounced. Water column organic P concentrations also increased during 1982 and 1983 in both estuaries.

The tissue P concentration of the western populations (Fig. 4) showed a marked decrease in early 1984 and this correlates with:

(a) A drop in Harvey mean chlorophyll a concentration for the March-May period in 1984 (Table 1) and the absence of an Oscillatoria bloom in 1984.

(b) An increase in N:P ratios, especially in the Harvey (Fig. 5).

(c) An increase in post-Nodularia bloom ammonium nitrogen concentrations in 1984.

(d) A drop in water column organic P concentrations following the 1983/84 Nodularia bloom.

(e) A drop in the phosphorus concentration of the top 1 cm of sediment in the Harvey in the post-Nodularia bloom period of 1983/84 compared to 1982/83. The data for station 1 (mid-Harvey) are presented as an example (Fig. 6). No earlier sediment data are available.

The above points (a-e), and the drop in tissue P concentrations in 1984, suggest that there may have been a reduction in P recycling and availability after December 1983 compared with the period from winter 1981 to December 1983.

Possible effect of the Dawesville Channel

Assuming that light is the primary limiting factor at present for macroalgal growth, and that the increase in light attenuation in the Peel-Harvey system is largely due to Nodularia, then if the Dawesville Channel reduces Nodularia biomass, light attenuation should decrease. As a consequence macroalgal biomass should increase, perhaps to levels similar to those experienced in 1978 and 1979. Macroalgal growth may well take place further south in Harvey Estuary.

The channel will also reduce nutrient retention, by improving flushing and this will presumably mainly affect the Dawesville and Falcon areas. The eastern Peel populations will be less affected by the channel, except that light conditions should improve which may lead to further macroalgal growth. A reduction in macroalgal growth in that area will presumably depend largely upon a reduction in nutrient (especially phosphorus) loading from the Murray and Serpentine catchments.

Table 1. Mean chlorophyll a concentrations for the period March-May.

Year	Chlorophyll a ($\mu g\ l^{-1}$) Peel	Harvey
1978	2.4	6.5
1979	1.7	3.5
1980	4.6	3.6
1981	3.8	9.0
1982	3.8	17.8
1983	3.7	24.7
1984	3.0	10.1

Table 2. Mean attenuation coefficient for the period December-March

Year	Attenuation Coefficient (Em^{-1}) Peel	Harvey
1977/78	0.38	0.47
1978/79	0.35	1.22
1979/80	0.42	0.44
1980/81	0.75	1.71
1981/82	0.93	1.98
1982/83	0.41	1.12
1983/84	0.35	1.06

Table 3. Mean chlorophyll a concentration for the period December-May

Year	Chlorophyll a ($\mu g\ l^{-1}$) Peel	Harvey
1977/78	2.2	5.9
1978/79	3.1	18.6
1979/80	1.2	3.5
1980/81	39.8	85.4
1981/82	28.4	100.3
1982/83	7.2	60.8
1983/84	11.5	38.3

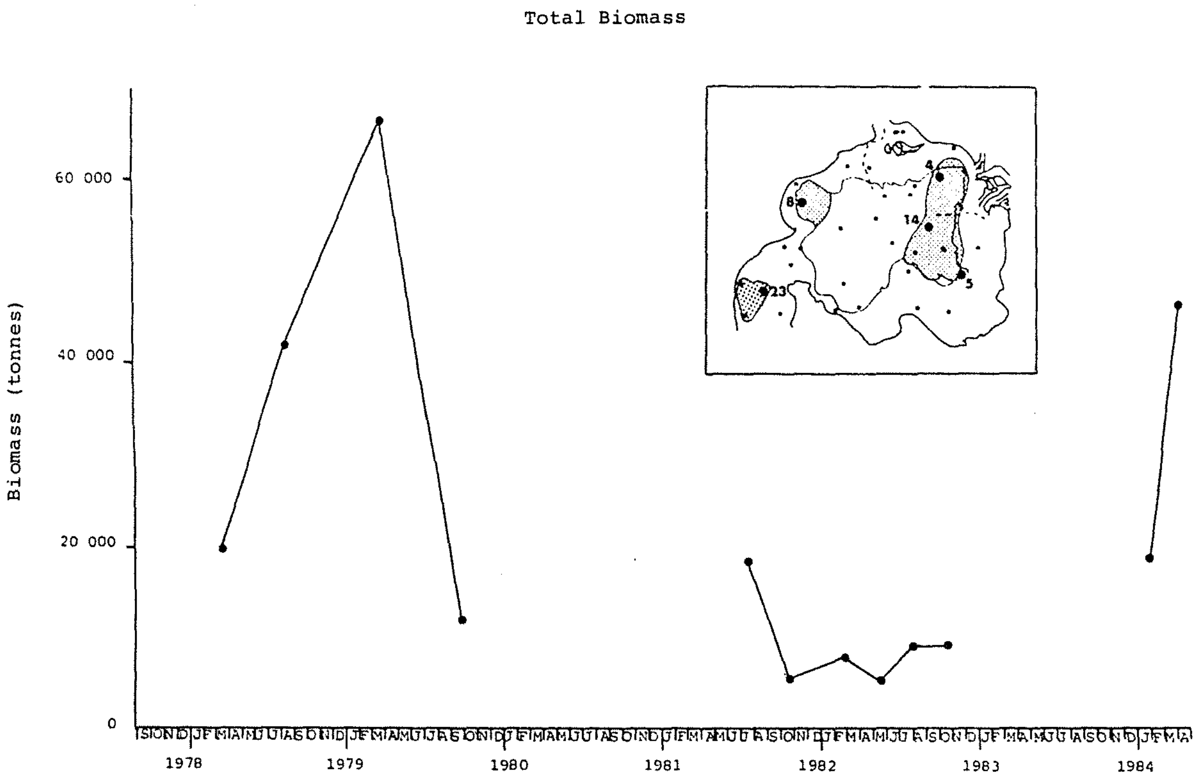


Figure 1. Total macrophyte biomass in the Peel-Harvey system. Inset: Location of sampling sites and principal macroalgal growth areas (stippled).

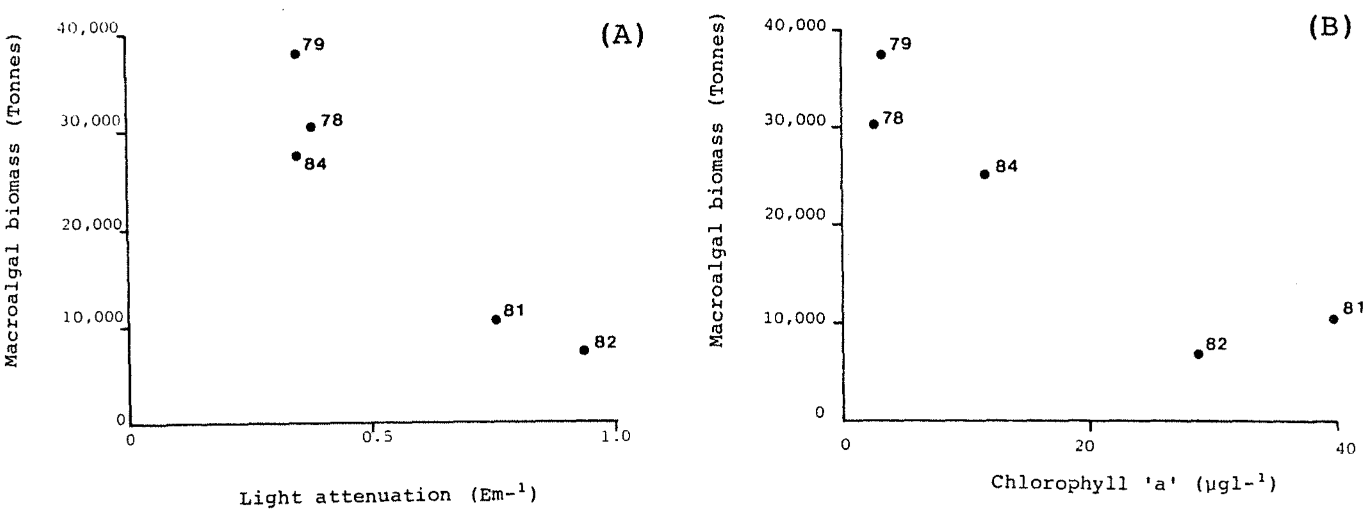


Figure 2. The relationship between macroalgal biomass and A) mean attenuation coefficient for the period December to March, and B) mean chlorophyll 'a' for the period December to May

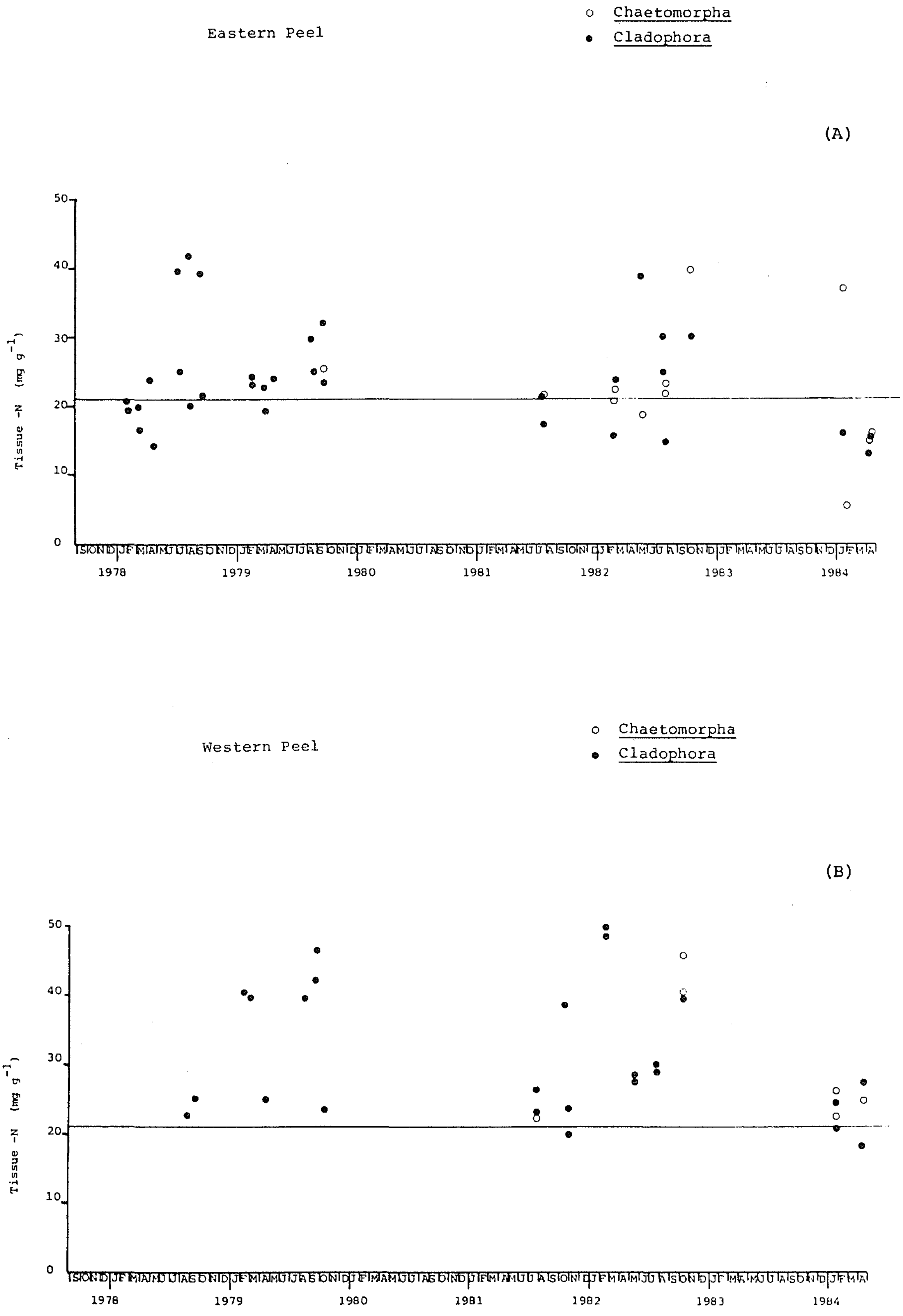
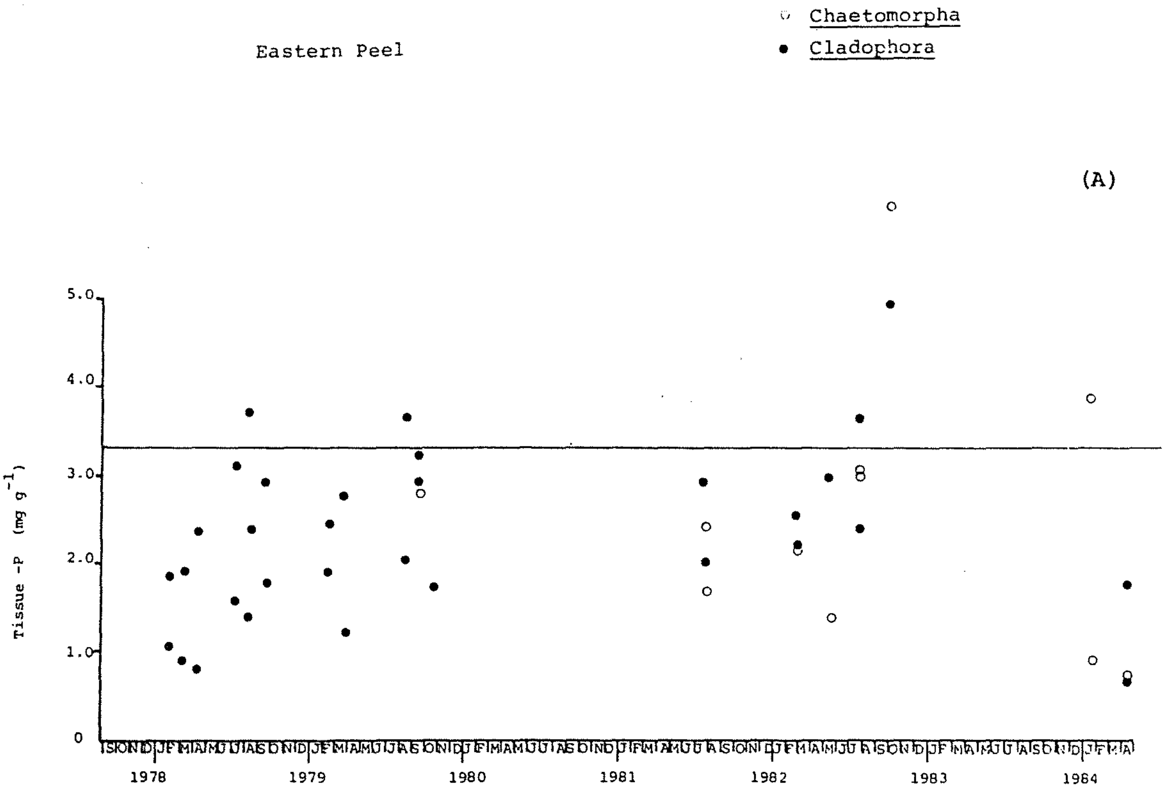


Figure 3. Tissue nitrogen concentrations in the eastern (A) and western (B) Peel macroalgal populations. The line drawn is the critical concentration for Cladophora.



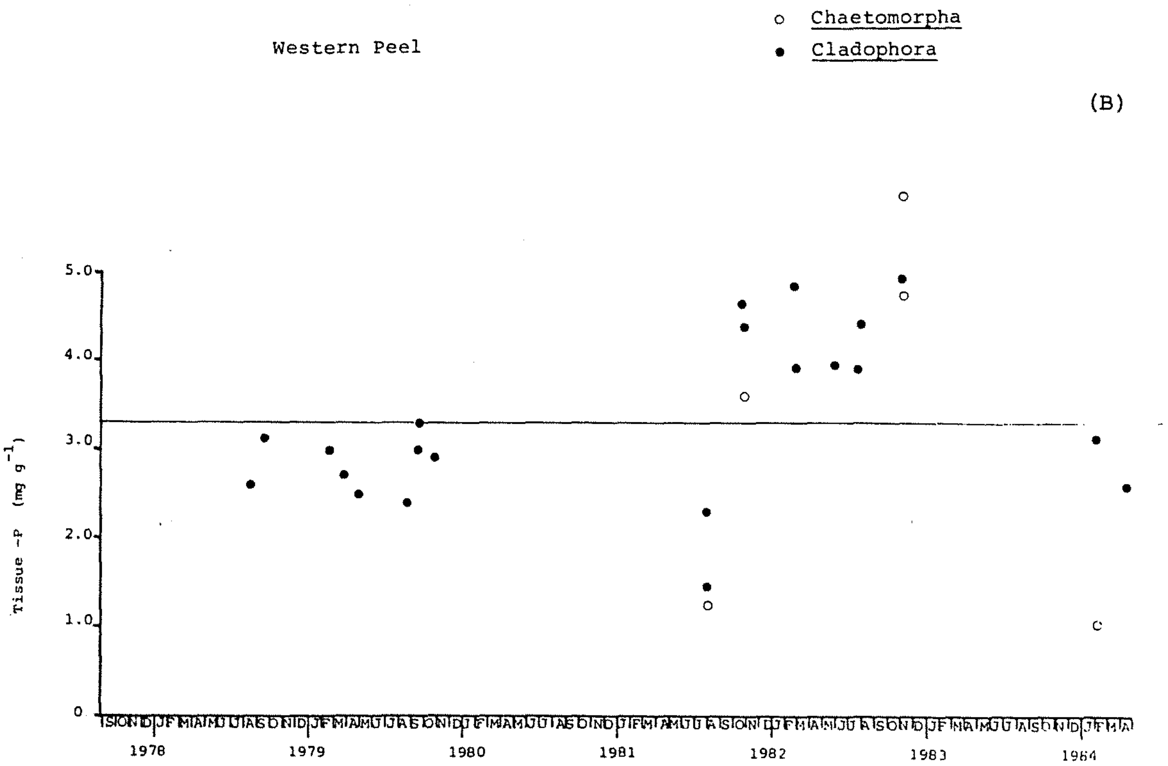


Figure 4. Tissue phosphorus concentrations in the eastern (A) and western (B) Peel macroalgal populations. The line drawn is the critical concentration for Cladophora.

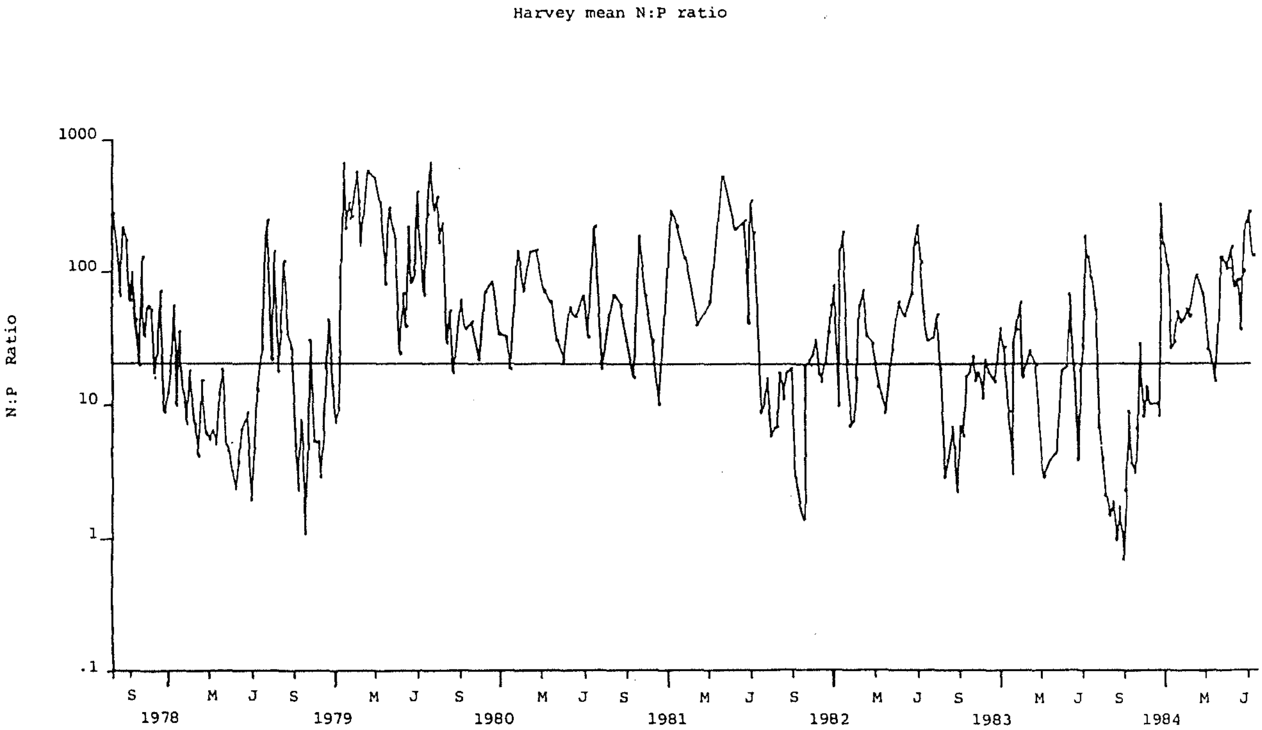


Figure 5. Harvey Estuary mean nitrogen to phosphorus ratio (inorganics by atom). The line drawn represents a ratio of 20:1.

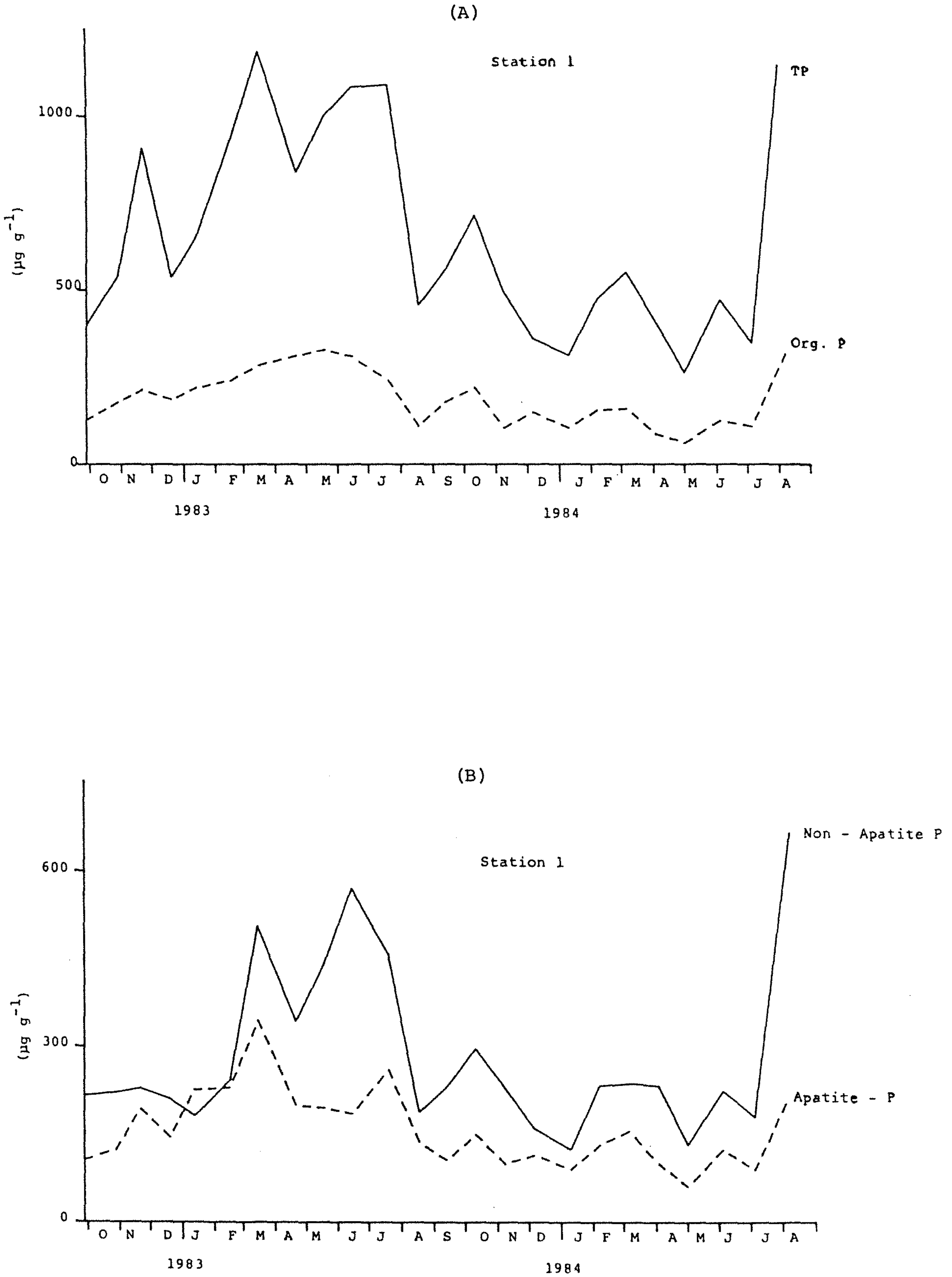


Figure 6. The concentration of phosphorus in the top 1 cm of sediment at Station 1 (mid-Harvey). A) Total and organic phosphorus concentrations. B) Apatite and non-apatite phosphorus concentrations.

2. Phytoplankton and nutrients

Introduction

In the Peel-Harvey system some 90% of riverflow and nutrient loading occurs in the winter months. Diatom blooms immediately follow riverflow, but are replaced by *Nodularia* blooms in spring. Analysis of data collected between 1977 and 1983 showed that the magnitude of the *Nodularia* bloom in Harvey Estuary in summer was related to the minimum salinity of the estuary, and total riverine phosphorus loading, in the previous winter. The relationship had a predictive capacity.

The diatom blooms trap phosphorus, which is sedimented largely as faecal pellets and senescent cells; this phosphorus is recycled and supports *Nodularia* growth under warmer conditions, and the amount available determines *Nodularia* biomass. *Nodularia* blooms collapse when summer salinities reach 30 ^{o}/oo.

In this section the relationship between nutrient input and phytoplankton biomass, over the previous 12 months, is assessed.

Analysis of 1983/84 data

Harvey Estuary mean surface chlorophyll 'a' concentration, which is a measure of phytoplankton biomass, is shown in Fig. 7. Between 1981 and 1983 progressively larger diatom blooms followed the collapse of the *Nodularia* bloom. Fig. 7 and Table 1 show that there was a significant decrease in post-*Nodularia* bloom chlorophyll 'a' levels in 1984 in Harvey Estuary. The 1983/84 *Nodularia* bloom was much smaller than the previous two years.

The much smaller post-*Nodularia* diatom bloom in 1984 may have been due to a reduction in phosphorus recycling and availability after December 1983, compared to the previous two years (see above). Harvey Estuary N:P ratios (Fig. 5) also tend to support the suggestion of a reduction in phosphorus recycling and availability in 1984 (see above). The N:P ratios in Harvey Estuary increased dramatically following the collapse of the 1983/84 Nodularia bloom in late December 1983.

The concentrations of organic nitrogen and phosphorus in the water column of Harvey Estuary, following the Nodularia bloom were lower in 1984 than 1983 (Table 4), as were chlorophyll 'a' concentrations (Table 1). This suggests that the eutrophication of the Harvey Estuary has not yet reached an irreversible stage. Nutrient levels in Peel Inlet in 1984 were similar to 1983 levels.

The relationship between the magnitude of the Nodularia bloom in summer, and minimum salinity (Fig. 8a) and total riverine phosphorus loading (Fig. 8b), in the previous winter, did not follow in 1983 and 1984, the trend established between 1977 - 1982. The 1983/84 Nodularia bloom was smaller than expected on the basis of minimum salinity and river phosphorus loading, and the 1984 bloom was much larger than expected, considering that there was little difference between the river phosphorus loading in 1984, and that in 1979, when no Nodularia bloom was recorded.

There appears to be no obvious explanation for the small Nodularia bloom in 1983. The bloom collapsed in mid-December, earlier than previous years, and salinities had not reached 30 ^{o}/oo.

The difference in the magnitude of the Nodularia blooms in 1979 and 1984 may have been due to a) the larger phytoplankton biomass in the winter of 1984 compared to 1979, b) lower salinities in 1984, and c) carryover of sediment phosphorus from 1983.

Mean Harvey chlorophyll 'a' concentrations for the winter period (May - September) in 1979 and 1984 are shown in Fig. 9. The winter phytoplankton bloom was much larger in 1984 compared to 1979. Total river phosphorus loading was similar in both years, but in 1979 a large proportion of the river phosphorus load was received in one large flood event in July. In 1984 the river phosphorus loading was more evenly distributed over a number of small flood events. As a result the winter phytoplankton bloom was much larger and sustained over a longer period than the 1979 bloom. The size of the winter phytoplankton bloom may affect the amount of phosphorus releasd from the sediment (see below). Sediment phosphorus release following the collapse of the winter phytoplankton bloom may have been much greater in 1984 as a result of the larger winter phytoplankton biomass.

Total river flow in 1979 was much lower than total flow in 1984. River phosphorus load was similar in both years because there was a marked reduction in the mean flow-weighted phosphorus concentration of the river water in 1984. As a result salinities were much lower in 1984 and the degree of stratification was much more pronounced especially in September and October (Fig. 10), the time of initiation of the Nodularia bloom. Sediment phosphorus release may have been much greater in 1984 due to the marked stratification. Under stratified conditions, dissolved oxygen in the bottom waters is rapidly depleted and the sediment surface becomes anaerobic. Sediment phosphorus release rates are much higher under anaerobic conditions (see below).

The maximum phosphorus load of the water column due to Nodularia biomass, expressed as a percentage of total river phosphorus load, is shown in Table 5. The water column phosphorus load varied between 14 and 38 tonnes, and this represents 12 - 69% of total riverine phosphorus load. The percentage of total riverine phosphorus load contained by the 1983 Nodularia bloom was much lower than that estimated for the previous three years. The amount of phosphorus lost from the Harvey Estuary, due to flushing, during the Nodularia bloom, would have been less in 1983 compared to the previous three years. This phosphorus may have been available to the 1984 Nodularia bloom and may account for the apparent large percentage retention of total riverine phosphorus load found in the 1984 bloom.

Possible effects of the Dawesville Channel.

The Dawesville Channel should in the relatively short-term result in a marked improvement in water quality in the Peel-Harvey system. This will mainly be brought about by a reduction in phytoplankton biomass and a concomitant decrease in water column nutrient levels, due to increased nutrient export from the system as a result of increased flushing.

If Nodularia blooms do occur, their duration will be reduced due to the increase in salinities.

Table 4. Harvey Estuary mean organic nitrogen and phosphorus concentrations for the period March - May.

Year	Organic nitrogen ($\mu g\ l^{-1}$)	Organic phosphorus ($\mu g\ l^{-1}$)
1978	868	96
1979	841	68
1980	913	43
1981	955	74
1982	1439	71
1983	2116	173
1984	1222	90

Table 5. Harvey Estuary peak water column phosphorus load due to Nodularia expressed as a percentage of annual input.

Year	Peak phosphorus load due to Nodularia (tonnes)	% of annual input
1978	13.7 - 19.2	12.2 - 17.1
1980	25.1 - 35.1	24.8 - 34.7
1981	27.5 - 38.5	20.6 - 28.9
1982	19.6 - 27.4	26.5 - 37.0
1983	17.9 - 25.1	16.1 - 22.5
1984	27.2 - 38.0	49.4 - 69.0

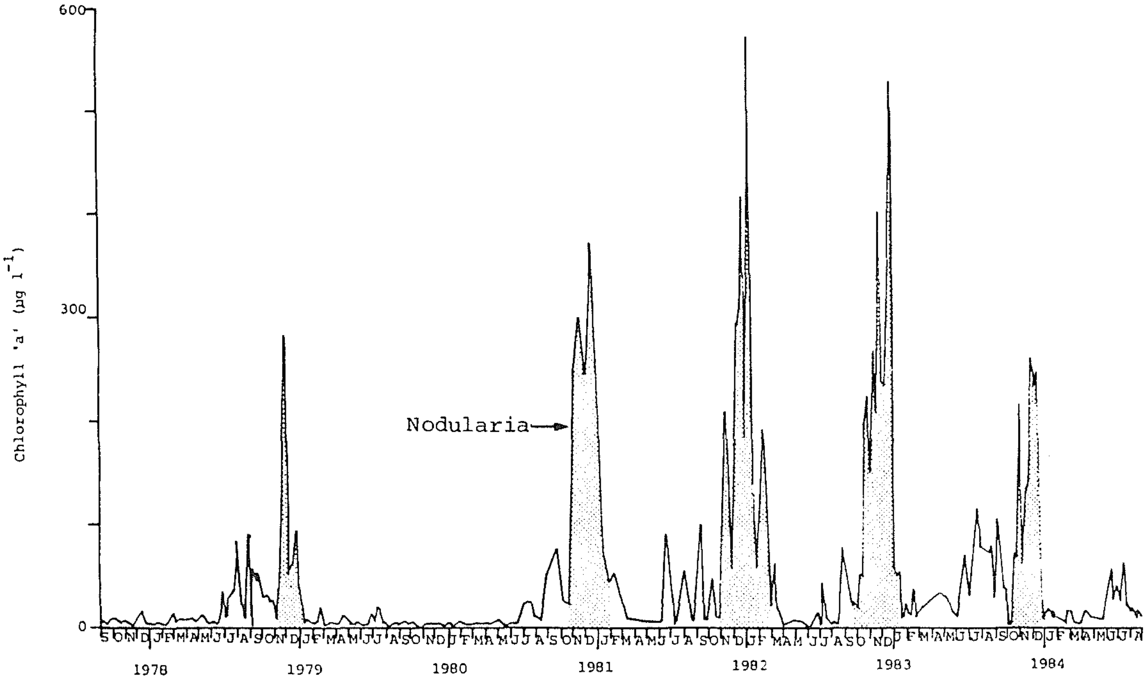


Figure 7. Harvey Estuary mean surface chlorophyll 'a'.

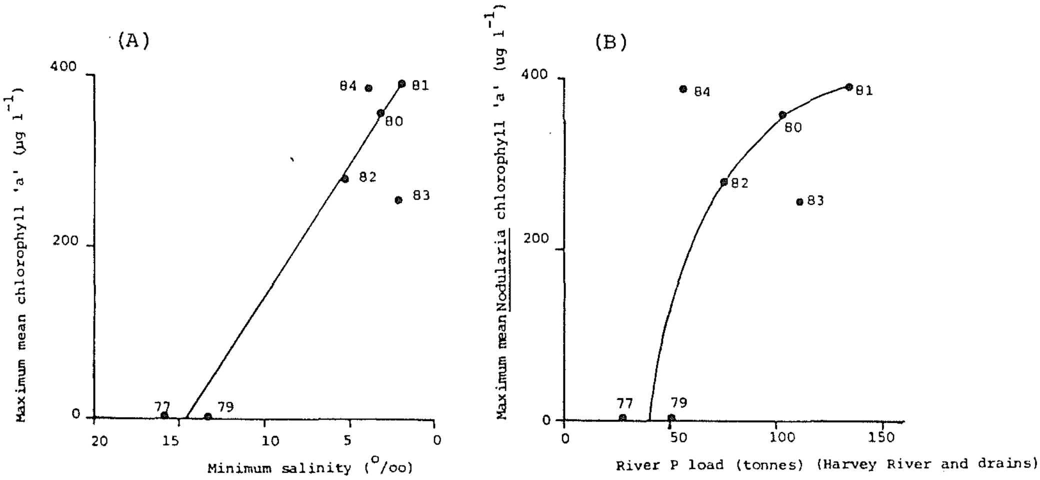
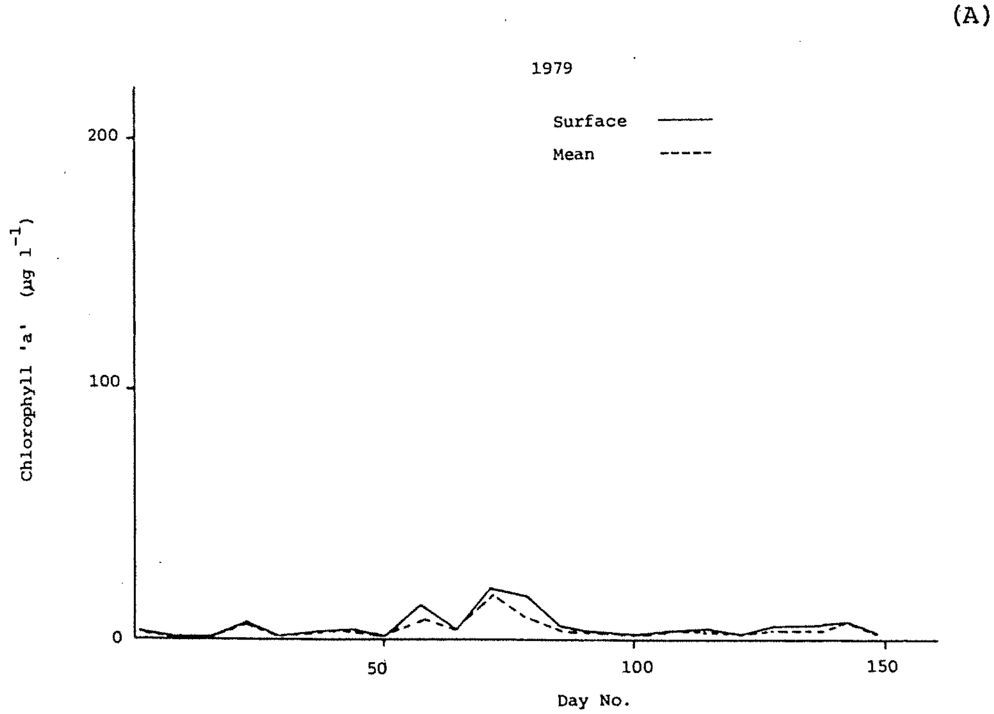


Figure 8. (A) The relationship between the summer maximum Nodularia chlorophyll 'a' concentration (averaged between surface and bottom concentrations) and the minimum salinity recorded in the estuary each preceding winter.
(B) The relationship between summer maximum Nodularia chlorophyll 'a' concentration and total river phosphorus load (Load data courtesy of P.B. Birch).



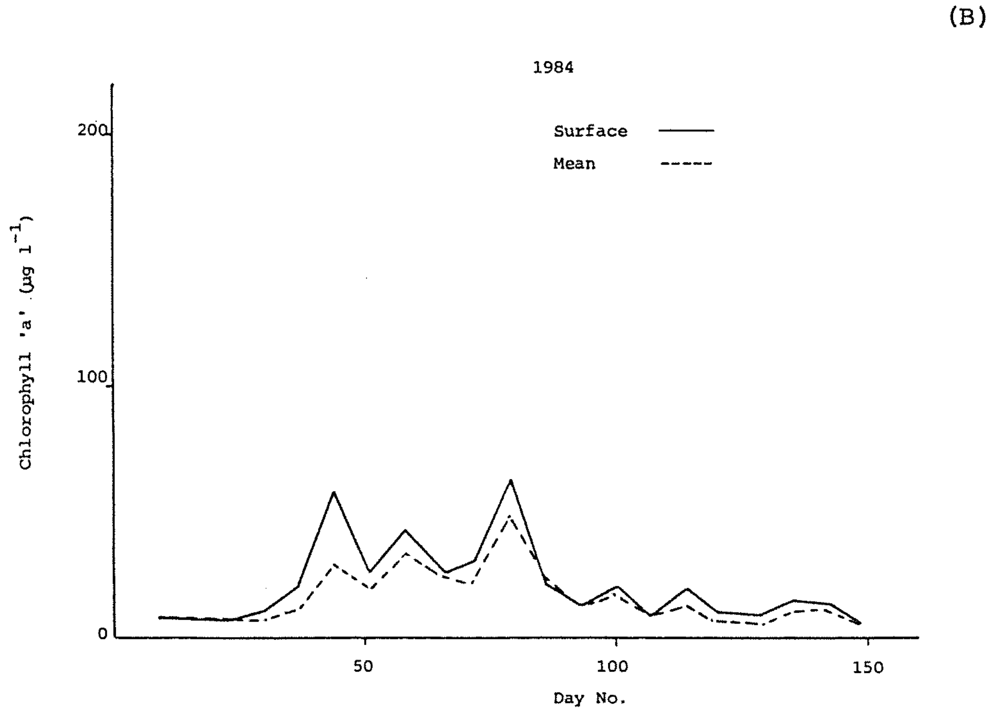


Figure 9. Harvey Estuary chlorophyll 'a' concentrations for the winter period (May - September inclusive) for 1979(A) and 1984(B).

3. Role of the Sediment Phosphorus Store

Introduction

Sediments play a major role in the phosphorus cycle in the Peel-Harvey system. The Nodularia blooms rely on the sediments as their major source of phosphorus, and there is approximately a 100 day lag between peak riverine phosphorus input and the initiation of the Nodularia bloom. The macroalgae also rely on the sediments as their major source of phosphorus, and at the time of peak phosphorus input, light and temperature limit macroalgal growth. The sediments have accumulated phosphorus because riverine phosphorus input greatly exceeds phosphorus losses. The main trapping mechanism appears to be the winter phytoplankton blooms which are closely linked to riverine phosphorus input (Lukatelich, 1984).

As noted above, until 1984/85 there was a close relationship between river phosphorus loading and maximum biomass of the following Nodularia bloom in Harvey Estuary. However, in 1984/85 the Nodularia bloom was much larger than expected on the basis of river phosphorus loading. Phosphorus release from the sediments in 1984 was greater than previous years. Unless the phosphorus loading to the sediments is reduced, the sediments will continue to accumulate phosphorus until they reach saturation. In time the sediments may become so phosphorus enriched that they may be able to sustain algal blooms with no further additions of phosphorus. The size of the sediment phosphorus store and potential phosphorus release from the surface sediments is examined below.

Phosphorus Store

For comparative purposes, the characteristics of the top 1cm of sediment for Peel Inlet, Harvey Estuary, and an ocean site, approximately 4 km NW of the entrance channel, are shown in Table 6. The Peel and Harvey sediments had a higher water and organic content, although the difference between the organic content of Peel Inlet sediment and the ocean was small. The total phosphorus content of the ocean sediment was higher than Peel Inlet sediment and lower than Harvey Estuary sediment. The organic phosphorus content of the ocean sediment was much lower than both the Peel and Harvey sediments. The striking difference between the ocean and Peel and Harvey sediments, was the large difference in the amounts of apatite and non-apatite phosphorus. Of the total phosphorus in the ocean sediment, 85% was apatite phosphorus (HCL extractable-P), whereas only 25% of the phosphorus in the Peel and Harvey sediments was in this form. Apatite phosphorus is usually sparingly available to algae (Hegemann et al 1983, Rosich and Cullen, 1980). The non-apatite (NaOH extractable- P) phosphorus fraction accounted for 50% of the total phosphorus in the Peel and Harvey sediments, but only 6% in the ocean sediment. Usually a large fraction of this non-apatite phosphorus is available to algae (e.g. Rosich and Cullen, 1980).

The total phosphorus concentration of the top 1 cm of sediment at the ocean site was very similar to that found in Harvey sediment and higher than that found in Peel sediment. There is no significant correlation between the total phosphorus content of sediments and the trophic state of the overlying water (Williams and Mayer, 1972). It is the amount of bioavailable phosphorus (non-apatite P) and the potential for its release and recycling that determines the contribution of the sediment phosphorus store to the overlying waters. At least half of the total phosphorus of the Peel-Harvey sediments is potentially available to the algae.

Depth profiles of Harvey Estuary sediment are shown in Fig. 11. There is a rapid drop in the water, total phosphorus and total nitrogen content of the sediment over the top 5 cm. These continued to fall over the next 15 cm but at a much slower rate. The organic content of the sediment dropped over the top 3 cm, and was then fairly uniform with depth. Only the top 5 cm of sediment are nutrient enriched compared with the rest of the sediment profile.

Sediment Phosphorus Release

The sediment data presented in Table 6 and Fig. 11 have shown that Harvey surface sediment contains a large amount of bioavailable phosphorus. The potential release of this phosphorus to the overlying water has been studied both in the laboratory and in situ. Sediment release rates measured in the laboratory are shown in Fig. 12. The rates are the mean total phosphorus release over the first 10 days of incubation. The laboratory studies measured potential phosphorus release, because conditions are optimum for this process. The release rates varied between 2 and 205 mg of total phosphorus per m^2 per day. On most occasions more than 75% of the total phosphorus released was in the form of phosphate, readily available for algae uptake.

Using the measured release rates, the surface sediment has the potential, on most occasions, to release about 30 tonnes of phosphate phosphorus to the overlying water column over 10 days, given ideal conditions. This is similar to the maximum phosphorus content of the water column measured during *Nodularia* blooms (Table 5). Obviously the sediments have the potential to sustain massive algal growth.

The release rate measured on a particular occasion was in general correlated with the oxic state of the sediment. On those occasions when the sediment and overlying water rapidly became anaerobic, the highest release rates were measured. Other factors such as the amount of utilizable carbon in the sediment are important and account for some of the variability.

In situ estimates of phosphorus release rates are shown in Fig. 13. These varied between -2 and 40 mg phosphate phosphorus per m^2 per day, considerably lower than the rates measured in the laboratory. Total phosphous release rates would be higher, but it is not possible to determine these. On some occasions release rates similar to those measured in the laboratory were recorded. In these experiments algal uptake of released phosphorus was not precluded, and this may have resulted in underestimates of release rate. Under aerobic conditions, the sediments can remove phosphorus from the overlying water, and this was observed on a number of occasions (Fig. 13).

As mentioned above, uptake by winter phytoplankton blooms is the major mechanism of trapping phosphorus in the Harvey Estuary. The phosphorus sediments out in the form of senescent cells or faecal pellets as a result of zooplankton grazing. The sedimenting cells and faecal pellets also represent a large organic carbon source for the sediments. Anaerobic conditions may develop at the sediment surface after aerobic bacteria have used up all the available dissolved oxygen in the decomposition of this organic matter. Under anaerobic conditions, anaerobic bacteria continue the decomposition process. The degradation of organic matter results in the production of electrons, and in the absence of oxygen other reducible species such as nitrate, sulphate or high valency cations (e.g. Fe^{3+}) function as electron acceptors. When insoluble iron (III) compounds are reduced phosphorus is released from the sediments.

The results from an experiment, designed to investigate enhanced sediment phosphorus release due to sedimentation of organic matter, are shown in Fig. 14. The 'sediment-plus-diatoms' treatment released much more phosphorus to the overlying water than the other treatments. The diatoms load the sediment with carbon as well as phosphorus. If anaerobic conditions result, this allows the release of phosphorus from the sediment, in addition to the phosphorus released from decomposition of the diatoms themselves.

Possible effects of the Dawesville Channel

If the channel reduces phosphorus and carbon loading to the sediments, due to increased flushing, and light attenuation decreases as a consequence, the sediments should remain oxic for most of the year. Under aerobic (oxic) conditions sediment phosphorus release rates are an order of magnitude lower than those under anaerobic conditions (Holdren and Armstrong, 1980).

Aerobic and anaerobic release rates for Harvey Estuary sediment are shown in Table 7. Under aerobic (oxygenated) conditions the phosphorus release rates were much lower. The Dawesville Channel should result in a significant decrease in phosphorus release from the sediments, and as a consequence there should be a marked improvement in water quality.

Table 6. The phosphorus content of the top 1cm of sediment from Peel Inlet, Harvey Estuary and Ocean (Collected May 1984).

	Peel Inlet $\bar{x}$, n = 12	Harvey Estuary $\bar{x}$, n = 15	Ocean
Water content (%)	43.3	56.1	26.9
Organic content (%)	6.9	12.4	6.4
Total phosphorus ($\mu g\ g^{-1}$)	235	433	377
Organic phosphorus ($\mu g\ g^{-1}$)	65	123	33
Apatite phosphorus ($\mu g\ g^{-1}$)	59	93	321
Non-apatite phosphorus ($\mu g\ g^{-1}$)	113	224	23

Table 7. Total phosphorus release from oxygenated and non-oxygenated Harvey Estuary sediments.

October 1984	10 day mean release rate mg T.P. $m^{-2}\ day^{-1}$
Oxygenated	2
Non - oxygenated	20
November 1984	
Oxygenated	0
Non - oxygenated	57

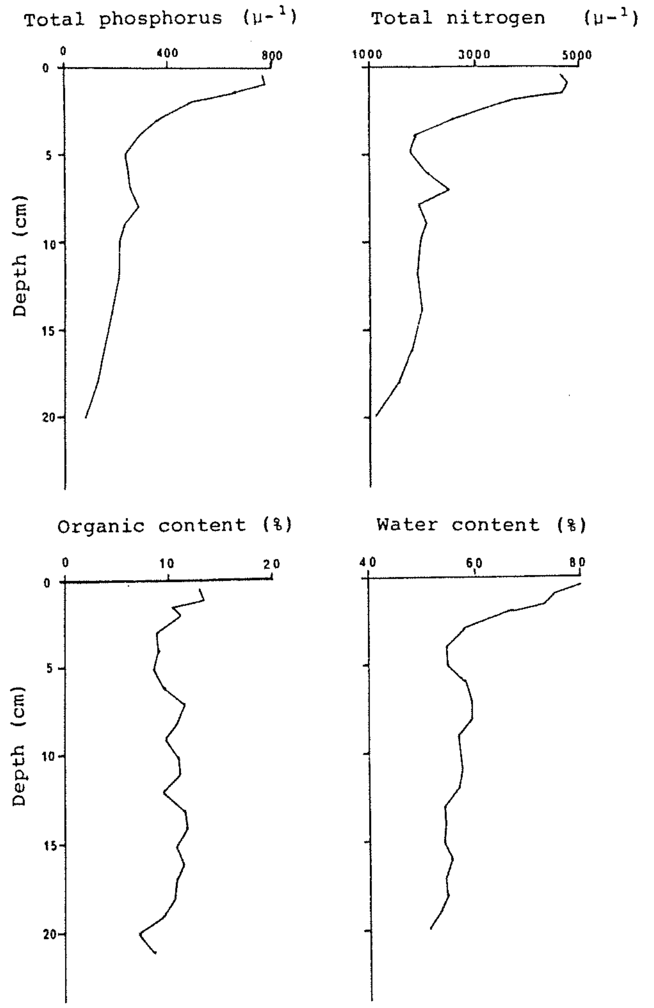


Figure 11. Depth profiles of the nutrient, organic and water content of the Harvey Estuary sediment.

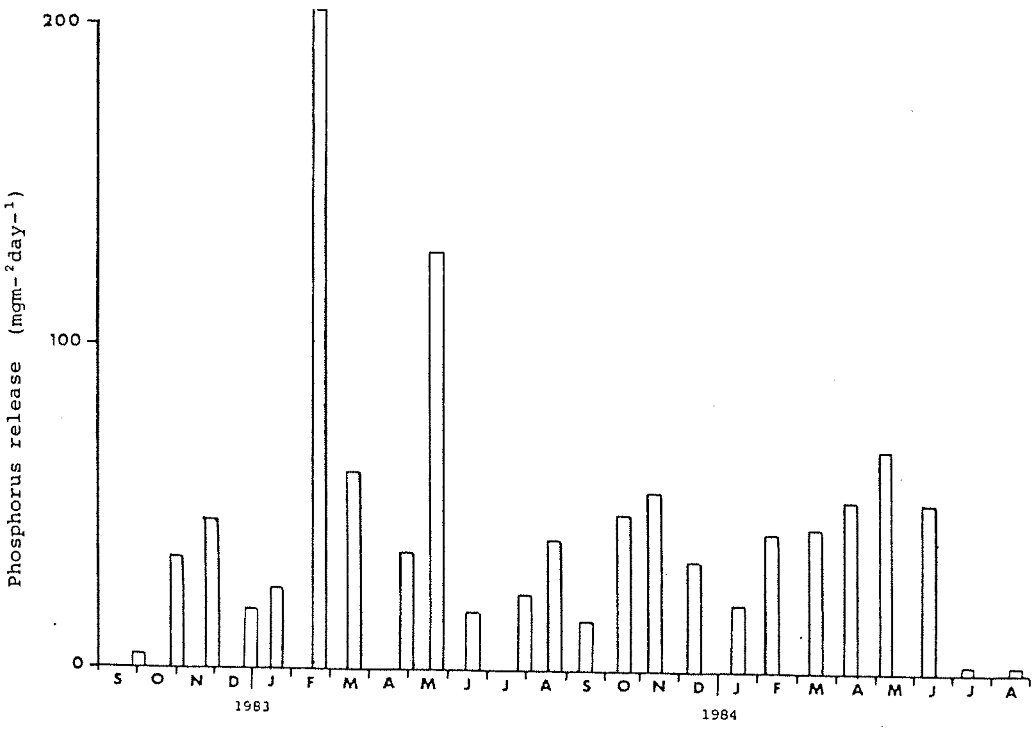


Figure 12. Phosphorus release (10 day mean) from Harvey Estuary sediment cores.

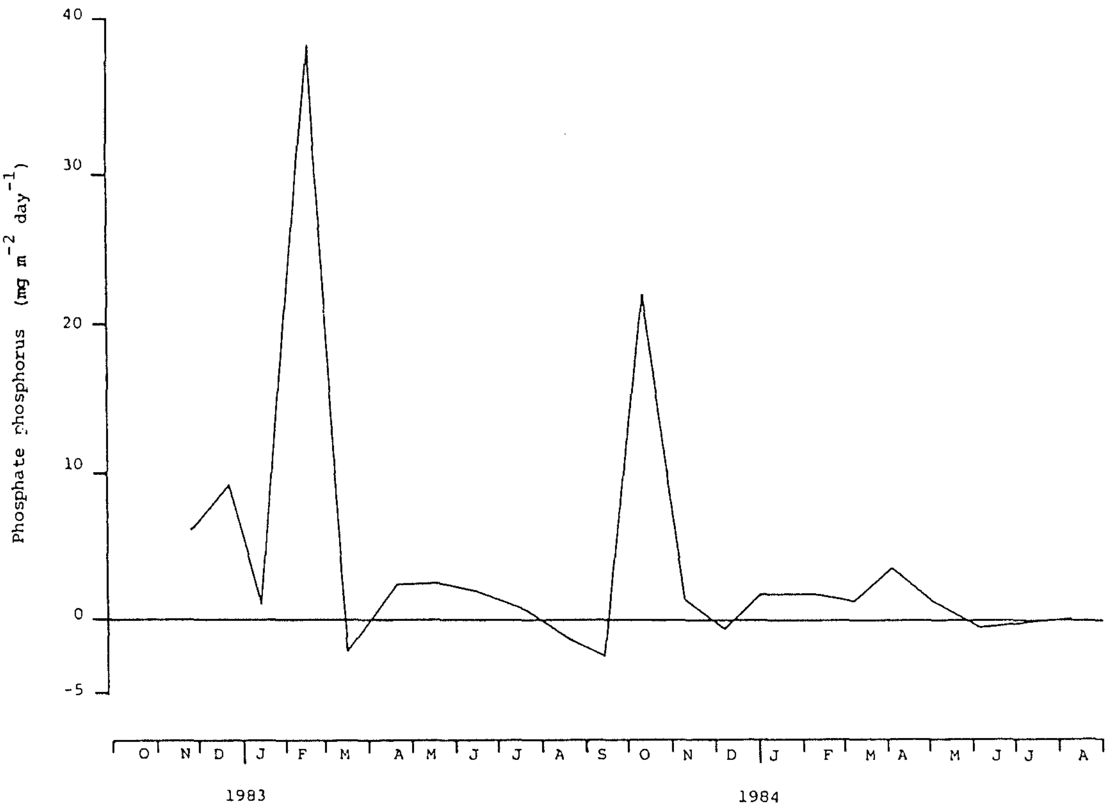


Figure 13. In situ phosphorus release rates from Harvey Estuary sediment.

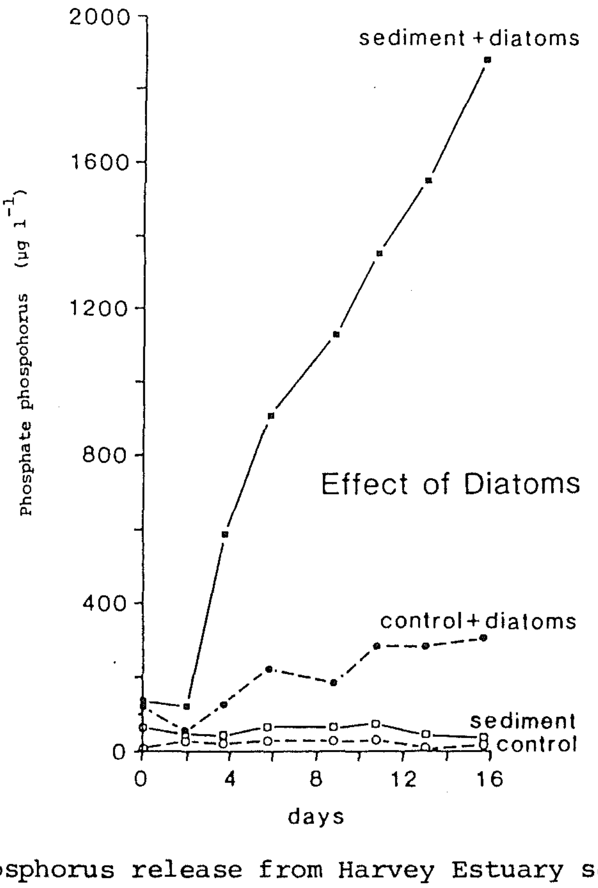


Figure 14. Phosphorus release from Harvey Estuary sediment cores with and without the addition of diatoms (control = estuary water). (Data of J.O. Gabrielson).

4. Zooplankton-possible changes due to the proposed Dawesville Channel.

Introduction

The zooplankton provide an important link between primary production and higher trophic levels in the Peel-Harvey system. They also play an important role in phosphorus retention in the Peel-Harvey system because they remove particulate phosphorus (phytoplankton) from the water column. This phosphorus sediments out in faecal pellets. Selective grazing by zooplankton has been suggested as a possible cause for the succession from winter diatom blooms to Nodularia blooms in the Peel-Harvey system (Lukatelich 1984).

In view of the important role of the zooplankton in the system any changes in species composition and abundance due to the proposed Dawesville Channel could have a significant ecological effect.

The most significant effect on zooplankton will be the changes in salinity. With the channel minimum winter salinities will be much higher, and maximum summer salinities will be lower, than those now experienced. Most of the zooplankton species in the system can tolerate the wide range in salinities (5-50 ppt) now experienced, i.e., they are euryhaline. With the proposed channel the salinity range will fall within that now experienced, and these euryhaline species will not be affected. However, some zooplankton species can only tolerate a narrow range of salinity, and these species may be eliminated or the length of time during which they can survive be reduced.

Possible changes in species composition and abundance of the zooplankton as a result of the proposed Dawesville channel are outlined below.

Harvey Estuary

The seasonal succession in the zooplankton of Harvey Estuary is shown in Fig. 15. The mysids and amphipods are generally only minor components of the zooplankton in Harvey Estuary and they are unlikely to be affected by the Dawesville Channel. The mysid (*Gastrosaccus* sp.) and amphipods (*Corophium minor*, *Paracorophium* sp. and *Melita* sp.) can tolerate a wide range of salinities.

Cladocerans (1 sp.) dominated the zooplankton for a short period in 1983 (Fig. 15). Cladocerans are only found in the zooplankton during wet winters and may become the dominant zooplankton if salinities remain below 5 ^{o}/oo for at least 2 - 3 weeks. The cladocerans cannot tolerate salinities above 15 ^{o}/oo. With the new channel, salinities are unlikely to fall below 5 ^{o}/oo, even in wet winters, except for short periods. Copepods currently dominate the zooplankton in average to dry winters (e.g. 1980). Cladocerans will be replaced by copepods, either *Gladioferans* sp. or *Sulcanus conflictus*, depending on new minimum salinities.

Copepods dominate the zooplankton in Harvey Estuary most of the time (Fig. 15). The composition of the copepods is shown in Fig. 16. *Sulcanus conflictus* usually becomes the dominant zooplankter each spring. *Sulcanus* is only found in large numbers when salinities have fallen below 20 ^{o}/oo for at least two weeks. Salinities will still fall below 20 ^{o}/oo with the channel, but the time below 20 ^{o}/oo will be significantly reduced. *Sulcanus* may be replaced by the marine calanoid copepod *Acartia*. *Sulcanus* is replaced by *Acartia* in spring, as salinities increase, in the lower reaches of the Swan River.

The cyclapoid copepods are the only other group likely to be affected by the proposed channel. Cyclapoids of the Peel-Harvey system are mainly marine species (e.g. *Oithona* and *Acartia*) and at present are only a minor component of the zooplankton (Fig. 16). With the channel more marine species of zooplankton may inhabit Harvey Estuary. Salinities during the summer-autumn period should be much closer to marine levels following instruction of the channel.

Primary productivity far exceeds secondary production in the Peel-Harvey system at the present time. A significant decrease in primary production would be required to significantly reduce zooplankton productivity. Primary productivity will decrease to some extent with the channel, however it is unlikely to severely affect zooplankton productivity.

Peel Inlet

The composition of the zooplankton in Peel Inlet (Fig. 17) is very similar to that of Harvey Estuary. The main differences are the increase in dominance of the mysids and amphipods and the relatively small cladoceran bloom in 1983. The higher winter salinities, as a result of the close proximity of the Peel to the ocean, compared to the Harvey, limits the size of the cladoceran bloom in Peel Inlet. The salinity range in Peel Inlet at present falls within that found in the Harvey Estuary. Following construction of the channel, the salinity range in Peel Inlet will be reduced even further. The predicted changes in zooplankton composition and abundance in Harvey Estuary, as a result of the Dawesville channel, also apply to Peel Inlet.

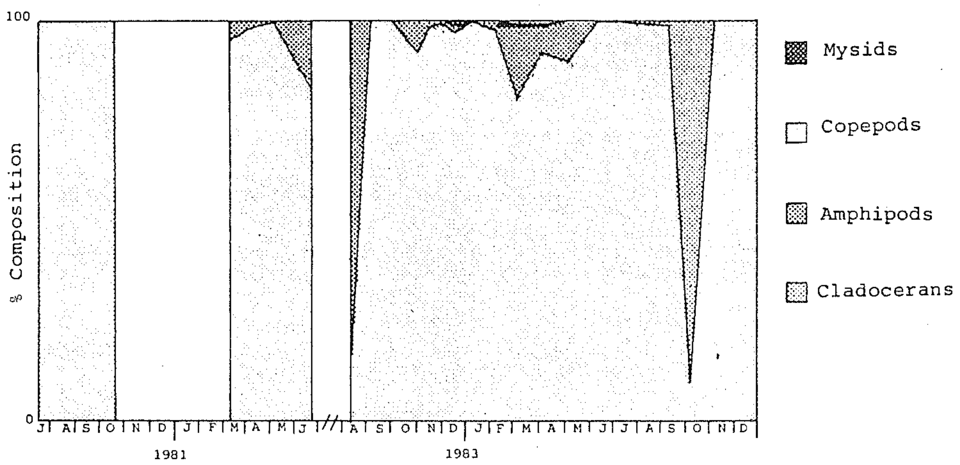


Figure 15. Relative abundance of the major groups of zooplankton in Harvey Estuary.

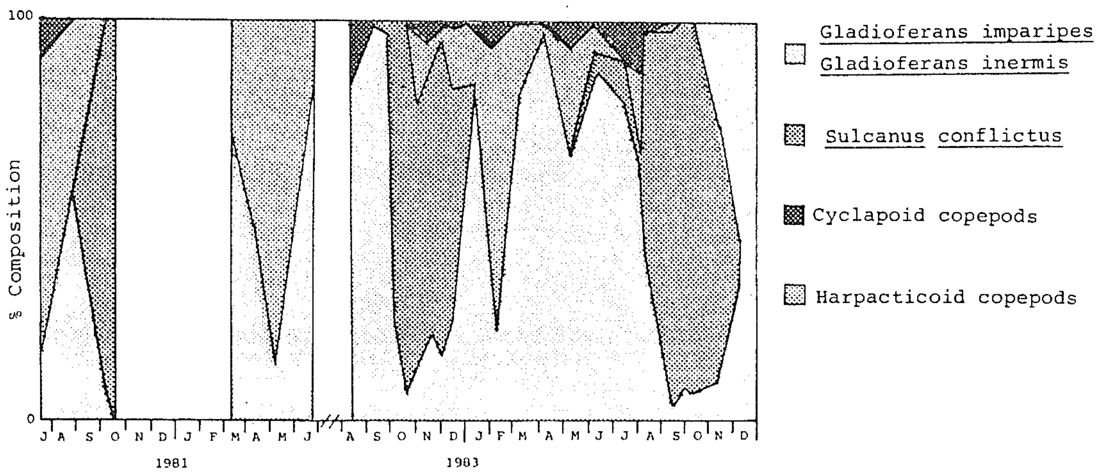


Figure 16. Relative abundance of copepods in Harvey Estuary.

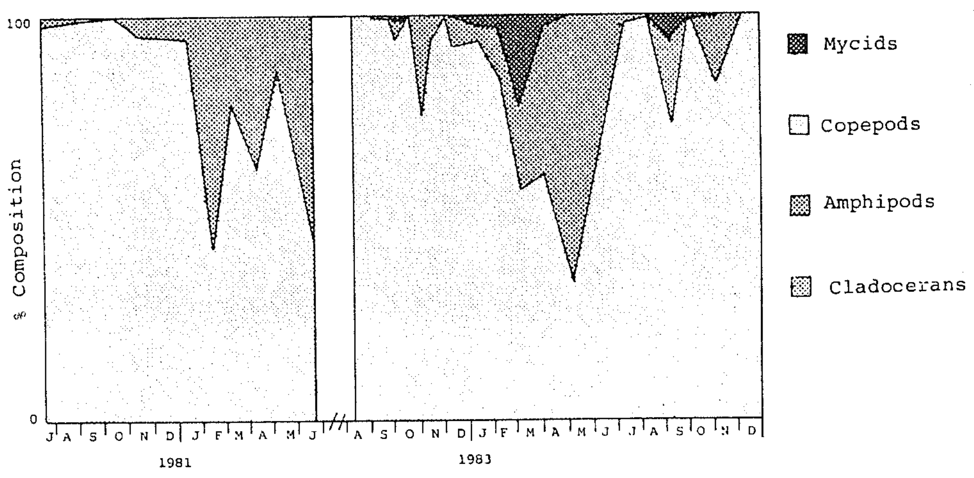


Figure 17. Relative abundance of the major groups of zooplankton in Peel Inlet.

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The Dawesville Channel: Predicted Response of Macrophytes

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Introduction

The proposed Dawesville Channel is expected to cause changes in the salinity regime, tidal dynamics, nutrient levels and light penetration of waters in the Peel-Harvey estuarine system. All of these factors have the potential to affect the growth and distribution of macrophytes. Responses of macrophytes to the Channel have been predicted using available information on these plants for both the Peel-Harvey estuarine system, and a number of other well-studied estuaries in southwestern Australia (notably the Swan River Estuary, Blackwood River Estuary, and Leschenault Inlet). Since different types of macrophytes are affected to different degrees by various factors, responses have been examined separately for the three main groups of macrophytes: fringing or marsh vegetation, seagrasses and macro-algae.

Fringing Vegetation

Fringing vegetation occupies the upper tidal zone, from about mean water level (MWL) to just above extreme high water mark (EHWM). In the Peel-Harvey system there are only three extensive areas of fringing vegetation: the junction of Peel Inlet and the inlet channel, eastern Peel Inlet, and southern Harvey estuary. The remainder of the system carries only a narrow band of fringing vegetation, in part due to the abrupt slope of the shores, and in part because of urban and agricultural development. The importance of fringing vegetation lies in five main areas:

(i) their function in maintaining estuaries as efficient waterways;

(ii) shoreline stabilization;

(iii) provision of sheltered habitats for birds;

(iv) their role as a major plant nutrient pool;

(v) their aesthetic appeal.

In addition, since fringing vegetation occupies the upper tidal zone, it is subject to tidal inundation, which logically implies nutrient exchange with the open water. A degree of controversy exists as to whether there is any net export of nutrients from fringing marshes, or net import from the open water. However, the current opinion is that although there may be a considerable degree of exchange between the fringing vegetation and open water, there is no significant net flux either way. That is, import of nutrients from the open water equals export from the marsh. Research on local estuaries tends to support this theory, and suggests that if there is a trend, local estuarine fringing marsh may accumulate nutrients from the water.

Within the area occupied by fringing vegetation, there is a zonation of species with increasing distance from the water's edge and increasing elevation. This zonation is dictated by the ability of different plants to tolerate high salinities and degrees of inundation. Broadly speaking, close to the water's edge only plants capable of withstanding high salinities and levels of inundation are found. At higher elevations, where inundation is less frequent, and where the higher water levels occur in winter when salinities are low, species which are less tolerant of high salinities and flooding can become established. It is salinity extremes, not averages, that determine the species present, and since hypersaline conditions are experienced during summer in the Peel-Harvey system, fringing vegetation is dominated by salt tolerant species of rush and samphires. Behind the fringe of Juncus marsh, there also occur occasional areas of impeded drainage where salinities rise because of ponding and evaporation of water containing salt, and where samphires dominate.

The Dawesville Channel will cause four changes that are likely to affect fringing vegetation:

(i) EHWM will be higher, although MWL will remain the same;

(ii) the greater astronomic tidal effects will cause increased frequency of inundation and exposure of intertidal areas over a broader range;

(iii) waters will be less saline in summer;

(iv) waters will be more saline in winter.

According to computer modelling predictions, few of these changes will be experienced by fringing vegetation around the existing inlet channel, since this area already experiences astronomic tides similar to those which will be experienced by the remainder of the estuary with the Channel. Changes to fringing vegetation in the remainder of the estuary can be summarised as follows:

1. The present lower limit of fringing vegetation will not change since MWL will remain the same, assuming that there are no sudden changes in sedimentation and erosion patterns.
2. EHWM will be higher, and so fringing vegetation can be expected to extend to slightly higher ground. This will not be very significant along the eastern and western Harvey estuary and western Peel Inlet, since beach ridge slopes are fairly abrupt, but there will be an extension of marshes at eastern Peel Inlet and southern Harvey Estuary. However, any such changes will occur slowly (over a period of years).
3. Increased frequency of inundation of the fringing vegetation will increase the nutrient exchange with the open water, but there is unlikely to be any net nutrient flux. Increased inundation and lower summer salinities will generally enable

less salt tolerant plants to move into areas where they cannot survive at present. This is because the increased flushing and lower salinities will lower soil salinities. The higher salinities in winter are unlikely to cause any changes in their own right, since during winter river discharge fringing vegetation will tend to be flushed by the upper layer of low salinity water prior to wind mixing events.

4. The improved flushing and less extreme salinity regime should lead to an improvement in marsh status.

Two other points should be made. Firstly, areas of fringing vegetation that have been degraded by macroalgal accumulations in the 1970's are no longer stabilised, and increased tidal fluctuations may cause erosion. Thought should be given to replanting fringing vegetation in these areas. Secondly, the increased tidal amplitude may result in occasional inundation of areas that are presently completely dry throughout summer. This may cause an extension of the mosquito breeding season, and the topography of two areas in particular, Goegerup Lake and Yunderup Canals, should be investigated with this point in mind.

Seagrasses

Unlike algae, seagrasses have true roots, rhizomes, leaves and flowers, and as the name suggests, look rather like terrestrial grasses. There are extensive areas of seagrasses in the shallow waters of Peel Inlet, with Ruppia megacarpa in the shallowest waters, and Halophila ovalis in slighly deeper waters. There is also a small area of the essentially marine species Zostera mucronata near the inlet channel. There are no extensive meadows of seagrasses in Harvey Estuary because the turbidity of the water does not allow sufficient light to reach benthic plants, and the salinity regime is also too extreme for most seagrasses.

Seagrasses are generally considered more ecologically desirable than macroalgae. Since they are rooted in the sediments, they are not as easily washed up on the shores, and although leaves may detach and accumulate on the shores in some months, they do not rot as offensively as macroalgae. Seagrasses are also ecologically important for the following reasons:

(i) they are very productive - it is acknowledged that estuaries dominated by seagrasses are just as if not more productive than those dominated by macroalgae or phytoplankton;

(ii) they are capable of forming dense, productive meadows in very nutrient-poor waters, since they can tap sediment nutrient supplies;

(iii) they support extensive detrital food webs. Although some seagrasses are grazed by ducks and swans, most seagrass production becomes detritus, and is utilized by benthic invertebrates;

(iv) the dense canopy of meadows provides protection for fauna from predators, and softens water movement to provide a calm environment;

(v) their structural complexity (root, rhizomes, stems, leaves) provides a variety of attaching surfaces for epiphytic organisms, and an increased diversity of microhabitats for fauna.

Factors affecting seagrasses include light, salinity, nutrient levels in the water column (an indirect effect on seagrasses), current velocity and degree of exposure. Seagrasses cannot grow if less than approximately 2-5% of surface light reaches the bottom, and some species require much more light than this. H. ovalis is fairly tolerant of low light levels, but R.

megacarpa, which occurs in the shallows, prefers higher light levels. Salinity tolerances also vary between seagrasses, and the presence or absence of a species in an estuary is usually determined by tolerance to low salinities. For instance, Z. mucronata only grows in essentially marine waters, H. ovalis prefers marine salinities but tolerates short periods of low salinities, and R. megacarpa can tolerate waters from fresh to hypersaline.

Water column nutrient levels affect seagrasses indirectly because high nutrient levels cause excessive growth of macroalgae, epiphytic algae (on seagrasses) and phytoplankton, all of which can block the light supply reaching seagrasses. Macroalgal accumulations have already caused dieback of seagrass meadows in Peel Inlet. Regarding current velocity and degree of exposure, H. ovalis and especially R. megacarpa prefer calm waters, whilst Z. mucronata can tolerate moderate current velocity. However, R. megacarpa can tolerate short periods of exposure, whilst the other two species are essentially subtidal.

With the Dawesville Channel, light penetration is expected to improve as Nodularia and other phytoplankton blooms decrease in both Peel Inlet and Harvey Estuary, and as easily suspended sediments in the Harvey Estuary are lost through oceanic exchange. The Harvey Estuary is expected to become more marine, and water column nutrient levels will decrease. The subtidal area of the estuary will decrease slightly, but intertidal areas will be inundated more frequently. Of these changes, salinity and light will have the most impact on seagrasses. The improved light penetration in Peel Inlet will allow seagrasses to extend to deeper waters. In Harvey Estuary, the improved light climate should enable the establishment of seagrasses in the shallows, particularly H. ovalis since the new salinity regime will be favourable for this species. Light penetration in the Harvey is unlikely to become as good as in Peel Inlet in the short term because of its typical resuspension of fine sediments due to wind-generated waves. However, in the longer term, as these fine suspended sediments are gradually lost through oceanic exchange, seagrasses should be able to move into deeper waters. On the other hand, there will probably be slight losses of seagrasses from shallow waters in Peel Inlet because of exposure of hitherto pemanently submerged areas.

As far as more minor effects are concerned, the lower water column nutrient levels should favour seagrasses by resulting in less epiphytic growth. Current velocities expected near the proposed Channel will probably prevent H. ovalis and certainly R. megacarpa from establishing. However the essentially marine conditions expected in this area should favour the establishment of the more robust Z. mucronata. As a final point, there is the possibility of using transplanting methods to establish seagrass meadows. Transplanting techniques have been used successfully overseas, and extensive meadows may both help tie up the excess of sediment nutrients that has developed in recent years, and maintain the high productivity of the estuary.

Macroalgae

The management problems of macroalgal accumulations in the Peel-Harvey estuarine system need no introduction, but it is worth pointing out that as far as estuarine fauna are concerned, macroalgae have many of the benefits of seagrasses. That is, they are highly productive, support detrital food chains, provide cover from predators and provide attaching surfaces for epiphytic organisms. It is also worth emphasizing that macroalgae are a natural feature of estuaries, and even oligotrophic systems have occasional shore accumulations.

As far as the Dawesville Channel is concerned, critical factors affecting macroalgal populations will be light penetration and nutrient levels. Salinity changes can be discounted, because all the nuisance algae in the system have broad salinity tolerances. The more marine salinity regime expected with the Channel will enable a few of the more coastal species to penetrate the estuary, but will not detrimentally affect present nuisance species.

The Dawesville Channel is expected to cause an improvment in light penetration in the Peel Inlet. Since macroalgal populations in northern and eastern Peel Inlet appear to depend on nutrients from the Murray and Serpentine Rivers, and macroalgal populations have only been low in recent years because of high water turbidity, it is likely that the Dawesville Channel may cause an increase in macroalgal populations in these areas in the short term. There is also evidence that macroalgae overlying sediments can create localised anaerobic conditions, thus increasing rates of nutrient release from the sediments. Since sediments in both Peel Inlet and Harvey Estuary contain considerable reserves of nutrients 'available' for plant growth, macroalgae may be sustained even if water column nutrient levels are low. However, in the longer term, as nutrient supplies are depleted, macroalgae levels should decrease.

In Harvey Estuary and western Peel Inlet macoalgae depend on nutrients from the Harvey River, but again, sediment reserves are sufficient to sustain large accumulations even if nutrient supplies from the river cease. Thus the improved light penetration with the Dawesville Channel will probably lead to an increase in macroalgae populations in the short term, although accumulations are unlikely to occur near the Channel because of increased water velocities. It is unlikely that macroalgae accumulations the size of those in Peel Inlet will occur, because much of the water turbidity is due to resuspension of fine sediments, and waters will not become as clear as in Peel Inlet in the short term. In the longer term, the considerably increased flushing rate may well cause a marked improvement in water clarity, but will also deplete nutrient levels. Therefore macroalgae levels in western Peel Inlet and Harvey Estuary should also decrease in the longer term. It is difficult to predict precisely how long sediment nutrient reserves will take to deplete is difficult to predict; more research is needed in this area.

Summary

- Fringing vegetation will extend to slightly higher ground, and species zonation will change. Overall, the status of fringing vegetation is expected to improve.

- Seagrasses may recede from shallow waters in Peel Inlet, but extend into slightly deeper waters. In Harvey Estuary, seagrasses are expected to establish in the shallows, and extend into deeper waters as light penetration continues to improve.

- In northern and eastern Peel Inlet, macroalgae will increase in the short term, then decrease in the long term. In Harvey Estuary and western Peel Inlet macroalgae will also increase in the short term, except near the Channel, but populations should not be as large as in northern and eastern Peel Inlet. In the longer term, these populations will also decrease.

- Management options include replanting areas of fringing vegetation in degraded areas and using transplanting techniques to establish seagrass meadows in Harvey Estuary. Harvesting of macroalgae from the shores is expected to be an ongoing need, at least in the short term.

THE LIKELY IMPACT OF THE PROPOSED "DAWESVILLE CHANNEL" ON THE BENTHIC FAUNA OF THE PEEL-HARVEY ESTUARINE SYSTEM

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INTRODUCTION

Of the soft-bottom habitats along the southwestern Australian coast, benthic fauna achieve their highest densities in estuaries such as the Peel-Harvey (Le Provost, Semeniuk and Chalmer, 1983). These estuaries form an ideal environment for benthic fauna as they provide a vast food resource, are protected from current, wave and storm activity, and also restrict the activities of predators to some extent. Within the estuarine environment, benthic fauna themselves provide a food resource for higher order predators in the food chain, such as fish and waterbirds. For example, in southwestern Australian estuaries benthic fauna are eaten by 15 of the 17 most commercially important fish species (Le provost, Semeniuk and Chalmer, 1983). Thus benthic fauna are an integral part of any estuarine ecosystem, and any changes to the environment which may affect the benthic fauna could also have substantial repercussions on other components of the estuarine ecosystem.

The proposed Dawesville Channel will greatly alter key factors in the Peel-Harvey estuarine environment. This paper examines the likely impacts of the Channel on the benthic fauna community. In order to carry out this exercise, the factors which affect the biology of benthic fauna and the characteristics of the abundant species are examined first. The possible effects of the Channel on these factors is then discussed. Finally, the likely impact of expected alterations in these factors on the benthic fauna is predicted.

At this stage, it should be pointed out that this paper is largely a desk study based on results of previous research in estuaries other than the Peel-Harvey, although some data for the latter are available. It should also be emphasised that the likely effects of the Channel on benthic fauna are only assessed at a gross level. Exact effects cannot be quantitatively predicted because of uncertainties in predictions on the physico-chemical state of the estuary, and on resident flora, should the Channel proceed, and because of the complexity of the ecosystem at the benthic fauna trophic level. Additionally, modelling of the exact changes in the tidal and salinity regimes due to the Channel is not yet available.

FACTORS AFFECTING THE BIOLOGY OF ESTUARINE BENTHIC FAUNA

A range of studies have identified the major factors which determine the composition, distribution and abundance of benthic fauna in southwestern Australian estuaries. Those studies suggest that the most important factors - in approximate order of importance - are:

(i) Salinity
(ii) Substrate
(iii) Tidal level, depth
(iv) Deoxygenation

(v) Productivity
(vi) Temperature
(vii) Estuarine plants

Each of these factors is separately discussed below.

Salinity

Estuaries typicaly undergo seasonal extremes in many environmental factors, but salinity is considered the single most important factor affecting benthic fauna. According to their ability to tolerate salinity extremes, benthic fauna in estuaries can be grouped into four main categories (Chalmer et al 1976):

Group 1 Marine species - which have no more than temporary or sporadic estuarine representation. These species are essentially marine, and are believed to invade estuaries each year as planktonic larvae. They settle and mature in waters near the mouths of estuaries during those months when marine salinities prevail (summer and autumn in local estuaries), and are killed by the winter freshwater flush.

Group 2 Species of marine affinity - which have a more or less continuous estuarine representation. Although these species prefer marine salinities, they are able to tolerate short periods of less saline conditions. They are usually found in the lower reaches of estuaries, and may extend upstream during periods of dry winters.

Group 3 Species of exclusively estuarine affinity - which have neither marine nor freshwater representation. These species are confined to estuaries, and since they tolerate a broad range of salinities (from almost freshwater to hypersaline conditions), they are found in lower, middle and upper estuarine reaches.

Group 4 Species of freshwater affinity - which have limited estuarine and no marine representation. These species are found in the upper reaches of estuaries, and/or when river flow results in temporary freshwater conditions.

The estuaries of southwestern Australia have an impoverished species richness compared to coastal areas, which has been attributed to their extreme hydrological regime. Most of the species of benthic invertebrates found in estuaries belong to the first two categories listed above. Therefore the species richness and the distribution of species within any estuary is greatly affected by the degree of marine influence it experiences. Estuaries with a greater marine influcence have a greater species richness, because more marine and marine affinity species are present. This can be seen if, for example, mollusc species richness in the Swan River estuary and the Peel-Harvey estuarine system is compared; the former, which experiences the greater marine influence, has 89 species whereas the latter has only 22 species (Wells et al, 1980) although it should be mentioned that other factors (habitat diversity, temperature extremes) are also partly responsible. Obviously the distance upstream at which marine and marine affinity species are found is also determined by degree of marine influence.

Substrate

Substrate type ranges from sand to mud, although hard substrates such as submerged logs and rocks are present to a minor degree. Benthic fauna are usually more abundant in sandy substrates, which tend to occur on the shallow marginal shelves of estuaries (Le provost, Semeniuk and Chalmer, 1983). Mud substrates, which most often occur in the deeper central basins of estuaries, tend to have lower numbers of benthic fauna. In the Peel-Harvey estuarine system, sandy substrates were extensive on the shallow marginal shelves, but the recent algal blooms have resulted in mud being deposited over much of these areas.

Tidal level/depth

Both tidal level and depth are important in determining the composition and abundance of benthic fauna. Studies on the vertical distribution of benthic fauna within local estuaries have shown that both the highest abundance and species diversity are reached on the shallow subtidal sandflats (Wallace, 1976, 1977; Wells et al, 1980; Le Provost, Semeniuk and Chalmer, 1983; Chalmer and Scott, 1984).

Benthic fauna are abundant in the lower intertidal zone (mean water level to low water mark), although species richness is less, with the main orgainisms being polychaete worms and some molluscs, particularly *Hydrococcus brazieri* and *Arthritica semen*. However, the deep muddy basins contain low numbers of benthic fauna and amphipods, larger polychaete worms and most molluscs are notably absent. An exception is the bivalve *Spisula trigonella*, which although more abundant in shallow sandy areas, is often found in muddy areas during the summer/autumn period (Hughes, 1973; Wallace, 1976, 1977; Le Provost, Semeniuk and Chalmer, 1983). The bivalve *Tellina deltoidalis*, and the gastropods *Velacumantus australis*, *Nassarius burchardi* and *N. pauperatus* may also be found in deeper muddy areas.

The low numbers of benthic invertebrates in the deeper muddy areas of local estuaries is attributed by Wallace (1977) and Atkinson and Edward (1984) to low oxygen availability, which in turn is related to sediment particle size, water depth, and high bacterial populations in the organic-rich mud. Low abundance of benthic fauna in the upper intertidal zone is largely caused by dessication and/or temperature stress. In the Peel-Harvey estuarine system, the fauna of the lower intertidal zone are also restricted to a fairly narrow band, because, although long-term (meteorological) changes in water depth are little attenuated in the system, only approximately 10% of daily (astronomic) tidal amplitudes are experienced. Thus only a very narrow zone is exposed and inundated on a daily basis.

Deoxygenation

Deoxygenation may cause mortality of benthic fauna if it is severe. In particular, severe oxygen depletion has been reported from the Peel-Harvey during *Nodularia* blooms, with widespread mortality of benthic fauna (Hodgkin, pers. comm).

Productivity

Productivity is characteristcally high in estuaries, where high plant productivity supports high benthic community productivity. This is reflected in the high abundance of benthic fauna is southwestern Australian estuaries relative to adjacent coastal areas (Le Provost, Semeniuk and Chalmer, 1983). In the Peel-Harvey estuarine system densities of benthic fauna as high as 107 000 per m^2 have been recorded (Chalmer and Scott, 1984). However, despite the abundance of benthic fauna in the estuary, Atkinson and Edward (1984) report that the results of a recent survey indicate only one twentieth of daily primary production is accounted for by these orgainisms.

Temperature

Temperature in estuaries fluctuates widely on a diurnal seasonal basis (eg Day, 1981). Temperature is most likely to affect benthic fauna through its influence on growth rates, reproductive rates and behaviour (eg Wells et al, 1980).

Estuarine Plants

The type and abundance of estuarine plants can affect the composition and density of benthic fauna. For instance, detritivores may be more favoured in an estuary dominated by seagrass beds, whereas filter feeders may be favoured in a phytoplankton dominated system. As an example, amphipod and polychaete worms are reported to comprise 60% of the benthic fauna on shallow sandy platforms carrying dense seagrass beds in Leschenault Inlet (Le Provost et al, 1983; Chalmer and Scott, 1984), whereas in the currently phytoplankton dominated Peel-Harvey estuarine system, molluscs are reported to comprise up to 95% of total benthic invertebrate biomass (Cheal et al, 1983).

While the above factors are all important in affecting benthic fauna, it should be noted that some of these fators, for instance salinity, tidal inundation, deoxygenation and temperature, are likely to vary on a diurnal, seasonal or annual basis. Benthic fauna which are successful in estuaries cope with such fluctuations in two ways. Firstly, they are extremely tolerant of wide fluctuations in these factors, and have physiological or behaviourable means of surviving the extreme conditions in estuaries. Secondly, if conditions become sufficiently extreme to cause mortality of the benthic fauna, their population characteristics are such that they rapidly re-invade and re-establish when conditions become favourable again.

THE CHARACTERISTICS OF THE ABUNDANT BENTHIC FAUNA

While marine and marine affinity species constitute the majority of species found in estuaries, a relatively small number of species of exclusively estuarine affinity (Group 3) dominate population abundances and biomass. These few species are often extremely abundant in the estuaries because they are better adapted to cope with the typically extreme conditions, and consequently can take full advantage of the sheltered conditions and rich food supply available. Thus compared to coastal areas, estuaries are poor in species but rich in individuals (Day, 1981), which is largely due to the productivity of a few truly estuarine species.

In Table 1 the suite of estuarine species that have been found to comprise up to 95% of population densities in the Blackwood River Estuary, Swan River estuary, Leschenault inlet and the Peel-Harvey estuarine system is listed (Wallace, 1976; Wallace, 1977; Wells et al, 1980; Cheal et al, 1983; Le Provost, Semeniuk and Chalmer, 1983 and Scott, 1984). The importance of species within the suite appears to vary according to the estuary.

In addition to the highly successful estuarine species listed in Table 1, few species of marine affinity have been recorded in high numbers in the lower to middle reaches of estuaries during the summer-autumn period. Such species include the gastropods Nassarius burchardi. N. pauperatus and Velacumantus australis (the latter in the Swan River estuary only, the bivalves Spisula trigonella, Sanguinolaria biradiata, Tellina deltoidalis, and in estuaries south of the Blackwood, Katelysia spp. (Chalmer et al, 1976; Wallace, 1976; Wells et al, 1980).

It should be pointed out that while these few marine affinity species are abundant in the lower to middle reaches of estuaries with a strong marine influence (eg Swan River estuary and Leschenault Inlet), salinity extremes and/or the shallow depths (and therefore lack of a deepwater refuge of oceanic salinity, such as in the Swan River estuary) of the Peel-Harvey estuarine system are sufficient to confine most of these species to the inlet channel. Sanguinolaria biradiata and Tellina deltoidalis are found in Peel Inlet during summer and autumn but only Spisula trigonella is found in Harvey Estuary as well (Wells et al, 1980).

In South-Western Australian estuaries marine and marine affinity species tend to reach peak abundances in the summer/autumn period, although absolute abundances may vary considerably from year to year. The peak abundance clearly coincides with the most favourable conditions (ie marine salinities) for these species. Certain estuarine species such as the polychaete worms, palaemonid shrimps and amphipods also follow this seasonal pattern (Wallace, 1976). However, there is a considerable variation in seasonal patterns of abundance of estuarine molluscs. Some species (eg Potamopyrgus sp., Hydrococcus brazieri) are reported as having a winter maximum, and others in spring (eg Arthritica semen) (Wells et al, 1980).

The data of Wells et al (1980) for moluscs in the Peel-Harvey estuarine system also indicate that both the seasonal pattern and absolute abundance of any one species may change considerably from year to year. For instance in 1977 Hydrococcus brazieri reached peak abundance in late winter, but in 1978 overall abundances were lower and the maximum was reached in early summer. In the same study, Arthritica semen and Potamopyrgus sp. were considerably more abundant in 1977 than in 1978, but the reverse was true for Tornatina sp. Wide fluctuations in the abundance of different species of benthic invertebrates seem to be a characteristic feature of estuarine populations (Loveland and Vouglitois, 1984, and references cited therein). Within the suite of dominant estuarine species, one species may be extremely aboundant one year, then almost disappear the next, when another species becomes abundant.

CHANGES IN THE PEEL-HARVEY ESTUARINE SYSTEM DUE TO THE DAWESVILLE CHANNEL

The major changes in the Peel-Harvey system resulting from the Dawesville Channel which are likely to affect the benthich fauna are:

(i) Estuarine waters will become more marine

(ii) there will be a larger intertidal area as a result of increased tidal amplitude, and the frequency of inundation will be greater.

(iii) a tidal delta is likely to be formed in the Harvey Estuary adjacent to the Channel

(iv) the composition of aquatic vegetation may change, and primary production may decline to some extent.

(v) *Nodularia* blooms should decrease.

The above points are discussed in detail by other Symposium speakers, and therefore are not considered further here.

LIKELY EFFECTS OF THE DAWESVILLE CHANNEL ON THE BENTHIC FAUNA

Given that the Peel-Harvey estuarine system will change as described above if the Dawesville Channel is constructed, the likely effects on benthic fauna can be summarised as follows:

(i) the suite of abundant estuarine species is unlikely to change

(ii) the benthic fauna should remain abundant overall

(iii) fluctuations in abundance of benthic fauna are likely to decrease

(iv) more marine species are likely to invade the system

(v) there is likely to be a local decrease in abundance of benthic fauna on the tidal delta.

(vi) widespread mortality of benthic fauna due to *Nodularia* blooms should decrease.

(i) Abundant estuarine species

The suite of estuarine species which are most abundant at present are vey tolerant of variations in environmental conditions such as salinity, tidal exposure and vegetation composition. These species should be capable of withstanding the changes caused by the Channel, which will be relatively minor compared to existing natural fluctuations.

(ii) Overall abundance

The abundance of benthic fauna overall should remain high. Changes to the salinity regime are likely to be favourable to benthic fauna. Although the intertidal area will be increased, the frequency of inundation will also increase and thereby reduce dessication stress. A possible change from an algal dominated to a more seagrass dominated system is not likely to affect benthic fauna abundance, because high levels of primary production will still be available to maintain the food webs.

(iii) Fluctuations in abundance

At present, the extreme saline regime has a severe impact on the benthic fauna, with low salinities in winter resulting from river input causing widespread mortality. The Channel will reduce the degree and duration of these low salinity periods, and thus the benthic fauna are more likely to persist in high numbers throughout the winter than they are at present.

(iv) Marine species

The more marine conditions created by the Channel will allow marine species of benthic fauna to colonise the estuary. In addition, the short channel to the sea and greater impact of marine water will allow easier access to the estuary by planktonic larval phases of marine benthic fauna, thereby enhancing colonisation by these species. While the species richness of the benthic fauna should increase, the addition of these low-density marine species is unlikely to have any significant effect on the estuary in a general sense.

(v) Tidal delta

The tidal delta likely to be formed in Harvey Estuary adjacent to the Channel will consist largely of sand. The delta may support a lower abundance of benthic fauna than the area does at present, but this effect will be restricted to the local area of the delta.

(vi) Nodularia blooms

At present Nodularia blooms cause widespread and massive mortality of benthic fauna. if Nodularia blooms decrease after the Channel is opened, the accompanying mortality of benthic fauna should also decrease.

GENERAL COMMENTS

The successful species of benthic fauna in southwestern Australian estuaries are very tolerant of the extreme environmental conditions which prevail. Construction of the proposed Dawesville Channel will, in effect, make the Peel-Harvey estuarine system a less extreme environment, and thus benthic fauna are not expected to suffer detrimental effects to any degree.

This conclusion is supported by the evidence available from Leschenault Inlet - which had a channel cut through to the sea in 1951, and the Swan River estuary - from which the bar at the mouth was removed in the 1890's. The benthic fauna of both these estuaries is in a satisfactory state, and while changes in the benthic fauna may have occurred, they have never been considered detrimental to the ecology of the estuaries.

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Table 1: Estuarine affinity species of benthic invertebrates that are abundant in southwestern Australian estuaries.

Polychateta

Australonereis ehlersi
Capitella capitata
Ceratonereis erythraeensis
Haploscoloplos kerguelensis
Marphysa sanguinea
Prionospio spp.
Scoloplos simplex

Mollusca

Bivalvia
Arthritica semen
Fluviolanatus amara
Xenostrobus securis

Gastropoda
Batillariella estuarina
Hydrococcus brazieri
Potamopyrgus sp.

Crustacea

Amphipoda
Corophium spp.
Melita spp.
Paracorophium spp.

Decapoda
Halicarcinus australis
Halicarcinus bedfordi
Palaemonetes australis

The response of the fish and crustacean fauna and the fishery to options for management of the Peel-Harvey estuary.

R.C.J. Lenanton,[1] I.C. Potter[2] and N.R. Loneragan[2]

I INTRODUCTION

Results of comprehensive research work over the past eight years have indicated that in order to overcome the algal problems in the Peel-Harvey estuary, the amount of nutrients, particularly phosphorus available to the algae must be reduced. In order to achieve this a number of preferred management strategies and supplementary management measures have been recommended (Dept. of Conservation and the Environment, 1984).

The preferred strategies include:

1. Weed harvesting offshore and from beaches.
2. Modification of agricultural practices i.e. rationalisation of fertiliser use.
3. Creation of a new channel from the Harvey estuary to the ocean i.e. "Dawesville Channel",

   while supplementary options, needing further investigation, include:

   1. Use of algicides to prevent *Nodularia* blooms.
   2. Bauxite amendment of leaching soils.
   3. Wetland filters at the point source of nutrient input.
   4. Changes in current land use.
   5. Improvements of the existing Mandurah channel.

The overall effect of a reduction in the amount of phosphorus available to algae will lead to the elimination of *Nodularia* blooms, and the eventual reduction in the biomass of macroalgae in the estuary. The response of the fish fauna can be determined by reviewing the results of our recent research into the relationships of both macroalgae and *Nodularia* with the fish fauna and the scale fishery (Lenanton *et al*., 1984; Potter *et al*., 1983a; Lenanton *et al*., in prep.)

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The direct and more specific effects of individual "within estuary" management options can at present be assessed from the results of recent research into the ecology of the fish fauna (Potter *et al*., 1983b) and blue manna crab (*Portunus pelagicus* (Potter *et al*., 1983c). At a later date, further assessment will be possible from the results of ongoing research into the trophic inter-relationships between fish and the macrobenthos, and into the fish community structure with emphasis on physical and floral habitat preferences.

II OVERALL EFFECTS

Reduction in the biomass of macroalgae

Scale fisheries in both the Peel-Harvey and Swan-Avon estuaries have developed in similar ways, use the same fishing techniques and are exposed to similar market demands.

Comparisons have been made between the trends in catch per unit of effort (CPUE) for sea mullet (*Mugil cephalus*), yelloweye mullet (*Aldrichetta forsteri*) and cobbler (*Cnidoglanis macrocephalus*) and for the total scale fisheries of both estuaries, prior to and during a period of excessive macroalgae growth in the Peel-Harvey estuary (Lenanton *et al*, 1984).

Results indicate that the total scale fishery in the Peel-Harvey estuary increased by 1.8 times during the 1970-1979 period of macroalgal increase, while in the nearby Swan-Avon estuary, which experienced no comparable period of macroalgae growth, the scale fishery increased by only 1.2 times. The Peel-Harvey fisheries for yelloweye mullet, sea mullet and cobbler increased by 1.9, 2.1 and 3.3 times respectively, while no significant changes occurred with sea mullet and cobbler from the Swan-Avon estuary (Table 1, Figure 1). Thus any reduction in the biomass of macroalgae in the Peel-Harvey estuary below the 1970 level has the potential to reduce the CPUE for the total scale fishery, and for the dominant species such as yelloweye mullet, sea mullet and cobbler.

Elimination of Nodularia

Despite the fact that *Nodularia* blooms became a problem during the late 1970's and the early 1980's, the trend in CPUE for the total scale fishery has continued to increase (Fig. 2).

During these years of *Nodularia* blooms, investigations were made into the relationships between *Nodularia* density, (measured by the chlorophyll *a* density ($\mu g l^{-1}$)) and the mean number of fish (mainly juveniles) taken at beach seine sites throughout the Peel-Harvey system between November and March of the "non-*Nodularia*" year of 1979/80, and the "*Nodularia*" years of 1980/81 and 1981/82 (Potter *et el*, 1983a). The results showed that juvenile fish were being affected by *Nodularia*. The mean numbers of fish were lower at sites affected by *Nodularia* during 1980/81 and 1981/82, than at the same sites in 1979/80 when *Nodularia* was negligible. By contrast at sites not affected by *Nodularia*, mean values were higher in the "Nodularia" than the "non Nodularia" years (Fig. 3). The species which were largely responsible for the differences in fish numbers between "Nodularia" and "non Nodularia" years were the gobbleguts (Apogon rueppellii), six-lined trumpeter (Pelates sexlineatus), devil fish (Gymnapistes marmoratus) and the yelloweye mullet (Aldrichetta forsteri). Nodularia concentrations above 100 $\mu g l^{-1}$ appeared to affect fish in this way.

During the course of these investigations, claims were made that fishermen and the large commercial sized fish were also being affected by Nodularia blooms. In order to investigate these claims, the activities of a representative group of commercial fishermen were monitored during the 1982/83 period of Nodularia blooms (Lenanton et al, in prep.) Specially designed log books were distributed to fishermen in order that data could be collected to enable comparisons to be made between trends in the CPUE of the total scale fishery, and the dominant species taken by gill netting and haul netting from four areas of the Peel-Harvey estuary. The areas ranged from one in which Nodularia was scarce (Northern Peel) to another in which Nodularia blooms were dense (Southern Harvey) (Fig. 4). The extent and duration of Nodularia blooms during October to December 1982 were measured by chlorophyll a density, while an index of water clarity was provided by secchi depth readings. Both these sets of data were provided by the Botany Department, University of Western Australia.

Traditionally, the fishermen of Peel Inlet and Harvey estuary fished only within their respective estuaries, showing a preference for haul netting when water clarity was high, but gill netting when water clarity was poor.

Increases in chlorophyll a concentrations in the late spring and early summer of 1982 resulted in a lowering of secchi depth readings of water clarity. This was particularly pronounced in northern and southern Harvey (Fig. 5). Thus fishermen were forced to depend on gill netting during this period (Fig. 6). Post Nodularia increases in water clarity in December in Peel Inlet and later in January in Harvey estuary were associated with changes from gill netting to haul netting in both estuaries. However, during subsequent pronounced falls in secchi depth readings during June 1983, chlorophyll a levels remained unchanged. On this occasion, secchi depth readings reflected an increase in turbidity associated with the first winter freshwater flush. This turbidity increase was accompanied by a change from haul netting back to gill netting in all areas. Thus, trends in fishing effort and CPUE over this period indicated that during October and November, 1982 in Nodularia affected areas i.e. Southern Harvey, fishermen used gill netting rather than the more productive haul netting technique (Fig. 6), and that to haul, some fishermen were forced to relocate their activities away from areas that experienced the most intense Nodularia blooms i.e. they moved from Harvey to Peel to fish. It should be noted that while these haul net fishermen were absent, the remaining fishermen were still able to catch reduced numbers of fish, gill netting in Harvey estuary (Fig. 6).

In addition to the CPUE analyses, two of the logbook fishermen were chartered and directed to fish equally in each of the four fishing regions for four days both prior to (September 1983) and during (November 1983) Nodularia blooms. Analyses revealed that the range of Nodularia density encountered during the experiment was relatively low (mostly ≁ 100 $\mu g l^{-1}$). These low levels probably account for the fact that only the catches of yellow-eye mullet appeared to be affected by Nodularia.

Fishermen were also chartered and directed to fish in areas of Harvey estuary badly affected by Nodularia for four days during late November early December 1984. Preliminary analyses revealed a significant negative relationship between Nodularia density and the abundance of sea mullet and western sand whiting (Sillago schomburgkii). Ongoing comparisons between CPUE data for these fishermen and other logbook fishermen from Harvey estuary prior to and following the 1984 Nodularia bloom period indicate that although fishermen still caught commercial sized fish in regions affected by Nodularia, sea mullet were less abundant in areas where Nodularia density exceeded 200 $\mu g l^{-1}$. Finally, fishermen also reported seeing dead fish (mostly cobbler) and blue manna crabs in areas where Nodularia was dense (Potter et al 1983a).

From our data, it would appear that the elimination of Nodularia would reduce the incidence of fish and blue manna crab deaths. It would also allow juveniles and large representatives of commercial species to be distributed in greater numbers in areas previously affected by Nodularia and thus permit fishermen to operate more profitably in these areas.

III SPECIFIC EFFECTS

Here we are addressing only the longer term effects, not the immediate effects which could be expected such as those related to the dredging operations associated with the Dawesville channel construction.

"Dawesville Channel"

It has been anticipated that as well as providing an additional ocean entrance to the estuarine system, the proposed "Dawesville Channel" will alter the present hydrological regime of the Harvey estuary in particular. One of the major effects of this will be to allow more marine conditions to be established in the Harvey estuary earlier in the spring and to persist longer into the autumn/winter. It will also alter the seasonal temperature regime and improve summer water clarity. In addition, the increased daily and seasonal amplitude of the tide has the potential to affect the fish and crustacean fauna.

As well as having the capacity to affect fish directly, hydrological changes have the ability to affect fish indirectly, through changes to their food supply and the structure of their habitats.

As a basis for predicting the response of the fauna to the above direct effects of the "Channel", extensive monthly beach seine, gill net and otter trawl samples of the fish fauna and the blue manna crab have been taken in the Peel-Harvey estuary over the period April 1979 to July 1981 (Potter et al, 1983b,c). Environmental characteristics such as salinity, temperature, water depth, and prevailing weather conditions were recorded after each sample was taken. Resultant length frequency and catch data have provided an account of the relative abundance and the age composition of the various fish species and the blue manna crab found seasonally in different regions of the estuarine system. The preferred salinity range of the blue manna crab is also reported. Further evidence is available from this research which indicates that juvenile fishes tend to be distributed mostly over shallow banks near the shoreline.

Seasonal trends in total monthly catch, effort and catch per unit of effort (CPUE) since 1960 is also presented.

(i) An additional ocean entrance

This will clearly provide a further avenue for the recruitment of the blue manna crab and the western king prawn and all the marine fish that use the system. However, without a better understanding of such factors as the precise mode of recruitment of many of the marine species, and the availability of larvae/post-larvae/ small juveniles, the extent of utilisation of this new entrance is difficult to predict.

(ii) Hydrological regime

From data on the seasonal changes in relative abundances of the fish fauna (Figs 7 & 8), it is clear that longer summer/autumn periods of marine conditions will result in an increase in species diversity in Harvey estuary. A number of the true marine species should be found in the "Channel" and in estuarine areas in close proximity to the "Channel". The more euryhaline fish species such as the non-commercial devil fish, six-lined trumpeter and the gobbleguts, and the commercially important tailor (Pomatomus saltator), cobbler and yelloweye mullet, which at present are more abundantly distributed in Peel Inlet, should be more abundant in Harvey estuary.

However, the anticipated changes are not likely to favour species such as the sea mullet, which presently is more abundant in the Harvey estuary than Peel Inlet. Other species that may be adversely affected include the western sand whiting (Sillago schomburgkii), Ogilby's hardyhead (Pranesus ogilbyi) and the roach (Gerres subfasciatus). Data on seasonal changes in relative abundance of the blue manna crab throughout the system (Fig. 9) and on the preferred salinity range of this species (Fig. 10) clearly indicate that extended summer periods of more marine salinities are likely to lead to a more prolonged period of colonisation of the Harvey Estuary by P. pelagicus.

Such marine conditions will also provide clearer water conditions which are likely to encourage increased usage of the more productive haul netting fishing techniques.

(iii) Tidal influence

Although the mean water level will not change, the "Channel" will cause increases in the daily and seasonal tidal amplitude which will clearly produce more extensive intertidal areas, and reduced areas of subtidal shallows permanently under water, both of which are likely to affect the manner in which fish and crustaceans utilise the banks. It is also possible that professional and amateur fishermen's access to shallow banks may be affected.

(iv) Indirect effects

Hydrological changes from the "Channel" (and the effects of reductions in the amount of phosphorus entering the estuary, mentioned earlier) also have the capacity to change the structure of the nearshore floral and benthic invertebrate community.

Structural habitat changes such as increases in macrophyte biomass in Harvey estuary may, for example, improve the available cover for fish, and thus further increase the survival of juveniles, particularly the mullets and cobbler that are presently abundant over the nearshore shallow banks and are thought to depend on macroalgal cover for protection from predators (Potter et al 1983b; Lenanton et al, 1982, 1984). Results of the ongoing work on habitat preferences of fish should help predict the effects of such changes.

Benthic invertebrate and detrital food source changes will also probably affect the manner in which juvenile fish utilise the shallows. A more detailed assessment of these effects should be possible when the results of the ongoing research into the trophic inter-relationships of fish and benthic invertebrates become available. Some preliminary judgements may be possible from the results of some earlier research by Chalmer & Scott (1984) carried out before the advent of the major nuisance algae. However, benthic invertebrate and detrital food resources are presently abundant in estuaries, and most fish found feeding in our estuaries display a high degree of opportunism (Thomson, 1957; Wallace, 1976). Thus, the anticipated changes in the benthic community may not affect fish greatly.

Continued weed harvesting

Results of research on the fish fauna of the metropolitan nearshore-marine environment indicate that juveniles of a number of commercially important species, particularly cobbler, are highly dependent on drift macrophytes for food and shelter (Lenanton et al, 1982; Robertson and Lenanton, 1984). Although similar research has not been carried out in Peel-Harvey estuary, observations during sampling programmes suggest that there is a similar dependence between cobbler and macroalgae in this system. Thus, extensive harvesting of macroalgae may place species such as cobbler at risk.

IV MONITORING

In the event that Government decides to go ahead with the "Dawesville Channel" option, it is essential that the direct effects of the "Channel" on the fish fauna and the fishery be monitored and compared whenever possible with data collected over recent years.

Commercially Important Crustaceans

From our basic knowledge of the biology of the western king prawn acquired from work throughout its geographical range (Penn, 1981); and from the substantial and increasing catch of this species in the entrance channel during autumn over recent years of nutrient enrichment, it is clear that this species utilises Peel-Harvey estuary extensively during the summer as a nursery area. However, when our research programme commenced blue manna crabs were considered the most commercially important crustacean. Thus, there are no data available on the distribution and abundance of juvenile western king prawn stages in Peel-Harvey estuary. At other localities throughout its geographical range, where populations are most abundant, juvenile stages are most abundant in areas where salinities range from seawater strength to hypersaline (Penn, 1981). A lessening of the summer hypersaline conditions in Harvey estuary therefore, may make the estuary less attractive to this most important species. Thus it is important that a detailed study be made of the ecology of this species both in the Peel-Harvey estuary and the adjacent ocean before and after the "Channel" is constructed.

Trends in the commercial fishery

The existing ABS catch and effort data collection system does not distinguish between catches from Peel Inlet and Harvey estuary i.e. Peel-Harvey estuary is considered to be a single commercial statistical block. Both parts of the estuarine system are to a considerable extent, biologically distinct and have both responded differently to enrichment. In view of this and the fact that the "Dawesville cut" option may be accepted by Government, it is important that a distinction be made between commercial catch and effort data expended in each part of the estuarine system and that the fishery in both parts be monitored on a continuing basis. Thus the appropriate changes should be made to the present statistical block status of Peel-Harvey estuary, and the present logbook system continued until such time as a comparable alternative data collection system is introduced.

V ACKNOWLEDGEMENTS

Technical staff from the Environmental and Life Sciences School of Murdoch University, and the estuarine scale fish section of Western Australian Marine Research Laboratories provided valuable assistance during the preparation of this manuscript.

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SPECIES	PERIOD	MEAN MONTHLY CATCH PER BOAT (kg)				SWAN-AVON vs PEEL-HARVEY P VALUES
		PEEL-HARVEY $\bar{x}$ (95% CL)	BETWEEN DECADES P VALUES	SWAN-AVON $\bar{x}$ (95% CL)	BETWEEN DECADES P VALUES	
Total catch	1960-69	738 (458-1189)	<0.001	638 (422-965)	<0.05	NS
	1970-79	1327 (600-2937)		772 (569-1048)		<0.001
Aldrichetta forsteri	1960-69	249 (125-496)	<0.01	37 (9-146)	<0.01	<0.001
	1970-79	469 (116-1903)		74 (34-159)		<0.001
Mugil cephalus	1960-69	192 (105-351)	<0.001	190 (94-384)	NS	NS
	1970-79	400 (138-1244)		187 (122-285)		<0.001
Cnidoglanis macrocephalus	1960-69	70 (2-2310)	<0.05	101 (33-315)	NS	NS
	1970-79	234 (53-1062)		95 (39-231)		<0.01

TABLE 1

The geometric mean monthly catch per boat, together with 95% confidence limits, in the estuaries of the Peel-Harvey and Swan-Avon systems for the 10 years before (1960-1969) and during (1970-1979) the period of macroalgal abundance in the Peel-Harvey system. Means within and between systems were compared by a Student's t-test (from Lenanton *et al*, 1984)

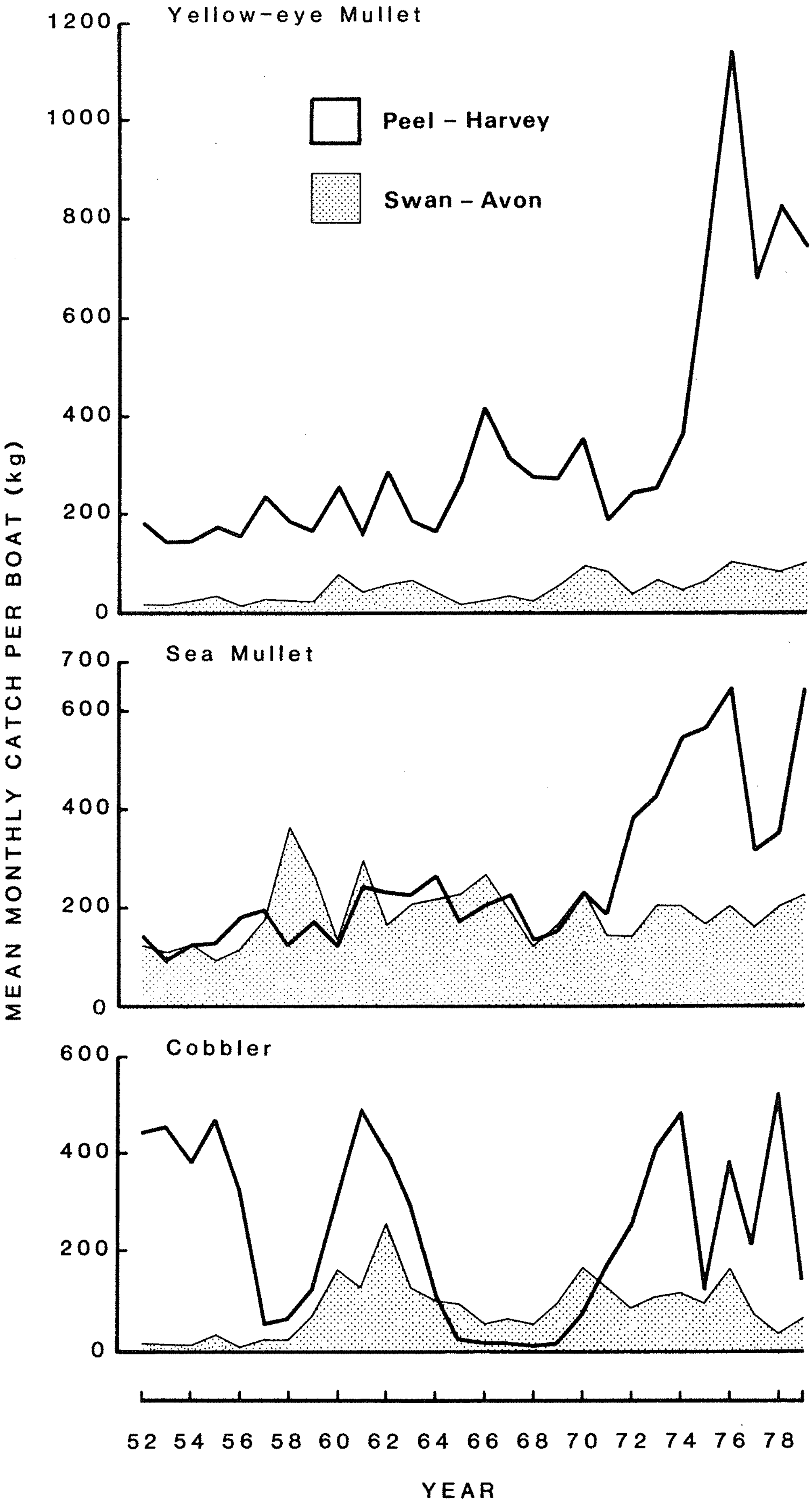

Fig. 1 The mean monthly catch per boat for Yellow-eye mullet, Sea mullet and Cobbler in the Peel-Harvey and Swan-Avon systems in each of the years between 1952 and 1979. (a) Yellow-eye mullet; (b) Sea mullet; (c) Cobbler (from Lenanton et al, 1984).

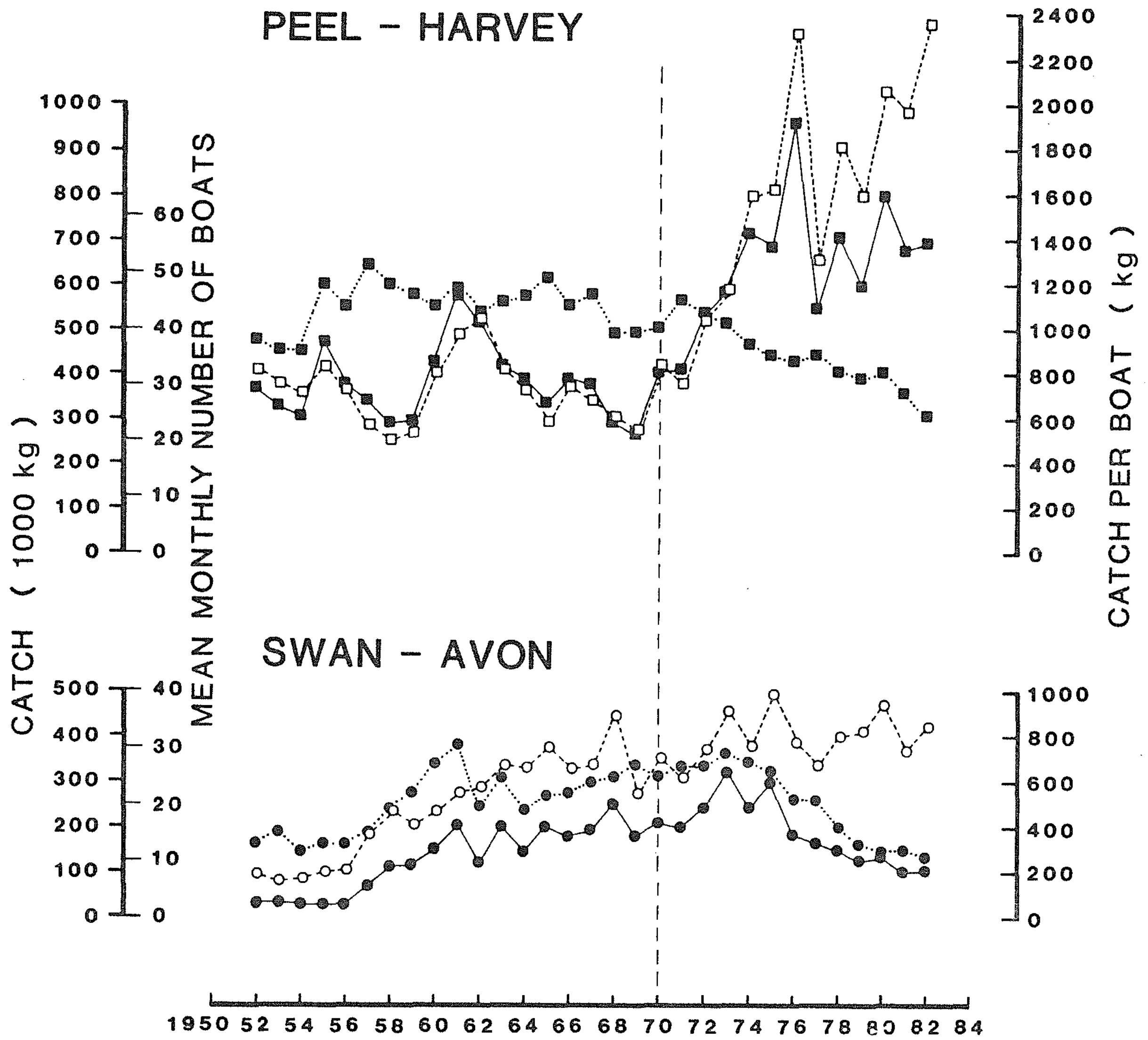

Fig. 2 The total catch (kg) mean monthly number of boats, and the catch per boat (CPUE) in the Peel-Harvey and Swan-Avon estuarine systems between 1952 and 1982. ■——■ Total catch, ■·······■ mean number of boats/month, □- - -□ CPUE in the Peel-Harvey system; ●——● Total catch, ●·······● , mean number of boats/month, ○- - -○ CPUE in the Swan-Avon system. (--- signifies the beginning of the period of excessive macroalgal growth).

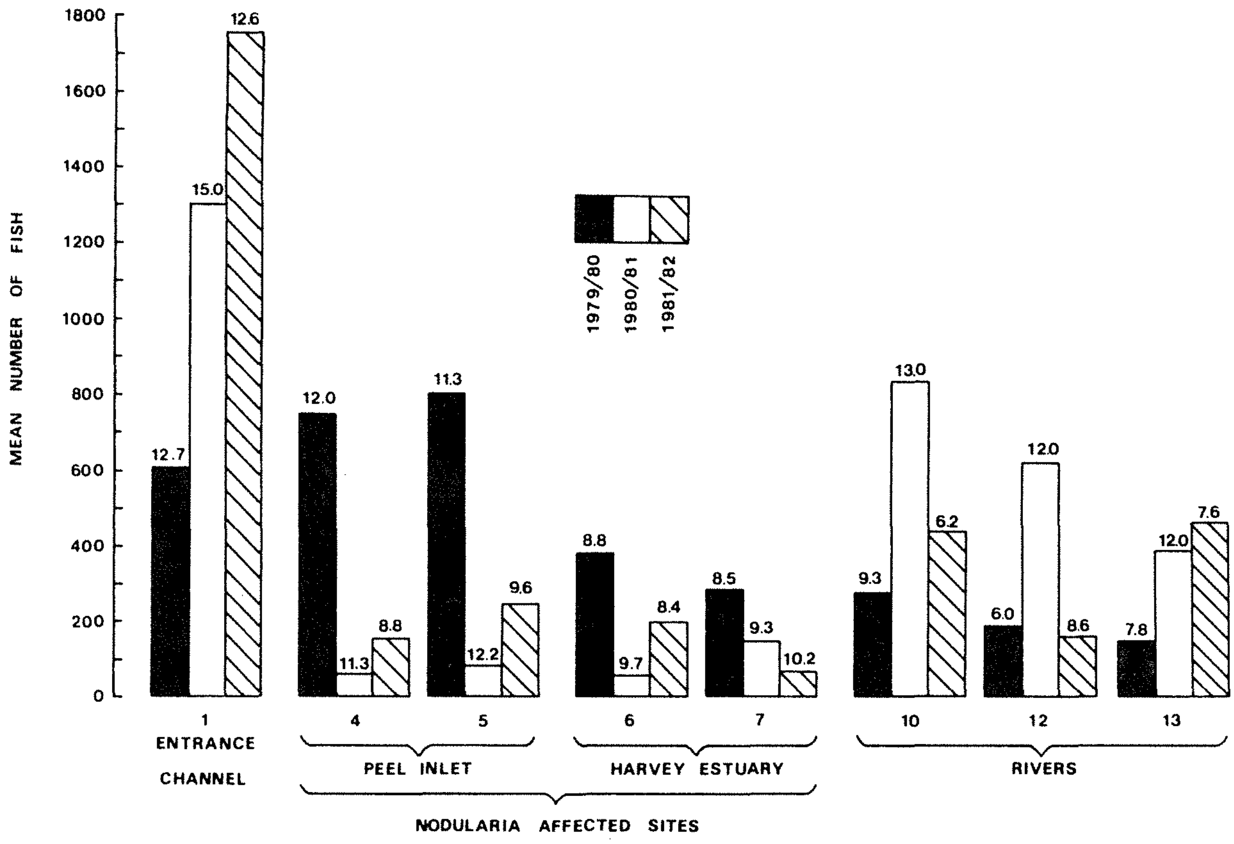

Fig. 3 Histograms showing the geometric mean number for all the fish caught in the Peel-Harvey estuarine system between November and March of 1979-1980, 1980-1981 and 1981-1982. The mean number of species is given above each histogram. (From Potter et al, 1983a).

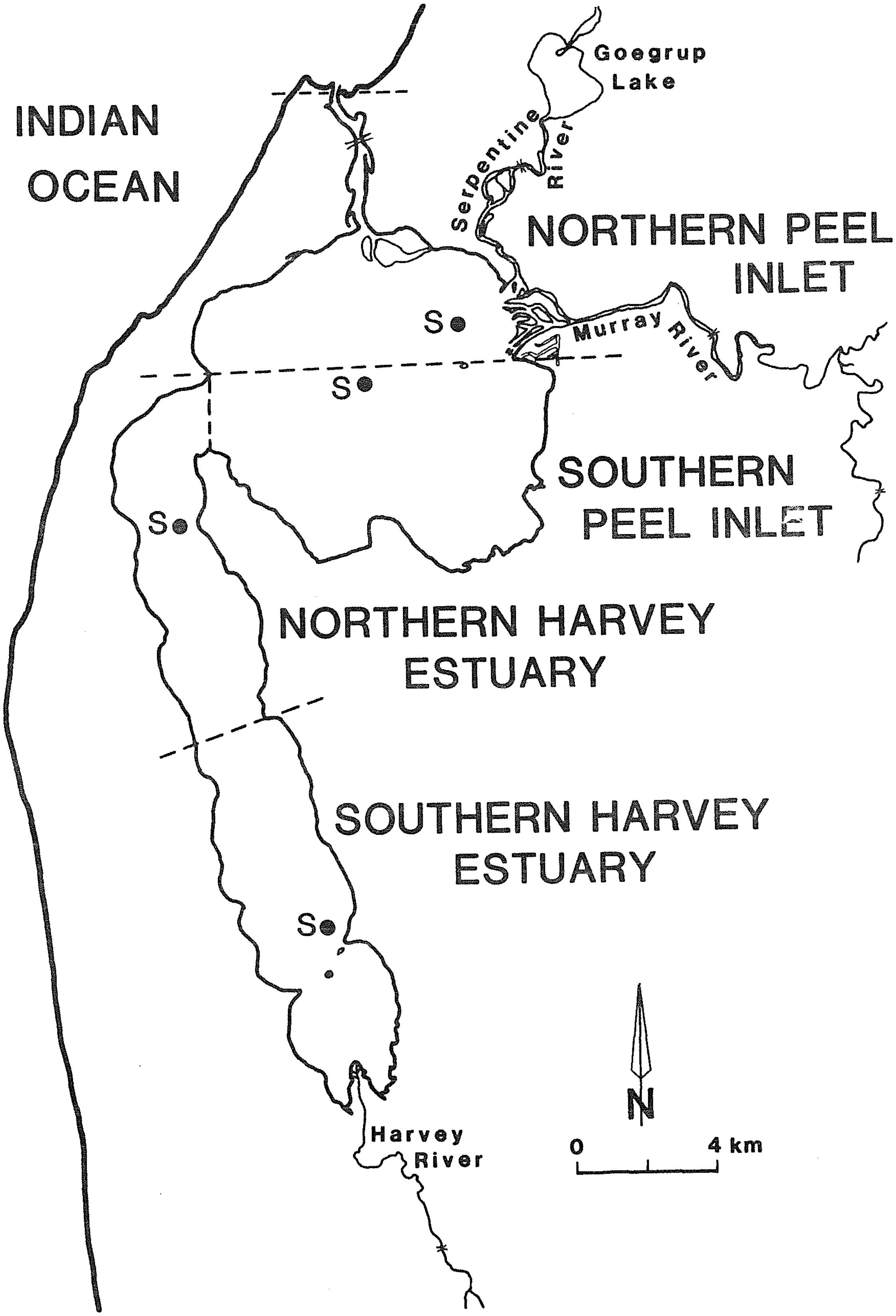

Fig. 4 A map of the Peel-Harvey estuary showing the four fishing regions and the hydrological sampling site within each region.

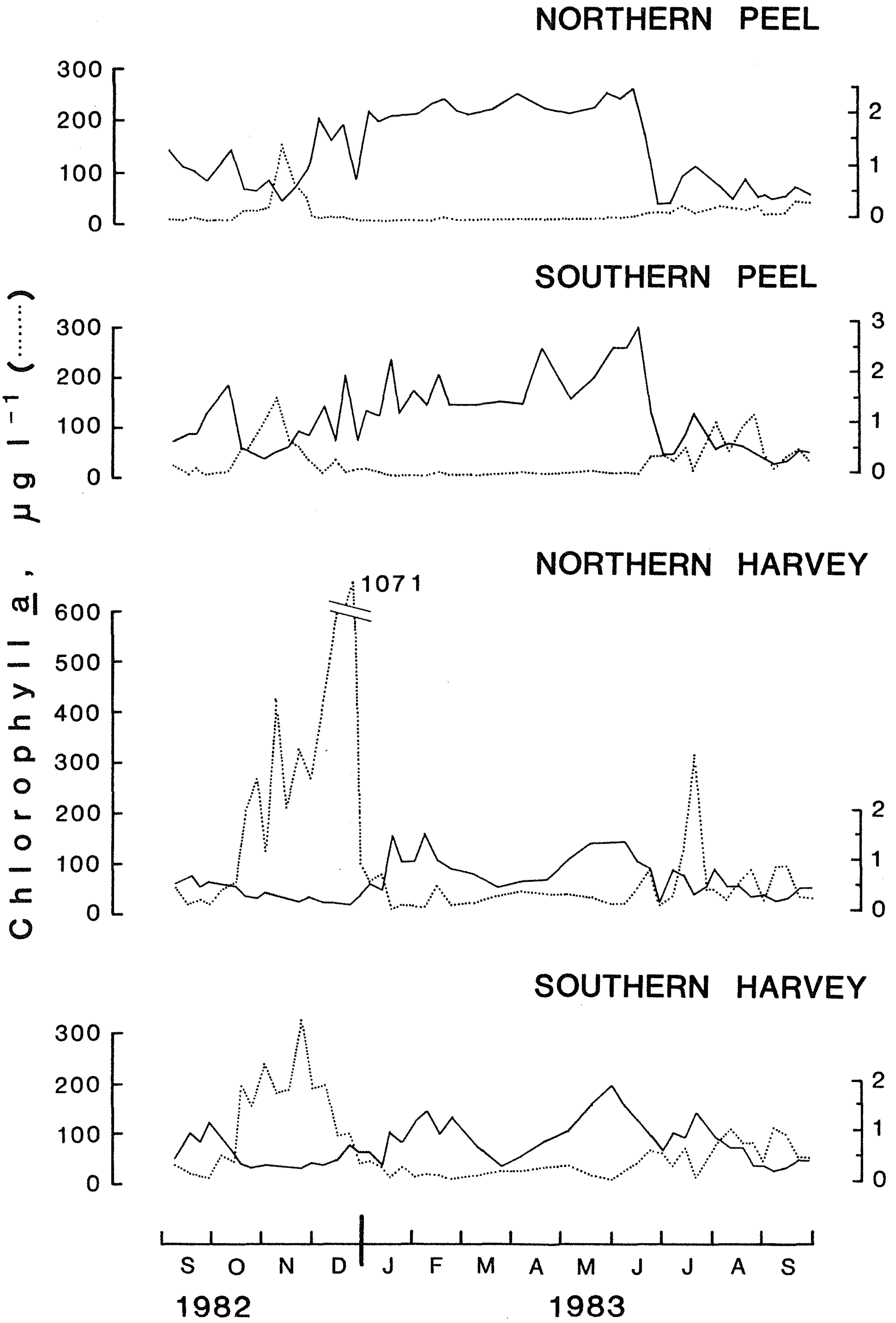

Fig. 5 Secchi depth readings —— and chlorophyll *a* measurements ... taken in each of the four fishing regions of Peel-Harvey estuary between September 1982 and September 1983.

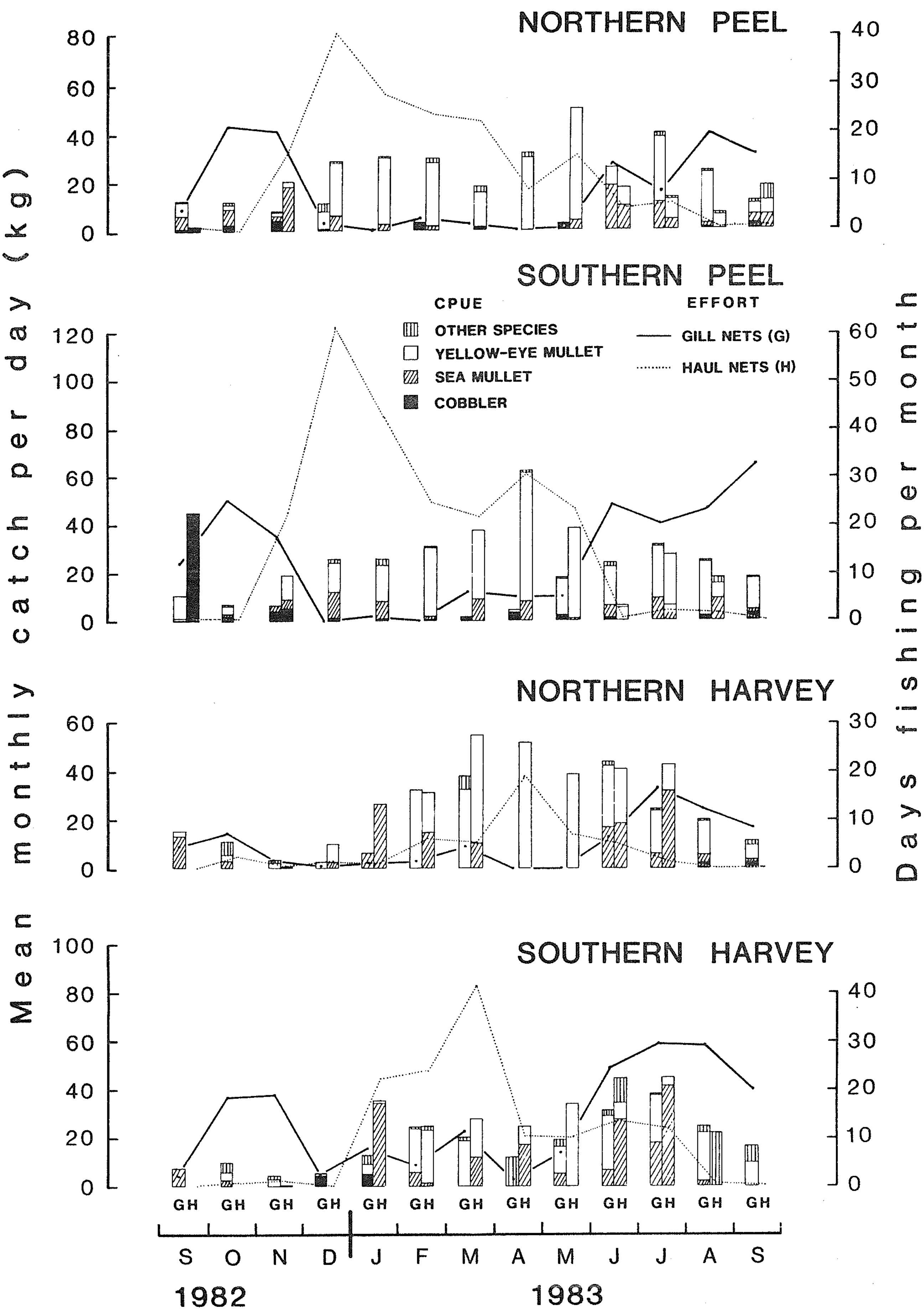

Fig. 6 Trends in effort and CPUE for the major gill and haul net caught species and the total scale fishery in each of the four fishing regions of the Peel-Harvey estuary between September 1982 and September 1983.

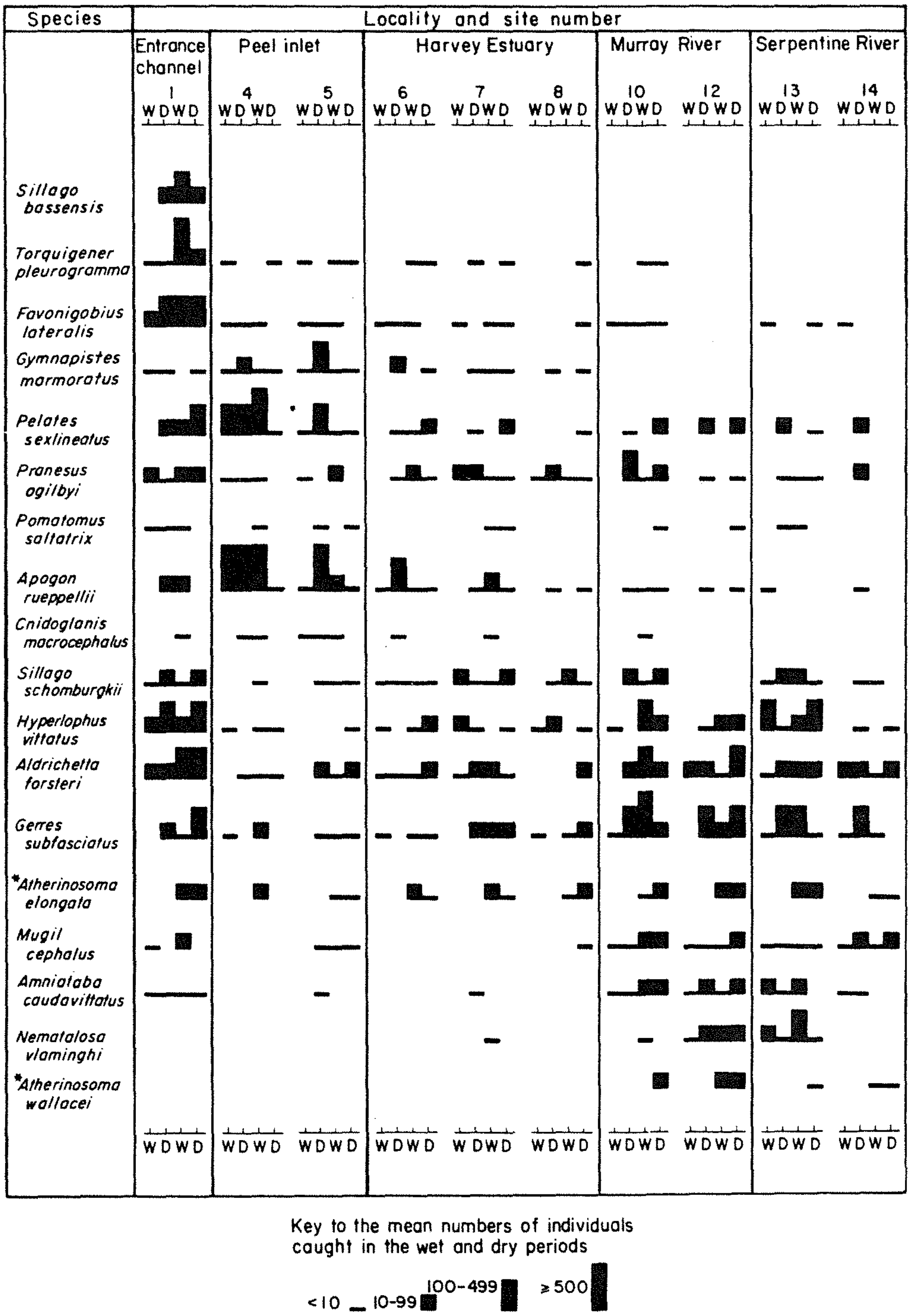

Fig. 7 The relative abundance of the 15 most frequently caught species in beach seines during wet (W) and dry (D) periods (see Materials and methods) showing a gradation in distribution with the system from a species which is restricted to the Entrance Channel to one that is found only in the rivers. Beach seine data are also included for three additional species (*Mugil cephalus*, *Pomatomus saltatrix* and *Cnidoglanis macrocephalus*) which were relatively very abundant in gill net samples. *Data only available after August 1980. (From Potter *et al*, 1983b).

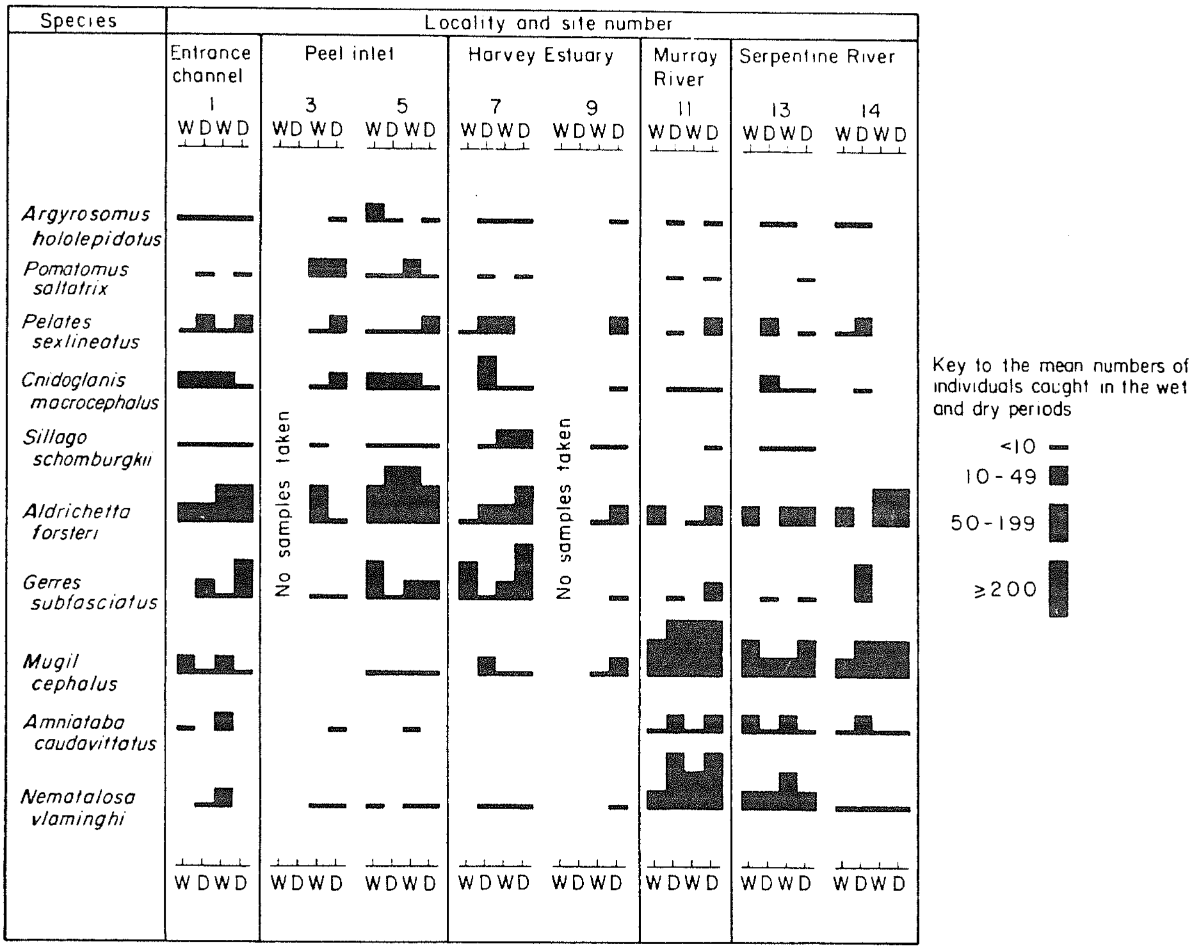

Fig. 8 The relative abundance of the ten species most frequently caught in gill nets during wet (W) and dry (D) periods showing a gradation in distribution from those predominating in the Entrance Channel and basins to those that were more abundant in the rivers. (From Potter et al, 1983b).

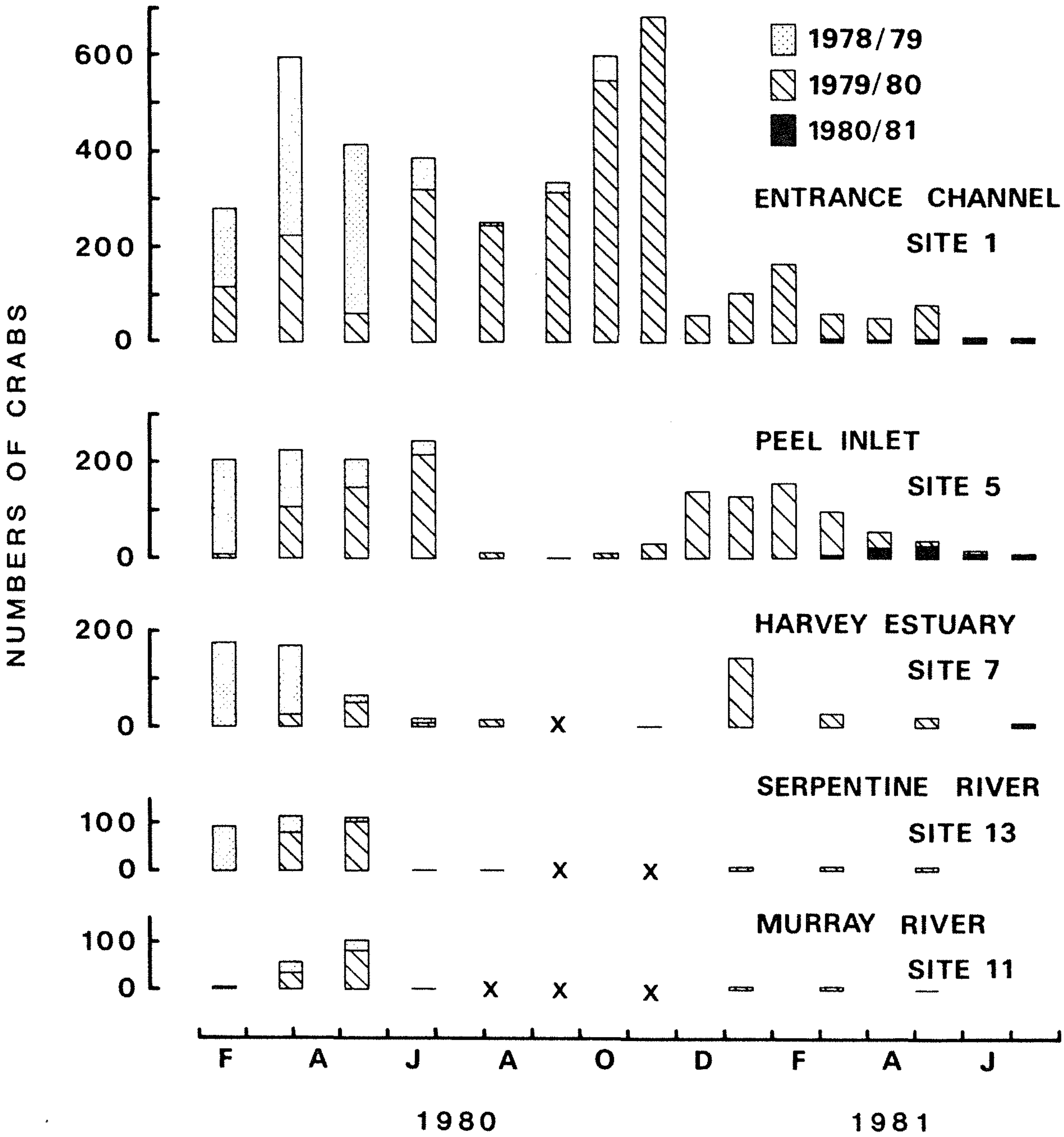

Fig. 9 Portunus pelagicus. Histograms showing number of crabs caught at various localities in Peel-Harvey system, based in each case on the same beach seine, gill net and otter trawl sampling method. Histograms distinguish between individuals recruited in the summers of 1979, 1980 and 1981. X denotes no crabs in sample (from Potter et al, 1983c).

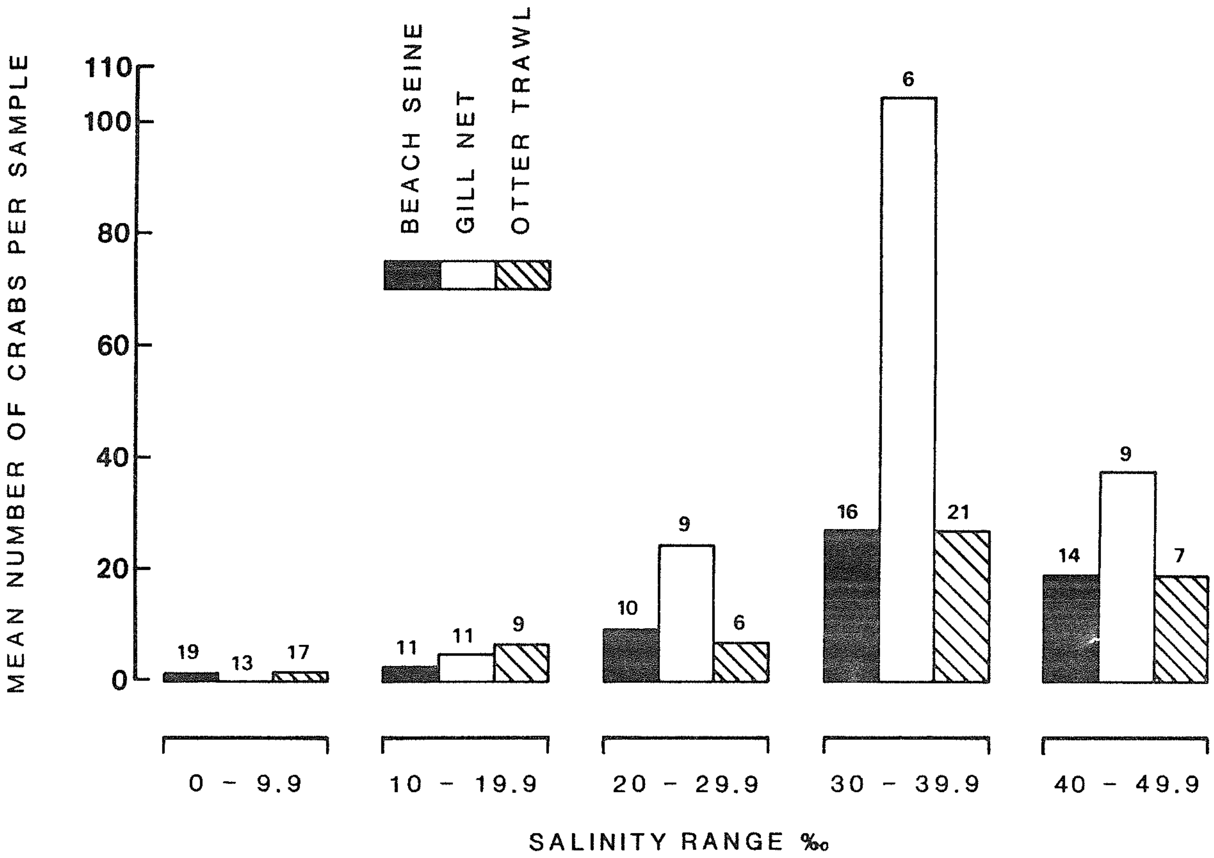

Fig. 10 Portunus pelagicus. Histograms showing mean number of crabs caught by beach seine, gill net and otter trawl in different salinity categories. Number of samples is given above each histogram (from Potter et al, 1983c).

WEED HARVESTING

R.F. BRINDLEY

INTRODUCTION:

In 1984 the Public Works Department carried out a detailed investigation into the macro algae harvesting and beach cleaning operations of the Peel Inlet Management Authority.

The investigation, which was requested by the Waterways Commission, was carried out in three stages.

Firstly, the Peel Inlet Management Authority provided detailed information relating to costs and the amount of material removed from the foreshores of Peel Inlet.

Secondly, the Mechanical Branch of the Public Works Department arranged a series of weed removal trials under field conditions using front end loaders of different manufacture.

Thirdly, the Harbours and Rivers Branch of the Public Works Department reviewed the cost structure of the weed removal operation and investigated several alternative options.

It was found that daily harvest productivity could be significantly increased by upgrading the performance of the two onshore front end loaders and by allowing plant operators to work additional overtime during critical periods. It was also recommended that detailed biomass surveys be carried out in all harvest areas prior to the commencment of the main harvest season and that those surveys be used to provide background information for a review of harvesting operations on a continuing basis.

The final report of the Harbours and Rivers Branch was tabled in Parliament and its major recommendations have now been implemented by the Peel Inlet Management Authority.

REVIEW OF OPERATIONS

The Peel Inlet Management Authority has maintained records of material removed from the foreshores and shallow water off Coodanup and Novara since 1979.

Figure 1 shows the amount of material removed by the front end loaders and the underwater harvesters. The costs of removal of that material for the period commencing July, 1981 are also shown. The costs include allowances for plant maintenance and lease payments.

The cost of the onshore operation is now about $100 000 per year, whilst the offshore operation costs about $60 000 per year. The onshore operation is considered to be essential and is a long term committment. It may be compared with the cost of the beach cleaning operations of the Swan River Management Authority which amounts to between $60 000 and $80 000 annually.

With reference to Figure 1, the sharp rise in costs during the 1982/83 financial year was due to the purchase of the second Volvo front end loader and the underwater harvesting equipment. The increases during the 1983/84 financial year were mainly due to increased maintenance costs relating to the front end loaders and were considered to be excessive.

With regard to results achieved for the amount of money expended the Peel Inlet Management Authority considers that foreshore conditions at Coodanup and Novara have not deteriorated during the past two years. Indeed, conditions which have existed at those locations so far this summer are much improved with respect to recent years. Notwithstanding, the Peel Inlet Management Authority considers that the overall condition of these estuary foreshores are a nuisance to the public for a period of about three months each year.

ONSHORE HARVESTING OPERATIONS

The Mechanical Branch of the Public Works Department carried out extensive field trials using a number of front end loaders of different manufacture. Arising out of those investigations, the two Volvo 65 KW front end loaders were replaced by two Clark Michigan 70KW front end loaders late in 1984. The design of the skid plate on each loader bucket was also changed.

The performance of the new machines in terms of efficiency of operation far exceeds the performance of the machines which they replaced. Not only can the new machines operate at a higher work rate with greater payloads, but the amount of sand being removed from the foreshores has been significantly reduced. So far maintenance costs have been minimal.

The performance of the new machines will now be monitored and kept under constant review.

OFFSHORE HARVESTING OPERATIONS

In 1984 the Aquamarine transporter was converted to a harvester, thus enabling both machines to operate either as transporters or harvesters. On many occasions this diversity of operations has been found to be an advantage.

Experiments with a set of dewatering rollers, designed to reduce the water content of the algae being transported to shore were also carried out in 1984. The rollers were found to be unsatisfactory due to buoyancy and variable algae density effects. No further experiments are contemplated.

It would appear that the capabilities of the underwater harvesters are limited, due to the physical restraints brought about by the extensive shallow areas within Peel Inlet and the necessity for them to operate in thick banks of algae. Their continual use in banks offshore does reduce the intensity of use of the onshore machinery somewhat.

GENERAL MACHINE OPERATION

The Peel Inlet Management Authority allots one half day per week per machine for general plant maintenance and servicing. In doing so the availability of the machines is reduced by 10%.

In addition, the daily servicing carried out and the travelling to and from the various work sites effectively reduces the number of daily productive working hours of all of the machines from eight to about six. Taking these factors into account, it can be seen that the total weekly productivity of machines is only about two thirds of the maximum achievable during normal working hours. Clearly productivity may be significantly increased by:

(a) allowing plant operators to work overtime each day during critical periods; and

(b) employing a mechanic to carry out the weekly servicing of machines of Saturdays.

The final report of the Harbours and Rivers Branch recommended that a mechanic be employed on a full time basis, since it was found during the course of the investigation that plant operators at Mandurah were becoming involved in workshop activities for which they were not originally employed.

It should be noted that the use of standard earthmoving equipment in the salt waters of the estuary is not possible since earthmoving companies will not allow their unprotected machinery to work in the harsh estuarine environment.

Currently the situation at Mandurah is that plant operators are working up to twelve hours per day and are also working on weekends; the mechanic from the Swan River Management Authority carries out field maintenance on a fortnightly basis and the services of a full time mechanic have been requested of the Public Service Board.

SLUDGE REMOVAL

Part of the study brief of the Harbours and Rivers Branch was to investigate the feasibility of obtaining a machine which could remove organic sludge as well as fibrous algae.

Cloth, centrifugal and pressure filters were considered but it was found that extensive development work would be required to develop a viable system and it did not seem that a machine of practical size would have the capacity to handle the task.

One method of sludge removal which is akin to dredging is by the use of a sludge pump mounted on an amphibious dredge. Again however, such a proposal is not really practicable and so detailed consideration of such a system was not proceeded with.

MODIFICATIONS TO EXISTING EQUIPMENT

The front end loaders can harvest algae in water not exceeding 20 cm in depth, whilst the underwater harvesters can harvest algae in water depths as shallow as 40 cm. There remains, therefore, a relatively large area of the estuary off Coodanup and Novara which is not currently worked by machines. A special harvesting machine to operate in this area of limited depth water has often been suggested.

Although a conceptual design of such a machine has been considered, additional information is required before this idea can be developed further, particularly with respect to the amount and distribution of the harvestable biomass.

Acting on the advice of the Harbours and Rivers Branch, the Peel Inlet Management Authority commenced biomass surveys in the shallow water off Coodanup in October, 1984. This was at a time when the waters north of Creery Island and off Coodanup were filled with algae and had the appearance of a green paddock.

Quadrate samples, 1 square metre in area, were taken in areas of aquatic growth which were, on a visual inspection, considered to be the most dense within the area under investigation. The samples were weighed, washed and allowed to dry exposed to normal atmospheric conditions. Drying times and weight reductions are shown in Figure 2. The results and observations of the distribution of Enteromorpha and Ruppia were found to be similar to those recorded by Carstairs in 1978.

Quadrate samples were next taken in the same general weed banks but in areas which were, on a visual inspection considered to be an average of the conditions existing at the time. An assessment of the area over which this algae existed was also made. Drying times and weight reductions are shown in Figure 3.

Subsequent inspections carried out on virtually a daily basis by Peel Inlet Management Authority staff, but on a monthly basis by Waterways Commission staff have shown the near shore biomass levels to have remained fairly constant, although varying in precise location.

The area off Coodanup over which the average conditions were estimated to exist was 40 hectares. Hence, from Figure 3 a total standing crop of macro algae and sea grass of about 800 wet tonnes was calculated.

During the period under review, the front end loaders were able to maintain acceptable conditions on most occasions. The amount of material removed by them is shown in Table 1. The only conclusion drawn is that the 'bank' of offshore aquatic growth was depleted and replenished at a variable rate, depending on weather conditions, but the figures point to the need for onshore machinery to have the capacity to remove in excess of 100 tonnes of material daily.

Now if a specialised machine was to operate in the ultra shallow water within this 'bank' area and be cost effective, it would need to cover the whole of the 40 hectares in about ten working days. Such a machine would therefore need to operate at about 4 hectares per day, or alternatively additional machines used.

All research work carried out to date on harvesting aquatic weeds, both in Australia and overseas, has pointed to the need to upgrade underwater harvesting rates to make them more comparable with analagous terrestrial harvesting rates. The Harbours and Rivers Branch report considered that meadow hay is the terrestrial crop most analagous to the macro algae found in Peel Inlet and found that a hay baler, under good conditions could cover about two to three actual hectares of land per day when baling windrowed hay.

This collection rate can be taken as the upper limit for an on-land machine, hence the collection rate of an in-water machine will be much less. It is therefore concluded that an ultra shallow water harvester is not a practical proposition at this stage.

CONCLUSION

It is concluded that the machinery which the Peel Inlet Management Authority now operates is effective in providing the foreshore cleaning service which Peel Inlet requires at Coodanup and Novara, provided it is regularly maintained and extensively used during critical periods.

At this time there appears to be no cost effective alternative solution to the methods of beach cleaning currently being employed.

Records of operation and biomass within the harvest areas are being regularly obtained and reviewed.

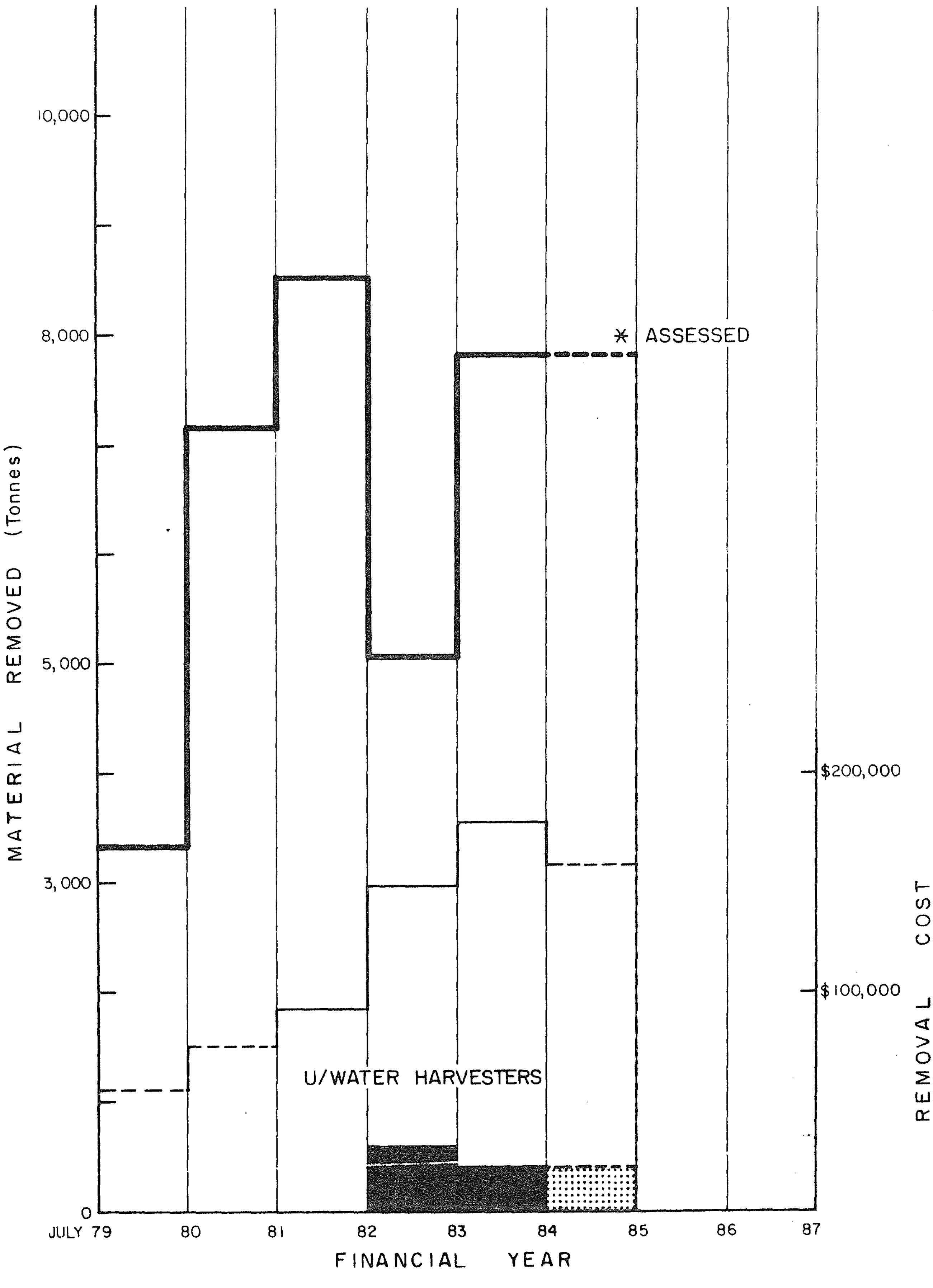

FIG. I. REMOVAL OF MATERIAL FROM COODANUP AND NOVARA FORESHORES

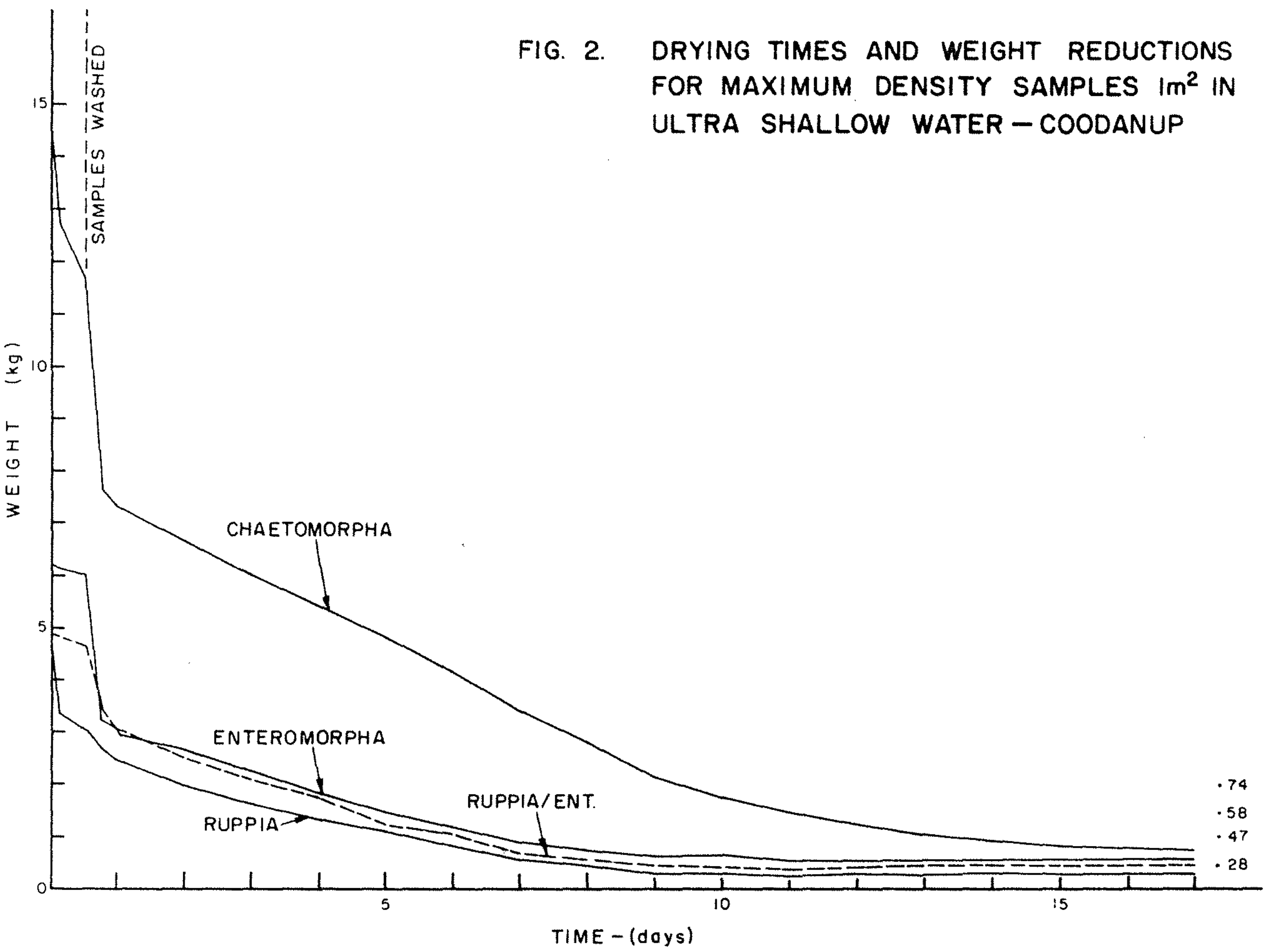

FIG. 2. DRYING TIMES AND WEIGHT REDUCTIONS FOR MAXIMUM DENSITY SAMPLES 1m² IN ULTRA SHALLOW WATER — COODANUP

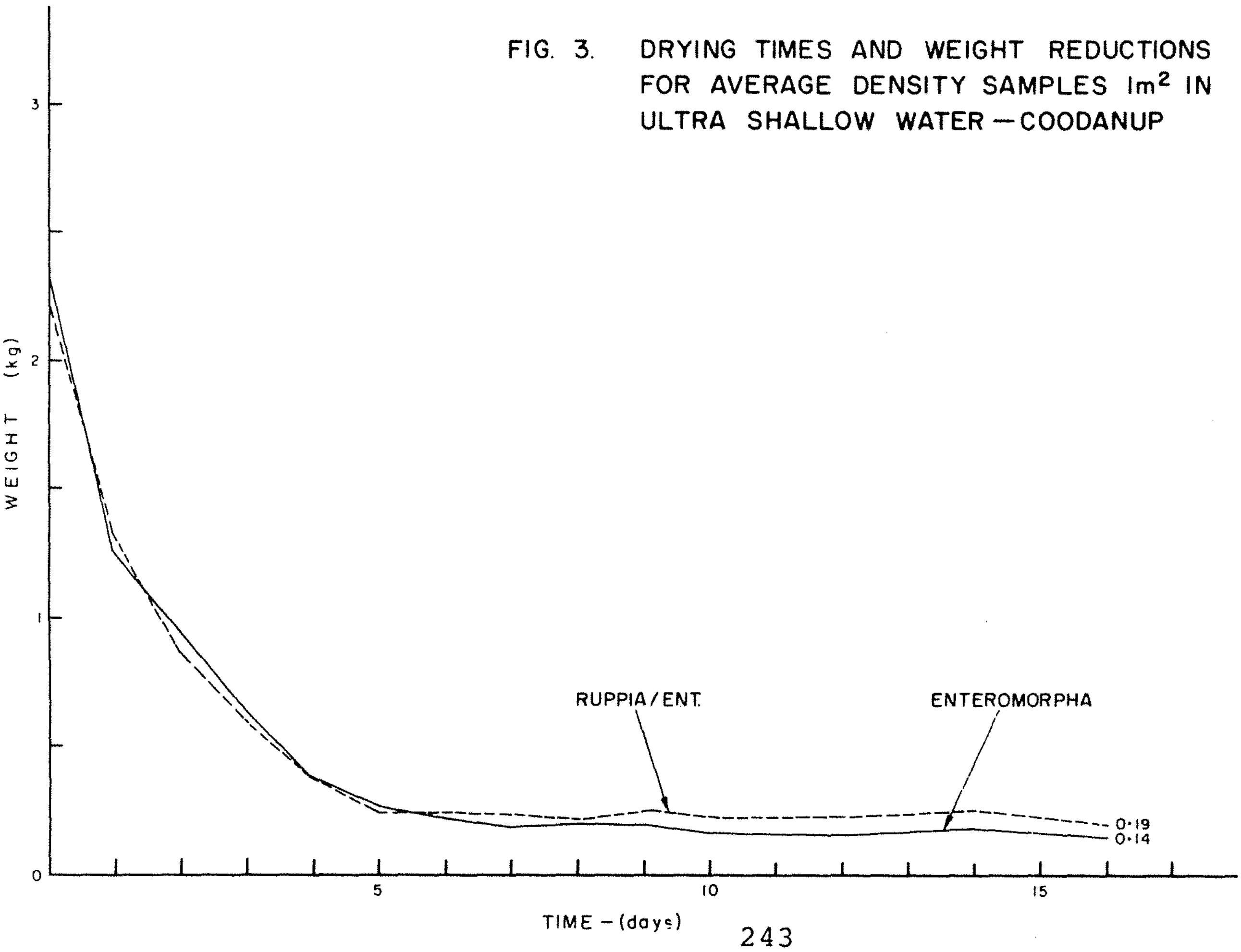

FIG. 3. DRYING TIMES AND WEIGHT REDUCTIONS FOR AVERAGE DENSITY SAMPLES 1m² IN ULTRA SHALLOW WATER — COODANUP

Month	Weight Removed	Assessed wet weight of algae Removed
October '84	204	120
November '84	1 420	852
December '84	393	236
January '85	860	516
February '85	>635	>381

TABLE 1: Material removed from Coodanup foreshores by front end loaders.

THE POTENTIAL USE OF ALGICIDES IN THE PEEL-HARVEY ESTUARIES

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INTRODUCTION

Chemical control of nuisance algae was first used in the late 19th century in Europe and North America. A wide range of compounds, including copper sulphate, simazine, diuron and terbutryn are known to act as algicides. Some years ago Fitzgerald et al (1952) investigated about 300 different chemicals to determine their toxicity to the green algae.

In recent years various organic compounds have been developed and a number are used in Australia for the control of submerged vascular macrophytes with any effect on macroalgae and photoplankta being reported incidentally. A number of compounds have been used for the control of nuisance macroalgae and phytoplankton (Fitzgerald 1981).

For a substance to be a good algicide it must fulfill the following criteria:

be effective against the nuisance algae
be non-toxic to fish, crabs and most fish-food organisms at the algae killing concentration
not seriously affect the ecology of the aquatic system
be non-toxic to humans
be reasonable in cost.

Bowmer (1984) has reviewed the potential use of algal growth inhibitors in the Peel Harvey estuary system and has determined that information on the following characteristics and behaviour would be required:

the efficacy of the algicide in controlling diatoms, cyanophytes (e.g. Nodularia and Oscillatorial), and concentration and exposure time required and possible selectivity which could lead to beneficial or deleterious changes in species dominance.

the effect of water quality on efficacy, particularly possible inactivation by absorption onto suspended particulate matter and reaction and precipitation in saline water.

the potential for small-scale treatment, and availability of special formulations to maintain contact between algicide and target organism which might be reduced during flow or mixing events.

the direct toxicity of algicides to fish and other sensitive organisms

any indirect or long-term detrimental effects which might be expected from algicide use.

Of the chemicals studied, terbutryn, a photosynthetic inhibitor is preferred because it is effective in controlling phytoplankton at low concentrations (0.02-0.05 mg/l). Terbutryn has been widely studied and used. It has been shown to have the fewest undesirable side effects, have a wide safety margin for fish and to be cheaper than alternatives. In Britain, terbutryn has been approved and cleared for use in fresh water since 1974. Tebutryn in the formulation of Clarosan, which contains a 1% active ingredient, has been cleared for use by the Pesticides Safety Precautions Scheme. The fact that it is less effective in controlling diatoms is an advantage since diatoms are important in aiding the generation of zooplankton and hence maintaining fish productivity.

Terbutryn does not appear to accumulate in the food chain, however, possible side effects on the ecosystem must be carefully investigated using local species and conditions. Bowmer (1984) drew attention to crustacea which are reported to be rather more sensitive to terbutryn than fish. This is obviously of major importance in the Peel Harvey esturary system. The effect on sea grasses also needs to be considered.

TOXICITY TESTING

A variety of tests have been developed to evaluate the true effects of chemicals in the aquatic environment. These range from laboratory tests to more extensive field testing.

In order to express dose-response relationships in a meaningful way a number of influencing factors need to be considered in the design of the test.

These include the following:

1. Physical considerations: temperature, exposure time, dose regimen or method of exposure, light intensity and periodicity, etc.

2. Chemical considerations: formulation, mode of action, pH, (CO_2 O_2 etc), dissolved inorganics, dissolved organics, colloidal materials etc.

3. Biological considerations: animal size, life stage (age), physiological stress, nutritional status, etc.

The data obtained in these tests must be analysed and interpreted. The types of studies carried out would involve the collection of results on:

1. Mortality/survival studies - LC_{50} etc

2. Physiological effects - immobilization, respiration etc

3. Ecological impact - distribution of numbers in trophic levels, quantity and quality changes in yields for recreation, food or other uses.

An overall Hazard Assessment Programme has been proposed by Maki and Duthie (1978) (Fig. 1).

Evaluation of the hazard to aquatic organisms must consider many factors and their appropriate contribution in carrying out an effective and efficient assessment procedure.

The data in Phase I comes from information for similarly structured materials and chemical/physical data. An estimate of the patterns of usage, disposal, and release including probability and frequency of reaching the aquatic environment is also of importance. Although many circumstances exist, which may obviate the need for aquatic toxicity testing, an assessment of physical-chemical data on most materials, whose manufacture, transportation, use, or disposal will involve a potential of reaching surface waters, will normally require at least minimal aquatic toxicity testing, thus proceeding to phase II.

In this case as the chemical, terbutryn, is to be deliberately used on a body of water then it is essential to proceed to Phase II and Phase III.

The decision to proceed to Phase III implies the identified need for life-cycle chronic data and bioconcentration testing. Chronic or partially chronic tests will permit the definition of an observed "no effect concentration" (maximum allowable toxic concentration (MATC) which is ultimately an important requirement for the establishment of acceptable surface water.

The final assessment of hazard in Phase III, reaching the decision alternatives of unlimited use, use with monitoring or discarding the material, will appropriately be based on very substantially different amounts and kinds of physical, chemical and biological data, for different materials.

Terbutryn has undergone Phase I evaluation and a decision was made that Phase II evaluation should be undertaken. Aquatic toxicity screening tests are currently being undertaken.

Initial laboratory based experiments have shown terbutryn to inhibit Nodularia growth. Algae cultured in the laboratory were exposed to terbutryn and the lowest terbutryn concentration to inhibit Nodularia growth was 0.1 - 0.2 mg/l active ingredient in sediment.

Acute toxic effects of terbutryn on non-target estuarine organisms also needs evaluation. Overseas research shows crustacea to be more sensitive than fish to terbutryn and the effects of terbutryn on crustacea is under investigation. The estuarine grass shrimp Palaemontes australis which is found in most rivers and estuaries of the south west of Western Australia has been chosen as test organism in present tests.

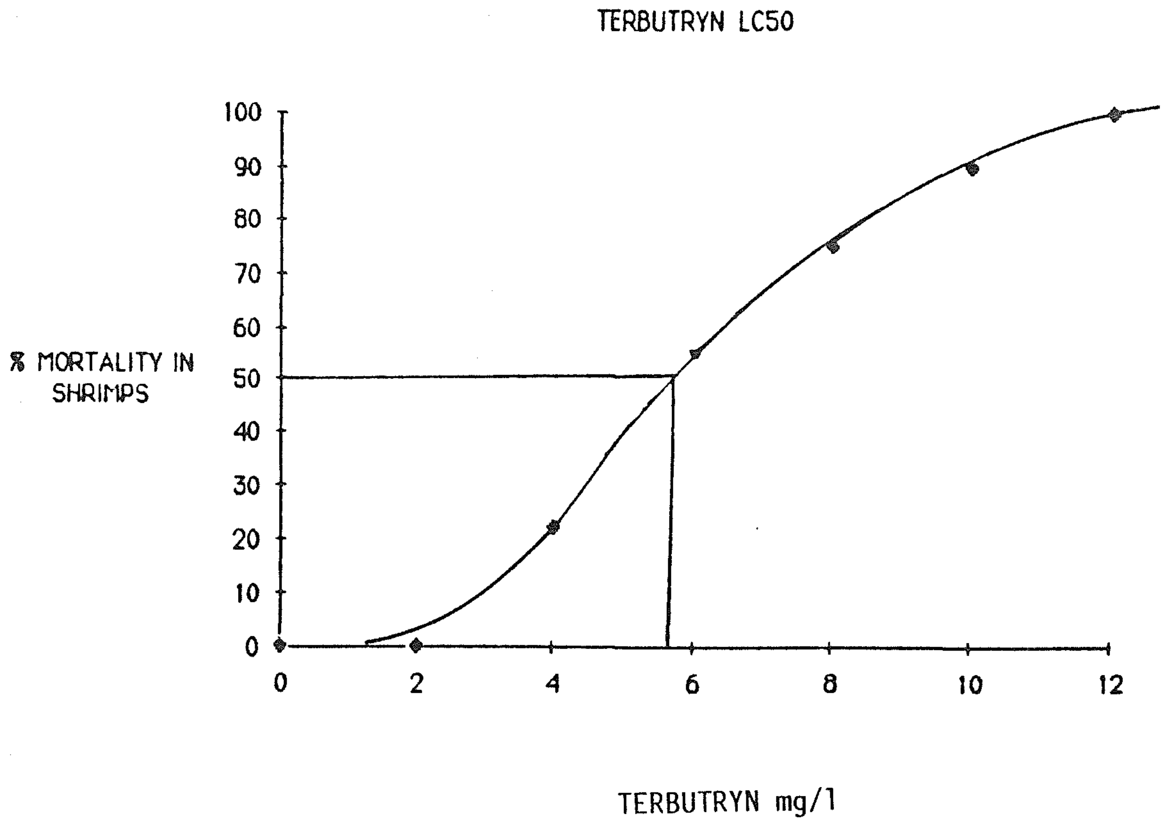
An acute lethal concentration assay, the LC_{50}, has been conducted on the grass shrimps over 96 hours. Shrimps have been exposed to one of a number of terbutryn concentrations and the percentage of each group of shrimps killed by the chemical determined. Results are generally given as the LC_{50}; the chemical concentration at which 50% of the exposed organisms die.

Table 1: Percent fatality of grass shrimps after 96 hours exposure to terbutryn.

Concentration of Terbutryn (mg/l)	Percent fatality of shrimps after 96 hours.
0	0
1	0
2	0
5	22
6	55
8	75
10	90
15	100

The results (Table 1) are illustrated in graph 1. The LC_{50} is the concentration of terbutryn that is lethal to 50% of a shrimp population after exposure of 96 hours. From Graph 1, it is seen that the LC_{50} is 5.7 mg/l.

The LC_{50} test was conducted at a salinity of 17 mg/l as is commonly found in estuaries. Further tests have been conducted in fresh water and in sea water (35 mg/l) and the experimental LC_{50} results have not been significantly different from the above results.



The highest concentration of terbutryn that caused no effect (death) was 2 mg/l (Table 1). Thus no concentration greater than 2 mg/l can be tolerated by the shrimps.

The LC_{50} test provides only limited information because of its 96 hour duration. The effects seen are due to acute toxic reactions and the criteria used is fatality. No information as to possible sub-lethal effects such as inhibition of growth or reproduction can be derived from the LC_{50} test.

Sub-lethal effects are those which may occur at a concentration of less than 2 mg/l. Preliminary investigations into possible sub lethal effects are focussed on exposure of shrimps to 0.1 - 1 mg/l terbutryn. Shrimps will be exposed to one of these sub-lethal concentrations for a number of months by giving three repeat doses of terbutryn at three weekly intervals. This procedure is intended to model the likely administration if the chemical were to be used in the Peel Harvey Inlet.

Data from sub-lethal toxicity tests will provide information on effects of repeated terbutryn application to waters containing crustacea.

The evaluation of data from these and further tests will assist in the decision making process as to whether terbutryn can be of viable use, be discarded or be subjected to further evaluation in this case.

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3. Maki, A.W. and Duthie, T.R. (1974) Summary of proposed procedures for the evaluation of aquatic hazard in etimating the hazard of chemical substances to aquatic life. ASTM STP 657. Cairns, J., Dickson, K. L. and Marki, A. W. Eds. ASTM p.153.

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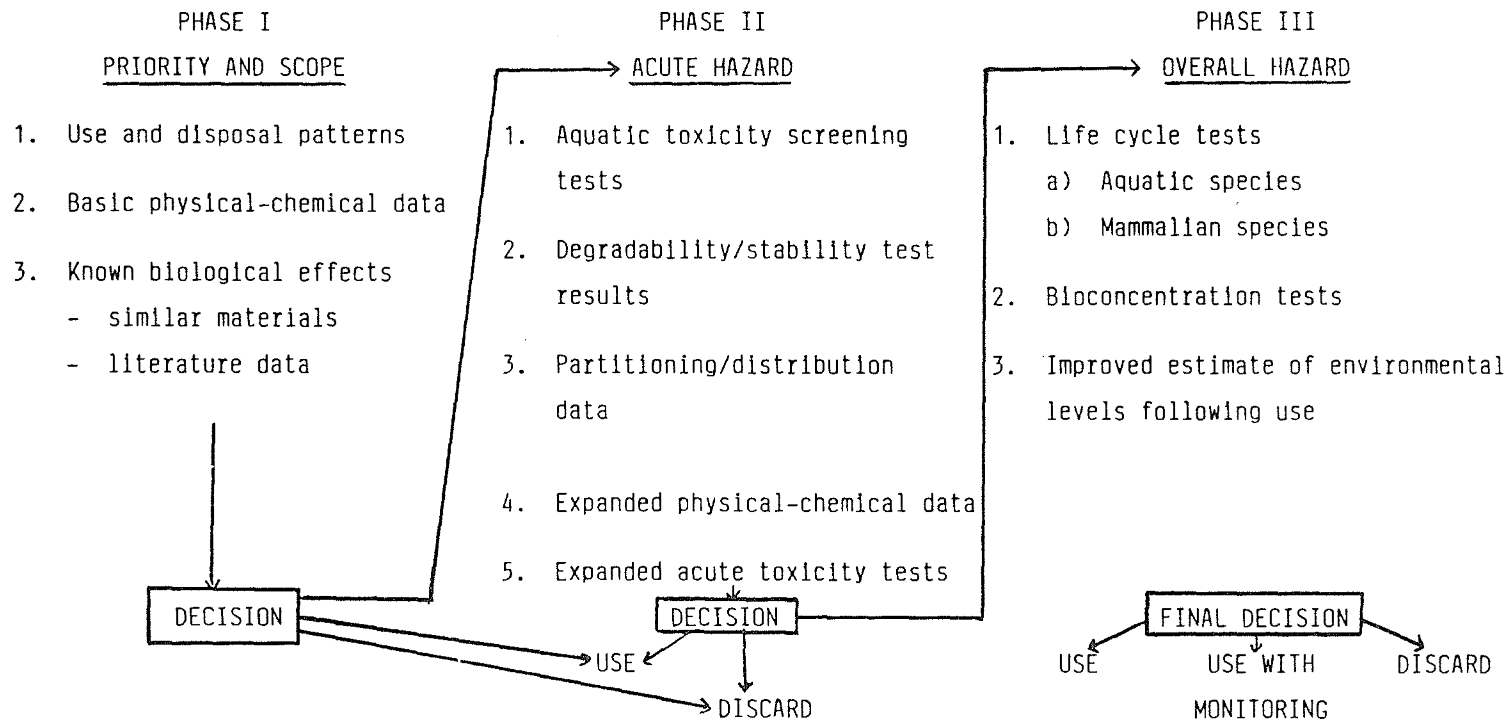
AQUATIC HAZARD EVALUATION SCHEME

SUMMARY DATA INPUTS



A Cost-Benefit Study of Alternative Strategies for Reducing the Algae Nuisance in the Peel-Harvey Estuary

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D.A. Morrison

Western Australian Department of Agriculture

March, 1985

INTRODUCTION

To make an informed decision on reducing the algae nuisance in the Peel-Harvey estuary, information on the costs and benefits of various levels of reduction of algae nuisance is required. The aim of this paper is to present data on costs and benefits as an aid to decision making.

This paper uses Cost-Benefit Analysis (C.B.A.) techniques to assess various levels of reduction of the algae nuisance. This approach is different from the Peel-Harvey Study Groups approach in so far as it is not constrained to achieving an "acceptable" level of reduction in algae nuisance, in a "realistic" time period. Rather by including for each strategy the level of reduction expected and the time before it is effective, the technique arrives at reductions and timing which maximise the net benefit to society.

The paper is divided into three parts:

- Costs of strategies to reduce algae nuisance.
- Benefits from reducing algae nuisance.
- Comparison of costs and benefits.

The first two parts provide the key costs and benefit information and the third part combines this information as an aid to decision making.

PART 1.

COSTS OF STRATEGIES TO REDUCE ALGAE NUISANCE

INTRODUCTION

Reducing the algae nuisance will involve costs to the government and hence to society. As part of making the decision as to which strategy or combination of strategies to adopt, information on costs is needed.

Strategies considered for reducing the algae nuisance are, fertilizer modification, bauxite residue incorporation, *P. pinaster*, *E. globulus* and the Dawesville channel. These strategies have emerged as worthy of further analysis following investigation of a much larger list.

For the forestry strategies there are costs to farmers of both agricultural income foregone and the planting and tending of trees. These costs are offset by returns from selling the forest products. If the profitability of forestry strategies is greater than current agriculture, farmers may convert voluntarily without large costs to government.

The costs of each strategy need to be assessed and compared from society's perspective . As each strategy achieves a different level of reduction of estuarine phosphate, a method of directly comparing strategies cost-effectiveness is required. Also recognising that some strategies have limited potential for reducing the estuarine phosphate, the least-cost strategy or combination of strategies for a range of reductions is required.

This part of the paper investigates firstly the profitability of catchment options from the farmer's perspective. Then from society's perspective, the cost-effectiveness of strategies is estimated, and finally least-cost strategy or combination of strategies for phospate reductions between 30% and 75% of present estuarine phosphate, are found.

METHOD

The following description covers only the major aspects of the method. Details of the analysis are available in separate appendices available from the authors.

Cost-Benefit Analysis (CBA) techniques, are used throughout the analysis (Mishan, 1976). By estimating the costs and benefits for various levels of reduction in algae nuisance the Study Group objective of an "acceptable" reduction in algae nuisance is not required in this analysis.

In keeping with standard practice in CBA only direct benefits and costs are accounted for although some indirect effects are discussed (Wesney & Woolcock, 1978).

Uncertainty exists about both the cost of some strategies and the benefits from strategies. Where uncertainty occurs a "best" or optimistic scenario and a "worst" or pessimistic, scenarios, are considered. This allows the best currently available data to be used for assessing strategies.

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). (see Morrison 1984). Discounting effectively internalizes the Study Group's second objective of a solution in a "realistic" time within the analysis.

A major difficulty in CBA is the selection of an appropriate discount rate (Pearce, 1983). A review of the literature provides support for a real discount rate in the range 3 to 5% (Gregory and Duncan, 1979: Porter, 1979). However State Treasury argues for a real discount rate with a lower bound of 3.5% rising to an upper bound of 10% (Brown pers comm.) whereas another study suggests a discount rate of 2.5% to 3% is appropriate (Randall, 1981). Due to the wide range of discount rates advocated, in this study CBA is conducted for discount rates in the range 0% to 8%. Highest credibility is attached to rates in the range 3% to 5% and 4% is used where a single rate is considered.

The strategies for reducing eutrophication of Peel-Harvey estuary considered are:

Catchment strategies;

i) Fertilizer Modification Programme (see Yeates, this publication).

ii) Bauxite Residue Incorporation (see Glenister, this publication).

iii) P.pinaster for sawlog production (see Morrison, 1984).

iv) E.globulus for chipwood production (see Morrison, 1984).

Estuary strategy;

i) Dawesville channel (see Paul, this publication).

Cost and phosphate reduction data were collected for these strategies, the sources being shown in Table I-1. Table I-2 shows the key data used to calculate the costs of each strategy. With the exception of P. pinaster, data on the 'best' and 'worst' scenarios is also shown. Other costs and benefits are given in the separate appendices.

Firstly the costs and benefits of forestry strategies fertilizer strategy and current agriculture were assessed. These are discounted over a ninety year period, for a range of discount rates. This allows the alternative strategies to be compared with agriculture to determine if a profit incentive exists for farmers to voluntarily convert from current agriculture.

TABLE I-1: Sources of costs and phosphate reduction data

Strategy	Data Source(s)
Present Agriculture	Farm survey, Farm Budget ME/83
Fertiliser modification	J. Yeates pers. comm. PSK fertiliser recommendation model 1984 soil sample forms
Bauxite residue incorporation	S. Ward pers. comm. D. Glenister pers. comm.
P. pinaster	Western Australian Forests Department (WAFD)
E. globulus	Western Australian Chip & Pulp Co. WAFD, Victorian Forest Commission
Dawesville Channel	I. Hutton pers. comm. J. Yeates pers. comm.

TABLE I-2: Principal data in the best and worst scenarios for each strategy.

Strategy	"Best" scenario	"Worst" scenario
Fertiliser	Benefits from converting from past fertiliser practices to optimal new coastal super. Research and extension cost = $250,000 in Year 1, falling to $50,000. Phosphate reduction = 50%.	Benefit from converting from optimal super to optimal new coastal super. Costs as in "Best". Phosphate reduction = 30%.
Bauxite	Treatment rate = 150 t/ha Cost = $4.65/t. Benefit to Alcoa = $0.91/t Benefit to farmers, yield response on Gavins and transition sands	Treatment rate = 200 t/ha Cost and benefit to Alcoa, as per "Best". No benefit to farmers.
P. pinaster	Clearfell in Year 45 MAI = 11.6 Phosphate reduction = 80% on treated area.	
E. globulus	MAI = $20m^3$/ha/pa Price = $9.50/m^3$ Phosphate reduction = 80% on treated area.	MAI as for "Best" Price = $6.77/m^3$ Phosphate reduction = 75% on treated area.
Dawesville Channel	Redevelopment benefit $15m No sand bypassing No contingency costs Phosphate reduction = 40% equivalent.	No redevelopment benefit. Sand bypassing costs. 20% contingency costs. Phosphate reduction as for "Best".

Secondly CBA was conducted considering costs and benefits from a society's perspective. Where a landuse change is assessed the opportunity cost of current agriculture is included. When considering the costs from society's perspective care was taken to exclude transfer payments.

Using the social NPV at 4% discount rate and dividing it by the phosphate reduction, the cost-effectiveness for each strategy was calculated (see Morrison 1984). Where "best" and "worst" scenario for both cost and phosphate reduction occurred, the highest cost was divided by the lowest phosphate reduction to give a "worst" cost-effectiveness, and the lowest cost divided by the highest reduction for the "best" cost-effectiveness. Cost-effectiveness was then used to rank strategies.

The least-cost solutions for a range of phosphate reductions were found using the costs, and phosphate reduction in a linear programming model. The model calculated the least cost strategies between 30% and 75% phosphate reduction at 5% intervals. Again two extremes, the "best" and "worst" scenarios, were specified.

RESULTS AND DISCUSSION

Farmers Perspective : Profitibility of Catchment Strategies.

Figure I.1 shows the NPV's of *P.pinaster,* and *E.globulus*, fertilizer plus current agriculture and current agriculture. In the range 3 to 5 per cent discount rate, regarded as most appropriate for this comparison, agriculture is more profitable than the *P.pinaster* strategy. In fact over the whole range of discount rates considered by economists *P. pinaster* is less profitable than current agriculture. It follows that there is no financial incentive for farmers to convert from agriculture to *P. pinaster*. Therefore farmers would not be expected to voluntarily convert to *P. pinaster*.

Figure I-1

Net present value to farmers of alternative land uses

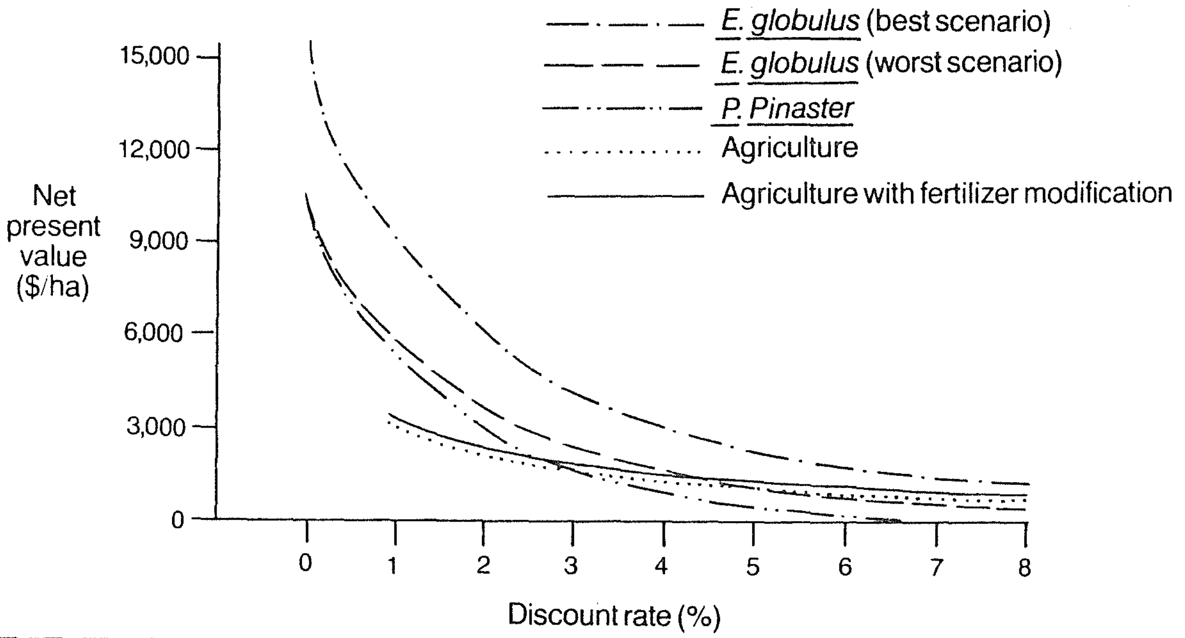


TABLE I-3: Costs, phosphate reduction and cost-effectiveness for different strategies of reducing the algae nuisance.

	Agriculture		Alternative land use		Estuary Based
	Fertiliser Modification	Bauxite Residue	Eucalpytus Globulus	Private Pines	Channel
NPV $'000 at 4%	500 to 2,100	-12,000 to -16,200	27,300 to - 2,100	-7,000	-12,100 to -30,500
Phosphate percentage reduction in estuary	30 to 50	67 to 75	66 to 67	23	40
Cost-effectiveness $'000% P	16.7 to 42.0	-160.0 to -241.8	407.5 to - 38.2	-321.8	-302.5 to -762.5

The second forestry strategy, E. globulus is more profitable than P.pinaster and at least as profitable as agriculture. If the best scenario occurred then E. globulus would be far more profitable than current agriculture. In spite of the potential profitability of converting from current agriculture to E.globulus farmers may not voluntarily convert because:

- Market and yield uncertainty for wood chips.

- Cash flow problems arising from the fact that no income is received until clear-felling after 15 years.

- Non-pecuniary benefits from agriculture may be higher than from forestry. (e.g. farmer conservatism and risk aversion).

- Farmers are not aware of the potential increased profit from E. globulus.

To overcome some of these reasons a research and extension programme would be needed. Also a scheme of Government underwriting and annuity payments would encourage farmers to convert.

Figure I.1 also shows agriculture with the fertilizer strategy is more profitable than current agriculture. An increased profit of about $5/ha/yr provides an incentive for farmers to adopt this strategy. This higher profitability is being used successfully to extend to farmers the fertilizer strategy (see Yeates, this publication).

From Society's Perspective

Table I-3 shows the NPV costs of the strategies for reducing the algae nuisance. "Best" E.globulus and the fertilizer strategies, have the unusual outcome of having net benefits rather than costs. These strategies generate sufficient income to farmers to offset all the costs of research and extension except in the case of the 'worst' scenario for E. globulus. Only in the 'worst' scenario for E.globulus, was there a cost of $2.1m, which is low in relation to the other strategies.

Thus there is a case to pursue the fertilizer and E. globulus strategies purely on the net benefits these generate within the catchment. Benefits from reducing the phosphate levels within the estuary could be viewed as an added benefit.

The costs of incorporating bauxite residue on both Bassendean and Coolup sands is between $12m and $16.2m depending on the rate of bauxite residue application. The Dawesville channel is between $12.1m and $30.5m depending on the extent to which development opportunities offseat costs and contingency costs.

Costs not included in Table I-3 are irreversible and option costs. Each strategy has these costs to varying degrees. The irreversible and option costs become particularly important when considering the Dawesville channel. This is because there is little that can be salvaged once the channel is constructed. This is not the case with a forestry strategy such as E. globulus. Also, once the channel is constructed there is little option left to use other strategies. This is an important cost given the uncertainty of known cheaper strategies effectiveness and the chance that other cost-effective strategies may be found.

TableI-3 also shows the cost-effectiveness of the different strategies. To compare the strategies they are ranked from the most cost-effective to the least cost-effective. The fertilizer strategy and E. globulus are the two most cost-effective strategies, followed by the bauxite strategy. The two least cost-effective strategies are the P.pinaster and Dawesville channel. If cost-effectiveness alone was used as a criterion for choice then fertilizer or E.globulus strategies would be chosen.

It was recognised that a strategy may not be highly cost-effective yet it may be justified because it gives a higher level of reduction of algae nuisance. Figure I-2 shows the cost for various levels of reduction in estuarine phosphate. E. globulus is not included in the analyses. The two curves are the "best" and "worst" scenarios. The upper curve, the "worst" scenario, shows that fertilizer is able to achieve a control of up to thirty percent at a net benefit. After thirty percent it becomes necessary to use the bauxite strategy at a cost. Up to sixty-seven percent the bauxite displaces the fertilizer strategy as the least-cost solution. Levels of control above sixty-seven percent are achieved with the fertilizer and channel strategy. The lower curve, the "best" scenario, follows a similar pattern, only the costs are far less and the level of reduction before bauxite residue enters the least-cost solution is fifty percent.

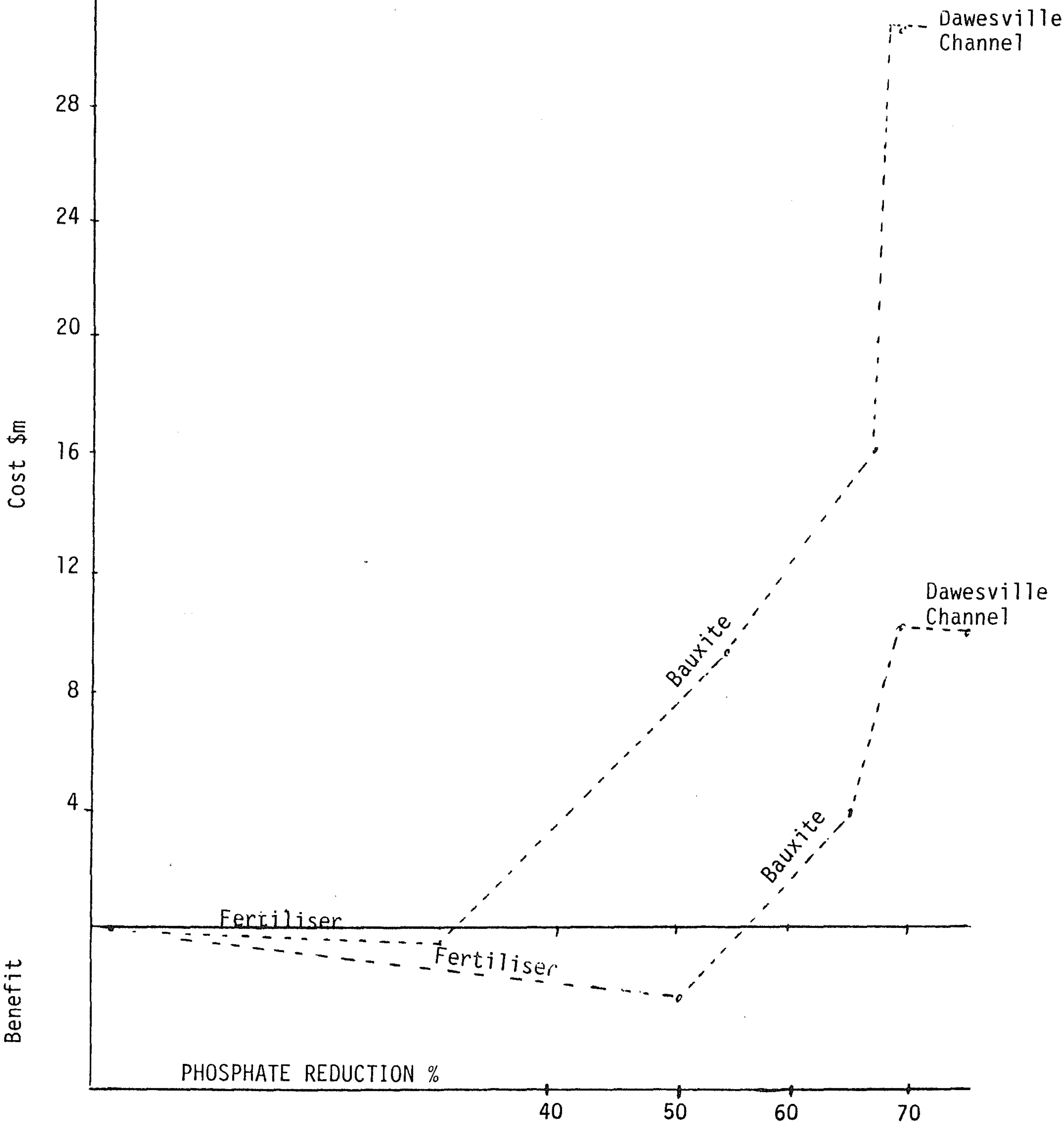
P. pinaster is not included as a least-cost strategy at any level of reduction. On the best available data, P. pinaster is inferior to other strategies for reducing the algae nuisance. Hence P. pinaster is not considered in the remainder of this analysis. However if improved yield or royalty data at some future time was available it may warrant a re-consideration.

The bauxite strategy provides an intermediate level of reduction of phosphate. Given the shape of the least-cost curve both before and after the bauxite strategy it is possible but unlikely that benefits would warrant a solution in the bauxite range. Hence bauxite is not considered in the remainder of the analysis. This is consistent with the Study Group's decision not to include bauxite as a prefered option (DCE Bulletin 170).

The fertilizer strategy or the fertilizer plus channel are the two most likely strategies for which a decision needs to be made. Given that they achieve different levels of reduction of phosphate at very different costs an estimate of the benefit likely from each is required.

Figure I-2

LEAST-COST SOLUTIONS FOR A RANGE OF PHOSPHATE REDUCTIONS (WITHOUT E. GLOBULUS)



IMPLICATIONS FOR MANAGEMENT

Given the fertilizer strategy has a net benefit within the catchment and if the channel is constructed the fertilizer is needed to complement the channel, it follows that the fertilizer strategy should be continued.

Given that E. globulus is protentially a more profitable land-use, an implication for management can be drawn from this alone. Further research into the yield and market for E. globulus is warranted. E. globulus and P. pinaster were the only forestry variety considered, further research could also identify other species that may be as profitable as E. globulus. While researching E. globulus as a potentially better land-use, consideration could be given to the phosphate export reduction from E. globulus.

Widespread adoption of E. globulus could be achieved using government/farmer co-operative ventures as suggested by Treloar (1984). Such a scheme could involve the government in providing farmers with a guaranteed annual income at a level at least equivalent to current agriculture. The government would recoupe its costs at clearfelling after 12-15 years. The profit after all costs, including the annual payment, being shared between government and farmers. Further investigations into such schemes are required.

The least-cost results showed a low level of phosphate reduction could be achieved at a net benefit and a high reduction at a substantial cost. No implication for management can be drawn from this result without an estimate of the benefits at the low and high reductions. Part II sets out to estimate these benefits.

PART II

BENEFITS FROM A REDUCTION IN ALGAE NUISANCE

In Part I it was established that low levels of reduction of phosphate could be achieved with a net benefit to society, but high reductions could be achieved only at a high cost. Consequently it was argued that an estimate of the benefits to society at the two levels was required. In this part the method and results of estimating the benefits are presented.

Method

People who would directly benefit from a substantial reduction in algae nuisance were identified as:

i) residents and potential residents of Mandurah

ii) visitors and potential visitors who use, or would use the Peel-Harvey estuary

iii) professional fishermen who use, or would use the Peel-Harvey estuary

iv) others, people who may never visit the estuary but benefit from:

- having the option of visiting
- knowing it exists
- bequeathing an unpolluted environment (Pearce, 1983).

As the net benefit to professional fishermen appears small or negative (Potter, 1984), they are not considered in this analysis. People falling in the "other" category given the type of benefit, would be expected to have lower individual benefits than residents and visitors. Detailed assessment of the benefit only to current residents and visitors was made. This does not imply that the other groups or part of groups should be ignored, but rather the principal groups relevant to a decision at this time are residents and visitors. In this part the benefits to residents and visitors are considered separately.

Residents

Effect and Number:

Skitmore (this publication) provides a descriptive analyses of the affect algae nuisance has on current residents. From this, the principal affect of algae are summarised in Table II-1.

The effect the algae nuisance has on residents will be different depending on their location and their recreational use of the estuary. Recreational use of the estuary by residents would be influenced by location with those living further away having alternative sites to recreate at lower travel cost.

The Mandurah region was divided into four zones (see Figure II-1) based on the extent to which they are affected by the algae nuisance. They range from the first zone encompassing the most effected homes which are homes within 500m of the estuary and affected by smell, to the fourth zone which is only very occasionally affected by smell and more than 2km from the estuary.

The affect of the algae nuisance would also be different for permanent residents and holiday residents. In recognition of this permanent and holiday residents are treated separately. The total number of permanent and holiday residents in each zone for 1984 was estimated using census data and are shown in Figure II-1 (A.B.S. 1976 and 1981).

Valuation Method 1:

As the nuisance developed over time it is to be expected that land prices in zones more effected by the nuisance would fall in relation to other land prices not effected by the nuisance.

A regression model using 280 land sales in the period 1976 to 1982 was constructed.[1] Independent variables for algae nuisance, distance to the sea and estuary, block size, corner blocks and

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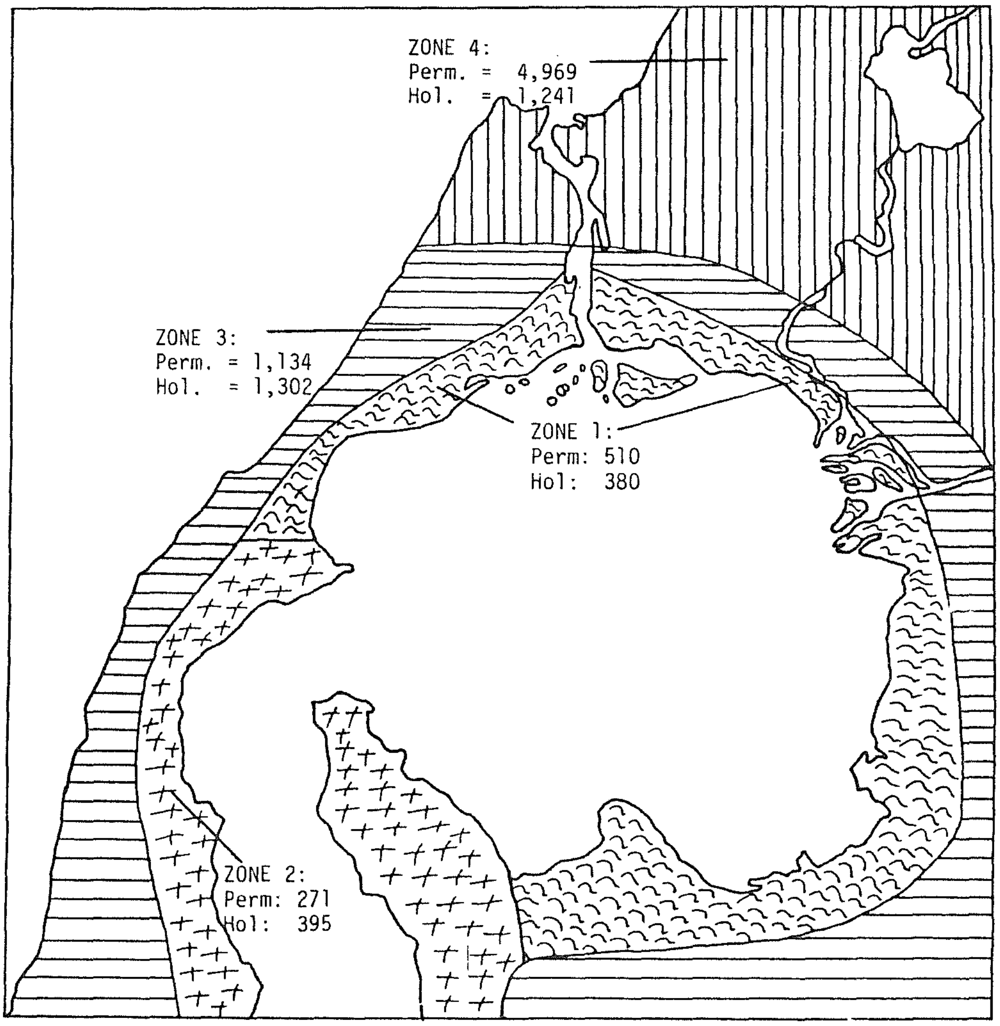
1 This technique is refered to as hedonic house (land) price in the literature. For details refer to Freeman (1979), McLoed (1981).

Figure II-1: Algae nuisance zones and number of permanent and holiday dwellings.



Perm. Permanent dwellings

Hol. Holiday dwellings

TABLE II-1: The effect of algae nuisance on Mandurah residents.

Category	Effect
Neighbourhood environment	Putrid smell
Aesthetic	Unsightly
Recreation	Putrid smell
	Unsightly
	Uncomfortable
	Obstructive
	Changed fish and crustacean resources

time were used. The algae nuisance variable was modelled in a number of ways to include lags and differences within the zones. The coefficient for the algae nuisance variable is interpreted as the dis-benefit to the buyers of bearing the algae nuisance.

In using the regression model to determine the value of the algae nuisance a number of assumptions were made. Firstly, it was assumed that a competitive land market exists with an upward sloping supply curve. This was verified by checking the volume of sales and avoiding new land releases or areas where land cartels operated. Secondly, it was assumed that buyers knew about the algae nuisance and expected it to continue. A survey of Mandurah residents was conducted to check these assumptions.

Valuation Method 2:
This method consisted of a survey of 57 Mandurah residents in which a hypothetical valuation question [2] was asked to determine the value of reducing the algae nuisance.

Hypothetical valuation questions have been verified against other valuation methods (Sinden and Worrell, 1979; Schulze et al., 1981). One problem identified is, respondents realizing the hypothetical nature and making a strategic response to influence the survey outcome. In the case of algae nuisance the respondents are considered likely to over-state their valuation of the algae nuisance.

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2 In a hypothetical valuation question a respondent is given information about a change, in this case an environmental change. A hypothetical situation is framed in which the respondent is required to contribute towards the change. The respondent is asked to identify what is the most they are willing to pay for the change. The hypothetical valuation question finds a willingness to pay (WTP). For further details on hypothetical valuation questions, see Sinden and Worrell (1979), Schulze et al (1981).

A pilot study identified mosquitoes as a major problem, often ranked worse than algae. The pilot study found respondents could identify with a hypothetical valuation question about reducing mosquitoes because they could envisage paying for additional mosquito control. Once the respondent had answered the mosquitoe question it was found they better understood the algae nuisance question.

In the main survey of Mandurah residents conducted in late December, respondents were asked to choose between a solution to a reduction in mosquitoes, green suspended algae (nodullaria) and weed (beaching algae) and also to rank the problems. This provided a check on consistency of answers . The main survey asked first a hypothetical valuation question for mosquitoes and then for algae nuisance.

Visitors

Effect and Number:
Skitmore (this publication) highlighted the lack of data on numbers of visitors to Mandurah. Hence a telephone survey of 157 Perth telephone subscribers was used to estimate the number of visitors in the past 12 months, and the number of people who would have visited if the algae had been substantially reduced.

Valuation Method:
Visitors and potential visitors who use or would use the estuary would benefit from a reduction in algae nuisance. The affect of algae nuisance on visitors would be similar to the affect on resident's recreation. However the value of a reduction in algae nuisance to visitors will probably be less than to residents because they use the estuary less and it is easier and less expensive for them to substitute other recreation sites and activities.

A similar survey approach to that used for residents was used for visitors. A survey using hypothetical valuation questions was used to determine the value to visitors of a substantial reduction in algae nuisance. Respondents were asked to identify problems and nuisances. Two hypothetical valuation questions were asked, firstly about another problem/nuisance and then about the algae nuisance.

Results and Discussion

Residents

Figure II-1 shows there are only 510 permanent residents in zone 1 compared to 4969 in the least affected zone 4. Hence the smell nuisance associated with the algae blooms affects only a small proportion of the Mandurah residents.

Representative specification and results of the land-value regression are shown in Table II-2 The regression explained 82 percent of the variance in the data. The variable for algae nuisance was not significant for this and for all other specifications. This indicates that the algae nuisance had not affected the land values. This finding was confirmed by valuers from the Valuer General's Department in their recent (1984) revalution of properties in the Mandurah region.

The finding that the land values are unaffected by the algae nuisance can be interpreted in two ways:

i) The algae nuisance has a low value

ii) Buyers did not know about the algae, or expected it to be solved very soon and at negligible cost to them.

In a survey of Mandurah residents (55 useful responses) it was found that 11 had bought before a nuisance existed, 18 did not know about the nuisance before buying, and 26 knew about either the nodullaria or macro-algae. Of the 26 who knew about the

TABLE II-2: Results of land value regression for a representative run.

Variable	Specification	Regression Coefficient	F-ratio
ALGAE NUISANCE	DUMMY FOR ZONE 1, NO LAG	1057	0.8
Time i	Linear)	6012	154.51*
	Squared) Third degree polynomial	-1599	74.79*
	Cubic)	147	55.09*
Distance to Estuary	Reciprocal of distance in tens of meters	39802	67.974*
Distance to Ocean	Reciprocal of distance in tens of meters	76345	322.08*
Constant		-1286	

r^2 = 0.82

* = significant at 99% confidence

TABLE II-3: Results of Mandurah resident hypothetical valuation question.

	Zones*		
	One	Three	Four
MEAN	$32.92 (1)	$27.00	$41.07
Uppper 95% confidence limit	$72.32	$133.58	$106.66

* No survey was conducted in Zone 2.
It is assumed for the remainder of the analysis that they have values the same as Zone 1.

(1) Willingness to pay (WTP) derived from hypothetical valuation questions.

nuisance, 13 thought it would continue indefinitely when they bought. Even though the proportion of respondents who said they both knew about the algae and expected it to continue was small, an effect on land-values would be expected or these buyers did not consider the algae a nuisance when buying.

When respondents in the Mandurah resident survey were asked to indicate whether they preferred a solution to mosquitoes, suspended green algae (nodullaria) or weed (beaching algae), 62 percent of the sample chose mosquitoes [1]. This indicates that the algae nuisance is not perceived by residents to be the most serious problem.

The results of the algae nuisance hypothetical valuation question asked of Mandurah residents is shown in Table II-3. The unexpected result of zone 4 having a higher valuation than zone 1 can possibly be explained by strategic error by 3 respondents in zone 4. However for the purpose of this analysis the responses are accepted as true valuations.

The valuations by residents of a substantial reduction in algae nuisance are lower than some researchers would expect. Three reasons are offerred for this:

i) Short duration of nodullaria nuisance; the nodullaria is only a nuisance for a few weeks of the year

ii) Low appreciation of neighbourhood environment

iii) Substitute sites and activities.
It was found that residents generally preferred fishing and boating in the ocean or Mandurah channel to the estuary even without the algae. If the estuary was the only recreation site available then it would be expected that residents would place a higher valuation on it.

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1 Within this sample there were proportionately more people from zone 1 than zone 4.

Using the hypothetical valuation responses for zone 1, the land values would be expected to be depressed by about $600 a block. The land value technique could isolate a $600 effect but did not. This would indicate that either,

(i) The hypothetical valuation question over-valued the algae nuisance. (Strategic error provides a plausible explanation for this).

(ii) The land value technique under-valued the algae nuisance. (The assumptions underlying the land-valuation technique were not fully met and could explain this).

(iii) The nuisance occurs uniformly over the Mandurah region, hence the land-value technique is inappropriate.

It follows from (i), (ii) and (iii) that the hypothetical valuation method provides a plausible upper estimate of values and the land valuation technique a plausible lower estimate. For the remainder of the analysis the higher hypothetical valuations are assumed to be the true value (WTP) of reducing the algae nuisance.

Visitors:

Based on a telephone survey of Perth subscribers an estimated 230,000 (± 10%) people visited Mandurah in the past 12 months and a further 18,000 would have visited if the algae was substantially reduced. The telephone survey indicated that most people visited in the summer or autumn after the algae nuisance has subsided.

The results of a survey of 45 visitors, in Mandurah, in January is shown in Table II-4. The sample was small and at one time of the year only. Further research is needed to verify these results. However an indication can be drawn from the survey. Forty-two percent of those surveyed did not identify algae as a nuisance in

TABLE II-4: Results of visitor survey.

Description	Result
Sample size	45
No algae nuisance (1)	19
Algae nuisance zero value (2)	17
Mean value of algae nuisance	$1.41
Standard deviation	$3.57

(1) Did not identify algae as a nuisance in the Mandurah region.

(2) Were not willing to pay for an improvement in a higher-ranked problem nuisance or algae nuisance in a hypothetical valuation question.

the Mandurah region. A further 38 percent identified it as a nuisance, but had a zero valuation for a reduction of the nuisance. Hence 80 percent of the respondents were either unaffected by the nuisance or had a zero value for a reduction in the nuisance. This finding is in accord with that reported in the Mandurah Tourism Development Plan (1984).

The remaining 20 percent had positive valuations for a reduction in algae nuisance as determined by a hypothetical valuation question. As with the resident survey a few respondents had values over $150/yr, these may be strategic error. However they are included as true valuations for the remainder of the analysis in keeping with the approach that when in doubt we accept the higher estimate of the nuisance.

Three reasons are offered to explain the low effect of the algae nuisance on visitors;

i) Timing and Duration. Data from the Mandurah Tourism Development Plan and the telephone survey indicate that most visits are in late summer and autumn when no nodullaria nuisance is apparent. Few people visit in the short time during the nodullaria blooms.

ii) Even if the algae were substantially reduced the telephone and Mandurah survey indicated that most visitors prefer to visit other sites (e.g. ocean, bridge, channel) or engage in non-water related activities (e.g. visiting shops, hotels, fairgrounds).

iii) Those visitors who prefer using the estuary either time their visits to avoid the algae nuisance, or substitute other site and activities with only a small loss in pleasure.

Further research into timing of visits, substitute sites, activities could validate the explanation for the current low value to visitor of reducing the algae nuisance.

At some future time it is conceivable that tastes would change and more likely crowding at substitute sites and activities would result in a higher value to visitors of reducing the algae nuisance. These changes in values may warrant re-assessment of nuisance at some future stage.

With the benefits from a reduction in algae nuisance estimated for the residents and visitors, what remains to be done is:

- The benefits from reductions associated with both the fertilizer strategy and the fertilizer plus channel need to be estimated.

- then these benefits need to be compared with the costs estimated from Part I.

Then the decision on either the fertilizer or fertilizer plus channel can be made based on maximising the net social benefit.

IMPLICATIONS FOR MANAGEMENT

No implications for management of the algae nuisance can be drawn from the benefits alone. However it is observed that the effect of the algae nuisance is low for both residents and visitors suggesting that costly strategies may not be warranted.

PART III

COSTS AND BENEFITS OF THE FERTILIZER STRATEGY AND FERTILIZER PLUS CHANNEL STRATEGY.

The costs of strategies was found in Part I and expressed with associated reduction in phosphate. Benefits from a reduction in algae nuisance was given in Part II. What remains to be done is the costs and benefits need to be described using a common reduction in algae nuisance, so that they can be directly compared.

Here the costs and benefits from the first two parts are both expressed for two strategies. The aim is to compare costs and benefits for the fertilizer strategy and fertilizer plus channel strategy. From this the strategy that maximises the net benefit to society can be chosen.

Method

The method adopted in this third part, firstly identifies the estuary response to the fertilizer strategy and the fertilizer plus channel strategy. From this the cost and benefits can be interpreted in terms of the estuary response, and finally the data are presented in a number of different ways which are relevant to making a decision.

Estuary Response

To account for the uncertainty about how the estuary will respond to the fertilizer strategy and fertilizer plus channel strategy, a "best" and "worst" outcome for each is considered. Table III-1 shows the long term estuary response for the two outcomes. Also shown is the expected time before the long term outcomes are realised.

TABLE III-1: Estuary response to fertiliser strategy and fertiliser plus Dawesville Channel strategy

Estuary outcome	Fertiliser strategy	Fertiliser strategy plus Dawesville Channel strategy
Worst possible outcome	No further deterioration	Nodularia blooms on average three years in ten. No reduction in macro-algae
Best possible outcome	Nodularia blooms on average three years in ten. Forty per cent reduction in beaching macro-algae	Nodularia blooms on average one year in ten. Forty per cent reduction in beaching macro-algae

Estuary Response, Costs and Benefits

The discounted costs found in Part I are directly applicable to both the "best" and "worst" estuary outcomes. However the benefits for a reduction from Part II need to be weighed by the total number of individuals, adjusted for the actual estuary outcomes and timing before effective.

The first step was to weight the individual benefits identified in Part II by the number of individuals in each group. This involves a value judgement on the weighting to be given to each individual. Guided by the social norm, each individual is assumed to have a unitary weighting. Holiday residents were assumed to have the same benefit as permanent residents in each zone. Most likely this would over-estimate the benefits. People who currently do not visit but would if the algae were reduced were assumed to have the same benefit as current visitors. This may under-estimate the benefits.

The second problem was to define what proportion of the nuisance is attributable to nodullaria and macro-algae. The residential survey found residents ranked the nodullaria either equal to or slightly above the beaching macro-algae as a nuisance. Two alternative assumptions are considered for the components of the nuisance. Firstly, the more plausible assumption in which nodullaria accounts for 60 percent of the nuisance and macro-algae 40 percent. Secondly, the alternative assumption, in which nodullaria accounts for 100 percent of the nuisance.

The third problem was to relate the benefits to the different outcomes. In the case of nodullaria, the frequency of blooms are expressed as averages which are different for each outcome. It is assumed that the benefits from not having a nodullaria bloom, is independent of the frequency of nodullaria blooms. For the beaching algae it is assumed that benefits are linearly related to the percentage reduction in algae. With these two assumptions the benefits are weighed by the frequency of nodullaria free years and the percentage reduction in beaching algae for both the "best" and "worst" outcomes.

Benefits are discounted to allow for differences in time before the estuary response is fully realized. A zero benefit is assumed until the estuary reaches the long term reduction [1]. This assumption would tend to underestimate the benefits, particularly for the slower responding fertilizer strategy.

Decision Making

A rational objective for society is to maximize the net social benefit, that is, maximise the surplus between benefits and costs. The net cost from Part I are deducted from the calculated benefits for both the fertilizer strategy and fertilizer plus channel strategy. Then the strategy that maximizes the social net benefit can be identified.

Results and Discussion

Two reasons for cautious interpretation of results are:

(i) The results from both Part I and II were based on the best available data, however there is uncertainty and high variance which is shown by the "best", "worst" scenarios, and the confidence intervals. Hence the results are only indicative, and should not be taken as definitive.

(ii) The benefits data were drawn for only current residents and visitors, these benefits are hence relevant for present decision making. It is unlikely, although possible that other current group could benefit significantly and hence change the conclusion.

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1 Further work will improve upon the calculation of benefits for the lead in time.

Table III-2 shows the discount costs and the benefits for both the fertilizer strategy and the fertilizer plus channel strategy. The fertilizer strategy has the rather unusual result of a net benefit rather than cost within the catchment as well as a "best" benefit within the estuary of between $6.0m and $7.25m. This contrasts with the fertilizer plus channel strategy which has a cost of between $10.0m and $30.0m and a benefit at most of $11.4m.

Table III-2 also shows the net social benefit of the two strategies. The Dawesville channel has a negative net (net cost) benefit under all but the most optimistic scenario. For channel benefits to exceed costs it is necessary to assume that developers are willing to contribute $15m, that costs are low and the best estuary outcome results.

The numbers shown in brackets are the net benefit at the upper 95 percent confidence intervals. Given that the high variance was due to a few responses which could have been over-statements the upper limit is unlikely.

The social objective of maximizing the net social benefit is achieved for all estuary outcomes except "worst" fertilizer and "best" channel, by the fertilizer strategy. In fact even if the benefits were substantially higher the likely shape of the benefits curve would most likely result in the net social benefit being maximized by the fertilizer strategy.

TABLE III-2: Costs, benefits and net social cost of the fertiliser strategy and the fertiliser plus channel strategy.

Scenario		Fertiliser Strategy	Fertiliser plus channel strategy
Worst	Cost Benefit	+0.5m 0	-30m 5.3m to 8.9m (29.0m to 48.3m)*
	Net Social Benefit	+0.5m	-24.7m to -21.9m
Best	Cost	+2.1m	-10m
	Benefit	6.0m to 7.2m (32.6m to 39.3m)	8.9m to 11.4m (48.3m to 62.1m
	Net Social Benefit	+8.1m to +9.3m	-1.1m to +1.4m

* Numbers in brackets referto upper 95% confidence limit

IMPLICATIONS FOR MANAGEMENT

Although further research is required, best available estimates suggest the construction of the Dawesville channel would result in a net social cost. The implication for management from this is not to construct the channel at this time.

If it was decided that a high reduction in algae nuisance was "required", then it would be rational to delay a decision on the channel to establish what level of reduction would be achieved by catchment stragegies. After a short period it would be clearer as to whether the catchment strategies alone could achieve a high reduction in algae nuisance.

If the decision to delay was made then an increased research and extension effort into E. globulus and other cost-effective strategies is warranted. The promising results for E. globulus found in Part I need to be confirmed before farmers can be expected to plant E. globulus voluntarily.

If it was decided not to proceed with the channel a re-assessment at some future time may be warranted. At this time the benefits may have increased, due to changes in recreation taste and crowding at substitute sites. It could then be rational to construct the channel. Therefore it may be rational to take whatever steps are necessary to preserve the option to construct the channel.

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THE SOCIAL SCENE

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1. Introduction

In examining the social implications of the proposed Dawesville Channel there are two fundamental issues which must be addressed. Firstly, is the proposed Dawesville Channel justified in the social sense, i.e. is it needed for social reasons? Secondly, what is the probable social impact of the channel for tourists (existing and potential), residents (existing and potential) and other people in WA?

The available data on which to answer these two questions are both limited and highly subjective, notwithstanding this, it is essential that Phase 3 studies are not based solely on the physical environment but also take adequate account of the social environment. Failure to relate social needs or aspirations with management options could result in one particular option being put forward which does not match the social need for a solution to algal blooms or to the ability of the community to finance the option. Accordingly, social values could provide a key indicator towards selection of a suitable management option.

Of particular relevance to social needs, is the establishment of acceptable levels and frequencies of algal blooms which the community is prepared to accept. In addition, the time period within which these acceptable levels should be achieved will provide a clear indication as to which management option meets the communities needs. In the absence of social based acceptable levels, the Phase 3 studies have adopted broad based levels suggesting that Nodularia blooms should not occur more than once in five years on average and macro algae (weed) should not foul beaches near populated areas. These levels would appear to be acceptable in social terms.

To examine the social impact of the proposed Dawesville channel, it is necessary to investigate the social characteristics of the population of Mandurah and to a certain extent its visitors. It is also necessary to examine in detail, social impact of the existing algal regime and what aspects of the impact would be alleviated or removed by the construction of the Dawesville Channel. Lastly, the specific advantages and disadvantages of the channel in terms of its construction, location and opportunities presented, require examination.

Many people and documents refer to the 'algal problem' in the Peel-Harvey system. This has been well documented in biophysical terms, however there is little valid data to quantify how residents and visitors are effected by algal blooms. Notwithstanding this lack of data, it is clear from observation and general public comment that people perceive a major social problem.

A review of available information on social impact of the algal blooms, reveals that there is a high degree of subjectivity involved and that caution needs to be exercised in treating this information as scientific data. It is however the only basis on which to make any assessment and could be used to give an indication of public perceptions rather than a quantification of them.

Information sources for the study have included :

- 1976 and 1981 Commonwealth Census
- Mandurah Tourism Development Plan
- A small scale attitudinal survey carried out by the Department of Agriculture
- A community group survey by the Department of Conservation & Environment. (Comments were sought from Mandurah Shire Council, the local Tourist Bureau, Peel Inlet Management Authority, Peel Preston Preservation Group, local real estate agents, the Mandurah Professional Fisherman's Association and the Department of Youth Sport & Recreation).

It has been assumed for the purposes of this paper, that the Dawesville Channel will achieve the results predicted in terms of its effect on alage growth in the Peel-Harvey System.

2. Principle Social Characteristics of Mandurah

Mandurah has a very high percentage of retired people (taken as over 65 years of age). From the 1981 census, the Mandurah area has a retired population which averages 19% (Perth's is 9%) but it varies considerably over different areas of Mandurah. South of the Murray River, it is 6%, which reflects the farming activities of the area. In Mandurah town area, it is 21% and at Caddadup it is 23%. It should be anticipated therefore, that the perceptions, aspirations and recreational patterns of this group will be significant and it is essential to make specific provision for any potential bias in any social survey data.

The age group of 5 - 14 years is similar for Perth and Mandurah. This phenomenon may be due to an increasing trend for young families to reside in Mandurah. Employment opportunities available in resource industries to the east of Mandurah together with a wide range of residential land being available are probably related to this trend. Provision must be made to account for the needs of this age group especially in terms of recreational patterns.

A comparison of 1981 data with those collected in 1976 relative to retirement percentages, show that for most sections of Mandurah, there is a trend towards a reducing percentage of people in this group. The only exceptions to this trend were at Caddadup and near the mouth of the Murray River. This possible trend should be appreciated in order to understand the changing social structure of Mandurah generally and of individual areas specifically.

The number of persons in the Mandurah area with tertiary qualifications is almost half that of the Perth average i.e. 5% against 9%. With the complex and technical issues involved in understanding and managing the Estuary, account must be made of the educational levels of the community when carrying out and interpreting social surveys.

The percentage of holiday homes in Mandurah varies between 10 and 66% with the average being close to 30%. Areas of highest percentages of holiday homes are south of Mandurah along the coast. A comparison of 1976 and 1981 data indicates that with the exception of the Halls Head area, there is a clear trend towards a reduction in the percentage of holiday homes in Mandurah. The area is slowly changing from a holiday home/retirement area, to one with an increasing number of younger people and permanent homes. How far this trend will extend, or at what level it will stabilize is unkown. This changing character of Mandurah will have an effect on recreational patterns of the population; although tourist recreational patterns should be unaltered.

3. Mandurah Tourism Development Plan

This plan was prepared in 1984 for the Mandurah Shire Council and the Western Australian Tourism Commission. Part of the research carried out was to analyse tourist use and perceptions of the Mandurah Region. Although the survey was carried out on only 400 people in the Perth Metropolitan area, it does provide some useful information in assessing recreational patterns of tourists to Mandurah.

Generally, and in Mandurah particularly, recreational activity patterns are highly flexible and are easily adjusted to cater for environmental perturbations. Mandurah has a large range (and thus wide choice) of attractions and people have the ability to easily replace one recreational activity with another. This phenomenon means that the loss of, or temporary inability to use a particular recreation resource has a low impact on the overall recreational attraction of Mandurah.

The survey conducted for the Plan, indicated that the largest single tourist attraction at Mandurah was fishing and crabbing (29% of the responses), then beaches (17.4%), followed closely by Inlet/Estuary/Boats (16.4%). When discussing the disadvantages of holidaying in Mandurah, only 6.2% of responses related to cleaning up the Inlet/Estuary, an indication that tourists do not believe that it is a big problem. This percentage needs to be treated with caution as it is uncertain whether the 6.2% of responses refers to the total number of people interviewed in the survey, or to the number of people in the survey who had actually visited Mandurah in the last 12 months.

The survey work undertaken therefore indicates that water quality is not a problem in developing tourism within the central Mandurah area. However, it is a factor in limiting development south and east of Mandurah. Operators of tour facilities considered that bad press coverage of algal blooms was a greater problem in terms of tourism, than the algae itself.

It is important to note that of the people surveyed, only 26% of respondents had actually visited Mandurah in the last 12 months. Therefore, if the 6.2% response indicating a need to clear up the estuary was calculated solely from the group who had actucally visited Mandurah, they would constitute 23%. However, even a figure of 23% does not necessarily indicate a major problem. Of the operators surveyed 20% indicated that algae was a guest problem. All of these operators were located on the river or inlet system.

The Plan recommended that further surveys be carried out on actual visitors to the Mandurah area to provide more accurate data of the effect of algae on visitors. Tourist operators in the central Mandurah area indicated that algae was not a guest problem.

4. Additional Survey by the Department of Agriculture (December 1984)

The survey was conducted by door to door interviews selected at random. It sought to identify and quantify attitudes of local residents to the growth and accumulation of algae and weed in the Peel-Harvey System. Only six questions which were considered to give useful social data are analysed for the purpose of this paper.

Residents from Mandurah town, Halls Head, Coodanup, Miami, Falcon and Navara Beach were interviewed in mid-December during working hours. Although it was originally intended to interview a significantly larger number of residents, only fifty seven were eventually interviewed and of these five were unacceptable for various reasons such as not enough information was recorded for them, or the person being interviewed did not understand the questions asked. Table 1 below compares the proportion of people (representing an individual household attitude) interviewed to the total number of households for the area.

Table 1

AREA	NO. OF HOUSEHOLDS SURVEYED		NO. OF HOUSEHOLDS IN AREA	% OF HOUSEHOLDS INTERVIEWED
Mandurah	14		2728	0.5
Coodanup	10		558	2
Halls Head	8		512	2
Falcon	4)			
Navara Beach	9)	20	238	8.4
Miami	7)			
TOTAL	52		4036	1.29

The table illustrates firstly the small proportion of people interviewed compared with the total population, and secondly how biased the results are in favour of Falcon, Miami, and Navara Beach, where the algae and weed problem is worst.

Of the 52 responses received, 32 (62%) were from retired people. Mandurah Shire Statistics (Source: Australian Bureau of Statistics) show the average proportion of retired people in the Shire to be 19% of the total population. Consequently, for the survey data to more accurately represent attitudes of local residents, responses from retired people were statistically reduced to represent 20% of the total number of responses. Caution must therefore be exercised when considering the results of the survey as the number of responses is too small to obtain a representative attitude for people living in these areas, but they may be useful in indicating a trend.

Tables 2 and 3 are presented to show the sums of raw data for both retired and non-retired responses and the percentages based on adjusted data to illustrate responses to each question.

TABLE 2

RAW DATA FOR RETIRED AND NOT RETIRED RESPONSES

	NOT RETIRED			RETIRED		
QUESTION	ANSWER	NO.	%	ANSWER	NO.	%
Holiday home or permanant residence?	PR	30	93	PR	16	80
	HH	2	7	HH	3	15
	?	1	5			
Does algae affect household ? (Yes/No)	Yes	21	65	Yes	11	55
	No	10	31	No	8	40
	?	1	4	?	1	5
Does weed affect household ? (Yes/No)	Yes	19	59	Yes	9	45
	No	11	34	No	10	50
	?	2	7	?	1	5
Know about algae before moving in ? (Yes/No)	Yes	9		Yes	10	
	No	10		No	7	
	N/A	13		N/A	3	
Know about weed before moving in ? (Yes/No)	Yes	13		Yes	7	
	No	16		No	10	
	?	3		?	3	
Worst problem algae and weed or mosquitoes ?	M	18	56	M	16	80
	A & W	14	44	A & W	4	20
First priority problem: algae and weed or other ?	M	13	41	M	13	65
	A & W	13	41	A & W	5	25
	O	6	18	O	2	10
Would reduction in algae and weed affect leisure activities ? (Yes/No)	Yes	19	59	Yes	14	70
	No	13	41	No	4	20
				?	2	10
	TOTAL SURVEYED 32			TOTAL SURVEYED 20		

TABLE 3

PERCENTAGES BASED IN CORRECTED DATA
(Bias towards retired people adjusted)

QUESTION		ANSWER	%
Holiday home or permanent residence ?		Perm. residence	83
		Holiday home	13
		?	4
Does algae affect household ?	(Yes/No)	Yes	57
		No	38
		?	5
Does weed affect household ?	(Yes/No)	Yes	48
		No	47
		?	5
Know about algae before moving in ?	(Yes/No)	Yes	66
		No	34
		N/A	20
Know about weed before moving in ?	(Yes/No)	Yes	36
		No	50
		?	14
Worst problem algae and weed or mosquitoes ?		Mosquitoes	75
		Algae and weed	25
First priority problem: algae and weed or other ?		Mosquitoes	60
		Algae and weed	28
		Other	12
Would reduction in algae and weed affect leisure activities ?	(Yes/No)	Yes	68
		No	24
		?	8
		TOTAL 25	

? = answer not clear
N/A = question not applicable - residents moved in prior to 1977

It is appropriate to examine each of the six questions in turn and attempt to identify any fundamental attitudes (and reasons for these) to algal growth in the Peel-Harvey System.

- HOLIDAY HOME OR PERMANENT RESIDENCE

  There was a very high percentage people in permanent residences (83%), and figures show that more non-retired respondents are living in permanent residences. This high figure of permnanent residents is however a reflection of the relative absence of holiday home answers from the survey.

- DOES ALGAE/WEED AFFECT HOUSEHOLD

  On average, a little over half the respondents said they were affected by algae and weed. In the retired group, slightly less are affected than in the non-retired group (reason unkown).

- KNOW ABOUT WEED AND ALGAE BEFORE MOVING IN

  More people (40%) knew about algae before moving into the area than those who knew about the weed (36%). This may relate to more people perceiving algae as a problem as opposed to weed, as well as the publicity associated with it. There is however, much confusion in the community as to the difference between algae and weed.

- WORST PROBLEM : ALGAE AND WEED OR MOSQUITOES

  Most households (75%) indicated mosquitoes to be the worst problem. Retired respondents considered mosquitoes to be by far the most important with 80%, whereas non-retired people see the problems as approximately equal (this may be because retired persons spend much of their time at home and are therefore more exposed to the insects. Local variations in mosquito numbers could also affect the responses.

TABLE 4

ADVANTAGES AND DISADVANTAGES FOR THE DAWESVILLE CHANNEL

Group	Advantages : Dawesville Channel	Disadvantages : Dawesville Channel
Mandurah Shire*	Windsurfing - ocean coast very good for windsurfing, with creation of artificial waves at the channel, could attract major sponsorship bringing thousands of tourists. - boost flagging land values as a result of algae pollution	- where will algae weed go when flushed out of estuary? Tidal range on ocean side may not be great enough to disperse it, and it may accumulate on ocean beach - will spoil existing beach - land values may decrease if channel not successful - will lead to loss of one of Mandurah's premier surfing locations, and may lead to overcrowding on other beaches - may change bathymetry north and south of channel which may indirectly alter other surfing locations - expensive maintenance and repairs
Peel Inlet Management Authority (PIMA)	- quick relief from algae and weed problem in estuary	- channel may help to eliminate Nodularia but macroalgae may still be present that will still have to be cleared away as an area of tidal flats will accentuate the problem
Peel Presentation Group (PPG)	- access to ocean for small boats through sheltered boat launching facilities which has been a local concern for some time - even if not 100% successful the channel will be a valuable adjunct for dis-persal of nutrients	- danger of wild land speculation

* Result of meeting to discuss only the recreational advantages and disadvantages of the channel.

Group	Advantages : Dawesville Channel	Disadvantages : Dawesville Channel
PPG (cont'd)	- will provide good opportunities for marine developments along coast - will present excellent fishing possibilities for residents from traffic bridge across Old Coast Road - good potential for tourist industry if land speculators are kept under control	
Real Estate Institute of W.A. (REIWA) (Mandurah branch)	- will stimulate residential and economic growth, as well as tourism in Mandurah. Feel it has been stifled by publicity of algae problem in estuary and inlet in past. - channel will aleviate problem of decreasing land value in area - has potential to be prime real estate.	
Mandurah Professional Fishermen's Association (MPFA)		- Increase in tidal range of estuary from 5 to 40cm per day will have adverse effects on the fishing industry - at low tide banks will be exposed, reducing fishing grounds by 50% - difficult to haul fish during strong tide - tide will flood low lying areas - impossible to set nets overnight in winter with increase in daily tidal flow - boat launching facilities only useable at certain times unless rebuilt.

Group	Advantages : Dawesville Channel	Disadvantages : Dawesville Channel
MPFA (cont'd)		- increase in salinity of estuary and clean water will mean decrease in numbers of mullet and yellow eyed mullet - current basis of crayfish bait industry - increase in numbers of table fish such as whiting, tailor and herring which have a limited market at a viable price - flushing may be too effective in removing nutrients and there may be no food for fish - sand and weed from the sea deposited in the estuary through tidal exchange may become a problem - movement of pleasure boats through the channel and estuary may increase net damage and disturb and break up schools of fish.
Department of Youth, Sport and Recreation) Mandurah Tourist Bureau)	- No specific advantages or disadvantages, they just raised points to consider.	

- FIRST PRIORITY : MOSQUITOES, ALGAE AND WEED, OR OTHER

  People were asked which problem would they personally give first priority to : either algae and weed, mosquitoes, or 'other' (e.g. traffic congestion, hospital, sand bar dredging). In general, 60% indicated mosquitoes to be their first priority. Retired respondents gave a priority of 65% whereas non-retired respondents gave equal importance to both mosquitoes and algae and weed (both 41%). It is noticable that 'other' issues rating first priority for correction was 12% overall and 18% in the non-retired group.

- WOULD REDUCTION IN ALGAE AND WEED AFFECT LEISURE ACTIVITIES

  58% of respondents stated that a reduction in algae and weed in the estuary would directly influence their individual leisure activities.

  Retired respondents indicated that this reduction would significantly influence them (70%) and non-retired respondents less so with 60%.

These data give an indicator of the impact of algal blooms at Mandurah, but none can be used to provide a definite level of impact.

The subsequent attitudinal survey to be carried out early in 1985 will hopefully be able to provide further information on the questions of impact, however due to the inherent problems associated with social surveys and issues, it will probably only provide an indicator and not scientifically usable data.

4. Community Group Survey by Department of Conservation and Environment

A range of groups and agencies which have a knowledge of and interest in the Mandurah area were surveyed by letter, Table 4 contains a summary of their responses.

With the exception of the professional fishermen, and the surfing fraternity, there was general support for the Dawesville Channel as a management option.

5. Present Social Impact of Existing Algal Blooms in the Peel-Harvey Estuary

Whilst there is no data to quantify the level of existing social impact of algal blooms in Peel-Harvey Estuary and it is unlikely that any meaningful data could be obtained; it is possible however, to identify perceived social impact.

- **Economic Impact** - the present algae problem does not present an encouraging future for either existing developments or those proposed. Specifically the tourist trade could suffer considerably during algal blooms and especially those oriented to the estuary. The Mandurah Tourist Plan states that 60% of retail expenditure is generated in the area from non-residents. Accordingly, any loss of tourists, especially in the October - January period could have major impact.

  Mention has been made of depressed real estate values, however this has not been proven by studies carried out by the Department of Agriculture. Some individual values may be depressed for near estuary properties, especially areas such as Navara and Coodanup. Impact on some individuals can be substantial if houses have to be sold and prices or selling times are altered because of the algae problem. This can be especially serious for retired people as they are likely to have invested a substantial amount of money in their retirement property.

  Some development proposals have been deferred because of the algal blooms, this possible loss of development could have repercussions through the local community. In addition, the present state of the estuary has made the assessment of some proposals extremely difficult and contentious, the canal proposals are an example.

  There have been high management costs associated with weed harvesting and collection. Associated with the depressed real estate market, and recreational disadvantages, is the need to maintain a beach clearance programme for estuary foreshores. These high management costs, in the order of $160,000 p.a., are met by the Government through PIMA (Peel Inlet Management Authority).

  There have also been high costs associated with numerous studies undertaken to establish the cause and extent of the problem, and the identification of management options. Hundreds of thousands of dollars have already been spent and more is to be committed for future studies. Implementation of a preferred management plan and its costs will be covered in the specific impact of the channel. Also related to this aspect is public demand for interim measures, e.g. public demand for dredging the Mandurah channel to improve flushing and navigation.

Fishing has also been affected. At present the estuary is experiencing a reduced amateur catch as a result of the Nodularia blooms. At other times of the year the catch may be increased due to macro algae growth, however overall species diversity is reduced. While nutrients encourage algae and weed to grow, this may provide shelter from natural predators and provide food e.g. the recent good prawn seasons, but too much weed sometimes lead to deoxygenation and result in fish mortality. Mullet and yellow eyed mullet favour nutrient rich environments and this is good for professional fishermen who sell them for rock lobster bait.

- **Community Impact** - general community concern for the reducing environmental value of the estuary is widespread. Also the community is concerned with the press coverage of the algal problem and the economic and social implications it may have.

There have also been conflicting community priorities for any large expenditure of funds in the Mandurah area. Some people support the development of the Dawesville Channel, while others believe that mosquitoes or a hospital are more important issues.

The community has been clearly divided on a whole range of issues directly related to the algal problem. The canals debate in particular caused a major division of the local community. It could be argued that if the estuary was in a healthy condition this matter would not have achieved the degree of concern that it did.

There may also have been altered community perceptions of desirable suburbs, and those which suffer from weed accumulation and consequent odours may be less desirable or less socially acceptable. In the longer term, this aspect lends to reduced house and land values.

Although the community is concerned about the quality of the estuary, it is also expressing concern about possible adverse impacts of management options, this is particularly relevant amongst the professional fishermen.

The operation of Local Government in Mandurah has certainly been affected during the years of major algal blooms, and in particular over the canals issue. The community respect for Local Government as an institution and a means of reflecting community aims and aspirations has certainly been altered.

- **Personal Impact** - at a personal level, residents and tourists have lost or suffered severely diminished aesthetic values of the estuary. The rotting weed can create very unpleasant odours. The impact of these odours range from annoyance through to affect on health, both in a physical and mental sense. It is not uncommon for people to have to leave their residence for varying periods of time to escape the smell. This problem also relates to the management staff of PIMA who are involved in the collection, transportation and disposal of rotting weed.

  There is a substantial loss of recreational opportunities including water sports such as boating, swimming and ski-ing. Residents and tourists have also experienced a loss of crabbing and fishing to a certain extent.

  Personal loss of property due to a drop in real estate values in the worst affected areas can seriously disadvantage low income residents such as retired people.

The cumulative social impact of the existing algal blooms can not be quantified and is often highly subjective. In essence, it could be argued that collectively the people of Mandurah and the State are not affected to a high degree by the problem. However there are a number of people in specific areas adjacent to the estuary who are affected to a high degree for varying period. As previously stated, the recreational and leisure resources of the Mandurah region are considerable and the community appears well able to adjust its use of the estuary to those periods when the water quality is suitable for their particular activities. This is extremely important in viewing the impact of algal blooms on recreational activities.

Providing the Dawesville Channel achieves its design performance relative to salinity regimes and losses of phosphorous from the system, almost all social impacts of the existing algal blooms will be removed. Some however will take longer to resolve than others.

6. Possible Social Impact of the Dawesville Channel

Apart from overcoming the existing problems associated with the algal blooms, the channel will have impacts specific to its construction and location. In addition, its impact on the estuary will cause physical and biological changes.

- **Economic** - the 'cleaning up' of the estuary will increase development options in the area. Development will be revived and opportunities created for the development of lands adjacent to the channel itself. This land would provide opportunitites for a whole range of recreational, tourist and residential development and facilities and provide a most exciting feature linking the ocean to the estuary.

  Mandurah Tourism Development Plan states there is presently not a single resort development offering an array of accommodation, restaurants and other tourist support facilities near the beachfront. As the beach is considered one of the major tourist attractions of the Mandurah area, this sort of development must occur. Development associated with the Dawesville Channel (including marina, boat harbour, tourist accommodation, recreation facilities, and shopping areas) could provide a solution.

  Professional fishing in the estuary may be affected primarily through reducing fishing areas (due to tides) and increased boating activity in the estuary. In addition, minor changes to species may affect the present exploitation of large numbers of bait fish by professionals.

- **Community** - there will be major benefits in community values of the Mandurah area generally and the near estuary lands in particular. Localities near the estuary will again become sought after for aesthetic values.

  Recreation opportunities will be actually created by the construction of the channel and as well as providing safe access to the ocean south of the Mandurah Channel. A sheltered harbour and rescue facilities could also be included in the development associated with the land adjacent to the channel.

- **Political** - the construction of the Dawesville Channel would be seen by the people of Mandurah and W.A. as the Government fulfilling its promise to resolve the algal problem. It would justify all of the time and money spent in studying the estuary.

  In addition, the growth in development and creation of opportunities for expanded tourist and recreational facilities would be seen as a direct result of Government action. The employment opportunities created by the actual construction of the channel and associated tourist/recreational developments could be considerable. Also re-vitalised development in the strip between the ocean and the estuary would see additional employment opportunities.

The following table puts into perspective the whole range of opportunities created by the Dawesville Channel and lists all disadvantages identified. Upon examination it is clear that the advantages in social terms clearly outweight disadvantages.

SOCIAL ADVANTAGES AND DISADVANTAGES OF THE DAWESVILLE CHANNEL

Geographical Location	Advantages		Disadvantages
Ocean	. swimming . surfing . windsurfing . water ski-ing . skin & scuba diving . boating	. fishing, including fishing from groyne . could increase productivity of near shore waters	. potential destruction of abalone beds offshore . possible alteration in surfing area may put additional pressure on other beaches
Ocean foreshore/ beach	. sunbathing . scenic lookout . picnics . walkways . creation of sheltered beach north of channel . boat launching facilities		. loss of 200 m of ocean foreshore
Inlet/ Channel	. swimming, fishing, crabbing, prawning in channel, scenic views . easy & safe access to estuary & ocean for boats . marina for ocean boats, yachts (shelter) . inland sheltered recreational water (channel waters) . sea rescue facilities . in excess of 3 km of channel foreshore would be created		
Land surrounding channel	. walkways . cycleways . picnic area . scenic views . general increase in overall aesthetic appeal in area . increase in value of real estate & development opportunities	. camping & caravan parks . tourist accommodation . residential accommodation . hotels, shopping facilities . quick relief from existing Nodularia blooms . increased tourist potential	. areas adjacent to channel no longer isolated and quiet eg Tims Thicket, Caddadup Reserve . disruption during construction period
Estuary foreshore/ beach	. sunbathing . walkways . picnic area . cleaner foreshore (no Nodularia) although some weed accumulation will still occur	. camping & caravan parks . boat launching facilities . fishing, crabbing, prawning, windsurfing	. loss of 200 m of foreshore . disruption of prawning and fishing area offshore . more competition for windsurfer hire and use . due to greater tidal range, existing boat launching facilities may have to be extended, and channels dredged
Estuary	. swimming . water ski-ing . fishing (may improve percentage of table fish in catch as well as increase fish species) . boating . windsurfing . crab numbers should increase . decrease in occurrence of Nodularia blooms and reduction in other blue-green algae		. low tide will expose more mud flats than at present. Aesthetics and usability of Estuary will be affected accordingly . difficult to haul & set fishing nets during a strong tide . at low tide, fishing grounds will be reduced . increased congestion through boat activity in estuary and channel . increased boat activity may break up schools of fish and affect professional catch . increase in extreme high water mark may increase mosquito problem . increase in water salinity may alter prawn catch, and will alter present fish population . may reduce present bait fish species and present commercial patterns
Mandurah Region	. cessation of adverse media coverage of Nodularia blooms . general improved perception of Mandurah as a tourist destination . development of tourist facilities and recreational opportunities around the Dawesville Channel will compliment overall recreation & development potential of Mandurah		. possibility that new development may be attracted away from Mandurah
State	. resolution of environmental problem for present and future generations . stimulation of tourist development and recreational opportunities of State significance . public confidence in Government's willingness and ability to achieve proper environmental management		. cost of $31,000,000 and foregone opportunities for expenditure of these funds for other uses

7. Conclusions

Notwithstanding the paucity of valid data but rather from the available information on the existing impact of algal blooms on the people of Mandurah and tourists,it is considered that:

.1 The algal blooms in the Peel-Harvey Estuary are not a major problem to the residents in the Mandurah region

.2 The blooms affect residents and tourists more in the areas south of Mandurah adjacent to the Harvey estuary

.3 Those people who are affected to a high degree constitute a minor portion of Mandurah's population

.4 There is no proof that the tourist trade is significantly affected by the algal blooms

.5 People surveyed in the area clearly believe that mosquitoes are a greater problem than algae and should receive first priority

.6 Tourists are less affected by algal blooms than residents of the area

.7 If the Dawesville Channel is constructed and achieves its design performance, most of the existing adverse social impacts of algal blooms would be removed or would be manageable

.8 Generally, community groups in the area are in favour of the Dawesville Channel (except professional fishermen)

.9 The channel would provide substantial recreational, tourist and development opportunities if constructed

.10 Any adverse impacts of the channel could tend to be biophysical rather than social, although some existing recreational patterns would be altered

.11 Whilst the social and biophysical advantages of the Dawesville Channel are clear, the justification for spending $31 million on it is a political decision

.12 Because of the issues involved and the inherent difficulties of obtaining usable data on social or community perspectives, it is believed that even with more extensive social surveys, the above conclusions would remain valid and can be used as an input to the decision making process

.13 Should a decision be made to construct the channel it would be highly desirable to monitor the social impact of it as well as the biophysical. The data obtained could provide a most valuable base on which to assess social impact of future development projects.

THE ERMP AND THE ATTITUDINAL SURVEY

Ron Black
Kinhill Stearns

1 INTRODUCTION

Before construction works can commence on the Dawesville Channel or on improvements to the Mandurah Channel, it will be necessary to expose the entire management strategy to the public participation process known as environmental impact assessment (EIA). In Western Australia, this can involve the preparation of an Environmental Review and Management Programme (ERMP).

This paper describes the ERMP for the 'preferred strategy', i.e. the package of management measures described in Bulletin 170 (Department of Conservation and Environment 1984a) as being essential to restore the health, or at least prevent any further decline, of the Peel Inlet and Harvey Estuary. As part of the EIA process, a series of telephone, face-to-face and group interviews are being undertaken, involving local residents and special interest groups. This is referred to as the 'Attitudinal Survey' and is designed to produce a clear picture of the public perception of the estuary's problems and their acceptance of measures proposed for their solution.

2 THE ERMP

2.1 Why have an ERMP for the preferred strategy?

Because the preferred strategy includes an engineering measure (or measures) which will have significant environmental impacts, both during and post construction, the EPA has considered that it is necessary to evaluate these, and to expose the issues to public debate.

A set of 'guidelines' for the preparation of the ERMP has been prepared by the Evaluations Branch of DCE, and subsequently endorsed by the EPA.

2.2 Staged ERMPs

The EPA favours the presentation of the ERMP in more than one stage when the proposals are of such magnitude and/or diversity, or have such significant environmental consequences that it is rendered too complex for a single document.

The Dawesville Channel Management Package, as it may be referred to, is a clear example of such a proposal. It was thought necessary to provide the opportunity for the public to react to this 'preferred strategy' before undertaking the evaluation of the considerable potential environmental consequences of these measures. An additional benefit is the opportunity to expose the public to the alternative strategies that were evaluated in the process of determining a combination of measures which, if implemented, could reduce the algal nuisance to acceptable levels.

2.3 Stage 1 ERMP

As explained above, this will address the rationale for the selection of the preferred strategy. Stage 2 will then canvas in detail the potential environmental, social and economic costs of the Dawesville Channel management package. It should be remembered that a decision to proceed with the Dawesville Channel has not yet been made; this will take place after current investigations are complete and both stages of the ERMP have been assessed by the EPA.

The Stage 1 document is in preparation at the time of writing (March 1985).

Guidelines for the Stage 1 ERMP

It is clear that it will be necessary to draw heavily upon and refer to the material presented in Bulletin 165 - Management Options (Humphries and Croft, DCE (1985b)) and Bulletin 170 - Report of Research Findings and Options for Management (Kinhill Stearns and Study Team, DCE (1985a)). The former is a technical document which explains the procedure for and conclusions of the analysis of alternatives for solving the estuary's algal problems. The latter is a public report, intended for the non-technical reader.

In summary, the major areas to be addressed in the Stage 1 ERMP are as set out below:

1 Introduction
2 Need for the proposal
3 Management objectives
4 Evaluation of alternatives
5 The preferred strategy
6 Further studies
7 Conclusions
8 References

The full guidelines have been approved by the EPA and published by DCE.

3 THE ATTITUDINAL SURVEY

The final session of this symposium is concerned with:

- how people view the estuary
- how people view the potential management measures, especially the Dawesville Channel.

Whilst these were not part of the original brief given to the Study Team by the Premier and Cabinet, it is clear they must be considered. For this reason the Study Team and the Policy Advisory Group decided to carry out an 'attitudinal survey' to canvas these views.

Why have a survey?

There are numerous reasons other than those enunciated above, but three obvious ones are to:

- determine the local and regional views on the estuary's problems and what should be done;
- provide input to the EIA process;
- show the community that it clearly has a role in the decision-making process.

3.1 Questionnaire Design

This is not an easy matter and the constraints included the need to avoid:

- asking leading questions (if the opening questions simply take for granted that there is a problem, everyone will agree that it should be solved);
- asking too many questions (the validity of the responses will suffer if people become bored).

The Study Team devised the questionnaire and discussed it with others with an interest in the social and planning issues. This trial questionnaire was then 'piloted' on the weekend of 2/3 February 1985. Twenty valid telephone interviews were conducted, a process which took twelve person hours. The pilot survey revealed no significant problems with questionnaire design and established interview time, achievement rates and administrative problems.

3.2 The main survey

This was carried out on the weekend of 2-4 March 1985 (the Labor Day long weekend) and involved 100 telephone and 50 personal interviews. It is appreciated that timing is a problem; whilst the choice of a long weekend would maximise the number of visitors to Mandurah and the estuary, it could well result in a biased perception of the town's problems, e.g. traffic difficulties at Mandurah Bridge might well be seen as a major issue at that time.

Results of the survey are currently being processed and analysed.

3.3 Public meetings

A concern expressed about previous public meetings has been that particular interest groups, such as the professional fishermen, might be unable to get their point of view across in a forum strongly supportive of some contrary position.

For this reason, it was decided to hold meetings with such local groups so that a true reflection of their views could be obtained. These meetings will be held on 9-10 March 1985.

Separate meetings will be conducted with:

- the Mandurah Professional Fishermen's Association
- the Peel Preservation Group
- the Falcon Ratepayers Association
- the Southern Estuaries Ratepayers Association
- a group of John Street, Coodanup residents

The Peel Preservation Group is representative of the local conservation movement, whilst the latter three groups are those most affected by the smell and other problems associated with weed accumulation and removal, as well as Nodularia.

3.4 Results

The questionnaire, and the full analysis of all interviews and meetings, will be published in full in the final report of the Study Team (April 1985).

4 REFERENCES

Department of Conservation and Environment (1984a): 'Management of Peel Inlet and Harvey Estuary. Report of research findings and options for management.' DCE Bulletin 170, May 1984.

Department of Conservation and Environment (1984b): 'Management of the eutrophication of the Peel Harvey Estuarine system.' DCE Bulletin 165, May 1984.

1985 PEEL-HARVEY ESTUARINE SYSTEM SYPOSIUM

<u>What the management measures can achieve</u>

Ernest P. Hodgkin

Tuesday's discussions revolved around finding an answer to Jim Barrow's question: How do we supply phosphorus to plants without supplying it to the estuary? The answer is we can't; but, as the various speakers showed, it will be possible to minimise the loss of agricultural phosphorus. Peter Birch estimated the achievable reduction in input to the estuary at 20 to 40% in 3-5 years and a further reduction of up to 60% in 10 to 15 years.

Those were the percentages we had to take on board when considering what the reduced average levels of input will do towards solving the problems of the estuary and what other measures will be necessary if our management objectives are to be achieved. I stress average, because of the experience of 1984 when there was a <u>Nodularia</u> bloom despite the small input of phosphorus - less than half that of the three previous years (Fig. 1).

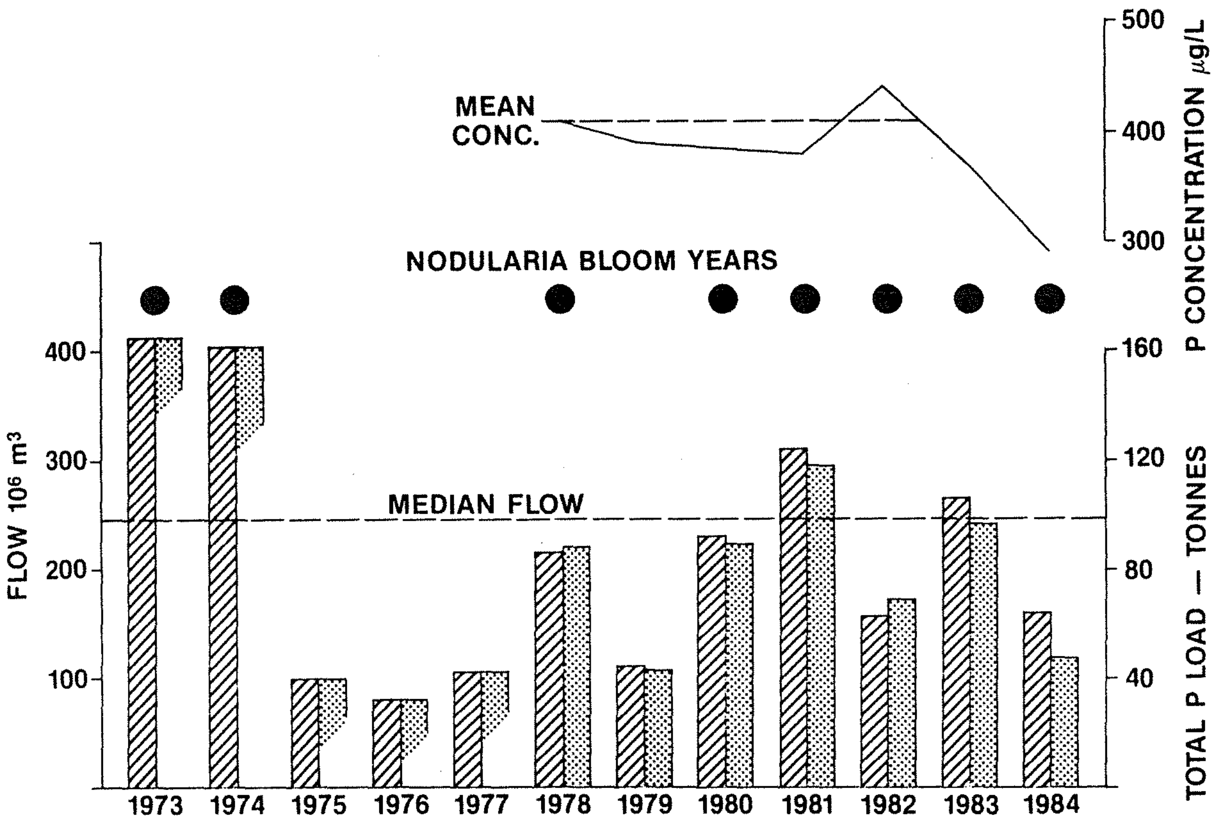

Figure 1. Harvey River flows and phosphours loads, May - September. Phosphours loads: 1978-84 observed, 1973-77, estimated only.

Peter Birch gave us a clear summary of Tuesday's discussions and I don't propose to repeat what he said. However, there are a few points which I wish to pick up because they relate directly to management of the estuary. First, as he said, "this level of reduction will only ameliorate the problems of the estuary in <u>the short term</u>". As Ron Black has pointed out more than once, the brief of the Project Team was to recommend measures which will solve the algal problems of the estuary as quickly as possible; that is, in the short term, which I take to be 3-5 years.

It will be for Government, not us, to decide to wait 10 or 15 years to see whether the catchment management measures can reduce input of phosphorus sufficiently to cure the algal problems. Perhaps we will be better able to assess the situation before the first bulldozer bites into the Wannanup dunes (the site of the Dawesville Channel).

The continued success of the catchment management program will depend on the continued co-operation of farmers, and that in turn on the continued high profile of the Department of Agriculture in the catchment, to give acceptable advice to individual farmers and to develop appropriate fertilizers. We were reminded that pollution of the Peel-Harvey estuary is the best thing that has happened to farmers on the coastal plain. The fertilizer modification campaign has had real benefits for farmers as well as for the estuary, but, as was asked: if soil testing and advice is left to farmers, what happens to the estuary if people get lackadaisical?

Turning now to the estuary itself, if we accept the fact that the catchment management measures cannot alone clean up the algal problems within the time frame we have been set, we have to consider how else the objectives can be achieved. That has been the main thrust of this second day's discussions and I will only refer indirectly to the social and economic issues which we have just been considering.

The emphasis has naturally been on what the Dawesville Channel proposal will do to supplement the catchment management measures by reducing the amount of phosphorus available for algal growth. Such a major interference with a natural ecosystem as the Channel will be requires full justification, not only because of its considerable maintenance and capital costs, but also because we need to be certain that the benefits it confers far outweigh any possible detrimental effects. For this reason, I particularly welcome two assurances we have been given.

First, we had Mike Paul's statement that the chosen location and alignment of the Channel presents us with less of the familiar problems associated with coastal engineering than was anticipated. The entrance should be stable, with no serious erosion of the shore line, and the long-shore drift of sand is small and will be of little concern. Problems of construction and maintenance are therefore expected to be manageable.

Then, on the biological side, we had Arthur McComb's assurance that although detailed predictions cannot be made concerning all of the responses of the biota to the Channel, there do not appear to be any areas of biological uncertainty of sufficient concern as to outweigh the known benefits which would follow construction. This will no doubt be the subject of public and government debate when the Stage 2 ERMP is released. While he added that there was no need for new programs of research for the ERMP, he did stress the need for continued and expanded monitoring of major aspects of the ecosystem and recommended that provision for this be included in the cost of construction and operation.

Assessment of the effects of the channel on the biota is of course dependent on predicted changes to the physical environment. Gary Long's modelling has given us these: changes in the salinity regime, tidal dynamics, water movement, nutrient levels, and clarity of the water. Referring back to my own remarks this morning, I see these changes as being wholly beneficial from the geomorphological point of view. However, it is more difficult to predict how particular elements of the human component of the biota will view some of the changes.

On the negative side, the modelling has yet to give us a clear picture of when we can expect phosphorus to be depleted to the point at which there is no longer an algal nuisance, and perhaps it cannot give the level of assurance we would like to have. There are elements of the complex ecosystem which it may be impossible to fit into any mathematical model, in particular the role of the sediment store of phosphorus.

It seems clear that we can say with confidence that once the Channel is open Nodularia blooms are likely to be infrequent events, if not because of reduced phosphorus then because of changes associated with increased salinity. It is comforting too, to have the assurance that Nodularia is not likely to be replaced by some other unwelcome micro-organism.

It is unfortunate that blue-green algal blooms, which we as scientists regard as the greater evil, are perceived by the public as the lesser of the algal problems. It is equally unfortunate, therefore, that we cannot predict the future of the macro-algal problem with any confidence. How long will it be before the beaches cease to fouled by rotting algae?

It is particularly disturbing to learn that the increased clarity of the water may cause a 'temporary' (time undefined) increase in macro-algal abundance and possible extension of the weed problem to Harvey Estuary. It is not very palatable to have to say this to our political masters when recommending implementation of the proposed management measures.

From the purely scientific point of view it will be fascinating to watch the changes in the biota which follow when implementation of the preferred strategy reverses the trend of the last 30 years from oligotrophy to eutrophy, from sea grasses to blue-green algae. For example, will the goat weed (Cladophora) of the 1970's supplant the present Chaetomorpha and Ulva as the major nuisance weed?

From the point of view of management it is more important to know how rapid the reversal will be and what will be the ultimate state of the estuary.

Much of the uncertainty as to how soon the algal nuisance will go away arises from our limited understanding of the role of the sediment phosphorus store and of how this will respond to the changed physical environment. It is clear that this store is a major immediate source of phosphorus, fuelling both Nodularia blooms and the macro-algae and, moreover, it is now also a carry over source, maintaining diatom and algal growth from one season to the next.

How rapidly will this store of available phosphorus become depleted, or unavailable to algae? The answer depends on a number of factors, most of which it is difficult or impossible to quantify.

In my crude diagram (Fig 2) the only item which is measured with reasonable accuracy is input, and that varies wildly from year to year (from 50 to 200 tonnes in the last 8 years). In 1978 export was estimated at 60 tonnes. The estimated release of sediment phosphorus to Nodularia was 33 tonnes in 1984-85. Could anyone ever measure loss to 'unavailable P' (M for mineralisation in my diagram)?

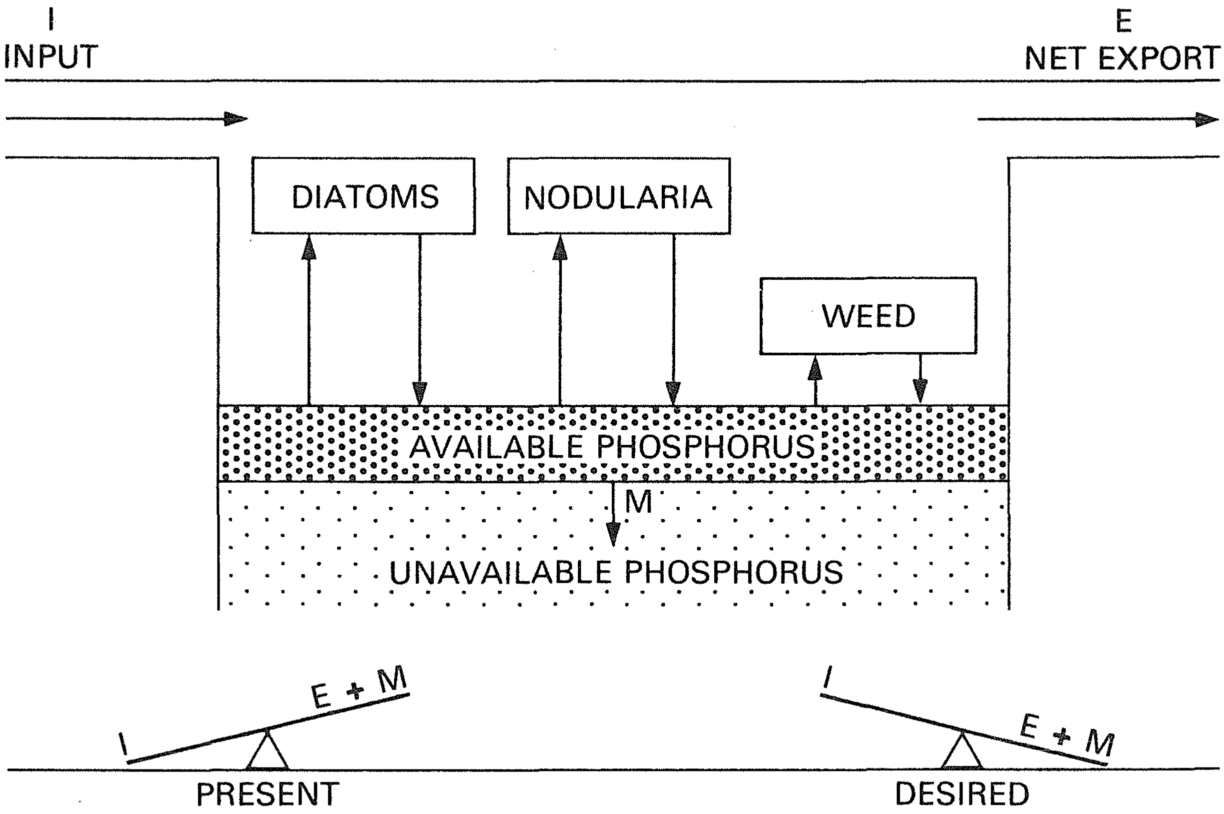

Figure 2: The phosphorus budget in the Peel-Harvey estuary.

The future of the estuary depends on our being able to tip the balance between input and export plus mineralisation. But of course it is not as simple as that. The 'available P' is released to plants primarily when there is a lack of oxygen at the surface of the sediment. We had an unresolved argument as to how often that will occur, how often there will be the required biomass to produce the necessary biological oxygen demand (BOD) to exhaust the oxygen, and whether improved tidal exchange will promote export of phosphorus from the estuary. This argument followed the rather surprising revelation that stratification is probably the norm rather than the exception in the shallow water of Harvey Estuary.

Some of these questions will no doubt be resolved by the further modelling which Gary Tong is doing. However, it is salutory to recall that the whole nasty business of excessive weed growth and accumulation began when Cladophora developed its own efficient anoxic system for extracting nutrients from the sediment; a system it will no doubt continue to operate as long as the vast store of available phosphorus persists. Hence, of course, the expectation that macro-algae will continue to flourish, and even increase for some time after the management measures are instituted. For this reason I believe we should look carefully at Ron Rossich's suggestion to use nitrate to deplete the organic carbon, oxidise the sediments, and hence greatly reduce the sediment store of available phosphorus.

It will be a happy day when seagrass roots again get access to that sediment store and replace the algae as the major plant producers (Karen Hillman assured us that they are just as productive). You can't please everyone, and someone will complain about healthy seagrass meadows, as they have done at Wilson Inlet.

The objectives of the study were stated to be to determine the causes of the algal problems of the estuary, to propose measures for their control, and to gain an understanding of the working of the ecosystem. These goals we have achieved. Now, when the management measures are implemented, the opportunity must be seized to observe, record and interpret the changes to the ecosystem, not only for their intrinsic scientific interest, but also because of the relevance of the knowledge to similar situations elsewhere.

In conclusion I want to note how much first class research has come from this study. Some 50 scientific papers are listed in our current bibliography and there are more to come. The work has helped to solve the problems of the estuary, but that is not all. There are many among the papers which contribute to real advances in knowledge in their own fields; these are first class studies. At a time when fundamental research is getting a raw deal, from ARGC especially, it gives me great satisfaction that in solving our problems we have been able to contribute, even in only a small way, to the support of scientific research for its own sake.

It is my firm belief that much can be gained from applied research, though that is no excuse for not funding basic research for its own sake. I can quite safely boast about what has been done, because whatever contribution I may have made to this study it has not been through any original research of mine. My contributions to the literatures have consistently plagiarised the work of the real researchers, and at this, probably the last scientific symposium of the Peel-Harvey Study, I want to express my gratitude to all who have contributed so much to its success and for the courtesy and patience shown to one who I am sure has not always been easy to get along with - thank you.

REDUCTION OF SEDIMENT PHOSPHORUS AVAILABLE TO ALGAE BY OXIDATION WITH NITRATE

R S Rosich
19 February 1985

1. THE NEED

Whilst definitive work on sediments from the Peel-Harvey system has not been carried out, the information available does allow an estimation of the potential supply of P from the sediments.

Taking an average concentration of 400 mg P kg^{-1} in the top 10 cm of sediment; assuming the availability to algae ,during several weeks of growth, of 50 % of that P (typical literature values show a range of 25 - 75 %); density of sediment of 1.5 and 50 % moisture content; we can calculate the availability of 15 g P m^{-2}. Thus for the whole estuary (133 km^2) we can calculate the availability of some 2,000 t of P.

Assuming that 50 t of P is lost from the estuary to the sea each year, we can see that the estuary has the potential to maintain present conditions for some 40 years.

The key question is what factors determine how much of the sediment P is actually available for plant growth ?

2. KEY PROCESSES IN THE AVAILABILITY OF SEDIMENT PHOSPHORUS

2.1 Oxidised sediments

With Fe in the oxidised (Fe(III)) state, and hence present as hydrated iron (III) oxides, P is tightly bound by adsorption and thus present at concentrations < 1 ug L^{-1}. Consequently, algae growth is very restricted.

2.2 Reduced sediments

If there is sufficient readily-utilizable organic carbon in the sediments, bacterial metabolism results in reducing conditions such that Fe(III) is converted to Fe(II). This in turn allows a very large increase in P concentration, up to about 10,000 ug L^{-1}. Consequently, algae growth can be very much greater.

Little is known about this so-called "readily-utilizable" organic carbon except that it seems to be only a few % of the total organic C content.

3. OXIDATION OF SEDIMENTS BY NITRATE

Addition of nitrate in high concentrations (of eg 40g nitrate N m^{-2}) to reduced sediments greatly stimulates bacterial metabolism resulting in a rapid depletion of the "readily-utilizable" organic C (converted to CO_2),production of N_2 (from the nitrate), conversion of the sediments to an oxidised state, and hence a large reduction in the availability of sediment P for algae growth.

4. RECOMMENDATIONS

4.1 While first priority strategies (such as catchment management) are being implemented, studies of the role of sediment P be continued.

4.2 Studies of the sediment P should include:

- laboratory studies and <u>in situ</u> field studies (in enclosures in the estuary) into the factors governing the release of sediment P and
- similar laboratory and <u>in situ</u> field studies of the oxidation of Peel-Harvey sediments by nitrate.

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