Eutrophication of a Western Australian estuary

Phosphorus
Benthic algae
Phytoplankton
Cladophora
Nodularia

Phosphore
Algues benthiques
Phytoplancton
Cladophora
Nodularia

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ABSTRACT

Two large, shallow (2 m) coastal lagoons of south western Australia have become eutrophic during the last 20 years. Abundant benthic green algae (principally *Cladophora* aff. *albida* and *Chaetomorpha* spp.) accumulate on the shores of one and there are dense phytoplankton blooms of the blue-green *Nodularia spumigena* in the other. The eutrophy is caused by a great increase in the input of nutrients, especially of phosphorus. This comes mainly in drainage from coastal plain soils to which phosphatic fertilizers are applied at an average rate of 20 kg P ha^{-1}.
Tidal range is small and exchange between estuary and ocean is restricted ; evaporation is high and salinity varies seasonally from 5 to 50 ‰ ; significant river flow is confined to about two winter months (July-August). At this time inorganic nutrient concentrations are high in lagoon water, but low temperature and low light conditions limit growth of benthic algae. However, diatom blooms retain nutrients and they are recycled to detrital sediment to become available to benthic algae and *Nodularia* when temperature and light are favourable for their growth in summer.
The most promising method of reducing the eutrophic condition of the estuary is to decrease the input of phosphorus by modifying agricultural fertilizer practices. This is now being investigated.

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RÉSUMÉ

Eutrophisation d'un estuaire en Australie occidentale.

Deux grandes lagunes côtières, de faible profondeur (2 m), dans le sud-ouest de l'Australie occidentale sont devenues dystrophes au cours des vingt dernières années. Les algues vertes du benthos (principalement *Cladophora* aff. *albida* et *Chaetomorpha* spp.) s'accumulent sur les plages d'une lagune ; l'autre supporte des floraisons intenses de l'algue bleu-vert *Nodularia spumigena.* Cette dystrophie est la conséquence d'une augmentation massive du flux entrant de nutriments, principalement le phosphore. Celui-ci provient du drainage de la plaine côtière qui reçoit environ 20 kg de P/ha par an d'origine agricole.
Les marées dans les deux lagunes sont faibles et les échanges entre l'estuaire et la mer peu importants. L'évaporation, par contre, est très élevée et la salinité varie suivant les saisons de 5 à 50 ‰. Les rivières coulent seulement pendant deux mois de l'hiver (juillet-août) et bien que le niveau des nutriments non organiques soit très élevé à cette époque, les températures basses et le manque de lumière limitent effectivement la croissance des algues du benthos. Les nutriments sont cependant maintenus dans l'écosystème par la floraison de diatomées pendant cette période, pour être ensuite libérés au profit des algues en été quand les conditions de température et de lumière sont plus favorables.
La méthode la plus efficace pour réduire le niveau d'eutrophisation dans l'estuaire serait de diminuer l'influx de phosphore par une modification de la pratique agricole dans la région. A l'heure actuelle, cette possibilité est en cours d'investigation.

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INTRODUCTION

The Peel-Harvey estuary is a large shallow coastal system connected to the sea by a narrow tidal channel (Fig. 1). It lies on the west coast of Western Australia at latitude 32°30'S, 70 km south of Perth. The estuary supports considerable commercial and amateur fisheries and fishermen complained about algae fouling their nets from the early 1960s. However, there is no evidence that the algae reduced fish production and records of commercial catches indicate that, on the contrary, production increased until 1979 (Lenanton, pers. comm.).

Complaints about the excessive growth and accumulation of green algae on the shores began about 1970. The decomposing algae foul the beaches and evolve hydrogen sulphide and other offensive gases. The algae also cause destruction of marginal vegetation (rushes and trees) both as the direct result of the accumulations and the damage caused by tractors which have been used to collect and remove algae from the shores since 1974.

More recently, the estuary has been subject to dense blooms of *Nodularia spumigena* in summer, especially in Harvey Estuary. The consequent deoxygenation of the water has resulted in the disappearance of fish from the worst affected areas, some mortality of fish and crabs, and considerable loss to the tourist industry. Collapse of the *Nodularia* bloom in January 1981 was followed by a great increase in the abundance of green algae, this time mainly *Chaetomorpha* spp., from March to June.

At first sight the excess of green algae in the estuarine waters was an obvious case of eutrophication, however the low concentrations of nitrogen and phosphorus found in preliminary sampling appeared to be incompatible with this conclusion. The investigation which began in 1976 aimed to resolve this discrepancy and to identify the cause of the excessive growth and accumulation of algae (Hodgkin *et al.*, 1980).

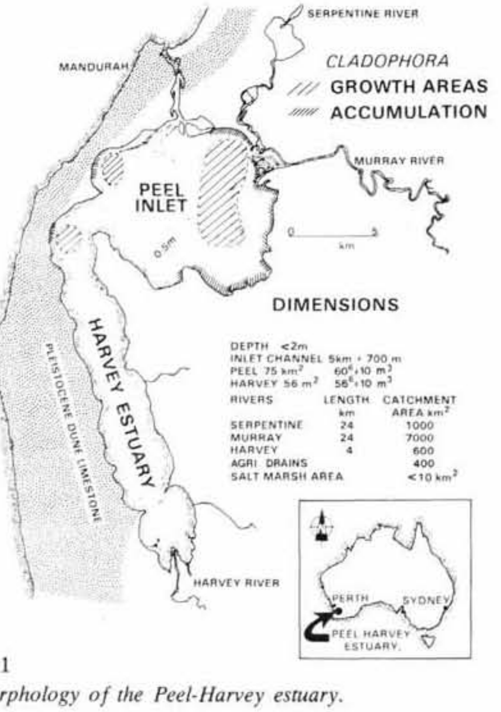

Figure 1
Geomorphology of the Peel-Harvey estuary.

THE ESTUARINE ENVIRONMENT

The dimensions and principal features of the estuary are shown in Figure 1. The two lagoons are shallow throughout, only 2 m deep, and Peel Inlet especially has extensive marginal shelves, parts of which are exposed at extreme low water. The sediments of these shelves are medium to fine quartz sand, while those of the central basin are sandy silty mud (Peel) or grey to black organic mud (Harvey).

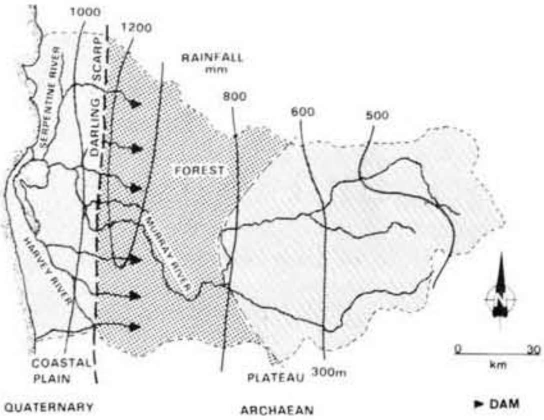

Figure 2
The catchment of the Peel-Harvey estuary.

The estuary lies on the Swan Coastal Plain, here about 25 km wide, and receives drainage from three rivers (Fig. 2). Two of these, the Serpentine and Harvey rivers, derive most of their drainage from the coastal plain while flow to the third, the Murray, comes mainly from the Archaean plateau. Flow from the coastal plain catchment is about 20 % of rainfall, but that from the Murray River averages 7.6 % (2.0 % in 1979, a year of low rainfall).

Rainfall and river flow vary greatly, both seasonally and between years (Fig. 3). The investigation was made during a

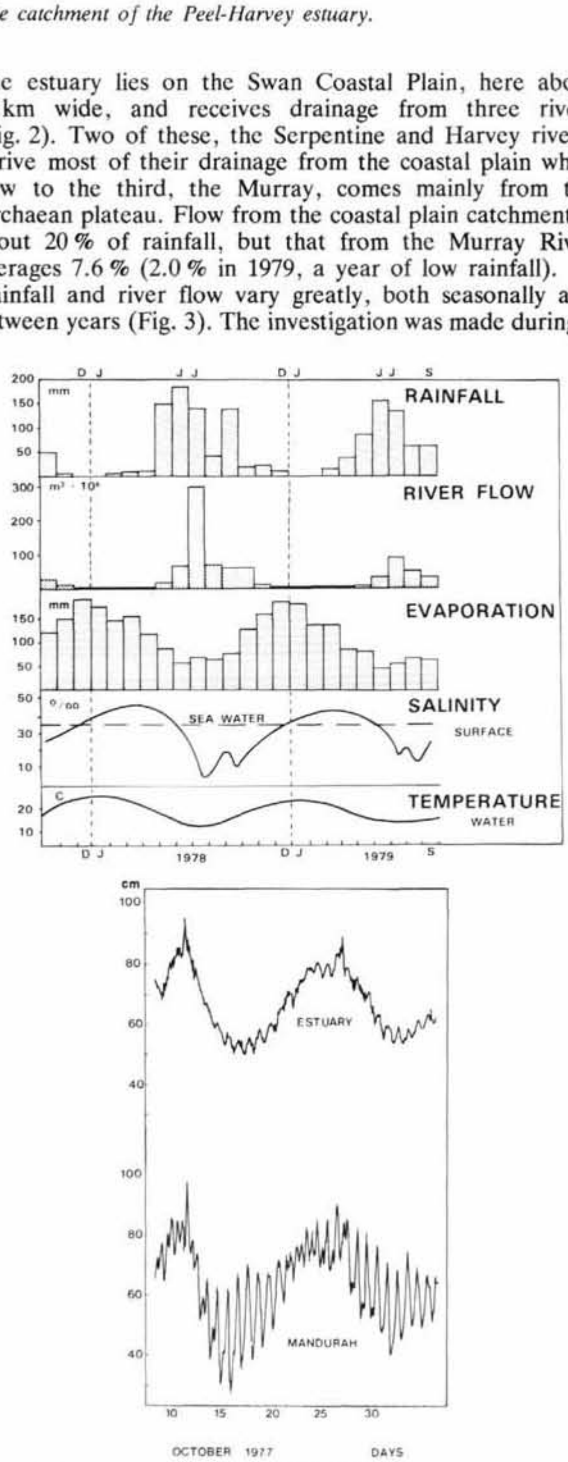

Figure 3
Environmental features of the Peel-Harvey estuary.

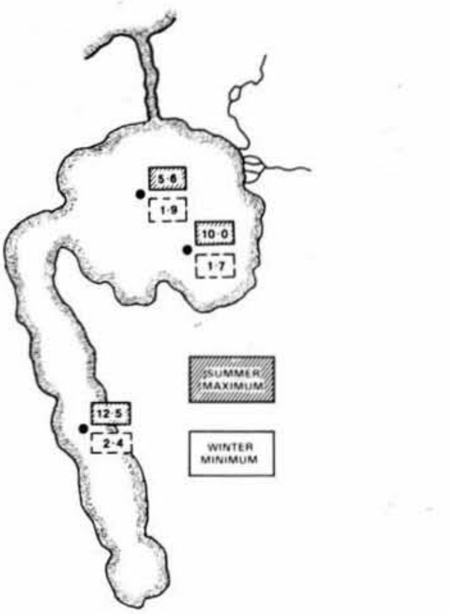

Figure 4
Flushing residence times in the Peel-Harvey estuary in weeks.

period of exceptionally low rainfall and only in 1978 did river flow approach the average. In that year 75 % of flow to the estuary came during 10 weeks (late June to August). Astronomic tides have a maximum daily range of 5 cm in the lagoons, being damped by the narrow inlet channel, however there are longer period (5 to 15 days) variations in water level of about 40 cm and these generate a significant flushing action (Fig. 4 ; Black *et al.*, 1981). The salinity of lagoon water varies from 5 ‰ in winter to 50 ‰ in autumn.

THE ALGAE

Cladophora aff. *albida* (Chlorophyta, Cladophorales) was the principal nuisance species during the early part of the investigation. It is a branching, filamentous alga that grows as small balls, 1-2 cm diameter, which roll over the bottom or float to the surface and drift with the wind (McComb *et al.*, 1981). This was the only algal species studied in detail. Recently other algae have become abundant and also accumulate on the shores. *Chaetomorpha aerea* and *C. linum* (Chlorophyta, Cladophorales) are unattached, benthic, filamentous algae which also float in the water and at times form extensive mats on the surface. *Enteromorpha* spp. are sometimes abundant in the shallows.
Large blooms of planktonic diatoms occur during river flow in winter. The dense summer blooms (November to February) of the nitrogen-fixing blue-green *Nodularia spumigena* (Cyanobacteria) occur mainly in Harvey Estuary, but affect Peel Inlet to a lesser extent. Under windy conditions *Nodularia* is well mixed through the water mass, but in calm weather it floats to the surface and is washed up on leeward shores where it accumulates and decomposes rapidly, emitting offensive odours.

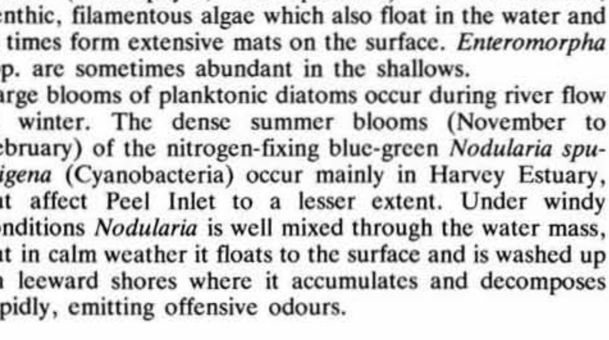

Figure 5
The effect of: (a) salinity ; and (b) temperature on photosynthetic rates of Cladophora.

CLADOPHORA BIOLOGY AND NUTRIENT CYCLING

Cladophora was found to grow equally well throughout the greater part of the salinity range experienced in the estuary (Fig. 5 *a*, McComb *et al.*, 1981). Growth is strongly temperature dependent with maximum growth rates at the summer water temperatures of 20-30 °C (Fig. 5 *b*). Light is limiting in winter when benthic light levels may be below the compensation point, even at the surface of the algal bed (Fig. 6 *a*). The algal bed may be several centimetres thick and light is inadequate for growth below about 1 cm, even when the water is clear in summer (Fig. 6 *b*) (Gordon *et al.*, 1980).

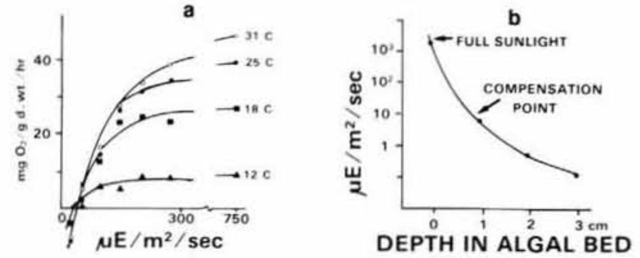

Figure 6
The effect of light on photosynthesis by Cladophora : *(a) at different temperatures ; (b) at different depths in the algal bed.*

Experiments with different nutrient concentrations showed that, when no other factors are limiting, levels of at least 0.1-0.2 mg L^{-1} inorganic nitrogen and 0.02-0.03 mg L^{-1} inorganic phosphorus are required for maximum growth rates of *Cladophora* (Fig. 7 *a*) (Gordon *et al.*, 1981). The minimum tissue concentrations required for maximum growth rates, the « critical concentrations », were 21 mg N g^{-1} and 3.2 mg P g^{-1} dry weight (Fig. 7 *b* ; Birch *et al.*, 1981).

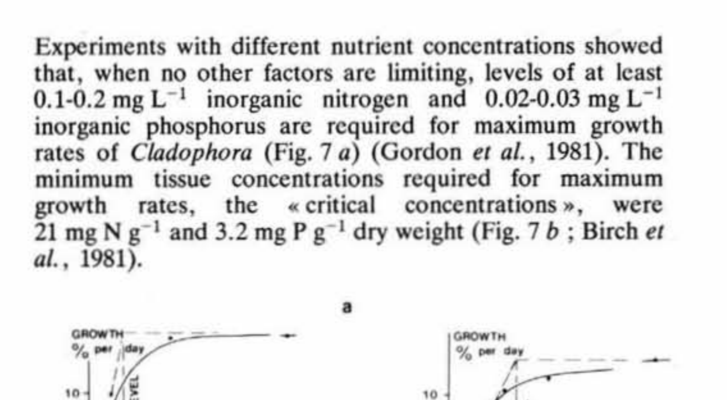

Figure 7
Relative growth rates of Cladophora : *(a) with different nutrient concentrations in the medium ; and (b) with different tissue nutrient concentrations.*

Figure 8 shows that field populations of *Cladophora* display seasonality in tissue nutrient concentrations and that nitrogen levels were generally greater than the critical concentration whilst phosphorus levels were generally below. Thus while *Cladophora* was rarely deficient in nitrogen its growth was generally limited by phosphorus. Only following the collapse of the massive *Nodularia* bloom in the summer of 1980-81 were tissue phosphorus levels above the critical concentration (Birch *et al.*, 1981). It is evident that there was rapid recycling of nutrients from *Nodularia* to *Cladophora* and other algae at this time.
Because of the mobility of *Cladophora* it was difficult to

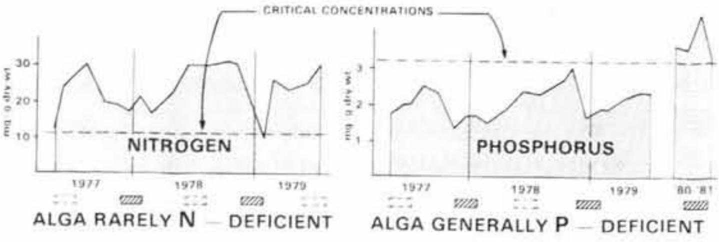

Figure 8

Observed tissue concentrations of: (a) nitrogen; and (b) phosphorus in Cladophora *from Peel Inlet.*

obtain reliable measures of growth rates and biomass under field conditions. The results of experiments with algal populations imprisoned in perforated plastic flasks *in situ* are shown in Figure 9 *a*. Growth rates of simulated populations, based on the above experimental data and field observations of light, temperature, and nutrient concentrations are shown in Figure 9 *b*. The simulated data were generated by computer using a simple mathematical model (Hodgkin *et al.*, 1980). These figures well illustrate the marked seasonality of growth of *Cladophora*.

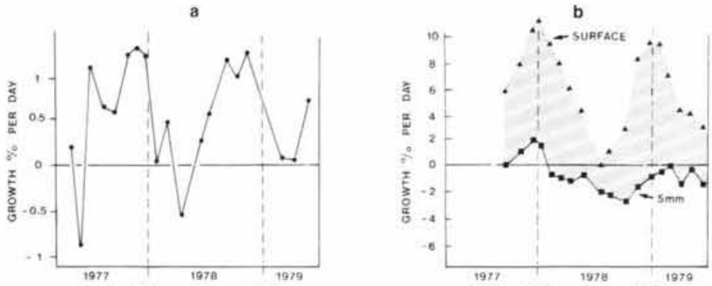

Figure 9

Growth of Cladophora : *(a) imprisoned field populations; and (b) computer simulated populations at two depths in the algal bed.*

In winter, when nutrient levels in the water are high (Fig. 10), growth is limited by temperature and also by light. When water temperatures are favourable for *Cladophora* growth in summer the phosphorus levels in Peel Inlet water are too low (10-20 $\mu g\ L^{-1}$) to account for the observed

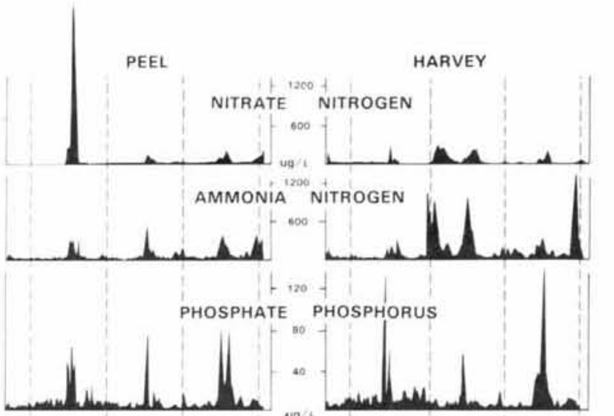

Figure 10

Nutrient concentrations and chlorophyll a in Peel Inlet and Harvey Estuary; weekly data.

growth of the alga. However, the growth habit of the alga puts it in contact with the surface sediment, a black anoxic ooze that consists largely of decomposing algae. Approximate PO_4-P concentrations in the overlying and interstitial water are:

overlying water	10 $\mu g\ L^{-1}$;
among living algae	90 $\mu g\ L^{-1}$;
among decomposing algae	500 $\mu g\ L^{-1}$;
in the muddy sand	300 $\mu g\ L^{-1}$.

Experiments with ^{32}P have demonstrated that algae take up phosphorus from this underlying store, the rate depending greatly on the degree of agitation of the substrate (Table 1; Gabrielson, pers. comm.).

While it is difficult to determine how much phosphorus is derived from this sediment source under field conditions it is clear that, together with stored phosphorus from non-photosynthetic winter uptake, it is adequate to account for the observed growth of *Cladophora*.

Table 1

Phosphate flux rates from detrital sediment to Cladophora *per m² per day (Gabrielson, pers. comm.).*

Measured rates using	^{32}P
still conditions	0.1-0.4 mgP
stirred conditions	1.4 mgP
This would support growth of	0.2-8 gDW
Max observed field growth	8 gDW
Simulated maximum	~ 13 gDW

PLANT NUTRIENT SOURCES

The extreme seasonality of nitrate nitrogen and phosphate phosphorus in estuary water (Fig. 10) reflects the seasonality of river flow and the consequent nutrient input to the estuary (Fig. 11). More than half the total phosphorus in river water is in the inorganic form. The inorganic nutrients disappear from the water rapidly as the result of uptake by the diatom blooms (Fig. 10) and probably also by flocculation and adsorbtion by sediments. The ammonia nitrogen data reflect not only river input but also decay of the *Nodularia* blooms (Fig. 10).

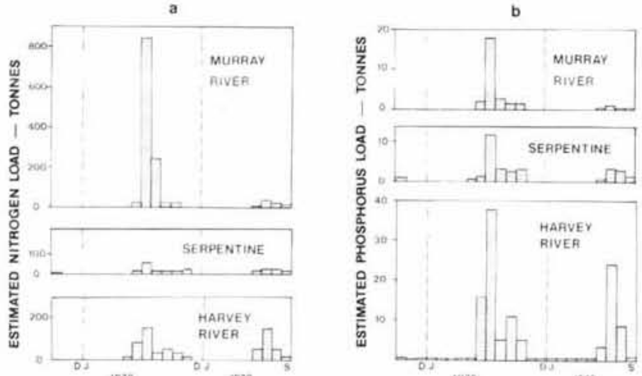

Figure 11

Nutrient loads to the Peel-Harvey estuary: (a) nitrogen; (b) phosphorus.

These Figures also explain why the preliminary sampling of 1976, like 1979 a year of very low rainfall, showed such unexpectedly low values of inorganic nutrients in Peel Inlet. It will be seen from Figure 11 that most of the river input of nitrogen comes from the Murray River (mainly from the plateau) and varies greatly with the volume of flow (a total of 1,500 t N in 1978 and 500 t N in 1979). On the other hand most of the phosphorus comes from coastal plain drainage, about half via the Harvey River (Birch, 1982). In consequence the N : P ratio is almost always high in Peel Inlet water (> 16 : 1 by wt) while in Harvey River water it is low

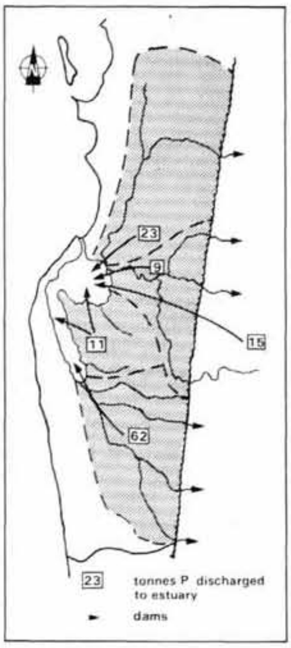

Figure 12

Estimated tonnages of phosphorus discharged to the Peel-Harvey estuary from coastal plain and plateau catchments in 1978.

(~ 4 : 1 by wt) and remains low in Harvey Estuary water until adjusted by the *Nodularia* blooms. Thus while phosphorus is the limiting nutrient for growth of macro-algae in Peel Inlet, the low N : P ratio in Harvey Estuary water favours the nitrogen-fixing *Nodularia,* so that it is probably too phosphorus limited.

The main external source of phosphorus, on which algal growth is ultimately dependent, is from agricultural drainage on the coastal plain (Fig. 12). Coastal plain soils are naturally deficient in phosphorus, however most of the area is now cleared for agriculture (mainly beef cattle and dairying) and phosphorus is applied as superphosphate at rates of 15 to 75 kg P ha^{-1} (average 20 kg P ha^{-1}). In 1978, 1,400 tonnes of phosphorus was applied to coastal plain catchments as fertilizer and in the same year 105 tonnes entered the estuary from coastal plain drainage (Table 2). While fertilizer was applied to agricultural land on the plateau at similar rates much less was released to drainage, probably because of heavier soil types and lower rainfall. The input of 120 t of phosphorus from rivers and drains in 1978, a year of near average rainfall, was double the estimated net loss to the sea so that there was a gain to the estuary of about 60 t of phosphorus. The urban population is small (< 15,000) and phosphorus input from this source contributes less than 10 % of total input.

The use of superphosphate has increased greatly over the last 35 years (Fig. 13) and usage is clearly related to price. However the input of phosphorus to the estuary is not simply related to quantity applied to the catchment. Limited data from the early 1950s indicate that the input of phosphorus in 1953 was only one tenth of that in 1978 (years of similar rainfall and river flow) even though application rates were similar. The reason for the increased rate of release to drainage is still not clear and is under further investigation.

Table 2

A phosphorus budget for the Peel-Harvey estuary: tonnes of phosphorus.

	1977-78	1978-79
Phosphorus applied to :		
plateau catchment	2,500	2,570
coastal plain catchment	1,400	1,400
Phosphorus entering estuary from :		
rivers and drains	120	90
sea water	50	50
total input	170	140
Phosphorus flushed to the sea	110	110
net gain to the estuary	60	30
Phosphorus present in estuarine compartments (1978)		
water	11	
large algae	90	
plankton	2-18	
detrital sediment (top 10 cm)	260	

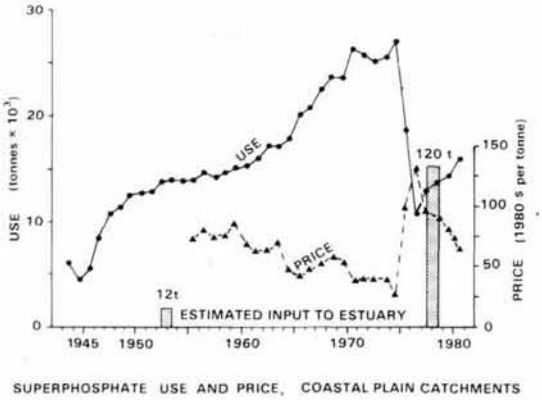

Figure 13

Superphosphate applied to coastal plain catchments 1943-1981. Price, adjusted to 1980 dollars values. Estimated input to the estuary 1953 and 1978.

MANAGEMENT

Reduction of the eutrophic condition of the estuary clearly requires a considerable reduction in the amount of phosphorus available to algae. In principal this can be achieved by one of the following measures :

1) *Reduce the input of phosphorus*
   a) by modifying agricultural practices ;
   b) by intercepting the phosphorus before it reaches the estuary ;
   c) by diverting river flow direct to the sea.
2) *Increase loss to the sea.*
3) *Deplete the estuary nutrient store by*
   a) harvesting algae ;
   b) removing the detrital sediment.

Of these the first, modifying agricultural fertilizer practices, appears to be the most likely to achieve a long-term solution to the problem, at least cost. The practicability of this measure is now being investigated.

CONCLUSION

The excessive growth and accumulation of green algae in the Peel-Harvey estuary has been caused by a great increase in nutrient input since the 1950s, especially of phosphorus. The estuary is now nutrient enriched, even though inorganic nutrient concentrations are generally only high briefly in winter. Phosphorus is the limiting nutrient most of the time. Part of the winter input of nutrients is retained in the estuary by plankton and flocculation and adsorbtion. Summer growth of algae is dependent on nutrients from cellular stores accumulated in winter and release from detrital nutrient stores.

The principal external source of phosphorus is from fertilizer applied to coastal plain soils that are naturally deficient in this nutrient. The input of phosphorus to the estuary from agricultural drainage was 120 tonnes in 1978 and the net loss to the sea was estimated to be only half this figure, with a consequent retention of about 60 tonnes in the estuary.

Acknowledgements

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