THE PEEL-HARVEY ESTUARINE SYSTEM
PROPOSALS FOR MANAGEMENT

REPORT 14 : APPENDIX 1
The background to management

Department of Conservation and Environment
Western Australia
Bulletin 241 January 1986

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INTRODUCTION

This document supplements Report 14 and amplifies certain aspects of it. As its title implies, its purpose is to give a fuller understanding of the causes and nature of the eutrophication of the Peel-Harvey estuarine system, as evidenced by the excessive growth of algae in its waters. It is intended to fill in some of the areas that are treated somewhat superficially in the Report which aimed at a much wider audience than this more detailed statement.

Chapter 1 considers the features of the estuary, and its catchment, which predispose it to become eutrophic. It is not simply the quantity of plant nutrients poured into it that is the cause of eutrophication; a more open, better flushed estuary could accept the annual dose of 150 tonnes of phosphorus with at most a localised response. The factors which favour growth of nuisance algae are discussed in Chapter 2 as are the reasons for placing the emphasis on limiting phosphorus availability in the recommendations for management. The great increase in the amount of phosphorus entering the estuary from the coastal plain catchment is the immediate cause of eutrophication and a reduction in phosphorus available for algal growth, by whatever means is practicable, is seen as the preferred way to reverse the eutrophication. Hills dams have reduced the amount of water available to flush the estuary, but not enough to cause the weed problem or contribute greatly to it.

Chapter 3 shows that the input of phosphorus from the catchment can be reduced, but that this will be a gradual process because of the large stores of phosphorus built up over the years in the sandy soils. A considerable reduction in the amount of phosphorus fertilizers applied to the coastal plain catchment has been achieved through cooperation of farmers in adopting recommendations made by the Department of Agriculture and there is evidence that this has already resulted in a signficant reduction in phosphorus entering the estuary from the Harvey River. The continued cooperation of farmers will be essential to success of the management measures. A better understanding of the complex processes involved in movement of phosphorus through the different soil types and of the fertilizers most appropriate for application to these soils have the potential to identify means to further reduce the loss of phosphorus to drainage, and research on these aspects must be continued.

Earlier reports have noted the potential of point sources, piggeries, sewerage systems, etc, to add to the amount of phosphorus entering the estuary. Since publication of Report 14 it has become evident that this is now a reality and measures will have to be taken to minimize loss from these sources. It is unthinkable that a new source of phosphorus should be allowed to reverse the success of measures which have already reduced the amount of phosphorus going into the estuary and which have the potential to further considerably reduce it.

CHAPTER 1

PHYSICAL FEATURES OF THE ESTUARY

The abundance of plant nutrients is the immediate cause of the eutrophic condition of the Peel-Harvey estuary, however the resultant algal problem, the multiplication and accumulation of nuisance algae, is facilitated by some of the physical features of the estuary.

The extreme seasonality of rainfall and river flow, the small tidal range, and the location on a cultivated coastal plain with sandy soils are important contributing factors. These features are common to other estuaries of the south-west, particularly the Swan River estuary and Leschenault Inlet; both are eutrophic to a degree but do not experience the serious algal problems of Peel-Harvey. The history of an earlier weed problem in the Swan, is recorded by Royce (1955).

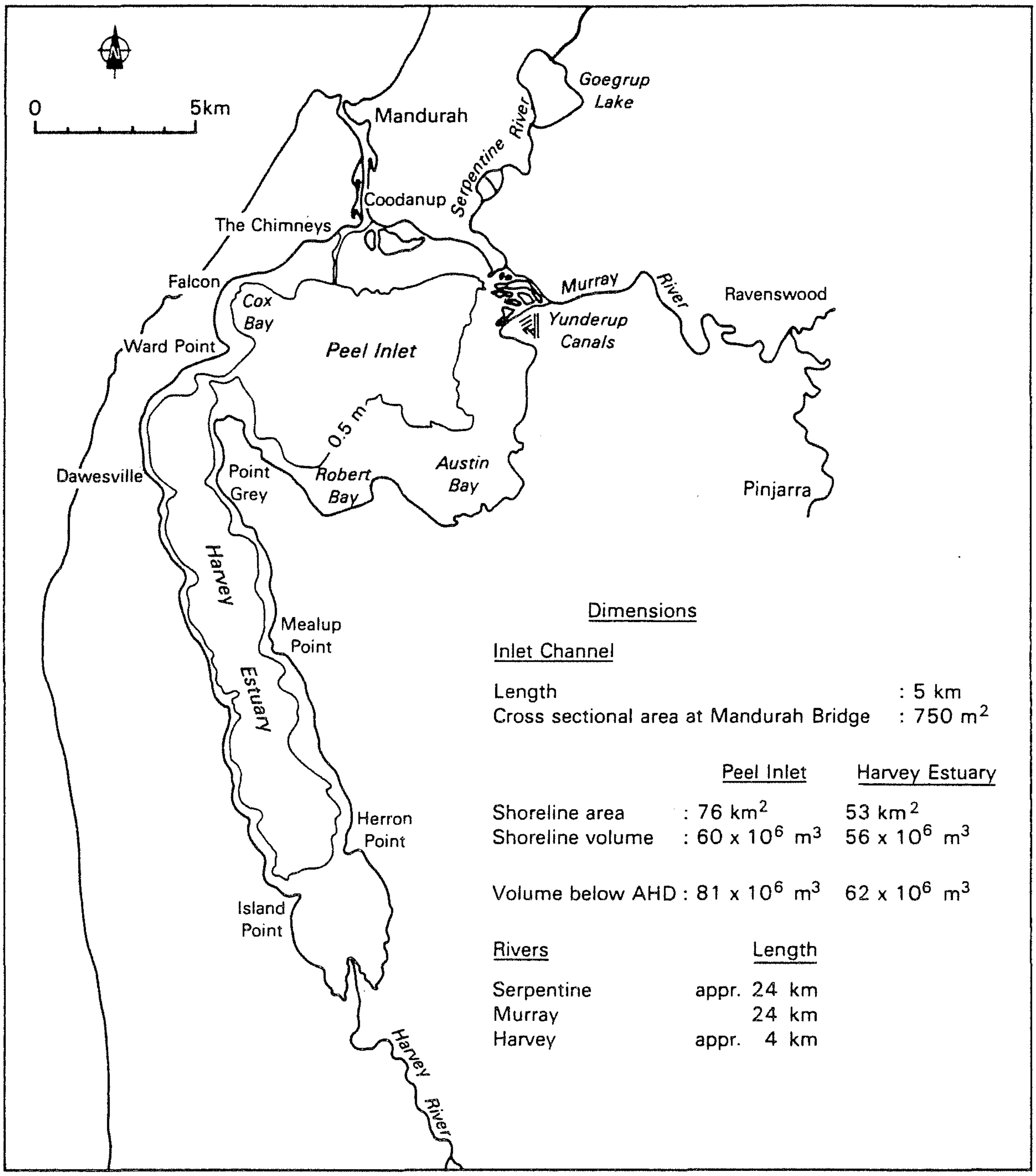
The features which particularly favour development of algal problems in Peel-Harvey are the large size of the estuary (130 km), the small channel to the sea and consequent restricted water exchange with the ocean, the location of the Harvey River delta at the furthest point (30 km) from the mouth of the estuary, and the shallow depth of the water. These conditions favour retention of plant nutrients in the estuary and allow sufficient light to reach the bottom for plant growth. They also place their particular constraints on the selection of appropriate measures to reverse the present eutrophic condition.

The estuary is not a closed ecosystem and cannot be considered in isolation from the wider environment if rational judgements are to be made about management. It is also a highly dynamic system, not only on the short time scale of the seasonal cycles, but on the geologically brief periods of european settlement and of the estuary's very existence, a mere 6 000 to 8 000 years.

THE PRESENT ESTUARINE ENVIRONMENT

The estuary consists of two coastal lagoons (Peel Inlet and Harvey Estuary), an inlet channel (Mandurah Estuary) and the tidal reaches of three rivers (Serpentine, Murray and Harvey) (Fig. 1.1).

Both Peel and Harvey are shallow; the central basins are only half the total area and are nowhere more than 2.5 m below AHD (approximately mean sea level). Extensive marginal shallows of less than 0.5 m below AHD constitute 37% of Peel Inlet and 14% of Harvey Estuary.



Dimensions

Inlet Channel

Length	: 5 km
Cross sectional area at Mandurah Bridge	: 750 m^2

	Peel Inlet	Harvey Estuary
Shoreline area	: 76 km^2	53 km^2
Shoreline volume	: 60 x 10^6 m^3	56 x 10^6 m^3
Volume below AHD	: 81 x 10^6 m^3	62 x 10^6 m^3

Rivers	Length
Serpentine	appr. 24 km
Murray	24 km
Harvey	appr. 4 km

Figure 1.1. The Peel-Harvey estuarine system.

The daily, astronomically induced, tidal range in the estuary is less than 10 cm (10% of the ocean tide) but variation in mean water level is about 50 cm in both sea and estuary, due mainly to barometric changes with a period of five to fifteen days. This 50 cm change in water level is equivalent to about 30% of the volume of the estuary below AHD and is the main factor controlling flushing of the estuary to the sea during the greater part of the year (Fig. 1.2).

There is additionally a seasonal change in mean sea level which may be as much as 30 cm; a significant factor in respect of inundation and exposure of fringing vegetation. River flow in winter may raise water level in the rivers considerably and cause extensive flooding, especially along the Murray River, but a 100-year flood would only cause a rise of about 1.6 m above AHD in Peel Inlet. At other times mean water level in the estuary is the same as in the sea. There is no perched water level. Wind set up may cause a difference of 30 cm between one side of the Inlet and the other.

The dimensions of the inlet channel greatly restrict tidal exchange with the sea and consequent flushing of estuary water. However, it is the tidal delta in Peel Inlet and silting of the ocean bar which are the principal obstructions to tidal exchange and hence to flushing of estuary water (Fig. 1.3).

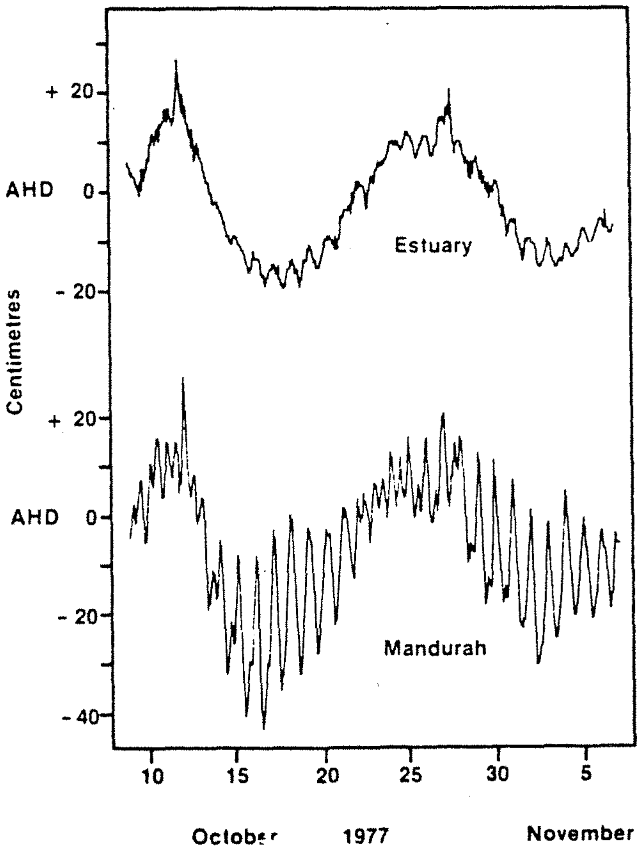


Figure 1.2. Tide Records from Peel Inlet and Mandurah (AHD - Australian Height Datum).

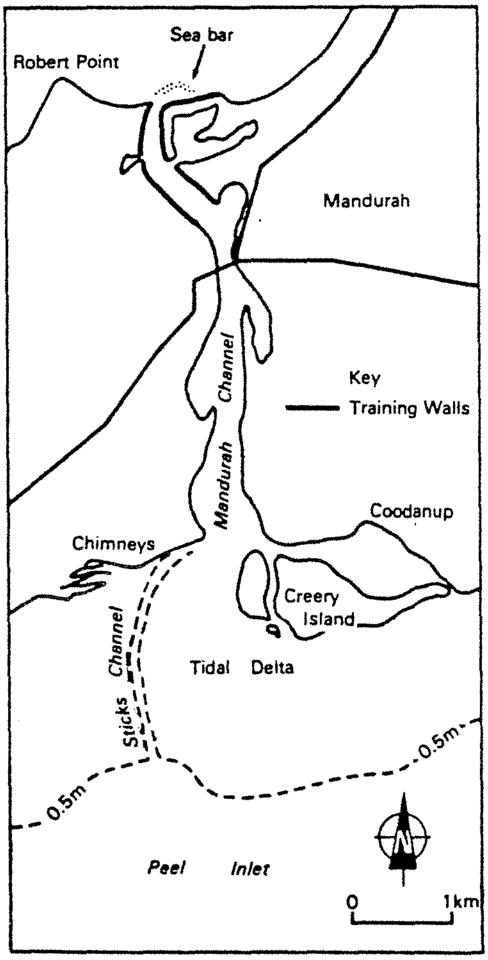


Figure 1.3. The Mandurah Channel, sea bar and tidal delta.

HYDROLOGY

The dominant feature of the hydrology is its extreme seasonality; throughout the estuary salinity changes from being nearly fresh in winter to more salt than the sea in summer (hypersaline) (Fig. 1.4). The salinity range tends to be greater in Harvey Estuary than in Peel Inlet because it is further from the mouth of the estuary. Restricted exchange with the sea, the brief period during which there is fresh water input, and the high summer evaporation rate combine to produce this unusual condition (Fig. 1.5). While this hydrological sequence is repeated annually, there are considerable differences in detail between years. These are related most obviously to variation in volume and timing of river flow, but direct rainfall onto the estuary and evaporation are both important. The evaporation rate of 1.4 m a year is equivalent to more than the volume of the estuary.

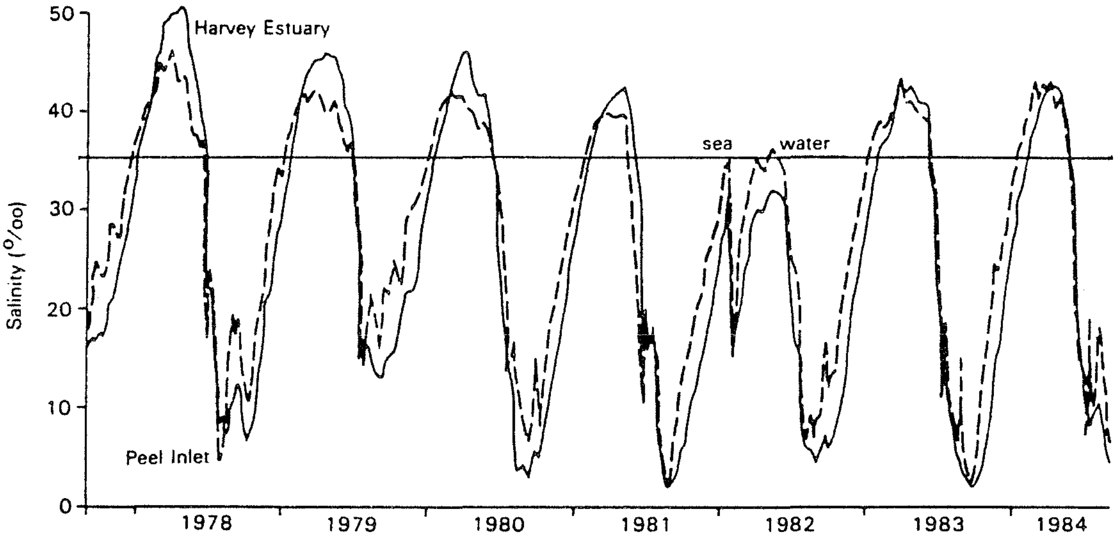


Figure 1.4. Surface salinity in Peel Inlet and Harvey Estuary (R Lukatelich).

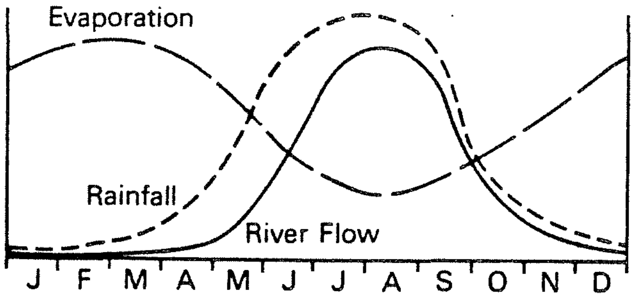


Figure 1.5.

Idealised seasonal cycles of fresh water input from river flow and rainfall and of evaporation from the surface.

The great salinity range makes the estuary an unfavourable habitat for all except a small number of plants and animals, the true estuarine flora and fauna, which are specially adapted to live continuously in this environment. The timing of salinity changes is important too for successful propagation of individual plants and animals of the estuary, including the nuisance algae.

Water temperature varies from 11-12°C in winter to 26-27°C in summer in open water, but more extreme temperatures are experienced in the shallows, with up to 38°C having been observed during a Nodularia bloom.

Water clarity varies greatly with the amount of suspended particulate matter and dissolved organic matter present in river water. The former includes both resuspended surface sediment and phytoplankton so that clarity of the water varies seasonally with growth of phytoplankton. Clarity has decreased progressively as a result of increasing phytoplankton abundance during the seven years that there have been detailed observations. It also varies considerably from day to day as a result of wind stirring and the consequent resuspension of surface sediment. In general the water tends to be somewhat clearer in Peel Inlet than in Harvey Estuary because of the greater quantity of resuspended sediment in the latter.

WATER SOURCES

The estuary receives its water, and the contained nutrients, from a number of sources with very different characteristics. During most of the year the sea is the main source, with a net input of sea water roughly equal to the volume of the estuary.

The greater part of freshwater input comes as flow in the three rivers. Flow from agricultural drains accounts for another 10% and groundwater flow only 1%. In a year of low rainfall, river and drain flow may total less than twice the volume of the estuary. Direct rainfall onto the surface of the estuary accounts for 20% to 30% of river and drain flow from the coastal plain catchment, and its effect in reducing salinity precedes by some weeks flow from the rivers because of the time taken to saturate soils of the catchment (Fig. 1.5).

River flow derives from two main sources: the plateau and the coastal plain. Almost all flow from the plateau now comes via the Murray River, other rivers being dammed near the escarpment, and of this most flow comes from the high rainfall (800 - 1200 mm) western part of the catchment which is largely forested. Runoff water here is fresh, but water from the eastern, low rainfall (400 - 800 mm) agricultural area is saline, averaging 2.3 ppt in the Hotham River (Collins, 1974). In consequence, river water at Pinjarra generally has a salinity greater than 1 ppt.

Rainfall on the coastal plain averages 900 - 1100 mm a year, decreasing westwards from the scarp. River flow in the Serpentine and Harvey Rivers is fresh (less than 1 ppt).

Figure 1.6 shows river flows during the study and it will be noted that flow in all three rivers was well below average. Flow from the plateau is much more variable than from the coastal plain and the yield (ratio of flow to rainfall) from the plateau (about 2% to 8%) is much less than from the coastal plain (Harvey River 15% to 25%).

Figure 1.7 shows the strong seasonality in river flow, with nearly 90% of flow in the four months June to September, but it is important to note that there is great variation from year to year, depending on volume, timing and periodicity of rainfall. Also, there is always considerable delay between the first rains and river flow because soils have first to be saturated. For example the unusually heavy rain of April 1984 resulted in negligible flow in the rivers; again, the record rains of November 1984 produced very little flow because of the prolonged dry period of the previous seven weeks.

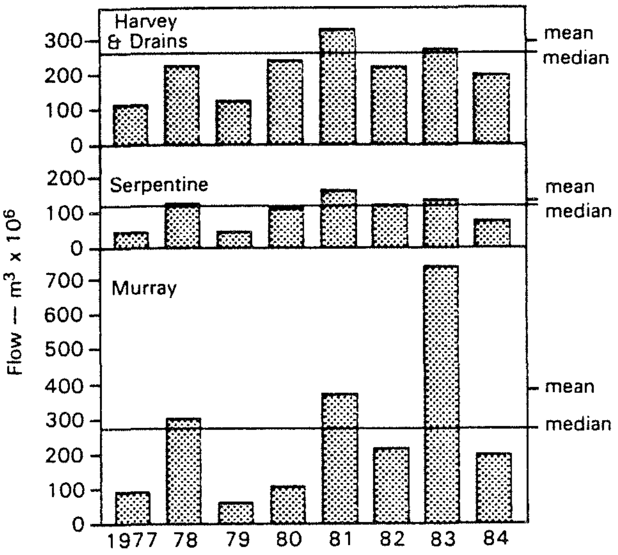


Figure 1.6. River flow to estuary 1977-1984.

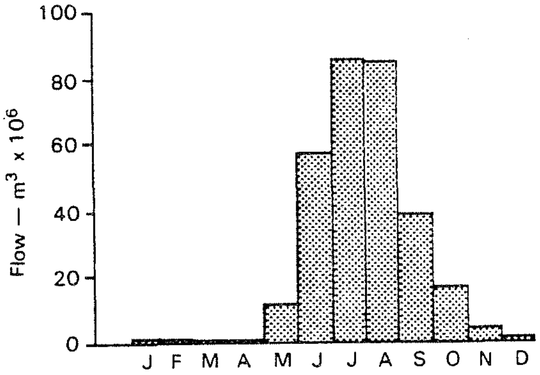


Figure 1.7. Mean monthly river flow to the estuary.

Changes to the patterns of river flow resulting from human activity are more difficult to quantify, but must nevertheless have affected the hydrology of the estuary. Construction of dams in the Serpentine, Harvey and Dandalup river catchments has cut off most flow to these rivers from the plateau, but this has probably been more than compensated in volume by increased runoff from the coastal plain as the result of the progressive clearing and drainage there during the 20th Century. The volume of flow is directly related to the density of drainage.

The pattern of flow must also have changed greatly. The coastal plain rivers now respond rapidly to rainfall with peak flow following within 24 hours of heavy rain and then rapidly returning to base flow (Fig. 1.8). Before clearing and drainage flow rates would have been greatly damped by the extensive swamps through which drainage water found its way to the estuary.

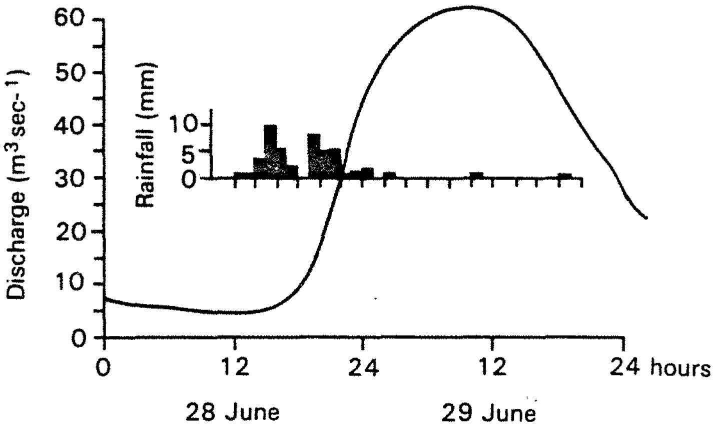


Figure 1.8. Harvey River 'first flush' hydrograph, 28-29 June 1979.

The volume and pattern of flow in the Murray River has also changed as the result of clearing in the upper part of the catchment. Because of the large size of the catchment the river is slow to respond following heavy rain, but clearing has both increased the volume of flow and the rate at which the catchment responds to rainfall. Sediment transport must also have increased.

It is not possible to say with any certainty how these changes in river flow have affected the hydrology of the estuary, nevertheless there can be little doubt that they have modified it, possibly mainly by increasing the salinity extremes. The first recorded data on hydrology of the estuary was that of CSIRO Fisheries in the early 1950s and there is no measurable difference between them and those experienced at the present time, but at the time of the CSIRO studies many of the changes noted above had already had their effect.

THE HISTORY OF THE ESTUARY

The estuary is not a static unchanging entity. On the geological time scale it has had a very brief life span of only 6 - 8 000 years and the geomorphological processes which have changed its form and character are still at work today. Some of them have been modified or accelerated by human activities. The history of the estuary, and of the processes which have formed it are relevant both to an understanding of the nature and origin of the algal problems and to evaluation of potential management measures.

There have been five main phases in the history of the estuary: its initial enclosure during the Pleistocene, a terrestrial phase during the last glacial period, its rejuvenation with the Holocene rise of sea level, reduced exchange with the ocean through the late Holocene, the period of European settlement since 1830.

The coastal dune barrier was built more than 125 000 years ago during the Pleistocene period at a time when sea level was little different from the present. Then, during the long period of lower sea level, it was a shallow terrestrial basin (Peel Inlet) and an interdune depression (Harvey Estuary), presumably with rivers through them and through the present Mandurah channel.

The estuary was again flooded, between 8 000 and 6 000 years ago, with the Holocene rise of sea level. Then, in the mid Holocene, until about 3 500 years ago the environment was similar to that of Oyster Harbour or Princess Royal Harbour at the present time. There would have been free exchange between ocean and estuary and salinity of the water would seldom have been less than 15-20 ppt, except perhaps briefly during periods of strong river flow. The fauna of Peel Inlet was that of a marine embayment, much more diverse than the present strictly estuarine fauna. There were probably extensive seagrass beds, of marine species (Zostera, Posidonia and Amphibolis). The scarcity of fossil material in cores from the Harvey Estuary sediments suggest that it was less marine than Peel Inlet.

The estuarine environment appears to have changed rather abruptly between 3 and 4 000 years ago, the marine fauna was replaced by the much less diverse fauna and flora characteristic of the hydrological extremes now experienced in the estuary.

This change in character came about as the result of reduced exchange with the ocean. There was considerable infilling of the Mandurah channel and possibly development of an ocean bar. But even more important was formation of the extensive tidal delta. There was probably also a fall in sea level (variously estimated at from 0.5 m to 3 m) which would have further reduced the effective dimensions of the channel.

During this late Holocene period there were probably times when the ocean bar closed completely, preventing all exchange between ocean and estuary for months at a time, as has happened periodically during the last 150 years. Such a closure occurred in the summer of 1914-15 causing water level in the estuary to drop by 60 cm during the five months (December to March) that the bar was closed - equivalent to a loss by evaporation of nearly half the volume of the estuary. Under such conditions the estuary would have been two closed lagoons of shallow, stagnant water with extensive areas of the margins dry.

Following extension of the training walls in 1967 and periodic dredging at the mouth, the estuary is once again continuously open to the sea and there can be little doubt that this has benefitted the ecosystem, although totally inadequate to return the estuary to the ocean embayment condition of the mid-Holocene.

Dredging of the Sticks channel through the tidal delta and boat channels through the deltas of the Murray and Serpentine rivers are unlikely to have made any great difference to the condition of the estuary. However, as noted above, changes to flow in the rivers as the result of damming and clearing in the catchments and the construction of drains on the coastal plain will certainly have modified the hydrology.

SEDIMENTATION

Even when first flooded 6 000 years ago the maximum depth of the estuarine basins was only about 5 m below AHD. Since then only 1-3 m of Holocene sediments have been deposited over the Pleistocene soils. This is a relatively slow rate of sedimentation, averaging only 0.2 mm a year. (For comparison, the estimated rate of sedimentation in Lake Illawarra, NSW, is 0.7-1.3 mm a year.) During the last 3 000 years the rate probably slowed to an average of 0.1 mm a year because only 300 mm of sediment appears to have accumulated in that time.

The same sedimentation processes continue at present possibly slightly accelerated as the result of clearing and drainage in the catchment. However, data from sediment trap experiments do not indicate any significant increase in the sedimentation rate. Over 90% of sediment collecting in these traps is sediment that has been resuspended by wave action.

While a considerable quantity of silt comes down the rivers, during floods from the Murray especially, it is probable that most of this goes out to sea either with flood water or subsequently when resuspended by wave action, so that the net sedimentation rate is now very slow.

Despite a sometimes firmly held belief to the contrary there is no evidence of any recent general shallowing of the estuary. Dredge spoil has filled areas adjacent to the Sticks channel and is reported to have extended the area of the shallows at the southern end of this channel. The river deltas may well be growing more rapidly with coarse bed load sediments brought down by floods, especially as the result of canalisation of the Harvey River. A small typical crows foot delta has formed at the mouth of Coolup Drain since it was dug in 1902.

The surface sediment is of different character both chemically and physically from the deeper sediments. It consists largely of decaying organic matter; where macroalgae (*Cladophora* especially) accumulate it forms an indefinite layer of black ooze composed of decaying algae, but beneath this and elsewhere in Peel Inlet the surface sediment is a fine sandy mud with a 20% water content. In Harvey Estuary the surface sediment consists largely of decaying phytoplankton and faecal pellets of the invertebrate fauna overlying mud with a 50% water content.

The sediments of the marginal shallows contain less organic matter than those of the central basins, except where there has been recent accumulation of decomposing algae. Along most of the eastern shore of Harvey Estuary the sand is clean, well sorted and mobile. Sands of the Peel Inlet shores are also said to have been clean before the weed problem, but they are of a coarser, less well sorted nature.

Considerable erosion of the Coodanup and Falcon shores has occurred following destruction of the marginal vegetation by tractors clearing the weed. Some sand has been carted away with the weed and some transported along the shore by wave action (as at Coodanup towards the mouth of the Serpentine River) or spread over inner areas of the shallows. The massive accumulation of decaying weed in Austin Bay has probably accelerated natural processes of sedimentation there.

CHAPTER 2

BIOLOGICAL FEATURES OF THE ESTUARY

A EUTROPHIC ENVIRONMENT

Symptoms of eutrophication have been evident in the estuary since the late 1960s; the masses of rotting algae accumulating on the shores and clogging fishermen's nets indicated that there was a plentiful supply of nutrients available to algae. However, the nature of the problem and the source of the nutrients only became clear with progress of the study (DCE Report No. 9).

There had been little warning that the estuarine environment was deteriorating, apart from complaints of fishermen about algae fouling their nets in the late 1950s and early 1960s. At that time the algal growth appears to have been attributed to closure of the bar and consequent stagnation of estuary water.

There was no evidence of nutrient enrichment when CSIRO Division of Fisheries conducted a hydrological survey of estuaries of the south-west in 1945-50 (CSIRO, 1952-57). The nutrient levels were then no higher in Peel Inlet than in any of the other estuaries surveyed. The rich growth of the seagrass *Ruppia*, which fishermen say characterized Harvey Estuary, is evidence of a healthy rather than a seriously nutrient enriched ecosystem.

The algal accumulations of the late 1960s and most of the 70s consisted predominantly of a single species of green alga, *Cladophora*, which carpeted the bottom of the eastern half of Peel Inlet. Harvey Estuary was largely free of macroalgae, then as now, except north of Dawesville.

When Report No 9 was written in 1980, two changes to the estuarine flora indicated a possible worsening of the eutrophic condition of the estuary: the increase in abundance of other species of macroalgae and the occurrence of dense phytoplankton blooms, especially of the blue-green algae *Nodularia*.

Since then, even though there has been no increase in macroalgae, and even at times a decrease, it is clear from the massive phytoplankton blooms that there has been further deterioration in the eutrophic condition of the estuary. This is underlined by the experience of 1984 when the *Nodularia* bloom was on the same scale as in previous years, despite a substantial reduction in the amount of phosphorous entering the estuary as compared with the four previous years. The probable reasons for this progressive deterioration are discussed later.

THE NUISANCE ALGAE

The nuisance algae of the estuary are principally of two radically different kinds: the large 'weed' or macroalgae and the planktonic *Nodularia*. The macroalgae are initially benthic, though not necessarily attached to the bottom, but they float to the surface and drift to the shallows where they accumulate and are washed onto the shores in varying stages of decomposition. While the masses of weed covering what was once clean sand are unattractive, it is their decomposition by bacterial action to a black sludge with the evolution of hydrogen sulphide gas that is especially distressing to residents. Much of the floating weed collects in shallow water 100 to 200 m offshore and decomposition is often well advanced before the weed reaches the shore.

The bulk of the weed now growing in Peel Inlet consists of a few species of green algae (Chlorophyta), species which have been in the estuary all along, but have increased greatly in abundance as a result of the nutrient enrichment. The various species differ in growth form and to some extent in the nature of the problem they cause. Until 1979 the principal species was *Cladophora montagleana* (goat weed), which grew as small cotton-wool like balls that formed a carpet over the bottom.

Since 1979 *Chaetomorpha linum* (rope weed) has been abundant and replaced the ball form of *Cladphora* as the commonest species. It grows as long, coarse filaments which often hang throughout the water body. From early 1983 the sea lettuce, *Ulva lactuca*, became abundant, particularly in water of half to one metre depth where the weed harvester could not work efficiently.

From early 1984 *Enteromorpha intestinalis* was the commonest algae. From time to time various species of red algae (Rhodophyta) have also been abundant.

These changes in composition of the macroalgae appear to be related to the decreasing clarity of the water and the consequent reduced light available to benthic plants. A disturbing feature of the change is that while both *Cladophora* and *Chaetomorpha* were relatively slow to decay, and easy to remove by the tractors, *Ulva* and *Enteromorpha* rapidly disintegrate in the shallows to a sloppy ooze that is difficult to remove. Moreover, with the rapid breakdown the contained nutrients become more rapidly available for re-use by other algae.

Research has concentrated on the biology of *Cladophora*, as reported in DCE Report No. 9 and elsewhere; while it is reasonable to extrapolate from these studies to other algae, as far as the potential for management is concerned, it must be noted that knowledge of the biology of other species is limited.

Macroalgae are not now abundant in Harvey Estuary, except north of Dawesville, probably mainly because light penetration to the bottom is greatly reduced by fine sediment resuspended in the water by wind and wave action.

This situation favours growth of phytoplankton; diatoms, dinoflagellates and especially Nodularia. The microscopic filaments of Nodularia are normally mixed throughout the water, but because the cells contain air they float to the surface in calm weather. There they form a green scum which is driven ashore by the wind where it decomposes with the evolution of hydrogen sulphide gas accompanied by the peculiarly nauseating smell characteristic of Nodularia.

Nodularia spumigena is a blue-green alga (Cyanophyta), (alternatively classified as a bacteria, Cyano-bacteria). Chains of cells form the fine filaments which can just be seen by the unaided eye. Nodularia grows rapidly, with a doubling time of 2-3 days, and under favourable conditions a bloom can develop to maximum size in 3 or 4 weeks (Fig. 2.1).

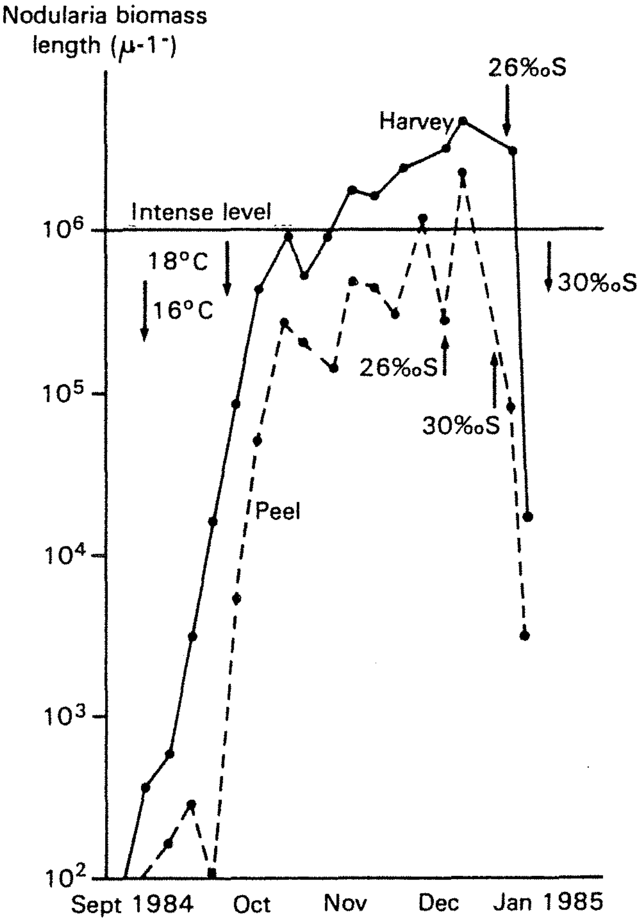


Figure 2.1. Mean Nodularia biomass in Peel Inlet and Harvey Estuary, surface to bottom integrated samples (A Huber).

In addition to its accumulation and decomposition on the beaches and unpleasant smell, Nodularia is a nuisance because the dense blooms so reduce light penetration into the water as to prevent growth of other plants and prevent fishermen seeing schools of fish. The dense blooms exhaust the oxygen in the water and result in the death of benthic animals and small fish. The scum formed in calm weather is unaesthetic. Nodularia spumigema is toxic if taken into the digestive tract and stock may die after drinking water containing Nodularia. Fish deaths have also been reported to be attritutable to Nodularia toxins. However, there is no evidence of either stock or fish being killed here, either from Nodularia or from the brief blooms of other toxic blue-green algae while the water was still fresh. Fish mortality, sometimes experienced locally during blooms, is believed to be caused by lack of oxygen following collapse and decomposition of the blooms.

Certain other features of the biology of Nodularia are relevant to understanding its role as a major nuisance alga. The filaments have special cells (heterocysts) which have the property of fixing molecular (atmospheric) nitrogen so that Nodularia is independent of the nitrates and ammonia on which most plants depend as a source of nitrogen. Other cells (akinetes) form resting spores which stay dormant in the sediment from one season to the next and germinate in spring when the water temperature reaches about 16°C. Although Nodularia can grow throughout the wide range of salinity experienced in the estuary, growth slows at salinities greater that 30 ppt, (Fig. 2.1) probably because the heterocysts no longer function efficiently in fixing nitrogen.

Small blooms of other species of planktonic blue-green algae have occured in Harvey Estuary in winter when the water was fresh. Some of these are also known to be toxic.

A benthic blue-green alga, Oscillatoria, has also been common in Harvey Estuary since 1982. This forms a slimy felted mat on the surface of the sediment and when growing strongly breaks off in lumps that float to the surface. These are unsightly, but so far have only been a minor problem in the estuary. Oscillatoria is common in eutrophic waters elsewhere.

LIMITING FACTORS FOR PLANT GROWTH

Aquatic estuarine plants require a complex of appropriate physical and chemical conditions for optimum growth. The size of the crop may be limited by any one of a number of factors and this 'limiting factor' may be the nutrient, usually nitrogen or phosphorus, in shortest supply or by inappropriate levels of light, temperature, salinity, water movement, the availability of suitable substrates for attachment, or by the abundance of grazing animals. The limiting factor may change from time to time and it can be difficult to determine which is limiting at any particular time.

LIGHT

When the estuary water is clean there is ample light for plant growth throughout the shallow water of the estuary. However, in spring or early summer plankton blooms are now so dense as to inhibit growth of benthic algae.

In Harvey Estuary light penetration is further reduced by resuspended sediment so that there is now insufficient light for growth of benthic plants (algae or seagrasses) most of the time. There are also times when Nodularia blooms are so dense as to be self-shading, making light the limiting factor for its growth.

Too much light may also inhibit growth of aquatic plants adapted to relatively low light intensities. Nodularia may be killed by the high light, and temperature, levels when it forms a scum, if this condition is prolonged.

TEMPERATURE

Water temperature affects the rate of algal growth, but temperatures experienced in estuary water probably never limit growth of the weed species. However, temperature is an important limiting factor for Nodularia; the akinetes require a temperature of 16^{o}C to germinate and blooms only form at temperatures greater that 18^{o}C (Fig. 2.1).

With respect to growth rates, it is relevant to note the following approximate times for doubling the biomass of important plants in the aquatic ecosystem under optimum conditions for growth: Cladophora 5-6 days, Nodularia 2-3 days, planktonic diatoms 24 hours, benthic bacteria 2-3 hours.

SALINITY

The extreme range of salinity experienced is an important factor in limiting the diversity of plant and animal life in the estuary, thus favouring the relatively few species which can survive under these conditions. There is no evidence that this salinity range affects growth of the green algae, and Cladophora grows equally well over the full range of salinities normally experienced in the estuary. The very low salinity sometimes occurring in winter may inhibit growth but there will be rapid recovery when salinity again exceeds about 2 ppt. Nodularia also grows equally well over the salinity range of the estuary under laboratory conditions, however, salinities in excess of 30 ppt appear to be unfavourable under estuarine conditions - growth slows and the blooms tend to die out.

The effects of light, temperature and salinity on growth are not independent of one another, but the nature of the effects of the interaction between them is beyond the scope of this report.

NUTRIENTS

A number of different nutrients are essential for the growth of aquatic plants, as for crops on land. It is because all necessary nutrients are now present in abundance in the Peel-Harvey estuary that it has become eutrophic. Nevertheless, given that physical conditions for growth are favourable, the size of the crop of nuisance algae (weed or *Nodularia*) will be controlled by the nutrient which is the shortest in supply, it will be the 'limiting nutrient'.

The two principal nutrients which at one time or another may limit growth of nuisance algae are nitrogen and phosphorus. Algae require these nutrients in a ratio of about 10 nitrogen to 1 phosphorus by weight (plankton 7:1, benthic algae 13:1).

Most of the time it is phosphorus rather than nitrogen that is the limiting nutrient in Peel Inlet water; the N:P ratio is seldom less than 10:1 because of the very high N:P ratio in water from the hills catchment of the Murray River (generally greater that 50:1). Harvey River water, in contrast, has a ratio of only about 4:1. However, *Nodularia* is independent of this source of nitrogen because of its ability to use atmospheric nitrogen. This nitrogen is subsequently available to other plants when the *Nodularia* die and decay, so that probably there is now seldom a shortage of nitrogen in Harvey Estuary water and here too phosphorus is the limiting nutrient.

Carbon is also an essential requirement for plant growth and its availability to aquatic plants as bicarbonate may also be limiting under extreme conditions. Silica also is essential for diatoms. Neither limits plant growth in the estuary, except transiently; a shortage of carbon may briefly depress the growth of *Nodularia*, and of silica the growth of diatoms.

GRAZING

It is evident that at the present time grazing by fish or other fauna has minimal effect on the abundance of green algae. On the other hand the winter diatom blooms are heavily grazed by animal plankton (copepod crustaceans especially) and this probably accounts for termination of the blooms. *Nodularia* blooms are also unaffected by grazing; *Nodularia* appears to be unpalatable.

It will be evident from what has been said that any of the above factors can limit the growth of algae and could, in theory, be manipulated to control growth of nuisance algae in the estuary. The only factor which it appears practical to limit is the nutrient supply, in this situation phosphorus.

EXTERNAL SOURCES OF NUTRIENTS

There are three principal external sources of nutrients to the estuary: the rivers and drains, the sea, and the atmosphere. In addition there is at present a relatively small (less than 10%) input of phosphorus from sewage and other urban sources. The ocean input is more than balanced by loss to the sea and in any case this source can only be controlled by reducing exchange with the sea.

The atmosphere is a substantial source of nitrogen, the estimated input of atmospheric nitrogen fixed by <u>Nodularia</u> during one large bloom was 700 tonnes. There is also considerable loss of nitrogen to the atmosphere by diffusion. There is no significant gain of phosphorus from the atmosphere, or loss to it.

Of the average annual river input of 1200 tonnes of nitrogen more than half comes from the plateau (Table 3.2). The amount varies greatly from year to year, principally as a result of the great variation in river flow from the plateau (Fig. 1.6).

Phosphorus, on the other hand, comes mainly (about 85%) from coastal plain drainage (Table 2.1) and it will be seen that the amount varies considerably from year to year. However, the concentration in river water remained remarkably constant until 1983 and differed little between the Harvey and Serpentine rivers (Table 3.2). The input of phosphorus to the estuary thus depends principally on the volume of flow in the coastal plain rivers (Fig. 1.2) and this in turn mainly on rainfall. The lower concentrations in Harvey River water in 1984 and 1985 (Fig. 2.2) are believed to result from reduced application of fertilizers to that catchment in those two years.

The source of the phosphorus is superphosphate applied as fertilizer to soils that are naturally deficient in phosphorus. The clay soils of the plateau, and the more restricted clay and loam soils of the coastal plain, lose little of the applied phosphorus. Sandy soils of the coastal plain, on the other hand, lose phosphorus to drainage at the rate of about one third of that applied as superphosphate. This rapid loss is attributable both to the very porous nature of the soil and to the lack of clay and iron or other minerals which have the capacity to bind phosphorus.

TABLE 2.1 Annual flow and total phosphorus loads in the rivers of the Peel-Harvey catchment

YEAR	HARVEY RIVER and DRAINS		SERPENTINE RIVER		MURRAY RIVER	
	FLOW 10^6 m^3	P LOAD Tonnes	FLOW 10^6 m^3	P LOAD Tonnes	FLOW 10^6 m^3	P LOAD Tonnes
1977	116	33	49	17	93	7
1978	290	112	132	49	289	25
1979	118	52	50	14	62	3
1980	256	101	117	47	112	10
1981	343	134	170	55	392	23
1982	227	90	121	44	284	34
1983	301	111	160	59	730	67
1984	202	56	156	54	237	13
1985*	175	58	85	32		

* Approximate flows and loads

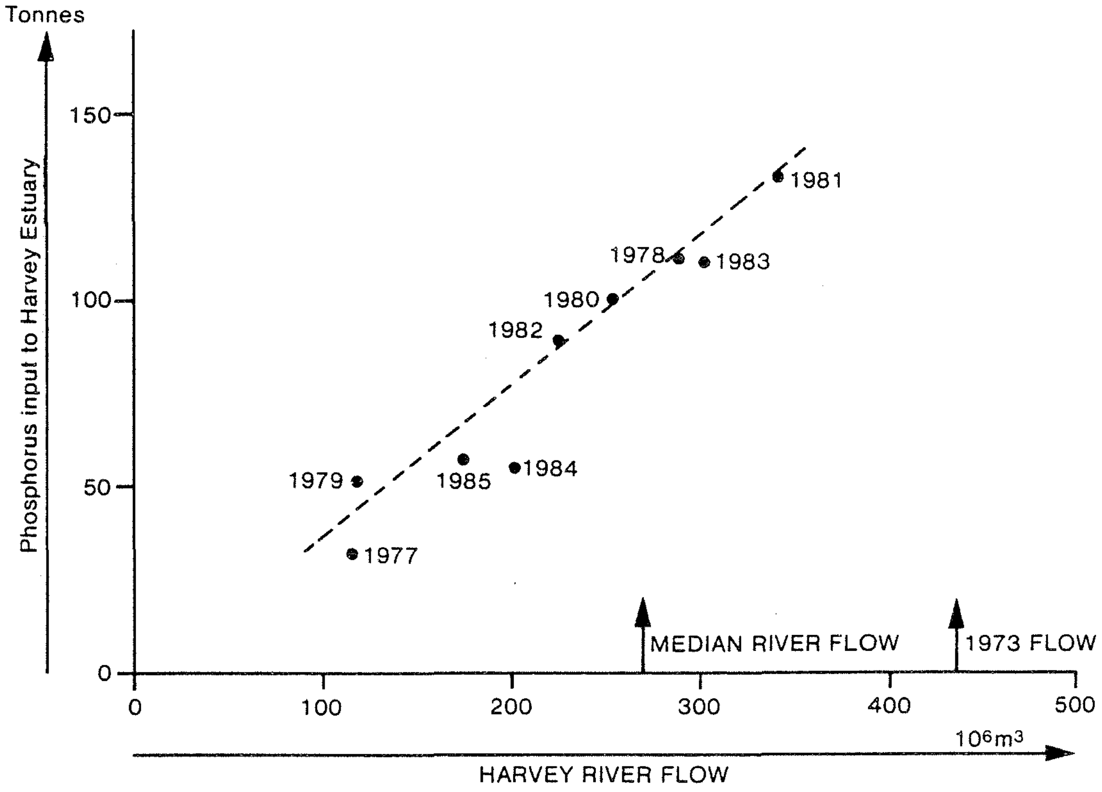


Figure 2.2. Harvey River flow and phosphorus load.

The great increase in phosphorus input to the estuary between the 1950s and the 1970s (Fig. 2.3) has been caused partly by the increased area of deep grey sands brought into cultivation in the 1970's and partly by the progressive increase in the amount of phosphorus released to drainage from the stores which have accumulated in the sandy soils. Of the phosphorus discharge to drainage, only about one third of the loss is attributable to fertilizer applied in the current year; the remaining two thirds comes from the soil store - the farmers' "super bank". On many farms, perhaps most, this store is now so large that it will probably take 5 to 10 years to run down, even if no more phosphorus is applied (Chapter 3).

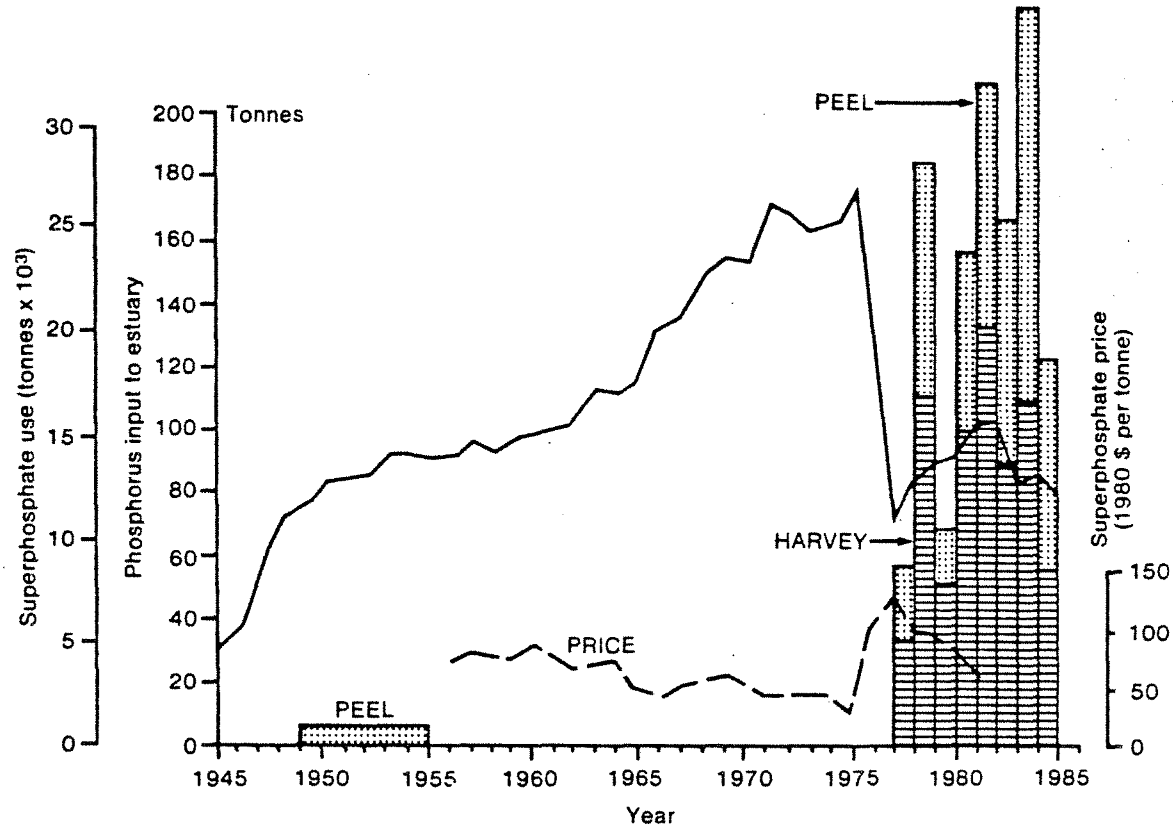


Figure 2.3. The input of phosphorus to the estuary, superphosphate use on the coastal plain catchment, and price of superphosphate.

NUTRIENTS IN THE ESTUARY

In the early stages of the investigation the estuary did not display the common features of an eutrophic aquatic environment, apart from the abundance of green algae. Most of the time there were neither the typical high levels of dissolved nutrients nor the abundant phytoplankton characteristic of eutrophic waters.

Since 1978 it has been found that there are times, albeit brief, when nutrient concentrations are very high. The estuary now also experiences massive blooms of phytoplankton. Latterly these blooms have included blooms of blue-green algae, another symptom of a eutrophic condition.

It is now clear that the total potential concentration of nutrients is high in the estuary and that much of the time there is a low concentration in the water because most of the supply is in the sediments and the algae. The available supply of nutrients is great and, under the appropriate conditions, the rate at which it circulates through the various elements of the system is high.

There is an estimated net loss of about 60 tonnes of phosphorus to the sea each year, as against an average input of about 150 tonnes from rivers and drains over the last 9 years. This excess of input over loss is not unusual in itself, what is unusual is the size of the imbalance between the two, and the development and persistence of conditions which favour the rapid recycling of nutrients within the system.

At any one time a substantial proportion of the nutrients may be incorporated in the mass of algae, of all kinds. It was estimated that in 1978 there was 55 tonnes of phosphorus in the Cladophora, then the principal alga, and probably almost as much again in other plants. However, there was also estimated to be 260 tonnes of phosphorus in the top 2cm of sediment. With the continued excess of phosphorus input to the estuary over export from it, the store of phosphorus in the sediment is being continually augmented.

The surface sediments are not an inert mass; in the upper detrital layers organic matter is being broken down by bacteria, making the nutrients available for reuse both by the abundant plant and animal life of the sediments themselves and by the plants of the overlying water.

Within the estuary the bottom sediment with its accumulation of detritus is the principal immediate source of nutrients. The diatoms of the winter bloom probably derive most of their phosphorus requirements direct from the incoming river water. However, the subsequent Nodularia and green algal crops derive their nutrient supply mainly through recycling from the sediment store. The chemical processes involved in this recycling are highly complex.

The nutrients are released to the water mainly when the bottom water is deficient in oxygen. This condition supervenes at times when there is a lot of decomposing organic matter on the bottom, such as that provided by collapse of the diatom and Nodularia blooms, by a carpet of decomposing weed, or when the water is stratified (when a layer of low salinity water overlies deeper water of greater salinity).

While the store of nutrients, particularly phosphorus, is certainly large it is not clear how much of it is present as 'available' phosphorus, phosphorus that is available for plant growth, and how much is in a chemical or physical form in which it is unavailable to plants. However, there is no doubt that with the present high levels of phosphorus coming into the estuary each winter the sediment plays a very important role in recycling enough phosphorus to support the annual Nodularia blooms.

It is unlikely that this store would long support excessive algal growth if the external supply of phosphorus was cut off. However, the experience of the last six years indicates that there is now a significant carry over of available nutrients from one season to the next and that this makes an important contribution to fertilizing the spring phytoplankton blooms and therefore to recycling phosphorus to Nodularia. (Fig. 2.4).

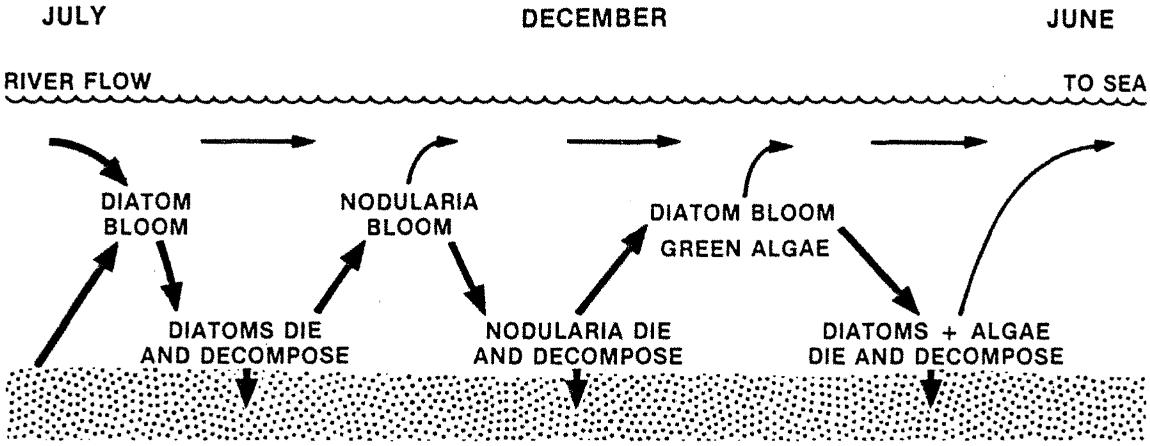


Figure 2.4. The fate of phosphorus in the estuary. The arrows represent the movement of phosphorus.

The important role played by the spring phytoplankton blooms of diatoms and dinoflagellates is shown by the rapid uptake of phosphorus for inflowing river water. Most of the phosphorus entering in the Harvey River flow is retained in Harvey Estuary by the phytoplankton, as is shown by Figure 2.5.

THE RESPONSE OF THE FLORA

The following is thought to have been the sequence of changes that have taken place in the plant life of the estuary.

The seagrasses Ruppia and Halophila are reported to have flourished in the estuary 20-30 years ago, but have now disappeared from Harvey Estuary and are relatively sparse in Peel Inlet. This seagrass loss was probably caused by a great increase in epiphytic algae, the algae favoured by abundant plant nutrients in the water, and consequent reduced light to the plants. Allender (pers comm) noted such a heavy growth of epiphytes and, apparently, the absence of seagrass from the deeper water of Harvey Estuary where the bottom was mainly black mud, in contrast to the sandy bottom in Peel Inlet.

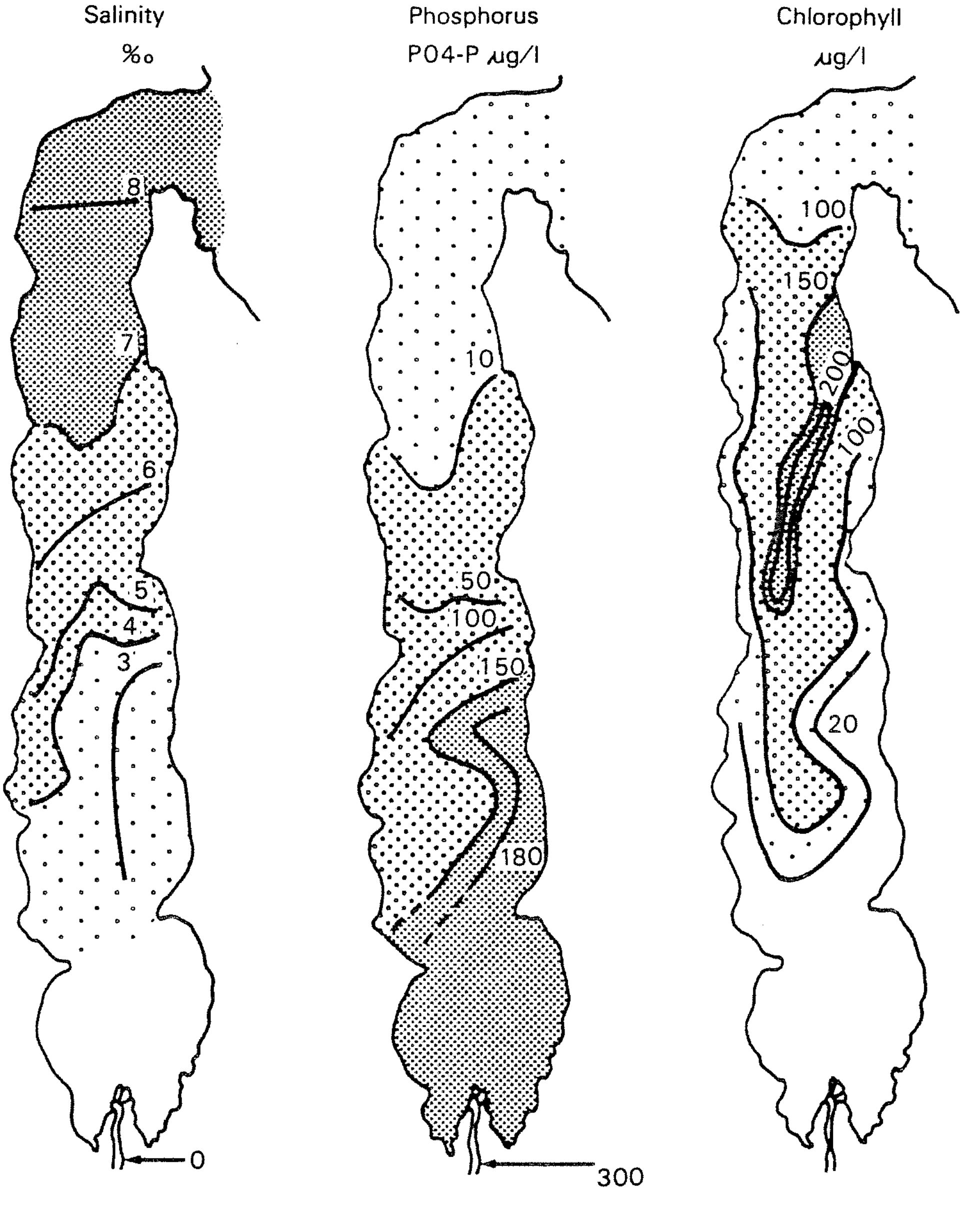


Figure 2.5. Surface salinity, phosphorus and chlorophyll concentrations in Harvey Estuary water 8 August 1983.

In Peel Inlet the decaying seagrass mass probably provided the initial detrital bed that nourished *Cladophora* growth, in the form of the benthic 'goat weed' balls that dominated the macroalgae of the estuary from the late 1960's until 1981.

The subsequent changes in composition of the algal flora, discussed above (page 14) were probably caused by the further reduction in light available to benthic plants by phytoplankton blooms which now recur annually following river flow, from August to December and sometimes into the following year.

It is difficult to measure the quantity of algae present in the water at all accurately and efforts to do so were only made at irregular intervals until recently. It seems certain that the amount of Cladophora accumulating on the Coodanup beach increased at least until 1974. In 1976 there was a thick carpet of living and decomposing Cladophora over the bottom eastern half of Peel Inlet and massive accumulations round most of the shore line (Fig. 2.6). Subsequent fluctuations in abundance, as determined by periodical surveys, are shown in Figure 2.7.

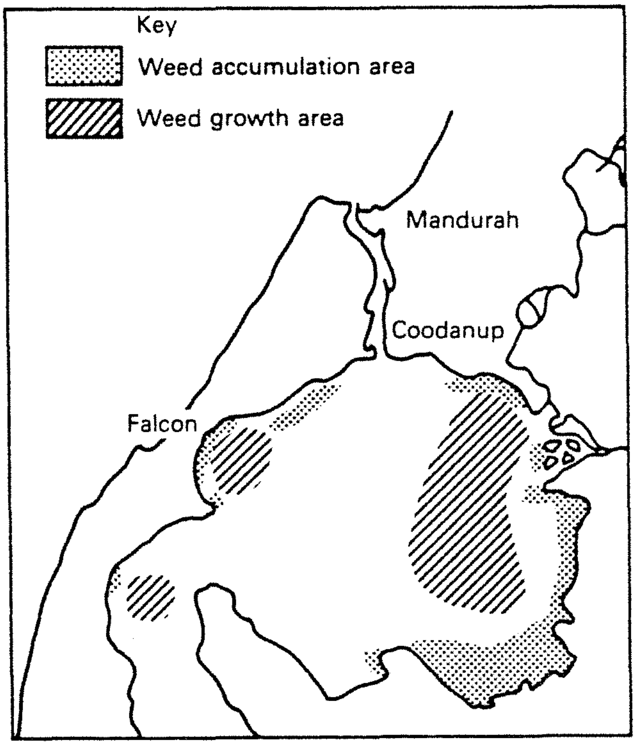


Figure 2.6. Principal areas of weed accumulation in the estuary.

In Harvey estuary the sequence of events has been somewhat different; there is no record of there ever having been the same abundance of green algae as in Peel Inlet, except north of Dawesville. Collapse of the seagrass flora must again have provided an abundant source of nutrients from the resultant detritus. In the less well flushed and more wave stirred conditions of Harvey Estuary this detritus also supplied a mass of readily resuspended particulate matter that greatly reduced light available to benthic plants. Faecal pellets now form a large part of the surface sediment.

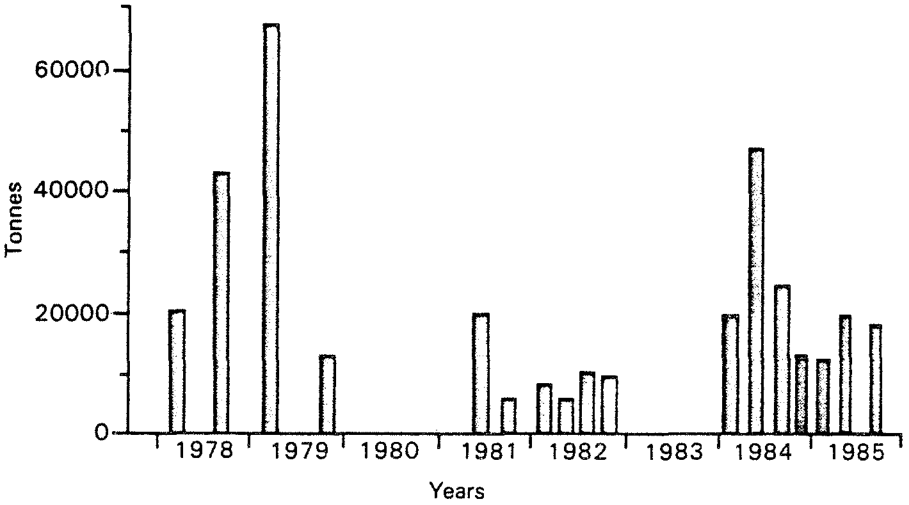


Figure 2.7. Biomass of weed in Peel Inlet at surveys (R Lukatelich).

The first sign of an algal problem in Harvey Estuary during this study was the Nodularia bloom of 1978, though blooms were recorded by Government Chemical Laboratories in the two very wet years 1973/74. There was no bloom in 1979, but there have been massive blooms in all succeeding years. The Nodularia blooms have been preceded by progressively larger blooms of diatoms and dinoflagellates (Fig. 2.8). The large post-Nodularia blooms of 1982 and 1983 were not repeated in 1984, when the water was unusually clear.

The size of Nodularia blooms in Harvey Estuary does not seem to have varied greatly since 1981 and it is probable that size is now limited more by light than by the available phosphorus. However, there has been considerable variation in the duration of blooms which appear to be terminated partly by exhaustion of available supplies of phosphorus and partly by the increasing salinity (Fig. 2.1).

The earlier decline of blooms in Peel Inlet reflects the earlier rise in salinity there than in Harvey Estuary. In most years blooms have died out quite abruptly in late December or early January, but the heavy rains of January 1981 prolonged the bloom into February when the renewed supply of phosphorus and the lowered salinity favoured peristence of the bloom.

The onset of blooms is keyed to water temperature. The resting spores (akinetes) in the surface sediment do not germinate until the temperature exceeds 16°C and blooms develop at about 18°C.

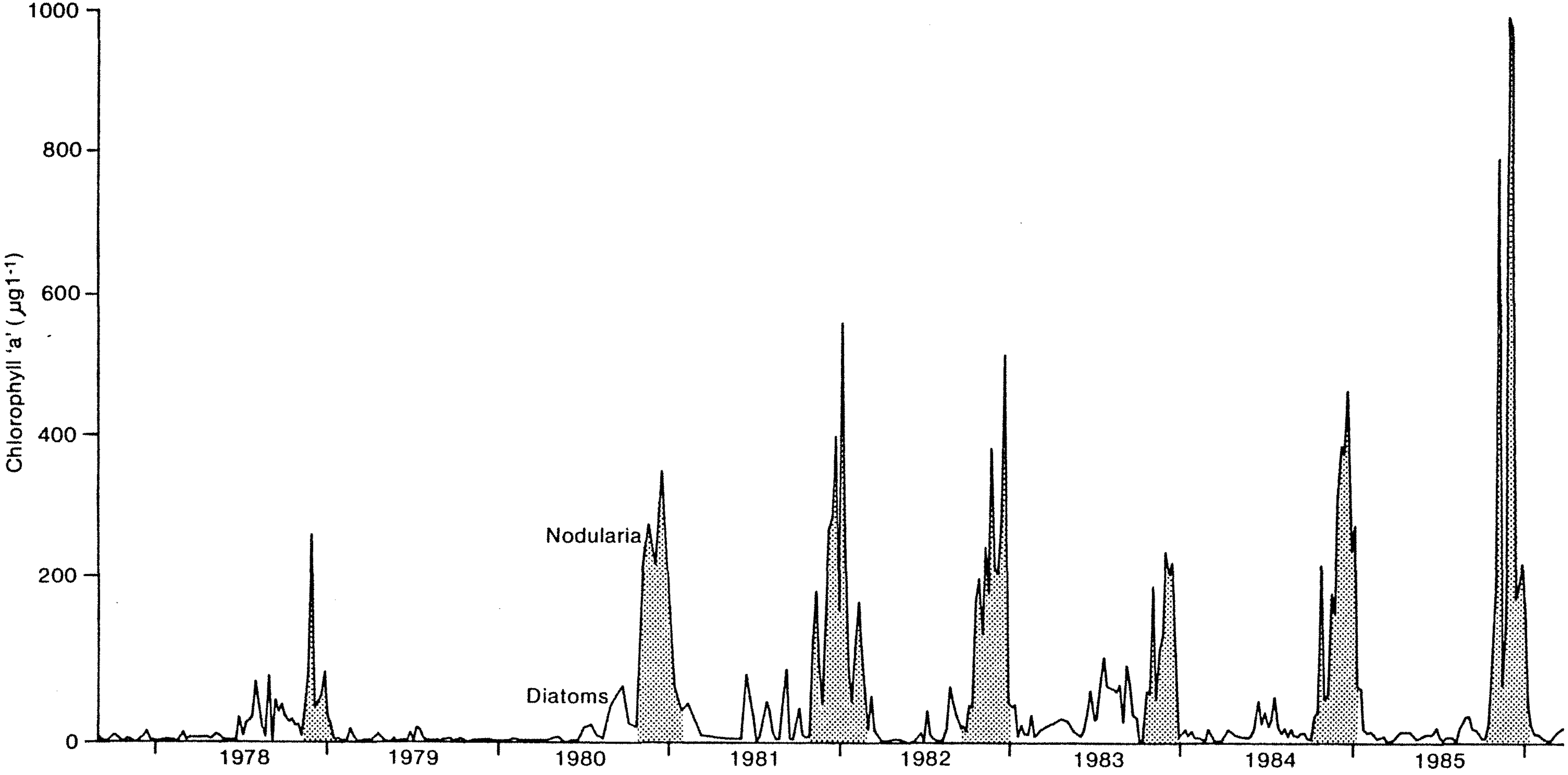


Figure 2.8. Harvey Estuary mean surface chlorophyll 'a'. (R Lukatelich).

The Nodularia bloom of 1978 was confined to Harvey Estuary and the 1980 bloom began there and spread into Peel Inlet, where there have been self generating blooms in succeeding years. Although of shorter duration they can be almost as intense as blooms in Harvey Estuary.

There is no single reason to explain the difference in response between Peel Inlet and Harvey Estuary. The two differ in several respects and there is too little information as to the past history to be confident of reconstructing the picture adequately. At the present time the salient factors appear to be as follows.

Peel Inlet is better flushed than Harvey Estuary because of the location of the Mandurah channel. The Serpentine and Murray rivers discharge to Peel Inlet only 5 km from the Mandurah channel, whereas the Harvey River discharges 24 km away at the south end of Harvey Estuary. This situation favours the retention of nutrients by phytoplankton and suspended sediment to a greater extent in Harvey Estuary than in Peel Inlet (Fig. 2.5).

The input of phosphorus to Harvey Estuary is generally greater than to Peel Inlet (Table 2.1) and the low N:P ratio of Harvey River water has probably favoured the nitrogen fixing Nodularia.

The water of Harvey Estuary is generally more turbid than that of Peel Inlet, the turbidity being caused mainly by phytoplankton and fine sediment resuspended by wave action. There is both more such material and greater wave action in Harvey Estuary than in Peel Inlet.

The surface sediment of Peel Inlet is sandy, with an average of 40% sand, while the Harvey Estuary sediments are almost pure mud throughout.

CHAPTER 3

THE SOURCE OF THE NUTRIENTS - THE CATCHMENT

PHYSICAL FEATURES AND LAND USE

The principal features of the estuary's catchment are depicted in Figure 3.1. It may be divided into three major regions: the coastal plain, the forest region, and the eastern agricultural region.

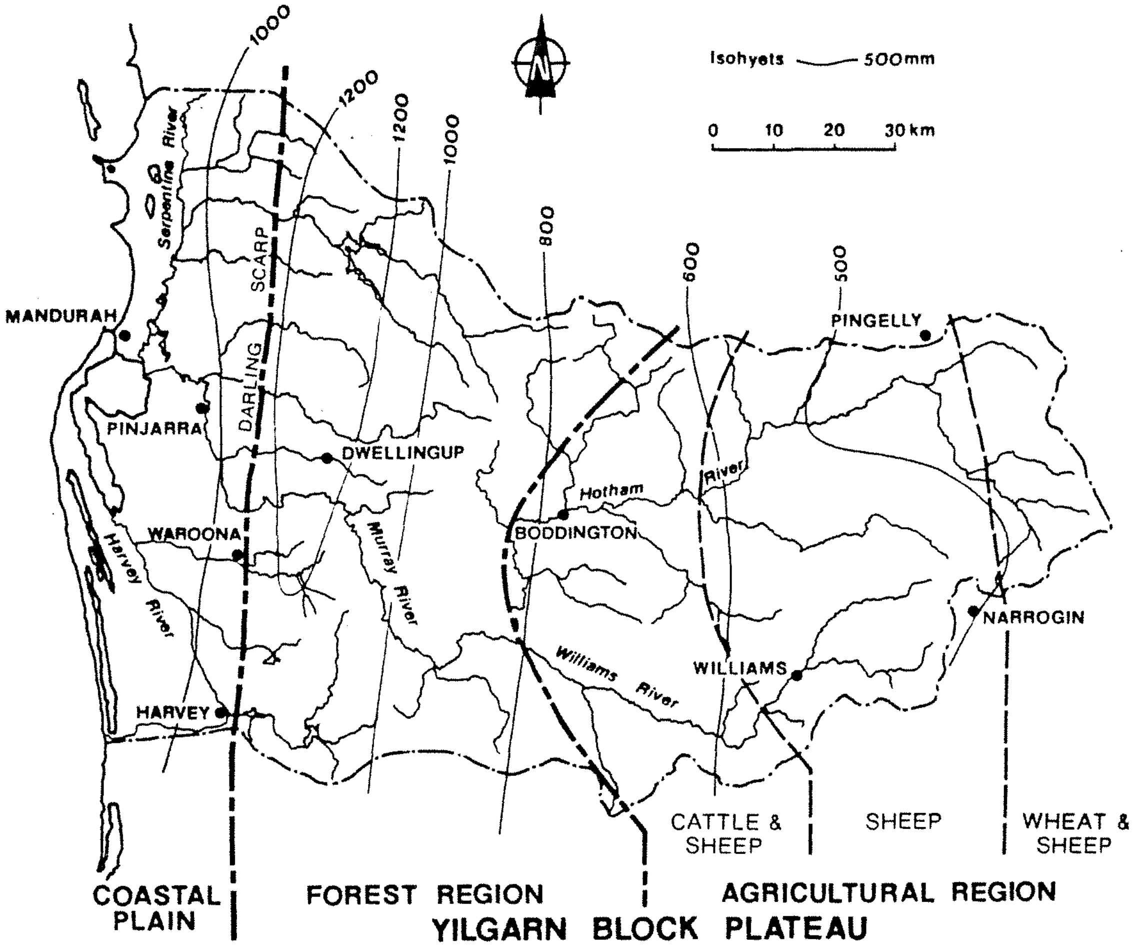


Figure 3.1. Physical features of the catchment of the Peel-Harvey estuarine system.

The major undammed catchments within the total catchment are those of the Murray River (7 600 km^2), the Serpentine River (910 km^2) and the Harvey River (plus adjacent agricultural drains) catchments (990 km^2) (Fig. 3.2). This gives a total undammed catchment area of some 9 500 km^2.

Since 1916 eight dams have been constructed in the hills with a total catchment area of 1720 km^2 giving an overall total catchment for the estuary of some 11 220 km^2.

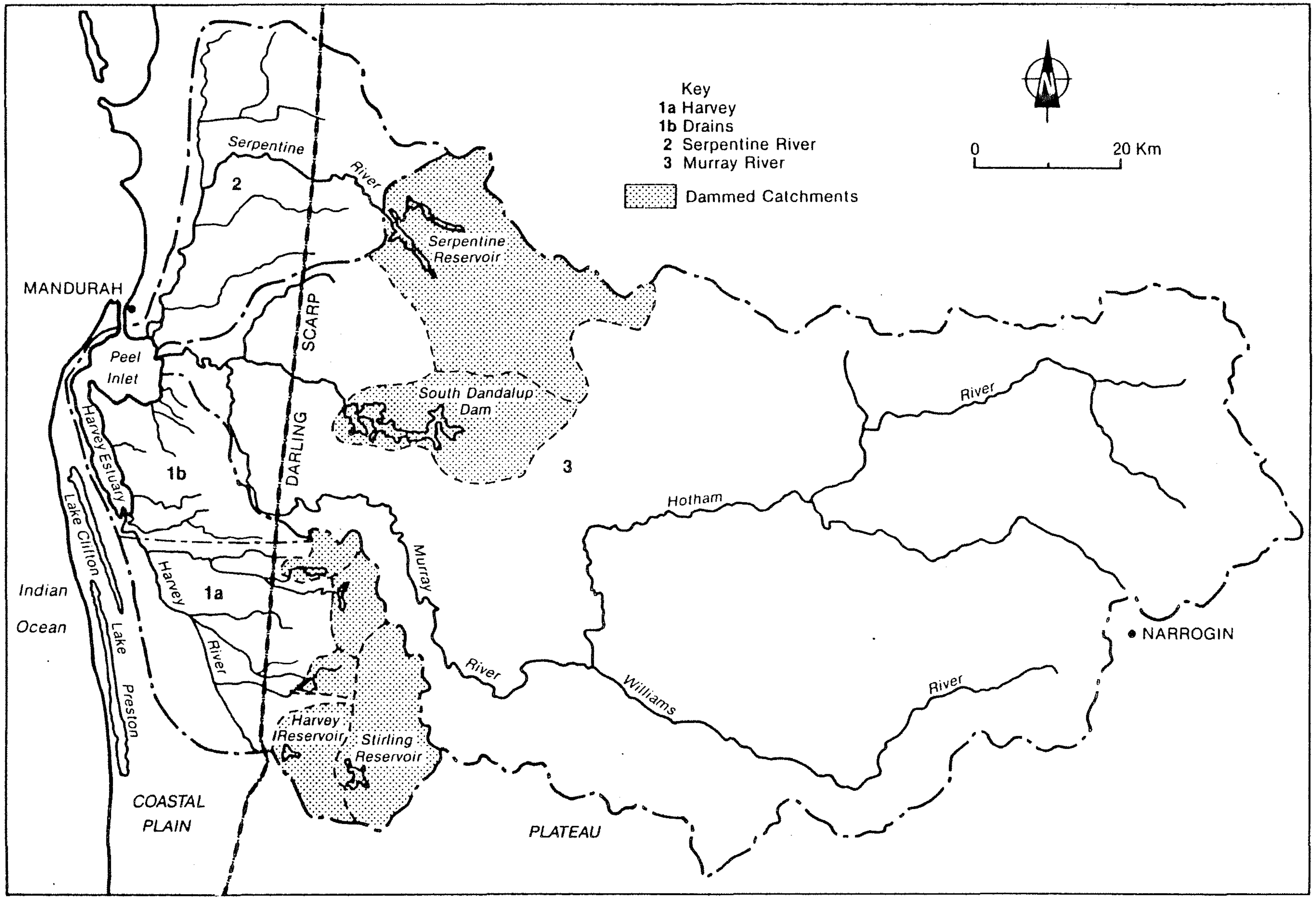


Figure 3.2. Catchment of the Peel-Harvey estuary.

Mean annual rainfall ranges from about 1000 mm per year on the coastal plain to 800-1200 mm per year in the forest region decreasing to 450-800 mm per year in the eastern agricultural region. 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 (Table 3.1). 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. 3.3). 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.

Table 3.1 Comparison of annual runoff volumes and catchment rainfall for the Harvey, Murray and Serpentine Rivers for the study period (1977-84) with the long term mean and median.

	Annual Rainfall $10^6 m^3$			Annual Rainfall mm	
River	1977-84	Long term Mean	Long term Median	1977-84	Long term Mean
Harvey & drains	230	300	270	970	1010
Serpentine	120	140	130	901	996
Murray	270	380	280	651	650

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.

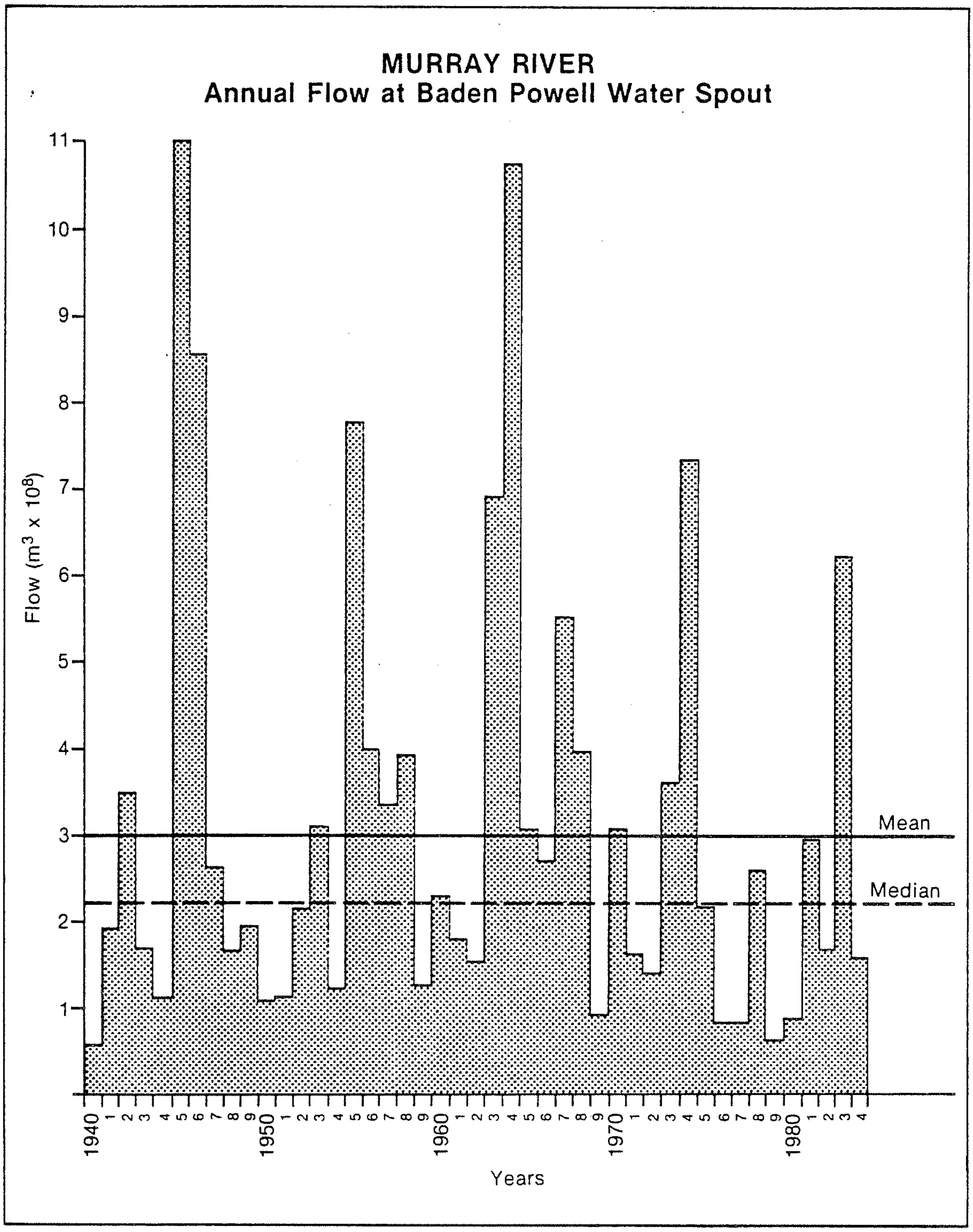


Figure 3.3. Murray River annual flows at Baden Powell Water Spout gauging Station (614006).

The coastal plain region is mostly cleared pasture for beef and dairy cattle and for sheep. Agricultural development began in the 19th century but progress was hampered by poor drainage and poor plant nutrition because the area is flat and is dominated by naturally infertile sandy soils (Fig. 3.4) with a shallow superficial groundwater system.

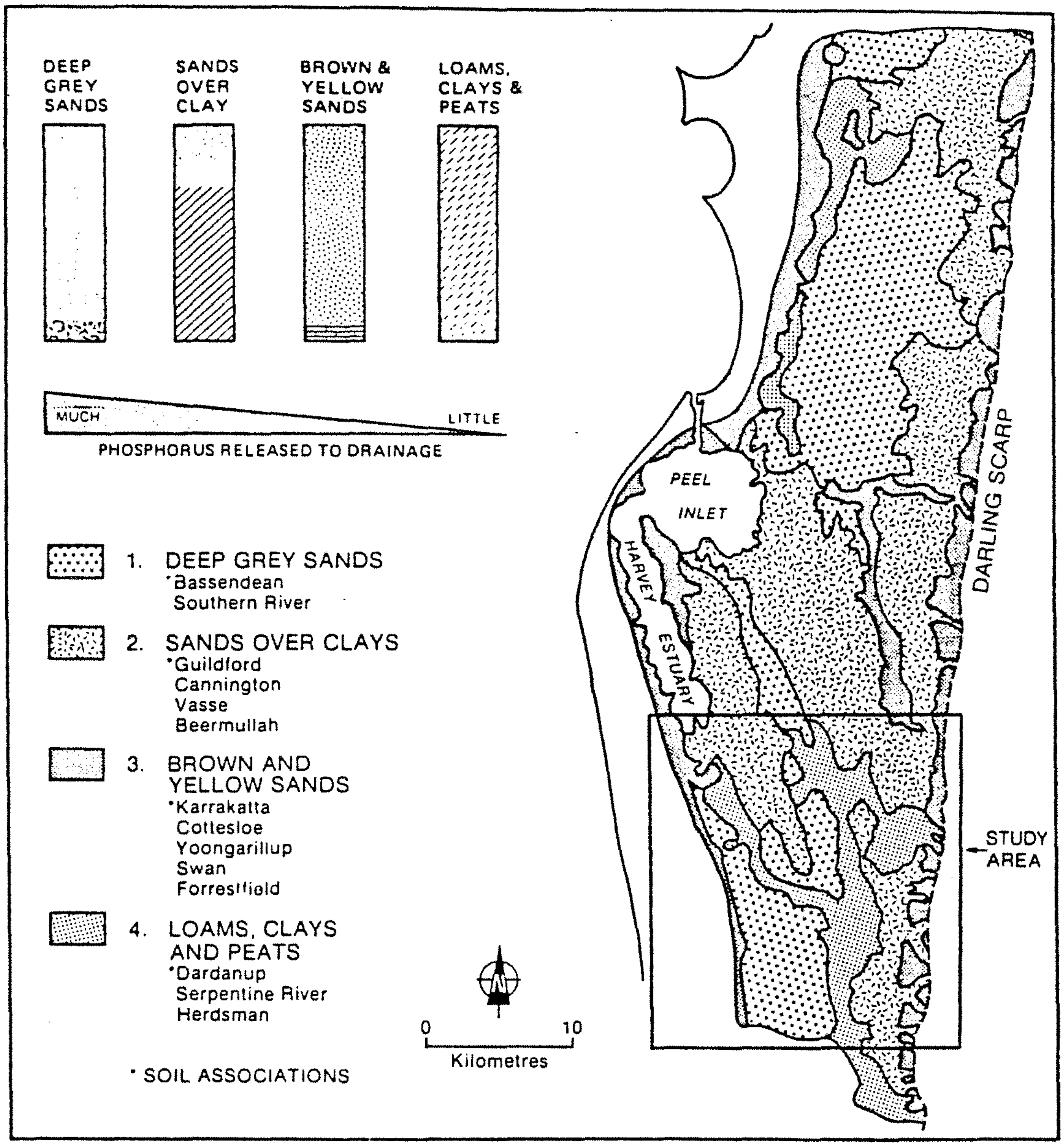


Figure 3.4. Soil categories on the coastal plain catchment of the Peel-Harvey estuary.

Since about 1900 drainage has been progressively improved so that by the 1950's an extensive network of drains both for flood relief and irrigation had been constructed and these have been continually upgraded during the period 1950-80. Improved drainage coupled with irrigation and the introduction of phosphatic fertilizers and subterranean clover since 1940 has resulted in significant advancement in agricultural development. Today the industry produces about $40 million worth of produce a year. However, the combination of continued superphosphate applications to extensively-drained, leaching sands with high winter rainfall has facilitated transport of significant amounts of phosphorus into the estuary from the coastal plain (nearly 90% of total inputs) and this is a primary cause of the waterway's eutrophication problem.

The forest region on the plateau is mostly covered with State forest composed of jarrah, marri and blackbutt. The area is one of rejuvenated drainage (Bettenay and Mulcahy 1972) with streams which have incised lateritic uplands and have cut through to basement granites and gneisses near the escarpment.

The eastern agricultural region is one of mature drainage with U-shaped valleys and flat valley floors (Bettenay and Mulcahy 1972). Soils are generally medium to heavy texture and retain applied phosphate.

Since about 1945 much of the eastern area has been cleared for livestock grazing and, in the eastern part, for cereal crops. Unlike the coastal plain local flooding has not been a problem and there is no extensive network of artificial drainage. This factor combined with generally heavier soils is the major reason why only about 10% of the total phosphorus input is derived from the plateau catchment, even though it represents 80% of the total undammed catchment area.

RUNOFF AND PHOSPHORUS INPUT TO THE ESTUARY

As previously stated nearly 90% of phosphorus inputs are derived from the coastal plain catchments of the Serpentine and Harvey plus drains catchments. Details for 1977-84 are given in Table 3.2.

Table 3.2 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 and Drains	Serpentine	Murray	Total to Estuary
Flow ($10^6 m^3$)	230	120	270	620
P Load (Tonnes)	86	42	23	151
P Conc (mg/L)	0.37	0.33	0.083	0.24
N Load (Tonnes)	380	210	610	1200
N Conc (mg/L)	1.7	1.7	2.2	1.9

SUPERPHOSPHATE USE AND PHOSPHORUS DISCHARGE

In a general sense widespread use of superphosphate since 1940 has resulted in the greatly increased input of phosphorus to the estuary (see Hodgkin et al 1980). However, in detail, it is the application to well-drained sandy soils that is of real importance. This is illustrated in Table 3.3 which shows that four times as much phosphorus was discharged from the cleared area of the deep grey sands of the Meredith Drain catchment compared to the clays and loams of the Samson Brook North catchment even though application rates of phosphorus to the latter were actually higher. An intermediate situation existed for the sand over clay catchment of the Mayfields 'G' catchment. Very little phosphorus was discharged from the partly-forested and unfertilized hills catchment of Clarke Brooke.

Table 3.3 Phosphorus export from various catchments of the Harvey Estuary. Runoff data are estimates for 1983 Winter (June-September).

	Catchment			
	Meredith drain	Mayfield G drain	Samson Brook N drain	Clarke Brook (Hills)
Area (km^2)	52	10	18	
Runoff (m^3/ha)	1200	3800	3300	4000
Drainage Density (km/km^2)	0.55	1.51	1.58	
P Conc (mg/L)	1.2	0.61	0.3	0.05
P exported[1] (kg/ha)	1.4(4.3)	2.3(2.3)	1.0(1.0)	0.20(-)
P applied[1] (kg/ha)	4(12)	12(12)	16(16)	little
$\frac{\text{P exp}}{\text{P applied}}$	35%	19%	6%	
Fertilizer History (yrs)	10-15	30-50	30-50	-
Dominant Soil Type	Deep Sands	Sand over clay	Clays & loams	Lateritic
Land Use[2]	1	1	1 & 2	3

1. Values in brackets are estimates for cleared area of the catchments.
2. Land Use Categories
    1. Non - irrigated pastures for beef and sheep.
    2. Irrigated pastures for beef and dairy.
    3. Mostly forest.

MECHANISMS OF PHOSPHORUS TRANSPORT

Understanding mechanisms of phosphorus transport in the catchments is a necessary prerequisite to devising effective management methods for reducing phosphorus input to the estuary.

As indicated earlier the transport rate is a function of

- soil type
- topography
- drainage
- fertilizer use
- rainfall

High phosphorus losses are associated with high rainfall and well-drained sandy soils to which abundant superphosphate has been applied. These are the conditions which occur over much of the coastal plain, but actual mechanisms of phosphorus transport depend on position in the landscape and soil type.

The importance of drainage density is illustrated in Figure 3.5. In Figure 3.5(b)it is hypothesized that increased drainage density increases surface and sub-surface flow and decreases evaporation while reducing flux to the deep groundwater system. This deeper system (the Leederville aquifer) does not intercept drainage to the estuary.

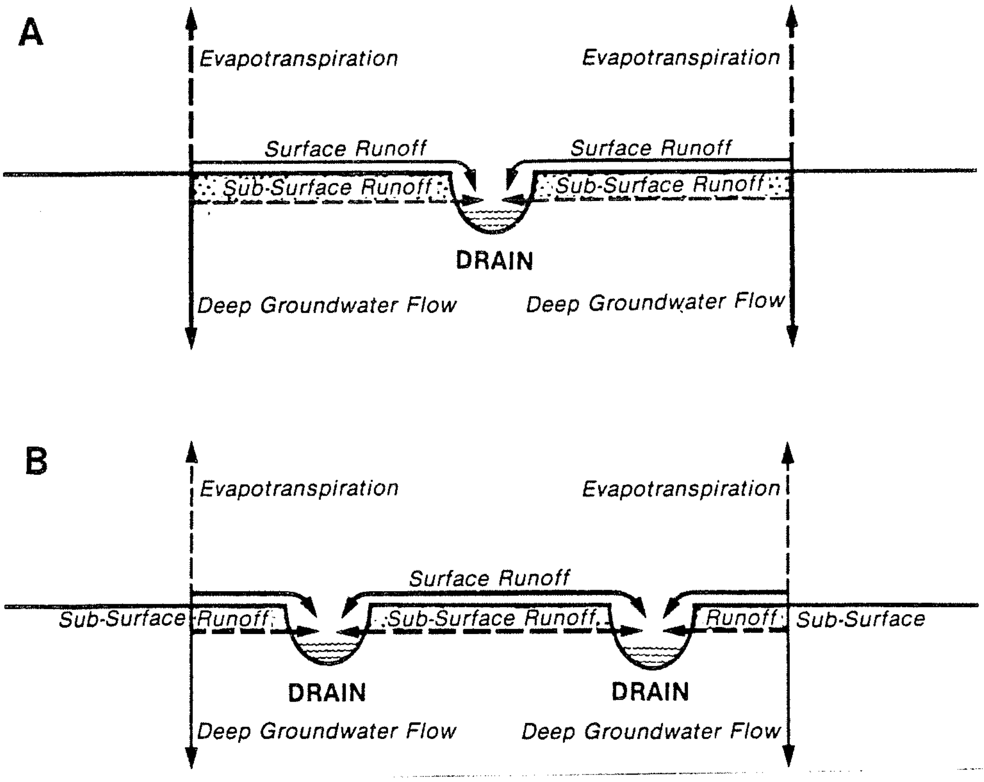


Figure 3.5. Conceptual model of effect of increased drainage density on runoff. It is hypothesised that with increased drainage density (Fig. 3.5B) that surface and near sub-surface runoff is greater whilst evapotranspiration and deep groundwater flow is lesser.

Two other major factors to consider are soil type and landscape. Within the coastal plain, soils may be broadly grouped into three major categories: deep grey sand, sand over clay, and clays and loams (Fig. 3.4). Figure 3.6 summarizes the major pathways for phosphorus movement in these soils and indicates the relative magnitude of runoff losses to the estuary from the three soil types. These are based on measured losses from the various soils and their respective areas in the Harvey River catchment. A generally similar situation would exist for the Serpentine River catchment.

Deep grey sands have the most complicated mechanism. About 60% of the phosphorus load is estimated to move via sub-surface flow, whilst about 40% travels as overland flow when the water table rises to the surface during winter on the flats. However, an unknown proportion of this (probably fairly small) is contributed from hillside seepage from the dunes (interflow). For sand over clay soils about 70% of the phosphorus load is estimated to be discharged by overland flow following saturation of the sandy horizon in early winter, the balance being delivered via sub-surface flow in the sandy horizon. For clays and loams most of the phosphorus is probably transported as overland flow.

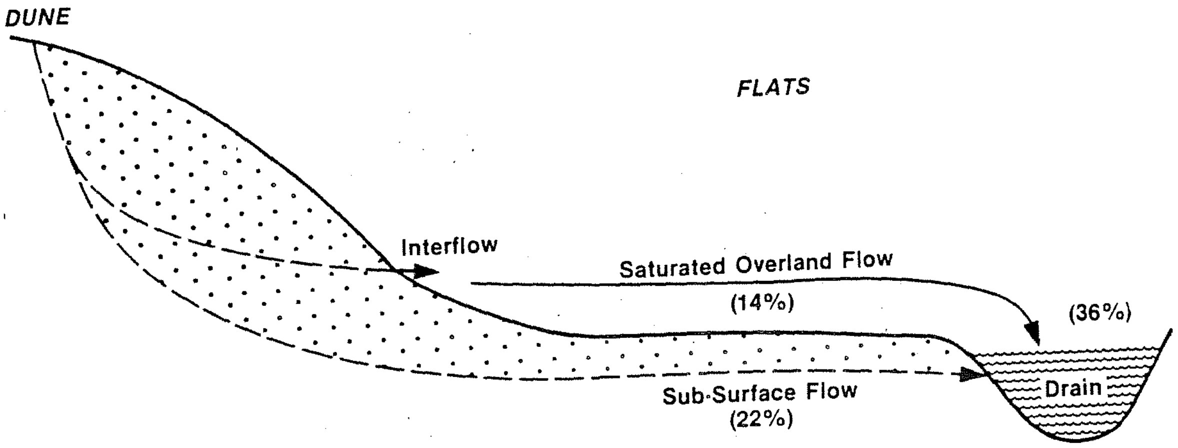
PHOSPHORUS BUDGETS FOR COASTAL PLAIN CATCHMENTS

An approximate phosphorus budget for deep grey sands and sand over clay soils is depicted in Figure 3.7. These budgets illustrate some of the details of phosphorus fluxes in the coastal plain catchments and, most importantly, show that the store of phosphorus in the surface soil is large in comparison to annual agricultural and runoff losses, especially for sand over clay soils. The budgets also show that fertilizer application rates which have been used until the Fertilizer Modification Campaign began in 1983 (those indicated in Fig. 3.7) have been in excess of losses and have therefore resulted in a gradual build up of phosphorus in the surface store. Therefore a significant reduction in application rates will be necessary to prevent further build up. Furthermore some of the present soil store is in excess of plant requirements and this should be depleted by appropriately reduced application rates. However, since, on average, only about 4% of the total soil store is removed per year from sand over clay soils, the rundown time will be slow.

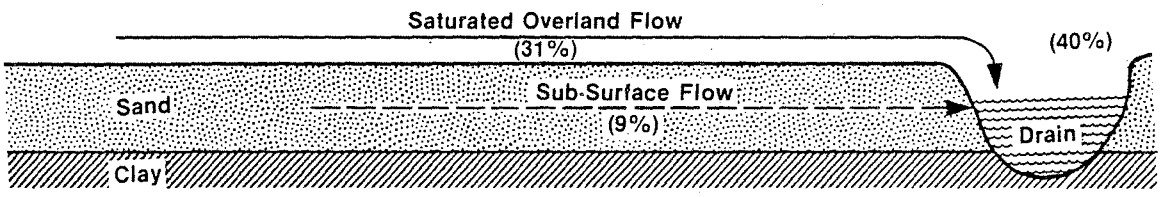
Investigations so far suggest that for an average duplex soil it could take more than 5 years, and possibly 10 to deplete the excess reserves of phosphorus.

Depletion rates would be faster for deep grey sands because less is stored and more is removed per year. Studies on these soils suggest depletion times of about 5 years are to be expected.

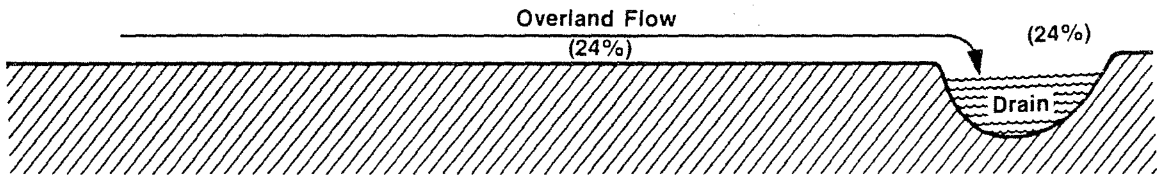
(a)
DEEP GREY SANDS



(b)
SAND OVER CLAY



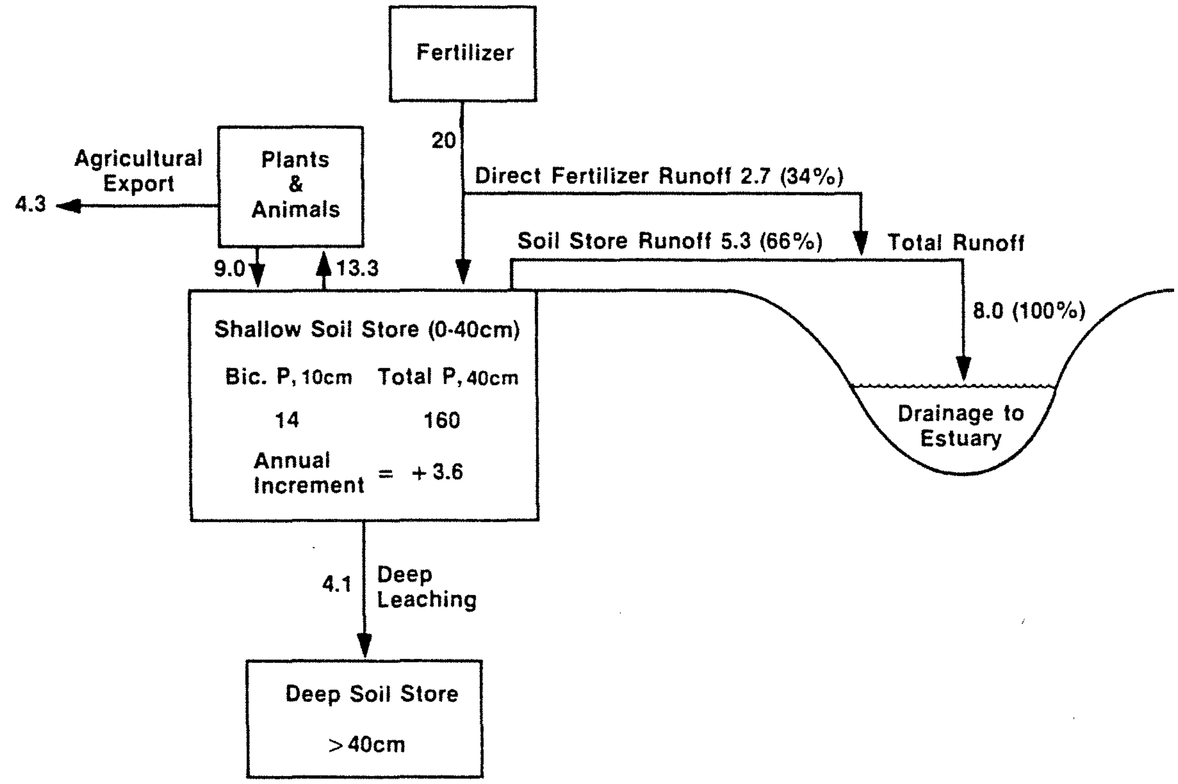
(c)
CLAYS AND LOAMS*



*Includes contribution of 25% from foothills soils

Figure 3.6. Conceptual diagram of phosphorus transport mechanisms for soil types in coastal plain catchments. Figures quoted are estimated percentage proportions of total phosphorus discharge.

Talbot Site (Deep Grey Sands)



Stacey Site (Sand Over Clay)

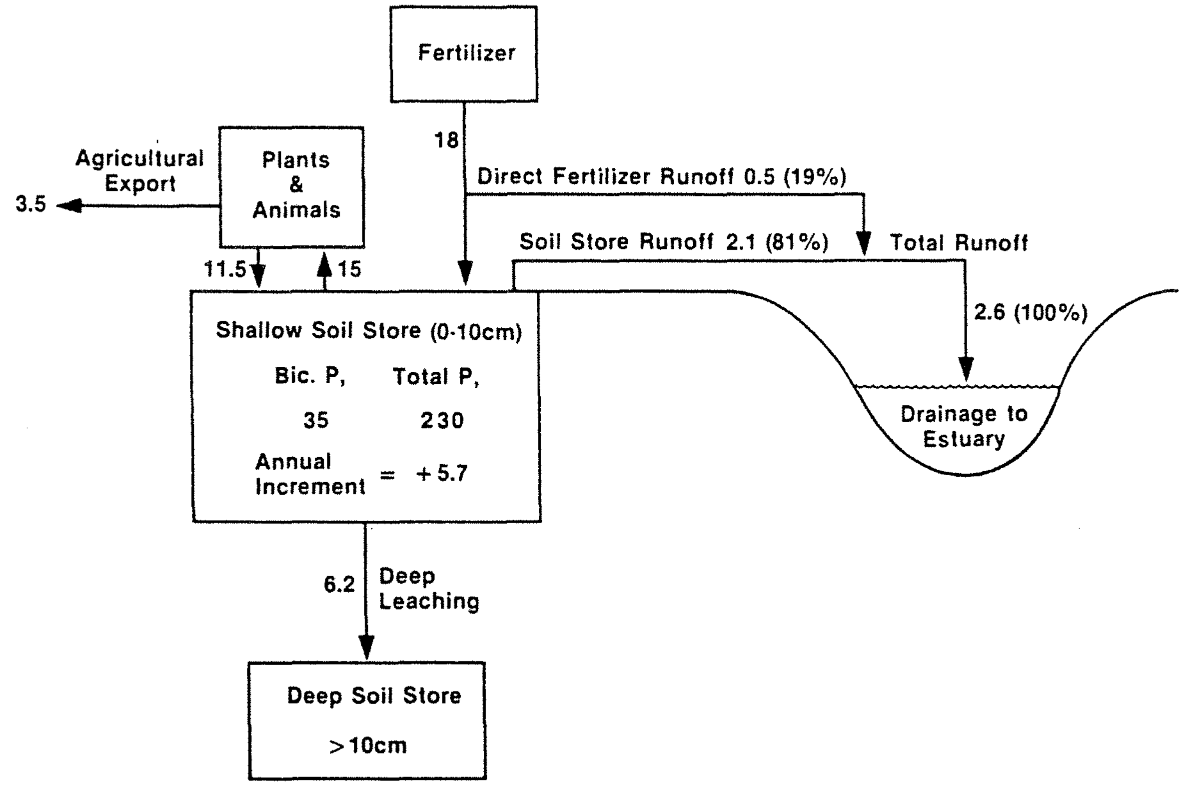


Figure 3.7. Total Phosphorus Budget in kg.P/ha/yr.

REFERENCES

The publications on which this appendix is largely based are not referenced in the text. A list of them appears in Report 14.

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