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Eutrophic waters of southwestern Australia

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Abstract

Water bodies in coastal areas of southwestern Australia are predisposed to eutrophication. The sandy soils of the catchments retain nutrients poorly, streamflow is highly seasonal, most freshwater wetlands are small and shallow, and the estuaries are poorly flushed. Nearshore waters lack the conventional upwelling of other coastal regions in these latitudes. Consequences include increased macroalgal growth and phytoplankton blooms, especially of cyanobacteria, and loss of seagrasses. Changes to fish and invertebrate populations result both from increased algal production and low oxygen concentrations. Algal toxins and outbreaks of botulism have caused waterbird casualties. Phosphorus is especially important in controlling plant biomass in freshwater wetlands and estuaries, and N in some wetlands and coastal embayments. In the examples reviewed here nutrients are derived mainly from fertilizer applications in catchments and rural industries, and from sewage and individual discharges to coastal waters.

Introduction

The biological consequences of nutrient enrichment have been well documented for water bodies in various parts of the world, including Australia, and it would not be appropriate to review this information comprehensively here. Instead, this paper presents an overview of examples of eutrophication from southwestern Australia, drawing together some of the information which has been scattered in the literature, in an attempt to seek generalisations and suggest a few areas in which it would be useful to obtain further information.

It is useful to begin with a brief comment about factors which may predispose water bodies of the south west to eutrophication, some of which are discussed in more detail in other parts of this volume. They are:

1. Soils with poor nutrient retention capacities. While there are exceptions, most soils of the south west, and especially the sands which mantle Pleistocene soils of the coastal plains, have a very poor capacity to retain nutrients. The natural soils are highly leached, and therefore generally have low ambient concentrations of available nutrients; the natural ecosystems which they carry are efficient at trapping and recycling these scarce resources, and in consequence undisturbed streams draining from them have low nutrient concentrations. The establishment of agriculture has relied extensively on the addition of nutrients, notably phosphatic fertilisers and trace elements, with N being added from fixation by legume rhizobia and nitrogenous fertiliser. When the natural vegetation is disturbed or replaced with agricultural systems, streamflow concentrations of nutrients increase sharply; their downstream effects on otherwise oligotrophic systems are especially obvious. On sandy soils, both P and N are lost to drainage; for the lateritic uplands, streamflow concentrations of N increase in relation to the amount of catchment cleared, but these soils

retain P more effectively than do the sands of the coastal plains [35, 2, 4, 40].

2. Streamflow is highly seasonal. Much of the south west has a Mediterranean climate with hot, dry summers and heavy winter rainfall and consequent winter streamflow. To the south the rain is distributed more uniformly across the seasons (although still much heavier in winter), while further inland rainfall is more erratic. At the end of the dry season, much of the pasture and crops has been removed or become desiccated *in situ*, and the soil surface is largely exposed and devoid of vegetation; the nutrients which remain in the soil have become largely mineralised. Towards the coast, farmers spread fertilizer towards the end of the dry period, because it is difficult to move machinery when the soil is saturated. The season often 'breaks' with heavy rain, which transports much of the available nutrients in streamflow.
3. Morphological features of wetlands. The south west has a diversity of natural wetlands, but the areas of open water which they contain are rarely more than ponds by international standards [30]. They are usually small and very shallow. They often do not have significant inflows of surface water, and if they do, the streams entering them usually drain agricultural land. In addition, few have significant outflows; this means that the water is concentrated by evaporation, so that the wetlands are vulnerable to the accumulation of dissolved substances such as salt and nutrients [16, 17]. In many cases the wetlands are surface expressions of the regional groundwater table, and their water quality may be strongly influenced by that of groundwater; in urban areas they are vulnerable to the effects of dissolved nutrients moving through the sandy soils referred to above [10].
4. Coastal waters lack conventional upwelling. Unlike other north–south oriented coasts of the southern hemisphere, that of the west coast of Australia lacks a strong, wind- and current-induced upwelling. As a consequence, southwestern Australia does not have a large offshore fishery, and its waters are nutrient poor. However, it does have extensive and characteristic nearshore macrophyte communities, especially seagrasses, and supports a large rock lobster industry; presumably these nearshore communities are very effective at trapping and recycling nutrients. This raises the possibility that the system may be particularly sensitive to nutrient enrichment, and as shown below, the communities of primary producers are strongly affected by nutrient addition.
5. A heritage of poor land-use and management decisions in the past. There is an increasing consciousness of the need to protect diminishing water resources in the face of an increasing population, whether for drinking purposes, garden watering, conservation or aesthetic reasons [42]. However, the quality of water in wetlands is in part a heritage of past decisions. Where they lie in agricultural land they may be grazed to the shoreline; they may be surrounded by heavily-fertilized vegetable gardens, sited near them because of the proximity of water and peaty soils; or they may lie in an urban area where they receive stormwater drainage or seepage from refuse disposal sites or septic tanks. Not surprisingly, although they may in principle be set aside for conservation and passive recreation, their waters are likely to show symptoms of eutrophication.

It may be emphasised here, however, that it has been a policy of successive governments to protect the catchments of reservoirs used to supply water for human consumption, and such catchments in the south west lie in uncleared forest subject to little disturbance apart from controlled logging. Although kept under review, eutrophication is not a major management problem for reticulated supplies to the larger urban areas of the south west.

Consequences of nutrient enrichment in southwestern water bodies

1. Primary producers

It is convenient to distinguish between the major functional groups of phytoplankton (including algae and cyanobacteria or 'blue-green' algae), macroalgae, and aquatic higher plants (including seagrasses).

(a) Phytoplankton

Planktonic species obtain dissolved nutrients from the surrounding water. If light and temperature are not at growth-limiting levels, the addition of an appropriate spectrum of nutrients will lead to an increase in phytoplankton growth rate. If the organisms are not lost from the system as rapidly as they reproduce, for example through grazing, there will be an increase in biomass; it is the increase in biomass, not the increase in growth rate, that is perceived as a symptom of nutrient enrichment. Conversely, an increase in the phytoplankton biomass of a water body immediately suggests nutrient enrichment from anthropogenic sources. It is clear that, while physical factors may limit growth rates under particular conditions, the addition of nutrients to many southwestern water bodies is all that has been required to lead to an increase in phytoplankton biomass. Thus high concentrations of phytoplankton have been reported for a number of water bodies, and attributed to nutrient enrichment. For example, three lakes – one in an established urban area, one in an area rapidly becoming urbanised, and one in a national park – showed very different phytoplankton population size [20]. Fertilizers applied to domestic gardens or grassed recreational areas are the principal sources of nutrients to urban wetlands on the Swan Coastal Plain and many are highly enriched [22]; concentrations of total P in the water column exceeded 200 $\mu g\,l^{-1}$ in approximately one-third of 40 wetlands studied. Enriched urban lakes in summer are characterised by large populations of blue- green algae, especially *Anabaena* [10] and *Microcystis* [46].

In shallow estuaries, the 'phytoplankton' species observed in summer may consist of benthic microalgae brought into the water column through wind-induced suspension, but planktonic genera of diatoms such as *Rhizosolenia* and *Chaetoceros* occur in winter and spring, when populations may be high in consequence of nutrient addition through streamflow. In summer in the Peel-Harvey estuarine system there are massive blooms of the planktonic blue-green *Nodularia spumigena* Mertens, and the size of the bloom is related to the amount of river flow in the previous winter [38, 39, 43].

In nearshore regions, much lower concentrations of phytoplankton are observed because of the exchange with the open ocean and consequent low residence time of water near the coast, but to the general public, concentrations of chlorophyll which are tolerated in lakes and estuaries are not tolerated in nearshore regions. In Cockburn Sound, an embayment with restricted ocean exchange, concentrations of 20–30 $\mu g\,l^{-1}$ are not considered acceptable, because they greatly exceed those found in offshore oceanic waters [9].

(b) Macroalgae

Increased macroalgal biomass is a common response to nutrient enrichment, and has been well documented in the south west. Large filamentous algae occur in fresh waters and may increase following enrichment, but it is in marine waters where there is the greatest macroalgal species diversity and biomass, and it is in estuaries where, although species diversity is less than in the open ocean, poor water exchange ensures that the effects of nutrient enrichment on macroalgae are particularly obvious.

A macroalgal problem in Peel Inlet is brought about almost entirely by increases in green algae of the genera *Cladophora, Chaetomorpha, Ulva* and *Enteromorpha*. The total biomass of all four has increased dramatically as a result of clearing of the catchments for agriculture, and the entry of nutrients in drainage to the estuary. The problem had assumed massive proportions by the mid-1960s, when the public complained of the smell of rotting algae, accumulations of algae on what were once clean, sandy beaches, the fouling of nets and boat propellers, impediments to the progress of boats by offshore algal banks, and the depression of real-estate values. Another significant change was the smothering of fringing marsh plants close to the estuary. These problems occurred in an estuary used heavily by locals and visitors from the Perth metropolitan area for recreation, fishing and crabbing, and which has the State's largest estuarine-based fishery.

The large biomass (estimated to reach some 35 000 tonnes in the estuary [43]) represents a large bank of nutrients in this enriched system [27]. The algae are essentially perennial, and in winter their growth is reduced through low temperatures, light intensities and (in some cases) by low salinity. As noted above, this period of riverflow is at a time when nutrient concentrations are particularly high in the system. The algae are able to take up nutrients in 'luxury uptake', i.e., accumulating them at higher concentrations than can be used in immediate growth, and redeploying them for growth when conditions become suitable. In addition, accumulations of algae create conditions in which the lower layers of algae and sediments, where light is attenuated by the biomass above, become anaerobic and release large amounts of nutrients, which are in part recycled and used by algae growing at the surface of the bed [45, 5, 31].

Light is often limiting in winter, and limits the growth of algae in beds or banks at all times of year; because light is so important in the control of growth rate, it strongly influences the amount of algae present in the estuary after a growing season [19, 18, 43]. Thus nutrients allow a large biomass of algae to accumulate, but light exerts an overriding control over the rate at which biomass increases.

There have been marked changes in species dominance among the algae in Peel Inlet. When the problem became most obvious, the nuisance organism was a ball-forming species of *Cladophora*, *C. montagneana* Kutz, which had not previously been recorded for Australia [21]. Over the years a deteriorating light climate has favoured *Chaetomorpha*, which is distributed through the water column, and *Ulva*, which occurs in shallows where it was once largely smothered by *Cladophora*. The deep beds of *Cladophora* were finally disrupted by a massive storm in 1978, and have never re-established [33, 32].

Macroalgal accumulations attributed to nutrient enrichment have been reported from other estuaries, including Oyster Harbour near Albany [3, 24], and Leschenault Inlet near Bunbury [37]. Rotting algae were considered a serious pollution problem in the Swan River in the 1960s and 70s, but are not currently a problem, for reasons which are not fully understood [26]. Other areas where accumulations have occurred, sufficient to arouse public comment, but which have been less extensive in space or time, include the Blackwood River Estuary and Wilson Inlet. In semi-enclosed marine embayments there are also problems – massive algal banks have replaced seagrass meadows in Princess Royal Harbour, and the increased growth of macroalgal epiphytes on seagrass leaves has been reported to follow nutrient enrichment in Cockburn Sound, as described below.

(c) Aquatic higher plants

Nutrient enrichment can lead to increases in the amount of higher plant material in aquatic systems, and especially in shallow freshwater wetlands. These macrophytes are able to take up nutrients from both water and sediments and occur on appropriate sediments down to a depth limit imposed by light intensity. Western Australia is not richly endowed with freshwater aquatics, perhaps because of a period of aridity during the Pleistocene, perhaps because of a general paucity of permanent wetlands, and perhaps because of low nutrient status. Certainly, such aquatics can extensively invade artificial, permanent wetlands (for example ponds surrounded by fertilised lawn). The introduced *Eichornia* is viewed as a major potential weed and was once well established on Lake Monger, near Perth, while the introduced fern *Salvinia* expanded rapidly in some areas, and was eliminated by hand from Tomato Lake, an urban wetland near Perth. However, there is little experimental information about these plants in the Western Australian context.

Many shallow-water, relatively pristine aquatic systems, such as Loch McNess in the Yanchep National Park, are dominated by sedge fen vegetation [44], which represents a large nutrient bank; the natural waters of such systems are nutrient poor [20].

The aquatic angiosperm *Ruppia megacarpa* Mason, which is able to grow in salt lakes and estuaries, has increased in biomass in recent years in Wilson Inlet, a mildly eutrophic estuary which receives nutrient-enriched runoff from farmland on sandy, coastal plain soils [40].

Locals complain of fouling of some of the more sheltered embayments in the estuary by rotting *Ruppia* biomass. In contrast, strongly eutrophic conditions have led to the virtual elimination of this plant from Peel Inlet; it is now found only in the extreme shallows where, presumably, light is not limiting [11] – elsewhere it has been largely replaced by macroalgae.

Nutrient enrichment can lead to the elimination of seagrass meadows over wide areas. (The term 'seagrass' is reserved for those aquatic higher plants which have submarine pollination and may be found in the open ocean [29].) The effect has been attributed to the enhanced growth of algae, which utilise nutrients from the water column and successfully compete with the seagrasses for light. In some cases large drifts or banks of algae have smothered and eliminated seagrasses, as in Oyster Harbor and Peel Inlet [3, 25]. In other instances the prolific growth of epiphytes, including both microscopic and macroscopic algae, have reduced the light reaching the leaves to growth-limiting levels. The most fully documented example has come from Cockburn Sound where, following industrial development on the shores commencing in 1955, some 3300 ha of seagrasses were lost, corresponding to 97% of the area originally occupied by seagrass and 83% of the annual organic production. The loss mainly took place over the period 1969–78 [7]. In this case, enrichment was occurring mainly as a result of the discharge of nutrients in industrial effluent, including that of a company which produces fertilisers at a factory on the shores of the Sound, with a smaller contribution from a sewerage outfall. Of several possible explanations, the prolific growth of epiphytes remained the most likely [6], and the suggestion was consistent with the growth of periphyton on artificial substrates, and measurements of light reduction in relation to photosynthetic responses to light intensity [56]. The major loss of seagrass was followed by reports of algal blooms in the area [6, 9]. More recently, light reduction by epiphytes has been shown to be critical for the survival of seagrasses in Princess Royal Harbour [41]. For a more complete discussion of seagrass loss in Australian waters see Shepherd *et al.* [55].

In summary, one can suggest from these observations and from information in the international literature (e.g. Wetzel [59]) that increasing nutrient concentrations might be expected to lead, firstly, to enhanced growth of aquatic higher plants; secondly, to the elimination of these aquatics through the growth of masses of larger algae; and thirdly, to the enhancement of algal blooms, and especially to increased blooms of planktonic cyanobacteria in fresh or estuarine waters.

2. The fauna

The increase in biomass and change in composition of primary producers resulting from eutrophication may have profound effects on the fauna, from altered habitats and food webs, and more directly, from reduced oxygen concentrations and toxins in the water. The elimination of seagrass meadows is accompanied by the loss of animal species dependent on this habitat, a reduction in species diversity, a loss of shelter for juvenile fish, and a loss of organic material to the detrital food chain on which many species depend.

Increased plant biomass can provide more food of different type with an increase in biomass and change in the composition of the fauna. Blooms of planktonic diatoms in the Peel-Harvey system are accompanied by increased numbers of grazing copepods which prevent the biomass of diatoms from reaching very high levels [36]. The consequent rain of detrital material provides one of the main mechanisms for sediment nutrient enrichment in the system [38] and the vast numbers of amphipods contribute to the detritus.

Commercial catches of scale fish almost doubled following the great increase in macroalgae and three detrital feeding species: the yellow-eye mullet (*Aldrichetta forsteri*), the sea mullet (*Mugil cephalus*) and the catfish (*Cnidoglanis macrocephalus*), were the main beneficiaries. However the increased abundance is attributed principally to the algae providing juvenile fish with additional shelter from predation, rather than to there being more of the already abundant food supply [52]. Blooms of the blue-green alga *Nodularia* appear to have had little effect on the size of the commercial catch of scale fish from the estuary [34], however, there was a reduction in abundance of sea mullet and yellow-eye mullet in badly affected areas [51, 34]. The reduced clarity of the water in these areas also forced fishermen to use gill nets instead of the more productive haul net technique normally employed.

The benthic alga *Cladophora* blankets the sediments and its initial dominance was accompanied by a decrease in prawn populations in the estuary, but these increased again when other species of algae replaced it and provided more favourable habitat [50].

In urban wetlands, those most enriched by fertilizer application generally support very large numbers of invertebrates; however, the increased abundance is usually accompanied by a decrease in richness [13, 8]. Moreover, moderately enriched wetlands support the richest invertebrate fauna and contain the greatest number of rare species [22], suggesting that a certain level of enrichment has a beneficial effect on wetland ecosystems.

Extant and decaying algal blooms provide an abundant food source for larvae of the non-biting midge *Polypedilum nubifer*. Vast swarms of midges emerge from nutrient-enriched wetlands in Perth; the midges are attracted to lights and make outdoor activities intolerable for nearby residents. The worst midge problems are near wetlands where concentrations of total P exceed 200 $\mu g\,l^{-1}$ [49].

In contrast, artificial wetlands created by sand mining in the south west are so low in nutrients that there are few algae and few invertebrates. Superphosphate is being added to the lakes to increase benthic primary and secondary production with the aim of establishing a sustainable food web to support waterbirds (J.M. Chambers, personal communication).

Increased organic material provides a respiratory substrate for microorganisms that can drive sediments anaerobic. This increases phosphate release and promotes the growth of macroalgae [31] and blooms of cyanobacteria [28]. The blooms cause shading at depth and lead to further decrease in oxygen (through lost photosynthesis) and enhanced P release [38]. These anaerobic conditions have been accompanied by massive mortality of worms, crabs and other benthic invertebrates, and localised fish kills in Peel-Harvey [51].

Several genera of cyanobacteria present in eutrophic waters of the south west are known to produce chemicals which are toxic to other organisms. Francis [15] documented the death of cattle, sheep and other animals drinking from pools containing *Nodularia spumigena* around the shoreline of Lake Alexandrina (then an estuarine basin in South Australia), providing the first scientific evidence for algal toxicity. The strain of *N. spumigena* found in Harvey Estuary can produce a toxin [53], though no toxic effects on pets or other animals have been reported from the field. However, sheep deaths have been attributed to drinking eutrophic farm dam water containing blue-greens such as *Microcystsis* and *Anabaena* [1].

Algal toxins and low levels of oxygen appear to be the main causes of the observed reduction in the numbers of species of larger predatory invertebrates, such as dragonflies (Odonata) and beetles (Coleoptera) in urban wetlands. The loss of such predators from a wetland decreases the overall diversity of the system and disrupts food chains; populations of organisms previously controlled by these predators, such as nuisance midges, may increase.

The death of waterbirds is a common feature of urban wetlands in Perth in late summer. This has been formally shown to be due to avian botulism on a few occasions [23], the toxin having been recovered from the bloodstream of a dead bird. Studies on the bacterium responsible (*Clostridium botulinum*) suggest that the warm temperatures, anaerobic conditions and high levels of decomposing organic matter which occur in shallow wetlands during summer favour the growth of *Clostridium* [47].

Nutrient limitation

While plants require an array of essential elements, N and P are of particular relevance to eutrophication; they are required in relatively high concentrations for optimum plant growth, are characteristically present at low concentrations in natural waters, and the amounts entering water bodies are likely to increase through human activity in a catchment. If these two elements are present at high concentrations, it remains possible that other factors, including other essential elements, may limit plant biomass.

Of particular importance is the presence in aquatic systems of a diversity of bacteria and cyanobacteria which are able to fix N, using as a source N_2 gas dissolved in the water and originating from the atmosphere or from sediment denitrification. Such N fixation has been demonstrated for a diversity of aquatic systems in the south west, including sediments of estuaries and lakes, the rhizospheres of emergent macrophytes, and root nodules of wetland legumes [14]. A particularly striking example of N fixation occurs in Harvey Estuary, where the summer blooms of *Nodularia spumigena* fix N_2 at high rates, and have been shown to contribute large amounts to the N budget of the estuary [28]. Thus aquatic systems supplied with relatively high concentrations of phosphate in streamflow or groundwater would not necessarily depend on external sources for N, but may develop large, nitrogen-fixing blooms of cyanobacteria. For this reason, the control of P addition is likely to be particularly significant for management of fresh or brackish water systems.

On the other hand, nearshore systems do not have the large filamentous cyanobacteria more characteristic of freshwaters, and such nearshore systems may be more responsive to N addition when P is available [54]. Fixation has been recorded in coastal waters of Western Australia for sediments around seagrass roots and for leaf epiphytes of seagrasses [48], but at low rates (which are nevertheless significant when multiplied up on a unit area basis). Blooms of the filamentous cyanobacterium *Oscillatoria* (*Trichodesmium*) occur irregularly offshore in summer [57] and rarely foul beaches, but are thought to be characteristic of nutrient-poor waters and not a response to eutrophication.

The generalisation that P is often limiting in fresh waters and N in marine systems provides a useful hypothesis for further testing in particular situations, but it should be emphasised that there are many exceptions worldwide (for discussion see [59]), and that seasonal differences might be expected in environments with extreme ranges of nutrients and salinities. More direct evidence about the relative significance of N or P comes from several sources: time-course data and N–P ratios [36, 43, 46, 61]; limiting nutrient bioassays carried out for water from the system at different times [45, 36]; laboratory and modelling studies relating macroalgal growth to concentrations of N and P; and concentrations of N and P in plant tissues.

Figure 1 shows the relationship between mean summer chlorophyll concentrations in estuaries of the south west, plotted against mean total P concentration. There does appear to be a rela-

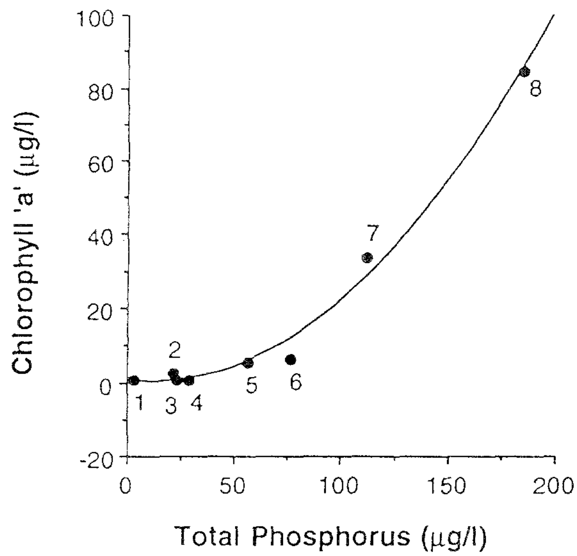

Fig. 1. The relationship between the mean concentrations of chlorophyll-*a* and total phosphorus for several estuaries in southwestern Australia. Data are for the spring and summer months. 1. Blackwood River Estuary, based on limited data for a system without obvious symptoms of eutrophication (Congdon and McComb, 1980). 2. Leschenault Inlet, a shallow system with a large biomass of macroalgae (Waterways Commission, unpublished data). 3. Princess Royal Harbour, a marine embayment showing loss of seagrass and a large biomass of macroalgae (Hillman *et al.* 1991). 4. Oyster Harbour, the estuary of the King and Kalgan rivers, exhibiting seagrass loss and large biomass of macroalgae (Hillman *et al.* 1991). 5. Wilson Inlet, an estuary exhibiting increased biomass of the seagrass *Ruppia megacarpa* without marked accumulations of macroalgae (Lukatelich *et al.* 1987). 6. Swan River Estuary, a relatively deep system with occasional, localised phytoplankton blooms and minor accumulations of macroalgae (Lukatelich *et al.* 1987). 7. Peel Inlet, a shallow system with large biomass of macroalgae (Lukatelich *et al.* 1987). 8. Harvey Estuary, a very eutrophic shallow system with large blooms of the cyanobacterium *Nodularia* (McComb *et al.* 1981).

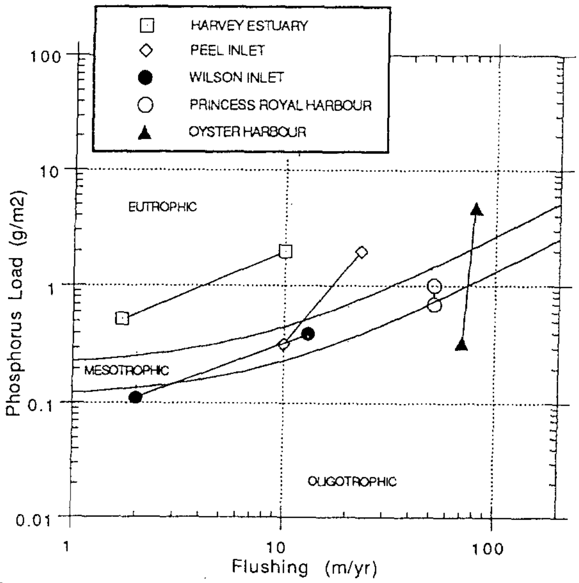

Fig. 2. Trophic status of some south west estuaries estimated from the phosphorus loading criteria developed for lakes by Vollenweider (1976).

tionship, which is not apparent when total N is used – there is much less spread in total N figures – and the relationship is consistent with the general subjective understanding of the degree of eutrophication observed in these systems.

Figure 2 shows P loadings estimated for a number of southwestern estuaries. Again, the data summarise the state of these estuaries as deduced from direct observations of plant biomass, and are consistent with the view that P is useful in defining the trophic status of these systems.

Conclusions

The freshwater, estuarine and nearshore aquatic ecosystems of southwestern Australia provide many examples of eutrophication, including increased macrophyte growth, loss of seagrasses, massive cyanobacterial blooms, and related effects on animal populations. The effects are attributable mainly to the use of fertilizers in catchments, and in some instances to industrial sources and sewage. In many lakes and estuaries, P appears of critical importance in controlling biomass, but in some lakes and nearshore systems N availability is clearly important.

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References

1. Aplin TEH and Main DC (1974) Toxic water blooms. Western Australian Department of Agriculture. Bulletin 3940
2. Barry SJ and Bell DT (1983) Water and nutrient balance in northern Jarrah forest catchments. In: Water Quality – Its significance in Western Australia, pp 110–117. Water Research Foundation of Australia: Perth, Western Australia
3. Bastyan GR (1986) Distribution of seagrasses in Princess Royal Harbour and Oyster Harbour on the southern coast of Western Australia. Western Australian Department of Conservation and Environment, Perth. Technical Series 1, 60 pp
4. Birch PB (1982) Phosphorus export from coastal plain drainage into the Peel-Harvey estuarine system of Western Australia. Aust J Mar Freshw Res 33: 23–32
5. Birch PB, Gabrielson JO and Hamel KS (1983) Decomposition of *Cladophora*. 1. Field studies in the Peel-Harvey estuarine system, Western Australia. Bot Mar 24: 381–87
6. Cambridge ML, Chiffings AW, Brittan C, Moore L and McComb AJ (1986) The loss of seagrass in Cockburn Sound, Western Australia. II. Possible causes of seagrass decline. Aquat Bot 24: 269–285
7. Cambridge, ML and McComb, AJ (1984) The loss of seagrass from Cockburn Sound, Western Australia. I. The time course and magnitude of seagrass decline in relation to industrial development. Aquat Bot 20: 229–243
8. Chambers J and Davis J (1989) How wetlands work. In: Lowe G (ed) Proceedings of the Swan Coastal Plain Groundwater Management Conference, pp 97–104. Western Australian Water Resources Publication No. 1/89
9. Chiffings AW and McComb AJ (1981) Boundaries in phytoplankton populations. Proc Aust Ecol Soc 11: 27–38
10. Congdon RA (1986) Nutrient loading and phytoplankton blooms in Lake Joondalup, Wanneroo, Western Australian Department of Conservation and Environment, Perth. Technical Series 6
11. Congdon RA and McComb AJ (1979) Productivity of *Ruppia*: seasonal changes and dependence on light in an Australian estuary. Aquat Bot 6: 121–132
12. Congdon RA and McComb AJ (1980) Nutrient pools of an estuarine system – the Blackwood River Estuary in southwestern Australia. J Ecol 68: 287–313
13. Davis JA and Rolls SW (1987) A baseline biological monitoring programme for the urban wetlands of the

Swan Coastal Plain, Western Australia – Seasonal variation in the macroinvertebrate fauna and water chemistry of five Perth lakes. Environmental Protection Authority, Western Australia. Bulletin No. 265, 80 pp
14. Finlayson M and McComb AJ (1978) Nitrogen fixation in wetlands of southwestern Australia. Search 9: 98–99
15. Francis G (1878) Poisonous Australian lake. Nature 18: 11–12
16. Froend RH, Heddle EM, Bell DT and McComb AJ (1986) Effects of salinity and waterlogging on the vegetation of Lake Toolibin, Western Australia. Aust J Ecol 12: 281–298
17. Froend RH and McComb AJ (1991) An account of the decline of Lake Towerrinning, a wheatbelt wetland. J Roy Soc West Aust 73: 123–128
18. Gordon DM and McComb AJ (1989) Growth and production of the green alga *Cladophora montagneana* in a eutrophic Australian estuary and its interpretation using a computer program. Wat Res 23: 633–645
19. Gordon DM, Birch PB and McComb AJ (1980) The effect of light, temperature and salinity on photosynthetic rates of an estuarine *Cladophora*. Bot Mar 23: 749–755
20. Gordon DM, Finlayson GM and McComb AJ (1981) Nutrients and phytoplankton in three shallow, freshwater lakes of different trophic status in Western Australia. Aust J Mar Freshw. Res 32: 541–553
21. Gordon DM, van den Hoek C and McComb AJ (1985) An aegagropeloid form of the green alga *Cladophora montagneana* Kutz. (Chlorophyta, Cladophorales) from southwestern Australia. Bot Mar 27: 37–65
22. Growns JE, Davis JA, Cheal F, Schmidt L, Rosich R and Bradley JS (1992). Multivariate pattern analysis of wetland invertebrate communities and environmental variables in Western Australia. Aust J Ecol 17: 275–288
23. Grubb WD (1964) Avian botulism in Western Australia. Aust J Exper Biol 42: 17–26
24. Hillman K, Lukatelich RJ and McComb AJ (1990) The impact of nutrient enrichment on nearshore and estuarine ecosystems in Western Australia. Proc Ecol Soc Aust 16: 39–53
25. Hillman K, Lukatelich RJ, Bastyan G and McComb AJ (1991) Water quality and seagrass biomass, productivity and epiphyte load in Princess Royal Harbour, Oyster Harbour and King George Sound. Technical Series No 39. Environmental Protection Authority, Perth, Western Australia, 44 pp
26. Hodgkin EP (1990) Eutrophication in estuaries of the southwest. Land & Wat Res News, 6: 6–12
27. Hodgkin EP, Birch PB, Black RE and Humphries RB (1980) The Peel-Harvey Estuarine System Study (1976–1980). Report No 9. Department of Conservation and Environment, Perth, Western Australia. 82 pp
28. Huber AL (1984) Physiology and Ecology of Cyanobacteria in the Peel-Harvey Estuarine System, Western Australia, with Particular Reference to *Nodularia spumigena*. PhD Thesis, University of Western Australia
29. Kuo J and McComb AJ (1989) Seagrass taxonomy, structure and development. In: Larkum AWD, McComb AJ and Sheperd SA (eds) Biology of Seagrasses, pp 6–67. Elsevier/N. Holland
30. Lane J and McComb AJ (1988) Wetlands of southwestern Australia. In: McComb AJ and Lake PS (eds) The Conservation of Australian Wetlands, pp 179–184. Surrey Beatty and Sons, Sydney
31. Lavery PS and McComb AJ (1991a). Macroalgal-sediment nutrient interactions and their importance to the nutrition of macroalgae in eutrophic estuaries. Est Coast Shelf Sci 32: 281–295
32. Lavery PS and McComb AJ (1991b) The nutritional eco-physiology of *Chaetomorpha limum* and *Ulva rigida* in Peel Inlet, Western Australia. Bot Mar 34: 251–260
33. Lavery PS, Lukatelich RJ and McComb AJ (1991) Changes in the biomass and species composition of macroalgae in a eutrophic estuary. Est Coast Shelf Sci 33: 1–22
34. Lenanton RCJ, Potter IC, Loneragan NR and Chrystal PJ (1985) Age structure and changes in abundance of three important species of teleost in a eutrophic estuary (Pisces: Teleostei). J Zool Lond 203: 311–327
35. Loh IC, Gilbert CJ and Browne, KP (1981) Nutrient concentrations of streamflow in the Murray River Basin, Western Australia. Water Resources Branch, Public Works Department, Western Australia. Report No 17
36. Lukatelich RJ (1987) Nutrients and Phytoplankton in the Peel-Harvey Estuarine System, Western Australia. PhD Thesis, University of Western Australia
37. Lukatelich RJ (1989) Leschenault Inlet macrophyte abundance and distribution. Waterways Commission Report No 15. WA
38. Lukatelich RJ and McComb AJ (1986a) Nutrient levels and the development of diatom and blue-green algal blooms in a shallow Australian estuary. J Plankton Res 8: 597–618
39. Lukatelich RJ and McComb AJ (1986b) Distribution and abundance of benthic microalgae in a shallow southwestern Australian estuarine system. Mar Ecol Prog Ser 27: 287–297
40. Lukatelich RJ, Schofield N and McComb AJ (1987) Nutrient loading and macrophyte growth in Wilson Inlet, a bar-built southwestern Australian estuary. Est Coast Shelf Sci 24: 141–165
41. Masini RJ, Cary JL, Simpson CJ and McComb AJ (1990) Effects of light and temperature on the photosynthesis of seagrasses, epiphytes and macroalgae and implications for management of the Albany harbours. Environmental Protection Authority Technical Series No 32
42. McComb AJ and Lake PS (1990) Australian Wetlands. Collins/Angus and Robertson, Australia
43. McComb AJ and Lukatelich RJ (1990) Interrelations between biological and physiochemical factors in a database for a shallow estuarine system. Environmental Monitoring and Assessment 14: 223–238
44. McComb JA and McComb AJ (1967) A preliminary account of the vegetation of Loch McNess, a swamp and fen formation in Western Australia. J Roy Soc WA 50: 105–113
45. McComb AJ, Atkins RP, Birch PB, Gordon DM and

Lukatelich RJ (1981) Eutrophication in the Peel-Harvey estuarine system, Western Australia. In: Nielson B and Cronin E. (eds) Estuaries and Nutrients, pp 323–342. Humana Press, New Jersey
46. McDougall BK and Ho GE (1991) A study of the eutrophication of North Lake, Western Australia. Wat Sci Tech 23: 163–173
47. McRoberts KM (1989) Investigation of avian botulism in an Australian urban wetland. Unpublished Honours Thesis, Murdoch University. Western Australia
48. Paling EI (1991) The relationship between nitrogen cycling and productivity in macroalgal stands and seagrass meadows. PhD Thesis, Botany Department, University of Western Australia
49. Pinder AM, Trayler KM and Davis JA (1991) Chironomid control in Perth wetlands. Final report and recommendations. Report prepared for the Midge Research Steering Committee, Western Australia
50. Potter IC, Manning RJG and Loneragan NR (1991) Size movements, distribution and gonadal stage of the Western king prawn (*Penaeus latisulcatus)* in a temperate estuary and local marine waters. J Zool Lond 223: 419–445
51. Potter IC, Loneragan NR, Lenanton RCJ and Chrystal PJ (1983) Blue-green algae and fish population changes in a eutrophic estuary. Mar Pollut Bull 14: 228–33
52. Potter IC, Loneragan NR, Lenanton RCJ, Chrystal PJ and Grant CG (1983) Abundance, distribution and age structure of fish populations in a Western Australian estuary. J Zool Lond 200: 21–50
53. Runnegar MTC, Jackson ARB and Falconer IR (1988) Toxicity of the cyanobacterium *Nodularia spumigena* Mertens. Toxicon, 26: 143–51
54. Ryther JH and Dunstan WM (1971) Nitrogen, phosphorus and eutrophication in the coastal marine environment. Science 117: 1008–1013
55. Shepherd SA, McComb AJ, Bulthuis DA, Neverauskas V, Steffensen DA and West R (1989) Decline of seagrasses. In: Larkum AWD, McComb AJ and Shepherd SA (eds) Biology of Seagrasses, pp 346–394. Elsevier/N. Holland
56. Silberstein K, Chiffings AW and McComb AJ (1986) The loss of seagrass in Cockburn Sound, Western Australia. III. The effect of epiphytes on productivity of *Posidonia australis* Hook. f. Aquat Bot 24: 355–371
57. Smith VH (1982) Predicting the effects of eutrophication: responses in the phytoplankton. In: O'Loughlin EM and Cullen P (eds) Prediction in water quality, pp 249–261. Proceedings of a symposium on water quality sponsored by the Australian Academy of Science and the Institute of Engineers
58. Vollenweider RA (1976) Advances in defining critical loading levels for phosphorus in lake eutrophication. Mem Inst Ital Idrobiol 33: 53–83
60. Wetzel RG (1975) Limnology. Saunders, Philadelphia
61. Wrigley TW, Rolls SW and Davis JA (1991) Limnological features of coastal plain wetlands on the Gnangara Mound, Perth, Western Australia. Aust J Mar Freshw Res 42(6): 761–773